UAF Department of Mechanical Engineering's
Unofficial Updated, Annotated & Expanded

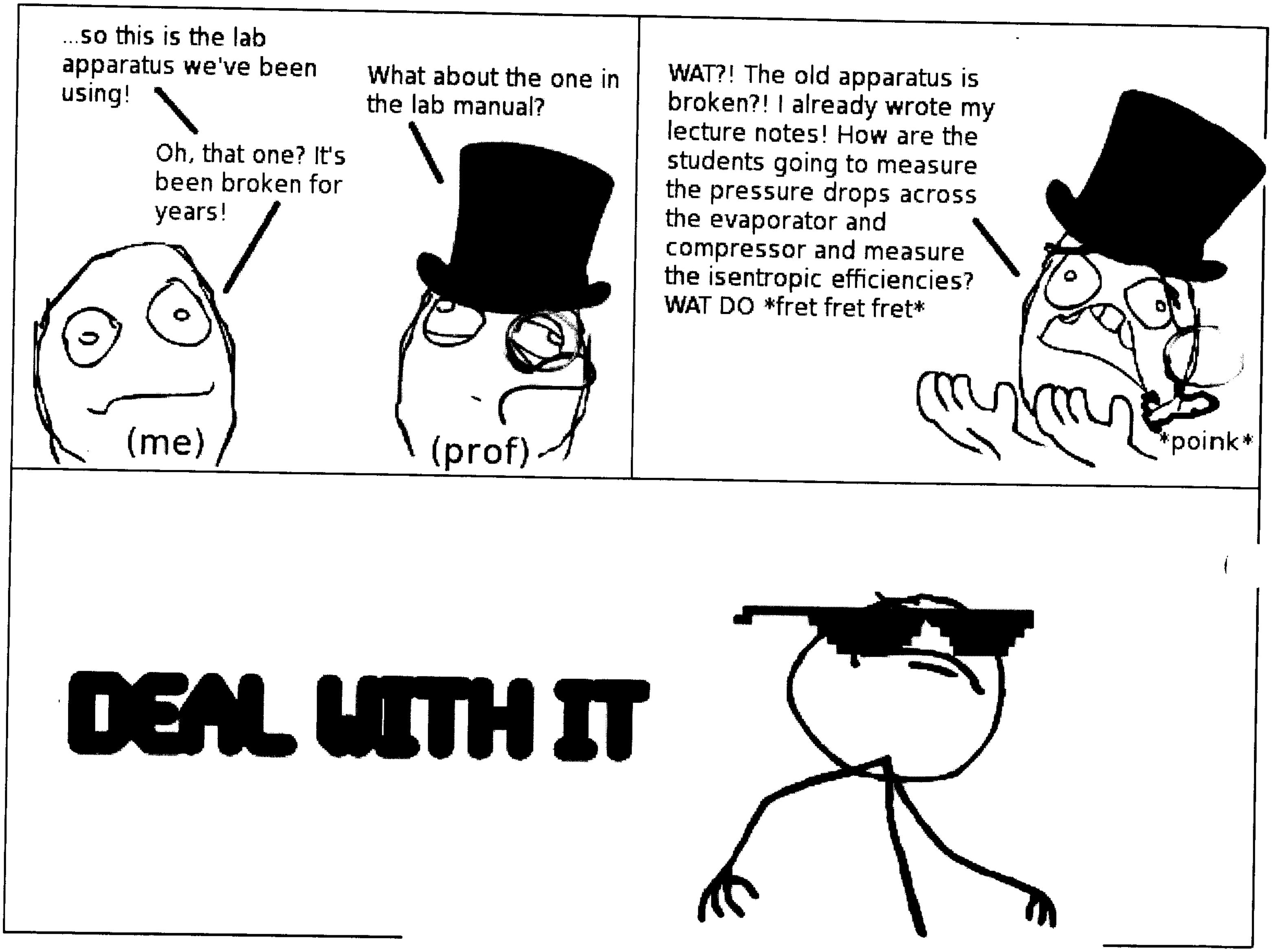
ME 415: Thermal Systems Laboratory Manual

2011 Edition

UAF™
UNIVERSITY OF ALASKA FAIRBANKS

H. Bargar, D. Das, J. Holbrook, R. Johnson, S. Kim & J. Zarling

EVERY WEDNESDAY:



...so this is the lab apparatus we've been using!
Oh, that one? It's been broken for years!
What about the one in the lab manual?
(me)
(prof)
WAT?! The old apparatus is broken?! I already wrote my lecture notes! How are the students going to measure the pressure drops across the evaporator and compressor and measure the isentropic efficiencies? WAT DO *fret fret fret*
poink
DEAL WITH IT

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Dedicated to H. Ed Bargar, PhD, PE.
Shine on, you crazy diamond.

Acknowledgements

This year's lab exercises would not have been possible without the help of Dr. Ed Bargar and Dr. Rorik Peterson. I am grateful to both.

Also: A last minute thank-you to Jeremy Spargur, who shared his lecture notes and Exam I.

Table of Contents:

Foreword to the 2011 Updated Annotated & Expanded Edition of ME 415: Thermal Systems Laboratory Manual

What a difference a year makes. Instead of being subjected to the shortcomings of ME 415, Thermal Systems Lab, I gained the responsibility of ensuring that ME 415 ran smoothly and iterated upon itself.

This manual reflects the current state of flux that this course is in. A quick history lesson: Dr. R. Johnson was, for many years, *the* Heat Transfer expert in our department. At one point in time, he wrote many of the original labs and lectured for the course. However, roughly a decade ago, he was involved in an accident that left him in a wheelchair, and effectively unable to teach lab courses. Dr. Bargar ended up filling the role, but merely kept the course afloat instead of iterating upon the labs.

Last year, Dr. Johnson officially was bestowed Emeritus status, and Dr. SunWoo Kim joined our faculty as the new Heat Transfer expert on-staff. This was his first year teaching the course, and, like all rookie faculty members, has much to learn, and given the state of ME 415 as of now, has a lot of work ahead of him.

However, even in this short period of time, Dr. Kim and I have been able to improve on this course. UAF's Mechanical Engineering department still has a lot of work ahead of itself. However, the general tone of the tome should be more hopeful.

The 2010 edition of the Updated & Annotated manual was just as much an avenue for me to vent as it was an effort to improve the documentation of the course. For examples:

> Many of the procedures in the original manual are woefully outdated. Perusal of its contents will reveal such gems as "plot on log-log paper" (that is, by hand). as well as directions for using MS DOS or some unknown, archaic form of BASIC.

> The author insists on such practices as using a DOS laptop to access Campbell data-loggers, coding said data-loggers by-hand, and more. What's worse, many of his explanations are incomplete and, at worst, wrong.

This edition of the manual, unlike the 2010 edition, contains not just annotated contents of the "traditional" manual and Dr. Ed Bargar's personal notes, but also original material detailing the current status of equipment, practical information on preparing the labs, and even some LabVIEW code where appropriate. However, some material is not included due to lack of availability, and many of the directions contained in this lab manual are still out-of-date.

As I said in the 2010 foreword, "This edition of the Thermal Systems Laboratory Manual is not intended to be complete, well-organized or even professional. However, with luck, it will be more useful." This is true now more than ever.

—Joshua Holbrook May 2011

Introduction

Twelve experimental procedures and discussions are presented in this manual. These experiments were developed by the faculty of the University of Alaska Fairbanks Mechanical Engineering Department to be used in the ME 415 – Thermal Systems Laboratory course. The experiments are based on engineering principles with which a senior in Mechanical Engineering should be familiar. These laboratory exercises are intended to demonstrate the theory learned in previous courses as well as familiarize the student with experimental methods and measurement techniques.

The objectives of the course are twofold.

First, the student acquires an understanding of the basic construction, operation, control, and performance of common mechanical equipment such as pumps, engines, and heat exchangers. Knowledge is gained in standardized testing procedures available from such engineering organizations as the American Society of Mechanical Engineers (ASME), the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), and others. Students also learn how to develop their own experimental procedures. In setting up and performing these tests, experience is also gained in instrumentation, data analysis, and the concept of instrument error.

Secondly, communications skills are developed through writing reports describing the experiments and their results.

The Thermal Systems Laboratory is a popular course with Mechanical Engineering students because it demonstrates the theory taught in other courses by providing physical evidence of the principles in effect. It also provides 'hands-on' experience in setting up laboratory procedures and test apparatus. This develops useful skills that engineers use throughout their careers in designing experimentation and instrument systems to investigate engineering phenomenon.

The experimental procedures contained in this manual include a discussion of the principle on which the experiment is based, background information, apparatus setup procedures, experimental and data collection methods, and useful equations to analyze the results. Name(s) of the faculty member(s) contributing to the development of each experiment are presented at the beginning of each procedure's description.

Details of the course such as meeting times, locations for each experiment, the schedule listing when each experiment shall be run, and other pertinent information are given in the course syllabus. The syllabus is distributed by the instructor along with this manual during the first scheduled meeting of the class.

The laboratory exercises are designed so that running the experiment for each topic should be able to be completed in one week of class meetings. The instructor shall give an introductory lecture for each experiment reviewing the engineering principles and introducing the experimental apparatus and procedure. The students then perform the experiment and gather the data during the laboratory session of each week's class time. A laboratory assistant is on hand to assist with apparatus setup and to answer student questions about the experimental procedure.

A required skill that cannot be overemphasized is the ability to present engineering work in an organized, logical, and straightforward manner. It is imperative that the engineering work not only be correct but that it is also correctly communicated to peers, clients, and other interested parties. To that end, the University has designated ME 415 as ME 415W which means that it fulfills the intensive writing requirement. The vehicle for communication in this course is the laboratory report.

Lab Reports

Each lab report should contain the following sections:

1. Title
2. Objective
3. Description of Apparatus
   - Schematic diagram or photograph with parts descriptions
4. Procedure
5. Results & Discussion
   - Results should be presented in the form of tables and plots
6. Conclusions
7. References
8. Appendices

Lab reports may be written partially as a group. Sections 1, 2, 3, and 4 may be written entirely as a group. The results and relevant references may also be written as a group. However, Section 6 must be written entirely individually, as well as the discussion of results in Section 5, and any references and appendices introduced to support individual work in Sections 5 and 6 must also be included (by the individual).

Citation Guidelines

Text Citation:

Within the text, references should be cited in numerical order according to their order of appearance. The numbered reference citation should be enclosed in brackets.

Example:

```
It was shown by Prusa [1] that the width of the plume decreases under these
conditions.
```

In the case of two citations, the numbers should be separated by a comma [1,2]. In the case of more than two reference citations, the numbers should be separated by a dash [5–7].

List of References:

References to original sources for cited material should be listed together at the end of the paper; footnotes should not be used for this purpose. References should be arranged in numerical order according to their order of appearance within the text.

1. Reference to journal articles and papers in serial publications should include:
    - last name of each author followed by their initials
    - year of publication
    - full title of the cited article in quotes, title capitalization
    - full name of the publication in which it appears
    - volume number (if any) in boldface (Do not include the abbreviation, "Vol.")
    - issue number (if any) in parentheses (Do not include the abbreviation, "No.")
    - inclusive page numbers of the cited article (include "pp.")
2. Reference to textbooks and monographs should include:
    - last name of each author followed by their initials
    - year of publication

- full title of the publication in italics
- publisher
- city of publication
- inclusive page numbers of the work being cited (include "pp."r)
- chapter number (if any) at the end of the citation following the abbreviation, "Chap."

3. Reference to individual conference papers, papers in compiled conference proceedings, or any other collection of works by numerous authors should include:

   - last name of each author followed by their initials
   - year of publication
   - full title of the cited paper in quotes, title capitalization
   - individual paper number (if any)
   - full title of the publication in italics
   - initials followed by last name of editors (if any), followed by the abbreviation, "eds."
   - publisher
   - city of publication
   - volume number (if any) in boldface if a single number, include, "Vol." if part of larger identifier (e.g., "PVP-Vol. 254")
   - inclusive page numbers of the work being cited (include "pp."b)

4. Reference to theses and technical reports should include:

   - last name of each author followed by their initials
   - year of publication
   - full title in quotes, title capitalization
   - report number (if any)
   - publisher or institution name, city

Sample References:

[1] Ning, X., and Lovell, M. R., 2002, "On the Sliding Friction Characteristics of Unidirectional Continuous FRP Composites," ASME J. Tribol., 124(1), pp. 5–13. [2] Barnes, M., 2001, "Stresses in Solenoids," J. Appl. Phys., 48(5), pp. 2000–2008. [3] Jones, J., 2000, Contact Mechanics, Cambridge University Press, Cambridge, UK, Chap. 6. [4] Lee, Y., Korpela, S. A., and Horne, R. N., 1982, "Structure of Multi-Cellular Natural Convection in a Tall Vertical Annulus," Proc. 7th International Heat Transfer Conference, U. Grigul et al.,

eds., Hemisphere, Washington, DC, 2, pp. 221–226. [5] Hashish, M., 2000, "600 MPa Waterjet Technology Development," High Pressure Technology, PVP-Vol. 406, pp. 135–140. [6] Watson, D. W., 1997, "Thermodynamic Analysis," ASME Paper No. 97-GT–288. [7] Tung, C. Y., 1982, "Evaporative Heat Transfer in the Contact Line of a Mixture," Ph.D. thesis, Rensselaer Polytechnic Institute, Troy, NY. [8] Kwon, O. K., and Pletcher, R. H., 1981, "Prediction of the Incompressible Flow Over A Rearward-Facing Step," Technical Report No. HTL–26, CFD–4, Iowa State Univ., Ames, IA. [9] Smith, R., 2002, "Conformal Lubricated Contact of Cylindrical Surfaces Involved in a Non-Steady Motion," Ph.D. thesis, http://www.cas.phys.unm.edu/rsmith/homepage.html

From the author's guide on ASME.org:

http://www.asme.org/Publications/ConfProceedings/Author/References_2.cfm

ME 415: Thermal Systems Laboratory (3 credits)
Spring 2011

Meeting time & location Wed (lecture) 8:00 – 9:30, Duckering 352
Thu (Lab, Section F01) 14:00 -17:10, Duckering 103 or 231
Fri (Lab, Section F02) 14:10 – 17:25, Duckering 103 or 231

Prerequisites ENGL 111X, 211X, or 213X, ES 341, ME 308, ME 313, ME 441

Instructor Dr. Sunwoo Kim
Room 337A, Duckering
E-mail: swkim@alaska.edu
Office hours: W, R, F 11:00 – 12:00

TA Joshua Holbrook
josh.holbrook@gmail.com

Text book

ME 415 Thermal Systems Laboratory Manual
(This text will be provided to the student during the first class.)

Course description

Testing and evaluation of components and energy systems such as pumps, fans, engines, heat exchangers, refrigerators, and heating/powerplants.

Course objectives

This course illustrates mechanical engineering concepts concerned with heat transfer, fluid mechanics, and energy systems through the use of laboratory experimentation. "Hands-on" experience is gained to both demonstrate the principles learned in previous study and train the student in experimental procedures that will be useful in an engineering career.

Instruction methods

A lecture reviewing each topic precedes a laboratory session which demonstrates the principle(s). The operation of laboratory apparatus and how it demonstrates the principle(s) may also be discussed in the lecture. Laboratory sessions follow the lecture where the student runs the apparatus and performs the experimentation required to illustrate the principle(s). Some of the experimental procedures are clearly defined in the course manual. Others may require the student to devise experimental and/or analytical procedures to obtain the desired outcome.

Grading

Final composite score to be based on:

Exam 1:	25%
Exam 2:	25%
Lab reports:	50%

Lab reports: Each lab section will work together as a group to perform the experimental procedures and gather all pertinent data. Students are encouraged to discuss the assigned lab work amongst themselves in order to gain a better understanding of the material. Each student shall prepare and submit an independent report for each lab exercise. All lab reports are due at beginning of class on date stated. No late work will be accepted without prior approval from the professor. Reports shall be submitted in electronic form by e-mailing them as attachments to the professor.

Grade ranges:
87 – 100%: A's; 77 – 86%: B's, 67 – 76%: C's, 57 – 66%: D's, <56: F

Course schedule

The course schedule shall be approximately as shown below. Some adjustment may be made.

Week	Topic	Lecture	Lab
1	Course introduction (on 1/26/2011)	Du 352	No lab
2	Transient heat transfer	Du 352	Du 103
3	Low temperature viscosity	Du 352	Du 103
4	Temperature profile in rods	Du 352	Du 103
5	Thermal conductivity	Du 352	Du 231
6	Refrigeration performance	Du 352	Du 103
7	Exam 1 (on 3/9/2011)	Du 352	No lab
-	Spring Break		
8	Centrifugal pump performance	Du 352	Du 231
9	Heat Exchanger Performance	Du 352	Du 231
10	Gas Turbine Performance	Du 352	Du 103
11	Diesel Engine Performance	Du 352	Du 103
12	Heat Exchanger Design Project	Du 352	No lab
13	Heat Exchanger Design Project Continues	No lecture	No lab
14	Exam 2 (on 5/4/2011)	Du 352	HW10

Class policy

Lecture and lab attendance is required. All lab experimentation must be performed on the dates scheduled. The professor reserves the right to adjust final grades up or down based on a student's course participation. Notify the instructor as soon as possible if you are unable to attend class or take exam at the scheduled time.

Students are responsible for all material covered in class. The work submitted for grading should represent their individual effort. However, students are permitted to work together on laboratory assignments. It is assumed that all group members will contribute to the successful completion of each laboratory assignment. The course requires students to respect UAF policies on ethics and professionalism.

ABET Criteria 3 – Program outcomes

This course helps students meet outcomes:

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) ability to design and conduct experiments, as well as to analyze and interpret data.
(g) ability to communicate effectively.
(j) a knowledge of contemporary issues

(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.
(l) an appreciation of significant engineering issues in the North

ABET Criteria 4 – Professional component

This course meets the professional requirements through section (b) professional component. Specifically, this course is part of the engineering topics, consisting of engineering sciences and engineering design appropriate to the student's field of study.

Reasonable accommodation will be provided for students with disabilities. Students will also find information concerning tutoring, other services and resources, and on disability services in the UAF Catalog.

Heating Value of a Gas

Heating Value of a Gas

R. Johnson

Background:

A continuous flow calorimeter is traditionally used to determine the heating value of fuel gases. As shown in figure 1, the water circulating around the calorimeter is heated by the combustion process. Once steady-state conditions are reached, the energy output of the fuel can be determined by equating it to the energy gained by the water. The latter is found from the mass flow rate and enthalpy difference between the water inlet and outlet.

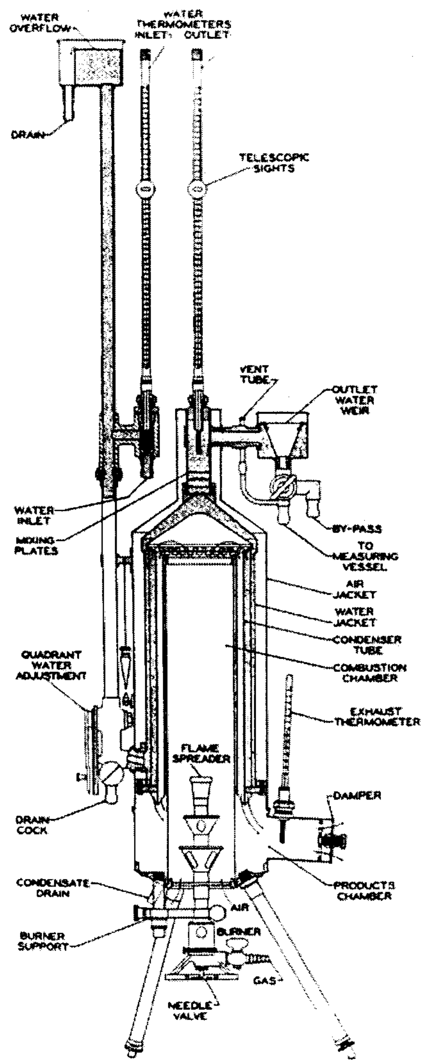
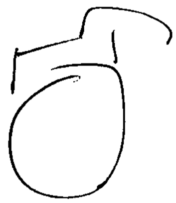


Figure 1. Cross-Section of Continuous Flow Calorimeter

Objective:

The objective of this lab exercise is to determine the heating value of the laboratory gas (propane). Express the heating value in units of $BTU/_{Lbm}$ and $BTU/_{1{,}000scf}$.



~~2,000~~

1.95

Procedure:

1. Connect the wet test meter between the fuel supply and the Bunsen burner.
2. Connect the water inlet and outlet hoses to the calorimeter and turn on the supply water to establish a steady flow of liquid through the jacket.
3. Insure that the manometer on the wet test meter is filled with water. This creates a water seal that prevents the gas from leaking into the room.
4. Turn the gas supply on and adjust the flow rate so that a single revolution of the meter takes several minutes. Ignite the burner and adjust the air supply to achieve a stable flame.
5. Insert the burner into the base of the calorimeter insuring that the flame remains lit. **WARNING:** If the flame goes out, shut off the gas supply immediately. Also insure that the water flow remains on while the flame is burning.
6. Adjust the water and/or gas flow rates so that the cooling water temperature rise across the calorimeter jacket is at least 10°F but less than 30°F.
7. When steady-state conditions are reached, record the gas and water flow rates and the appropriate temperatures and pressures.
8. Repeat the experiment for a different air/fuel ratio.

Theory:

The first law for a reacting system states:

$$Q_{CV} + \sum_R n_i \bar{h}_i = \sum_P n_e \bar{h}_e$$

where:
- R = reactants
- P = products
- n = number of moles
- $\bar{h}$ = enthalpy per mole
- i = reactant species
- e = product species

From this, we derive that the enthalpy of combustion on a molar basis is:

$$\bar{h}_{RP} \equiv \sum_P n_e \bar{h}_e - \sum_R n_i \bar{h}_i$$

What we want to calculate is the heat of reaction evaluated at the standard temperature of 25°C. On a mass basis this is:

$$h_{RP0} = \frac{\bar{h}_{RP}}{M.W.}$$

where:
- M.W. = molecular weight of the fuel
- 0 = subscript denotes value at 25°C

From an energy balance at steady-state across our system (the calorimeter) we observe:

$$\dot{m}_w C_{P,w}\left(T_e - T_i\right) = \dot{m}_f h_{RP0}$$

where:
- $\dot{m}_w$ = mass flow rate of water
- $\dot{m}_f$ = mass flow rate of gas
- $C_{P,w}$ = specific heat of water at constant pressure
- T_e = outlet water temperature
- T_i = inlet water temperature

Tables listing standard values for h_{RP0} are readily available for different fuels. One of the products of combustion for a fuel that contains hydrogen is water (H_2O). If the temperature of the combustion gases falls below its dew point, the water vapor in the combustion gases condenses thus releasing the heat of vaporization for the quantity of vapor that turns to liquid. The higher and lower heating values of a fuel depend on whether the water in the product is in the liquid or vapor state. If all of the water in the products of combustion remains in vapor state we have determined the *lower heating value* (LHV) for the fuel. If all of the water is condensed to liquid, we have determined the *higher heating value* (HHV) of the fuel.

For propane, the value of h_{RP0} is on the order of $20{,}000 \, {}^{BTU}\!/_{Lbm}$.

Report Considerations:

1. What is the combustion/chemical reaction occurring in this experiment?
2. Is the heating value for the propane calculated in this experiment the HHV, the LHV, or something else? Why?
3. Do the heating values calculated in this experiment match those listed in standard tables for propane? Explain any differences.
4. How would you modify this experiment (if it needs to be modified) to measure the HHV of the fuel gas?

Transient Temperature Measurement

Principles & Background:

Lumped Capacitance Method:

The *lumped capacitance method* is one method of analyzing transient heat transfer. It considers all three modes of heat transfer: conduction, convection, and radiation. The underlying energy balance for the method is:

$$\begin{pmatrix}\text{heat transfer into the} \\ \text{body during a given time}\end{pmatrix} = \begin{pmatrix}\text{the increase in energy in the} \\ \text{body during said given time}\end{pmatrix} \tag{1}$$

This general statement holds for heat transfer to or from the body if we establish and maintain an appropriate sign convention.

Heat transfer within the body is due to conduction. Heat transfer between the body and its surrounding fluid is due to convection and radiation. Using lumped capacitance assumes that the resistance to heat flow within the body is small compared to the resistance from the body to its surroundings. That is, the conductivity of the body is greatly superior to the convection and radiation between the body and its surroundings. This also implies that we can assume a relatively uniform temperature distribution within the body compared to the distribution between the body and its surroundings.

A good indicator as to whether the lumped capacitance method is applicable to a given transient heat transfer problem is the Biot Number (Bi).

$$Bi = \frac{(\text{convection at the surface})}{(\text{conduction in the body})} = \frac{hL_c}{k} \tag{2}$$

The characteristic length in the above equation can be taken to be:

$$L_c = \frac{V}{A} \tag{3}$$

The closer the Biot Number is to zero, the better the lumped capacitance method is at representing the true transient heat transfer occurring for a body.

Returning to the energy balance given in (1), we can write this in equation form as:

$$hA(T_\infty - T)dt = mc_p dT \tag{4}$$

In (4), the *h*-term represents a combination heat transfer coefficients for both convection and radiation. The mass of the object can be found as:

$$m = \rho V \tag{5}$$

Making these substitutions, the differential equation, (4), can be solved as:

$$\ln\left(\frac{T(t)-T_\infty}{T_i - T_\infty}\right) = \frac{-hA}{\rho V c_p} t \tag{6}$$

$$\Rightarrow \frac{T(t)-T_\infty}{T_i - T_\infty} = e^{-bt} \tag{7}$$

$$\text{where: } b = \frac{hA}{\rho V c_p} \tag{8}$$

The heat transfer coefficient, h, which is composed of convective and radiation components, is derived from experimental data for specific geometric configurations. For the spherical body used in this laboratory exercise, we approximate this coefficient as:

$$h = h_C + h_R \tag{9}$$

$$\frac{h_C d}{k} = 2 + \frac{0.589(Ra)^{(0.25)}}{\left[1+\left(\frac{0.469}{\Pr}\right)^{\left(9/16\right)}\right]^{\left(4/9\right)}} \tag{10}$$

$$h_R = \frac{\varepsilon\sigma\left(T^4 - T_\infty^4\right)}{T - T_\infty} \tag{11}$$

The Prandtl and Rayleigh Numbers in equation (10) are evaluated at the mean film temperature:

$$T_f = \frac{T_{avg} - T_\infty}{2} \tag{12}$$

$$T_{avg} = \frac{T_i - T_{final}}{2} \tag{13}$$

Thermocouples:

Seebeck discovered that, if two dissimilar metals are joined to form a junction, an electromagnetic force (emf or voltage) will be induced. Peltier later discovered that the magnitude of this emf is proportional to the temperature to which the junction is exposed. Then, Thompson discovered that the emf is also affected by the temperature to which the conductors in this dissimilar metal circuit are exposed. These discoveries are the basis of using thermocouples to measure temperatures. Thermocouples are dissimilar metal conductors brought together to form temperature measuring junctions.

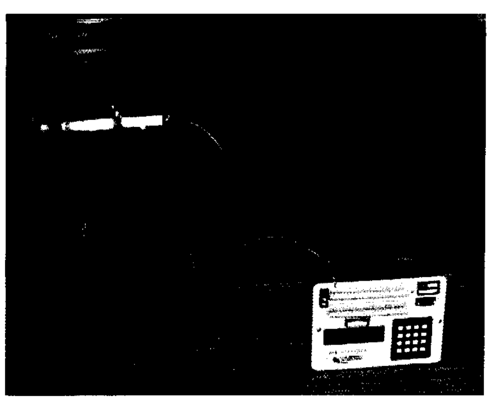
We rely on two important laws when using thermocouples. The first of these is the *Law of Intermediate Metals*. This law states that if other conductors are included in the thermocouple junction, they will not affect the strength of the emf induced if the additional junctions they create are at the same temperature as the original junction temperature. This allows us to mechanically fasten the thermocouple junctions through the use of metal connecting sleeves, solder, or other similar methods without changing the effectiveness of the temperature measuring circuit. It also allows us to insert voltage measuring meters into the circuit to "read" the emf create. This means that we can create a useful measuring instrument.

The *Law of Intermediate Temperatures* states that if a thermocouple (TC) circuit creates emf_1 when its measuring and reference junctions are exposed to temperatures T_1 and T_2 and creates emf_2 when exposed to T_2 and T_3, the TC circuit will induce an emf = (emf_1 + emf_2) when exposed to T_1 and T_3. This allows us to use a reference temperature other than that of 0°C for our TC measuring instrument. We look up what emf would be created at the reference temperature of the reference junction (usually the meter) and add this to the displayed emf. This total emf represents the temperature measured at the unknown TC junction.

Lab Procedure:

1. Measure the diameter of the sphere and note its material so that you can determine the appropriate parameters required to perform the heat transfer analysis.

2. Install the metal (brass or aluminum) sphere into the support stand.



3. Connect the thermocouple leads to the Campbell 21X Micrologger. Be sure to connect the leads with the correct polarity (more noble metal to positive). The brass sphere uses a Type-K (chromel-alumel) TC, the aluminum sphere uses a Type-T (copper-constantan) TC.

4. Program the datalogger as shown below.

5. Using a propane torch, Bunsen burner, or similar means, heat the sphere to approximately 450°F. Take care to heat the sphere only and don't scorch the protective wrap on the support rod.

6. Check the temperature readings to make sure that the TC is connected with the correct polarity. If not, switch the polarity.

7. Allow the sphere to cool to approximately room temperature.

8. With the assistance of the lab instructor, dump the data from the datalogger to a computer file. This file will be posted on the class Web site.

9. Shut off the datalogger, disconnect the sphere, and return the parts to storage ready for its next use.

Additional Information:

Datalogger Programming:

For this lab, you'll program the Campbell 21X Micrologger using its front panel key pad.

Turn ON the datalogger and allow it to complete is self-diagnostics. When the display shows all 1's with a single colon (:) and decimal point (.), the self test is complete and the datalogger is ready to program.

The following table shows the commands/key-strokes to enter and their purpose:

Logger Display	Enter	Purpose
11:11111.11	*1	Instructs the logger you are programming Table 1.
01:	15	Scan rate of 15 seconds.
01: P	17	Program panel (TC Ref.) temperature.
01:	1	Storage location for pnl temp is register 1.
02: P	14	Program differential TC.
01:	1	1 repetition (1 TC).
02:	2	Slow response up to 15mV (suitable to 500°F K & T TC).
03:	1	Input channel (TC connection point).

04:	3 or 1	3 for Type-K, 1 for Type-T TC.
05:	1	Location (register) for reference temp.
06:	2	Storage location (register) for TC temp.
07:	1D8	1.8 conversion factor for °C to °F.
08:	32	Scale offset for °C to °F.
03: P	86	Set the DO flag.
01:	10	Send/store input register data to output registers.
04: P	70	Set the sampling for the output registers.
01:	2	2 repetition/data point, the Pnl & TC temp.
02:	1	Memory/register location of the Pnl temp.
05: P	*0	Your program is complete. Compile & run Table 1.
LOG 1		You were successful & program in logging data.
	*6	Display input registers.
	A &/or B	Forward & back between Loc 1 & 2 to read pnl temp and TC temp.

Matlab Procedures:

Matlab is a good computer programming tool/environment to use to manipulate and display the data for this lab exercise.

You will gather a large amount of temperature data. Note that the datalogger records the sphere temperature every 15 seconds. You should sub-set this data to obtain a reasonable amount of data covering the entire period to display in your report.

Use Matlab's "plot( )" function to display the theoretical response of temperature vs. time with the sub-setted experimental data superimposed on the plot. The theoretical plot should be a continuous line plot. The data will appear as specific data points. To get both plots on the same axes you'll need to employ Matlab's "hold all" command or edit the plot in interactive mode.

Notes on "Transient Heat Transfer":

1. A few additional equations you'll need to know:
   a. $Ra = GrPr$
   b. $Gr = \frac{g\beta(T-T_\infty)L^3}{\nu}$ and for ideal gasses, $\beta = {}^{1}/_{T}$
   c. $Pr = \frac{\nu}{\alpha}$
2. The directions regarding the Campbell datalogger make it appear extremely out-of-date. An amusing anecdote played out in class as follows, after learning about the use of the Campbell datalogger's archaic interface:

   HEB: "Who remembers what the top bar [on the datalogger] says?"

   Class: "..."

   Student: "We've never seen that before."

   HEB: "You didn't use this datalogger in measurements?"

   JFH: "Good Heavens no! We used modern data loggers!"

   HEB: HOOOO boy!"

   Despite Bargar's use of MS-DOS to compile the Campbell datalogger's output, however, there is in fact modern software, called ~~PC-100~~, on Campbell's web site.

   PC500W

Can't figure out how to subset your data? Use this in MATLAB:

```
function outdata=subset(indata,n)
%subset(row_vector,spacing)
%subsets a row vector into a row vector with every
%nth entry of the original row vector.
%by Josh Holbrook and Dustin Ray.
    outdata=indata(floor(linspace(1,size(in,2),n)));
end
```

Viscosity at Low Temperatures

Principles & Background:

Viscosity:

Viscosity, or more correctly absolute (or dynamic) viscosity, which we generally denote with the Greek letter μ (mu), is a property of a fluid. The viscosity of a fluid is defined by *Newton's Law of Viscosity*. This law relates the shear stress applied to a fluid and its deformation or velocity gradient normal to the applied shear.

A Newtonian fluid has a linear relationship between the applied shear stress and deformation. In a non-Newtonian fluid, this relationship is non-linear.

If we apply a shear force to a solid, the material will deform by a finite amount. As long as the force remains within the elastic range for a material, the deformation of the material is related to the applied shear stress by the modulus of rigidity for the material. This yields the common equations you'll recall from Mechanics of Materials:

$$\tau = G\gamma \tag{1}$$

$$\tau = \frac{F}{A} \tag{2}$$

where: τ = shear stress in a given plane

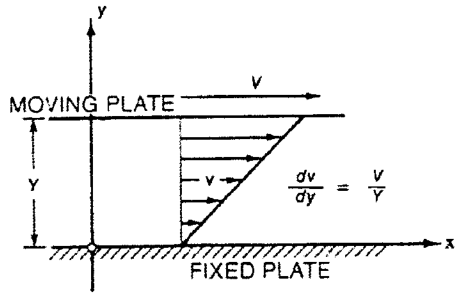
γ = deformation in that plane

G = modulus of rigidity for the material

F = shear force applied

A = area over which the shear force acts

Unlike a solid, if a shear force is applied to a fluid, the fluid will deform continuously as long as the force is present. Consider the example of a fluid between two plates. One plate is fixed and a force is applied to the other such that it moves at velocity, $\overline{V}$. From fluid mechanics, we know that the non-slip condition requires that the fluid velocity at the fixed plate remains zero and the velocity at the moving plate will be $\overline{V}$, the velocity of the plate.



If *F* is the force required to slide the top plate and the area of each plate is *A*, then we can define the relationship at any given point in the velocity field as:

$$\frac{F}{A} = \mu\left(\frac{V}{Y}\right) \tag{3}$$

Note that $\frac{F}{A}$ is the shear stress τ and $\frac{V}{Y}$ is the velocity gradient. We define μ, the constant of proportionality, to be the *absolute* or *dynamic viscosity*. Note that our velocity profile is for a laminar flow regime. This is *Newton's Law of Viscosity*. We can rewrite this equation in the form:

$$\tau = \mu\left(\frac{dv}{dy}\right) \tag{4}$$

Viscosity is primarily a function of temperature for a given fluid. For gases, viscosity generally increases as temperature increases. For liquids, viscosity generally decreases as temperature increases.

Given its definition, we can also look at viscosity as a resistance of adjacent fluid layers to deform when subjected to shear stress. The units of absolute viscosity are $\left[\frac{force \cdot time}{length^2}\right]$.

There is another type of viscosity which is often referred to when talking about a given fluid, the *kinematic viscosity*. The kinematic viscosity is generally denoted by the Greek letter ν (nu). The kinematic viscosity of a fluid is equal to its absolute viscosity divided by its density.

Lubricant Formulations:

You'll be testing conventional petroleum based lubricants and pure synthetic polymer lubricants.

You'll be testing lubricants with different SAE weights (e.g.; 10W – 40, 5W – 20). These weights specify the characteristic behavior of the lubricants at different temperatures. All of the lubricants tested are "multi-weight" lubricants. They exhibit the lo-temperature characteristics of the 1st number and the hi-temperature characteristics of the 2nd number. SAE (the Society of Automotive Engineers) establishes the standard test procedures and interpretations for weighting lubricants in this manner.

Petroleum based lubricants consist of several molecular chains. Some of these chains are parafins or waxes that precipitate out of solution at reduced temperatures. This is indicated by a "cloudy" appearance to the lubricant. It also adversely effects the lubricity of the lubricant. One change is to its viscosity. As a result of paraffin precipitation, viscosity is not likely to be uniform over the entire temperature range tested. You may also experience some difficulty in testing the petroleum based products at low temperature as they tend to "separate" and may not make good contact with the test spindle. This is also a problem in their use. They may not remain in good contact with the surfaces they are supposed to lubricate.

Synthetic lubricants are formulated of a uniform polymer chain. Therefore, no parafins are present to precipitate out as the temperature falls. The lubricity of synthetics should remain relatively consistent over the temperature range of the tests. This is advantageous for lubricants at low temperatures in actual use. They continue to lubricate even at high viscosities.

Lab Procedure:

Overview:

This week's lab involves the measurement of viscosity for several lubricating oils. You will measure the viscosity of:

Four motor oils:

- Pennzoil 10W – 40 conventional oil.
- Mobile 1 10W – 40 synthetic oil.
- Pennzoil 5W – 20 conventional oil.
- Mobile 1 5W – 20 synthetic oil.

The viscosity will be measured at several temperatures for each grade of oil. Viscosity shall be measured at approximately 10°F increments from –30°F to 100°F The samples shall initially be cooled in the environmental chamber to ~ -30°F You'll allow the samples to warm in room temperature while measuring the viscosity. You'll use a hot plate to heat the samples above room temperature in ~10°F increments to a maximum of ~100°F.

Procedure:

1. Read the manufacturer's Manual for the Brookfield DV-1 Viscometer which can be found as a .pdf file on the class Web site (in the .zip file under the "Additional Information" column).

2. Assemble the viscometer on the stand and prepare to test the lubricant samples. Decide which test spindle(s) to use. The spindles are LV spindles so this is the setting you'll use with the Factor Calculator when determining the sample viscosity.

3. With the aid of the Lab TA, retrieve the samples one at a time from the environmental chamber and test the viscosity at approximately 10°F intervals from –30°F to 100°F. Use the thermometer in the lab to determine the temperature to the nearest °F at each viscosity reading. Test similar weight lubricants in order to take advantage of the setup and spindle selection knowledge gained for each preceding test.

4. When you have tested all of the samples, disassemble the apparatus, clean the spindles and other parts of all lubricants, and return them to their storage case(s) for the next users.

5. You'll plot the viscosity vs. temperature data for all lubricants on a single set of axes showing data and regression lines for each lubricant data set in your report.

VISCOSITIES OF MOTOR OILS AT LOW TEMPERATURES

R. Johnson

Object:

To measure the viscosities of motor oils at various temperatures.

Apparatus:

Temperature control will be maintained using a refrigeration unit. The viscosity will be measured using a Brookfield Rotational Viscometer.

Here, the principle of operation is based upon sensing the torque developed by a cylinder rotating in the viscous fluid. Operating instructions are provided on pages 3-2 thru 3-6. (Also see manufacturer's Operating Instructions which are posted on the class Web site in a Portable Document Format (PDF) file. While some of the procedures described in the text are still suitable, this lab exercise uses a newer model viscometer which is described in the referenced PDF file.)

For the data points at lower temperatures, it is sufficient to place the sample in a refrigerator before testing and then test quickly before the sample warms up appreciably.

Report Considerations:

Plot oil viscosity vs. temperature letting spindle size and rotational speed be independent parameters. Comment on the influence of these variables upon measured viscosity.

THE BROOKFIELD DIGITAL VISCOMETER

Operating Instructions

Principle of Operation

The Brookfield Digital Viscometer rotates a sensing element in a fluid and measures the torque necessary to overcome the viscous resistance to the induced movement. This is accomplished by driving the immersed element, which is called a spindle, through a beryllium copper spring. The degree to which the spring is wound, detected by a rotational transducer, is proportional to the viscosity of the fluid.

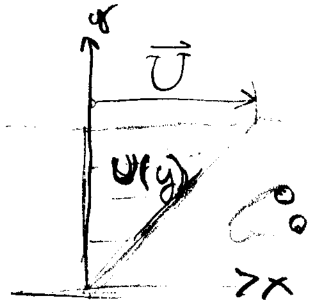
Continuous readout of viscosity can be accomplished in two ways: by means of the integral three-digit LED display, or by the 0-10 mV analog output signal which can be fed into a variety of indicating or recording devices.

The Viscometer is able to measure over a number of ranges since, for a given spring deflection, the actual viscosity is proportional to the spindle speed and is related to the spindle's size and shape. For a material of given viscosity, the drag will be greater as the spindle size and/or rotational speed increase. The minimum viscosity range is obtained by using the largest spindle at the highest speed; the maximum range by using the smallest spindle at the slowest speed.

Measurements made using the same spindle at different speeds are used to detect and evaluate the rheological properties of the test material. Our booklet, "Solutions to Sticky Problems" discusses the Viscometer's use in this respect .

Oils: 5W-20-conventional
5W-20-synthetic
10W-40-conventional
10W-40-synthetic

These are different by year.



Dynamic viscosity, aka "absolute viscosity"

$\tau = \mu \frac{du}{dy}$

Introduction :

The Digital Viscometer is powered by a precision synchronous motor. Exact speeds of rotation are assured as the motor will turn erratically and spasmodically if synchronism cannot be maintained.

Speed changes are effected by a transmission having eight speeds. The square speed control knob has two numbers on each face; by moving the knob through two complete turns the eight speeds may be selected in sequence. No trouble will be experienced in differentiating between the two speeds shown on each face, since each pair is in the ratio of 20:1.

To ensure rotation at the indicated speed it is important that the face of the knob upon which this speed is shown be closely parallel to the Viscometer's base. Although not absolutely necessary, it is advisable to change speeds while the motor is running.

LV Viscometers are provided with a set of four spindles and a narrow guard leg; RV Viscometers come with a set of seven spindles and a wider guard leg; HA and HB Viscometers come with a set of seven spindles and no guard leg.

The spindles are attached to the Viscometer by screwing them to the lower shaft. Note that the spindles have a left-hand thread. The lower shaft should be held in one hand and the spindle screwed to the left. The face of the spindle nut and the matching surface on the lower shaft should be smooth and clean to prevent eccentric rotation of the spindle. Spindles can be identified by the number on the side of the spindle nut.

Initial Setup:

1. Mount the Viscometer securely on a laboratory stand. Level the Viscometer, referring to the bubble level on the back of the instrument.
2. Verify that the Viscometer's (and recorder's, if used) power requirements match your power source before connecting it to power.

3. If using a recorder: connect Viscometer output cable to recorder terminals. Connect the red wire to the "+" terminal and the black wire to "-". Insert the plug on the other end of the cable into the Viscometer's output receptacle. Set the recorder's input selector (if so equipped) to 10 mV full scale.

   NOTE: D0 NOT CONNECT OUTPUT CABLE TO POWER!

Initialization:

1. Move power switch to "on', energizing Viscometer display. The power switch is on the left side of the front panel.
2. Check bubble level to be sure Viscometer is level. Move motor switch to "run" and set speed selector knob to 10 or 12 rpm (depending on model). The motor switch is on the right side of the front panel.
3. Allow Viscometer to run until display reading stabilizes (or fluctuates by no more than 0.1). Turn zero adjustment knob until the display reads 00.0. This also zeros the output signal.
4. If a recorder is used, it should be zeroed after the Viscometer has been zeroed. The Viscometer and the recorder input must be in the "run" mode. After the recorder is zeroed, switch it to the "standby" mode.
5. Move motor switch to "hold", placing Viscometer in standby mode.

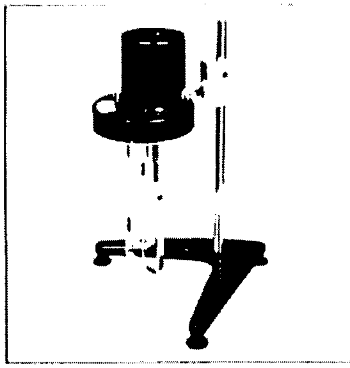
Operation :

1. Attach spindle to lower shaft. Lift the shaft slightly, holding it firmly with one hand while screwing the spindle on with the other (note left-hand thread). Avoid putting side thrust on the shaft.
2. Insert spindle in the test material until the fluid's level is at the immersion groove in the spindle's shaft. Try to avoid trapping air bubbles under the spindle. You may find it more convenient to immerse the spindle in the

1 Dr. Kim's (Revised) Expectations for Analysis and Discussion for the Low-Temperature Viscosity lab

Discuss how these tests reflect real-world conditions in a car engine and their effects on engine wear, performance and fuel economy.

BROOKFIELD FACTOR FINDER



VISCOMETER MODEL ▶

◀ SPINDLE NUMBER

SPEED-RPM

FACTOR
M = 1000

INSTRUCTIONS

This Factor Finder applies to Brookfield Viscometer models LV, RV, HA and HB with standard spindles. Insert slide in sleeve so appropriate Viscometer model is visible in window. The first two letters of the model designation are shown; i.e., "LV" applies to LVO, LVF or LVT models.

To convert Viscometer dial reading to centipoise (mPa·s), adjust slide until Viscometer model and spindle number being used appear in window. Multiply reading noted on Viscometer 0-100 scale by factor shown beside speed at which measurement is being made.

Dial reading X Factor = Viscosity in centipoise (mPa·s)

Example: LVT Viscometer with #1 spindle at 6 rpm
Dial Reading: 75 Factor: 10
75 x 10 = 750 centipoise (mPa·s)

Full scale viscosity range for any speed and spindle combination is equal to the factor X 100.

Factor X 100 = Full scale range

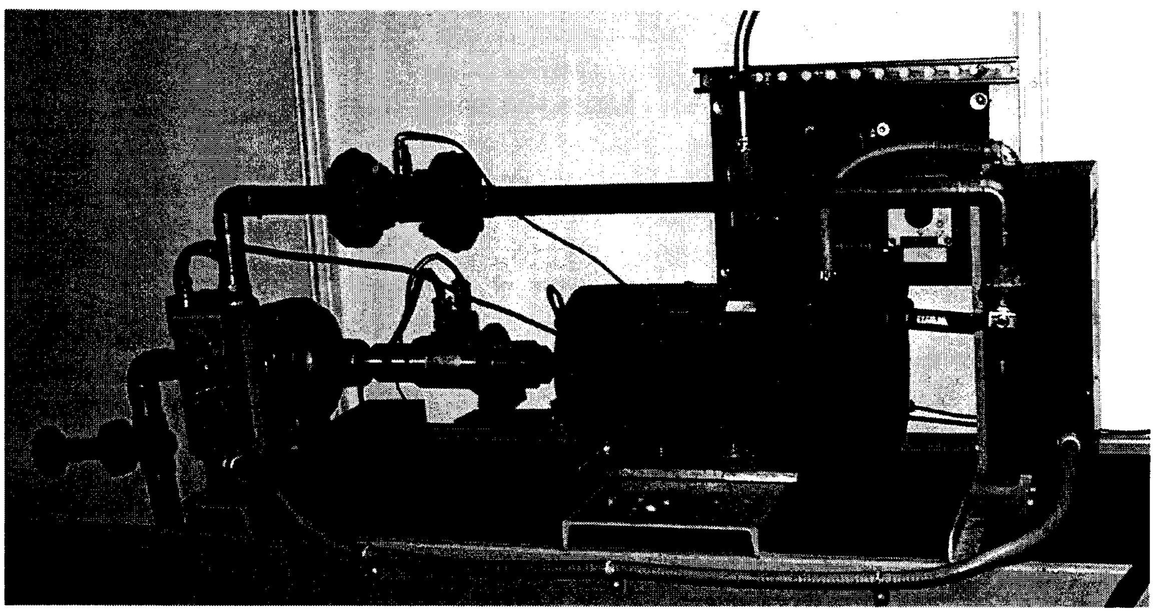
BROOKFIELD ENGINEERING LABORATORIES, INC. 240 CUSHING ST., STOUGHTON, MA 02072 USA TELEPHONE: (617) 344-4310 TELEX: 924-497

BROOKFIELD ENGINEERING LABORATORIES, INC. 240 CUSHING ST., STOUGHTON, MA 02072 USA TELEPHONE: (617) 344-4310 TELEX: 924-497

RV 1		RV 2		RV 3		RV 4		RV 5		RV 6		RV 7		LV 1		LV 2		LV 3		LV 4	
.5	200	.5	800	.5	2M	.5	4M	.5	8M	.5	20M	.5	80M	.3	200	.3	1M	.3	4M	.3	20M
1	100	1	400	1	1M	1	2M	1	4M	1	10M	1	40M	.6	100	.6	500	.6	2M	.6	10M
2	50	2	200	2	500	2	1M	2	2M	2	5M	2	20M	1.5	40	1.5	200	1.5	800	1.5	4M
2.5	40	2.5	160	2.5	400	2.5	800	2.5	1.6M	2.5	4M	2.5	16M	3	20	3	100	3	400	3	2M
4	25	4	100	4	250	4	500	4	1M	4	2.5M	4	10M	6	10	6	50	6	200	6	1M
5	20	5	80	5	200	5	400	5	800	5	2M	5	8M	12	5	12	25	12	100	12	500
10	10	10	40	10	100	10	200	10	400	10	1M	10	4M	30	2	30	10	30	40	30	200
20	5	20	20	20	50	20	100	20	200	20	500	20	2M	60	1	60	5	60	20	60	100
50	2	50	8	50	20	50	40	50	80	50	200	50	800								
100	1	100	4	100	10	100	20	100	40	100	100	100	400								

CENTRIFUGAL PUMP

PERFORMANCE



BROOKFIELD DIAL READING VISCOMETER
BROOKFIELD DIGITAL VISCOMETER
MODEL DV-I

Operating Instructions

Manual No. **M/85-150-D**

The following instructions are intended for use with all standard models of Brookfield **Digital** and **Dial Reading** Viscometers. Information has been provided for the proper operation and care of your Viscometer. Additional information is available in the Brookfield booklet "More Solutions to Sticky Problems." Please contact Brookfield (or your local dealer) for any other information you desire regarding viscosity measurement and control instrumentation. Thank you for the continued use of our products.

BROOKFIELD ENGINEERING LABORATORIES, INC.
11 Commerce Boulevard, Middleboro, MA 02346 USA

TEL 508-946-6200 or **800-628-8139** (USA excluding MA)
FAX 508-946-6262 INTERNET www.brookfieldengineering.com

Principle of Operation

The Brookfield Viscometer rotates a sensing element in a fluid and measures the torque necessary to overcome the viscous resistance to the induced movement. This is accomplished by driving the immersed element, which is called a spindle, through a beryllium copper spring. The degree to which the spring is wound, indicated by the red pointer or digital display, is proportional to the viscosity of the fluid.

With **Digital** models, continuous readout of viscosity can be accomplished in three ways: by means of the integral three-digit LED display, by the 0-10 mv, or the 0-1v analog output signal which can be fed into a variety of indicating or recording devices.

The Viscometer is able to measure over a number of ranges since, for a given spring deflection, the actual viscosity is proportional to the spindle speed and is related to the spindle's size and shape. For a material of given viscosity, the resistance will be greater as the spindle size and/or rotational speed increase. The minimum viscosity range is obtained by using the largest spindle at the highest speed; the maximum range by using the smallest spindle at the slowest speed.

Measurements made using the same spindle at different speeds are used to detect and evaluate the rheological properties of the test material. Our booklet, "More Solutions to Sticky Problems," discusses the Viscometer's use in this respect.

Introduction

The Brookfield Viscometer is powered by a precision synchronous motor. Exact speeds of rotation are assured as the motor will turn erratically and spasmodically if synchronism cannot be maintained.

Speed changes are affected by a transmission having eight speeds. For **Digital** models having serial numbers above AO2400, a round speed control knob rotates both clockwise and counter-clockwise. Maximum speed (rpm) will be set at full clockwise rotation and minimum speed at full counter-clockwise rotation. The speed setting is indicated by the number on the knob located opposite the button on the Viscometer housing. Although not absolutely necessary, it is advisable to change speeds while the motor is running.

For all **Dial Reading** Viscometers and **Digital** models having serial numbers below AO2400, speed changes are affected by a gear train having either four or eight speeds. Four speed Viscometers have a square speed control knob with one number shown on each of four faces. The instrument's rotational speed is indicated by the uppermost number. Eight speed models have a square speed control knob with two numbers on each face; by moving the knob through two complete turns speeds may be changed in sequence. No trouble will be experienced in differentiating between the two speeds shown on each face since each pair is in the ratio of 20:1. To insure rotation at the indicated speed, it is important that the face of the knob upon which this speed is shown be closely parallel to the Viscometer's dial. Although not absolutely necessary, it is advisable to change speeds on any model while the motor is running.

LV Viscometers are provided with a set of four spindles and a narrow guard leg; RV Viscometers come with a set of seven spindles and a wider guard leg; HA and HB Viscometers come with a set of seven spindles and no guard leg.

The spindles are attached to the Viscometer by screwing them to the lower shaft. Note that the spindles have a **left-hand thread.** The lower shaft should be held in one hand and the spindle screwed to the left. The face of the spindle nut and the matching surface on the lower shaft should be smooth and clean to prevent eccentric rotation of the spindle.

Spindles can be identified by the number on the side of the spindle nut.

All Brookfield **Dial Reading** Viscometers are provided with a clutch lever located at the back of the instrument. Depressing the lever raises the dial against the pointer and "holds" the instrument's reading. When the clutch is released the dial will lower and the pointer will be freed.

Any of the controls on the Viscometer - the motor switch, speed change knob, and clutch - may be operated independently of the other.

Initial Setup

1. Mount the Viscometer securely on a Brookfield laboratory stand. With **Dial Reading** models, it may be necessary to unscrew the nut located at the point where the power cord enters the Viscometer. This permits the metal handle to be inserted into the laboratory stand clamp.

   NOTE: The **position** of the laboratory stand clamp assembly is **important**. Refer to Parts Identification Sheet #82-0330 for proper alignment and positioning of the clamp assembly.

   Level the Viscometer referring to the bubble level on the instrument. If the Viscometer cannot be leveled, recheck the laboratory stand assembly as shown on sheet #82-0330.

2. Verify that the Viscometer's (and recorder's, if used) power requirements match your power source before connecting it to power.

3. If using a recorder: connect the **Digital** Viscometer output cable to recorder terminals. Connect the 0-10mv red wire to the "+" terminal and the black wire to "-". Insert the plug on the other end of the cable into the Viscometer's output receptacle. Set the recorder's input selector (if so equipped) to 10 mv full scale.

   NOTE: DO NOT CONNECT DIGITAL VISCOMETER OUTPUT CABLE TO POWER!

Initialization (Digital Viscometer Only)

1. Turn power switch "on" (up), energizing Viscometer display. The power switch is on the left side of the front panel.

2. Check bubble level to be sure Viscometer is level. Turn motor switch "on" (up) and set speed selector knob to 10 or 12 rpm (depending on model). The motor switch is on the right side of the front panel.

3. Allow Viscometer to run until display reading stabilizes (or fluctuates by no more than 0.1). Turn zero adjustment knob until the display reads 00.0. This also zeros the output signal.

4. If a recorder is used, it should be zeroed after the Viscometer has been zeroed. The recorder input must be in the "run" mode. After the recorder is zeroed, switch it to the "standby" mode.

5. Turn motor switch "off", placing Viscometer in standby mode.

Operation

1. Mount guard leg on Viscometer. Attach spindle to lower shaft. Lift the shaft slightly, holding it firmly with one hand while screwing the spindle on with the other (note left-hand thread). Avoid putting side thrust on the shaft.

2. Insert and center spindle in the test material until the fluid's level is at the immersion groove in the spindle's shaft. With a disc type spindle, it is sometimes necessary to tilt the instrument slightly while immersing to avoid trapping air bubbles on its surface. (You may find it more convenient to immerse the spindle in this fashion before attaching it to the Viscometer).

3. To make a viscosity measurement, turn the motor switch "on" which energizes the Viscometer drive motor. Allow time for the indicated reading to stabilize. The time required for stabilization will depend on the speed at which the Viscometer is running and the characteristics of the sample fluid. When making a measurement at high speeds, it will be necessary to depress the clutch and turn off the motor, with the red pointer in view, on the **Dial Reading** Viscometer.

   When making a viscosity measurement, the reading should be noted and multiplied by the factor appropriate to the Viscometer model/spindle/speed combination being used. The factor is obtained from the Brookfield Factor Finder. For maximum accuracy, display readings below 10.0 should be avoided.

   When using a **Digital** Viscometer with recorder, switch recorder to "run" mode to record Viscometer reading. Note that the paper used in the strip chart recorder has a 0-100 scale. The reading on the chart is utilized in the same fashion as the Viscometer display reading.

4. Turn the Viscometer motor switch "off" when changing a spindle, changing samples, etc. Remove spindle before cleaning. It is advisable to leave the **Digital** Viscometer power switch "on" between tests to minimize drifting of the Viscometer display.

   It is recommended, when operating the **Digital** Viscometer for a lengthy period, that zero be checked occasionally. Remove spindle from the Viscometer before performing this procedure.

5. The interpretation of results and the instrument's use with non-Newtonian and thixotropic materials is discussed in the booklet, "More Solutions to Sticky Problems."

Calibration

All models of the Brookfield Viscometer are guaranteed to be accurate to within 1% of whatever full scale range is employed when used in the specified manner. Readings should be reproducible to within 0.2% of full scale subject to variations in fluid temperature, etc. Additional calibration information is available in the Brookfield booklet "More Solutions to Sticky Problems."

If it is desired to calibrate the Viscometer, Viscosity Standards are available from Brookfield Engineering Laboratories. They are available in various viscosities to suit all models of the Brookfield Viscometer. The Viscometer's calibration should only be checked under controlled conditions of temperature and in accordance with the following procedures:

LV Models (LVF, LVT, LVTD)

These instruments are calibrated to Bureau of Standards values on the basis of immersion in an infinite body with the guard leg attached. They are accurate to within 1% of full scale when the spindle is centered in any container over 2-3/4" in diameter. Using the Viscometer in smaller containers will reduce the effective range of measurement provided by the #1 and #2 spindles. The calibration of the #3 and #4 spindles is unaffected by the size of the container used as long as the guard leg is attached.

Readings obtained in small containers and/or without the guard can be used only for comparative purposes unless correction factors are used with each spindle and with each container. Our booklet, "More Solutions to Sticky Problems," outlines the procedure to be followed in calculating these factors.

A condition of turbulent flow is created by the #1 spindle when rotating at 60 RPM in materials having viscosities less than 15 cps. If measurements are needed in this region, it is suggested that the UL Adapter accessory be used.

RV Models (RVF, RVF-100, RVT, RVTD)

These Viscometers are calibrated to Bureau of Standards values on the basis of the instrument's use, with its guard leg attached, in a 600 cc low form Griffin beaker. If the instrument is used in a larger container, the ranges over which the #1 and #2 spindles measure will be slightly increased. This effect is negligible with the other spindles (#'s 3-7) provided with the unit.

If it is desired to use the RV spindles in containers other than the one specified, it will be necessary to establish correction factors if values of absolute accuracy are required. The booklet, "More Solutions to Sticky Problems" outlines this procedure.

The #1 RV spindle should not be operated at 100 RPM because a condition of turbulent flow is produced which can cause inaccurate measurements. The lowest accurate viscosity measurable by the RV Viscometers, with standard spindles, is 100 cps.

If trouble is experienced in starting the instrument (particularly at a high speed setting), turn it "on" at a lower speed and shift to the higher speed while it is running.

H Models (HAF, HAT, HBF, HBT, HATD, HBTD)

Brookfield HA and HB Viscometers are used without guard legs. In all other respects, their calibration is based on the same operating conditions as those given previously for the RV model. It is not suggested that they be used for the measurement of viscosities below 200 cps (HA) and 800 cps (HB).

Fault Diagnosis

Problem	Cause	Action
Spindle doesn't rotate	Drive motor not energized	Turn power switch "on"
Display reads "---"	Underrange (Spindle jammed)	Consult factory
Display reads "EEE" Dial Reads 100	Overrange	Change speed and/or spindle
Recorder pen moves in wrong direction	Output polarity reversed	Exchange output leads
No recorder response	Viscometer is at zero reading	Check for output at upscale reading
	Recorder off	Check recorder power and power switch
	Output shorted	Check output connections
Display reads only "00.0" and will not respond to viscosity measurements	0-1v or 0-10mv output signal shorted	Check output connections

Specifications

Power Supply:	115V/60 Hz or 230V/50 Hz 115V/50 Hz or 230V/60 Hz	
*Output Signal: **Digital**	0-10mv DC Red (+) Black(-) For recording	0-1v DC White (+) Green (-) For analog to digital interface or optional recording
Output Impedence: **Digital**	1k ohms	20k ohms

*__Note:__ 0-1v DC output signal supplied on **Digital** Viscometers starting with serial number AO - - - -.

Repairs and Service

Any Brookfield Viscometer used in the United States requiring repair or service should be returned to:

Brookfield Engineering Laboratories, Inc
240 Cushing Street
Stoughton, Massachusetts 02072

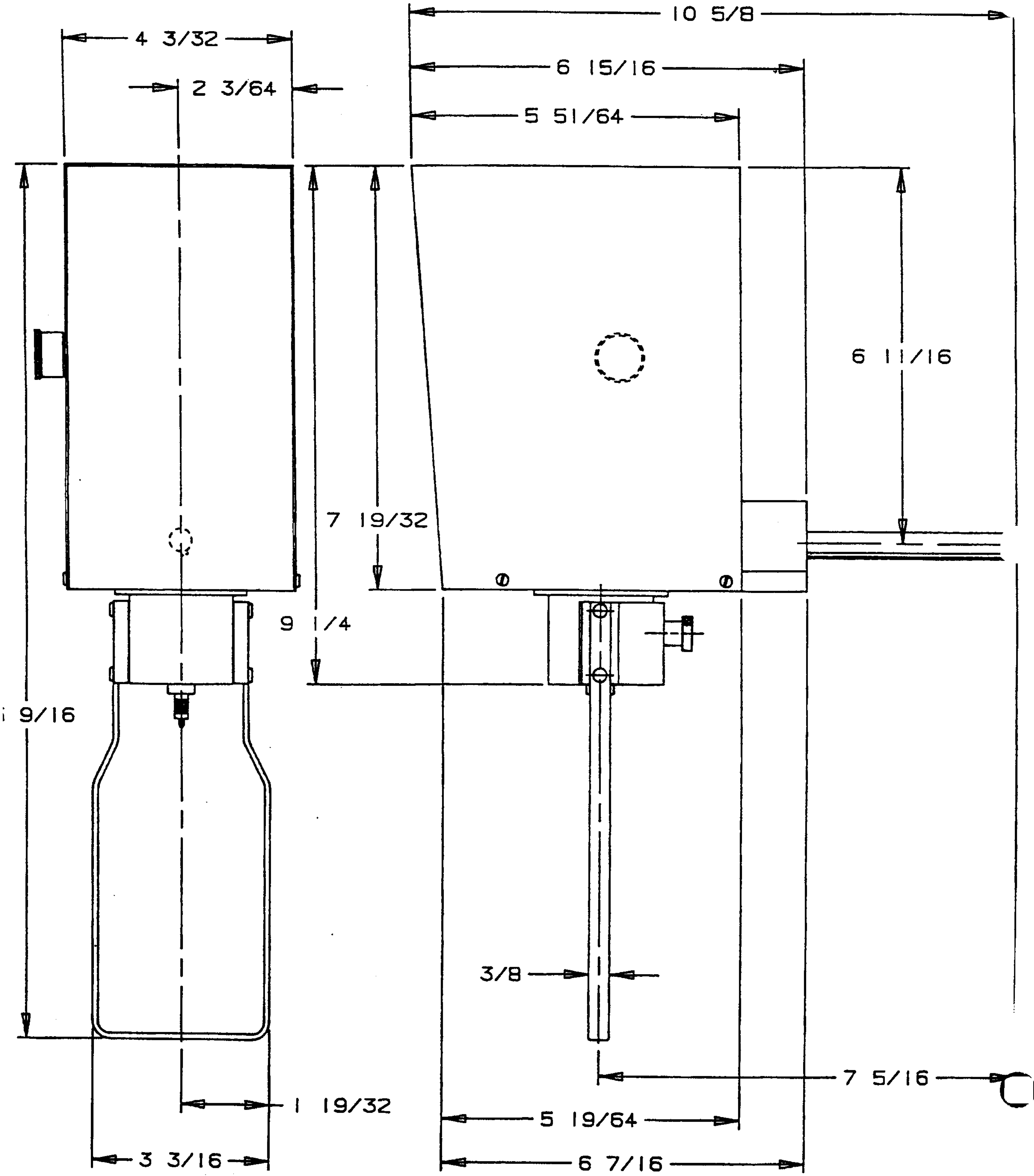
The Viscometer should be shipped in its carrying case together with all the spindles originally provided with the instrument.

For service on Viscometers located outside the United States, consult Brookfield Engineering Laboratories, Inc., or the dealer from whom you purchased the instrument.

Warranty

Brookfield Viscometers are guaranteed for one year from date of purchase against defects in materials and workmanship. The Viscometer must be returned to the manufacturer or dealer for no charge warranty service. Transportation is at purchaser's expense.

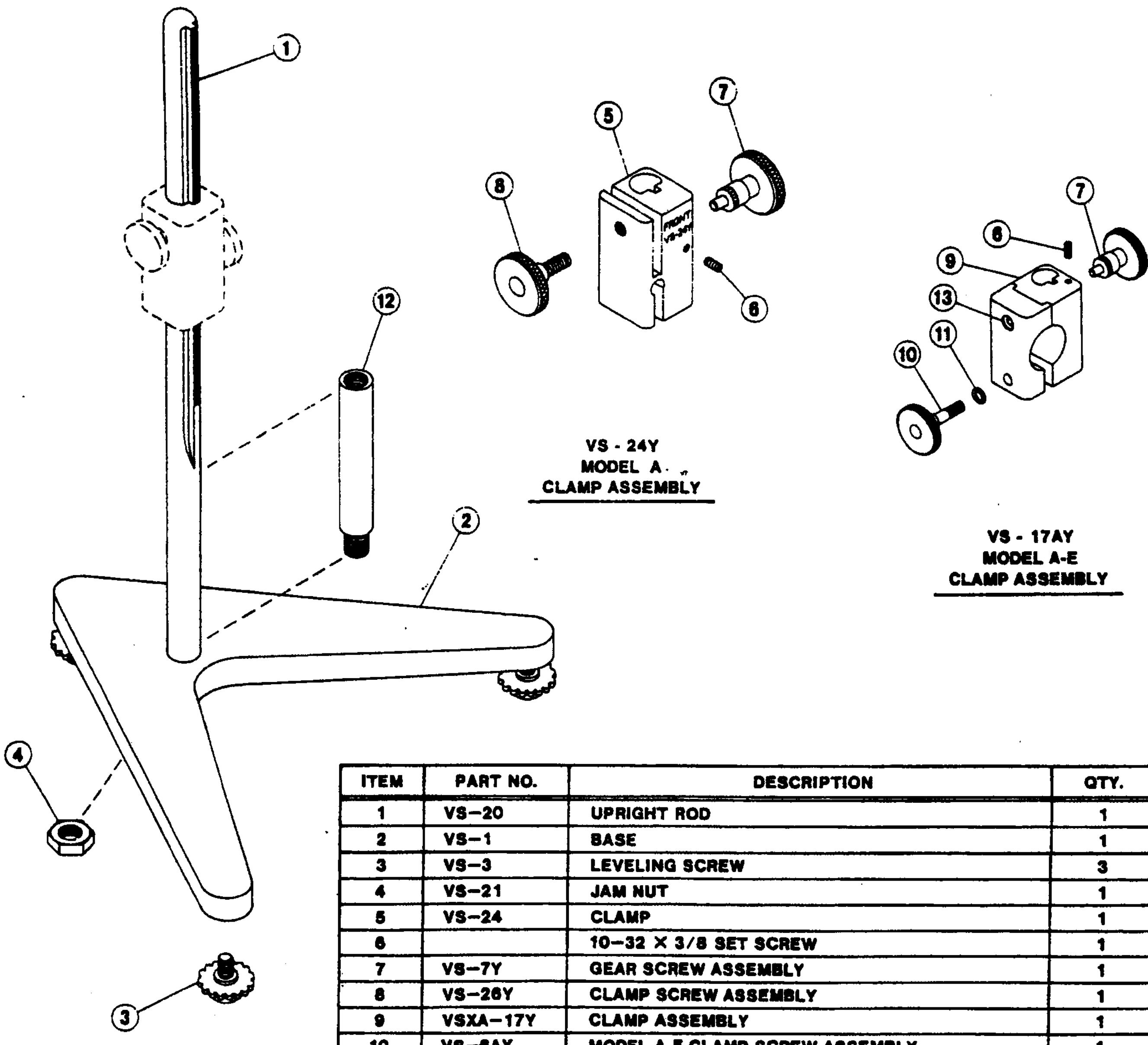
DVI & DVII HEAD DIMENSIONS
(WITH RV GUARD LEG & PIVOT CUP)



AC3-001

MODELS A & A-E LABORATORY STANDS

PARTS IDENTIFICATION



ITEM	PART NO.	DESCRIPTION	QTY.
1	VS–20	UPRIGHT ROD	1
2	VS–1	BASE	1
3	VS–3	LEVELING SCREW	3
4	VS–21	JAM NUT	1
5	VS–24	CLAMP	1
6		10–32 X 3/8 SET SCREW	1
7	VS–7Y	GEAR SCREW ASSEMBLY	1
8	VS–26Y	CLAMP SCREW ASSEMBLY	1
9	VSXA–17Y	CLAMP ASSEMBLY	1
10	VS–6AY	MODEL A-E CLAMP SCREW ASSEMBLY	1
11		1/4 I.D. X 3/8 O.D. WASHER	1
12	BLM–4E	ROD EXTENSION - 4" LONG	OPTIONAL
	BLM–4E–2	ROD EXTENSION - 8" LONG	OPTIONAL
13		1/4–20 X 3/4 HEX SOC HD SCREW	1

82–0330
REV. 1/3/86

MODELS A & A-E LABORATORY STAND INSTRUCTIONS

Unpacking

Check carefully to see that all the components are received with no concealed damage.

1 base	1 jam nut
3 leveling screws	1 clamp assembly
1 upright rod	

Remove the three (3) leveling screws from the base and discard the packing material. Remove the jam nut from the upright rod.

Assembly

Screw the leveling screws into the base. Insert the threaded end of the upright rod into the hole in the top of the base and attach the jam nut to the rod on the underside of the base. With the rod gear rack facing forward (toward the "V" in the base), gently tighten the jam nut. When using the rod extension, screw the threaded end of the upright rod into the extension, then insert the threaded end of the rod extension into the base.

Viscometer Mounting

Dial Viscometers:

Loosen the Viscometer handle retaining nut (if supplied) and slide it down the power cord. Slide the Viscometer handle (if supplied) toward the cord and remove it from the instrument. Insert the Viscometer handle core into the hole (with the cut-away slot) in the clamp assembly. Adjust the instrument level until the bubble is centered from right to left and tighten the clamp knob (clockwise).

Digital Viscometers:

Insert the Viscometer mounting rod into the hole (with the cut-away slot) in the clamp assembly. Adjust the instrument level until the bubble is centered from right to left and tighten the clamp knob (clockwise). **Note:** If the Digital Viscometer cannot be leveled, check to insure that the rod is installed with the gear rack facing forward (toward the "V" in the base).

Explosion Proof Viscometers:

Remove the hex socket screw (item 13) from the clamp assembly and separate the clamp. Place the handle of the Viscometer against the clamp/rod assembly and reinstall the clamp and hex socket screw. Adjust the instrument level until the bubble is centered from right to left and tighten the clamp knob (clockwise).

> **Caution: Do not tighten the clamp knob unless the handle core is inserted in the clamp assembly.**

Center the Viscometer relative to the stand base and retighten the jam nut as required. Referring to the Viscometer bubble level, adjust the leveling screws until the instrument is level.

The small screw on the clamp assembly may be loosened or tightened as necessary to provide smooth height adjustment and adequate support for the Viscometer.

Centrifugal Pump Performance

Principles & Background:

Centrifugal Pumps:

Pumps are designed to move or pump fluids in liquid phase. Liquids are generally considered to be incompressible. The first principle you probably learned when considering fluid flow was Bernoulli's Equation. Bernoulli's Equation applies to incompressible flow. Therefore, we can use it to analyze the flow of liquids and low speed (velocities less than ~ 100 m/s) gas flows.

Bernoulli's Equation assumes perfect flow. That is, there are no losses created by the flowing fluid. Obviously, this is a simplification that must be dealt with when considering "real world" flows. One of the forms of Bernoulli's Equation is:

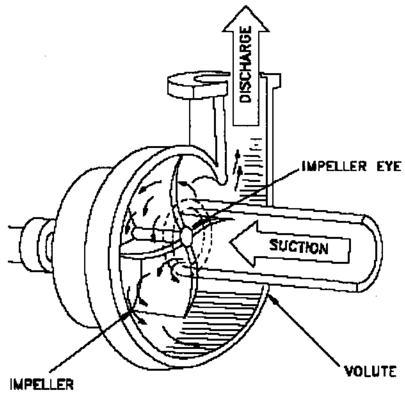
$$\frac{\Delta P}{\rho} + \frac{\Delta \overline{V}^2}{2} + g\Delta z = const \tag{1}$$

This equation is modified to account for losses in "real world" flow systems. One of these forms is known as the D'Arcy – Weisbach Equation which includes a head loss term to account for the friction losses created by the fluid moving through the piping or channels.

$$\frac{\Delta P}{\rho} + \frac{\Delta \overline{V}^2}{2} + g\Delta z + H_L = const \tag{2}$$

When we design pumping systems, we size the pump to produce a head (pressure gain) that is equal to the head loss in the flow system. This allows our system to flow under steady-state conditions.

How does a centrifugal pump create this pressure head? A centrifugal pump consists primarily of an *impellor* enclosed in a housing or *volute*. The impellor is rotated by the pump shaft which is driven by the prime mover. Generally an electric motor or possibly a turbine or other power source. This adds energy (converts shaft/mechanical energy) to energy in the fluid flow stream. Liquid is drawn in at the center or eye of the impellor and discharged on the periphery of the impellor. The liquid is drawn in at the suction pressure. It is discharged at the discharge pressure; a higher pressure. The differential pressure across the pump from suction to discharge is the head gain across the pump.



We can "see" how this increase in pressure comes about in two ways.

First, consider the pump strictly on a 1st Law of Thermodynamics basis. One of the forms of stating the energy balance equation for 1st Law analysis is:

$$e_{mech} = \frac{\Delta P}{\rho} + \frac{\Delta \overline{V}^2}{2} + g\Delta Z \qquad (3)$$

From conservation of mass considerations, there is no change in velocity between the pump suction and discharge side. The mass flow is the same (no storage in the volute) and the inlet and outlet diameters of the connections are basically the same. Therefore, the 2nd term in Eq. (3) goes away.

The change in elevation between the pump's inlet and outlet is negligible. Therefore, the 3rd term in Eq. (3) also goes away.

The pump is moving an incompressible fluid, so the density remains constant. Therefore, the energy added by the shaft, the left-side of Eq. (3) results in a pressure increase in the flow stream, the right-side of Eq. (3).

Alternatively, we can analyze the pump from its suction to discharge side by considering Bernoulli's Equation.

If there is a negligible change in elevation, then Eq. (1) involves only a static pressure term and a velocity pressure term.

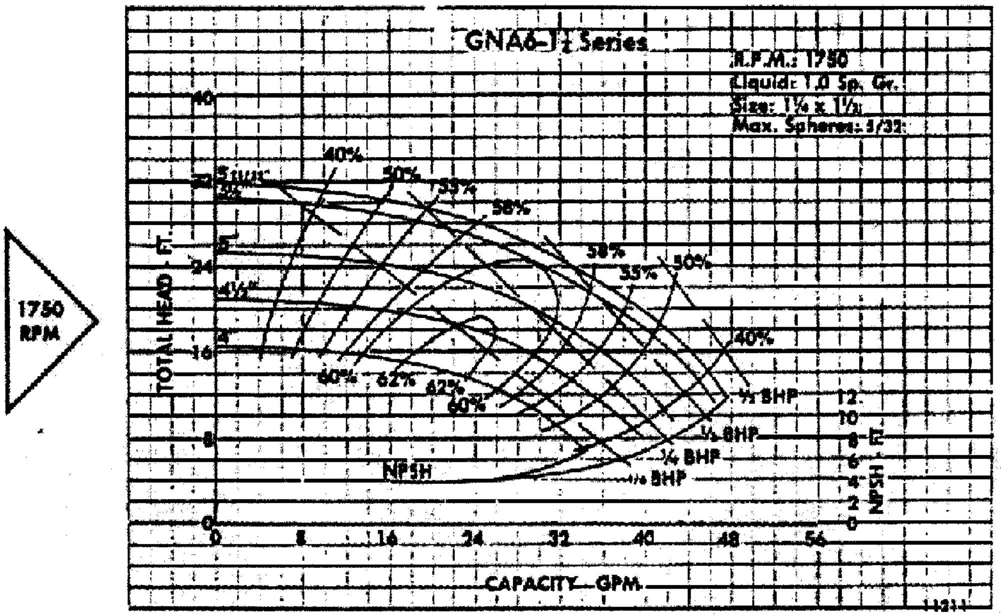
$$\frac{\Delta P}{\rho} + \frac{\Delta \overline{V}^2}{2} = const \qquad (4)$$

As fluid enters the eye of the impellor through the suction piping it has a certain static pressure (the suction pressure) and little velocity so, little velocity pressure. The impellor "grabs" the fluid due to its geometric design (raised surfaces, blading, etc.) and accelerates it outward radially toward the perimeter of the impellor. In so doing, static pressure is converted to velocity pressure. Eq. (4) requires that the total pressure must remain constant. The energy to accelerate the fluid is obtained from the shaft. When the fluid reaches the periphery of the impellor, it encounters the barrier of the volute (housing) which causes the velocity to return to near zero. In so doing, velocity pressure is converted to static pressure. Again, Eq. (4) requires the total pressure to remain constant. This static pressure is at a higher level than it was at the eye of the impellor because shaft energy was added during the acceleration of the fluid. Thus the fluid is discharged at a higher pressure than it entered the pump. This is the head gain across the pump.

From the above review, it seems that pump performance should be a function of such parameters as the size and design of the impellor and volute, the speed of rotation of the impellor, the pressure gain across the pump, and the flow rate of the pump (the above was done on a per unit mass basis, but, if we consider total flow, then total mass flow comes into play).

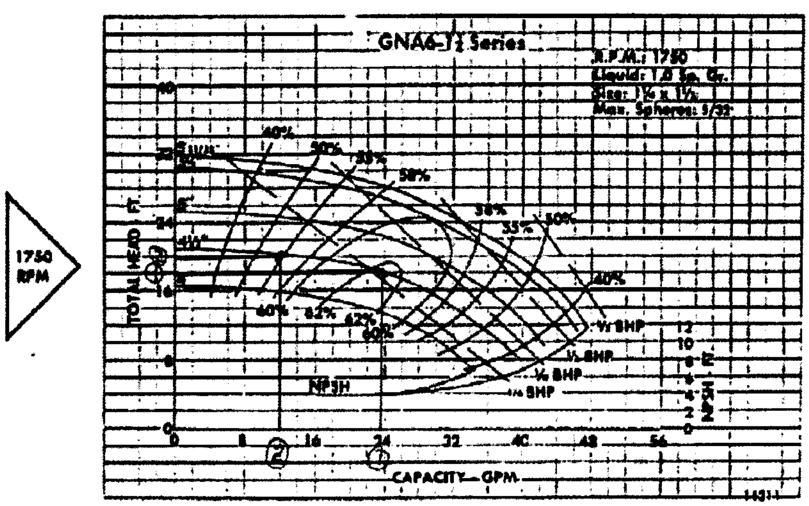
And, indeed, this is the case. Manufacturers of centrifugal pumps provide information about their pumps in the form of *pump curves*. These curves plot information concerning head vs. flow rate for various impellor sizes. Generally a family of curves is provided for different impellor sizes operating at a specific rpm. The plots also show the pump efficiency and power requirement data. A series of plots are provided for pumps of the same size (size is generally specified by inlet and outlet pipe connection sizes) operating at different common motor rpm's.

An example of a pump curve is shown below for a Burkes Pump (the manufacturer used in our lab apparatus).



Note that this is for a pump operating at 1750 rpm. The pressure gain is shown as head in units of ft (of water) on the y-axis. The flow rate is in gpm on the x-axis. Impellor sizes range from 4" to 511/32". Note that a particular pump will have an impellor trimmed to a specific diameter. Information on the pump efficiency and horse power requirements are also shown on this plot.

Note that a centrifugal pump will operate on its impellor curve. We select a pump to meet the flow required by our system or process and the head loss determined by our head loss calculations. But, if the head loss changes due to say a valve opening or closing, the flow rate will change based on the pump "riding its impellor curve". Consider the following example:



Our design flow rate and head loss (denoted as 1) were 24 gpm @ 18 ft H_2O. For some reason, the head loss in the system changed to 20 ft H_2O (point 2). The pump will "ride its curve" and produce a flow rate only of 12 gpm.

We can think of this as the only adjustments available to a simple pumped system. The impellor and volute design are fixed by the geometry. We can adjust these during the design/selection process but not while the pump is in operation. The rotational speed (1750 rpm) is the fixed rotating speed of the motor driving the pump. Note that we do get a change in horsepower requirement and efficiency of the pump due to riding the curve. But it is fixed by the shape of the curve.

As energy efficiency and cost of operations become increasingly important, it would be nice to design systems with more flexibility. We need to design our pumped systems for the "design conditions". For example, in a heating system, the hydronic loop needs to deliver enough heat (gpm at temperature) for the coldest day. But we seldom operate at that design condition. Flexibility to reduce costs during these off-peak times could save a great deal of money.

This is where the Pump Affinity Laws come into play. The Pump Affinity Laws relate the parameters involved in pump operation. In general, they can be stated as:

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} \tag{5}$$

$$\frac{Q_2}{Q_1} = \frac{D_2}{D_1} \tag{6}$$

$$\frac{h_2}{h_1} = \left(\frac{N_2}{N_1}\right)^2 \tag{7}$$

head

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3 \tag{8}$$

power

In Eq. (5) – (8), Q is the volumetric flow rate, N is the pump rotational speed, D is the impellor diameter, h is the developed head, and P is the required power. Based on these relations, if my flow rate is less for some off-peak condition, I should see a substantial reduction in pumping power if I use the same pump but slow its rotational speed by using a speed control on the drive mechanism. Note that there are still some limitations to the use of these laws based on physical/geometric limitation of pump design.

However, use of this theory is what leads us to the very popular variable air volume (VAV) and variable pumped loop systems used in today's HVAC and process industry.

Matlab Information:

In lab this week, you'll collect data on pump speed, flow rate, pressure loss, and torque and use it to confirm the pump affinity laws. To check the quadratic and cubic relations in the pump affinity laws, you'll need to do a non-linear, power function least-squares regression of the data you gather in the lab.

Matlab offers some excellent tools to do this type of regression analysis. The regression your trying to fit is of the form:

$$P = a_0 N^{a_1} \tag{9}$$

For example, the P in Eq. (9) might represent a ratio of pump power requirements while the N represents the pump speed at the same data points. The non-linear regression parameters are represented as a_0 & a_1. In the above case, we'd like to see a_0 equal 1 and a_1 equal 3 to confirm the pump affinity laws. We can find the regression parameters by using Matlab's *fminsearch()* function and passing it the function that represents our desired regression and residuals. 1st we need to create a Matlab function to represent the sum of the squares of the residuals.

```
function f = fSSR(a,xm,ym)
yp = a(1)*xm.^a(2);
f = sum((ym-yp).^2);
```

a represents our parameters (here a(1) & a(2) rather than a_0 & a_1) xm & ym are vectors of our data points. For the above case it would be the ratios of speed and power.

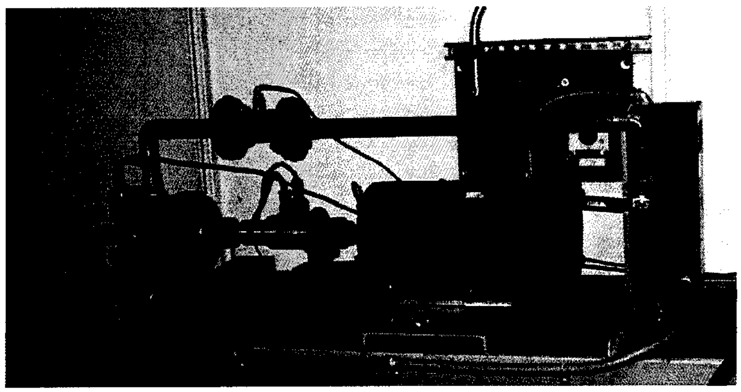
Next we enter the data (x & y vectors, pump data) and call *fminsearch()* to optimize (find the minimum) the parameters

```
>> x = [........];
>> y = [........];
>> fminsearch(@fSSR, [1, 1], [], x, y)
```

This exchange with Matlab at the command prompt will result in Matlab returning the curve fit parameters.

Lab Procedure:

The following is a photo of the apparatus used to test the Pump Affinity Laws in this lab exercise.



The apparatus consists of:

1. A Burks centrifugal pump driven by an electric motor equipped with a variable speed drive.

2. A tank to act as a source of water and a sink for the water in the pumped loop system. And piping to created a pumped loop.

3. A speed control to adjust the speed of the pump and a meter to measure the speed of the pump in [RPM].

4. A flow meter to measure the flow rate in the system in [GPM]

5. A ball valve to induce an artificial pressure drop to the pumped loop and a differential pressure sensor to measure the pressure drop in the flow loop in [psi]

6. A torque meter to measure the torque delivered from the motor shaft to the pump shaft in [in-Lbf]. This information can be used to determine the power consumed by the pump.

You will gather data on flow rate, pressure drop, pump speed, and torque for several different pump speeds and several different pressure drops.

1. Adjust the pump speed to 500 RPM.

   a. Set the valve to 0% open and gather data for the: pump speed, pressure drop, flow rate, & torque. (Note: the torque readout device can also display the power. Read this data and compare it to the values you calculate using the torque values.)

b. Adjust the valve to full open and again collect a complete set of data. Note that the valve is a ball valve. This is not a "linear plug" valve. Therefore, setting the valve to the half-open position does not result in ½ flow rate through the valve. By reading the flow rate at full open, you'll be able to calculate the ¼ , ½, and ¾ flow rate values. You'll use the flow rate meter to adjust the valve during the experimental procedure to obtain these flow rates.

c. Adjust the valve position to obtain flows of ¼, ½, and ¾. Take readings of the flow rate, pump speed, pressure drop, & torque for each of these flows.

2. Adjust the pump speed to 1100 RPM and repeat Step 1.

3. Adjust the pump speed to 1750 RPM and repeat Step 1

4. Adjust the pump speed to 2500 RPM and repeat Step 1

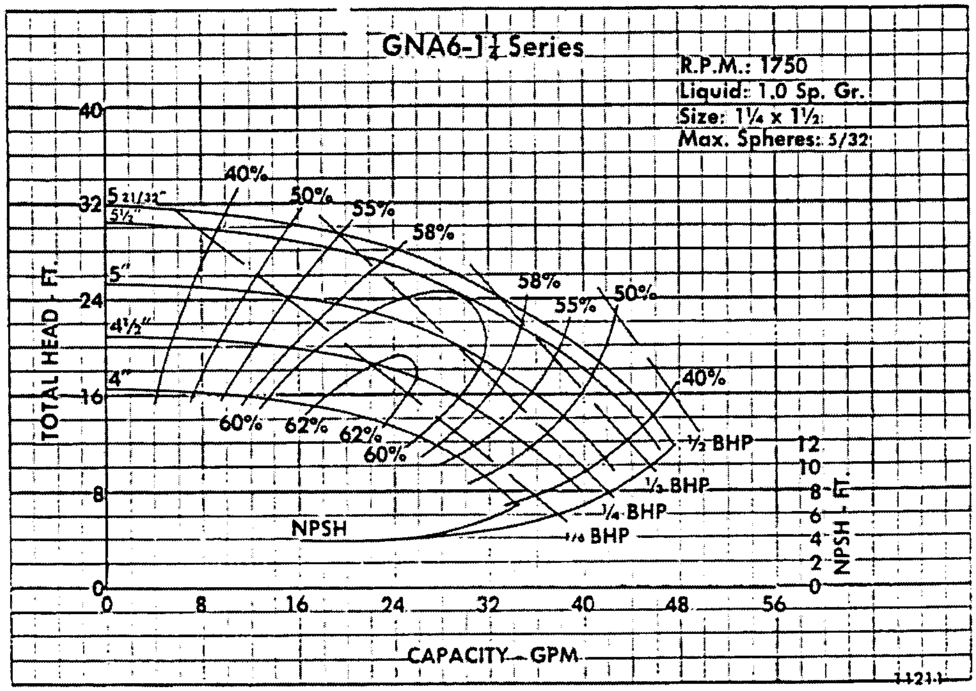
Using this data, perform a power regression and compare your results to the Pump Affinity Laws. If you observe any large deviations from the theory, explain what you expect may be wrong (it is likely to be a problem with our apparatus as the Pump Affinity Laws are well accepted).

burks pumps
P. O. Box 431 Decatur, Illinois 62525
Phone: 217/429-2591

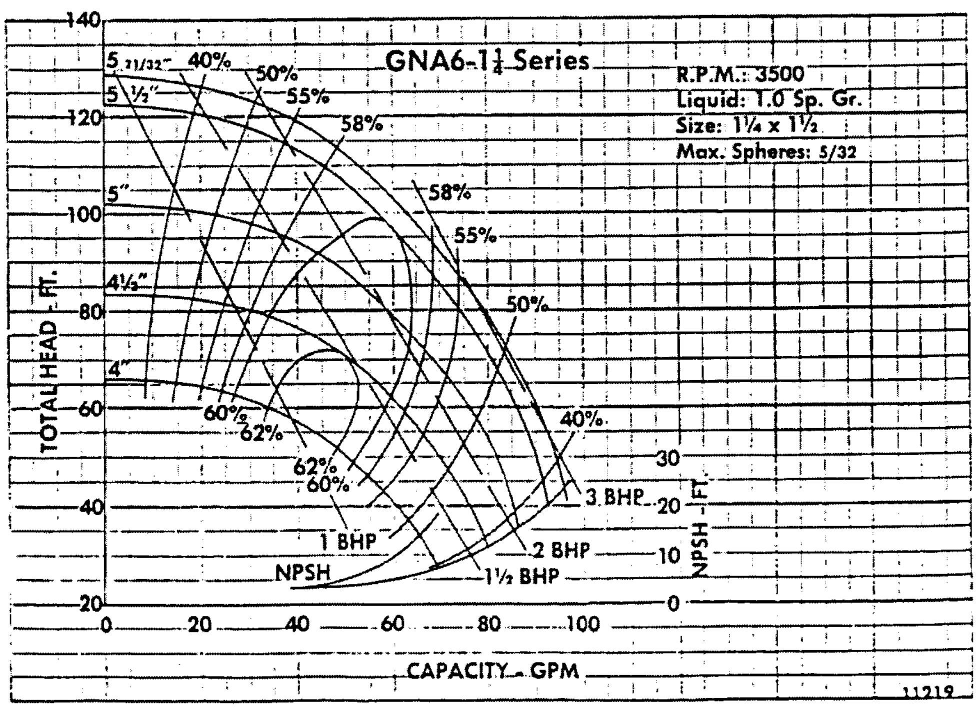
PERFORMANCE CURVES

INDEPENDENT END SUCTION CENTRIFUGAL PUMPS

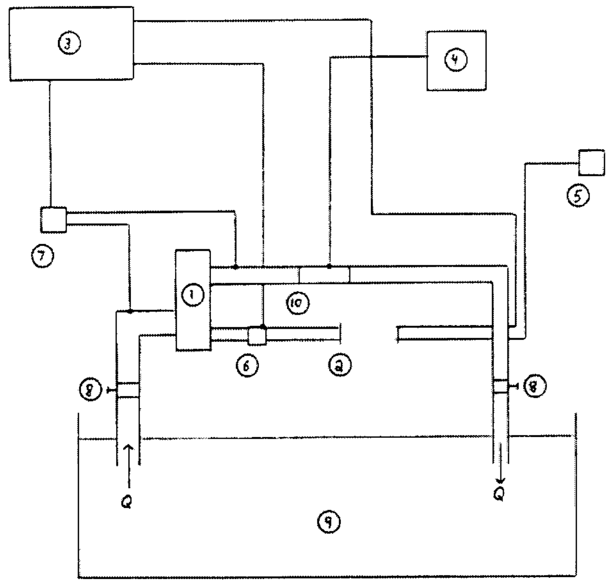
1750 RPM



3500 RPM



PUMP EXPERIMENTAL SET-UP



1) Centrifugal Burks Pump
   Serial number: 41928
2) 3 Hp. motor manufactured by Powertron Corp.
   serial number: 4-9407-1DE490
   UAF ID. number: 50961
3) Daytronic Model 9010/Digital Indicator 9530
4) Campbell Scientific Micrologger 21X
   serial number: 4643
   UAF ID number: 127095
5) Speed control
6) MCRT Torquemeter model 2-077 (5 – 1)
   serial number: 2T-318.5276
7) Daytronic differential pressure meter
   model 530-750
   serial number: 8.1
8) valve
9) water tank
10) Flow transmitter model 1.5-81F5C1
   serial number: 83470

TRANSDUCERS

Introduction:

This document is meant to outline some basic research I did on the transducers used in this lab, so that a future student or faculty member may have direction on how to replace instrumentation for the pump performance lab if they choose to do so.

Flow Meter:

Make/Model: Foxboro 1 1/2 - 81F5C1

This is the only transducer that requires a general DAQ tool to read. One bases their measurement on the primary frequency of the input signal, which is within the range of about +/- 1 V. The unit has a "meter factor" of 245.6 pulses/gallon. In other words:

```
GPM = (60/245.6)*f
```

This should be in the included VI.

Pressure Transducer:

Make/Model: Daytronic 513–75D

Web Site: http://www.daytronic.com/products/trans/t–513PT.htm

This unit seems to return analog voltage, with the following specs, with a full-scale range of 75 psid and an output of 2 mV/V. Therefore, it should be relatively simple to use LabVIEW to measure it.

Torquemeter:

Make/Model: S. Himmelstein & Co., MCRT 48201V–2308–191

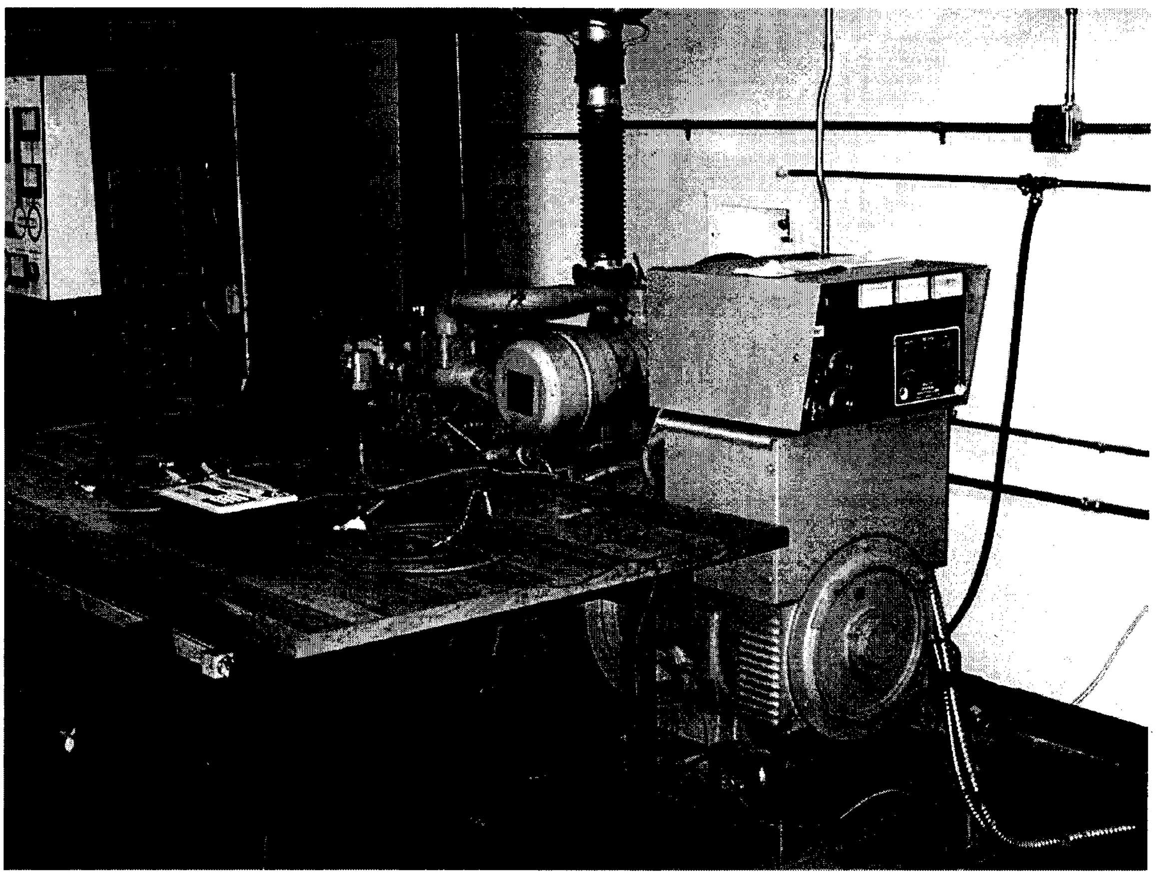
Web Site: http://www.himmelstein.com/48200v.asp

This unit is a *digital* torquemeter, and communicates with devices through a serial port. This is one of the primary reasons, besides time, that I decided not to try converting this lab to use LabVIEW throughout.

An important caveat with the torquemeter: Its RPM measurements are sound and its horsepower calculation is correct given its RPM and torque readings. **HOWEVER**, the torque reading is about **100** times too large. Reasons for this are currently unknown.

Diesel Engine Performance

DIESEL ENGINE PERFORMANCE



PERFORMANCE OF DIESEL ELECTRIC GENERATOR

R. Johnson

Background:

Diesel electric generators are widely used today for the production of electric power in remote locations. Applications include electrification, agriculture, telecommunications, military/security, marine/navigation and cathodic protection. Diesel plants represented 0.85% of the U.S. utility capacity in 1979 and 17% of the installed Alaskan capacity in 1984.

The vast majority of Alaskan rural communities rely on diesel electric generators to supply their electric power needs. With most villages requiring much more energy for space heating than for electricity, the cogeneration of heat and electricity is becoming more common. Heat is recovered from either the jacket water or both the jacket water and stack gas. The total efficiency of such systems can be much greater than that associated with electrical production alone.

Purpose of Laboratory and Apparatus :

The main objective of this laboratory is to measure the performance of a diesel electric generator both in producing electricity and useful heat. The specific apparatus we will use is a KEM MERLIN 45 KW generator set consisting of a Mitsubishi model 4D31TM diesel engine coupled to a Stamford model SC244C generator. The engine is a four cylinder, four cycle, inline water-cooled, turbocharged unit running at 1800 rpm. The generator is a directly connected A.C. revolving field type with 480 volts, 3 phase, 4 wire, and a power factor 0.80 or better. Jacket water heat is recovered using a unit mounted shell and tube heat exchanger. The electrical load is provided by an AVTRON Model K775 resistive load bank.

The electric power output will be sensed using an OSI wattmeter consisting of 2 current transformers and a voltmeter. The fuel consumption will be monitored gravimetrically using Lebow load cells upon which the fuel tank rests. Critical system temperatures will be measured using type T or K thermocouples and flow rates of water via Omega in-line turbine flow meters. The output signals from these transducers (either in mA or 0-5 volts) will be sent to a Campbell 21x datalogger which is connected to a personal computer via an RS 232 interface. Standard software can then be used to manipulate the data.

Procedure:

The general procedure is to allow the system to reach steady-state at a given load, say 30 KW. Then, use the performance data collected to measure the two critical efficiencies. Details are provided on the attached pages.

<u>**START UP DIESEL ENGINE**</u>

1. Turn on power to the load bank (the left hand switch on the wall mounted panel).
2. Turn on the IBM computer.
3. Turn on Campbell datalogger.
4. Plug cable from the computer into the Campbell's serial I/O port.
5. Load program into the datalogger by:
   a. Get into the logger subdirectory by typing **CD LOGGER**.
   b. Load the terminal program by typing **TERM DUCK**.
   c. Download a program by typing **D**.
   d. The program name is **RELAX**.
   e. Get out of the download mode by typing **E**.
   f. Go back to the menu by typing **Control -**.
   g. Leave the terminal program by typing **Q**.
   h. Unplug the cable that connects to the serial I/O port.
   i. **TURN OFF THE COMPUTER**.

6. Set the shop water flow rate to about 4 gallons/minute by:
    a. Display current values by pushing the * button on the datalogger and then the **6** key.
    b. Push the **A** key until the display shows **08: ####**. Then number is the shop water flow rate in gallons/minute.
7. Check the oil.
8. Turn the ignition key to **RUN <u>NOT TO START</u>**.
9. Push and hold the **OIL BYPASS BUTTON**.
10. Turn the key to **CRANK** until the engine starts.
11. When the oil pressure up release the **OIL BYPASS BUTTON**.
12. Turn on the load bank blower(located on the wall control panel).
13. Set the desired load using the switches on the load bank control panel.
14. Wait about 5 minutes.
15. Turn on the **MASTER LOAD SWITCH**.

SHUT DOWN

1. Turn off **MASTER LOAD SWITCH**.
2. Turn off all load switches.
3. Retrieve data (see DUMP DATA TO PC).
4. Wait 5 minutes.
5. Turn off blower.
6. Turn ignition switch to **OFF**.
7. Turn off load bank power.
8. Turn off shop water.

DUMP DATA TO PC

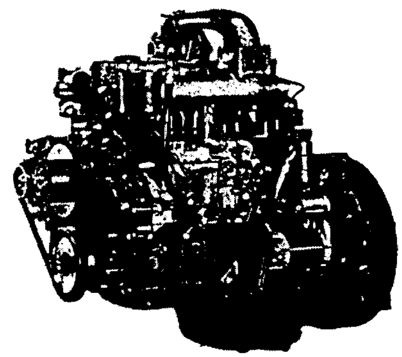
1. Plug the cable into the serial I/O port.
2. Turn on the computer.
3. Get into the logger subdirectory by typing **CD LOGGER**.

4. Load the terminal program by typing **TERM DUCK**.
5. Call the datalogger by typing **C**.
6. Hit **RETURN** until the * appears.
7. Get the datalogger status by typing **A**.
8. Find the number of data arrays (call that number S) by taking the number after the letter **L** and dividing by 11.
9. Back the pointer up S number of arrays by typing **S B**.
10. Go back to the main menu by typing **Control -**.
11. Receive a file by typing **R**.
12. The type of file is ASCII so type **A**.
13. Type in your filename **<u>WITHOUT A FILE EXTENSION!!</u>**
14. We don't have start and end parameters so type in **N**.
15. When back to the *, dump the data by typing **S D**.
16. Go back to the main menu by typing **Control -**.
17. Quit by typing **Q**.
18. Get the data in a form the Lotus will take by typing **STRIP** Filename.
19. Your data will be in Filename.DAT.

MITSUBISHI ENGINE

4D31-TM GENERATOR DRIVE ENGINE

Practical Value
Proven Dependable Power



Standard Specifications

Four-Stroke Cycle, Turbocharged, Liquid Cooled, Inline 4 Cylinder Diesel Engine

Bore and Stroke	3.94 x 4.13 ins.	100 x 105 mm
Displacement	201 cu. ins.	3.3 L
Approx. Dry Weight	771 lbs.	350 kg
Combustion Chamber	Direct Injection	
Compression Ratio	16:1	
Crankcase Coolant Capacity	2.19 U.S. Gallons	8.3 L

Rated Output	1800 RPM Standby	1800 RPM Prime	1500 RPM Standby	1500 RPM Prime
kW*	55	50	48	43.5
bhp	73.8	67.1	64.4	58.3
Approx. Fuel Consumption @ 3/4 output, with fan				
U.S. Gals./hr.	2.78	2.52	2.44	2.21
Liters/hr.	10.5	9.5	9.2	8.4

*Mathematical Equivalent of Gross Engine hp

Dimensions

Excludes fan drive; includes flywheel housing

Height: 34.3 ins. (871 mm)
Width: 25.9 ins. (657 mm)
Length: 33.7 ins. (857 mm)

Standard Equipment

Air Cleaner: Medium duty
Alternator*: 12 V/40 A with integral regulator
Engine Mounting: Front and rear
Exhaust Outlet*: 3.0 ins. (76 mm) dia., upwards with flange
Fan: 17.3 ins. (440 mm) dia.: pusher
Flywheel*: SAE 10 ins. (254 mm) dia.
Flywheel Housing*: SAE No. 4
Fuel Filter*: Spin-on, paper element
Governor*: Mechanical centrifugal
Inlet: 1.93 ins. (49 mm) dia.
Instruments: Hourmeter, 12-24 VDC; ignition switch; intake heater lamp*; tachometer 12 VDC
Lube Oil Filter*: Spin-on, by-pass paper element
Oil Cooler*: Tubular type
Oil Pan*: 1.85 U.S. gals. (7.0 L); rear sump; 30°
Publications*: Operation and maintenance manual
Radiator: Shipped loose with piping
Safety Devices: Coolant temperature shut-off switch @ 221°F (105°C); oil pressure shut-off switch @ 7.1 PSI (.5 kg/cm^2); overspeed switch @ 115%
Solenoid: Energize-to-run
Starter*: 12 V/2.2 kW
Starting Aid*: Intake heater, 12 VDC
Thermostat Opening Temperature: 169°F (76°C)
Turbocharger*: Mitsubishi

*Base engine component

Optional Equipment

Air Cleaner: ☐ Heavy duty
Alternator: ☐ 24 V/25 A ☐ 24 V/40 A
Coolant Heater: ☐ 100 VAC/300 W ☐ 200 VAC/300 W
Engine Mounting: ☐ Front and rear ☐ Front
• Exhaust Pipe Flex Connector: ☐ Shipped loose
• Exhaust Silencer: ☐ Shipped loose
Fan: ☐ 17.3 ins. (440 mm) dia.: puller
Flywheel Housing: ☐ SAE No. 3
Instruments: ☐ Ammeter ☐ Battery switch
☐ Hourmeter, electrical
☐ Oil pressure gauge, metric or zone graduation
☐ Pilot lamp
☐ Tachometer, 24 VDC
☐ Water temperature gauge, metric or zone graduation
Lube Oil Filter: ☐ Horizontal mount
Lube Oil Heater: ☐ 100 VAC/80 W ☐ 200 VAC/80 W
Oil Pan: ☐ 2.4 U.S. gals. (9.0 L)
☐ 35° ☐ Center sump
Publications: ☐ Parts catalogue ☐ Service manual

(Continued on back)

MM-GNE-SS-03A February, 1986 4D31-TM

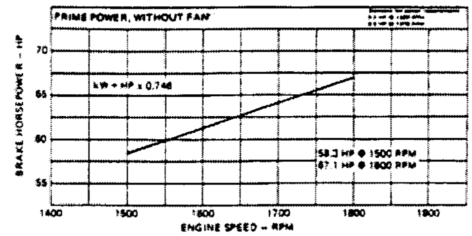
Optional Equipment — Continued

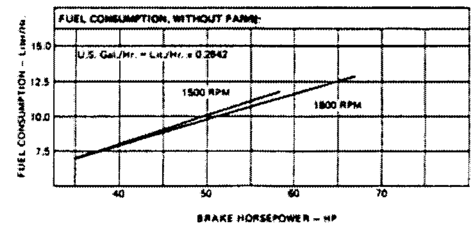
Radiator:		☐ High ambient with piping
Solenoid:		☐ Energize-to-stop
Spare Parts:		☐ Standard spare parts
Starter:	☐ 24 V/3.2 kW	☐ 24 V/5.0 kW
Starting Aid:		☐ Intake heater, 24 VDC
Tools:		☐ Standard tools
Water Separator:		☐ Shipped loose

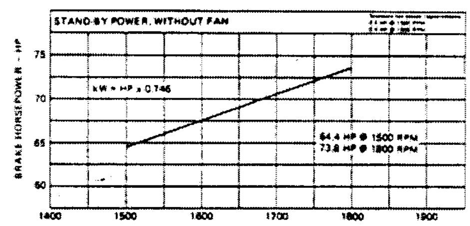
DESIGN FEATURES

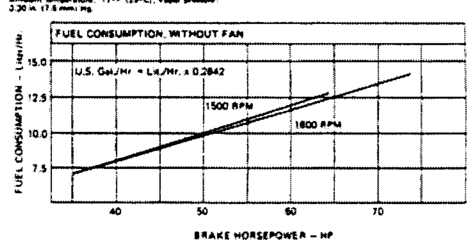
Bearings: • Proven tri-metal design • Steel-backed copper with lead alloy overlay • Main: 3.0 ins. (78 mm) dia. • Connecting rod: 2.3 ins. (60 mm) dia.
Camshaft: • Single forged steel alloy for durability • Wear-resistant, induction-hardened cams and journals • "Polydine" designed cam ramps improve performance • Tapered cam lobes extend life
Camshaft Tappet: • Chill-hardened for durability • Even wear promoted by spherical face design
Connecting Rod: • Forged, high-strength steel alloy • Weight matched for smooth engine performance
Cooling System: • V-belt driven centrifugal pump • Wax-type thermostat
Crankcase: • High-strength, grey-iron casting • Holographically designed for rigidity
Crankshaft: • Single piece, forged, high-strength steel alloy • Wear-resistant, induction-hardened journals, fillets and pins • Integrally forged counterweights
Cylinder Head: • Highly rigid casting of special grey iron • Replaceable valve seat and guide inserts ease serviceability • Two valves per cylinder • Internal coolant jet directs coolant to bridge between valve seats for improved valve life
Cylinder Sleeves: • Replaceable dry sleeves • Minimal oil consumption promoted by plateau honed bores
Fuel System: • Reliable • Bosch type inline pump • Efficient hydraulic injection nozzles • Convenient spin-on filter
Lubrication System: • Precision gear driven pump • Oil jets cool piston for improved performance • Quick-change spin-on by-pass filter • Effective integrated fin and tube type cooler is standard equipment
Piston: • Performance-proven three-ring design • "Ni-resist" top ring insert prevents temperature erosion • Low oil consumption and efficient heat transfer promoted by elliptically machined profile
Piston Pin: • Special alloy steel • Polished microfinish
Turbocharger: • Manufactured by the world leader in research and design — Mitsubishi • Matched for achieving optimum engine performance
Valve: • Special alloy steel • Stellite faced exhaust valve

ENGINE PERFORMANCE









MITSUBISHI ENGINE NORTH AMERICA, INC.
610 SUPREME DRIVE BENSENVILLE, ILLINOIS 60106
TELEPHONE: (312) 350-9540 TELEX: 280135 TELEFAX: 312-350-9552
Printed in U.S.A.

NEWAGE STAMFORD

Prime	35 – 75 kW 60 Hz 1800 Rev/Min 28 – 60 kW 50 Hz 1500 Rev/Min
Standby	36 – 80 kW 60 Hz 1800 Rev/Min 30 – 64 kW 50 Hz 1500 Rev/Min

'C' RANGE 4 POLE INDUSTRIAL BRUSHLESS A.C. GENERATOR

FRAME 2

Machine Designation: SC 244, 234

Available with SERIES 4 (SC244) or SERIES 3 (SC234) excitation systems

EXCITATION SYSTEMS

Series 4 (Self-excited)

The field of the rotating-armature a.c. exciter is fed from the stator winding via a solid-state A.V.R. (automatic voltage regulator), the machine's residual magnetism providing the necessary build-up. The A.V.R. compares the terminal voltage with an internal zener diode reference and amplifies any 'error' to maintain the required adjustable voltage level. The exciter armature feeds the main generator field winding through a three-phase full-wave silicon diode shaft-mounted rectifier. A semi-conductor surge suppressor protects the diodes against transient over-voltages induced by load surges or inexact paralleling. The A.V.R. includes a pre-set frequency-sensitive underspeed circuit which provides a volts-per-hertz charateristic below about 90% speed; this helps to protect the prime mover against high torque overloads and to protect the generator rotor against overexcitation during underspeed.

Series 3 (Permanent - Magnet Pilot)

A permanent magnet pilot exciter feeds the exciter field via the A.V.R., providing an excitation source independent of the machine output. The A.V.R. is generally similar to that used for Series 4, but is fitted also with an overexcitation circuit to de-energise the machine during a prolonged overload or fault or a field overcurrent produced by diode failure. The pilot exciter provides inherently a steady-state short-circuit current capability.

VOLTAGE RANGE/RECONNECTION

All machines offer the voltage-range/reconnection flexibility provided by the standard 12-wire stator winding (see p.2). Special requirements such as non-standard single voltages of voltage ranges, or a dual-frequency capability, can usually be made available at voltages of up to about 600V.

VOLTAGE REGULATION

The A.V.R. maintains the voltage within **±2%** (Series 4) or **±1%** (Series 3) at all loads and at power factors of **unity** to **0.8** lagging, inclusive of cold-to-hot and **4½%** engine speed variations. **±1%** is available at a small extra cost. The specified voltage range is covered by a trimmer in the A.V.R. but a separate trimmer for switchboard mounting is available as an extra.

WAVEFORM

The total (r.m.s.) waveform distortion (line-to-line and line-to-neutral) is of the order of **2%** on open circuit, and the corresponding on-load figure for a balanced linear load is about **3½%**. Standard THF (Telephone Harmonic Factor – a frequency-weighted r.m.s. distortion) values are better than **2%, and the correspondong NEMA TIF (Telephone Influence Factor) is better than 50.** All triplen harmonics (3, 9, etc.) are eliminated form the line-to-neutral waveform by the standard two-thirds-pitch winding.

RESPONSE

Ample excitation margin is provided for rapid response to load changes, and voltage recovery to within **3%** of the steady-state value takes place in less than **0.25** seconds. All machines meet the BS 4999 voltage regulation Grade VR2.23; compliance with VR2.31-33 should be checked with the factory.

MOTOR STARTING

A low-power-factor overload equivalent to a full-voltage current of **3 x f.l.** (Series 3) or **2½ x f.l.** (Series 4) can be sustained for up to 10 seconds.

SUSTAINED FAULT CURRENT

The Series 4 system offers no sustained short-circuit current. With Series 3 machines, however, up to **3 x f.l.** steady-state short-circuit current is available to operate external protective devices, and the internal over-excitation circuit will de-excite the generator after a minimum of 5 seconds to afford external device discrimination.

INSULATION/IMPREGNATION

In the Class H insulation system all windings are either **triple-dipped** in a moisture/oil/acid resistant thermo-setting polyester varnish or **vacuum/pressure impregnated (VPI)** in a polyester resin. For normal environments the standard coat of anti-tracking varnish provides a sufficient surface protection against air-borne moisture or condensation, but where moderate/severe salt or sand contamination is expected all the stationary windings can be given a heavy coat of epoxy resin at a small extra cost.

RADIO INTERFERENCE

The absence of any brushgear and the isolation of the A.V.R. ensure that radio interference is minimised. Standard additional suppression meets the requirements of BS 800 and VDE Classes G & N; the more stringent Class K can be met (at an extra cost), with Series 3 machines.

TORSIONAL APPROVAL

The responsibility for torsional compatibility lies with the generator set manufacturer, and full torsional generator data will be supplied on request.

MECHANICAL VERSATILITY

The generator is available in either two bearing or single bearing construction. Drive is by direct coupling to a prime mover and a standard range of flange adaptors is available. For single bearing machines a standard range of semi-flexible disc coupling is available.

ENCLOSURE

All standard machines are screen protected and drip-proof to the BS 4999 Part 20 (and IEC/DIN) designations below

Standard two-bearing – IP21 vertically drip-proof.

Standard single-bearing – IP22 (but 30°C drip-proof.)

As an optional extra, two-bearing machines can be offered to IP23 (60°C drip-proof)

TERMINAL BOX

A large sheet-steel terminal box with a multi-panel access to the main and auxiliary terminals, and with a separate externally-accessible A.V.R. compartment, is provided at the NDE. Both main and auxiliary terminals are rigidly mounted from the main frame itself. Ample space is provided for electrical accessories.

COMPLIANCE WITH STANDARDS

The machine has been designed to meet the requirements for rotating electrical machines laid down in NEMA MG1 - 22 or CSA C22.2 No. 100, IEC or BS.

CANADA
NEWAGE EQUIPMENT LIMITED
P.O. Box 427, Islington,
Ontario, M9A 4X4
Telephone: Toronto (416) 259 - 3741 Telex: 06 - 967676
Montreal (514) 286 - 4046
Vancouver (604) 430 - 8131 Telex: 04 - 55440

U.S.A.
NEWAGE LIMITED
P.O. Box 103, 3 Independence Court,
Folcroft Industrial Estate, Folcroft,
Pennsylvania 19032.
Telephone: Philadelphia (215) 534 9500 Telex: 845276

Head Office/Factory – Newage Engineers Ltd., P.O. Box 17, Stamford, Lincs. PE9 2NB, England.
Reg. Office. Park Works, Stamford, Lincs. Registered in England No 441273.

★ AVTRON MANUFACTURING, INC.
10409 MEECH AVENUE • CLEVELAND, OHIO 44105 • (216) 641-8310

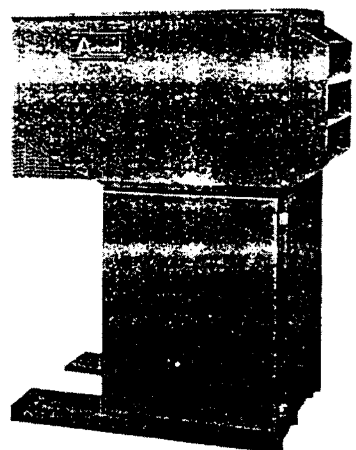
Model
K775

BULLETIN 259

PERMANENT, WEATHER-RESISTANT

Resistive Load Bank

15 to 75 kW



- Indoor/Outdoor Installation
- 15KW to 75KW Units
- 240 and 480 Volt Designs
- Built-in Forklift Channels
- Temperature Controlled Water tight Contactor Enclosure
- Needs No Cool Down Period ✓
- 19" Remote Control Panel with Optional Enclosure

A Rugged, Permanently Installed Load Bank for Testing and Exercising of Engine Generator Sets.

The Model K775 Load Bank is designed for permanent outdoor installation when 15KW to 75KW of load is required. The K775 series incorporates the latest in state-of-the-art load bank design techniques.

The K775 requires no cool down period after load is dropped. The contactors are enclosed in a thermostatically controlled heated enclosure. This enclosure has a hinged, lockable door with rubber gasketed protection.

The load bank contains resistive elements and a blower motor in a rigid structure of formed heavy gauge steel. Designed for outdoor installation, the load bank utilizes fixed louvers on the exhaust opening and a ground-facing inlet opening to protect the motor and resistive assemblies from the weather.

The K775 is available with ratings of 15KW to 75KW, 240V or 480V, three phase.

21X MICROLOGGER

A Rugged, Powerful Little Datalogger

The 21X is a textbook sized, D cell powered precision datalogger. The term "MICROLOGGER" is descriptive of this MICRO-computer based dataLOGGER's MICRO-size, MICRO-power and sub-MICRO-volt sensitivity. It is the combination of a micro-computer, clock, multimeter, calibrator, scanner, frequency counter, controller, and signal generator all in one small box. Small size, low power and the ability to operate in environmental extremes were primary design objectives for portable, remote operation.

SIGNIFICANT FEATURES

PERFORMANCE VERSUS COST: Measurement and processing throughput in excess of 100 channels per second and sensitivity of ⅓ of a microvolt at 25 channels per second at a remarkably low price.

PERFORMANCE VERSUS SIZE: Sixteen analog and four pulse counting channels plus all the features described here packaged smaller and lighter (including batteries) than the CRC Handbook of Chemistry and Physics.

PERFORMANCE VERSUS POWER CONSUMPTION: Scanning and processing all 16 channels at 1 minute intervals; the 8 alkaline D cells last about 6 months. The rechargeable batteries in the 21XL provide 2 months' operation per charge under the same conditions.

SENSITIVITY AND MEASUREMENT SPEED: Fourteen bit precision on 5 software selectable ranges. 0.33 microvolt resolution at 37 milliseconds per channel with 100 nanovolt RMS input noise. At 2.5ms per channel the input noise is 1.2 microvolt RMS.

SENSOR COMPATIBILITY WITHOUT EXTERNAL SIGNAL CONDITIONING: Linearized thermocouple measurements at 7.3 milliseconds per channel resolve to within 0.05 deg. C. Bridge excitation voltage selectable within a ±5 V range at .67 mV resolution. Resistance bridge measurements such as RTDs, load cells, pressure transducers, foil strain gages and thermistors optimize accuracy using AC excitation and ratiometric techniques. AC excitation also minimizes polarization errors in soil moisture, salinity, conductivity, and RH sensors. Four pulse counting channels accommodate magnetic pulse flow meters, photochopped or switch closure devices and incremental shaft encoders directly.

EXPANDABILITY: Analog inputs are expandable in 32 channel increments to a maximum of 192 channels using the Model AM32 Relay Scanner.

REAL-TIME DATA PROCESSING: User programmed processing includes linearization, algebraic and transcendental functions, engineering unit scaling, averaging, maximum/minimum, totalizing, standard deviation, wind vector integration with direction sigma, histograms, and more.

REMOTE PROGRAMMING: Programs, parameters and direct commands can be entered directly from the keyboard or via the serial communications port from a remote computer or terminal.

FLEXIBLE DATA STORAGE AND TRANSFER: Data is stored in memory for transfer to the display, cassette, printer, modem, or directly to a computer. Expansion of 21X memory allows storage of up to 19,200 data values. The cassette recorder stores up to 180,000 values on one side of a C60 cassette at a maximum rate of 100 values per second.

ANALOG AND DIGITAL CONTROL OUTPUTS: Two continuous analog outputs with 14 bit resolution are available for strip chart recorders or proportional control. Six digital outputs can be set based on time or processed input levels.

PROTECTED INPUTS AND OUTPUTS: All panel connections are protected from electrical transients using spark gaps or transzorbs.

OPERATION IN HARSH ENVIRONMENTS: -25 to +50 deg. C. 0 to 90% relative humidity. The 21X packaging provides protection from excessive humidity and contaminants. On special order, 21X's will be tested and guaranteed to operate over a -40 to +60 deg. C temperature range.

STANDARD CONFIGURATION

The standard 21X Micrologger includes 16 single ended analog inputs (any pair configurable as a differential input), 4 pulse counting inputs, 4 switched excitation outputs, 2 continuous analog outputs and 6 digital control outputs.

21X processing includes 23 instructions for measurements and control output, 39 instructions for data processing, and 9 instructions for program control.

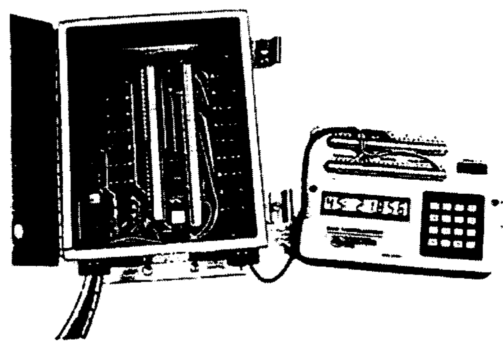
Data storage includes 28 locations for input and user-processed data, 64 locations for intermediate values, and 896 final storage locations. Data storage can be reallocated by the user. Each input location and each intermediate location uses 4 bytes of RAM and each final storage location uses 2 bytes of RAM. All expansion RAM is allocated for data storage.

A 9 pin D type connector on the front panel is used for serial data communication to cassette tape, memory module, modem or printer. It is also used for system programming via remote terminal or computer.

EXPANSION

Analog inputs can be added in 32 channel increments using the Model AM32 Relay Scanner. Up to 6 AM32s can be added for an additional 192 analog channels.

Memory sockets are available on the 21X CPU board allowing the addition of 44K bytes of memory for a total of 64K bytes. An expanded system with 24K bytes of ROM and 40K bytes of RAM can store 19,200 values in the final storage area.



21X Micrologger with the Model AM32 Relay Scanner for channel expansion.

COVER PHOTOGRAPH

The 21X is shown with D cells and some of the directly compatible sensors including a load cell, platinum resistance thermometer, thermocouple, silicon pyranometer and a pressure transducer. Background material is the official CAMPBELL of ARGYLE tartan.

Red - +5V
Black - Gnd
White - Sig +
Brown - Sig-gnd

DATALOGGER PROGRAM

*		1	Table 1 Programs	Complete program is in Table 1. Scan rate is every 5 seconds.
	01:	5	Sec. Execution Level	
01:		P17	Panel Temperature	Store the panel (room) temperature in input register 1.
	01:	1	Loc:	
02:		P14	Thermocouple Temp (DIFF)	5 type T thermocouples are attached to the datalogger starting at input 1 and reference the panel temp stored in input register 1. They record the temperatures in °F for $T_{ShopWaterin}$, T_{Swout}, $T_{JacketWaterin}$, T_{Jwout}, & T_{oil}. These temperatures are stored in sequential input registers starting at register 2.
	01:	5	Reps	
	02:	1	5 mV Slow Range	
	03:	1	INChan	
	04:	1	Type T (Copper-Constantan)	
	05:	1	Ref Temp Loc	
	06:	2	Loc:	
	07:	1.8	Mult	
	08:	32	Offset	
03:		P14	Thermocouple Temp (DIFF)	1 type K thermocouple is attached to the datalogger at input 6 and references the panel temp at input register 1. It records the exhaust gas temperature, T_{ex}, in input register 7 in °F.
	01:	1	1 Reps	
	02:	3	50 mV Slow Range	
	03:	6	IN Chan	
	04:	3	Type K (Chromel-Alumel)	
	05:	1	Ref Temp Loc	
	06:	7	Loc:	
	07:	1.8	Mult	
	08:	32	Offset	
04:		P3	Pulse	A turbine (pulse) flow meter is attached to the datalogger at pulse input 1. It measures the shop water (cooling water) flow rate and records the value in [gpm] in input register 8.
	01:	1	Rep	
	02:	1	Pulse Input Chan	
	03:	1	Low Level AC	
	04:	8	Loc:	
	05:	0.002	Mult	
	06:	0	Offset	
05:		P3	Pulse	A turbine (pulse) flow meter is attached to the datalogger at pulse input 2. It measures the jacket water flow rate and records the value in [gpm] in input register 9.
	01:	1	Rep	
	02:	2	Pulse Input Chan	
	03	1	Low Level AC	
	04:	9	Loc:	
	05:	0.1	Mult	
	06:	0	Offset	
06:		P8	Excite, Delay, Volt (DIFF)	The load cells are attached to input 7 of the datalogger. As strain-gage devices they must have an excitation voltage, we use 5 V. We delay 0.1 sec between excitation and reading the weight. The weight is converted to [gal] and stored at input register 10.
	01:	1	Rep	
	02:	3	50 mV Slow Range	
	03:	7	In Chan	
	04:	1	Excite all reps w/EXchan 1	
	05:	10	Delay (units=.01sec)	
	06:	5000	mV Excitation	
	07:	10	Loc:	
	08:	4.214	Mult	
	09:	-10	Offset	

#10: +5V
(Gnd: 11)

07:		P2	Volt (DIFF)	The generator load is measured by a current transducer that produces a voltage proportional to the KW load. It is attached to input 8. The voltage signal is converted to [KW] and stored at input register 11.
	01:	1	Rep	
	02:	5	5000 mV Slow Range	
	03:	8	IN Chan	
	04:	11	Loc:	
	05:	0.08	Mult	
	06:	0	Offset	
08:		P86	Do	Set the output flag
	01:	10	Set Flag 0 (Output)	
09:		P70	Sample	Move data stored in input registers 1 thru 11 to output registers.
	01:	11	Reps	
	02:	1	Loc:	
10:		P	End Table 1	Remember to press A after instruction 09:

Thermal Conductivity Measurement

Reference: ANACON User Manual *

SECTION I

INTRODUCTION

The determination of thermal conductivity (k-Factor) of insulating material has long been the subject of considerable study and research effort. The accepted standard method of test for thermal conductivity of insulation material utilizes the "guarded hot plate" principle. The analysis of foam materials by the guarded hot plate method has been successfully done for many years. This method is quite accurate and should be accepted as the standard. However, measurements of thermal conductivity are very time consuming and the equipment expensive. The need for a simplified low cost thermal conductivity tester capable of making fairly rapid determinations has long been recognized.

The features of the Model 88 are as follows: THIS WAS WRITTEN WHEN THE M-88 WAS NEW!!

1. A substantial reduction both in working time and elapsed, time per analysis is realized.

2. Direct digital readout of K-Factor thus eliminates the possibility of computational errors. Not with the new apparatus!

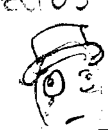
3. Instant check readouts for hot and cold plate controllers together with thickness indication.

4. Totally contained in a single, small lightweight bench top package. Anticipated long-term reliability due to the elimination of trouble-prone mechanical components. LOL

* 1) The ANACON apparatus is dead.

2) ANACON as a company is supposed defunct.

3) There's a new apparatus in town, by P.A. Hilton "for over 20 years!"


HMM YES

SECTION III

GENERAL DESCRIPTION OF INSTRUMENT

The apparatus illustrated on the title page is the standard Model 88 K-Factor instrument. The complete instrument is contained in an enclosure, dimensions 19 ¾" wide x 11 ¼" high and 19" deep. A 2" x 8" opening in the front panel (left side of instrument) is provided for purposes of inserting the sample into the controlled environment for "K" evaluation. The opening is sized to accommodate a ¼" to 2" thick x 8" x 8" square test sample.

The signal to the display digital voltmeter is selected by a multi-push button selector switch and is displayed by the readout on the right side of front panel.

The hot plate assembly consists of a 4" diameter copper plate 1/8" thick. Both thermistors sensors (for control and readout) are located in the aforementioned disc. See Figure 2. The heater disc, 4" in diameter, is located on the top surface of the assembly. The heat flow sensor is located on the bottom surfaces of the hot plate. The complete assembly is insulated and all surfaces are sealed with thermal compound.

The cold plate dimensions are identical to those given for the hot plate. The only difference between the two assemblies is the substitution of thermoelectric heat pumps and accessories for the disc heater. Two thermoelectric modules are thermally close coupled to both the analytical control surfaces and the heat exchanger.

Heat sink compound is used to further assure a good thermal bonding. The thermoelectric modules are held between the cold plate and the heat exchanger.

The hot plate assembly is supported by a threaded stud. The supporting stud is attached to the assembly in a manner such that vertical downward thrust can be applied to a point in the center of the plate, thus pressure is uniformly distributed over the entire sample surface. Rotary motion applied to a knob located on the front panel is transmitted through a torque gauge to the supporting stud. Rotary-

Principles & Background:

The thermal conductivity of a material is the proportionality constant that relates the heat conducted through a material to the driving temperature difference that exists across the material. This relationship for heat conduction is known as *Fourier's Law of Heat Conduction*. In its 1-dimension form in the Cartesian coordinate system, it is written as:

$$q = -kA\frac{dT}{dx}$$
$$or \qquad (1)$$
$$q' = {}^{q}\!/_{A} = -k\frac{dT}{dx}$$

The thermal conductivity of a material or assembly through which heat is being transferred is denoted as k in Eq. (1). Thus, we often refer to a material's thermal conductivity as its *k-factor*.

The negative sign in Fourier's Equation emphasizes the fact that heat flows from hot to cold. That is, in the opposite (negative) direction of the temperature gradient.

Developing methods to measure or quantify a material's thermal conductivity relies on our understanding of Fourier's Law.

Some methods rely on meticulously measuring the temperature difference across a material or assembly while, at the same time measuring the amount of heat added to the zone on one side of the assembly in order to maintain these temperatures at steady-state conditions. For these methods, we know the heat flow on the left-hand-side of Eq. (1) and the temperature gradient on the right-hand-side of Eq. (1). This allows us to calculate the k-factor for the material or assembly. In these methods, it is important to set up the geometry in a manner that we can discount heat flow in all directions except the x-direction (1-D) represented in Eq. (1).

The method we'll use in this lab exercise is to measure the heat flux while maintaining a known temperature difference across a material or assembly. Our apparatus will measure the heat flux with an instrument based on the thermopile.

Recall that Seebeck, and later Peltier and Thompson, discovered that if two dissimilar conductors are joined in a junction, they will produce an emf (voltage) that is proportional to the temperature to which they are exposed. In a typical thermocouple (TC) circuit, two junctions will be present. After all, we must form a complete electrical circuit. For measuring temperature, the typical use of a TC circuit, one of these junctions is exposed to an unknown temperature and the other to some known reference temperature. The voltage produced in the circuit can then be converted to a temperature at the unknown junction using the Law of Intermediate Temperatures. We've done this in several lab exercises already in this class. We could amplify the emf produce by using a thermopile, a collection of junctions connected in series.

But, it is not necessary that we know a reference temperature for a voltage to be induced in the circuit. If a temperature difference exists between the two junctions, an emf (voltage) will be induced in the circuit and current will flow. The voltage induced is proportional to the temperature difference that exists between the nodes (the Peltier effect). Note that this results in a relation that says the emf produced is proportional to the temperature difference.

Fourier's Law of Heat Conduction says that the heat flow is proportional to the temperature difference. If we equate these two concepts to each other, we should be able to create a heat flux sensor. This is the basis for the heat flux sensor in the apparatus we'll use in this lab exercise.

The apparatus uses an electric resistance heater to hold a hot plate at a prescribed temperature. It uses a chilled water loop (shop water in our case) to hold a cold plate at another prescribed temperature.

The test sample is placed between these two plates. Since we know the temperatures of each plate, we know the driving temperature differential causing heat to flow across the sample.

A thermopile based heat flux sensor located in series to this flow path is used to measure the heat flow through the sample.

By measuring the thickness of the sample, we obtain the dx in Fourier's Equation. We can measure the thickness externally before inserting the sample into the apparatus or by means of the loading screw the positions the sample properly between the hot and cold plate.

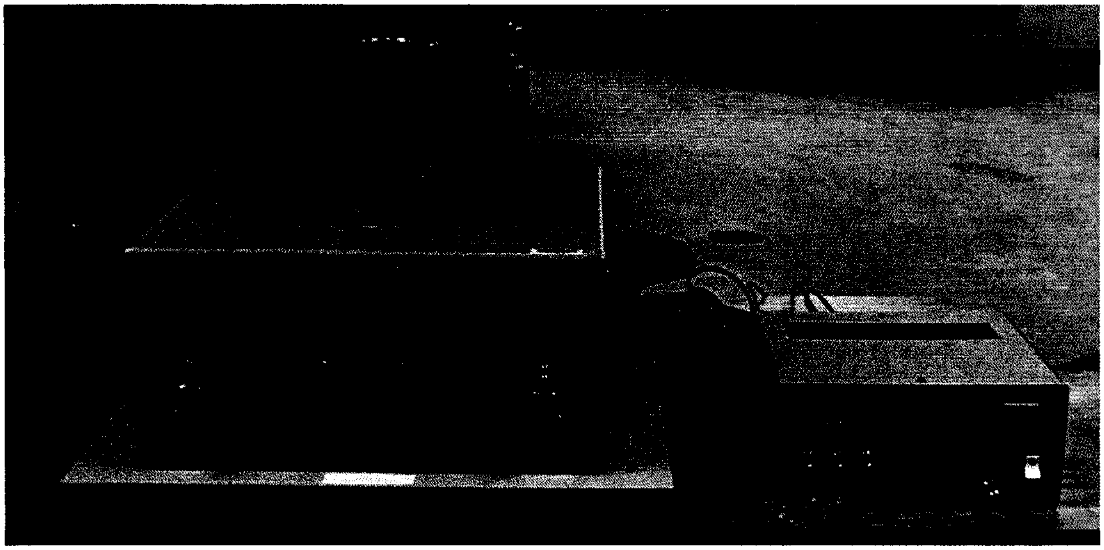
Armed with all of this information, it is possible to determine the thermal conductivity for the sample.

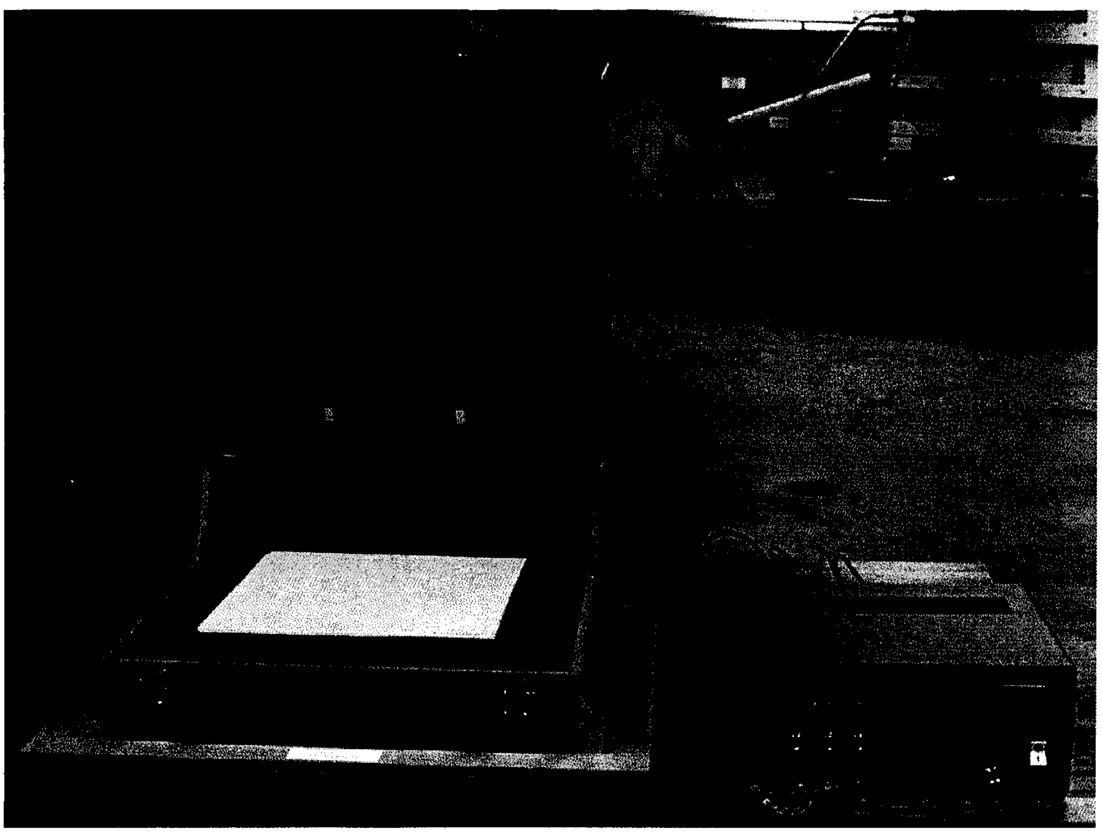
<u>Lab Procedure:</u>

In the lab exercise, we will measure the thermal conductivity of three samples:

- A sample of extruded, expanded polystyrene foam (Blue Board).
- A sample of a panel used to construct military shelters. Two thin aluminum skins separated by a honey-comb paper insulator.
- A sample of a composite panel material used to construct shelters. Two thin fiber-and-resin panels separated by a foam insulator.

To measure the thermal conductivity of the samples, we'll use the PA Hilton H111N – Thermal Conductivity of Building Materials apparatus.





1. Measure the thickness of each sample at several locations prior to inserting them into the conductivity apparatus. This will allow you to determine the average thickness of the sample. Also, use the procedures

described in the PA Hilton manual to determine the thickness using the loading mechanism lead screw.

2. Insert the sample into the apparatus and position it for testing i.a.w. the manual's directions.

3. Note the temperature of the cooling water being supplied to the cold plate by the shop water. Set the PID controller i.a.w. the instructions in the PA Hilton manual to maintain the hot plate at 15°C to 20°C above this temperature.

4. Monitor the TC and heat flux meter readings for stability. When these readings reach steady-state, record the information to use in your calculations.

5. Repeat these procedures for each of the samples.

The PA Hilton apparatus is designed for use using the SI unit system. Conduct the experiment and your calculations using SI units (make appropriate conversions to parameters such as thickness as required). In your report, you will also report the k-factor of each sample and its R-value in Customary English Units $\left(\frac{BTU \cdot in}{hr \cdot ft^2 \cdot {}^\circ F}\right) \& \left(\frac{hr \cdot ft^2 \cdot {}^\circ F}{BTU}\right)$ so that comparison to US industry standards can be easily deduced.

Calculations:

The PA Hilton apparatus has been factory calibrated to allow you to calculate a samples thermal conductivity by using the following equations along with the calibration constants provided with the unit.

$$R = \frac{l_s}{\lambda} \tag{2}$$

$$\lambda = \frac{l_s\left[\left(k_1 + k_2\overline{T}\right) + \left(k_3 + k_4\overline{T}\right)HFM + \left(k_5 + k_6\overline{T}\right)HFM^2\right]}{dT} \tag{3}$$

$$\overline{T} = \frac{T_1 + T_2}{2} \tag{4}$$

$$dT = T_2 - T_1 \tag{5}$$

R = Thermal Resistance $\left[\frac{m^2 \cdot K}{W}\right]$

l_s = Mean Sample Thickness $[m]$

λ = Thermal Conductivity $\left[\frac{W}{m \cdot K}\right]$

HFM = Heat Flow Meter reading

T_1 = Cold Plate Temperature $[°C]$

T_2 = Hot Plate Temperature $[°C]$

$k_{1\text{-}6}$ = Calibration Constants

For the unit used in this lab exercise, the calibration constants are:

$$k_1 = -29.1816$$
$$k_2 = 0.4471$$
$$k_3 = 3.5283$$
$$k_4 = 0.0016$$
$$k_5 = 0.0007$$
$$k_6 = 0.0001$$

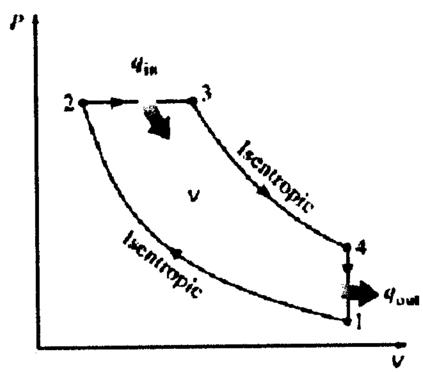
Principles & Background:

The Diesel Cycle is the ideal Thermodynamic cycle used to analyze the compression-ignition (CI), internal combustion engine. It is named for Rudolf Diesel who proposed the cycle in the 1890's.

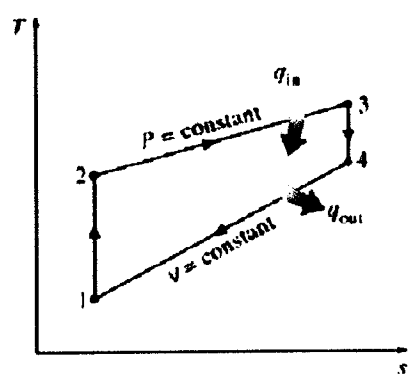
As was the case with the Brayton Cycle that we used to analyze the gas turbine, the Diesel Cycle is not truly a cycle as we define it in Thermodynamics. The system is not actually closed.

Air is brought into the piston-cylinder. In the ideal analysis, the piston rises compressing the air in an isentropic compression. As the piston approaches top dead center (TDC) in the cylinder, fuel is injected. The mixture of fuel and air at this elevated pressure and under the proper air-fuel ratio combusts in an isobaric (constant pressure) process. The piston is driven downward in the power stroke in an isentropic expansion. At the end of this expansion, the combustion products are actually expelled from the cylinder. However, in order to analyze the engine as a cycle, we "pretend" that the combustion products undergo a constant volume heat rejection and are then re-compressed as the piston moves back toward TDC for the next repeat of the cycle.

Depicting the Diesel Cycle on P-v and T-s Diagrams, we see:



P- v diagram



T-s diagram

We can determine the theoretical thermal efficiency of this ideal cycle as follows:

$$\eta_{th} = \frac{w_{net}}{q_{in}} \quad (1)$$

$$w_{net} = q_{in} - q_{out} \quad (2)$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} \quad (3)$$

If we treat the working fluid as an ideal gas (air), this can be further reduced to:

$$\eta_{th} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} \tag{4}$$

From this point, it is customary to further reduce the formula to one that determines thermal efficiency based solely on the compression ratio of the engine.

$$\eta_{th} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right] \tag{5}$$

In Eq. (5), r is the compression ratio for the particular engine. That is, the ratio of the pressures when the piston moves between BDC and TDC. r_c is the cut-off ratio. This is a value based on the geometry of the piston-cylinder design. It is determined as:

$$r_c = \frac{v_3}{v_2} \tag{6}$$

As was the case with the Brayton Cycle, the actual Diesel Cycle will depart from this ideal analysis due to loses that occur such as friction loss during flows, by-passes of gases during flows, and other unavoidable losses.

We can also compare the theoretical efficiency derived from Eq. (4) and (5) to the limiting efficiency of the Carnot Cycle. This would be an ideal heat engine operating between the high and low temperatures of our Diesel engine. It is determined as:

$$\eta_{th,Carnot} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H} \tag{7}$$

We would expect that the Carnot efficiency would be greater than the ideal Diesel Cycle efficiency which is, in turn, greater than the actual cycle's efficiency.

In this week's lab exercise, we look at the Diesel Cycle and the use of a Diesel-Electric Generator operating in co-generation mode. The efficiency of the Diesel-electric generator set for the production of electricity will be calculated by comparing the energy supplied to the system by the fuel to the electrical energy produced by the generator. The lab also considers the improvement in efficiency if the heat which is normally wasted to the jacket cooling water can be captured to use for a useful purpose such as district heating.

The predominate use of Diesel-electric generator sets is for the production of electricity as emergency stand-by power, for peaking power, or for off-grid power applications. In this mode, much of the energy supplied by the fuel is wasted as heat either 'up the stack' with the exhaust gases or through the jacket cooling system. If the generator set is used on a long term basis (i.e.; not for an emergency stand-by or peaking operation) and a use for the 'waste' heat can be found, then there can be significant improvements in the overall plant efficiency. The waste heat may be used for space heating, domestic hot water heating, or any other relatively low temperature heat demand load.

The simplest method of capturing the waste heat is to use a heat exchanger to capture the heat from the jacket cooling water. This basically replaces the radiator operation and captures the heat that would normally be dissipated to the surroundings by the radiator (a water-to-air heat exchanger).

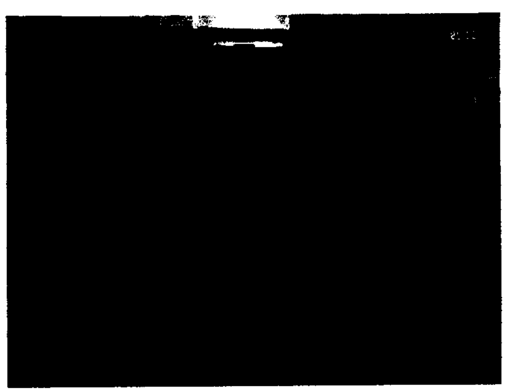
Additional heat can be captured by installing a stack gas heat exchanger on the Diesel exhaust. Substantial amounts of heat can be captured via this method but care must be taken if the exhaust gases are cooled below their condensation point (dew-point). The condensate will likely be corrosive including carbonic and carbolic acids as well as sulfur-based acids due to the combustion products of the fuel. Therefore, either the heat exchanger and its controls must be designed to prevent condensation from occurring or the design must be able to handle the corrosive condensate and its proper disposal.

Many Diesel generator based district heating systems have been installed in remote villages in Alaska. Most use only jacket-water heat recovery systems.

<u>Lab Procedure:</u>

Overview:

The apparatus for this lab exercise is a KEM Merlin 45 KW Diesel Generator set. The generator set matches a 4-cylinder, water cooled, turbocharged Mitsubishi Diesel engine with a Stamford revolving field, 3-Ph., 4-wire, 480 Volt, AC generator.



The Diesel-generator set has been instrumented to monitor the following parameters:

1. Shop water (cooling water) inlet temperature.
2. Shop water outlet temperature.
3. Diesel engine jacket water inlet temperature.
4. Diesel engine jacket water outlet temperature.
5. Diesel engine oil temperature.
6. Diesel engine exhaust gas temperature.
7. Shop water flow rate.
8. Diesel engine jacket water flow rate.
9. Diesel engine fuel tank level in gallons.
10. Generator power output.

Data Collection:

The data for the experimental run is monitored using a Campbell 21x datalogger. Sensor/transducer connections are as follows:

All temperatures are monitored via Type-T (copper-constantan) thermocouples except for the high temperature Diesel exhaust. These thermocouples are connected to the upper datalogger terminal strip with the copper lead connected to the high (H) terminal and the constantan lead connected to the low (L) terminal as follows:

Channel 1 – Shop Water In.
Channel 2 – Shop Water Out.
Channel 3 – Jacket Water In.
Channel 4 – Jacket Water Out.
Channel 5 – Oil Temperature.

The Diesel exhaust temperature is monitored by a Type-K (chromel-alumel) thermocouple connected to Channel 6. For our TC, connect the yellow lead to H and the red lead to L. Sometimes it is not possible to determine which lead is the chromel or alumel lead by appearance. The easiest way to determine the H/L connection in those instances is to connect the leads and then read the temperature. If the temperature is correct (i.e.; room temperature before firing the engine) then the connection is correct. If the reading is wrong, then switch the leads and check the temperature again. Note that this must be done after the datalogger has been programmed.

The shop water flow rate is monitored by a turbine meter. This provides a pulse input to Pulse Input Channel 1 of the datalogger. Connect the red lead to input terminal 1 and the white lead to the ground terminal.

The jacket water flow rate is monitored by a turbine meter. This provides a pulse input to Pulse Input Channel 2 of the datalogger. Connect the red lead to input terminal 1 and the white lead to the ground terminal.

The fill level of the fuel tank is monitored by load cells. The weight of the tank is converted to gallons via the programming in the datalogger. Load cells are a strain-gage device. They require an excitation signal in order that the bridge produce an output signal that is proportional to the weight. Connect the red lead from the load cells to datalogger Excitation terminal 1; connect the black lead to Excitation terminal ground; connect the white lead to Input Channel 7's H terminal; and the black lead to Input Channel 7's L terminal.

The generator's power output is monitored by current transformers. Power is (current) x (voltage). The current flowing from the generator induces a current in the current transformers attached to Input Channel 8 of the datalogger; red lead to H and black lead to L. The resistor soldered in parallel with these leads allow the datalogger to read this induced current as a voltage (mV) drop. Through the datalogger programming, the variable voltage signal is converted to display the power [KW] produced.

The Campbell 21x datalogger will be connected and pre-programmed for this exercise. The program is:

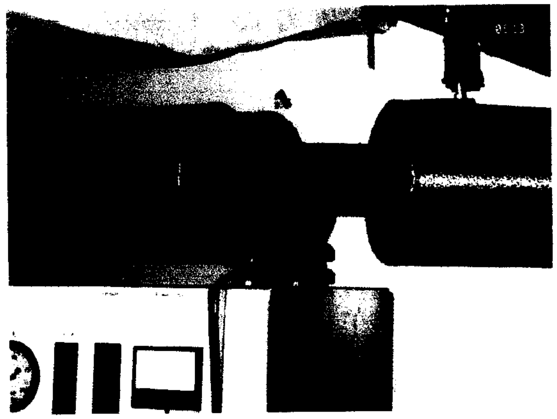
*		1	Table 1 Programs	Complete program is in Table 1. Scan rate is every 5 seconds.
	01:	5	Sec. Execution Level	
01:		P17	Panel Temperature	Store the panel (room) temperature in input register 1.
	01:	1	Loc:	
02:		P14	Thermocouple Temp (DIFF)	5 type T thermocouples are attached to the datalogger starting at input 1 and reference the panel temp stored in input register 1. They record the temperatures in °F for $T_{ShopWaterin}$, T_{Swout}, $T_{JacketWaterin}$, T_{Jwout}, & T_{oil}. These temperatures are stored in sequential input registers starting at register 2.
	01:	5	Reps	
	02:	1	5 mV Slow Range	
	03:	1	INChan	
	04:	1	Type T (Copper-Constantan)	
	05:	1	Ref Temp Loc	
	06:	2	Loc:	
	07:	1.8	Mult	
	08:	32	Offset	
03:		P14	Thermocouple Temp (DIFF)	1 type K thermocouple is attached to the datalogger at input 6 and references the panel temp at input register 1. It records the exhaust gas temperature, T_{ex}, in input register 7 in °F.
	01:	1	1 Reps	
	02:	3	50 mV Slow Range	
	03:	6	IN Chan	
	04:	3	Type K (Chromel-Alumel)	
	05:	1	Ref Temp Loc	
	06:	7	Loc:	
	07:	1.8	Mult	
	08:	32	Offset	

04:		P3	Pulse	A turbine (pulse) flow meter is attached to the datalogger at pulse input 1. It measures the shop water (cooling water) flow rate and records the value in [gpm] in input register 8.
	01:	1	Rep	
	02:	1	Pulse Input Chan	
	03:	1	Low Level AC	
	04:	8	Loc:	
	05:	0.002	Mult	
	06:	0	Offset	
05:		P3	Pulse	A turbine (pulse) flow meter is attached to the datalogger at pulse input 2. It measures the jacket water flow rate and records the value in [gpm] in input register 9.
	01:	1	Rep	
	02:	2	Pulse Input Chan	
	03	1	Low Level AC	
	04:	9	Loc:	
	05:	0.1	Mult	
	06:	0	Offset	
06:		P8	Excite, Delay, Volt (DIFF)	The load cells are attached to input 7 of the datalogger. As strain-gage devices they must have an excitation voltage, we use 5 V. We delay 0.1 sec between excitation and reading the weight. The weight is converted to [gal] and stored at input register 10.
	01:	1	Rep	
	02:	3	50 mV Slow Range	
	03:	7	In Chan	
	04:	1	Excite all reps w/EXchan 1	
	05:	10	Delay (units=.01sec)	
	06:	5000	mV Excitation	
	07:	10	Loc:	
	08:	4.214	Mult	
	09:	-10	Offset	
07:		P2	Volt (DIFF)	The generator load is measured by a current transducer that produces a voltage proportional to the KW load. It is attached to input 8. The voltage signal is converted to [KW] and stored at input register 11.
	01:	1	Rep	
	02:	5	5000 mV Slow Range	
	03:	8	IN Chan	
	04:	11	Loc:	
	05:	0.08	Mult	
	06:	0	Offset	
08:		P86	Do	Set the output flag
	01:	10	Set Flag 0 (Output)	
09:		P70	Sample	Move data stored in input registers 1 thru 11 to output registers.
	01:	11	Reps	
	02:	1	Loc:	
10:		P	End Table 1	Remember to press A after instruction 09:

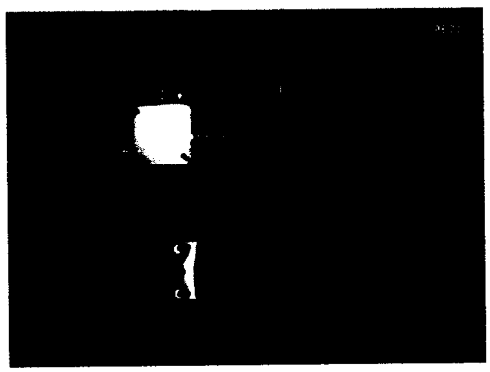
Starting the Diesel Engine & Collecting Data:

With the assistance of the lab instructor, start the Diesel engine and log data for two different load levels on the generator.

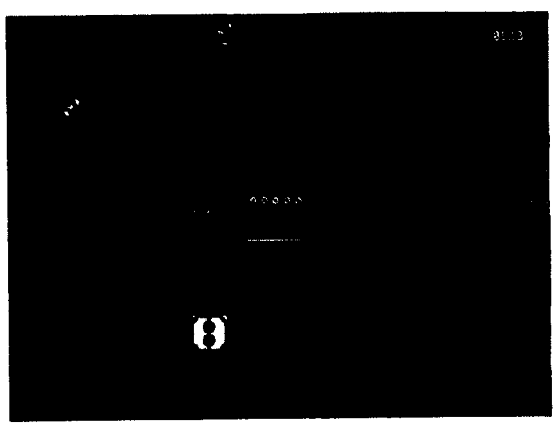
1. Confirm that the exhaust piping is configured to exhaust the Diesel engine and that the exhaust from the gas turbine apparatus is in the blank-off position.



2. Start the purge ventilation system for the lab by turning ON the wall switch.



3. Turn ON the main disconnect for the roof-mounted load bank. And turn ON the power on the load bank control panel:



4. Open the shop water valve and set the flow, as monitored by the datalogger, to about 8 – 10 gpm.

5. Turn the Diesel ignition key to the ON position (**not** start).

6. While pressing the "oil bypass button", crank the engine until it starts. Keep the oil bypass button depressed until oil pressure registers on the engine gage. Release the bypass button.

7. Turn ON the load bank blower. The red indicator light should go out indicating proof of fan flow on the load bank.

8. Set the load switches to the desired load. However, leave the "Master Load Switch" OFF.

9. Let the engine-gen set stabilize for about 5 minutes.

10. Turn ON the "Master Load Switch" and let the unit come to equilibrium.

11. Change the load on the unit and again let the unit come to equilibrium.

Shutting Down & Dumping Data:

1. Turn OFF the Master Load Switch and all individual load switches.
2. Dump the datalogger to file.
3. After at least 5 minutes, turn OFF the load bank blower.
4. Turn the Diesel ignition to OFF.
5. Turn OFF the load bank power.
6. Closed the shop water valve.
7. Turn OFF the purge ventilation switch.

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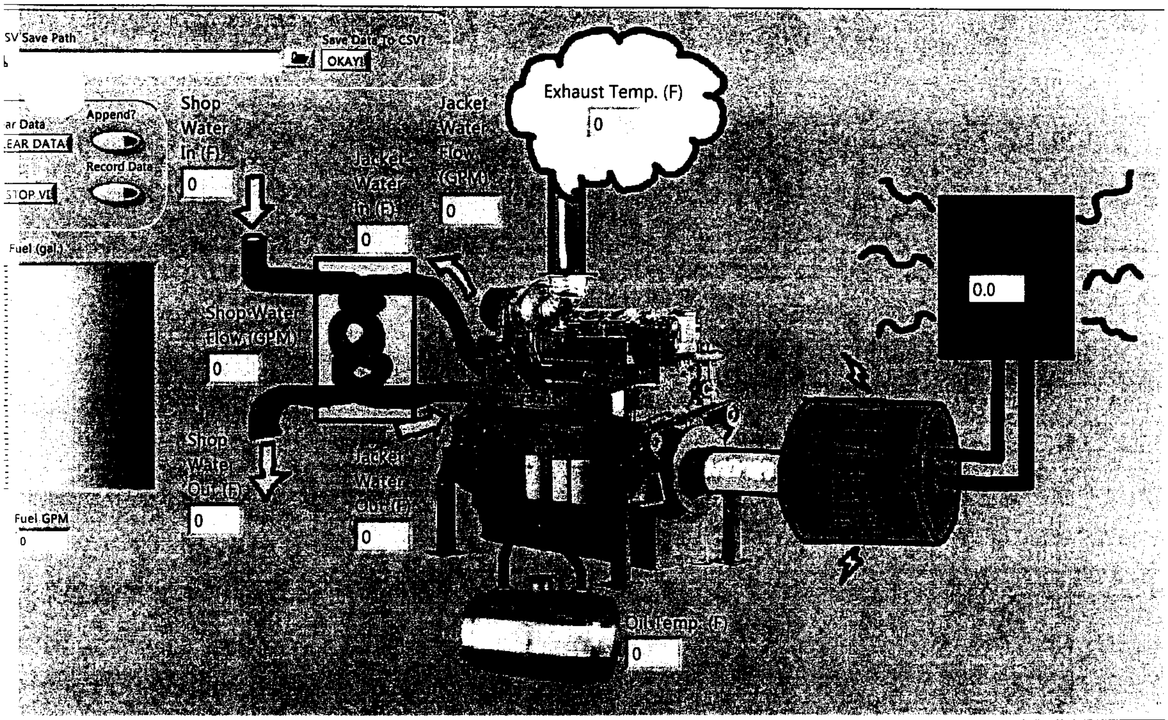

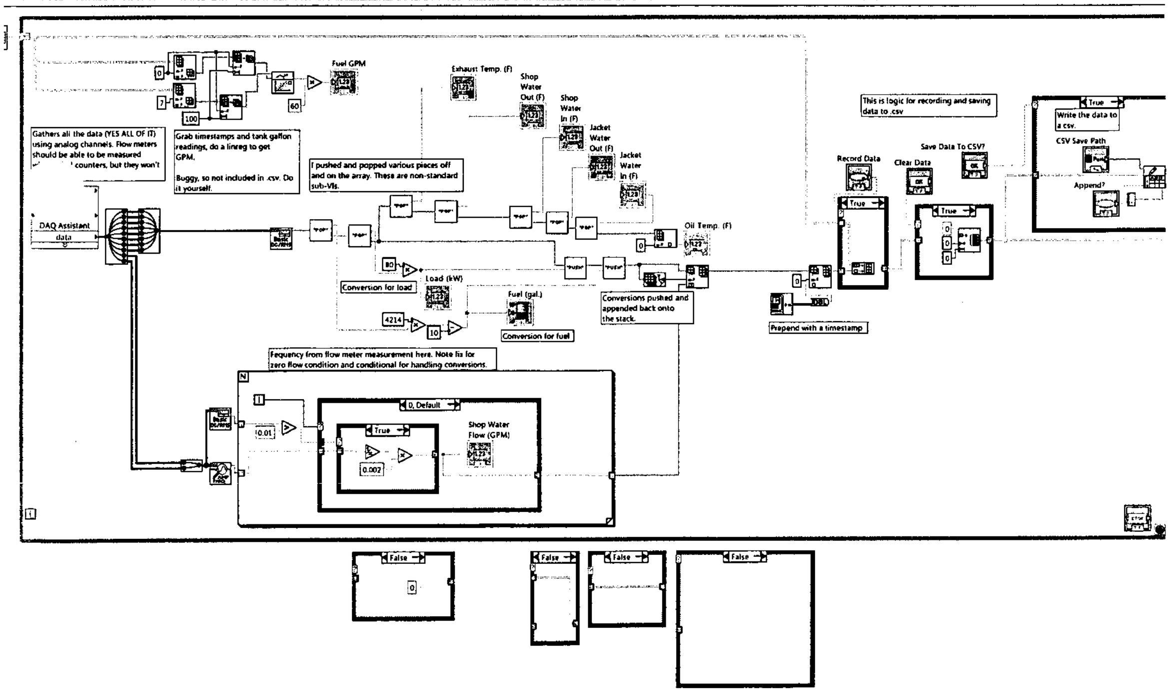

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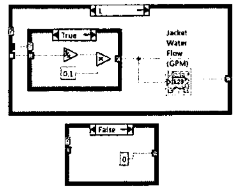

Write To Spreadsheet File (DBL).vi
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Write To Spreadsheet File.vi
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DAQ Assistant
DAQ Assistant
Creates, edits, and runs tasks using NI-DAQmx. Refer to the NI-DAQmx Readme for a complete listing of devices NI-DAQmx supports.

When you place this Express VI on the block diagram, the DAQ Assistant launches to create a new task. After you create a task, you can double-click the DAQ Assistant Express VI to edit that task. For continuou measurement or generation, place a while loop around the DAQ Assistant Express VI.

For continuous single-point input or output, the DAQ Assistant Express VI might not provide optimal performance. Refer to the Cont Acq&Graph Voltage-Single Point Optimization VI in examples\DAQmx\ Analog In\Measure Voltage.llb for an example of techniques to create higher-performance, single-poin I/O applications.

TRANSDUCERS

Introduction:

This document is meant to explain all the details known about the various transducers used in this lab, so that the information is not lost to future generations.

Thermocouples:

There are six of them: 5 Type T and 1 Type K. When wiring these to the USB-DAQ, make sure at least one of the thermocouples shares a ground with one of the analog grounds. I did this with a short piece of extra wire. This keeps the device from giving inaccurate readings due to static build-up.

Type T Thermocouples (x5):

+: Blue **-:** Red

Type K Thermocouple (x1):

+: Yellow **-:** Red

Load Bank Power Transducer:

This device uses a high-precision resistor to measure the current running through the system, which can be converted to power by multiplying by the known voltage through the system.

+: White **-:** Black

Conversion:

```
kW = 80 * volts
```

Load Cells:

This device operates using strain gages internally, but lucky for us it's all black-boxed. All you need to do is feed it 5V power from the USB-DAQ and take analog readings!

+5V: Red **Gnd:** Black **+Out:** White **-Out:** Brown

Conversion:

```
gallons = 4214 * volts - 10
```

Flow Meters:

These devices return frequencies and not proportional voltage signals.

Shop Water:

This device is known to be returning garbage values. It will likely be replaced, and was not used for this lab.

+: White -: Red

Conversion:

```
gpm = 0.002 * frequency
```

Jacket Water:

This device is known to have been sized larger than ideal, and as such is best for detecting relatively high flow rates on the part of the jacket water. It also has enough copper particulate inside it that it may sometimes get stuck. Tapping on the transducer usually fixes it.

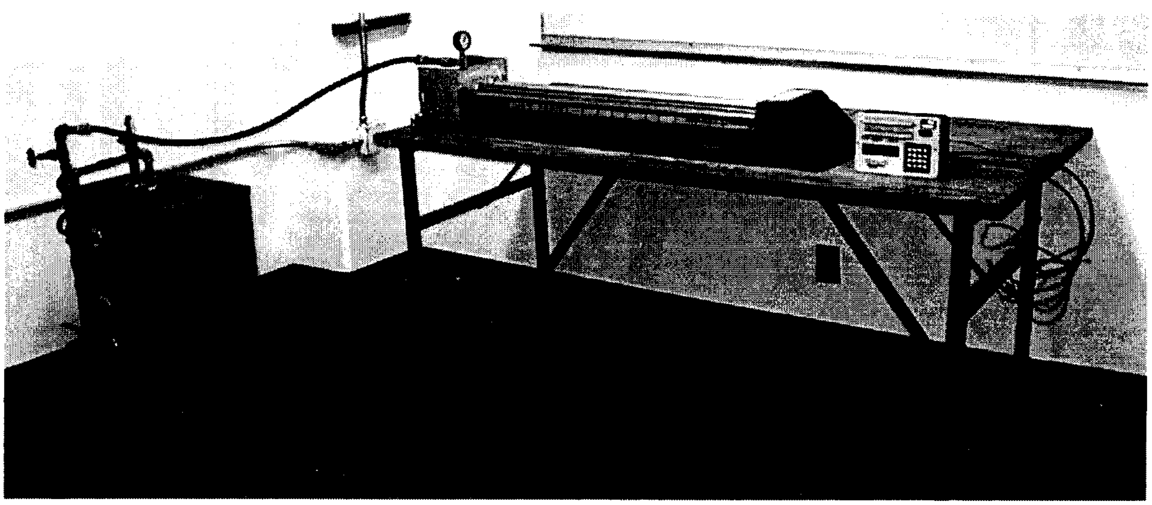
+: White -: Red

Conversion:

```
gpm = 0.1 * frequency
```

Temperature Profile in Rods

TEMPERATURE PROFILES IN RODS DUE TO HEAT CONDUCTION



Temperature Profiles in Solids

J. Zarling R. Johnson

For the transfer of thermal energy under both steady- and unsteady-state conditions, it is many times possible to exactly predict or to very nearly approximate the true temperature-distributions in a system. These temperature distributions are a function of both the mechanism of heat transfer and the geometry of the system. In order to calculate such temperature distributions, it is necessary that the "thermal energy-flux" be expressed in an exact manner. Such expressions are given by Fourier's law of heat conduction for conduction, Newton's law of cooling for convection and by the Stefan-Boltzmann law for radiation.

Quite frequently an exact analysis for the temperature distribution in a system becomes unwieldy and a simplified model can sometimes be used to very nearly approximate the actual situation. To illustrate the construction of such simplified models and to demonstrate the conditions under which such models are applicable, the temperature distribution along a rod, which is heated at one end, will be measured and analyzed in some detail.

Theory

A long, solid rod of uniform, circular cross-section, which is initially at a uniform temperature equal to that of its environment, is suddenly heated at one end by a constant-temperature energy-source. Consider the physical properties of the material to be constant (i.e., independent of temperature), the rod to be very long (mathematically infinite in length), the heat to be conducted along the rod in an axial direction only (i.e., the temperature to be uniform over any cross section) and the heat-transfer coefficient at the rod's cylindrical surface to be independent of position.

The differential energy-balance for this model is then

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} - \beta \left(T\text{-}T_a\right) \tag{1}$$

where:
A = cross-section area of rod
c_p = heat capacity
h = heat transfer coefficient
k = thermal conductivity
p = perimeter of rod
T = temperature
T_a = environmental temperature
t = time
x = axial distance
$\alpha = \frac{k}{(\rho)c_p}$; thermal diffusivity (has units of $\left[\frac{L^2}{t}\right]$)
$\beta = \frac{hp}{A(\rho)c_p}$; (has units of $[t^{-1}]$)

The boundary conditions for this differential balance are

$$@\ t \le 0,\quad T = T_a \text{ for } x \ge 0$$
$$@\ x = 0, T = T_s \text{ for } t > 0 \tag{2}$$
$$@\ x = \infty,\ T = T_a \text{ for } t > 0$$

where T_s is the temperature of the energy source.

A solution to Eq'n (1) is

$$\frac{T - T_a}{T_s - T_a} = \frac{1}{2}\left[e^{x\sqrt{\frac{\beta}{\alpha}}} erfc\left(\frac{x}{\sqrt{4\alpha t}} + \sqrt{\beta t}\right) + e^{-x\sqrt{\frac{\beta}{\alpha}}} erfc\left(\frac{x}{\sqrt{4\alpha t}} - \sqrt{\beta t}\right)\right] \tag{3}$$

where: $erf(y) = \frac{2}{\pi}\int_0^y e^{-n^2} dn$; the error function

$$erf(-y) = -erf(y)$$

$$erfc(y) = 1 - erf(y)$$

as $y \to \infty$, $erf(y) \to 1$ & $erfc(y) \to 0$

$\beta(h)$ $\alpha(k)$

For steady-state conditions:

$$\frac{T - T_a}{T_s - T_a} = e^{-\sqrt{\beta/\alpha}(x)} \Rightarrow \boxed{\ln\left(\frac{T_s - T_a}{T - T_a}\right) = \sqrt{\frac{\beta}{\alpha}}(x)} \qquad (4)$$

The heat, which is dissipated by the rod, is given by:

$$Q = -kA\left.\frac{dT}{dx}\right|_{x=0} \qquad (5)$$

where Q is the rate of energy dissipation.

In general:

$$Q = kA(T_s - T_a)\left[\frac{e^{-(\beta)t}}{\sqrt{4(\alpha)t}} + \sqrt{\beta/\alpha}\left(erf\sqrt{(\beta)t}\right)\right] \qquad (6)$$

and for steady-state conditions:

$$\boxed{Q = ka(T_s - T_a)\sqrt{\beta/\alpha}} \qquad (6.a\text{-}7)$$

The effectiveness of a rod as a heat dissipator can be estimated by defining an efficiency as follows:

$$\varepsilon = \frac{(HeatActuallyDissipatedByTheRod'sSurface)}{\left(\begin{array}{l} HeatWhichWouldBeDissipatedIfTheRod's \\ SurfaceTemperatureWereCons\tan tAtT_s \end{array}\right)} \qquad (6.a\text{-}8)$$

The efficiency of the mathematically infinite rod is then:

$$\boxed{\varepsilon = \frac{\sqrt{\alpha/\beta}}{x}} \qquad (6.a\text{-}9)$$

Apparatus

The apparatus consists of 1) steam chest (constant temperature energy-source) into which the ends of rods with circular cross-section may be inserted; 2) long rods with circular cross-section of different diameters and of different materials of construction wherein, at certain intervals, copper-constantan thermocouples are affixed; 3) copper-constantan thermocouple designed for measuring surface temperatures; 4) Data logger.

A typical apparatus and the construction details are shown in Figure 1. The design of the thermocouple used for measuring surface temperatures is also shown in Figure 1.

Procedure

1. Measure the initial temperatures of the rods and the temperature of their environment.

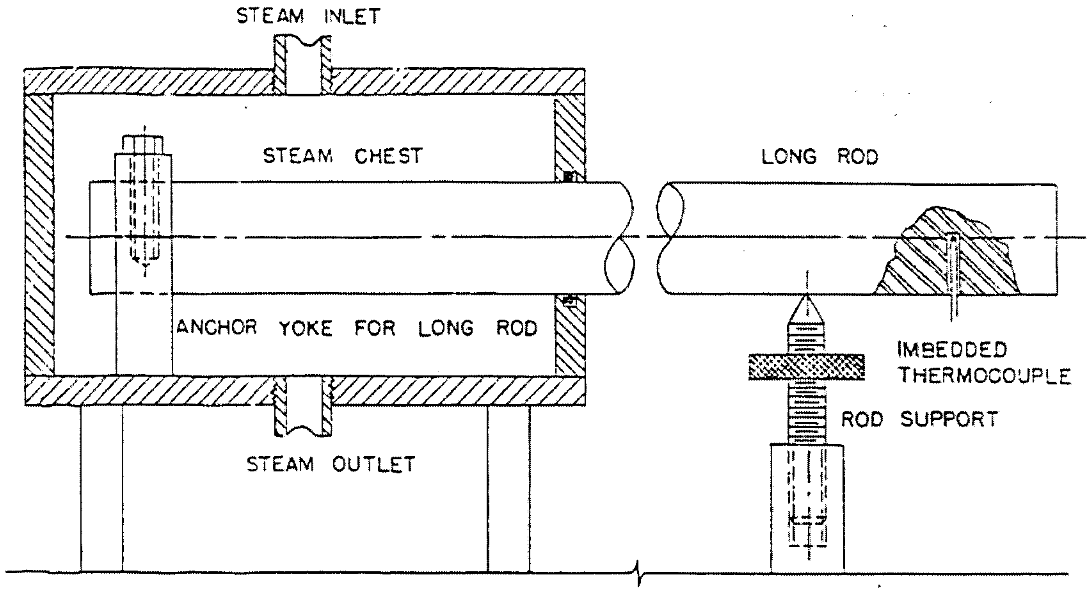
2. Determine the temperature history within a rod in the following manner:

   a. Clear the steam line of condensate before passing steam into the equipment.

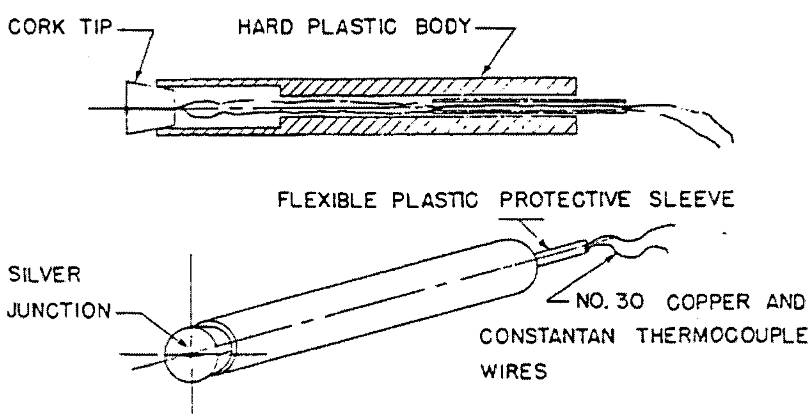
   b. Start the steam flowing into the equipment and maintain the pressure in the steam chest at about 10 to 20 psig.

   c. Once all residual condensate is removed from the equipment, start the stop watch. At regular time-intervals measure the temperature at successive thermocouple positions beginning with position No. 1. When two adjacent positions indicate the same temperature, return to position

No. 1 and repeat the measurements until near steady-rate conditions



CONSTRUCTION DETAILS OF EQUIPMENT FOR MEASURING TEMPERATURE DISTRIBUTION IN SOLIDS



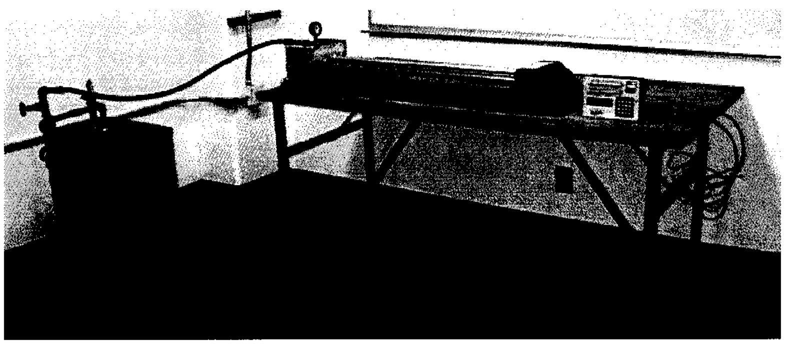
CONSTRUCTION DETAILS OF PORTABLE THERMOCOUPLE PROBE

Figure 1

Principles & Background:

This week's lab exercise takes another look at heat transfer. This time we are interested in both transient heat flow and steady-state heat flow.

In this lab experiment, we apply a constant temperature to the end of three rods. The rods are 1" aluminum, 1" stainless steel, and ½" stainless steel (nominal diameters). The constant temperature heat source consists of a *steam chest* that is kept charged with ~15 psig steam. The saturation temperature of 15 psig steam is ~250°F. As the steam condenses, the condensate is removed and new saturated steam fills the void. Therefore, the heat source remains at a constant ~250°F.



The heat transfer begins as a transient heat transfer problem. The rods are initially at a constant temperature (the lab ambient temperature) along their entire length. Heat is conducted into the ends of the rods connected to the steam chest. Heat conduction occurs along the length of the rods. While the rod temperature is rising along its length due to heat conduction, heat is being transferred away from the rod to the surrounding air via convection and radiation heat transfer. This is a time dependent or transient heat transfer phenomenon.

Eventually, the rods will reach equilibrium along their entire length with their surroundings. At this point in time, the heat conducted into each rod 'segment' will equal the heat lost by convection and radiation to the surroundings by each rod 'segment'. This will be evidenced by the temperatures, as measured along the rods by the thermocouples, remaining relatively constant. After this point in time, the problem is a steady-state heat transfer problem.

The Lab Manual discusses the theory behind this experiment. Review this along with your heat transfer text to refresh your memory on these types of problems.

Lab Procedure:

1. Connect the steam source (boiler) to the steam chest and set the boiler's thermostat to produces ~ 15 psig steam.

2. Program the Campbell dataloggers with the program listed below. Remember, the dataloggers must be started at the same time and this is also the time that the steam is admitted to the steam chest in order that all of the times in the experiment are synchronized.

3. When the dataloggers are programmed and the boiler is up to pressure, open the valve and allow steam to flow to the steam chest. Purge the condensate manually from the steam chest until steady operation of the pressure poppit is observed.

4. The steam chest attempts to maintain 15 psig pressure through use of a simple pressure regulation valve (poppit) as you might find on a household pressure cooker. The weight of the poppit closes an orifice in the valve. As steam pressure exceeds 15 psig, the poppit rises to relieve the pressure. The weight and orifice are sized based on the fact that pressure is a force per unit area. That is: $P = \frac{W}{A}$.

5. Monitor the pressure gage on the boiler and make minor thermostat adjustments as required to keep the pressure within range and prevent the poppit from dislodging.

6. Monitor the temperatures in the rods and note their progress toward steady-state conditions.

7. When steady-state heat transfer is achieved, read the temperatures in the two rods not connected to the dataloggers via the handheld TC reader.

8. With the help of the lab instructor, dump the datalogger data to file. This will be posted on the class Web site.

9. Disconnect the dataloggers and turn them off.

10. Drain the condensate from the steam chest and shutdown the boiler in preparation for the next lab.

Lab Report Information:

The lab report is due at the beginning of next week's lab. A report skeleton can be found at the class Web site.

Using the Lab Manual as a guide, write a Matlab m-file to predict the steady-state temperature distribution within the rods. Compare this to the data you collected.

Campbell Micrologger 21x Program:

Logger Display	Enter	Purpose
11:11111.1	*1	Instructs the logger you are programming Table 1
01:	30	Scan rate of 30 seconds
01: P	26	Initiate timer
01:	1	Store raw time in LOC 1
02: P	37	Process Z = X * F
01:	1	LOC of X value
02:	0D1	Value of F
03:	2	LOC of Z. Time in [sec] now stored at LOC 2.
03: P	17	Program TC reference Temp (Pnl Temp).
01:	3	Store Pnl Temp in register 3.
04: P	14	Program differential thermocouples.
01:	5	5 reps (5 TCs).
02:	1	Slow response up to 5 mV.
03:	1	Input channel (bus addr) of 1st TC.
04:	1	Type-T TC.
05:	3	Ref. Temp location.
06:	4	Storage register (LOC) for 1st TC.
07:	1D8	1.8 conversion factor for °C to ¯F.
08:	32	Scale offset for °C to °F.
05 P:	86	Set the DO flag.
01:	10	Send/store input register data to output registers.
06: P	70	Set the sampling for the output registers.
01:	7	7 input registers will be stored in output registers.
02:	2	LOC of 1st input register (time) to store.
07: P	*0	Compile & run program.
LOG 1		You were successful. Program is logging Data.
	*6	Enter display input register mode
	A/B	Use the A & B keys to advance and backspace thru the registers and monitor progress.

Note: This calculation has nothing to do with the calculation we were asked to do, nor does it do what its advertised as doing.

Computer Code to Calculate h "RODS-415"

```
10  //REM PROGRAM TO CALC H FOR CONDUCTION ALONG RODS
20  DISP "THERMAL COND, ROD DIAM, AMBIENT TEMP"
30  DISP "ENGLISH OR METRIC UNITS WITH ABS. TEMP NOT REQD"
40  INPUT K, D, TA // get K, D & Tinf
50  DIM X(10), T(10), H(10), DTDX(10), XMID(10) // 1x10 arrays
60  DISP "X(I) ARE THEMOCOUPLE LOCATIONS (INCHES)"
70  DISP "T(I) ARE TEMPERATURES (DEGREES f OR c)"
80  DISP "FIRST INPUT ALL X VALS THEN ALL T VALS"
90  FOR I=1 TO 10       //Fill in Xi's
100 INPUT X(I)
110 NEXT I
120 FOR I=1 TO 10       //fill in Ti's
130 INPUT T(I)
140 NEXT I
150 //REM NOW CALC H FROM SOLN TO D EQN
160 FOR J=1 TO 10
170 H(J)=3*K*D*(LOG((T(1)-TA)/(T((J)-TA))/X(J))^2      // Theoretical H
180 NEXT J
190 PRINT "CONVECTIVE HT. XFER COEF VS. LOCATION ALONG CYLINDRICAL ROD"
200 PRINT USING "2/"
210 PRINT "AMBIENT TEMP (DEG F)"
220 PRINT TA
230 PRINT "ROD DIAM (IN)"
240 PRINT D
250 PRINT "THERMAL CONDUCTIVITY (Btu/hr/ft/deg F)"
260 PRINT K
270 PRINT USING "2/"
280 PRINT "X(IN)            T(DEG F)"
290 FOR I=1 TO 10
300 PRINT USING "DD.D, 5X,DDD.D";X(I),T(I)      Prints X & T
310 NEXT I
320 PRINT USING "2/"
330 PRINT "FIRST VLS USING SOLN TO SS D EQN"
340 PRINT USING "2/"
350 PRINT "H(Btu/hr/ft^2/eeg F)       X(IN)"
360 FOR I=1 TO 10
370 PRINT USING "DD.DDE,10X,DD.DE";H(I),X(I)
380 NEXT I
390 //REM NOW CALC H USING DIFFERENTIATION OF DATA
400 //BELOW APPROX FOR TMID ONLY WORKS IF XMID(I+1) > X(I+1)
410 FOR I=1 TO 8
420 XMID(I+1)=(X(I+2)+X(I))/2
430 TMID(I+1)=T(I+1)+(T(I+2)-T(I+1))*(XMID(I+1)-X(I+1))/(X(I+2)-X(I+1))
440 DTDX(I+2)=(T(I+2)-T(I+1))/(X(I+2)-X(I+1))
450 DTDX(I+1)=(T(I+1)-T(I))/(X(I+1)-X(I))
460 H(I+1)=6*K*D*(DTDX(I+2)-DTDX(I+1))/(X(I+2)-X(I))/(TMID(I+1)-TA)
470 NEXT I                                  // FDM H
480 PRINT USING "2/"
490 PRINT "NOW H CALC USING FINITE DIFFERENCES"
500 PRINT USING "2/"
510 PRINT "H          X          T"
520 FOR I=2 TO 9
530 PRINT USING "DD.DDE,5X,DD.D,5X,DDD.D";H(I),XMID(I),TMID(I)
    NEXT I
    END
```

```
540     NEXT I
550     END
 89631

THERMAL COND, ROD DIAM, AMBIENT TEMP
ENGLISH OR METRIC UNITS WITH ABS. TEMP NOT REQD
?
95,1,74
X(I) ARE THEROCOUPLE LOCATIONS (INCHES)
T(I) ARE TEMPERATURES (DEGREES F OR C)
FIRST INPUT ALL X VLS THEN ALL T VLS
?
.5
?
1.5
?
3.5
?
6
?
9
?
12
?
18
?
24
?
30
?
36
?
242
?
229
?
206
?
184
?
164
?
148
?
126
?
111
```

?
104
?
99
CONVECTIVE HT. XFER COEF VS. LOCATION ALONG CYLINDRICAL ROD

AMBIENT TEMP (DEG F)
74
ROD DIAM (IN)
1
THERMAL CONDUCTIVITY (Btu/hr/ft/deg F)
95

X(IN)	T (DEG F)
.5	242.0
1.5	229.0
3.5	206.0
6.0	184.0
9.0	164.0
12.0	148.0
18.0	126.0
24.0	111.0
30.0	104.0
36.0	99.0

FIRST VALS USING SOLN TO SS D EQN

H(Btu/hr/ft^2/deg F)	X(I)
00.00E-001	50.0E-002
82.16E-002	15.0E-001
13.53E-001	35.0E-001
14.20E-001	60.0E-001
13.71E-001	90.0E-001
13.30E-001	12.0E+000
12.10E-001	18.0E+000
11.33E-001	24.0E+000
93.98E-002	30.0E+000
79.81E-002	36.0E+000

NOW H CALC USING FINITE DIFFERENCES

H	X	T
19.10E-001	2.0	223.3
26.35E-001	3.8	203.8
20.41E-001	6.3	182.3
14.07E-001	9.0	164.0
15.41E-001	13.5	142.5
10.66E-001	18.0	126.0
17.12E-001	24.0	111.0
52.78E-002	30.0	104.0

PURGE “RODS-415”
STORE “RODS-415”

How2HotShot: A Guide to Operating the Hot Shot Electric Boiler for Teaching Assistants

Joshua Holbrook

February 21, 2011

1 Introduction

The boiler, conceptually, is actually quite simple. It uses electric heating elements to boil water. Water is supplied with a hose, and hot steam comes out.

The water level is controlled by what is labelled as the "water level control" in Figure 1. Think of it kinda like a toilet float. The water level should be visible on the glass tube on the front of the boiler, at roughly 1/2 to 2/3 full.

The top-blow and bottom-blow valves (also labelled in Figure 1) are meant for clearing out steam/condensate and water, respectively, from the boiler. In practice, only the bottom-blow valve is used.

Unlike many boilers, the Hot Shot is temperature-controlled. If one wants a given pressure (a common occurrence), one should consult steam tables and assume saturated steam. For example, 15 psig is equivalent to about 300 degrees Fahrenheit, which happens to be around the upper end of the Hot Shot's capabilities.

2 Set-Up

1. Hook the water inlet to a water source.
2. Open the steam outlet. This allows air to escape so that the boiler can fill more quickly.

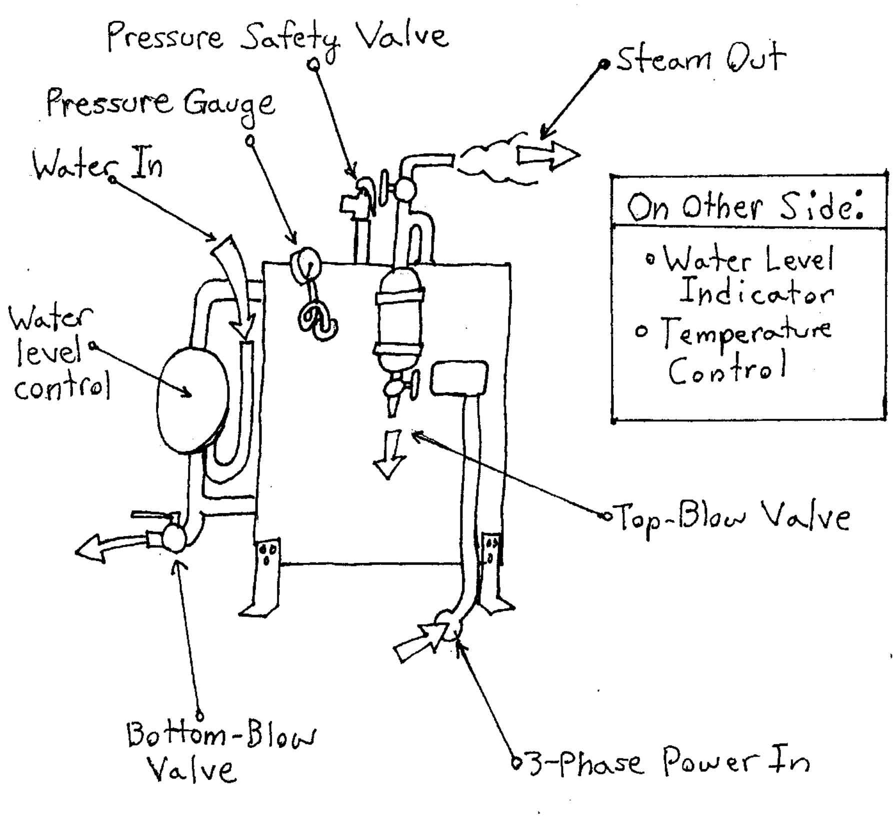


Figure 1: A sketch of the Hot Shot boiler, with important parts labelled.

3. Turn on the water, and wait for the device to fill.
4. Plug in the boiler and turn the temperature knob to the desired temperature.
5. It's not critical, but by my estimation, keeping the steam outlet closed while the boiler reaches temperature will make the process go faster.

3 Operation with the Temperature in Rods Apparatus

Operating the steam boiler—that is, utilizing the steam—is a process that depends somewhat on the device that's being supplied. In this case, the Hot Shot is used to run a "temperature in rods" lab.

1. Hook the device to the boiler using a washing machine hose.
2. Keep the condensate drain valve on the apparatus open.
3. Turn the boiler steam outlet valve open *slowly*.
4. By adjusting the boiler steam outlet valve and the condensate drain valve, try to get the steam pressure at 15 psig, with "spittle" coming from the drain valve and the pressure valve happily chattering.

4 Tear-Down

1. Allow the boiler to cool.
2. Connect a hose from the bottom-blow valve to a drain.
3. Open the steam outlet valve, the bottom-blow valve, and the water inlet valve.
4. Flush water through the boiler until it runs clear. Initially, it will be rusty and mucky.
5. Once the water runs clear, turn off the water inlet valve and allow the boiler to drain completely.
6. Disconnect everything and put the hoses away. You're done!

rodtemp.vi
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Last modified on 2/15/2011 at 3:55 PM
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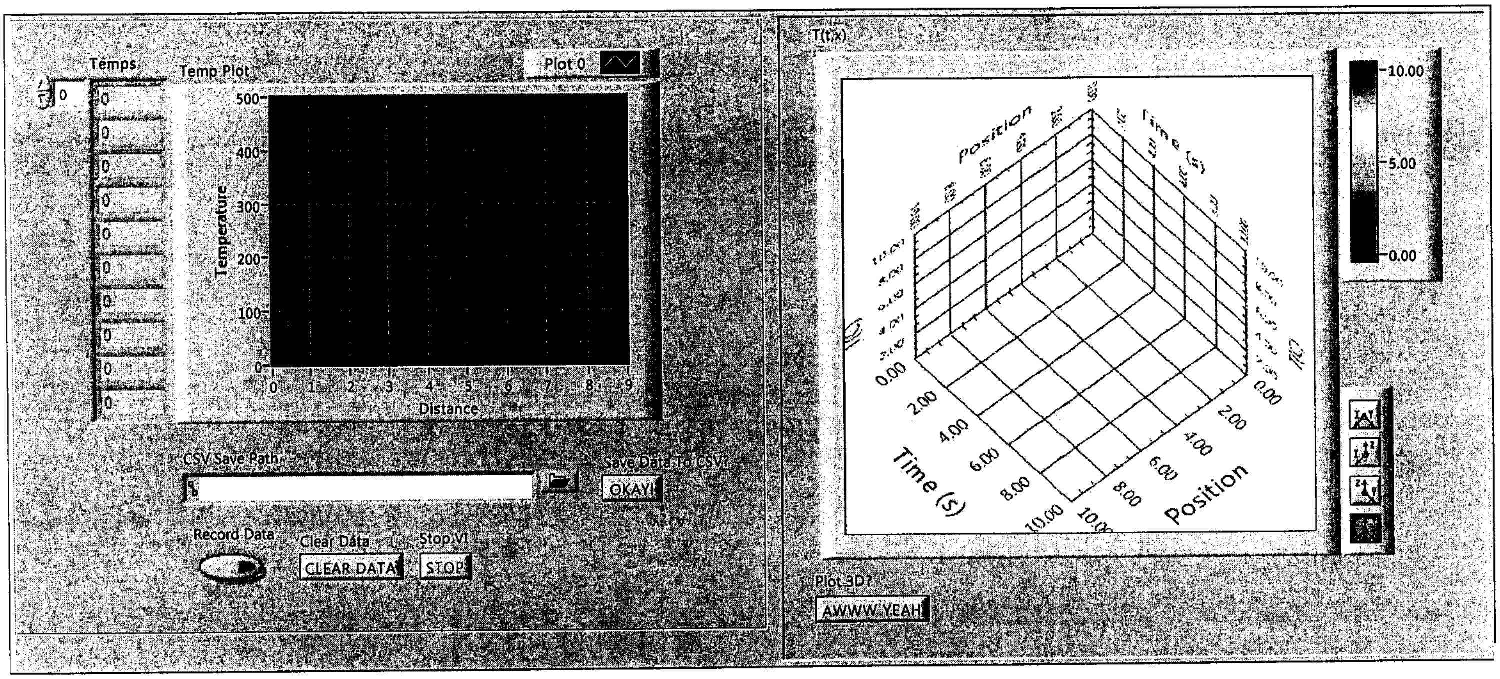
rodtemp.vi



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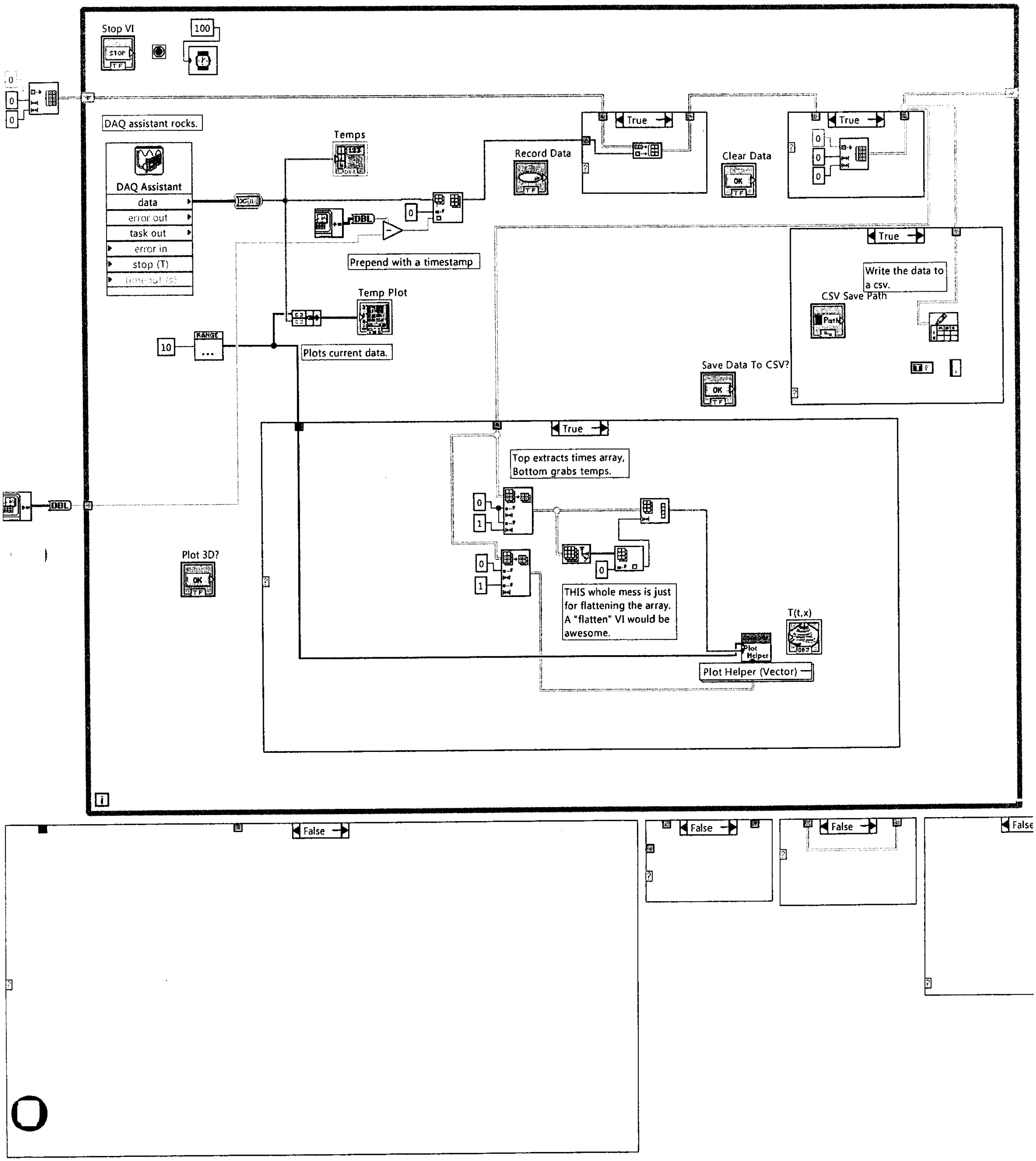

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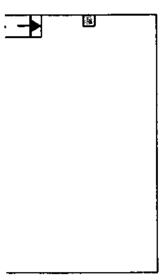

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DAQ Assistant
DAQ Assistant
Creates, edits, and runs tasks using NI-DAQmx. Refer to the NI-DAQmx Readme for a complete listing of devices NI-DAQmx supports.

When you place this Express VI on the block diagram, the DAQ Assistant launches to create a new task. After you create a task, you can double-click the DAQ Assistant Express VI to edit that task. For continuous measurement or generation, place a while loop around the DAQ Assistant Express VI.

For continuous single-point input or output, the DAQ Assistant Express VI might not provide optimal performance. Refer to the Cont Acq&Graph Voltage-Single Point Optimization VI in examples\DAQmx\Analog In\Measure Voltage.llb for an example of techniques to create higher-performance, single-point I/O applications.

Convert from Dynamic Data
Convert from Dynamic Data
Converts the dynamic data type to numeric, Boolean, waveform, and array data types for use with other VIs and functions.

Excerpt from Temperature Profile in Rods Feb. 19th 2010	ME 415 Thermal Systems Lab	Name: Joshua Holbrook	1 of 6

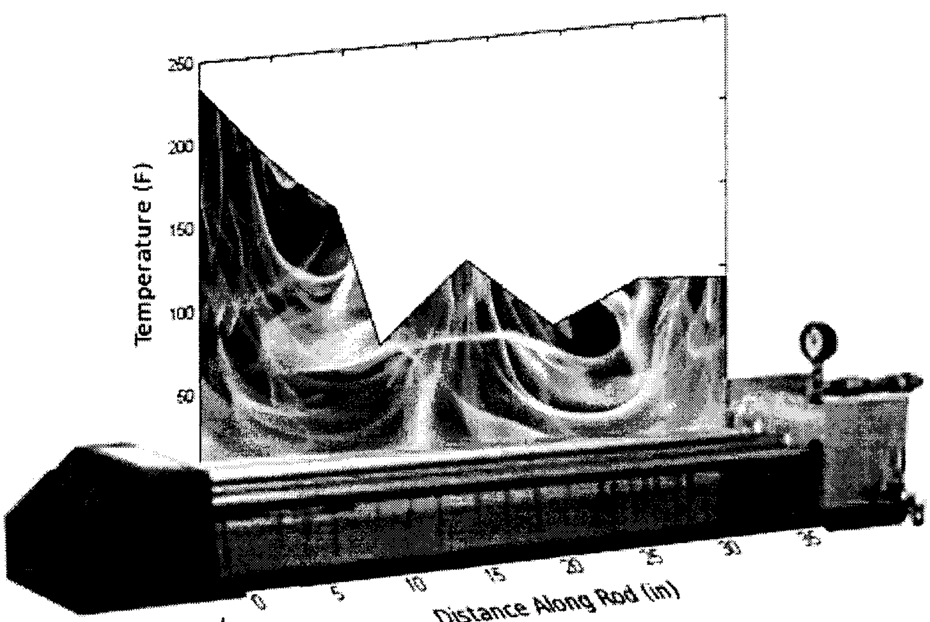
Data & Discussion:

After running the apparatus for roughly 1.8 hours, the temperatures in the ~~aluminum rod~~ were as follows:

3 rods

X (in)	Aluminum Rod (F)	Steel Rod 1" (F)	Steel Rod 1/2" (F)
36.5	233.3	212.6	228.3
30.5	219.8	171.1	197.0
24.5	195.3	121.9	165.1
18.5	174.1	96.2	140.0
12.5	154.9	79.1	117.5
9.5	70.7	74.1	102.3
6.5	116.8	69.6	85.7
4.0	72.4	69.5	77.5
1.5	95.8	69.8	74.1
0.0	92.5	70.2	72.8

As can be seen more clearly from the following chart depicting the temperatures of the aluminum rod, thermocouples at X_3 and X_5 were reading incorrectly.



1) Apparatus is depicted BACKWARDS

2) Tufte would disapprove.

Calculations & Discussion:

The heat loss in the rods is governed by fin temperature equations, which have the following finite difference formulation:

$$\left(\frac{1}{x_i - x_{i-1}}\right)T_{i-1} - \left(\frac{1}{(x_i - x_{i-1})} + \frac{1}{(x_{i+1} - x_i)} + 2Nu\frac{k_f}{k_s}(x_{i+1} + x_{i-1})\right)T_i + \left(\frac{1}{x_{i+1} - x_i}\right)T_{i+1} = -2Nu\frac{k_f}{k_s}(x_{i+1} + x_{i-1})T_\infty$$

Where i-1, i and i+1 refer to discrete sections of the beam. Since our beam was broken into 10 sections, we should have 8 such equations, from i=2 to i=9. Two more equations come from boundary conditions—The near end of the beam is maintained at 250 F, and the far end of the beam is unheated. This may be treated most easily, in my opinion, by allowing the temperature "far away" from the end to be maintained at T_∞.

What this means is that, in order to use the finite difference formulation, all the equations must be solved simultaneously, in matrix form, where $a_i = \left(\frac{1}{x_i - x_{i-1}}\right)$, $b_i = -\left(\frac{1}{(x_i - x_{i-1})} + \frac{1}{(x_{i+1} - x_i)} + 2Nu\frac{k_f}{k_s}(x_{i+1} + x_{i-1})\right)$, $c_i = \left(\frac{1}{x_{i+1} - x_i}\right)$ and $d_i = -2Nu\frac{k_f}{k_s}(x_{i+1} + x_{i-1})T_\infty$:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ a_1 & b_1 & c_1 & 0 & \cdots & 0 & 0 & 0 \\ 0 & a_2 & b_2 & c_2 & \cdots & 0 & 0 & 0 \\ 0 & 0 & a_3 & b_3 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & b_{10} & c_{10} & 0 \\ 0 & 0 & 0 & 0 & \cdots & a_{10} & b_{10} & c_{10} \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ \vdots \\ T_{10} \\ T_{11} \\ T_{12} \end{pmatrix} = \begin{pmatrix} T_0 \\ d_1 \\ d_2 \\ d_3 \\ \vdots \\ d_9 \\ d_{10} \\ T_\infty \end{pmatrix}$$

This matrix equation may be solved for $\vec{T}$ using a A\b left-divide in MATLAB or an equivalent operation from another programming environment.

Note, however, that the Nusselt numbers (Nu in these equations) are dependent on $\vec{T}$, meaning that this system isn't actually, strictly, linear. However, if we solve for $\overrightarrow{Nu}$ using an early guess for $\vec{T}$ (say, $\vec{T}_{n-1}$) and assume that the resulting $\overrightarrow{Nu}_{n-1} \sim \overrightarrow{Nu}_n$, we should be able to generate a better guess $\vec{T}_n$. Hence, one may still use this linear model and simply iterate until $\vec{T}_n$ isn't an appreciable improvement over $\vec{T}_{n-1}$. The best metric for this, as far as I know, is $r^2 = \vec{T}_{n-1}^T\vec{T}_n$--

that is, the sum of the squares of the differences. However, one may also simply iterate until the result looks "good enough," which is what I did in practice.

The implementation of this algorithm in my code looks like this in python:

```
#redo this thing a few times
for n in xrange(20):
    A=hstack((1, zeros(len(x)-1)))
    b=T[0]
    for j in xrange(1,len(x)-1):
        params.thermexp=1.0/T[j]
        Apart=zeros(x.size)
        Apart[j-1]=1.0/(x[j]-x[j-1])
        Apart[j+1]=1.0/(x[j+1]-x[j])
        hpoverka=params.hc(T[j],"rod") *rod.p *(x[j+1]-x[j-1])
/params.k_s/rod.xsect/2.0
        Apart[j]=-Apart[j-1]-Apart[j+1]-hpoverka
        b=vstack((b, -hpoverka*Tinf)) #check k_s vs. k_f
        A=vstack((A,Apart))
    A=vstack((A,hstack((zeros(len(x)-1),1)) ))
    b=vstack((b,Tinf))
    T=linalg.solve(A,b)
```

The loop utilizing "n" implements the iterative nature of the algorithm, while the loop utilizing "j" constructs the matrix using the finite difference formulation of the governing equations. When calculating h, I assumed that the radiation component of a combined h was negligible, hence the differences in h came from the thermal expansion coefficient β when calculating the Grashof and Prandtl numbers necessary to find h, as can be seen from these four snippets:

```
rod=geometry("rod",1.0/12.0) #rod with 1" diameter

Tinf=72.0

params=htparams(g=32.2, #gravity
        l=rod.d,
        xsect=rod.xsect,
        Tinf=72.0, #deg. F
        kvisc=0.00021, #courtesy Cengel
        k_f=0.01464,  #courtesy Cengel
        k_s=102.3, #courtesy Cengel
        alpha=0.00029)


...


class geometry:
    def __init__(self,geometry,lc):
        self.geom=geometry
        if self.geom=="sphere":
            self.d=lc
            self.r=lc/2.0
```

```
            self.xsect=pi*self.r**2.0
            self.sarea=4.0*self.xsect
            self.vol=(4.0/3.0)*pi*self.r**3.0
        elif self.geom=="rod":
            self.d=lc
            self.r=lc/2.0
            self.xsect=pi*self.r**2.0
            self.p=pi*lc
```

...

```
    def rayleigh(self,Tf):
        return self.grashof(Tf)*self.prandtl(Tf)

    def grashof(self,T):
        return (self.g*self.thermexp*(T-
self.Tinf)*((self.l)**3.0))/((self.kvisc)**2.0)

    def prandtl(self,T):
        return self.kvisc/self.alpha
```

...

```
    def hc(self,Tf, geom):
        #Tf is for "Tfilm" and is a hangover from how the first
assignment was specified.
        if geom=="sphere":
            #Incropera and Dewitt's empirical equation for hc
            return
(2+(0.589*(self.rayleigh(Tf))**0.25)/(1+(0.469/self.prandtl(Tf))**(9.0/
16.0))**(4.0/9.0))*(self.k_f/self.l)
        if geom=="rod":
            #Courtesy Cengel
            return
(self.k_f/self.l)*((0.387*(self.rayleigh(Tf)**(1.0/6.0)))/(1.0 +
(0.559/self.prandtl(Tf))**(9/16))**(8.0/27.0))**2.0
```

Note that all the values for k_f, k_g, α and the empirical equation for h_c came from Cengel's Heat and Mass Transfer. The dimensions of the rods were measured with calipers on-site.

The output of this program looks something like this:

```
__X__   __T__
0.0     250.0
0.5     244.597915499
1.5     234.272165832
3.5     215.418840417
6.0     194.828823926
9.0     173.855086343
12.0    156.254878258
18.0    129.416010545
24.0    110.159211369
30.0    95.9336086944
36.0    84.8596925169
100.0   72.0
```

For comparison purposes, I calculated the percent difference from measured temperatures for all the values: Note: This is probably not the best ~~way~~ or most sensical way to compare values.

i	Temperature (F) Simulated	Measured	Deviance from Measured
0	250.0		
1	244.6	212.6	15.1%
2	234.3	171.1	36.9%
3	215.4	121.9	76.7%
4	194.8	96.2	102.5%
5	173.9	79.1	119.8%
6	156.3	74.1	110.9%
7	129.4	69.6	85.9%
8	110.2	69.5	58.5%
9	95.9	69.8	37.4%
10	84.9	70.2	20.9%
11	72.0		

Note that, while the curves appear generally similar, that the simulation has higher temperatures than the real bar in the middle. I believe this is because of radiation-based heat loss, which I opted not to calculate in my analysis. In the future, I will presumably know better.

<u>Additional Commentary on Lab:</u>

Dr. Bargar's method did not call for solving the equations directly, and instead requested an iterative approach. I didn't do this because I didn't understand, at the time, how his method would work. His method should work if executed correctly, though his explanation left much to be desired. In a comment written well-after-the-fact, I sketched out the use of this method:

```
After wrestling with this thing for a long time, I finally figured out how Doc Bargar
wanted us to solve it. He's not very good at explaining things!
basically, he wants us to, for i in [2..8], solve for T_i using T_{i-1} and T_{i+1}. In
other words, while T_0 and T_10 get left alone (this is good! They're BCs!), the other T_i
are weighted-averaged on down the line. Of course, the solution after cycling through i in
[2..8] will be far from exact, but that's okay because it wasn't gonna be exact anyway
with h and all. You just have to iterate!  ...a lot.

Upshot: Bargar wasn't talking out of his ass after all.
Downshot: This method may have some pretty crummy convergence properties.
```

Unfortunately, Dr. Bargar was convinced that only by solving the equations using a weighted-average method could one call the whole thing a finite difference method. In addition, an iterative solver supposedly leads to more accurate solutions. Let me assure you that both assertions are wrong on many levels, but whatevs rite?

Yes, I took it personal.

Gas Turbine Performance

Principles & Background:

Gas Turbines in General:

Gas turbines have taken on many useful roles since the middle of the 20th century.

The gas turbine engine is also known as the turbojet or jet engine. In this configuration, its primary purpose is to provide thrust for aircraft flight.

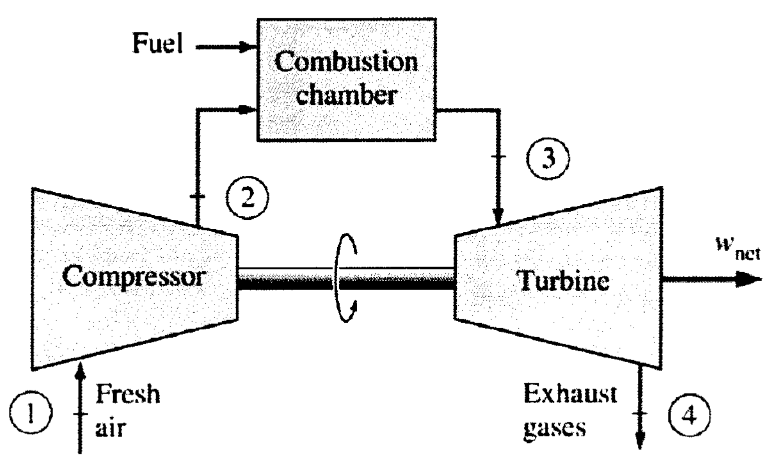
Gas turbines are also configured for stationary use. In this configuration, the gases are further expanded through the turbine stages robbing the exhaust of thrust. This energy is delivered to the shaft where it can produce useful work from the engine.

The term "gas" in *gas turbine* refers to the fact that combustion gases are expanded through the turbine to produce work and/or thrust. Fuels for gas turbines can be gaseous, liquid, or solid phase prior to combustion.

Thermodynamic Basics of Gas Turbines:

Gas turbines operate on the Brayton Cycle. George Brayton originally proposed this thermodynamic cycle around 1870 for use with a reciprocating engine. It is now generally associated with rotating engines that involve compression and expansion processes.

Typical components of a gas turbine engine operating on the Brayton Cycle can be seen in the following schematic diagram.



The diagram shows a compressor and turbine connected to a common shaft.

The compressor is initially operated by some external means and air is compressed. Our Cussons unit uses a fan to initially force air through the compressor.

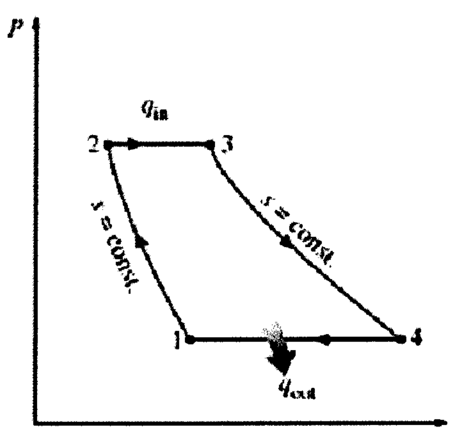
The compressed air exits the compressor and is mixed with fuel in the combustor. The air-fuel mixture is ignited, increasing its energy level, and the combustion gases are discharge through the turbine.

The initial stages (primary or high-pressure) of the turbine provide the power required to operate the compressor. In most modern gas turbines, the compressor and primary turbine stages are mounted on a common shaft. This facilitates the transmission of power from the turbine to the compressor. Once the primary turbine is producing sufficient power to sustain the compression of the incoming air, the external device initially used to drive the compressor is disconnected.

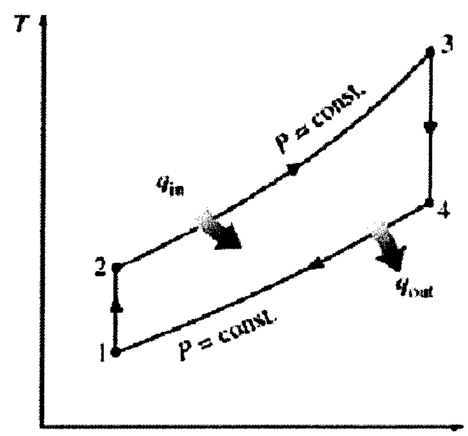
For jet engines, the remaining high pressure combustion products are discharged through the exhaust nozzle to provide thrust. Only sufficient power is removed from the gas stream to sustain the compressor and a few ancillary loads.

For stationary turbines, the combustion products are expanded through additional turbine stages to extract the remaining energy and the gas is exhausted to atmosphere. These additional stages are called the *power turbine* or *low pressure turbine*. In many cases, they are additional wheels housed within the same turbine housing on the common shaft. In other instances (our Cussons unit is an example), the power turbine is a separate turbine that takes input gas from the primary turbine and has its own power shaft connected to the load(s).

As usual in analyzing thermodynamic cycles, its helpful to plot the cycle on a phase diagram. We can view the idealized (no losses considered) Brayton Cycle on both a P-v Diagram and T-s Diagram as follows:



P-v diagram



T-s diagram

Air enters the compressor at state 1, undergoes an isentropic compression, and exits the compressor at state 2. The high-pressure air at state 2 is mixed with fuel and ignited in the combustor. It undergoes a constant pressure (isobaric) heat addition and exits the combustor at state 3. The high-pressure, high-temperature combustion gases at state 3 enter the turbine and undergo an isentropic expansion to state 4. For the open system shown in the schematic diagram there is no working fluid connection between states 4 and 1. However, for the Brayton Cycle to be complete, we treat the system as if there were a connection between the gases leaving the turbine at 4 and the air entering the compressor at 1. Remember, for it to be a thermodynamic *cycle*, the system needs to start at a given state point, proceed through a series of thermodynamic processes, and return to the original state point. We analyze the cycle as if the gases that exit at state 4 undergo a constant-pressure (isobaric) heat rejection process and enter the compressor at 1. Note that this ignores the presence of the fuel in the combustion gases. This does not result in a large error as, in practice, the fuel-air ratio results in a mixture that is very lean (predominately air).

As depicted, the ideal Brayton Cycle is a steady-flow cycle. Or, a cycle made up of several steady-flow processes. Performing an energy balance (1st Law analysis) on this cycle we see:

$$E_{in} = E_{out} \tag{1}$$

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{exit} - h_{inlet} \tag{2}$$

Eq. (2) is the general energy balance for a steady-flow system when PE & KE are neglected (which is valid for this case). However, for the closed diagrams shown in the P-v and T-s Diagrams above, the system is treated as a closed system and there are no inlet or exit conditions. For analysis of this case, Eq. (2) reduces to:

$$(q_{in} - q_{out}) = (w_{out} - w_{in}) = w_{net} \tag{3}$$

In analyzing the Brayton Cycle, we often assume that the working fluid is air (neglecting the fuel component) and that the air behaves as an ideal gas with constant specific heats. This allows us to further develop Eq. (3) as follows:

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2) \tag{4}$$

$$q_{out} = h_4 - h_1 = c_p(T_4 - T_1) \tag{5}$$

$$w_{out} = h_4 - h_3 = c_p(T_4 - T_3) \tag{6}$$

$$w_{in} = h_2 - h_1 = c_p\left(T_2 - T_1\right) \tag{7}$$

The thermal efficiency for the Brayton Cycle is defined as the net work out of the turbine divided by the energy provided to develop that work. Looking at the above diagrams and equations, we can write:

$$\eta_{th,Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \left(\frac{P_1}{P_2}\right)^{\left(\frac{k-1}{k}\right)} \tag{8}$$

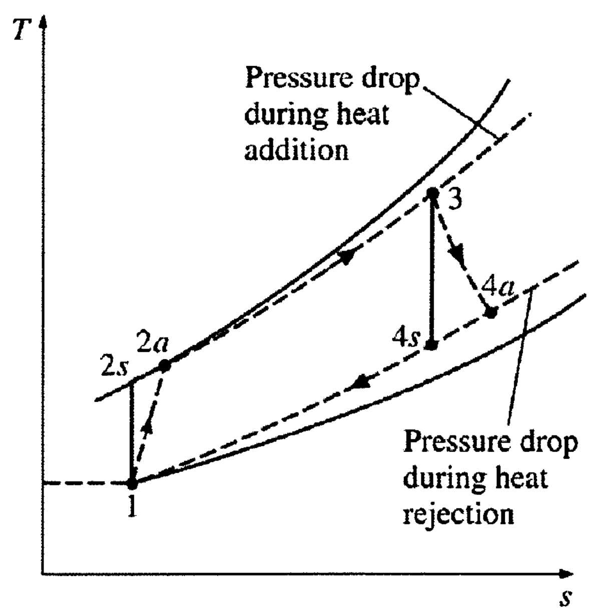
In Eq. (8), k is the ratio of specific heats. This is generally taken to be 1.4 for air.

The above analysis assumed an *ideal* Brayton Cycle. That is, we analyzed the cycle on a 1st Law basis. But, we know that 2nd Law considerations will come into play in real world equipment.

One such consideration is that there will be pressure drop in the flow streams as air and air-fuel/combustion products flow through actual devices. This means that our processes from 2 → 3 and 4 → 1 are not really isobaric.

A larger divergence from ideal conditions will appear due to the fact that neither our compressor nor turbine(s) are reversible devices. These devices will have specific efficiencies associated with them due to unavoidable losses (friction, by-pass flows, etc.) during their operation.

We can re-draw our T-s Diagram to show a more realistic cycle diagram for an actual Brayton Cycle.



The actual process lines are shown as dashed in the above diagram.

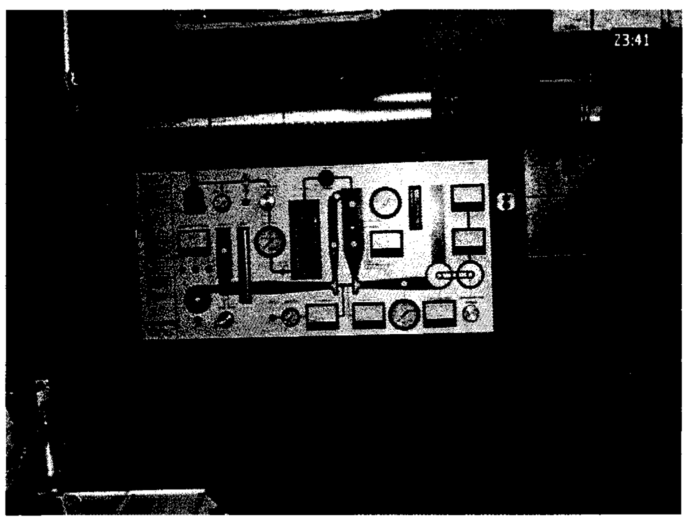
If we let subscripts of *s* and *a* denote ideal and actual condition, respectively, we can develop relations for the efficiencies of the compressors and turbines as follows:

$$\eta_{comp} = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} = \frac{T_{2s} - T_1}{T_{2a} - T_1} \tag{9}$$

$$\eta_{turb} = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} = \frac{T_3 - T_{4a}}{T_3 - T_{4s}} \tag{10}$$

Lab Procedure:

A gas turbine test/demonstration unit manufactured by G. Cussons Ltd will be used for this lab exercise.



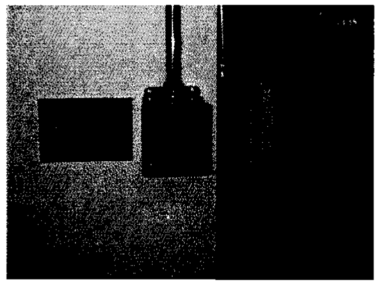
Turbine Unit Start-Up:

With the assistance of the lab instructor:

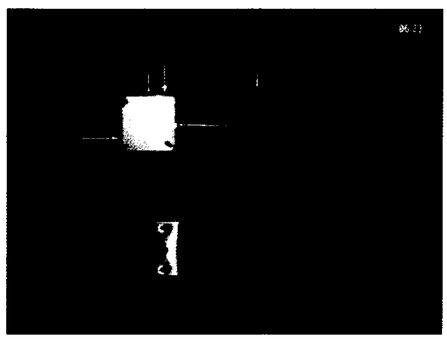
1. Open the exhaust stack to the turbine unit and close the exhaust stack to the Diesel engine. This is accomplished by insuring that the Diesel exhaust pipe is blocked with its blind flange fitting and the turbine exhaust pipe is not set with the blind flange in place.

2. Place the turbine unit's cooling water outlet in the lab's floor drain. Connect the cooling water supply line to the lab's water supply and turn the cooling water ON.

3. Insure that the gas (propane) supply Emergency Shut-Off Switch located adjacent to Duc 103's exit door is disengaged.

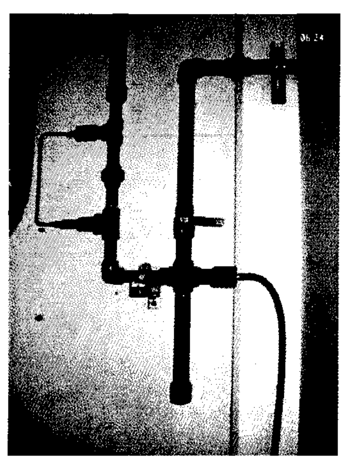


4. Energize the Duc 103 purge ventilation system by switching the ventilation system's wall toggle to ON.

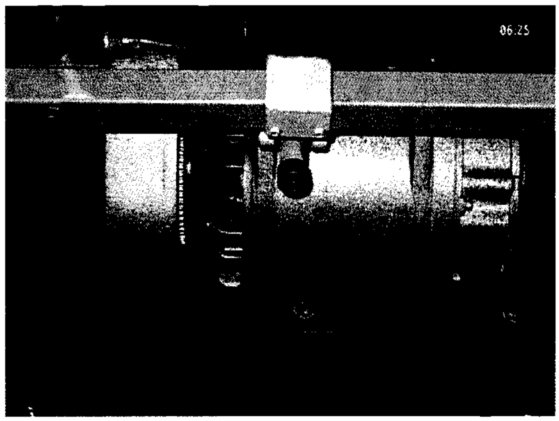


5. Connect the electrical supply for the turbine unit to the 208Vac, 1 Ph. , wall outlet in Duc 103.

6. Insure that the gas valve on the turbine unit is closed and open the ball valve on the gas supply line in Duc 103.



7. Insure that the knurled knob (clutch) located on the lower right end of the turbine unit is turned fully clockwise to disengage the pressure on the drive belt for the power turbine.



8. Set the turbine unit control to the "Start" position.

9. Set the dynamometer to maximum excitation.

10. Start the oil pump.

11. Press the "Reset" button. Insure that the unit energizes and that propane line pressure is registered.

12. Start the blower.

13. Set the gas pressure to ~ 2.0 bar with the "Pressure Reducing Valve". Note that this adjustment may have little effect until the unit is firing.

14. Press and hold the "Ignition" button while adjusting the gas flow rate to ~0.5 g/s to fire the unit.

    a. You should hear a "pop" as ignition occurs and the turbine speed and temperature (t_3) should begin to rise if ignition was successful.

    b. Release the "Ignition" button as soon as ignition occurs but not later than 5 seconds after pressing it.

    c. If ignition was not successful, shut the gas flow control to zero flow and allow time to purge the unburned gas from the unit. Then repeat step 14. Note: in some cases, you may need to return to Step 11 and begin from that point.

15. Open the gas flow control slowly and bring the unit up to ~1000 rev/s while keeping the combustion chamber temperature below 800°C. Note: this may take several minutes.

16. When the turbine and compressor appear to be self-sustaining, turn the control switch to the "Run" position and turn the blower OFF.

17. Allow the unit to stabilize for several more minutes under its own power.

18. Disengage the power turbine's belt clutch by turning the knurled knob counter-clockwise. Observe that the power turbine engages and the unit begins to generate power.

19. Adjust the dynamometer's excitation to take readings at at least two (2) different power outputs.

Data Recording:

Collect the following data at each power output to facilitate your analysis of the gas turbine cycle.

1. Gas supply pressure (P_G).
2. Gas supply temperature (T_G).
3. Gas flow rate $(\dot{m}_f)$.
4. Inlet air temperature (T_1).
5. Air flow rate $(\dot{m}_a)$.
6. Temperature of air after compressor (T_2).
7. Air pressure after compressor (P_2).
8. Combustion gas pressure before HP turbine (P_3).
9. Combustion gas temperature before HP Turbine (T_3).
10. Combustion gas temperature after HP turbine (T_4).
11. Combustion gas pressure after HP turbine (P_4).
12. Combustion gas pressure after LP turbine (P_5).

13. Combustion gas temperature after LP turbine (T_5).

14. Power output of LP turbine. This is obtained by recording the volts (V) and amps (A) for the generator.

15. Speed (rpm) of HP turbine/compressor.

16. Speed (rpm) of LP turbine.

Turbine Unit Shut-Down:

1. Close the gas line ball valve. The turbine unit will "pump down" the line and starve itself of fuel.

2. Close the gas valve on the turbine unit. **Do not** change the pressure regulator valve setting.

3. Disengage the power turbine drive belt by turning the knurled knob fully clockwise.

4. Set the unit control to "Start" and turn the blower ON.

5. Allow the unit to purge and cool for ~ 30 minutes.

6. Turn the blower and oil pump OFF. Set the unit control to OFF.

7. Close the cooling water supply valve, disconnect and drain the hoses, and re-coil them behind the unit ready for their next use.

8. Disconnect the unit's electrical supply and re-coil the cord and store it behind the unit for its next use.

The air flow rate for the Cussons gas turbine apparatus is measured by an obstruction (venturi) meter in the air flow stream. This type of meter relates the air flow rate to a pressure drop (head) across the meter. Our Cussons apparatus uses a manometer to read the pressure differential across the venturi meter in units of mm H_2O. The manometer fluid is believed to be colored water.

Based on historical notes on this lab exercise, the following information is presented:

To convert the manometer's head reading to flow rate, multiply the manometer reading by 12.2. The resulting number is the mass flow rate of air in g/s.

Example:

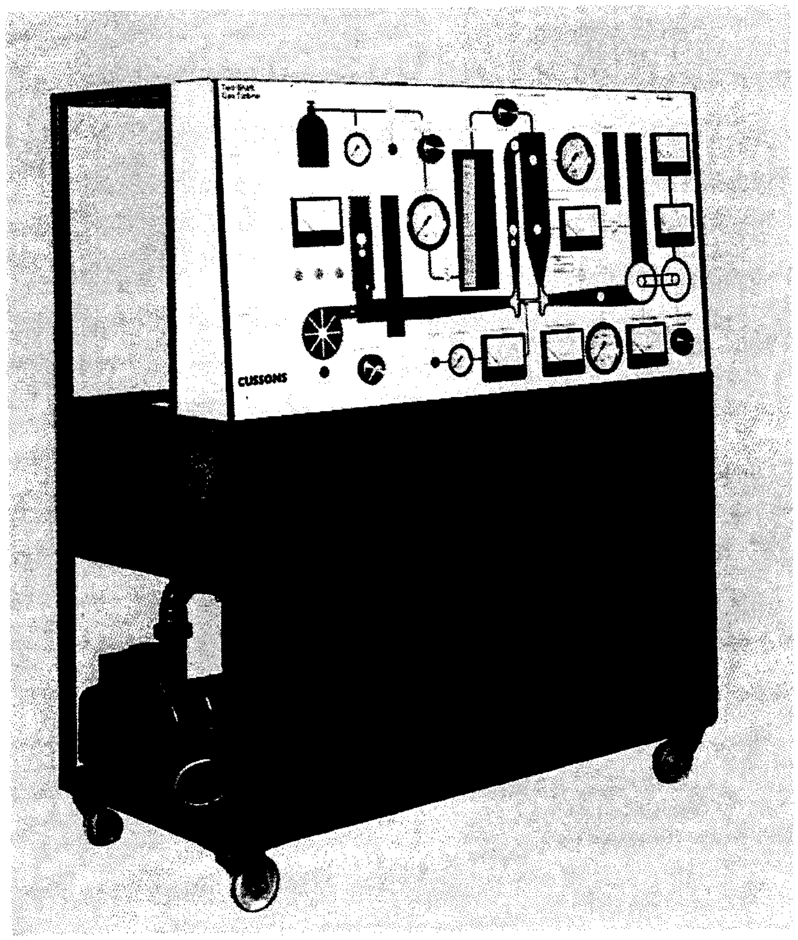
The manometer read 76 mm H_2O under steady-flow conditions.
The flow rate of air is:

$$\dot{m}_{air} = \left(12.2\, {}^{g}\!/\!_{mmH_2O \cdot s}\right)(76mmH_2O) = \underline{\underline{927.2\, {}^{g}\!/\!_{s}}}$$

Leaflet number T20

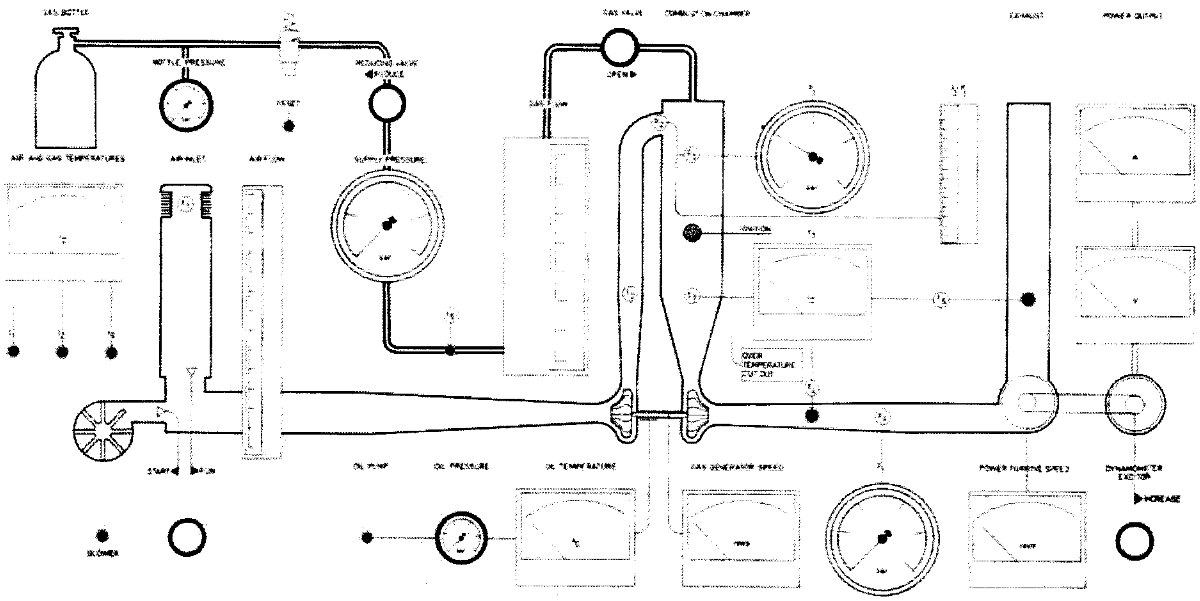
Two shaft gas turbine unit

CUSSONS



TWO SHAFT GAS TURBINE UNIT

Cussons Gas Turbine Unit which has been an outstanding success since it was first introduced has now been re-designed and incorporates the many improvements developed over recent years. The unit is now offered as a full two-shaft machine with built-in air starting equipment and choice of power absorption systems. It provides the means for carrying out an extensive programme of experiments in gas turbine technology using only the instrumentation provided.
Particular features of the Two Shaft Gas Turbine Unit are its versatility, ease of operation, safety and low noise level. All instrumentation and controls are carried on the panel which displays the flow diagram with a clear indication of all measurements identified by symbols and illuminated tell-tales. Measurement of power turbine torque may either be by the calibrated electrical dynamometer, successfully used in the earlier machine, or by an eddy current dynamometer with load cell.



General Design

The two Shaft Gas Turbine Unit employs a compressor and turbine both of the radial type, arranged back to back on a common shaft with a combustion chamber operating on propane or butane. Gases from the gas generator turbine pass to the power turbine which is a radial machine of larger size and thence to exhaust. The power turbine is loaded by a dynamometer system to absorb the power output and measure the power turbine torque. Starting is effected by an electrically driven auxilliary air blower, incorporated within the unit and delivering into the eye of the compressor, which accelerates the compressor/turbine initially and assists it until self-sustaining speed is reached after light-up. There is a lubrication system for both the compressor/turbine and the power turbine incorporating an electrically driven pump, filter, oil cooler and reservoir. Oil cooling is automatically controlled.

Flow Diagram

The flow diagram illustrated above is reproduced in colour on the instrument panel of the unit.

Instrumentation

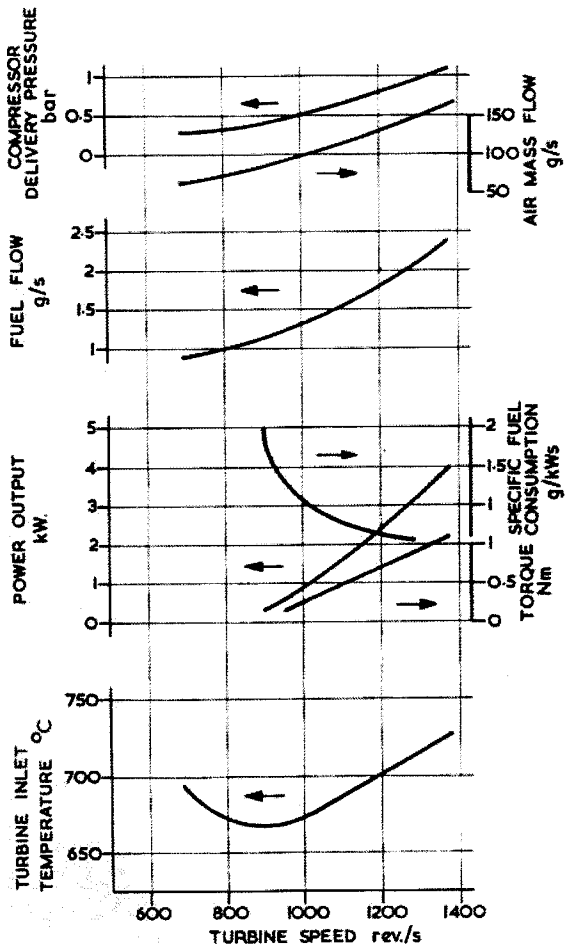
Instrumentation, all of which is carried on the front panel, is provided to measure temperatures and pressures throughout the cycle, flow rates of air and fuel, rotational speeds of the compressor/turbine unit and the power turbine and the power turbine output torque. Temperature measurement is by NiCr/NiAl thermocouple instrument for high temperatures and thermistors for low temperatures, pressure measurement is by manometer for differential pressure but otherwise by bourdon tube gauges, air flow by pitot head assembly, fuel flow by a variable area flow meter, rotational speeds by electronic tachometer and torque either by calibrated electrical machine or by a strain gauge load cell with analogue read out. The instrumentation has been located in a logical sequence to facilitate readings.

Assembly

The complete unit is built on a robust steel chassis on wheels carrying a melamine laminate instrument panel and steel cladding panels. The overall dimensions permit the unit to pass through any normal doorway and special attention has been paid to the requirements of easy installation, low noise level, convenience of operation and safety.

Fuel System

In temperate climates propane and in tropical climates butane, or mixtures of the two, supplied in bottles form the fuel supply to the unit. The use of bottled gas is particularly convenient and also is a significant safety feature as large quantities of fuel cannot build up in the system in the event of non light-up, stable combustion conditions are reached very quickly, and due to the small pressure excess necessary to inject the fuel any overspeeding of the set will cause a drop in fuel mass flow and provide worthwhile governing action.



Test Results for P.9005 Two Shaft Gas Turbine Unit

P.9005 Two Shaft Gas Turbine Unit

Specification
Two Shaft Gas Turbine Unit on self-contained moveable stand comprising single shaft compressor/turbine unit, combustion chamber for operation on propane or propane/butane mixtures, power turbine, calibrated electrical machine for torque and power measurement, ignition system, oil tank, circulating pump, cooler and filter, five colour instrument panel with flow diagram fitted inlet air flow meter, fuel flow meter, tachometers (2), multi-point pyrometer, thermistor instrument, thermo-couple instrument, sensitive pressure gauges (3), manometer, oil pressure gauge and fuel pressure gauge. Complete with starting air compressor set and all controls. Gas bottle and connecting pipe not included.
For 220/240 volt 50Hz mains. For other voltages and frequency to special order.

P.9006 Two Shaft Gas Turbine Unit (Eddy Current Dynamometer)

Specification
As P.9005 but eddy current dynamometer with load cell read-out for torque measurement in place of calibrated electrical machine.

P.9007 Sectioned Compressor/Turbine Unit

Specification
Compressor/Turbine Unit similar to Gas Generator of P.9005 and P.9006 sectioned to show all functions and mounted on base.

Shipping Specification

	Net Weight		Length		Width		Height	
	lb	kg	in	m	in	m	in	m
P.9005	770	350	54	1.37	34	0.86	63	1.60
P.9006	825	375	54	1.37	37	0.94	63	1.60
P.9007	12	5.5	12	0.30	12	0.30	10	0.25

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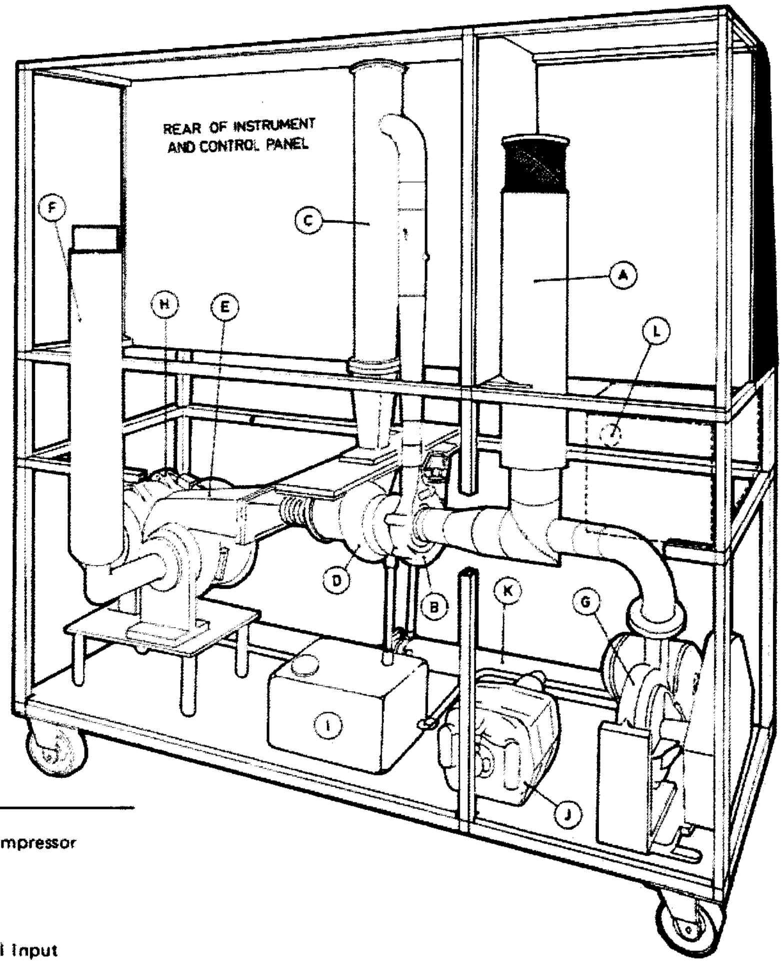


Rear view of Two Shaft Gas Turbine Unit

A	Inlet Air Silencer	G	Starting Air Compressor
B	Compressor	H	Dynamometer
C	Combustion Chamber	I	Oil Reservoir
D	Gas Generator Turbine	J	Oil Pump
E	Power Turbine	K	Oil Cooler
F	Exhaust Silencer	L	Mains Electrical Input

Compressor/Turbine System
The compressor is formed in light alloy and operates at a pressure ratio of approximately 2:1. The combustion chamber operates at high efficiency and permits stable operation over a wide range of mass flows with an even temperature distribution. The gas generator turbine operates over the speed range 500 to 1400 rev/second according to fuelling. The power turbine operates over the range 170 to 590 rev/second and develops a maximum power of about 4kW.

Safety Protection
Particular attention has been paid to questions of safety in operation. The unit is protected against over temperature, lubricating oil pressure failure and mains failure. A solenoid valve cuts the fuel supply in the event of any such malfunction and must be reset before the unit can be re-started. The compressor/turbine speed is limited by the fuel availability and power turbine excess speed causes a temperature rise which actuates the over temperature trip.

Operating Instructions and a Suggested Programme of Experimental Work
Complete operating instructions are provided with each unit and a comprehensive test programme is described in Cussons publication 'A First Course in Gas Turbine Technology' by T. H. Frost.

G. CUSSONS LTD., 102, Great Clowes Street, MANCHESTER, M7 9RH

P.9005 GAS TURBINE UNIT

NOTES ON OPERATION

1. Serial Number:

   In any correspondence or enquiry concerning this unit please quote the serial number.

2. Electricity Supply:

   All electrical systems operate from 240V 50 or 60 Hz single phase supply (for 110V systems a step up mains transformer will be provided). A 15A or 13A outlet provides sufficient power, but fuses must be of full rating and in good order. If they are not, failure may occur in switching on the starting blower.

3. Fuel Supply:

   The fuel to be used is propane in standard gas take-off bottles for which suitable fittings are provided. (Butane is unsuitable unless the vapour pressure is adequate at normal ambient temperatures i.e. above 50 lb/in^2 or 3.5 bar). Short period running is possible from 24 lb (11 kg) (net) bottles but 100 lb (45 kg) (net) bottles are recommended for normal use. Providing the ambient temperature is not too low one of these will allow adequate operating periods at full power. Where it is essential to site the bottles outside in cold conditions it may be necessary to couple two bottles in parallel to maintain an adequate supply. Consumption at full load is approximately 15 lb (7 kg) per hour; at no load idling, about 5 lb (2 kg) per hour. The level of liquid in the bottle during running can be seen from the dew condensing on the outside but for an accurate check on fuel available the bottle must be placed on a weighing platform or suspended from a spring balance.

4. Water Supply:

   An oil/water heat exchanger is included in the oil circuit and a raw water supply should be connected to the solenoid valve at the inlet to the heat exchanger and the water outlet should be connected to waste. The maximum water requirement is about 2 gallons (10 litres) per minute and the connection may be made by flexible hose of 3/8" (9 mm) bore capable of withstanding mains water pressure. The water supply should be connected at all times that the turbine is running and the oil temperature is automatically controlled by the thermostat and solenoid valve which admits water to the oil cooler.

5. Lubricating System:

The lubricating system is a continuous circulation one with separately driven pump, filter and heat exchanger. The capacity is approximately 1 gallon (5 litres) and the oil undergoes little deterioration and is normally changed only if the system has to be dismantled for any reason. Only the oil supplied by G. Cussons Ltd., may be used. Oils of higher viscosity such as normal motor oils will give difficult starting and reduce performance. The tank should not be filled with oil as gas blow-by may cause the oil to overflow the tank. The oil level should be half way up the tank. After initial filling run the oil pump for one minute to fill the oil filter etc. and then re-check the oil level in the tank.

A thermostat is fitted to the lubricating system which maintains the oil at about 95°C by means of a solenoid valve in the water supply.

6. Ignition System:

A high energy spark plug system is used for starting purposes only, it is only energised ,when the push button on the front panel is depressed.

The push button can be released as soon as ignition has occurred.

A suppressor is fitted to the HT lead but the suppressor may not be sufficient in respect of very sensitive instruments in the vicinity. The HT system must on no account be touched whilst energised as any shock from it could be dangerous. The energy levels are much higher than with normal vehicle ignition systems.

7. Starting System:

Starting is effected by blowing air into the compressor from a built-in blower.

The blower can normally be turned off when the gas generator turbine reaches a speed of 1000 rev/second although if the oil is very cold it may be necessary to keep the blower on until the oil has warmed.

8. Instrumentation:

Instrumentation included as standard consists of manometers for measurement of inlet air flow and pressure differential across the combustion chamber; pressure gauges for measurement of gas bottle pressure, lubricating oil pressure, combustion chamber pressure, power turbine inlet pressure and fuel supply pressure to the combustion chamber; variable area flowmeter for fuel supply measurement; tachometers for measurement of gas generator and power turbine speeds; voltmeter and ammeter for dynamometer power measurement; thermometers for temperature measurement at six points throughout the system.

The thermometry uses Chromel/Alumel thermocouples for the high temperatures, T_3, T_4, and T_5 and an electronic system for the low temperature T_1, T_2 and T_g.

The temperature readout push buttons are arranged so that T_3 is displayed unless the push button to select T_4, or T_5 is depressed. This arrangement allows more easy "driving" of the unit since the over temperature cut out is operated from T_3.

Calibration of the tachometers is performed before dispatch but calibration can be checked by disconnecting the tachometer input plug and connecting a signal generator in their place. (The generator should be capable of giving a 1V peak to peak sine wave signal).

The gas generator tachometer gives a reading of 1000 rev/second at 1000 Hz and the power turbine tachometer a reading of 500 rev/second at 4000 Hz.

Potentiometers are provided to adjust the meter reading, should this become necessary, and are accessible when the electrical control panel is hinged down (see Fig J).

A calibration curve for the fuel flowmeter is given in figure 4, to allow for changes in temperature of the gas.

9. <u>Electrical Loading System:</u>

The power turbine drives an alternator by toothed belt with a speed reduction of 4.5:1. The alternator excitation is varied by the control knob on the front panel and the alternator output is dissipated in a load bank mounted at the top of the unit.

A calibration curve for the alternator which takes into account electrical and belt losses is given in these instructions (Fig. 5).

The belt tension is automatically controlled by a hydraulic ram energised by the lubricating oil circuit. No adjustment to the system should be required but if at any time it is desired to check the functioning of the belt tensioner the pressure on the ram should be 2 bar (30 p.s.i.g.). This is controlled by a relief valve incorporated in the ram oil supply.

10. Protection:

Fuel is fed to the system via an electrically operated solenoid valve so that fuel is automatically cut off in the event of mains failure, loss of oil pressure or overtemperature of the gas generator turbine.

A "reset" button is provided so that the solenoid valve can be re-opened when the fault has been cleared.

The overtemperature cut out takes its signal from the thermocouple at T_3 and will see an overtemperature condition if the thermocouple goes open circuit by failure or disconnection.

Adjustment of the overtemperature cut out should not be necessary but it can be checked by letting T_3 rise to 800°C at which point it should operate to shut down the turbine. If it does not operate at this temperature loosen the locking screw on the cut out and adjust the setting until cut out occurs at 800°C (on the meter). Tighten the locking

NOTE: Do not exceed a setting of 800°C.

The figures on the overtemperature cut out are not °C.

The compressor/turbine speed is limited by the fuel and air availability and power turbine excess speed causes a temperature rise which actuates the overtemperature trip.

11. Installation:

The Gas Turbine Unit is self-contained and mounted on castors, it can be operated wherever services are available. Vibration is almost non-existent.

At idling the predominant noise is that of the oil pump, and at full power the noise is still much less than that of a small reciprocating engine.

The exhaust is non-toxic and clean but for extended running it should discharge into a duct leading into the open air. However, there must be a break in the system, usually in the form of a conical entry with the turbine exhaust discharging into the centre of the cone. The reason for this is the possibility of discharging an inflammable unburnt gas mixture into the exhaust system by incorrect starting procedure.

The controls for the unit are all identified on the front panel a drawing of which is reproduced in figure 1.

A rear view of the unit is reproduced in figure 2 with the main components identified.

Figure 3 identifies the electrical components on the control panel at the left hand end of the unit. The panel hinges down after removing the two fixing screws.

A wiring diagram for the unit is included at the rear of this instruction manual.

12. Starting:

Full starting and running instructions for the unit are printed on the left hand side of the front panel and are reproduced on page 8, of these instructions.

It is important that the fuel valve be closed if ignition does not occur within a few seconds of opening the fuel valve and pressing the ignition button to prevent a build up of unburned gas in the combustion chamber and exhaust system.

If ignition does not occur allow the blower to run for another minute or so and then try again.

Failure to ignite is usually due to cold oil preventing the turbine spinning.

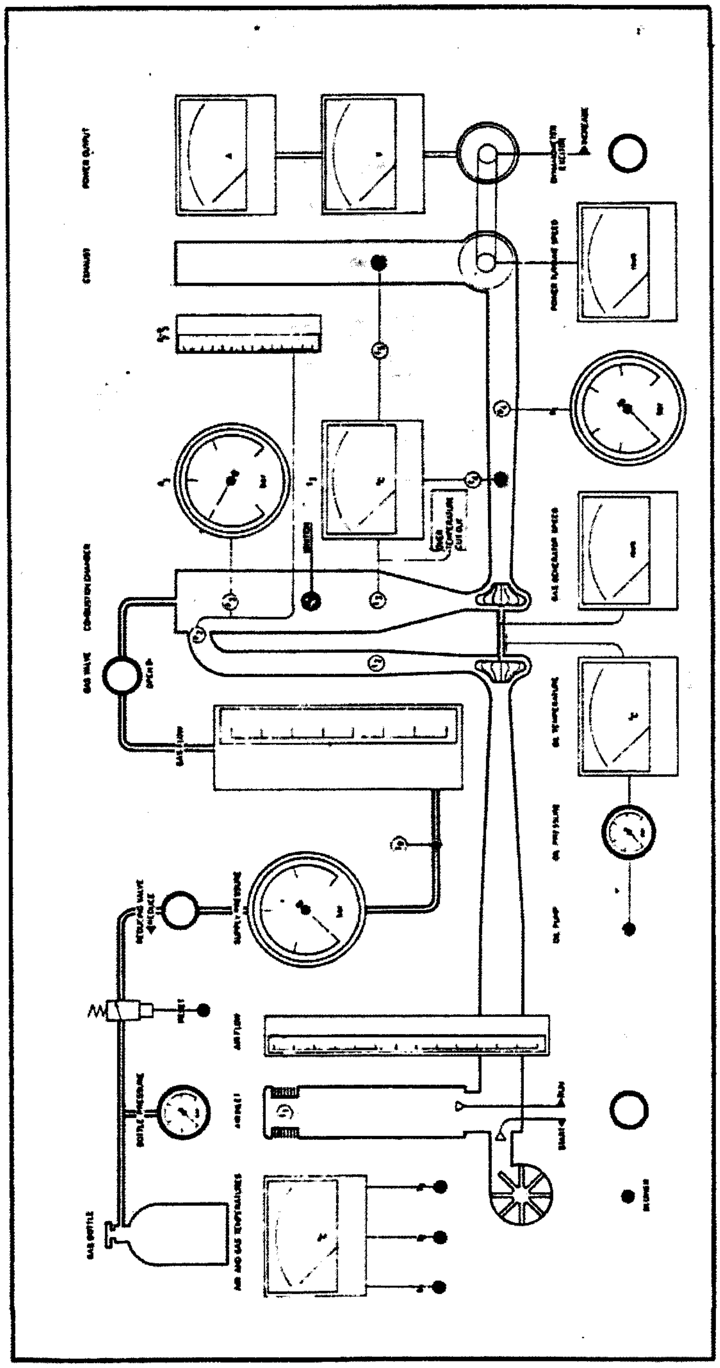
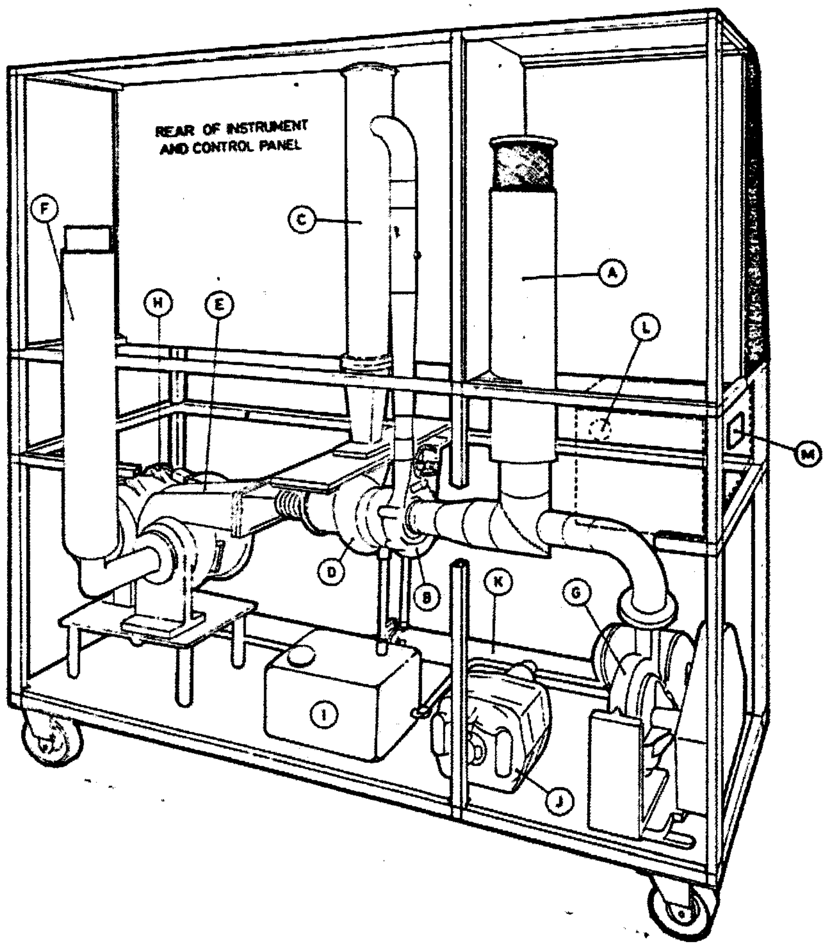


FIG. 1

FRONT PANEL LAYOUT OF GAS TURBINE UNIT



A - INLET AIR SILENCER
B - COMPRESSOR
C - COMBUSTION CHAMBER
D - GAS GENERATOR TURBINE
E - POWER TURBINE
F - EXHAUST SILENCER
G - STARTING AIR COMPRESSOR
H - DYNAMOMETER
I - OIL RESERVOIR
J - OIL PUMP
K - OIL COOLER
L - MAINS ELECTRICAL INPUT
M - OVER-TEMPERATURE CUT OUT

FIG. 2

REAR VIEW OF GAS TURBINE UNIT

Starting and running instructions as on Gas Turbine front panel.

STARTING:

1. Connect the cooling water supply and drain.
2. Connect the gas bottle.
3. Connect the electrical supply.
4. Set the air inlet control to the start position.
5. Close the gas valve and open the valve on the gas bottle.
6. Set the dynamometer excitation to maximum.
7. Start the oil pump.
8. Press the reset button.
9. Start the blower.
10. Set the gas pressure to 2.0 bar with the reducing valve.
11. Press the ignition button and hold it in whilst opening the gas valve to give a gas flow of 0.5 g/s.
12. If ignition, as shown by an increase in T_3 does not occur within 5 seconds of gas flow commencing close the gas valve to allow unburnt gas to clear the system before continuing from Item 11.
13. Release the ignition button.
14. Open the gas valve slowly to give gas generator speed of 1000 rev/s taking care to keep combustion chamber temperature below 800°C. (This operation may take some minutes depending on the oil temperature.)
15. Turn the inlet air control to the run position.
16. Switch off the blower.
17. Allow the turbine to run at 1000 rev/s until the oil temperature reaches 95°C.
18. Commence the test schedule.

NOTE:

a) Set the gas pressure to 1.5 bar before making gas flow readings.

b) Do not exceed 1500 rev/s gas generator speed. 90,000 rpm.

c) Do not exceed 600 rev/s power turbine speed. 36,000 rpm.

d) The gas turbine unit has certain safety features built into it. If the combustion chamber temperature T3 is allowed to exceed 800°C due to overfueling, or if the oil pressure falls below 1.5 bar then the gas supply will be shut off by means of a solenoid valve. To restart the turbine after operation of the solenoid valve follow starting instructions 4 – 17.

STOPPING.

1. Close the valve on the gas bottle.

2. Close the gas valve.

3. Leave the cooling water and oil pump on until the oil temperature falls below 50°C.

4. Disconnect the electrical supply.

A slight 'pop' will be heard when ignition occurs and a sharp rise in temperature will be seen on T_3.

If the gas valve is opened too quickly, T_3 will rise above 800°C and the overtemperature protection will operate. Should this occur, close the gas valve, press the reset button and restart the turbine.

On acceleration the temperature should be kept below 780°C slowly opening the gas valve as the turbine increases speed.

The initial rate of rise of speed will be slow but it will increase as the oil temperature rises.

When the speed reaches 1000 rev/s leave the gas valve set and turn the butterfly valve control knob to the 'run' position. The blower can now be switched off.

Allow the turbine to warm up at about 1000 rev/s.

No readings should be taken until the oil temperature reaches 90°C.

NOTE:

If the oil temperature reaches 100°C check that the water supply is turned on.

Do not exceed 780°C gas generator temperature (T_3).

Do not exceed 1500 rev/second gas generator speed (N_1).

Do not exceed 600 rev/second power turbine speed (N_2).

It is convenient when taking readings to first set the fuel flow at various levels by adjustment of the fuel control valve and, if necessary, adjustment of the reducing valve control to correct the fuel supply pressure to 1.5 bar.

As the gas generator speed can be varied over the range 660 – 1300 rev/s and the power turbine speed can be independently varied over the range 160 – 600 rev/s the scope for experimental work is very great. Suggestions for a series of tests are given on Cussons Catalogue Sheet T20 and publication "A First Course in Gas Turbine Technology".

When varying the load on the power turbine sudden movements of the alternator excitor control should be avoided as they can result in large transient loads on the belt which may lead to it jumping the pulleys and causing damage.

13. Shutting Down.

Fuel should be cut off at the gas bottle valve and as the pressure drops the gas control valve on the panel should be closed completely. The oil pump and water cooling system should be left running for about 15 minutes after shut down to avoid overheating the oil in the bearings.

CORRECTION FACTOR CURVES FOR ROTAMETER R.768146-55 WHEN USED FO
PROPANE AT 1·5 BAR GAUGE AND VARIOUS TEMPERATURES.

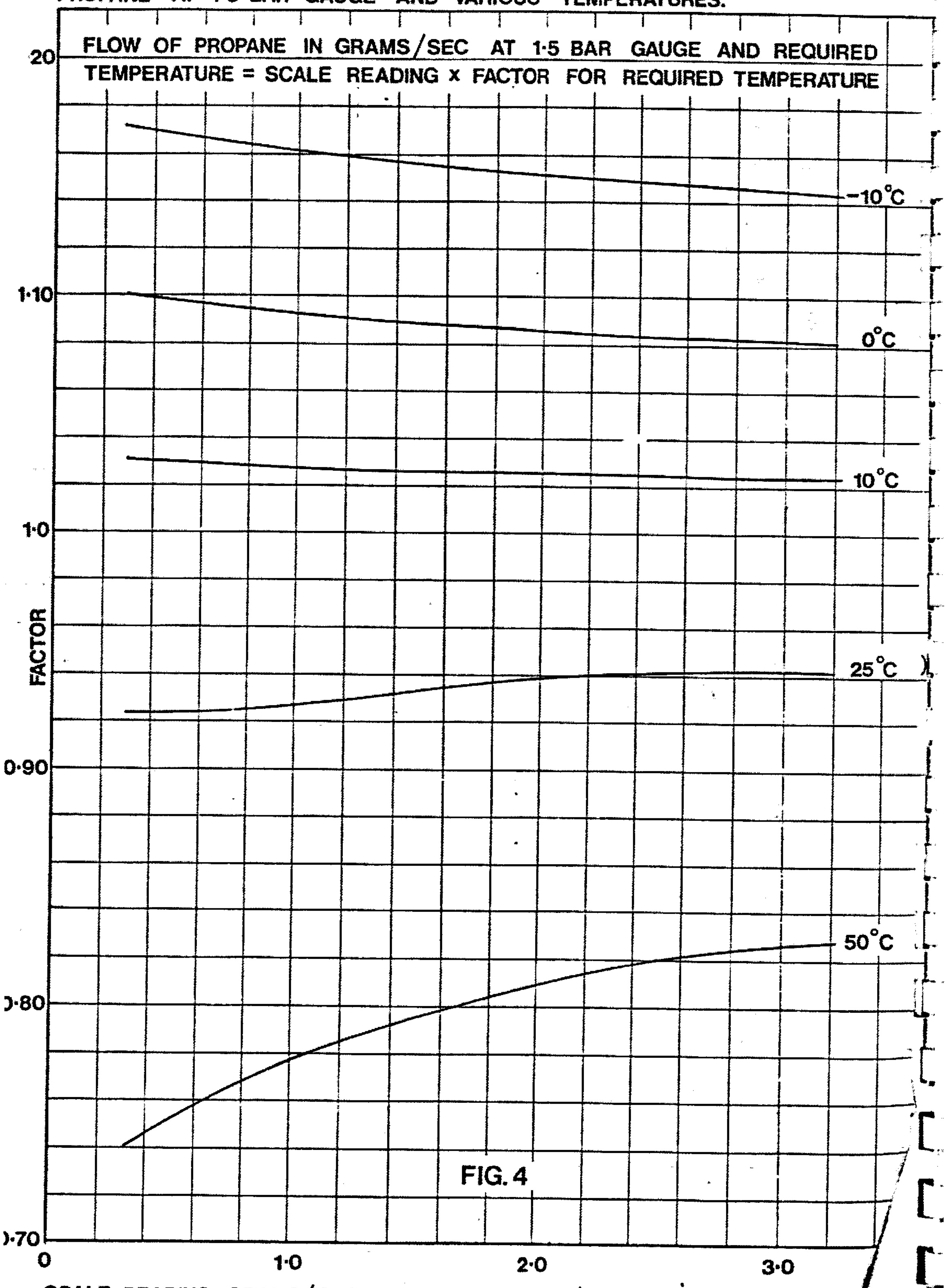
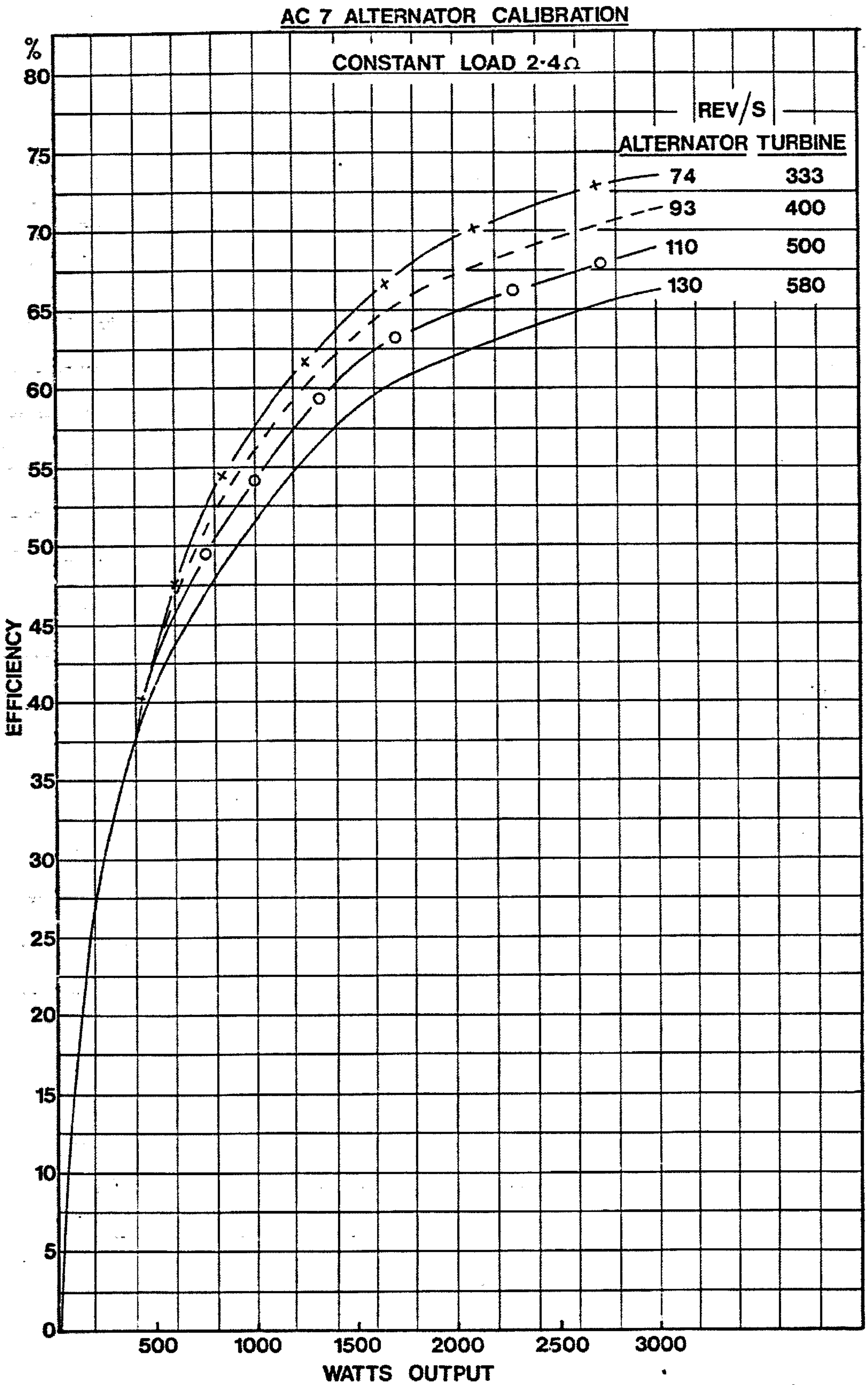


FIG. 4

R.776594 G.


AC 7 ALTERNATOR CALIBRATION
CONSTANT LOAD 2·4Ω
REV/S
ALTERNATOR TURBINE
74 333
93 400
110 500
130 580
%
EFFICIENCY
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
500
1000
1500
2000
2500
3000
WATTS OUTPUT

(FIG. 5)

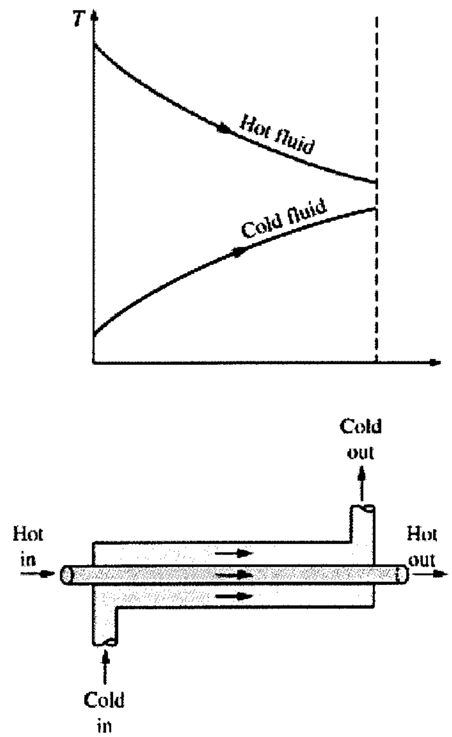
Heat Exchanger Performance

Principles & Background:

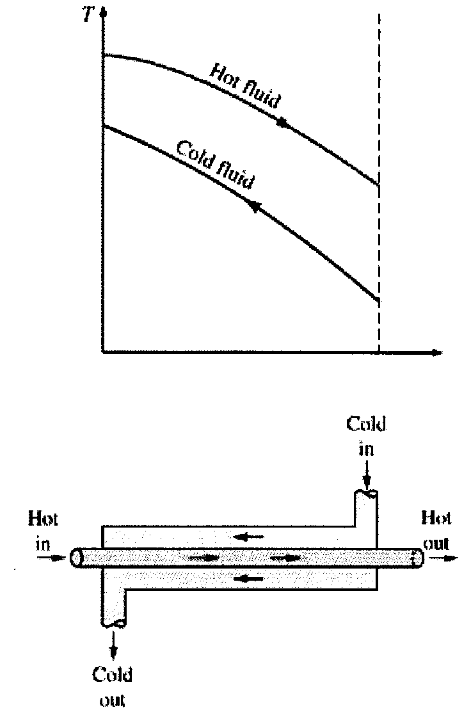
Heat Exchanger Performance:

This week's experiment measures the performance of a parallel flow and counter flow tube-in-tube heat exchanger. In the experimental apparatus, temperature controlled air flows in the central tube. This constitutes the "hot side" of the heat exchanger. Cooling water flows in the annular space (external tube). This constitutes the "cold side" of the heat exchanger.

Heat exchanger theory predicts the following temperature distribution in the hot side and cold side fluids dependent on whether the fluid flow is occurs in a parallel or counter flow configuration.



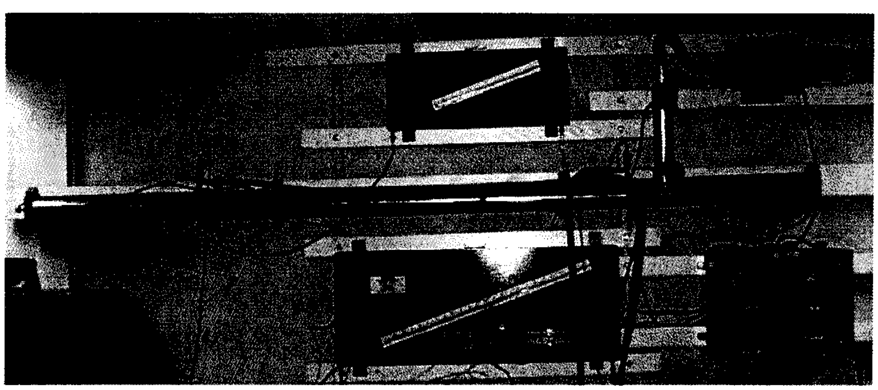
(a) Parallel flow



(b) Counter flow

Experimental Apparatus:

The laboratory apparatus was manufactured by Reader & Sons, Ltd. A description of the apparatus is included in the course lab manual and the manufacturer's Installation and Operating Instructions which are posted at the class Web site.



The heat exchanger is comprised of a copper tube run through a shell (external tube) of circular cross-section. Air flows inside the copper tube and water flows through the shell. By changing the water connections (hoses) the heat exchanger can be configured as parallel flow or counter flow. In parallel flow, both the water and air enter at the right end and exit at the left end of the heat exchanger. In counter flow, the water enters at the end where the air exits (left end) and exits at the end where the air enters (right end).

We will make some modifications to the apparatus and procedures that are described in the lab manual and the Reader Installation & Operating Instructions.

First, we will use a Type-T thermocouple reader to determine the temperatures of the pipe and air inlet and outlet conditions. The TC reader is connected to a common lead from the apparatus' selector switch. By selecting the desired position, the temperature is read on channel 2 of the TC reader. The lab manual shows the use of a Campbell datalogger for this purpose and the manufacturer's manual shows the use of an apparatus mounted meter.

We will use thermistors and a thermistor reader to determine the inlet and outlet water temperatures. The manufacturer's manual shows thermometers for this purpose.

Both the lab manual and the manufacturer's manual mention setting the air flow to maximum for certain operations. We will **not** do this. The pressure drop across the tube at maximum air flow rate is greater than that which can be measured by the manometer connected across these pressure ports. If the apparatus is adjusted to maximum air flow, the manometer fluid is "blown out". Limit the "Blower Regulator" (variac) selector to approximately 220 – 230 on its index scale. This may be adjusted as the temperature of the air changes to keep the manometer fluid intact.

We will also not set the "Heater Regulator" (variac) to its maximum value. To do so would cause the apparatus to overheat at certain air flow rates and the over-temperature cut-out safety would shut the unit down. Limit the heater input to approximately 220 on the variac scale. Again, this may be adjusted as the flow is varied. As noted in the text, limit the inlet air temperature to no more than 480°F.

Note that the variac control knob scales do not represent any physical unit such as flow rate or power input. They are merely index settings.

Review of Bernoulli's' Theory and Darcy-Weisbach Equation:

Bernoulli developed a theory that related the flow of a fluid to the head loss of the fluid. This theory is applicable to incompressible flows only. Since we are applying it to air (a possibly compressible fluid), we need to check the velocities after we complete this experiment to make sure the air flow has remained less than the velocity for compressible flow (~325 ft/s). Bernoulli also assumes that no friction loss occurs during the flow.

The Darcy-Wiesbach Equation modifies Bernoulli's Equation to include considerations for head loss during the flow.

$$\frac{P}{\rho g} + \frac{V^2}{2g} + Z + H_L = const. \tag{1}$$

The first term relates the change in static pressure between two points in a system.

The second term relates the change in velocity at two points in a system. This is concerned with the velocity or dynamic pressure changes.

The third term relates the elevation or head changes between two points within a system.

The final term relates the losses in the system between the two points. These are often referred to a *major* and *minor losses*. *Major losses* are generally those due to friction of the fluid flowing through "straight" pipe in the system. *Minor losses* generally account for the flow through the fittings in the system. Don't be confused by their names. Minor losses are often greater in magnitude than major losses. Especially in small, closed-loop systems.

We will utilize this principle to determine the flow rate of the air in our heat exchanger tube by relating the pressure drop we measure across the tube to the friction losses in the tube. That is, we will relate the $\frac{P}{\rho g}$ term to the H_L term.

Our tube is mounted horizontally, so there is no difference in elevation between the inlet and outlet. That is, the *Z* term cancels between inlet and outlet.

The inlet and outlet areas of the tube are equal, so the velocity pressure term also cancels between inlet and outlet.

One method to determine the friction losses in a flow channel, a tube in our case, is the Darcy-Weisbach relationship.

$$H_L = f\left(\frac{L}{D}\right)\left(\frac{\overline{V}^2}{2g}\right) \tag{2}$$

where:
- f = Fanning friction factor
- L = length of flow
- D = characteristic dimension
- V = velocity of the flow steam
- g = gravitation acceleration

A dimensional analysis of this equation yields the result is a measure of length. This is good since that is also the units for each term Eq. (1) stated above. The Fanning friction factor, *f*, is found from the Moody Diagram.

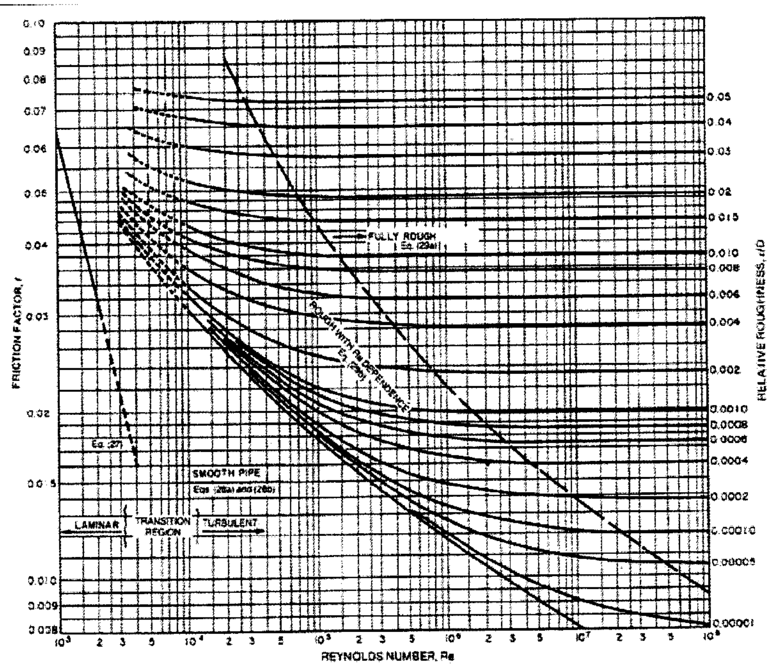


Fig. 13 Relation Between Friction Factor and Reynolds Number (Moody 1944)

To use the Moody Diagram, we need to determine the Reynolds Number for the flow and know the relative roughness of the flow channel.

The Reynolds Number for pipe or tube flow is:

$$\mathrm{Re} = \frac{\rho V D}{\mu} \tag{3}$$

The relative roughness is:

$$\frac{\varepsilon}{D} \tag{4}$$

In this lab, we need to determine the flow rate of the air in the tube. We know the pressure drop across the tube caused by friction loss. Therefore, we can solve the Darcy-Weisbach equation for velocity:

$$\overline{V} = \sqrt{\frac{2 H_L D g}{f L}} \tag{5}$$

Knowing the velocity and the cross-sectional area of the tube, we can determine the volumetric flow rate. The only catch is that the friction factor, *f*, in the above equation is a function of velocity (the Reynold's Number on the Moody Diagram). Therefore, this becomes an iterative solution. [Suggestion: for this apparatus, start with f = 0.025 as your 1st guess to reach convergence in a few iterative steps.]

Lab Procedure:

1. As described in the lab manual, make at least four separate runs in both parallel and counter flow configuration. Variation in the runs is produced by varying the air flow rate and/or the water flow rate. Suggested settings are contained in the lab manual. However, remember not to use air flows which exceed the capacity of the manometer. It is suggested that only one of these rates is changed between each test run.

2. During each test run, record all of the temperatures and the pressure drop across the tube. Also record the settings of the variacs and the flow rate of the water.

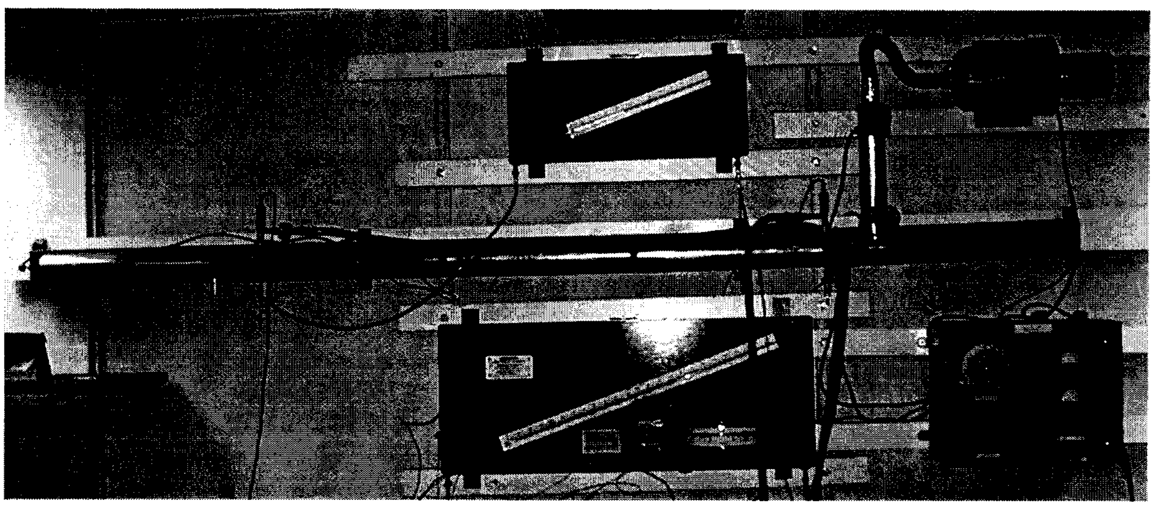
    a. The water flow rate is determined by the weigh tank method.

        i. Set the hose-bib to an approximate position.
        ii. Using a stop watch, time the water entering a container on the scale.
        iii. Determine the flow rate by dividing the amount of water that entered the container by the time it took to enter.
        iv. Make appropriate adjustments to the hose-bib to achieve the desired flow rate.

    b. You will also need to determine the flow rate of the air within the heat exchanger for each experimental run.

        i. There is no instrumentation on the apparatus that directly measures air flow rate.
        ii. We do measure the pressure drop across the length of the heat exchange tube. We will use this and a knowledge of fluid mechanics to approximate the air flow rate.

HEAT EXCHANGER EXPERIMENT



HEAT EXCHANGER EXPERIMENT

R. Johnson J. Zarling J. Tiedeman

I. PURPOSE:

To perform a series of tests on a tube and shell heat exchanger in parallel and counter flow.

II. APPARATUS:

1) Reader Standard Heat Transfer Apparatus
2) Thermistor, Thermocouples
3) Scale and Stopwatch

III. PROCEDURE:

1) Do not turn on heater until water is attached and running!
2) Attach water hoses to inlet and exit. Right end is inlet for parallel flow.
3) Turn on water and adjust for moderate flow (approx. 15 lb/min for beginning the experiment).
4) Set both variac controls to zero.
5) Turn on main power .
6) Adjust fan variac ~~for full flow.~~ such that the pressure head < 20 in (not shooting out of manometer).
7) Adjust heater variac to about 75% of full scale (just to begin the test).
8) Wait while unit comes to equilibrium.
9) You can read four temperatures on the thermocouple indicator mounted on the wall and the two thermistors for water temperatures.

Switch #
1. Inlet air temperature
2. Inlet tube temperature
4. Outlet air temperature
5. Outlet tube temperature

10) Make four parallel flow and four counter flow runs under the following conditions:

    1. Fan and heater at maximum position (constant air flow)

       Water flow rate: Approximately 20, 15, 10, 5 lb/min.

    2. Heater at maximum position. Water flow at approximately 15 lb/min (constant). Monitor Tair in. It should not exceed 480°F. Air flow rate: max; 3/4 max; 1/2 max; 1/4 max.

<u>Results:</u> Compute V, Re, h, LMTD, e, $U_{the.}$, $U_{exp.}$, $\dot{q}$ for all runs and tabulate results for comparison. Examine these values and comment on the results with regards to parallel and counter flow operation. From $U_{the.}$ and $U_{exp.}$ explain how close our estimates on fouling factors are. For the tests in which the inside fluid velocity (only) was varied, compute h_i and plot these results on log paper to determine the constants in the equation $h_i = CV_i^n$,where V_i is the velocity of fluid in the tube. For the same tests (V_i varied), determine the equation for h_i and h_o by following this method: Consider the approximate equation $\frac{1}{U} = \frac{1}{h_o} + \frac{1}{CV_i^{0.8}}$ and plot experimental results of $\frac{1}{U}$ on ordinates against $\frac{1}{V_i^{0.8}}$, on rectangular coordinates. This should result in a straight line with slope $\frac{1}{C}$ and y-intercept $\frac{1}{h_o}$.

Simple heat exchanger

The basic element in most heat exchangers is a metal tube or pipe, with one fluid flowing through it, the other flowing around it. Since the metal conductance is high, most of the heat-flow resistance occurs in the fluid films at the two surfaces. Hence the designer requires first an accurate knowledge of film coefficients and secondly a method of evaluating the temperature differences.

The film coefficients may be estimated from the basic convection equations, such as Eqs. 2 , 3. Since heat-exchanger surfaces are seldom perfectly clean, the estimation of in-service coefficients should include "fouling factors" as additional terms in the resistance equation.

$$\frac{1}{U_o} = \frac{D_o}{h_i D_i} + R_i \frac{D_o}{D_i} + \frac{D_o Ln\left(D_o / D_i\right)}{2k} + \frac{1}{h_o} + R_o$$

where:

i & o	=	inside & outside of the tube
U_o	=	overall coefficient based on outside tube area
h_i & h_o	=	surface coefficients for clean surfaces
k	=	conductivity of metal tube wall
R_i & R_o	=	fouling factors, expressed as heat-transfer resistances per unit area

Typical values for fouling factors in $\left[m^2 \cdot K/W\right]$ are 0.0001 – 0.0002 for clean treated city water and for recirculated water, 0.0002 for river water and light clean oil, and as high as 0.001 for diesel-engine exhaust gas and for residual oils. For industrial air it is 0.0004 and about 0.0001 for clean air.

At every point in the exchanger, a certain temperature difference exists, fluid to tube or fluid to fluid. But frequently the only places where these temperature differences may be conveniently measured are at the inlet and the outlet, i.e., the two ends of the unit. Hence it is desirable to have an expression for the log mean temperature difference (lmtd) in terms of the inlet and outlet temperatures.

If the pipe surface temperature and bulk fluid temperature difference is less than 10°F, then:

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n}$$

n = 0.4 for heating (1)

n = 0.3 for cooling

For temperature differences greater than 10°F:

$$Nu = 0.027\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.333}\left(\frac{\mu}{\mu_s}\right)^{0.14} \tag{2}$$

Where μ_s is evaluated at the pipe surface temperature and all other properties at the bulk temperature.

For short tubes, the starting length may have an effect which is accounted for in the following expression:

$$Nu = 0.036\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}\left(\frac{\mu}{\mu_s}\right)^{0.14}\left(\frac{D}{L}\right)^{1/18} \tag{3}$$

For an annulus, replace the tube diameter with the equivalent diameter, or:

$$D_E = \frac{4(AREA)}{WettedPerimeter} = D_o - D_i$$

In the above expressions, the following nomenclature applies:

$Nu = \left(\frac{hD}{k}\right)$ Nusselt Number

$$\Pr = \left(\frac{\mu C_p}{k} \right)$$ Prandtl Number

$$\text{Re} = \left(\frac{VD\rho}{\mu} \right)$$ Reynolds Number

Where k, ρ, μ, and C_p are fluid properties.

Consider a liquid or a gas flowing through a tube in a given direction, say left to right. If another fluid is to flow over the tube, there are obviously three simple choices of the direction of its flow: (1) parallel flow in the same direction as the fluid within the tube. (2) counter flow in the opposite direction to the flow within the tube, and (3) cross flow at right angles across the tube. In parallel flow and counter flow, both fluids progressively change in temperature along the tube. In cross flow, the entire length of the tube is subjected to the same temperature of the fluid outside the tube and this case is therefore similar to that in which a vapor is condensing or a liquid is being evaporated outside the tube.

If the specific heats and the film coefficients of the two fluids are substantially constant, it can be shown by integration that for parallel flow, counter flow, or cross flow the true average temperature difference is the so-called *logarithmic mean* between the two temperature differences ΔT_1 and ΔT_2 measured at the extreme ends of the unit. Calling the larger temperature difference (at one end) ΔT_1 and the lesser temperature difference (at the other end) ΔT_2, the logarithmic mean temperature difference can be expressed as:

$$lmtd = \frac{\Delta T_1 - \Delta T_2}{Ln\left(\Delta T_1 / \Delta T_2 \right)} \tag{5}$$

$$q = UA(lmtd)$$

Most commercial heat exchangers depart from ideal counter flow and they are not parallel flow or cross flow in arrangement; hence the log mtd does not apply directly. Correction factors are available in graphical form for most of the common shell-and-tube arrangements. These factors are multipliers to be applied to the log mtd to give a close approximation to the true L mtd.

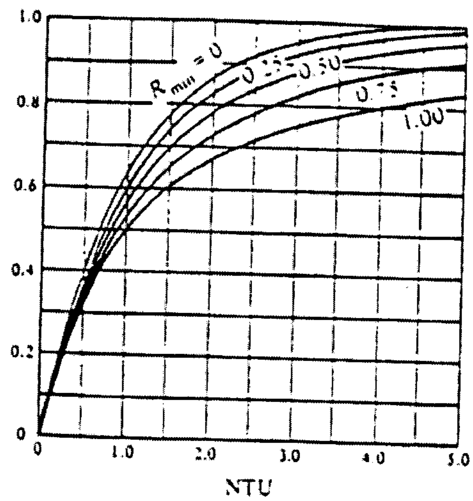
An ideal heat exchanger would be one that raised the temperature of the cold fluid to the entering temperature of the hot fluid (or vice versa), i.e., one that utilized the entire temperature potential ($T_{hi} - T_{ci}$). Although this performance is impossible, because heat flow requires potential difference, it can be approached by a very large counter flow exchanger having a very high heat-transfer coefficient. Heat-exchanger effectiveness e is the measure of the approach to this ideal:

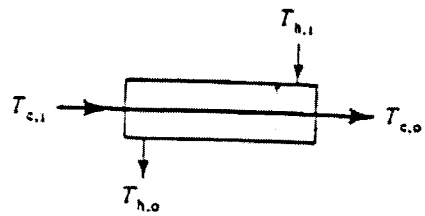
$$e = \frac{C_h(T_{hi} - T_{ho})}{C_{\min}(T_{hi} - T_{ci})} \quad \text{or} \quad e = \frac{C_c(T_{co} - T_{ci})}{C_{\min}(T_{hi} - T_{ci})}; \quad C = \dot{m}C_p$$

In a liquid or gas heat exchanger, the temperature change of each fluid depends, of course, on its heat-storing capacity $\dot{m}C_p$ (mass-rate of flow X specific heat). The fluid of minimum capacity would show the greater temperature change. It is therefore convenient to plot the heat-exchanger effectiveness against the dimensionless ratio of heat-exchange capacity over heat-storage capacity $\frac{AU}{\dot{m}C_p}$, This ratio is usually called the "number of transfer units" (NTU) .

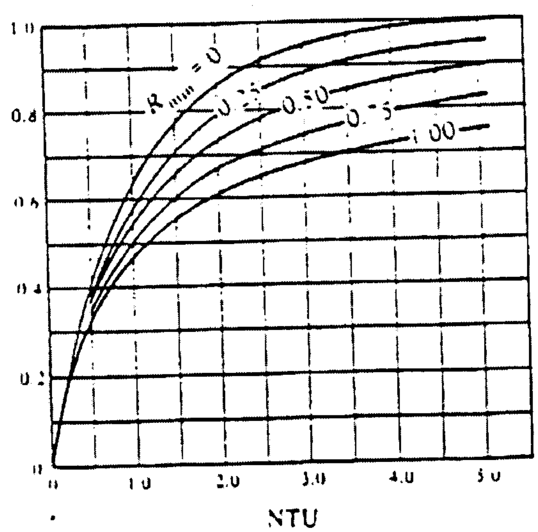
$$NTU = \frac{AU}{\dot{m}C_p}$$

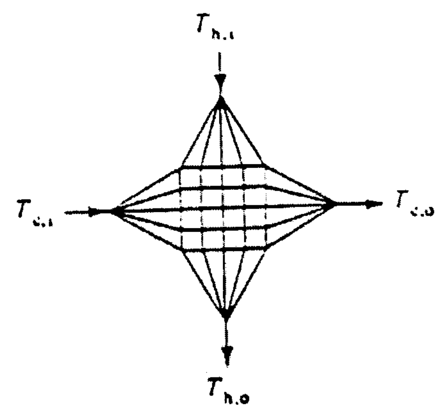
This is a nondimensional index of the heat-transfer capacity of a given exchanger operating under a given condition. Usually the lesser value $\dot{m}C_{p,\min}$ is used, thus resulting in NTU_{max}. The effectiveness is then plotted against NTU_{max}, with a family of curves, one for each value of $\frac{\dot{m}C_{p,\min}}{\dot{m}C_{p,\max}}$, as shown.



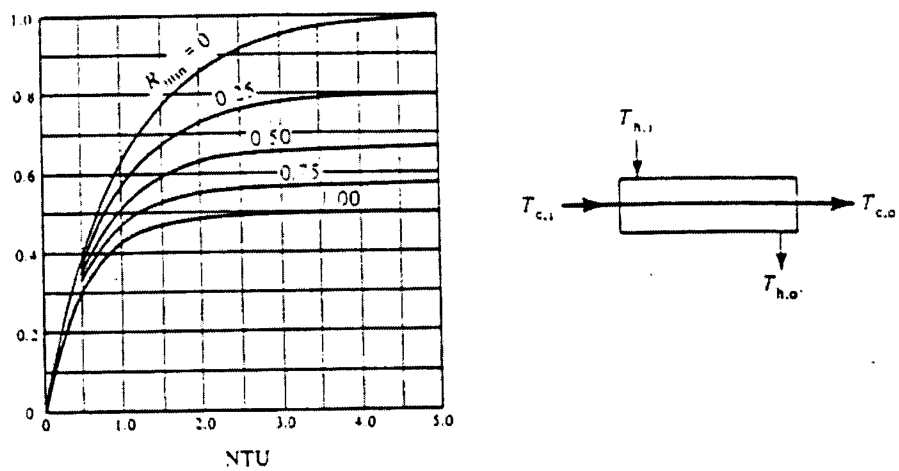


Effectiveness for a counter-flow heat exchanger, from *Compact Heat Exchangers* by Kays, W. M. and A. L. London. Copyright 1964, by McGraw-Hill, Inc.





Effectiveness for cross-flow heat exchanger with both fluids unmixed, from *Compact Heat Exchangers* by Kays, W. M. and A. L. London. Copyright 1964, by McGraw- Hill, Inc.



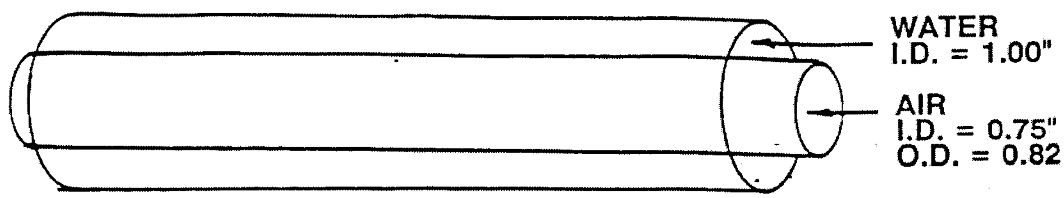
Effectiveness for parallel-flow heat exchanger, from *Compact Heat Exchangers* by Kays, W. M. and A. L. London. Copyright 1964, by McGraw-

When the value $\frac{(mc)_{min}}{(mc)_{max}} = 1$, it describes an exchanger with the same fluid flowing at the same rate in both inside and outside circuits. The value $\frac{(mc)_{min}}{(mc)_{max}} = 0$ approximately describes an exchanger in which one fluid is a vapor being condensed or evaporated at constant pressure, since the temperature of that fluid remains constant, or the specific heat is infinite.

Economic factors usually prescribe the limits in the design and operation of a heat exchanger. Increasing the size and the tube length is expensive. Fluid velocities and pressure losses must be kept within limits because of pumping losses.

APPARATUS

The apparatus to be used is a double-pipe heat exchanger consisting of a straight tube or pipe within a larger straight pipe. A means is provided for accurate measurement of the mixed-fluid temperature at each end of each tube.



Inside Surface Area (Air Tube) = 169.7in^2

Outside Surface Area (Air Tube) = 185.96 in ^{2}

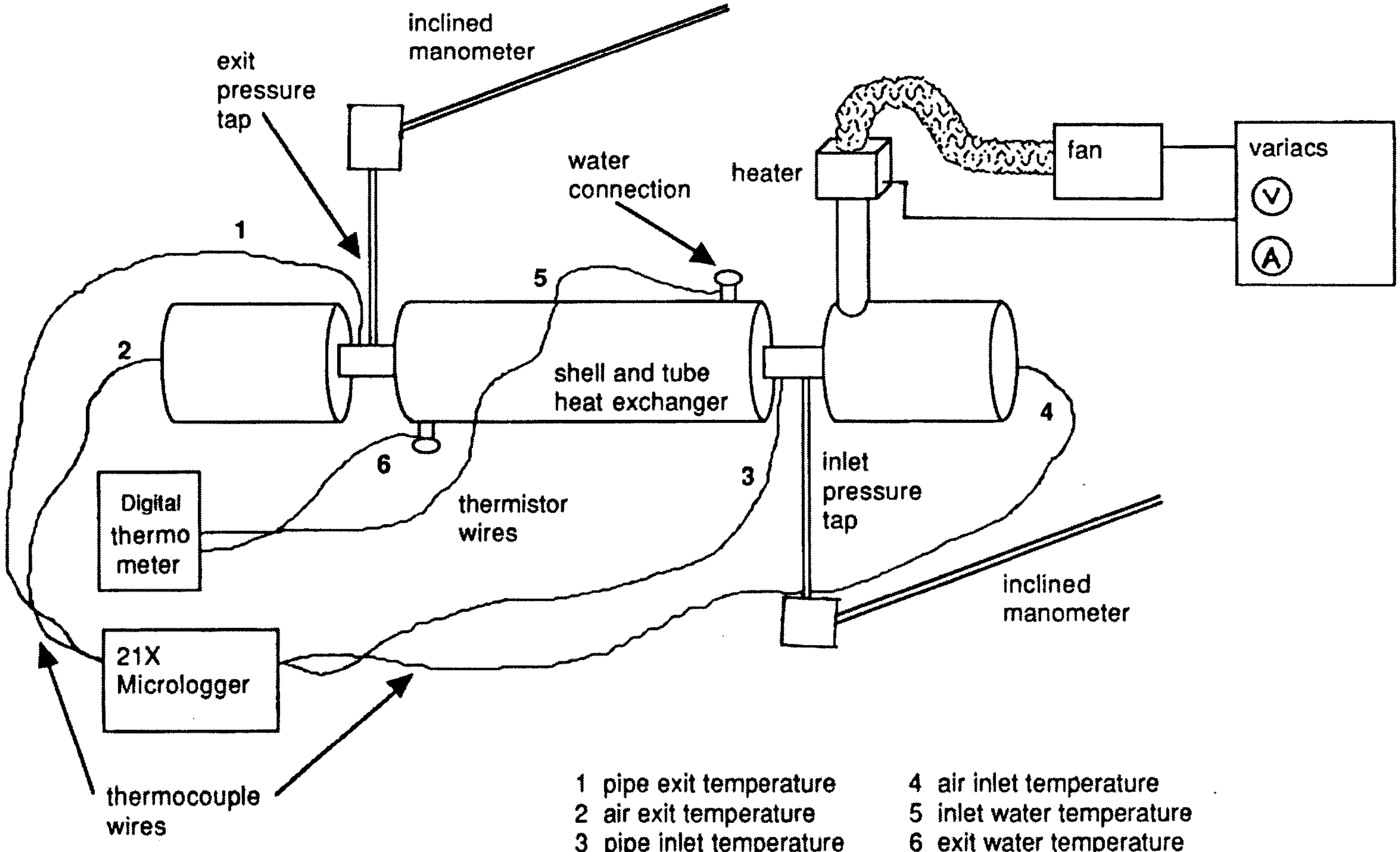
Distance Between Monometer Points = 6.3 Ft

INSTRUCTIONS

Predictions. Performance of the heat exchanger is to be predicted first, then confirmed by test. Estimate the surface coefficients and fouling factors and compute U for conditions prescribed. Predict results for both parallel flow and counter flow. Including heat exchange capacity Btu per hour, exit temperature, and exchanger effectiveness for each set of conditions.

Determinations. Make sufficient test runs to determine the effect of parallel-flow and counter-flow operation on the capacity of the exchanger and the effect of velocity of each fluid on the overall coefficient. The chief requirement for accuracy in these tests is that true equilibrium exists during each entire run. It is advisable to start all readings as soon as a new setting of the conditions has been made and continuing the run until the readings show steady conditions throughout.

EXPERIMENTAL SET-UP



A: AIR
P: PIPE

List of Equipment

--Heat exchanger (copper inner tube)
--Thermocouples for air and tube temperatures
--Thermistors for water temperatures
--Campbell 21X Micro Logger (UA 172724)
--Yellow Springs Scale (MN 42SC)
--Reader heat transfer apparatus (#30838)
--Hot Air Heater: Secomak hot air attachment
--Inclined manometers

Data & Discussion:

Data collected from the experiment may be seen in the following table:

Table 1: Collected Data

Water Mass (lb)	Time (Sec)	Flow Rate (lb/min)	Water Inlet Temp (F)	Water Outlet Temp (F)	Air Inlet Temp (F)	Air Outlet Temp (F)	Pipe Inlet Temp (F)	Pipe Outlet Temp (F)	D Pressure (in)	Title
10	30	20.0	67.9	69.8	139.0	92.9	93.0	74.7	10.00	Counter-flow
5	30	10.0	67.3	70.9	143.8	95.8	96.2	75.5	10.00	
5	30	10.0	67.2	70.2	154.7	95.9	94.8	74.9	4.85	
1.25	17.65	4.2	67.8	73.6	155.5	97.8	98.1	75.7	4.85	
10	28.9	20.8	65.2	66.5	144.0	95.0	94.2	75.9	9.90	Parallel Flow
5	32.6	9.2	66.3	69.0	158.6	98.7	95.6	77.9	5.00	
5	32.6	9.2	65.5	68.8	148.6	98.5	96.6	78.4	9.85	
5	29.57	10.1	67.3	72.0	158.3	100.7	96.6	80.3	4.90	

Calculations & Discussion:

The flow rate of air is solved using the pressure differential and the Darcy-Wiesbach equation:

$$\frac{\Delta P}{\rho g} + \frac{\Delta(v^2)}{2g} + \Delta z + H_L = 0$$

In this equation, ΔP is the pressure difference, $\Delta(v^2)$ is the difference in the squares of velocity, Δz is the height difference, and H_L is frictional head loss, which for straight pipe is a function of velocity:

$$H_L = f\left(\frac{L}{D}\right)\left(\frac{\bar{v}^2}{2g}\right)$$

L is the length of the pipe, D is the diameter, and $\bar{v}$ is the average velocity of the pipe. f is the Fanning friction factor, which is a function of the Reynolds number of the flow and the relative roughness of the pipe's surface.

In order to use these equations to find the velocity of the pipe, we assume that the air flowing through the pipe is incompressible (and for the velocities we expected, this should make sense), meaning that $\Delta(v^2) = 0$. In addition, since the pipe is more-or-less level, we may assume $\Delta z = 0$ as well. We measured absolute pressure head, or $|\Delta P/\rho g|$, meaning that what we measured was exactly equivalent to head loss. Head loss, in turn, may be used to solve for velocity by rearranging the equation for straight-pipe head loss:

$$v = \sqrt{\frac{2H_L Dg}{f}}$$

Since f is itself a complicated function of Re, and consequently v (see the Moody Diagram and the Colebrook Equation), solving for v is an iterative process. A value for v is assumed and is used to solve for f. This f is then used to calculate a new v, which is then used to repeat the process. This is continued until v converges onto a value with reasonably small levels of change over subsequent iterations.

In my Python code, this appears as so:

```
while (vold-v)**2 > 1e-6 * (units.ft/units.s)**2 :
    vold = v
    v = ((2*delp*d*g)/(frictionfactor(vold*d/nu,roughness/d)*length))**0.5
```

The frictionfactor() function uses an approximation of the Colebrook equation known as Serghide's solution when velocities indicate a turbulent regime, which was derived by applying Steffensen's method, a root-finding method, to the Colebrook equation. Otherwise, it uses the $64/Re$ method for laminar flow, and returns an error for transition-range flows.

The volumetric flow rate of the air may be calculated by multiplying the velocity of the air by the pipe cross-sectional area ($^3/_4$ in, according to the apparatus manual).

The water's volumetric flow rate may be found by dividing the mass flow rate of the water (which we found) by water's density. Given a pipe cross-sectional area, a water velocity may also be found. Similarly, a mass flow rate for air may be found by multiplying the volumetric flow rate by air's density. Not all of these calculations were actually executed, since the mass flow rate of air was not required, and the cross-sectional area of the water's section of the heat exchanger was unknown.

The log mean temperature difference may be found as follows:

$$LMTD = \frac{\Delta T_A - \Delta T_B}{\log\left({}^{\Delta T_A}/_{\Delta T_B}\right)}$$

In this case, ΔT_A is the temperature difference at side A of the heat exchanger, and similarly for ΔT_B. Note that these relations are positional, and not dependent

on the hot or cold sides of the flow! This relation works for both parallel flow and counter-flow heat exchangers.
The heat transfer rates may be calculated using $\dot{Q} = \dot{m}C_P\Delta T$ for either fluid, since they should both be the same.

The maximum heat transfer rates are calculated similarly, but with some important differences:

$$\dot{Q}_{max} = (\dot{m}C_P)_{min}(T_{h,in} - T_{c,in})$$

First, the temperature difference used is the temperature difference between the incoming streams, and not the temperature change along either stream. Second, $\dot{m}C_P$ is minimized. This means that $\dot{m}C_P$ is found for both streams (air in water in our case), and the smallest value is used. Physically, this means that in the best case, the temperature of the stream with the smallest $\dot{m}C_P$will change from its incoming flow temperature to the incoming flow of the other fluid as it flows through the exchanger.

The heat transfer coefficients are used in the following relation:

$$\dot{Q} = UA\,(LMTD)$$

Where U is the heat transfer coefficient and A is the surface area through which heat is being transferred. Because A is slightly different on the air side vs. the water side, U will also be different depending on which surface area is referenced. U may be solved for by finding $\dot{Q}$ by the previously-discussed method, the $LMTD$ found as before, and the cross-sectional areas found in the apparatus manual. U_{max} may also be found similarly, though it requires using $\dot{Q}_{max}$and finding $LMTD_{max}$ using the temperatures which would be seen in the best case. The theoretical maximum LMTD was not calculated, and hence, neither was U_{max}.

Finally, the effectiveness of the heat exchanger may be found simply by using the following equation:

$$E = \frac{\dot{Q}}{\dot{Q}_{max}}$$

The values calculated by the author are in tables 3 and 4. Constants used are in table 2 and were found either in the apparatus manual, Cengel or White.

Table 2: Constants used in calculations

Item	Value
Specific gravity of manometer fluid	0.985
Air pipe inner diameter	0.75 in
Density of water	1.0 kg/L
Cp of water	4.184 kJ/kg/C
Cp * density of air	0.001297 J/mL/C
Inside surface area	169.668 sq.in
Outside surface area	185.9561 sq.in
Kinematic viscosity of air	0.00022 sft/s
Roughness of copper pipe	0.00006 in
Pipe length	6.302 ft

Table 3: Air and water flow rates, LMTD and calculated heat transfers

Trial #	Air velocity (ft/s)	Air flow rate (cft/s)	Water flow rate (cft/s)	LMTD (F)	Qdot, air (W)	Qdot, water (W)
1	2.82	0.0087	0.0053	43.4	8.14	668
2	2.82	0.0087	0.0027	47.3	8.48	633
3	1.80	0.0055	0.0027	51.7	6.64	527
4	1.80	0.0055	0.0011	51.7	6.52	433
5	2.80	0.0086	0.0055	49.9	8.60	474
6	1.84	0.0056	0.0025	56.2	6.90	437
7	2.80	0.0086	0.0025	53.0	8.77	534
8	1.82	0.0056	0.0027	55.7	6.55	838

Table 4: Heat transfer coefficients, ideal heat transfer and effectiveness using air's calculated heat transfer rate

Trial #	Qdot, air (W)	U inside (W/m^2/F)	U outside (W/m^2/F)	Qdot, ideal (W)	Effectiveness (%)
1	8.14	1.71	1.56	12.56	65
2	8.48	1.64	1.49	13.51	63
3	6.64	1.17	1.07	9.89	67
4	6.52	1.15	1.05	9.91	66
5	8.60	1.57	1.44	13.83	62
6	6.90	1.12	1.02	10.63	65
7	8.77	1.51	1.38	14.54	60
8	6.55	1.07	0.98	10.35	63

Conclusions & Comments:

The calculated heat transfers for air and water, clearly, did not agree. In fact, the calculated values are of different orders of magnitude. The methods used for checking the values were double-checked, and results from other students were similar in magnitude. While the heat transfer coefficients, ideal heat transfer rate and effectiveness were all calculated with air's calculated heat transfer rate in mind (in order to give effectiveness a reasonable value), they should not be trusted since clearly something else was happening in the apparatus. One suggestion is that the pipes themselves were conducting heat from the air heater directly; whether this suggestion has merit or not is debatable. It is also possible that some of the instruments were malfunctioning, or that flow rate calculations were faulty.

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Heat Transfer Apparatus

Installation and Operating Instructions

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NOTTINGHAM
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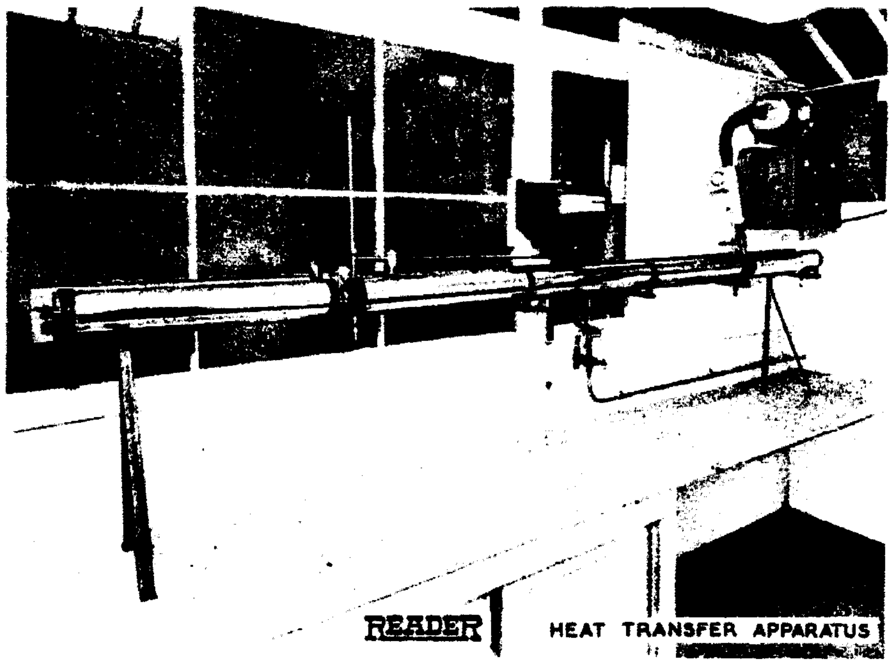
NOTTINGHAM 82194

TELEGRAMS:
READERS NOTTINGHAM

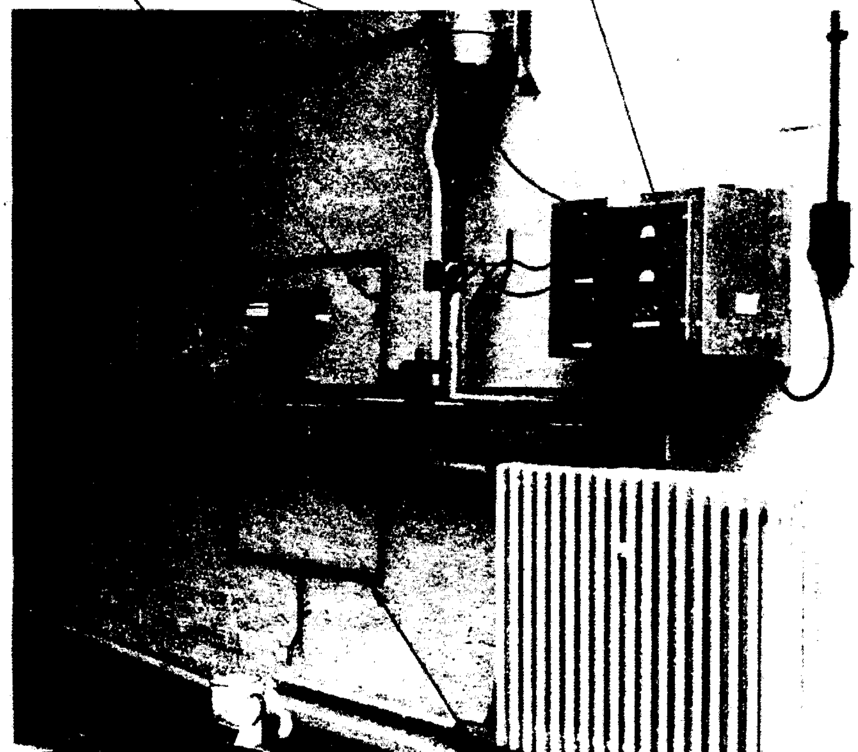
READER



APPARATUS CAN BE ARRANGED FOR

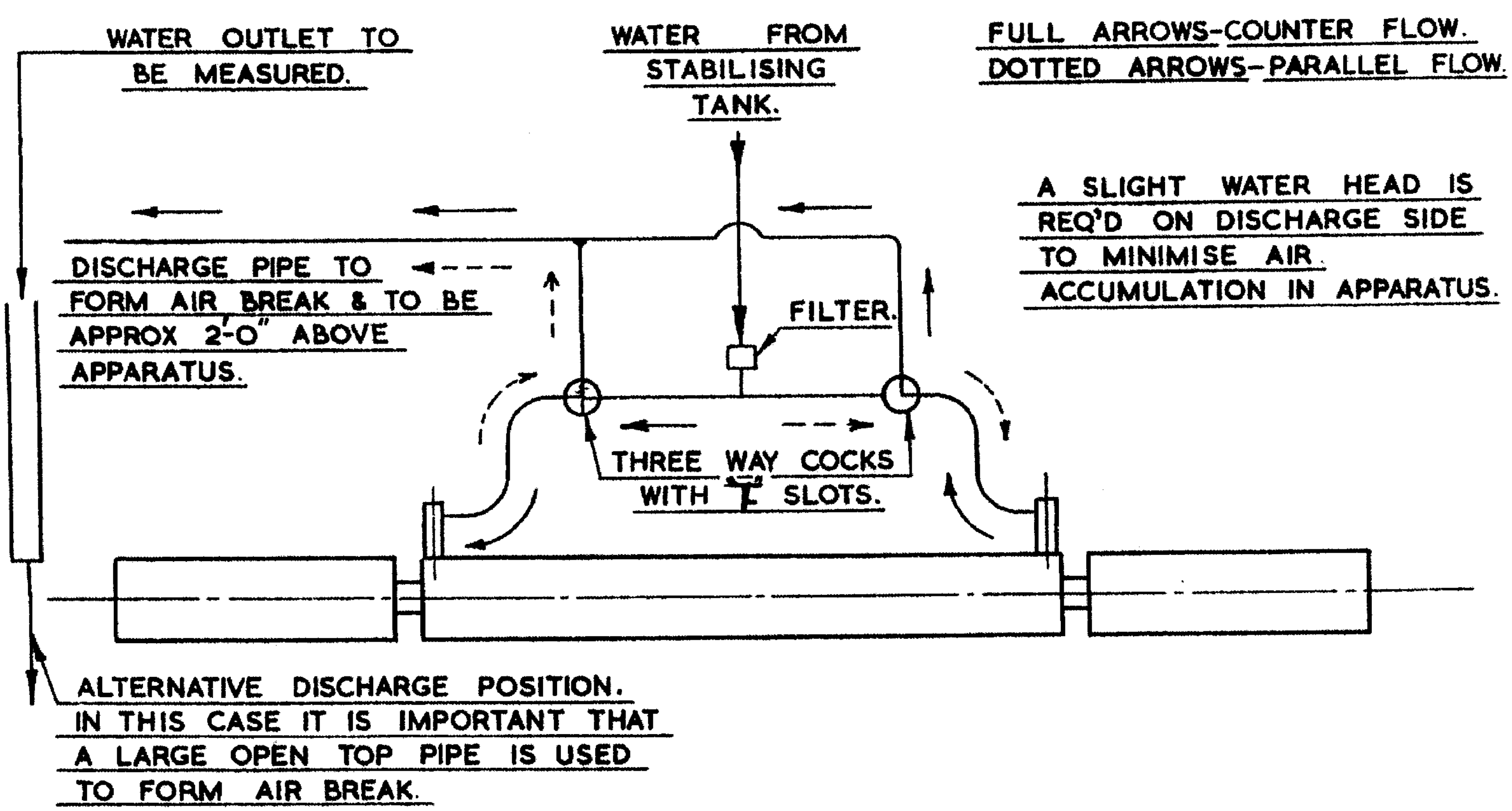
WALL OR BENCH MOUNTING

READER



TYPICAL INSTALLATION OF

H.T.A.



SUGGESTED DIAGRAMMATIC ARRANGEMENT OF WATER PIPES FOR ADVANCED HEAT TRANSFER APPARATUS.

Notes on Installation and Operation etc., for

Standard Heat Transfer Apparatus and

Advanced Heat Transfer Apparatus

---

1) When installing this apparatus it is important that the tubes and blowers be horizontal, as illustrated on drawing No .82-52 and 82-100.

2) The water flow should be checked and the apparatus inspected for possible leaks, at the same time it is essential that the water supply be steady, i.e., no momentary changes in water pressure. Further, ensure that the water head is sufficient for the apparatus to pass a maximum of approximately 200 g.p.h., for the Standard Heat Transfer Apparatus; alternatively 300 g.p.h. for the Advanced Heat Transfer Apparatus. For installation of water pipes see Item 9.

3) When testing the Electric Control Panel it is advisable to check for earth leaks and also to ensure it is correctly phased out, i.e., the line supply is on the Contactor Terminal marked 'L1' (RED) and the Neutral is on 'L3' (BLACK) .

4) The Thermocouples are calibrated at our Works and the total resistance of each Thermocouple lead with balance coil is 40 ohms (excluding the instrument). For the Standard Unit Copper/Constantan Thermocouples are incorporated and in the Advanced model Nickel Chromium/Nickel Aluminum Thermocouples are used. For the Standard Unit the Copper lead (Positive) is to be fixed to the back connection on the instrument and the Constantan lead (Negative) connected to the balance coil and thence to the front connection of the instrument. The Advanced Heat Transfer Apparatus where Nickel Chromium/Nickel Aluminum Thermocouples are used, the Nickel Chromium (Positive) should be connected to the Positive Terminal and the Nickel Aluminum connected to the Negative Terminal. A complete

diagram of Thermocouple Connections for the Advanced Unit is shown on drawing No.82/130A.

Copper/Constantan Temperature/EMF characteristics are shown on Pages Nos: 9 and 10.

Nickel Chromium/Nickel Aluminum Temperature/EMF characteristics are shown on Pages Nos: 11 and 12.

The instruments are normally supplied with the apparatus and employ double pole switching.

Special Note: Under no circumstances must a 'Megger' be used on the instrument.

5) The Manometers are calibrated to read directly inches of water using DI-BUTYL OXALATE as a filling medium. This liquid has been chosen for its stability as regards evaporation and possible discolouration; also for its ability to wet the glass tube and give a good meniscus; further, it is non-corrosive on metal contact. The specific gravity of the fluid is 0.985. One manometer is connected across the Manometer points on the apparatus, to record the pressure drop across the test length. The other is connected to the Manometer point at the inlet of the test length and is required to measure the air pressure at this point above atmosphere. The necessary Tee connection and rubber tubing are not supplied with the apparatus.

6) The Mercury-in-Glass Thermometers supplied are calibrated for the designed immersion and it is important that suitable Thermometers are fitted at the various points, as if Thermometers having a different immersion are fitted, this will give incorrect temperature readings.

7) Run the apparatus and check that there are no air leaks. This should be done with the blower working at full speed and the heater 'Variac' in the zero position, i.e., no heat being imparted to the air.

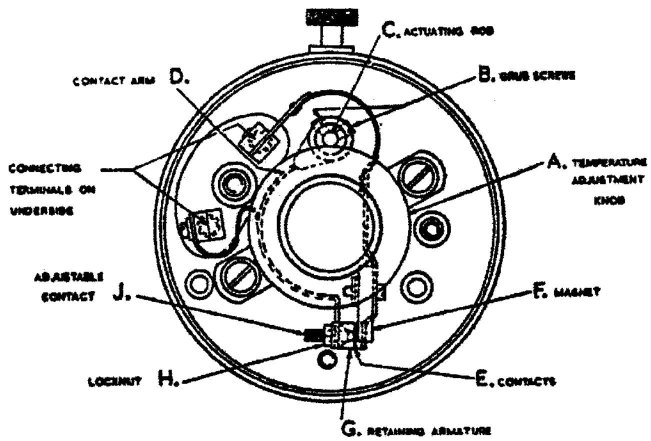
Note: The heat must not be switched on until water is flowing.

8) With the blower running at full speed, gradually increase the heat input (note the Voltmeter and Ammeter in the Panel only record the heating load) and check that the Thermocouples and Thermometers are working correctly; also that the Thermostat (if fitted) is cutting out at about 550°F. For instructions regarding the setting of the Thermostat see page No: 8.

9) The apparatus is arranged for using water as a coolant. Further, the water should be supplied from a stabilization tank at a suitable head. The water supply pipes must feed the water into the connection adjacent to the end thermometer. Further, the water must be carried away from the connection provided adjacent to the other end thermometer (as shown on drawing No.82-52 or 82-100) in order that it may be measured. Small drain cocks are provided at each end of the apparatus (on the underside) and these are for draining the apparatus when not in use. However, these cocks must be kept closed when the apparatus is in operation. In order that parallel and counter flow tests may be taken, rubber supply pipes may be used to facilitate ease of reversing the flow, as in photograph on Page 1. Alternatively, a pipe arrangement complete with wheel valves as shown in the photograph on Page. 2 may be fitted, in which case, it is advisable to incorporate a small length of rubber or similar material pipe between this pipe assembly and the apparatus in order to prevent conduction between the supply and drain pipes and the apparatus. In view of the variety of pipe arrangements necessary to suit the various laboratory lay-outs, we do not supply any water pipes or wheel valves to control the water flow.

10) After all the above have been carried out, the apparatus should be started with the blower at approximately full speed; the heater at its desired output, also water flowing. After a suitable length of time has elapsed to allow the Unit to settle, tests should commence. Typical test results of a Standard Unit are shown on Page No.13.

11) After the tests have been completed, the heater 'Variac' should be turned to the zero position and the blower run for a minutes to remove heat from the tubes; with this completed, the electrical supply should be switched off at the mains and the water supply turned off; drain cocks should be opened and the apparatus emptied of water.



INSTRUCTIONS FOR SETTING THERMOSTAT

This adjustable thermostat is scaled in arbitrary units and is supplied set, with normally closed contacts. The design of the bimetals is such that normally closed contacts tend to open when heated.

TO SET THE THERMOSTAT:

Set the pointer on the temperature adjustment knob 'A' to the centre of the scale and then remove the cover. Knob 'A' has been accurately set on its spindle and its position must not be altered. Loosen the two grub screws 'B' at the end of the actuating rod ‘C’. The contact arm 'D' can now be moved freely.

Insert the thermostat into the apparatus and raise the air heat to the required cut-out temperature. Move the contact arm 'D' until the two contacts 'E' meet, raise the contact arm 'D' on its spindle 'G' so as to leave a clearance of approximately 1/32 ins. between the arm and the bush on the thermostat base, and then tighten the grub screws 'B' to lock the arm in the required position. Replace the cover.

TEMPERATURE - MILLIVOLT EQUIVALENTS

COPPER V. CONSTANTAN.

DEGREES FAHRENHEIT — COLD JUNCTION 32°F

°C	0	10	20	30	40	50	60	70	80	90	100
					Millivolts						
300	-5.29	-5.378	-5.48	-5.54							
200	-4.10	-4.26	-4.376	-4.51	-4.66	-4.76	-4.89	-4.99	-5.10	-5.20	-5.29
100	-2.55	-2.74	-2.89	-3.063	-3.23	-3.37	-3.53	-3.68	-3.83	-3.96	-4.10
-0	-0.67	-0.88	-1.10	-1.28	-1.466	-1.68	-1.88	-2.06	-2.22	-2.40	-2.55
+0	-0.67	-0.46	-0.265	-0.02	+0.19	0.387	0.62	0.84	1.04	1.26	1.50
100	+1.50	1.73	2.00	2.22	2.467	2.70	2.95	3.21	3.47	3.72	3.96
200	3.96	4.20	4.47	4.747	5.02	5.28	5.56	5.84	6.11	6.39	6.67
300	6.67	6.94	7.205	7.50	7.79	8.06	8.36	8.64	8.93	9.20	9.53
400	9.53	9.82	10.12	10.45	10.74	11.05	11.35	11.68	11.98	12.28	12.571
500	12.571	12.91	13.22	13.54	13.85	14.15	14.48	14.80	15.10	15.443	15.77
600	15.77	16.10	16.45	16.75	17.10	17.45	17.75	18.10	18.478	18.78	19.10
700	19.10	19.46	19.78	20.10	20.46	20.78					

In accordance with British Standard Code No.1827 : 1952

5.B.

TEMPERATURE - MILLIVOLT EQUIVALENTS

COPPER V. CONSTANTAN.

DEGREES CENTIGRADE COLD JUNCTION 0°C

°C	0	10	20	30	40	50	60	70	80	90	100
						Millivolts					
-200	-5.539										
-100	-3.349	-3.623	-3.886	-4.137	-4.376	-4.602	-4.815	-5.016	-5.204	-5.378	
-0		-0.381	-0.752	-1.114	-1.466	-1.807	-2.137	-2.456	-2.765	-3.063	
+0		+0.387	0.787	1.194	1.610	2.034	2.467	2.908	3.356	3.812	
100	4.276	4.747	5.225	5.710	6.202	6.700	7.205	7.716	8.233	8.756	
200	9.285	9.820	10.360	10.905	11.455	12.010	12.571	13.136	13.706	14.280	
300	14.859	15.443	16.030	16.621	17.216	17.815	18.418	19.025	19.635	20.248	
400	20.865										

In accordance with British Standard Code No.1827 : 1952

[NOTE: PAGES 11 AND 12 ARE MISSING FROM THE ORIGINAL MANUAL]

TYPICAL TEST RESULTS ON H.T.A. UNIT.

PARALLEL AND COUNTER FLOW.

SURFACE AREA OF TEST TUBE 169·668 IN² INSIDE.

SURFACE AREA OF TEST TUBE 185·9561 IN² OUTSIDE.

AIR TUBE ¾" BORE. 0·822" OUTSIDE DIAMETER. WATER TUBE 1" BORE.

DISTANCE BETWEEN MANOMETER POINTS (AIR) 6·302 FT.

EQUIVALENT DIAMETER OF WATER ANNULUS = 4 TIMES HYDRAULIC MEAN DEPTH = $(D_1 - d_1)$ = 0·1778".

FIGURES TAKEN DURING TEST.

AIR TEMP. AT INLET OF TEST LENGTH °F.		412	418	435	175	430	447	437	500	358
AIR TEMP. AT OUTLET OF TEST LENGTH °F.		148	148	153	93	188	176	158	152	128
WATER TEMP. AT INLET OF TEST LENGTH °F.		58·8	57	57·9	64·3	56·8	56·8	56·5	56·5	61·8
WATER TEMP. AT OUTLET OF TEST LENGTH °F.		54·7	54·6	55·1	58·8	95·6	87·6	79·6	75·4	89·0
TUBE TEMP. AT INLET OF TEST LENGTH °F.		154	156	162	100	193	180	162	160	122
TUBE TEMP. AT OUTLET OF TEST LENGTH °F.		70	70	75	68	116	103	93·0	88·0	97·0
WATER GAUGE READING OVER TEST LENGTH. INS.		1·87	1·88	1·8	1·98	2·98	1·27	0·58	0·13	—
TIME TAKEN TO PASS ONE GALLON OF WATER.		31·9 SECS	20·1 SECS	23·4 SECS	2MINS 47·6 S.	4MINS 53SECS	4MINS 56·7 S.	4MINS 57 S.	4MINS 54·2 S.	17MINS 24SECS
WATER GAUGE READING AT INLET TO TEST LENGTH TO ATM. INS. (PRESS)		5·9	6·1	6·0	4·9	9·7	4·7	2·4	1·1	0·6
VOLTS (HEATER)		235	235	232	110	248	216	185	185	110
AMPS (HEATER)		8·5	8·5	8·5	4·0	9·2	7·8	6·3	6·3	4·0
ATMOSPHERIC TEMP. °F		68	69	79	75	75	75	75	75	75

FIGURES CALCULATED FROM TEST DATA.

GALLONS OF WATER PER. HOUR.		113	179	153·5	21·5	12·3	12·13	12·12	12·22	3·52
HEAT ABSORBED BY WATER BTU./HOUR.		4640	4300	4300	1180	4770	3740	2800	2310	957
LOG. MEAN TEMP. DIFFERENCE AIR TO WATER °F.		198	198	207	65·2	201·2	203	191	209	126·5
LOG. MEAN TEMP. DIFFERENCE AIR TO TUBE °F.		151	152	155·5	45·6	138·5	150	145·5	165·5	101
LOG. MEAN TEMP. DIFFERENCE WATER TO TUBE °F.		43·7	45	51	19·2	61·3	52·0	44·6	43·2	25·8
COEFF. OF HEAT TRANSFER AIR TO WATER BTU/FT²/°F/HR.		18·1	16·8	16·1	14·05	18·3	14·25	11·35	8·58	5·86
COEFF. OF HEAT TRANSFER AIR TO TUBE. BTU/FT²/°F/HR		26	24	23·4	21·9	29·2	21·2	16·4	11·8	8·03
COEFF. OF HEAT TRANSFER WATER TO TUBE BTU/FT²/°F/HR.		82·2	74·2	65·4	47·7	60·4	55·7	48·6	41·4	28·7
AVERAGE WATER TEMP. °F.		56·75	55·8	56·5	61·5	76·2	72·2	68·0	66·0	75·4
COEFF. VISCOSITY WATER (TECH. UNITS. 10^{-6}) TAKEN FROM TABLES.		24·5	25·5	25	23·5	18·8	20·0	21·7	22·0	19·0
WATER VELOCITY FT/SEC.		2·64	4·5	3·85	·539	·325	·320	·320	·323	·0884
REYNOLDS No. WATER.		33 20	5050	4430	656	494·5	457·5	422	420	133
AVERAGE AIR TEMP. AIR °F.		280	283	294	134	309	311·5	297·5	326	243
COEFF. VISCOSITY AIR. (TECH. UNITS 10^{-6}) TAKEN FROM TABLES.		·532	·534	·544	·432	·555	·556	·545	·565	·5075
AIR VELOCITY FT/SEC.		121	110	105·5	79·5	140·5	100·4	71·5	49·4	27·39
REYNOLDS No. AIR.		24400	21800	20400	24200	25830	18160	13450	8610	5930
$C_p(T_2 - T_1)$. AIR.		63·5	65	67·8	19·7	58·3	65·2	67·2	83·8	55·4
LBS. OF AIR PER HOUR.		73·2	66·2	63·4	60	81·7	57·4	41·7	27·6	17·25
		← COUNTER FLOW			→	← PARALLEL FLOW				→

NOTES. LAGGING LOSS VERY SMALL AND VELOCITY ENERGY NEGLIGIBLE, THEREFORE WEIGHT OF AIR IS OBTAINED FROM THE EQUATION HEAT GAINED = HEAT LOST.

THE VARIATION OF SPECIFIC HEAT IS TAKEN INTO ACCOUNT.

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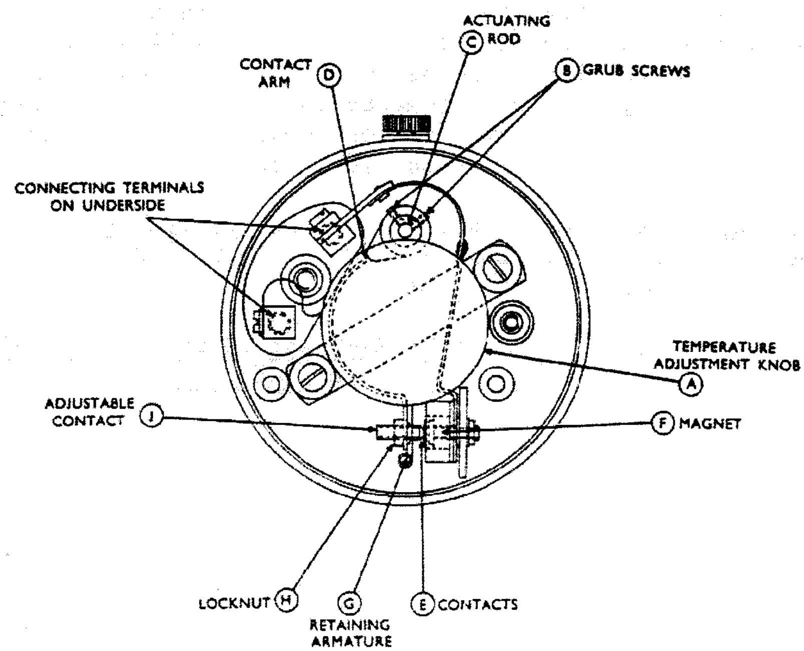
1 – Heat Transfer Apparatus comprising: –

1 – Tube Unit
1 – Cleaning rod
1 – Control panel
1 – Thermocouple indicator
1 – Heater and 1 – Thermostat
1 – Blower and 1 – Connecting hose
2 – Thermometers 50° – 70°F
1 – Thermometer 0° – 100°F
2 – Thermometers Magnifiers
1 – Thermometer 30° – 212°F
2 – Bench supports
1 – 8 pint measuring vessel
1 – 0 – 6" Manometer
1 – 0 – 12" Manometer
2 – Bottles of Di-Butyl Oxalate

Gross weight	7 cwts
Nett weight	5 cwts 1 qr
Measurements	8'0" x 2'8" x 3'6"

INSTALLATION INSTRUCTIONS FOR ADJUSTABLE BIMETAL THERMOSTATS TYPES TS1, TS2, TS3 and TS7.

These adjustable thermostats are scaled in arbitrary units and are supplied unset, and with normally open or normally closed contacts.. The design of the bimetals is such that normally closed contacts tend to open when heated, and normally open contacts to close.



Set the Thermostat

Set the pointer on the temperature adjustment knob A to the centre of the scale and then remove the cover. Then remove the plate fixed between the contacts, which protects them from transit shocks. Knob A has been accurately set on its spindle and its position must NOT be altered. Loosen the two grub screws B at the end of the actuating rod C. The contact arm D can now be moved freely.

Insert the thermostat into the oven or other operating media and raise it to the required central temperature. Move the contact arm D until the two contacts E meet, raise the contact arm D on its spindle C, so as to leave a clearance of approximately 1/32" between the arm and the bush on the thermostat base, and then tighten the grub screws B to lock the arm in the required position. Replace the cover.

Differential

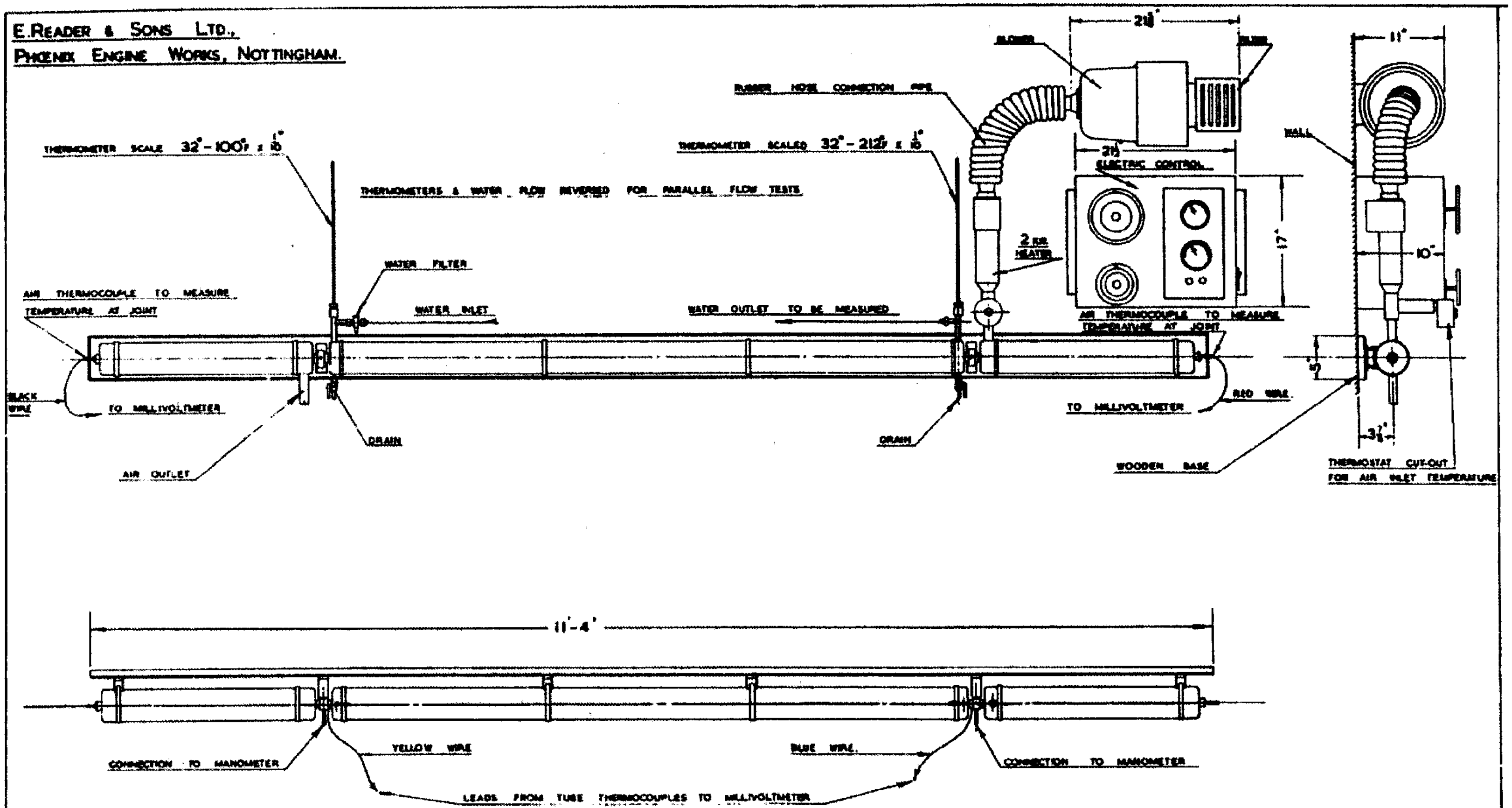
The differential of the thermostat is determined by the distance between the magnet F and the retaining armature G. This can be adjusted by slackening the locknut H on the adjustable contact J, screwing in to reduce the differential and unscrewing to increase it. The locknut H must be tightened after making the setting.

When the adjustable contact J is screwed in to widen the gap, the magnetic snap-action and the contact pressure will be weakened. Since the current-carrying capacity depends on the snap-action it is important to lower the current as snap-action is reduced for small differentials. If carried too far, the contact pressure will be reduced to zero, causing undue sparking on the contacts and indeterminate operation.

Turning the knob on either side of the central position will now give adjustment of ±20°C for TS.1, : ±60°C for TS.2, ±20°C for type TS.3, and ±7°C for type TS 7.

IT IS EXTREMELY DANGEROUS TO MAKE ANY INTERNAL ADJUSTMENT TO THIS INSTRUMENT WHEN THE MAINS SUPPLY IS SWITCHED ON.

Associated Electrical Industries Limited
Instrumentation Division. Domestic and Industrial Components Dept.
P.O. BOX ONE HARLOW. ESSEX .Phone Harlow 26761 Grams Sunvic Harlow Essex



Arrangement of Heat Transfer Apparatus for Wall Mounting
with Thermostat Cut-Out.

DRG. No. 82-52

3 Dr. Kim's (Revised) Expectations for Analysis and Discussion for the Heat Exchanger Performance

In addition to using the Moody Chart (or, as I personally recommended, using an approximate solution to the Colebrook Equations, such as the *Serghides' Solution*), Dr. Kim also wanted his students to use the *Dittus-Boelter correlations* in order to eventually calculate the *effectiveness* (ϵ), $U_{\text{experimental}}$ and $U_{\text{theoretical}}$. Then, discuss the effects of flow rate and temperatures on ϵ and the differences in U-values.

Serghides' Solution and the Dittus-Boelter correlations may be found on Wikipedia. Both may be easily programmed in MATLAB or a similar scripting language.

Laser Doppler Velocimetry

ME 415 - THERMAL SYSTEMS LABORATORY

D.K. DAS

EXPERIMENT Fluid Flow Measurement Using Laser Doppler Velocimeter (LDV).

INTRODUCTION

The theory behind LDV and experimental set-up with schematic diagram (see Figure 3) plus a complete list of equipment (see Table 1) are explained in the article starting on the third page. It also includes the method of data processing for this experiment.

SCOPE OF THIS LAB

Velocity of a Wire: First you will measure the velocity of a wire which is attached to a disk. This disk is rotated by a small motor. During a revolution of the disk, the wire cuts through the measuring volume formed at the intersection of laser beams as shown in Figure 3. The receiving optics with the photomultiplier system need not be exactly behind the transmitting optics as shown in Figure 2. It can be arranged at an angle to the transmitting beam, but it must be focused precisely on the measurement volume by means of the alignment eyepiece. For the wire velocity, you can see good quality Doppler burst in oscilloscope, as shown in Figure 7 because it will be similar to a single particle passing through the ellipsoidal measuring volume.

Velocity of Air: After becoming familiar with measuring the velocity of wire, the next step will be air velocity. Measure air velocities at various sections of a small transparent test tunnel by keeping the laser setup stationary while moving the 10 cm X 10 cm plexiglass test section. Compare the velocity with that obtained using the Kurz anemometer probe to confirm that your LDV system gives similar values. Move the Kurz probe up and down to get a velocity profile at a cross section. Prepare plots of velocity profiles obtained by the LDV and by the Kurz hot wire aneomometer. A computer output of velocity obtained from the software for data collection is shown below.

2 inches from top of tunnel

Cycles	Mantissa	Exponent	Frequency	Velocity
32	2763	7	361925.5	9.178812
32	2334	7	428449.1	10.86592
32	2815	7	355239.8	9.009258
32	3478	8	143760.8	3.645926
32	2631	7	380083.6	9.639322
32	2959	7	337952	8.570821
32	2965	7	337268.1	8.553476
32	2965	7	337268.1	8.553476
32	2892	7	345781.5	8.769382
32	2785	7	359066.5	9.106303
32	2456	7	407166.1	10.32616
32	2456	7	407166.1	10.32616
32	3804	7	262881.2	6.666945
32	2173	7	460193.3	11.67099
32	3689	7	271076.2	6.874779
32	2275	7	439560.5	11.14772
32	3800	6	526315.8	13.34792
32	2491	7	401445.2	10.18107
32	3774	7	264970.9	6.719941
32	2513	8	198965.4	5.045973
8.910019	99.43045	2.287615	25.67464	0
3.645926	13.34792	0	0	0
1	3.645926	4.616126	0	0
2	4.616126	5.586326	1	0
3	5.586326	6.556525	0	0
4	6.556525	7.526726	3	0

MEAN VELOCITY

$\overline{V} = 8.9$

STD. DEVIATION

$\sigma = 2.3$

An Experimental Study of Flow Measurements using a Laser Doppler Velocimeter

Dr. Debendra K. Das*

The Laser Doppler velocimeter system has emerged as a very attractive flow measurement technique during the last decade. This paper describes the theory and operation of a single component Laser Doppler velocimeter. A complete list of equipment, their total cost, and an experimental set up has been explained in detail. Functions of each component have been discussed. This information may be useful to experimenters contemplating the use of laser velocimeters in a number of fluid dynamic experiments.

1. INTRODUCTION

Fluid flow measurements influence the design of many products that we encounter every day. Some common examples are automobiles, airplanes and ships, whose designs are highly dependent on the fluid flow patterns around them. In industry, extensive use of flow measurement techniques assist in understanding and improving the performance of turbomachinery, engine combustion chambers, jets, hydrofoils, helicopter rotors and magneto-hydrodynamic channels. Even in blood flow experiments in transparent tubes, flow visualization technique is playing a major role. Today, the Laser Doppler velocimeter (LDV) finds application in all of these areas helping to improve designs by measuring in minute detail, the flow fields, something that was not possible before.

The concept of using laser light to measure fluid velocity originated with Yeh and Cummins (1964). With continued research commercial equipment was available by 1974 that made the Doppler technique accessible to interested industries and research laboratories. The most distinguishing feature of LDV is that it is a non-invasive velocity measurement technique (i.e., nothing is protruding into the flow field, unlike hot-wire or hot-film probes that can alter the flow field). The velocity is inferred by instruments from the scattering of laser light by particles moving with the flow. Velocity is proportional to the Doppler shift in the frequency of scattered light that is measured by a photodetector. By carefully processing and filtering the photodetector output in a signal processor, the desired velocity component can be obtained directly. LDV can measure flow velocities in a very broad range of 10 μm/s to 1 km/s (Adrian, 1983).

2.0 THEORY OF LDV

The laser beam provides a monochromatic (single wave length) light. The LDV system employed in our experimental set up has a Helium-Neon laser (Fig. 1). The wavelength λ of this laser light is 632.8×10^{-9}m and the beam is red in color. Monochromaticity makes the laser excellent for light scattering experiments. The laser light is well collimated and spreads little; so this phenomenon yields good directionality and makes the laser an ideal tool for alignment. Lasers concentrate large amounts of light energy into a very narrow beam, so in all experiments it produces a good signal even though there is the presence of unavoidable noise. All waves of a laser light have the same phase, amplitude and direction as they exit the laser. This is called spatial coherence and this property is especially valuable for interferometry experiments. A highly focused, coherent monochromatic light is supplied by the laser

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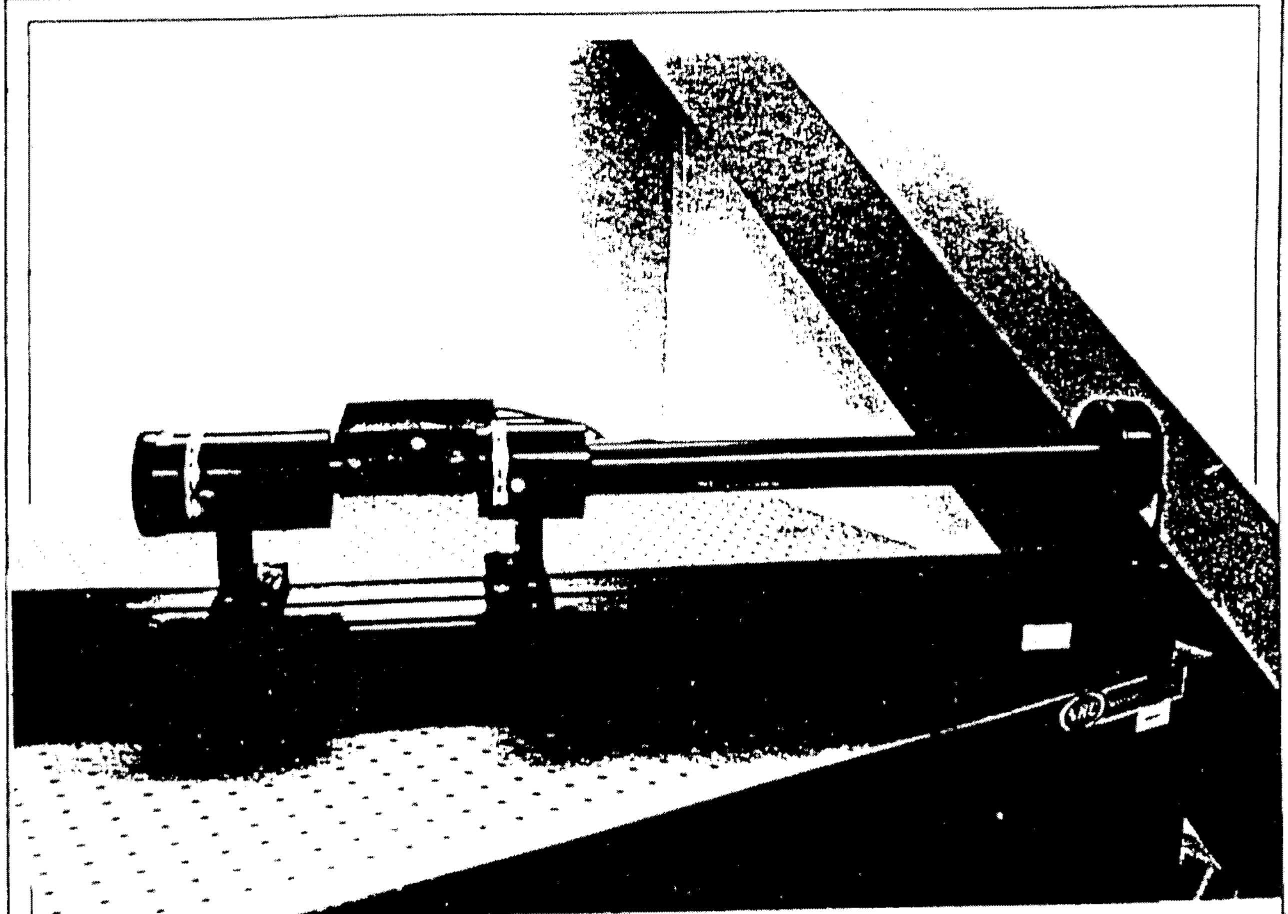

Figure 1 A 20 mW Helium-Neon laser and the transmitting optics mounted on the same base. The laser exciter is in the back.

which passes through the test section. When this light is scattered from a moving particle in the flow, a stationary observer can detect a change, or Doppler shift, in the frequency of the scattered light. The frequency shift υ_{Di} is proportional to the velocity of the particle. Extensive descriptions of LDV theory and practice are given in Durrani and Greated (1977) and Durst *et al.* (1981).

We have employed the popular dual-beam mode of laser Doppler anemometry whose complete assembly is displayed in Figure 2. The basic theory behind the dual-beam LDV following Adrian (1983) is to illuminate a scattering particle with two plane light waves, E_{01} and E_{02} propagating in two different directions, $\hat{s}_1$ and $\hat{s}_2$, respectively. The *i*th particle scatters two waves, E_{1i} from E_{01} and E_{2i} from E_{02}, and the frequencies of these waves in the scattering direction $\hat{r}$ are

$$\upsilon_{1i} = \upsilon_{01} + \frac{\mathbf{v}_i \cdot (\hat{r} - \hat{s}_1)}{\lambda} \text{ and } \upsilon_{2i} = \upsilon_{02} + \frac{\mathbf{v}_i \cdot (\hat{r} - \hat{s}_2)}{\lambda} \quad (1)$$

The frequency difference is

$$\upsilon_{1i} - \upsilon_{2i} = \upsilon_s + \upsilon_{Di} \text{ where } \upsilon_s = \upsilon_{01} - \upsilon_{02} \quad (2)$$

is a constant frequency difference determined by the illuminating-beam frequencies, and

$$\upsilon_{Di} = \frac{\mathbf{v}_i \cdot (\hat{s}_2 - \hat{s}_1)}{\lambda} \quad (3)$$

is the difference between the Doppler shifts. This difference is independent of the scattering direction $\hat{r}$, so the heterodyne frequency is the same at every point on the photodetector and independent of the detector's location. Following Adrian, Eq. (3) can be written in the form

$$v_{Di} = \frac{K.v_i}{2\pi} \quad \text{where} \quad K = \frac{2\pi(\hat{s}_2-\hat{s}_1)}{\lambda} \qquad (4)$$

is a wave vector in the direction $\hat{s}_2 - \hat{s}_1$. Then, if we always arrange to let $u_i(t)$ be the component of v_i in the $\hat{s}_2 - \hat{s}_1$ direction, we have

$$v_{Di} = \frac{ku_i(t)}{2\pi} \quad \text{where the wave number}$$

$$|K| = k = \frac{4\pi \sin \kappa}{\lambda} \qquad (5)$$

is from simple geometry. Thus, v_{Di} depends only upon beam intersection angle κ, wave length λ, and the single velocity component u_i, which lies in the plane of the illuminating beams and perpendicular to their bisector. The velocity u_i from equation (5) is

$$u_i = \frac{\lambda v_{Di}}{2 \sin \kappa} \qquad (6)$$

In equation (6) half of the beam intersection angle κ is given by the inverse tangent of the half beam spacing divided by the focal length of the focusing lens. The Doppler frequency v_{Di} is the measured quantity. Using this information, equation (6) yields the fluid velocity.

2.1 Measurement Volume

The beam splitter splits the laser light into two beams and the transmitting optics focuses them into the test section, where they cross each other with an included angle of 2κ. Their intersection, which is the measurement volume, is an ellipsoid. Figure 3 shows this detail. It is the convention in LDV theory that the edges of the ellipsoid are defined as the point where the amplitude of the Doppler signal produced by a particle is $1/e^2$ of the maximum amplitude occurring at the center line. The dimensions of this ellipsoidal measurement volume as shown in Figure 2, with axes in the x, y, and z directions are given by

$$d_m = \frac{d_e^{-2}}{\cos \kappa}, \quad l_m = \frac{d_e^{-2}}{\sin \kappa}, \quad h_m = d_e^{-2} \qquad (7)$$

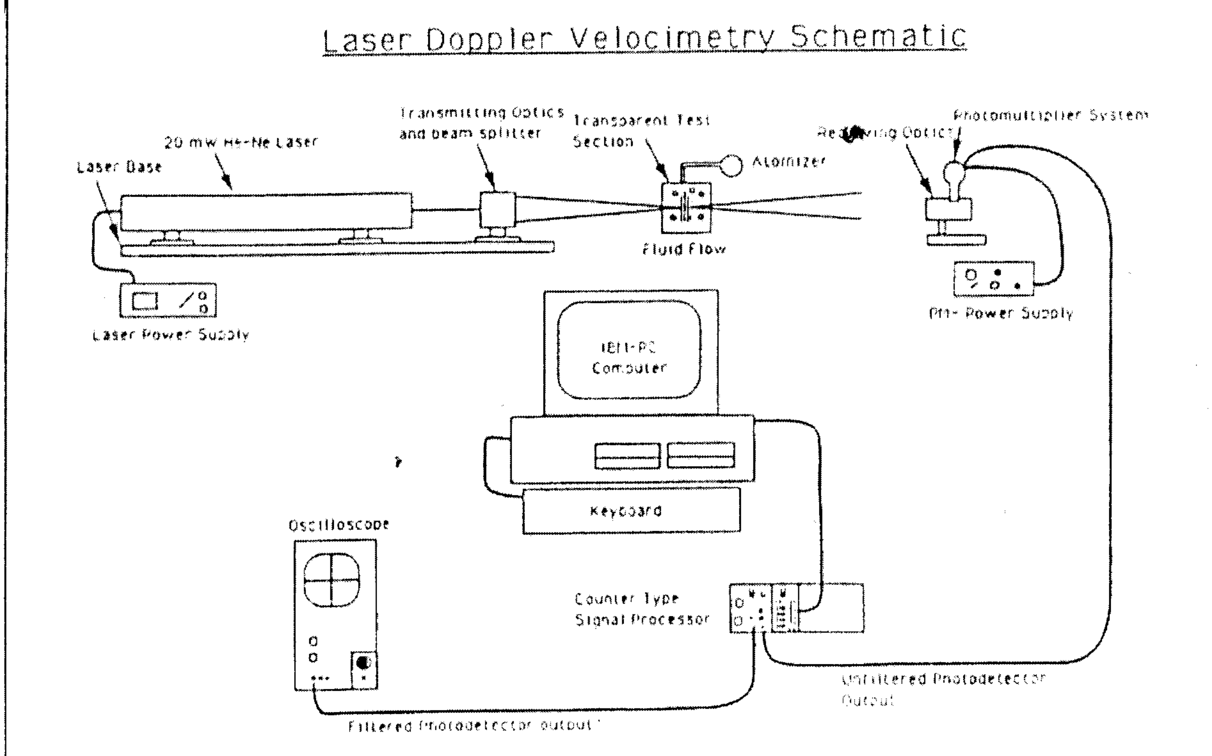

Figure 2 A schematic diagram showing all components of a single component LDV system including data acquisition equipment

respectively. Here d_e-2 is e^{-2} the diameter of focused gaussian illuminating beam. The volume enclosed by the ellipsoid is

$$V_D = \frac{\pi d^3_{e^{-2}}}{6 \cos \kappa \sin \kappa} \quad (8)$$

The seeding particle pass through this measuring volume and scatter the beams. The volume becomes very long in the y direction when $\sin \kappa$ is small. Typical dimensions are $d_m \approx$ 0.1 mm, $l_m \approx$ 0.8 mm, and $h_m \approx$ 0.1 mm, but they can be varied with special design.

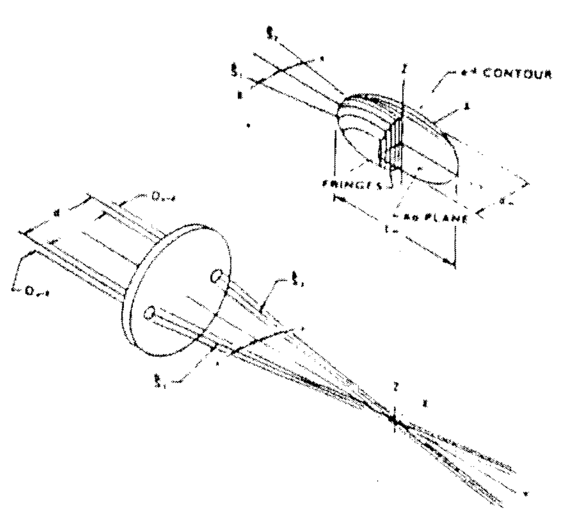

Figure 3 Dual beam intersection and the formation of the measuring volume in the shape of an ellipsoid

2.2 Fringe Model

The "fringe model" has been used widely in the LDV literature (Durst *et al.*, 1981 and Durrani and Greated, 1977) to explain the principle of a dual-beam system and in obtaining frequency calculation. According to this model, the light waves of the illuminating beams will interfere to form a set of interference fringes at the intersection of the beams. The interference fringes, shown in Figure 3, lie in planes parallel to the yz plane. The spacing between fringes is given by $2k\, d_f \sin \kappa = 2\pi$, so that

$$d_f = \frac{\lambda}{2 \sin \kappa} \quad (9)$$

When a very small seeding particle crosses this fringe pattern, it scatters light such that the intensity of the scattered light is proportional to fringe intensity. Then the scattered light flux will oscillate sinusoidally as the particle crosses the fringes, and the frequency of the oscillation will be

$$v_D = \frac{u}{d_f} = \frac{2u \sin \kappa}{\lambda} \quad (10)$$

since d_f/u is the time for the particle to cross one fringe. This frequency is exactly the same as that obtained from Doppler shift considerations, and the wave number defined in Eq. (5) is just $k = 2\pi/d_f$. Thus the results from fringe model agrees exactly with the Doppler shift theory. The number of fringes in the ellipsoidal measuring volume, defined as

$$N_{FR} = \frac{d_m}{d_f} \quad (11)$$

is an important parameter that characterizes many of the LDV signal properties.

The scattered lights pass through the receiving optics to the photodetector shown in Figure 4, which converts the light into an electric signal. The unfiltered output is then fed into a counter-type signal processor which converts the electrical signal to a filtered output in the form of a voltage that can either be displayed or stored in an oscilloscope or a personal computer. The signal processor and the oscilloscope are shown in Figure 5.

3.0 EXPERIMENTAL SET-UP

A single channel LDV system, at the minimum, requires six subgroups of equipment : (i) laser and base, (ii) transmitting optics, (iii) receiving optics, (iv) signal processor, (v) alignment accessories, and (vi) particle generator. A detailed list of these subgroups and the total cost of the experimental set-up follows.

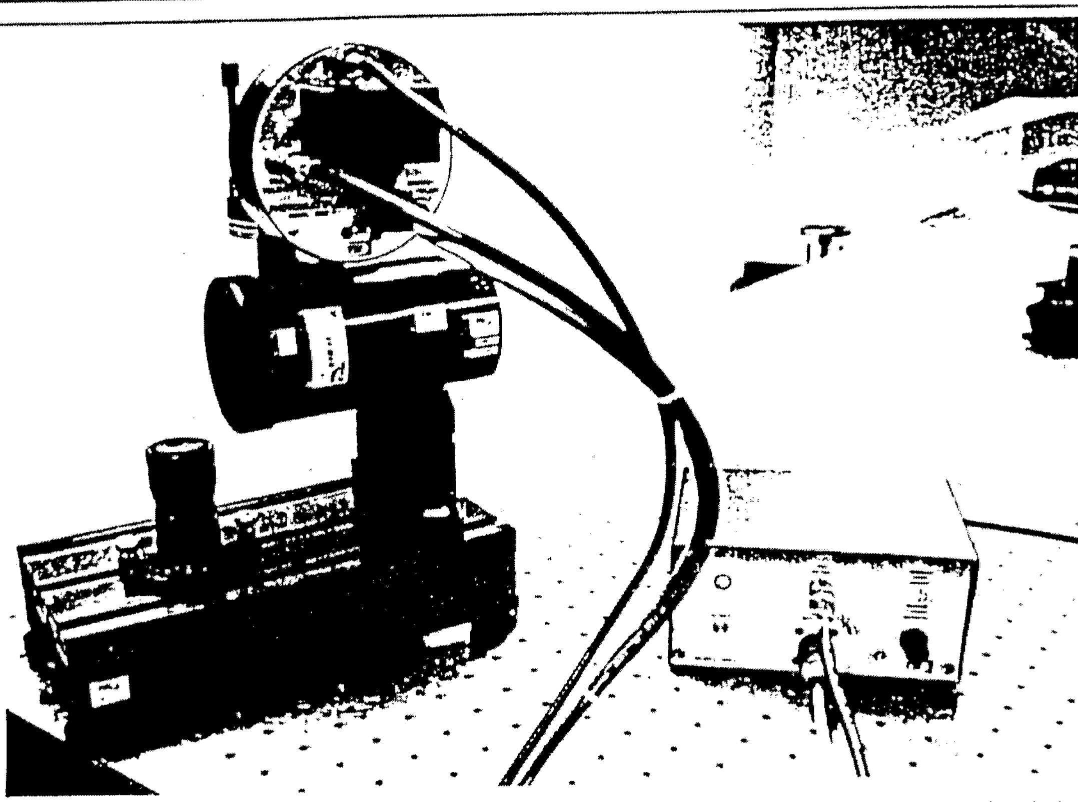

Figure 4 The receiving optics and photodetector mounted on the same base. The alignment eyepiece is placed on the base to the left and the photomultiplier power supply is on the right.

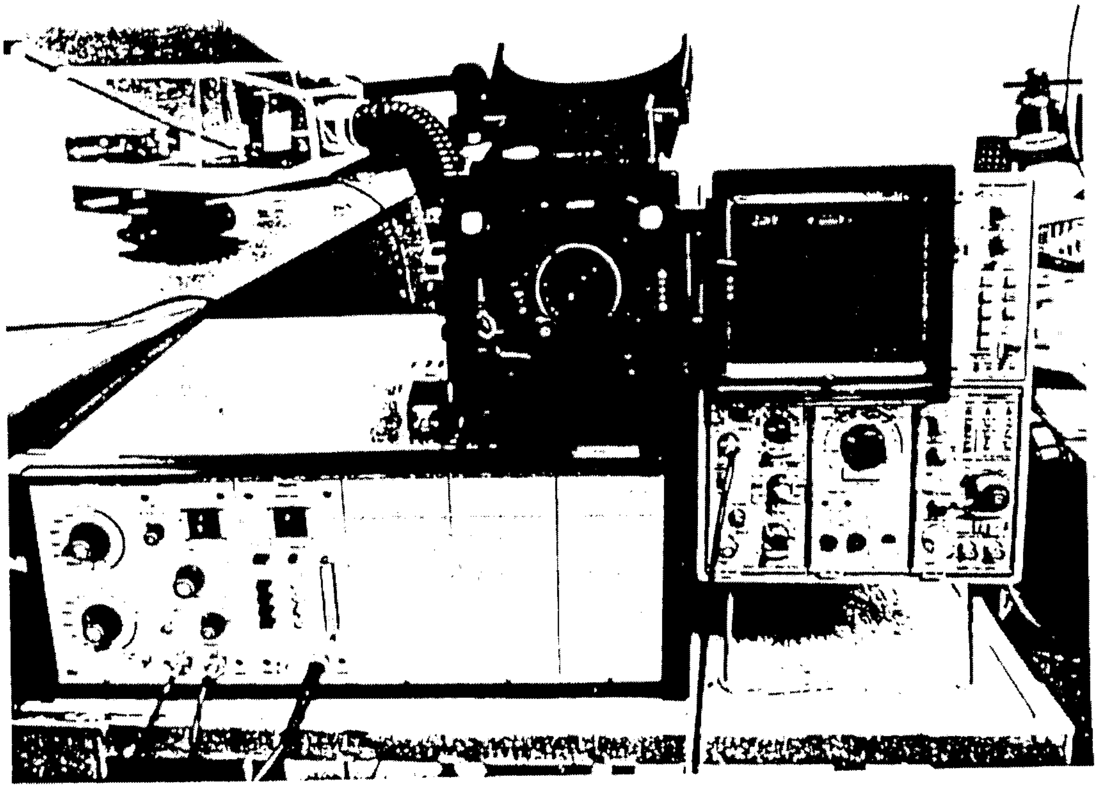

Figure 5 The counter type signal processor is on the left and the oscilloscope with the camera is on the right. Notice the transparent test tunnel with air hose on the back.

The total cost of equipment listed in Table 1 was about $27,000 in 1987. Additionally, one would require an oscilloscope to view and ensure that good quality Doppler bursts are generated while the measurements are being taken. Also a personal computer is recommended for processing the output of the signal processor. In our experiment, computer software was employed to perform statistical analysis of signal processor output to obtain frequency, mean velocities and standard deviations at different points in a flow field.

Referring back to Figure 2 for the experimental set-up, we note that it consists of a 20 mW Helium-Neon Laser mounted on its base. The power supply to the laser comes through an exciter with a key-switch as shown. The beam splitters and the transmitting optics are mounted in front of the laser on the same laser

Table 1. List of equipments and manufacturer's model numbers

Items	Description	Model Number
LASER & BASE		
	20 mW He-Ne laser*	106-1
	Laser exciter*	216-1
	Laser base and rotating mount adapter	9223-120
	Rotating mount	9179
TRANSMITTING OPTICS		
	Beam splitter	9115-2
	Rotating mount for beam splitter	9178-2
	Achromat focusing lens	9119
RECEIVING OPTICS		
	Receiving optics assembly	9140
	Photomultiplier power supply	9165
	Photomultiplier	9162
	Six feet of BNC Cable	10114-6
	Photomultiplier tube cable	909070
	Terminal box	900980
	Receiving optics base	9121
	Focusing lens	9119-600
SIGNAL PROCESSOR		
	High resolution counter type signal processor with input conditioner & timer	1980B
	Accessory kit	990002
	Manual	1990146
ALIGNMENT ACCESSORIES		
	Microscope objective & polarization axis finder	10092
	Polarizer	10901
	Alignment eyepiece	10096
	Optics case & accessories kit	10097A
PARTICLE GENERATOR		
	Jet atomizer with pressure regulator and gauge	9302

* The first two items are manufactured by Spectra Physics. All other items are manufactured by TSI, Inc.

base. A 10cm x 10cm test section made of Plexiglass is placed ahead of the transmitting ptics; it carries the fluid whose velocity is to ɔe measured. The receiving optics and the photodetector system are placed on the other side of the test section. The photodetector system receives its electrical power through its power supply regulator as shown in Figure 4. In this experimental set-up, a counter/type signal processor is employed to process photodetector signals. The filtered signal is displayed or stored by means of the accompanying oscilloscope. The entire set-up is clearly displayed in Figure 6. An IBM personal computer is used to store and analyze the velocity data. As a precautionary measure, it is advisable to never look directly into the laser beam during alignment of the transmitting and receiving optics.

3.1 Particle Seeding

In this experiment we measured the velocity of air in a transparent open circuit test tunnel. To scatter light there must be some scattering particle present in the flow field. This was accomplished by an atomizer. The atomizer located on top of the test tunnel (Figure 6) injects small water droplets into the flow field which act as the scattering particles. Sometimes solid particles in fine powder form can be used for seeding the flow field. In liquids, normal impurities often serve as scatterers, but gases generally need to be seeded. The seeding particles generated by our atomizer range in diameter from 1-2 μm. They are small enough to track the flow accurately, yet large enough to scatter sufficient light to generate a proper signal for the photodetector and the signal processor.

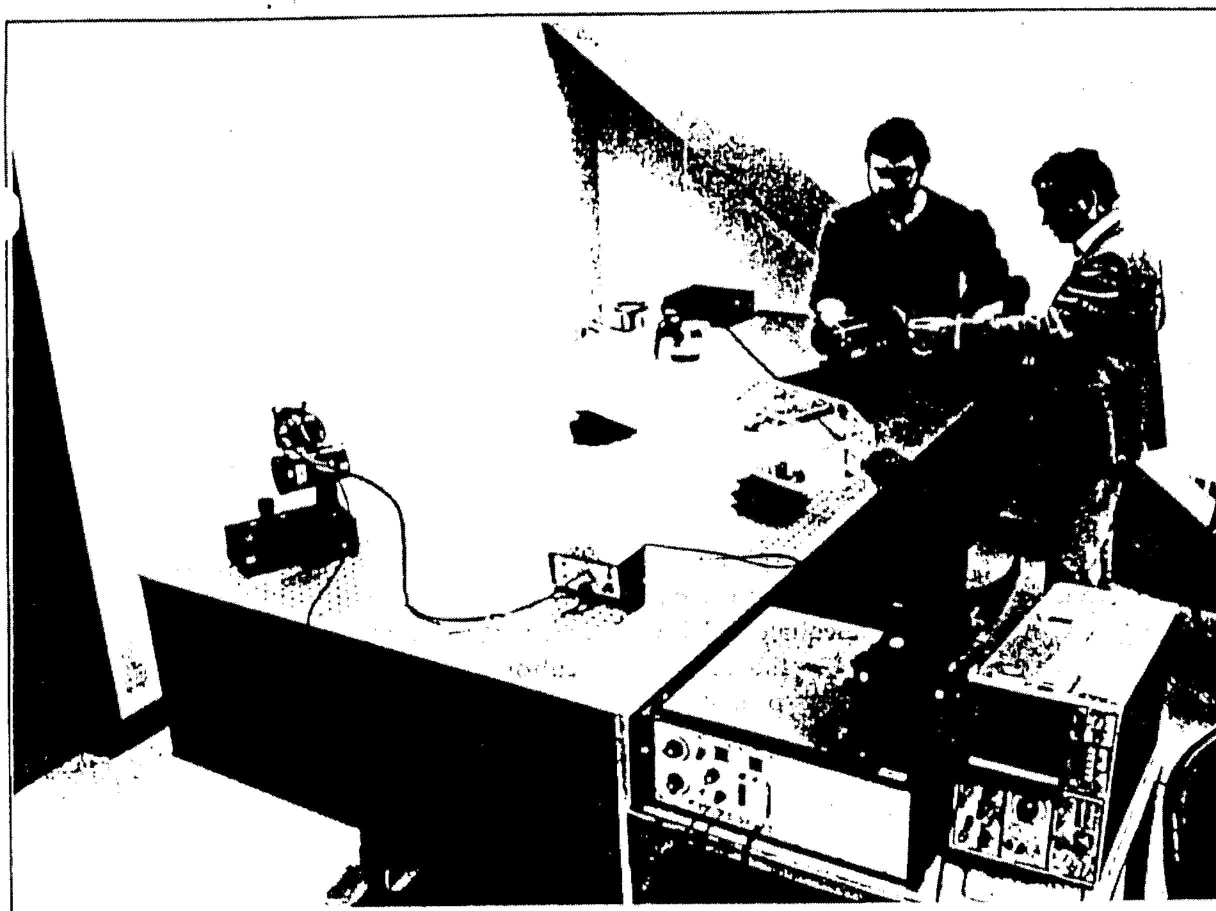

Figure 6 The entire assembly of the LDV system including the laser, transmitting optics, receiving optics, photomultiplier, signal processor and oscilloscope. Laser beams intersect at the center of the transparent test tunnel, with atomizer resting on top. The whole arrangement is mounted on a vibration free air cushion table.

It is desirable to assess the requirements for the seed particles during the planning stage of the experiment. Their aerodynamic characteristics should be just right, so that they follow the flow. As described in TSI Inc. (1987) the aerodynamic diameter of a particle is defined as the diameter of a unit density sphere with the same settling velocity as the particle in question. The aerodynamic diameter primarily depends on the size, density and shape of the particle. The particle velocity at any time, t, after a step change in fluid velocity is given by ($\rho g << \rho p$)

$$\frac{Vg - Vp}{Vgi - Vpi} = e^{-t/\tau} \qquad (12)$$

where Vg is gas velocity after a step change, Vp is particle velocity at time t, Vgi and Vpi are gas and particle velocities before the step change and relaxation time of the particle is

$$\tau = \frac{\rho_p d_p^2}{18\mu} \qquad (13)$$

The frequency response can be calculated from τ as follows :

$$f = \frac{1}{2\pi\tau}\left[\frac{1}{A_r^2} - 1\right]^{1/2} \qquad (14)$$

where A_r is particle oscillation amplitude divided by fluid oscillation amplitude.

The relaxation time should be quick so that particles adjust to any change in flow velocity and follow the flow with adequate fidelity. Another factor of importance is the settling velocity, which should be low so that the particles remain buoyant for a sufficient time in the flow field. As an example, for a particle of 1 μm aerodynamic diameter (the size generated by our atomizer), appropriate values of settling velocity and relaxation time are 3.0×10^{-3} cm/sec and 3.1×10^{-6} seconds respectively.

The number of particles and their size inside the measuring volume at a given instant of time is an important consideration for generating a good signal and in minimizing the noise. For LDV applications, aerosols of nearly uniform size are desirable. Monodispersity is a measure of the uniformity of particle size. This is expressed by σ_g, the geometric standard deviation, defined by the equation

$$\sigma_g = \frac{d_{84\%}}{d_{50\%}} \qquad (15)$$

(The diameter of 84% of the particles is smaller than $d_{84\%}$ and the diameter of 50% of the particles is smaller than $d_{50\%}$). Ideally, $\sigma_g = 1$, but an aerosol is called monodisperse when $\sigma_g \leq 1.2$, and that is accepted as a uniform diameter in an experiment.

3.2 Signals and Data Processing

The primary result of a laser anemometer measurement is a pulse from a photodetector as shown in Figure 4. This pulse contains the frequency information relating to the velocity to be measured and it also contains some noise which must be minimized by filtering. The scattered light must be of sufficient intensity and quality to give an adequate signal-to-noise ratio (SNR) for the signal processor used. This is perhaps the most important question and tends to involve the entire velocimeter system including the characteristics of the particle that scatters the light. The ideal dual-beam LDV signal is obtained when all background light, spurious heterodyne signals, and electronic noises are negligible, and a single scattering particle resides at the center of the ellipsoidal control volume. But this is not the case; so it is necessary to evaluate by the following formulas the SNR at the time of planning an experiment. It gives us a better idea on the limit the noise power imposes on the signal power and what the expected signal quality is. The SNR at the maximum signal amplitude from Adrian (1983) is given by

$$SNR_{peak} = \frac{\pi^2}{256}\,\frac{\eta_q P_o}{h\upsilon_o\,\Delta f}\,\left(\frac{D_a D_r^{-2}}{ff}\,\frac{d_{pi}}{\lambda}\right)^2 G_i \overline{V_i}^{-2} \qquad (16)$$

Equation (16) is applicable for a spherical particle with diameter d_{pi}. Here η_q is quantum efficiency, P_o is a laser beam power, h is Planck's constant, v_o is laser frequency, Δf is band width, D_a is aperture diameter, D_e^{-2} is e^2 diameter of unfocused illuminating beam, f is focal length and f_c is collecting-aperture distance from measuring volume. The scattering gain G_i is given by

$$G_i = \frac{2(P_{1i} + P_{2i})}{k^2 d_{pi}^2 \ \Omega} \qquad (17)$$

where P_{1i} and P_{2i} are the powers of two beams and Ω is the solid angle subtended by collecting aperture. The primary implication of Eq. (16) is that the peak signal-to-noise ratio for the ith particle is proportional to the scattering power of the particle and the square of the visibility of the heterodyne signal V_i^2. Thus, doubling the signal visibility by an appropriate choice of particles is as effective as quadrupling the laser power.

The factor in parenthesis in Eq. (16) contains first-order effects of the LDV geometry, and it implies that the SNR decreases as the fourth power of the focal distance if $f_c = f$, which is the case in most applications. Thus, long-range measurements usually suffer from very low signal-to-noise ratios. One remedy is to expand the unfocused illuminating-beam diameter so as to keep De/f constant. Beam expansion is generally desirable because it also produces smaller measurement volumes for the same focal distance. However, the limitations of physical size and the alignment accuracy required to cross two small focal spots at large distances usually make beam expansions greater than about 10:1 difficult.

Figure 7 shows a signal of Doppler burst, on an oscilloscope as in Figure 5, derived from the photodetector. This is a band-pass filtered signal that comes out of the signal processor. Wave forms like these are burst type Doppler signals which are usually generated in low seeding concentration, when a single particle passes through the measuring volume. Figure 8 is a multi-particle signal when more than one particle is present in the measuring volume simultaneously.

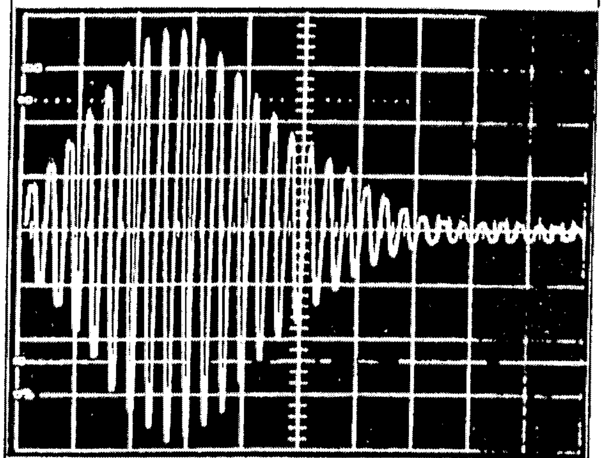

Figure 7 Detector signal of Doppler burst as displayed on an oscilloscope after being filtered by a bandpass.

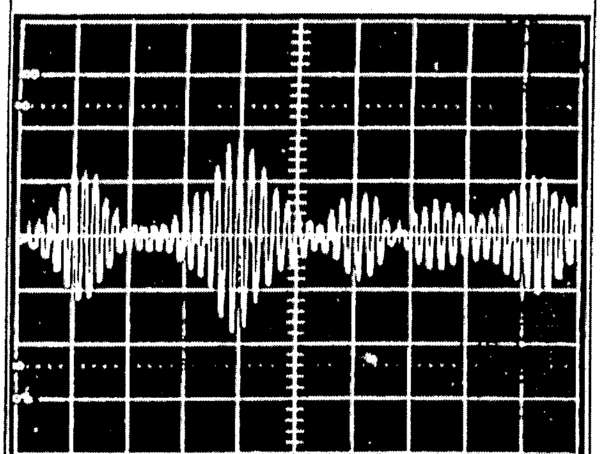

Figure 8 Filtered signal of multiparticle Doppler bursts

For high speed flows, the signal processor imposes a limit on the minimum diameter of the measurement volume. This volume defines the spatial resolution of the LDV system. The minimum measurement volume diameter is

$$d_m = \frac{V\max N_o}{f_{D\max}} \qquad (18)$$

where Vmax is maximum flow velocity, N_o is the number of cycles (fringes) required by the signal processor, and f_{Dmax} is the maximum Doppler frequency the signal processor can measure. Our experimental setup uses a counter type signal processor. This processor will operate at any burst density or data density as long as the signal-to-noise ratio is high, say greater than ten. It is most often used with low data density. The counter measures the time, τ_i for n_i cycles of the Doppler signal. The frequency is then calculated from

$$f_{Di} = n_i/\tau_i \qquad (19)$$

The signal processor (Figure 5) used here is a versatile one because it can operate under several modes; continuous mode, single measurement per burst mode, total burst count mode and total burst mode (TSI, Inc., 1986). Each one has its advantage in processing a certain type of signal. After the signal processor has inferred the frequency, data analysis is done by a computer. Most minicomputers have interfaces available and permit up to 500,000 16 bit words per second to be transferred to memory. This is sufficiently fast for LDV and avoids the need for any other type of separate instrument. In our experimental setup we can view a large volume of data (e.g., number of cycles, frequency, mean velocity, standard deviation, etc.) on the computer screen and subsequently transfer it to discs or printouts.

4.0 APPLICATIONS

The following applications of the LDV system are proofs of its utilization in industry and academic institutions in recent years. Data gathered from these experiments have proven the versatility and usefulness of this technology at the present time. Listed below are a number of experimental studies in the United States as reported in literatures (e.g., TSI, Inc., 1986).

i. Experimental turboprop operation in transonic wind tunnel (NASA, Lewis Research Centre).

ii. Propeller operation in water tunnel (Massachusetts Institute of Technology, Ocean Engineering).

iii. Wind tunnel study of wind effects in architectural design, i.e., building models in large-scale atmospheric wind tunnel (Cermak/Peterka & Associates).

iv. Boundary layer transition on gas turbine blades (University of Minnesota).

v. LDV study of velocity in high temperature zone of a combustor (Sandia National Laboratory).

vi. Wing juncture flow field study in low turbulence pressure tunnel (NASA, Langley Research Centre).

vii. Bow flow field study on ship model operated in towing basin (U.S. Naval Ship Research and Development Centre).

5.0 SUGGESTED LABORATORY EXPERIMENTS

For the education of engineering students as well as practising professionals, a number of experiments can be undertaken to familiarize them with the LDV system for fluid dynamics research. Measurements of flow over cylinders will simulate bridge piers, stack vibration and illustrate vortex shedding. Experiments on internal flow through pipes and channels displaying laminar and turbulent regimes can also be demonstrated with the LDV system. The measurements of laminar and turbulent boundary layers, jets and wakes and their spreading can lead to an understanding of turbulence characteristics, root mean square fluctuations, and Reynolds stresses. Some of these works can be pursued in academic institutions at the undergraduate and graduate level and also in research laboratories by practicing engineers. Use of these instruments will familiarize engineers with state-of-the-art concepts in fluid mechanics involving measurements, data acquisition and analysis.

6.0 CONCLUSIONS

ser Doppler velocimeters are a very accurate technique for measuring fluid velocities. The fluid and the test section must be transparent so the laser beam can pass through. It is a nonintrusive technique, so the flow field is not altered by the presence of a probe. The measurement volume is very small, allowing one to measure the velocity field in very narrow regions formerly inaccessible to hot wire or hot film anemometers. Many examples of present day applications prove its utility. The drawbacks of this system are that the technique is complex and the cost of the equipment is fairly high, even for a single component velocimeter.

7.0 REFERENCES

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2. Durrani, T.S., & Greated, C.A., 1977, *Laser Systems in Flow Measurement*, Plenum Press, New York.
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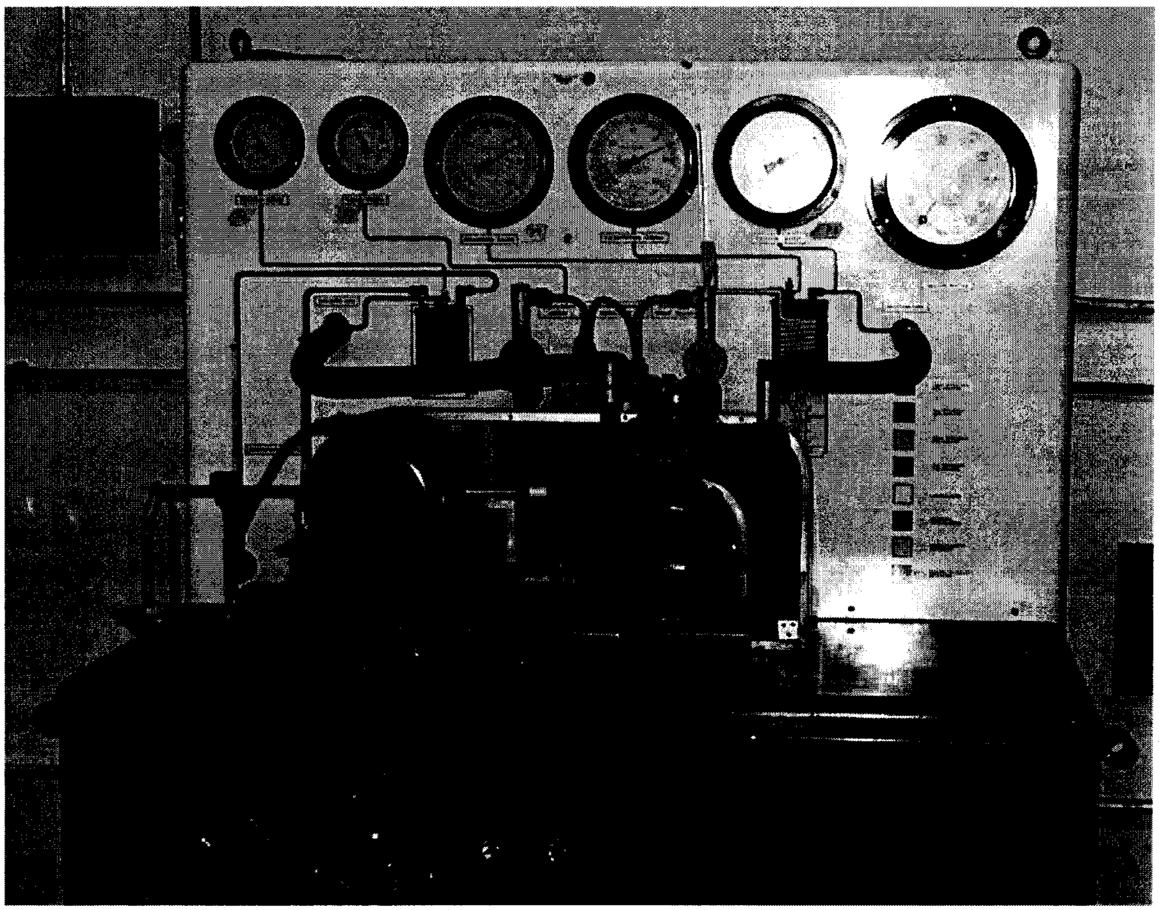
PERFORMANCE OF A VAPOR COMPRESSION REFRIGERATOR



Broken apparatus

Refrigerator Performance

Principles & Background:

The Vapor-Compression Refrigeration Cycle (Rankine Cycle):

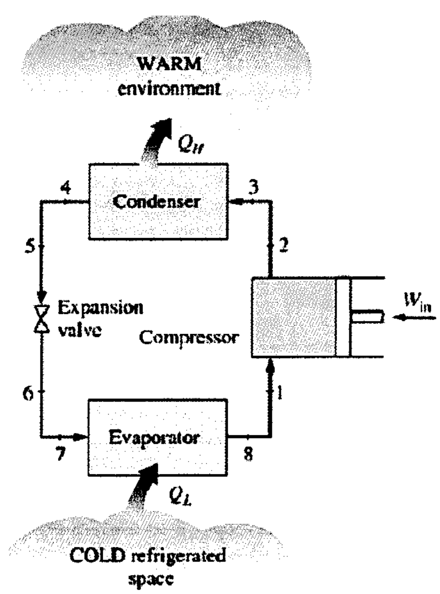
The 1st Law of Thermodynamics states that we cannot create nor destroy energy. However, we can transfer energy and transform it from one form to another. Our goal as engineers is to utilize energy as efficiently as possible. Unfortunately, the 2nd Law of Thermodynamics requires that there will be inefficiencies in everything that we do. As such, we can never be 100% energy efficient. So, how can we live within these constraints and still achieve our desired end goals?

The Rankine Cycle is a Thermodynamic cycle in which we input work in order to force heat to transfer from a low temperature heat source to a higher temperature heat sink. We must input work (energy) since we desire to move heat (energy) from a cold source to a warm sink. This is opposite to the direction that heat flows naturally; from a warm source to a cold sink.

One of the metrics used to judge the efficiency (effectiveness) of a refrigeration cycle is the Coefficient of Performance (COP). The COP is a ratio of the useful energy effect resulting from the thermodynamic cycle to the amount of energy supplied to that cycle to produce the effect. In the case of a vapor-compression refrigeration cycle, it can be written as:

$$COP = \frac{\text{Useful Refrigeration Produced}}{\text{Net Energy Supplied}} \tag{1}$$

Let's look at a schematic of the Rankine Cycle and its depiction on a T-s Process Diagram.



Heat, Q_L, is absorbed from the low temperature source in the evaporator. The evaporator is a heat exchanger. The Rankine Cycle is designed in such a way as to insure that the temperature of the working fluid (refrigerant) within the evaporator is colder than the heat source surrounding the evaporator. This temperature, often referred to as the saturated suction temperature (SST) is one of the parameters engineers use to establish the design of the entire cycle and in selecting the proper refrigerant for the job. Thus, heat will flow into the working fluid from the low temperature source during process 7 → 8. The working fluid changes phase from liquid to vapor within the evaporator.

As the refrigerant flows through the connecting piping during process 8 → 1, it is subject to friction losses due to fluid flow and heat transfer with the environment surrounding the piping. This is part of the unavoidable losses associated with a "real world" Thermodynamic cycle.

Work, W_{in}, is added to the cycle by the compressor. This is the energy added to the system. By adding energy during process 1 → 2, the working fluid's pressure and temperature are increased. Because the compressor is not an ideal, adiabatic machine, we also have losses associated with this process that add to the overall inefficiency of the cycle.

During the working fluid's transit through the piping from the compressor discharge to the condenser inlet, process 2 → 3, it is again subject to friction loss and heat transfer with its surroundings.

At the condenser, the working fluid rejects heat, Q_H, to the hot sink. During process 3 → 4, the working fluid changes state from a superheated vapor to a sub-cooled liquid. The temperature is reduced but the pressure remains that of the "high side" system pressure. The condenser is a heat exchanger. In order to get the heat to flow from the working fluid to the surrounding hot sink, the cycle needed to raise the temperature of the refrigerant to a temperature greater than the surrounding environment. Thus, the work input at the compressor was required. This condensing temperature is the other temperature that engineers use in designing the overall cycle and selecting the refrigerant to use.

We again introduce pipe friction and heat transfer inefficiencies as the refrigerant flows from the condenser outlet to the expansion (metering) valve. This is depicted as process 4 → 5.

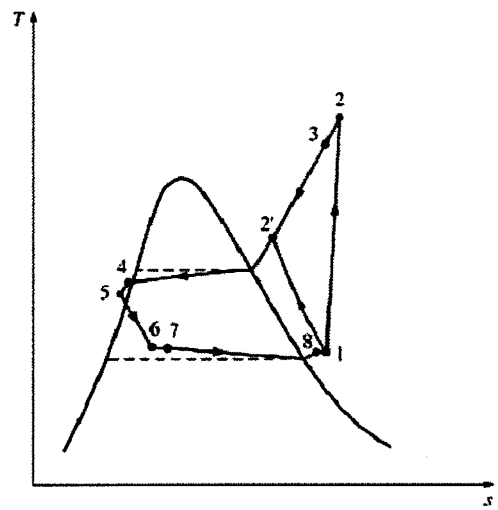
The condenser exists at the high-side system pressure. The evaporator exists at the low-side system pressure. There must be some device in the system to reduce the pressure when it exits the condenser before it can enter the evaporator. That device is often a thermostatic expansion valve.

In general, this device is called a metering device. There has been some work on large systems to install small turbines as the metering devices. Turbines reduce the pressure. They also create useful work that can offset some of the energy required at the compressor. In general, the Process from 5 → 6 reduces the pressure of the working fluid. Some of the sub-cooled liquid is flashed to vapor which causes it to give up heat. This vapor re-mixes with the remaining liquid. The end state of the refrigerant leaving the metering device is a mixture of saturate liquid and vapor. at the low-side pressure.

The working fluid encounters its final set of inefficiency losses during process 6 → 7. Once again, it encounters friction loss in the piping and transfers heat with its surroundings.

Finally, at 7, the refrigerant enters the evaporator again and the cycle repeats itself.

If we plot this cycle on a T-s Process Diagram, we can observe each of these state transitions and observe the processes graphically. This is a great tool to use in analyzing the cycle.

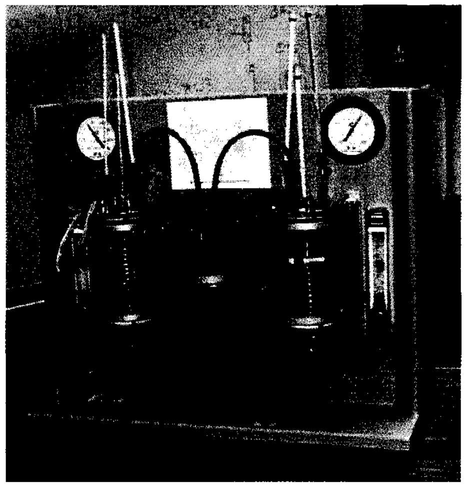


Given the definition of the COP in Eq. (1), for the Rankine Cycle described above the COP is defined as:

$$COP = \frac{Q_L}{W_{in}} \qquad (2)$$

Lab Procedure:

This week's lab exercise will use a refrigeration cycle demonstration unit manufactured by P.A. Hilton.



The manual for this unit is posted on the class Web site under the "Additional Information" column. This unit utilizes R-11 (trichlorofluoromethane) as its refrigerant. This is a CFC class refrigerant which is no longer manufactured due to its ozone depletion potential. It is permissible to use this refrigerant, we just can obtain any more (at a reasonable price) should the refrigerant escape from this apparatus. Thermodynamic Property Tables for R-11 are included at the class Web site.

For this lab exercise, you will operate the apparatus at steady-state conditions. Gather the information required to determine the heat absorbed at the evaporator. Gather the information required to determine the heat rejected at the condenser. Gather the information require to determine the work supplied by the compressor.

You will calculate:

1. The effective refrigeration effect.

2. The heat rejected to the high temperature sink.

3. The work provided by the compressor.

4. The COP of the unit under the operational conditions.

Finish and Materials in the construction of Hilton products

All components parts used in the construction of Hilton products are finished or manufactured in materials resistant to corrosive attack.

Stainless steels are widely used and other ferrous components are either electro-plated nickel or zinc, or electro-statically coated with an attractive and durable epoxy-resin.

Pipe fittings are manufactured in brass, bronze or stainless steel whilst connecting pipes are copper, plastic or electro-plated steel according to the application.

INSTALLATION AND ASSEMBLY AND OPERATING INSTRUCTIONS ARE SUPPLIED WITH THE EQUIPMENT .

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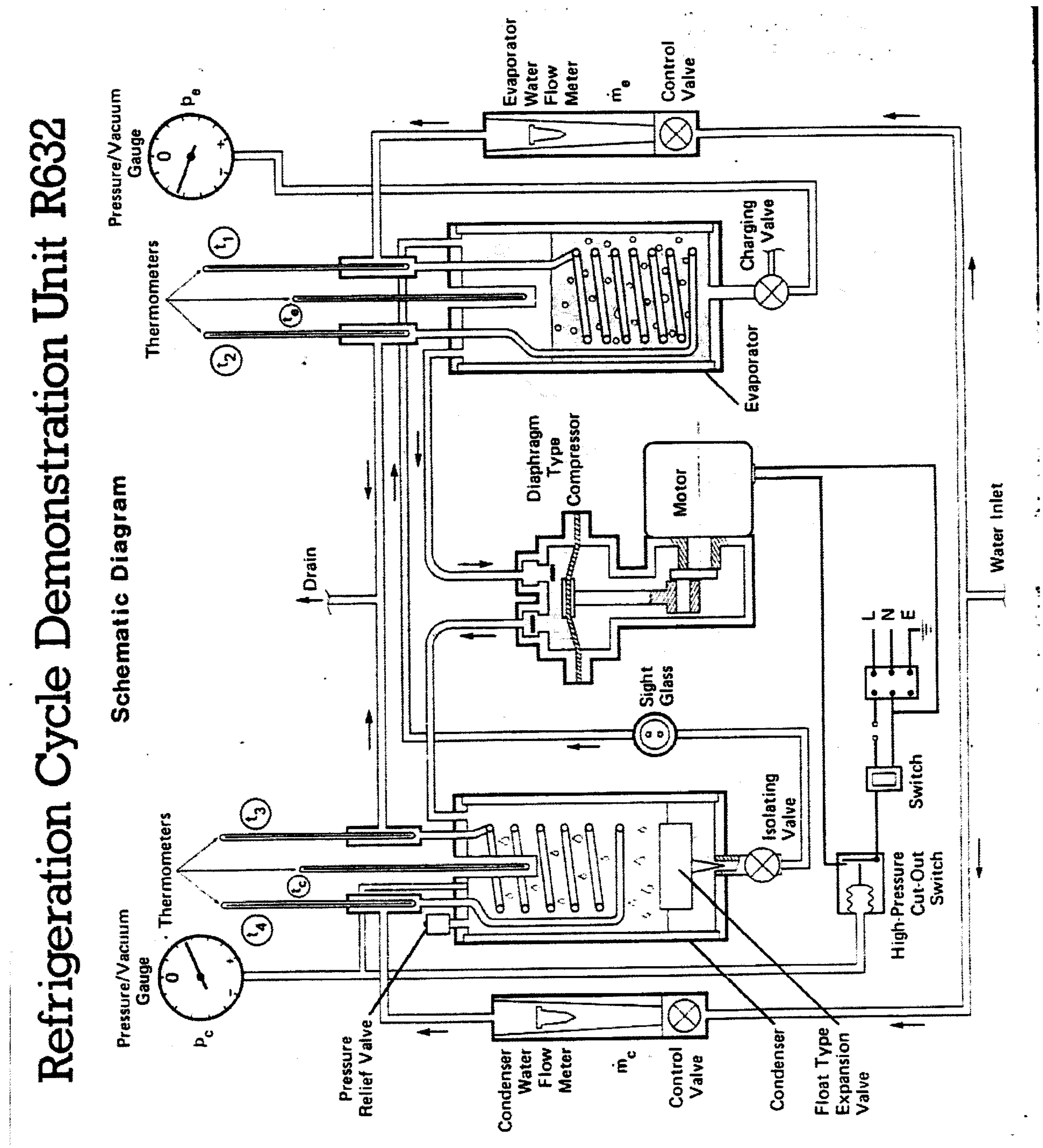

Refrigeration Cycle Demonstration Unit R632
Schematic Diagram
Pressure/Vacuum Gauge
p_e
Thermometers
t_1
t_2
t_e
Evaporator Water Flow Meter
$\dot{m}_e$
Control Valve
Charging Valve
Evaporator
Diaphragm Type Compressor
Motor
Drain
Sight Glass
L
N
E
Switch
Water Inlet
Pressure/Vacuum Gauge
p_c
Thermometers
t_3
t_4
t_c
Isolating Valve
High-Pressure Cut-Out Switch
Pressure Relief Valve
Condenser Water Flow Meter
$\dot{m}_c$
Control Valve
Condenser
Float Type Expansion Valve

SYMBOLS AND UNITS

Symbol		Unit
t_c	Refrigerant Saturation Temperature in Condenser	°C
t_e	Refrigerant Saturation Temperature in Evaporator	°C
p_c	Pressure of Refrigerant in Condenser	$kN\ m^{-2*}$
p_e	Pressure of Refrigerant in Evaporator	$kN\ m^{-2*}$
$\dot{m}_c$	Water Mass Flow Rate through Condenser	$kg\ s^{-1}$
$\dot{m}_e$	Water Mass Flow Rate through Evaporator	$kg\ s^{-1}$
t_1	Temperature of Water entering Evaporator	°C
t_2	Temperature of Water leaving Evaporator	°C
t_3	Temperature of Water entering Condenser	°C
t_4	Temperature of Water leaving Condenser	°C
t_a	Ambient Temperature	°C
	Overall Heat Transfer Coefficient	$W\ m^{-2}\ K^{-1}$

* pressure = Gauge reading + atmospheric pressure

THE HILTON REFRIGERATION CYCLE DEMONSTRATION UNIT

USEFUL DATA

Compressor swept volume: $1.18\ dm^3\ S^{-1} = 1.18 \times 10^{-3}\ m^3\ S^{-1}$ (50Hz.)
$1.4\ dm^3\ S^{-1} = 1.4 \times 10^{-3}\ m^3\ S^{-1}$ (60Hz.)

Condenser:

Water coil surface area: $0.032 m^2$

Evaporator:

Water coil surface area: $0.032 m^2$

Heat Transfer to or from the surroundings:

At the condenser: $0.8\ (t_a - t_c)$ W*

At the evaporator: $0.8\ (t_a - t_e)$ W*

At the compressor: -20 W (typical value)*

*Found by experiment under still air conditions.

Specific heat capacity of water (Cp): $4.18\ kJ\ kg^{-1}\ K^{-1}$

Refrigerant:

R11 Trichloro-fluoromethane $C\ Cl_3\ F$

Quantity: 400 to $500\ cm^3$ (580 to 730 gm)

THE REFRIGERATION (OR HEAT PUMP) CYCLE

A refrigerator is defined as a machine whose prime function is to remove heat from a low temperature region. Since energy cannot be destroyed, the heat taken in at a low temperature plus any other energy input must be dissipated to the surroundings. If the temperature at which the heat is dissipated is high enough to be useful, e.g. for space heating, the machine is then called a heat pump.

The Clausius Statement of the Second Law of Thermodynamics states that heat will not pass from a cold to a hotter region without the aid of an "external agency". Thus, a refrigerator will require an "external agency", i.e. an input of high grade energy, for it to operate.

This energy input may be in the form of work, or a heat transfer at a high temperature.

The most common type of refrigerator or heat pump uses a WORK INPUT and operates on the VAPOUR COMPRESSION CYCLE.

THE VAPOUR COMPRESSION CYCLE

The work input to the vapour Compression Cycle drives a compressor which maintains a low pressure in an EVAPORATOR and a higher pressure in CONDENSER.

The temperature at which a liquid will evaporate (or a vapour will condense) is dependent on the pressure, thus if a suitable fluid is introduced it will evaporate at a low temperature in the low pressure evaporator (taking in heat) and will condense at a higher temperature in the high pressure condenser (rejecting heat).

The high pressure liquid formed in the condenser must then be returned to the evaporator at a controlled rate.

Thus, the simple vapour compression refrigeration cycle has four main components,

(1) An evaporator where heat is taken in at a low temperature as a liquid evaporates at a low pressure.

(2) A compressor which uses a work input to increase the pressure of the vapour.

(3) A condenser where the high pressure vapour condenses, rejecting heat to its surroundings.

(4) A flow control device which controls the flow of liquids back to the evaporator and which brings about the pressure reduction.

The refrigeration cycle is most interesting from the thermodynamic view point. It is one of the few practical plants which operates on a true thermodynamic cycle and involves

(a) Nucleate boiling and film wise condensation.

(b) Steady flow processes, i.e. throttling, compression and heat exchange.

(c) Flow control.

(d) The thermodynamic properties, i.e. pressure, specific volume, temperature, specific enthalpy and specific entropy, of a pure substance at all conditions between sub-cooled liquid and super-heated vapour.

Although the vapour compression cycle is simple to those who are familiar with it many students find great difficulty in visualizing and understanding the events within the various components.

With this in mind P.A. Hilton Ltd., designed the Refrigeration Cycle Demonstration Unit in which the major part of the cycle takes place inside glass chambers and can therefore be observed.

The unit is a valuable teaching aid for students in a wide range of courses from craft and technician training to first degree at a University or Polytechnic.

DESCRIPTION

(Please refer to the front cover and schematic diagram on Page 3)

The evaporator is a vertical glass cylinder with plated metal end plates. A helical coil of copper tube conveys water through a pool of refrigerant in the cylinder. The compressor maintains a low pressure in the evaporator and this causes the refrigerant to boil at a low temperature, extracting heat from the water and reducing the temperature.

The low pressure vapour formed in the evaporator is drawn into the compressor where its pressure is increased and is then delivered to the condenser. The compressor is of the diaphragm type and is direct coupled to an electric motor.

The condenser is also a vertical glass cylinder fitted with metal end plates, the upper one supporting a helical coil of tube through which cooling water flows. High pressure vapour from the compressor condenses as it transfers heat to the cooling water which becomes warmer.

The high pressure liquid collects in the bottom of the condenser and its level controls a float operated expansion valve. This valve reaches an equilibrium position and discharges refrigerant liquid back to the evaporator at the same rate as it is formed.

As the warm high pressure liquid passes through the valve seating its pressure decreases to that in the evaporator and its temperature must fall to the saturation temperature at the lower pressure. The fall of temperature is accompanied by the formation of "flash vapour" and the vapour bubbles formed may be seen through a sight glass fitted after the needle valve.

On entering the evaporator the low pressure liquid and vapour separate, the liquid passing into the "pool" for re-evaporation, while the vapour mixes with the other vapour passing to the compressor.

Instrumentation is provided to measure

(i) The temperature and pressure of the refrigerant in the evaporator and condenser.

(ii) The temperature of the water entering and leaving the coils in the evaporator and condenser.

(iii) The water flow rates through both coils.

An isolating valve is fitted at the condenser outlet and this may be closed to demonstrate "pumping over".

SPECIFICATION

Compressor: Reciprocating diaphragm type, close coupled to 375W electric motor running at approximately 1450 rev/min (50Hz) or 1750 rev/min (60Hz). Special long-life diaphragm coated with P.T.F.E. Displacement approximately 1180 cm^3s^{-1} (50Hz) 1400 cm^3s^{-1} (60Hz).

Condenser Vertical, thick walled high strength glass cylinder with reverse tapered ends to give tension free connection to nickel plated brass end plates with P.T.F.E. seals. Cooling surface – 9 coils of 6.3 mm dia. copper tube through which water flows, fitted to upper end plate. Cooling area 0.032 m^2.

Evaporator Flooded type -construction similar to condenser.

Expansion Valve "High side" float operated needle valve fitted in condenser.

<u>Instruments</u>

<u>Pressure gauges</u> – Two

one, Range -100 to +100 kN m^{-2} gauge.
one, Range -100 to +250 kN m^{-2} gauge.
To indicate evaporator and condenser pressures.

<u>Thermometers</u> – Six

Five, Range 0°C to 50°C x 150mm long,
glass. one, Range -10 to 110°C x 150mm long, glass.
Fitted in pockets to indicate:
Water inlet and outlet temperatures at condenser and at evaporator, evaporation temperature and condensation temperature.

<u>Flow meters</u> – Two

Tapered glass tube type, with stainless steel bobbin, each fitted with a control valve. Range 0 to 50 gramme s^{-1}. To indicate water flow rate through evaporator and condenser coils.

<u>Charging and Drain Valve</u>

Fitted to base of evaporator – used to introduce or discharge refrigerant.

<u>Sight Glass</u>

Fitted in pipe between expansion valve and evaporator – to show "flash" vapour.

<u>Safety</u>

All moving parts guarded. Relief valve set to 250 kN m^{-2} gauge fitted to condenser. High pressure cut out fitted to stop compressor if condenser pressure exceeds 220 kN m^{-2} gauge. Main switch fitted with neon warning lamp. Fuse fitted.

Panel and Base Plate	Constructed from G.R.P. – attractive moonstone wipe clean finish.
Dimensions	Height 620mm Width 750mm Depth 380mm Weight 45 kg
Software	Instruction Manual. Large plastic coated pressure-specific enthalpy diagram for R11.

PERMITTED REFRIGERANTS

As already stated, an important feature of this unit is the use of glass for the evaporator and condenser shells. These shells have a safe working pressure of 300 kN m^{-2} gauge and safety features are incorporated in the unit to ensure that this is not exceeded.

In all normal environments, R11 has a suitable pressure-temperature relationship.

CAUTION

This unit has been designed to operate on R11 ($C\ Cl_3\ F$) and no other refrigerant should be charged into the system.

INSTALLATION

Remove the unit from its packing case and carefully examine it for damage. If any is found, notify the insurers immediately.

Stand the unit on a table at a convenient height and close to an electrical supply, a water supply and a drain.

(i) Connect the mains water supply to the water inlet at the rear of the unit.

(ii) Connect the water outlet (also at the rear of the unit) to a suitable drain using the plastic pipe provided.

(iii) Check that the voltage stated on the rear panel of the unit agrees with that of the supply and is single phase, then connect the cable* provided to the mains electrical supply,

Brown cable	LIVE LINE
Blue cable	NEUTRAL
Green/Yellow cable	EARTH

using a connection which meets the local electrical installation regulations.

*The cable is stowed inside the cabinet during transport. The rear panel must be replaced before switching on.

(v) Remove the <u>transport bracket</u> fixing the compressor head to the instrument panel. Discard this bracket.

MAINTENANCE

High Pressure Cut Out

At intervals not exceeding 3 months, the high pressure cut out should be tested as follows:

Turn on the water supplies to the evaporator and condenser and switch on the compressor.

Gradually reduce the condenser water flow, thus increasing the condenser pressure. When the condenser pressure reaches 220 kN m^{-2} gauge, the high pressure cut out should operate and switch off the compressor. Turn the condenser water to its maximum flow rate and when the pressure has fallen to about 120 kN m^{-2} gauge the compressor should restart.

If it is necessary to adjust the high pressure cut out disconnect the unit from the electrical supply, then remove the rear panel from the unit.

The high pressure cut out will be found on the top of the switch and this should be turned clockwise to increase the pressure at which the cut out operates.

After adjustment, the rear cover should be replaced and the action of the cut out retested.

Compressor

The compressor and motor bearings have been lubricated "for life" and should need no attention.

Should the compressor fail to produce the expected pressure difference or if it “knocks”, the diaphragm should be inspected as follows:

Disconnect the unit from the mains electricity.

Disconnect at the nylon suction and delivery pipes from the cylinder head by unscrewing the brass hexagonal union nuts at the lower ends.

Remove the six slotted head screws around the cylinder head and lift off the cylinder head.

Examine the diaphragm and replace it if found to be defective.

The diaphragm may be removed by undoing the central screw which attaches it to the connecting rod.

Replace in reverse order, turning the compressor by hand to check freedom before switching on.

Thermometers

If thermometers are broken in their pockets, broken glass and mercury may be removed by turning the unit upside down. Mercury should be caught in a suitable vessel and disposed of according to the local safety regulations.

Due to the relatively small temperature differences between water inlet and outlet temperatures, it is advisable to use calibrated or matched pairs of thermometers when the heat transfers are to be evaluated.

Should the column of liquid in a thermometer become separated it may be rejoined by a responsible person in the following manner.

Remove the thermometer from the unit, then place it in water so that its scale can be observed. Gently heat the water until the liquid in the thermometer enters the enlarged portion at the top of the column. When the separated liquid has united the thermometer should then be allowed to cool slowly.

Caution

Since the thermometer will burst if overheated, eye protection should be worn.

Calibration of Thermometers

The thermometers supplied with this unit are of commercial accuracy at 0, 20, 40 and 5O°C.

At intervals, and as a valuable student exercise, the thermometers should be calibrated against a standard thermometer* in the following manner.

Remove all thermometers from the unit and affix labels to each for identification.

Place all the thermometers, together with the standard thermometer, in a vessel containing at least 1 litre of cold water.

Note: (i) Wicks on wet bulb thermometers (where applicable) need not be removed.

(ii) Ensure that the bulb of each thermometer is immersed to a depth of 75mm.

Gently stir the water for about 2 minutes then record the temperature indicated by each thermometer.

Increase the water temperature in increments of about 5K, repeating the above procedure until the expected operating range of the thermometers has been covered.

When the individual thermometer readings are compared with the standard, any corrections necessary will become evident. These corrections should be recorded and applied to the appropriate thermometer when in use.

*If no standard thermometer is available one of the supplied thermometers (indicating approximately mean temperatures) should be selected and used as the standard.

<u>Panel</u>

This may be cleaned with a mild detergent and then polished with a soft cloth. Abrasive cleaners must not be used.

The plastic dust cover provided should be kept in position when the unit is not in use.

<u>Checking for Leaks</u>

If a leak in the refrigerant circuit is suspected, e.g. if there is a loss of refrigerant from the system, the following procedure should be adopted:

(A) <u>If there is refrigerant in the system:</u>

Place the unit in a warm place until its temperature reaches 25-30°C. The pressure throughout the system will now be above atmospheric and the leak may be located either by

(i) Applying a strong soap or detergent solution to all joints,

(ii) Using a Halogen leak detector,

(iii) Using an electronic leak detector.

(B) <u>If there is no refrigerant in the system:</u>

Either

(i) Introduce about 100ml of R11 into the evaporator (by disconnecting the suction pipe at its top) and then proceed as in A.

or

(ii) Pressurize the system to 50 kN m^{-2} with air by applying a manual pump, e.g. motor car tyre pump, to the charging valve at the base of the evaporator. The leak may then be located as in A (i).

<u>Charging or Recharging</u>

(This is also a valuable demonstration for students.)

<u>Preparation</u>

Place the filled 1kg cylinder of R11 (supplied by P.A. Hilton Ltd.) in water at up to 50°C for about 5 minutes.

Remove the cylinder from the water and screw the knurled nut on to the end ensuring that the washer is in place.

Screw the charging adaptor into the knurled nut (two threads only) and connect the flexible hose (provided) between the cone fitting on the valve at the bottom of the condenser.

By rotating the cylinder of R11, fully screw the adaptor into the knurled nut, using a spanner if necessary. As the adaptor is screwed in, it will open the valve in the top of the cylinder and allow R11 to enter the hose.

The unit is now ready for charging.

Charging

Set the condenser water flow rate to the maximum and the evaporator flow to a small flow – approximately 10 gm s^{-1}.

Switch on the compressor.

Pull gently on the relief valve spindle to discharge air from the condenser.

Switch off the compressor when the pressure in the evaporator has fallen to -30 to -50 kN m^{-2}.

Invert the refrigerant container, so that the outlet is at the bottom.

Ease open the valve at the base of the evaporator and allow R11 liquid to flow into the evaporator (a certain amount of flash vapour will be produced during this process).

When the R11 liquid covers the coils in the evaporator, the charging valve on the evaporator should be closed and the compressor started.

Allow the unit to run for about 5 minutes until the float valve in the condenser floats freely.

Switch off the compressor, open the charging valve and continue the charging process until the liquid level in the evaporator is 15mm above the top coil of the heat exchanger.

Close the charging valve and disconnect the charging pipe. Remove the knurled nut and charging adaptor from the R11 cylinder and store these carefully.

The R11 cylinder should be stored away from direct sunlight and other heat sources.

If it is desired to demonstrate the charging of R11 vapour into the evaporator the R11 container should be kept valve uppermost in water at a maximum temperature of 50°C.

Charging may now proceed as before but with the compressor running continuously until the correct level is reached.

It should be appreciated that this is a much slower process than charging with liquid.

Discharging

The evaporator may be emptied by opening the charging valve and directing the liquid into a suitable container. If the evaporator is below atmospheric pressure slacken the hexagonal union nut on the top cover of the evaporator to allow air to enter the system.

OPERATION

Adjust the water flow through both the evaporator and condenser to about 50 gm s^{-1}. Turn on the mains switch. The strip lights should now illuminate the condenser and evaporator and the compressor should run. If not, check the fuse which is adjacent to the switch.

Reduce the condenser water flow until the condenser pressure rises to about 50 kN m^{-2} gauge. Check that the condenser temperature agrees with the saturation temperature corresponding with the condenser pressure (See Page 37). Any discrepancy is probably due to air in the condenser. This may be expelled by stopping the compressor, then gently pulling on the relief valve spindle.

The unit may now be set to operate on any conditions within its capability.

The evaporating and condensing pressure and temperature are determined only by the inlet temperature and flow rates through the coils.

CAPABILITIES OF THE REFRIGERATION CYCLE DEMONSTRATION UNIT

1. Demonstration of the vapour compression refrigeration or heat pump cycle with visual observation of the important processes.
2. Investigation/demonstration of the saturation pressure-temperature relationship during evaporation and condensation.
3. Demonstration of "pumping over" into the condenser.
4. Demonstration of charging.
5. Demonstration of effect of air in refrigeration system.
6. Determination of effect of evaporating and condensing temperatures on the refrigeration rate and production of performance curves.
7. Estimation of coefficient of performance.
8. Determination of overall heat transfer coefficient in a simple coil and tube type evaporator or condenser.

1. DEMONSTRATION OF VAPOUR COMPRESSION REFRIGERATION OR HEAT PUMP CYCLE

Having started the unit, allow it to stabilise with moderate water flow rates through the coils.

The Vapour Compression Cycle can now be examined and the following noted:

(i) The compressor creates a low pressure in the evaporator and a higher pressure in the condenser.

(ii) In the evaporator, the refrigerant boils at a low temperature, taking heat from the water flowing through the coils. The water is thus chilled and leaves at a lower temperature.

(iii) In the condenser, the refrigerant condenses at a higher temperature, rejecting heat to the water flowing through the coil. The water is thus warmed and leaves at a higher temperature.

(iv) The high pressure liquid leaves the condenser through the float controlled expansion valve and returns to the evaporator. As it flows through the sight glass, the refrigerant is a mixture of vapour and liquid. The temperature of the refrigerant after the expansion valve is the same as the evaporator temperature and well below that of the liquid in the condenser.

Effect of Evaporating Temperature

If the water flow rate through the evaporator coil is reduced (without changing condenser conditions), the evaporating pressure and temperature will fall. As this happens, it will be seen that the rate of condensation on the condenser coil decreases.

This confirms the expectations that the refrigerant mass flow rate falls as evaporating temperatures (and pressure) decrease. This is mainly due to the increased specific volume of the refrigerant and reduced volumetric efficiency of the compressor.

Effect of Condensing Temperature

If the water flow rate through the condenser coil is reduced (without changing the evaporator conditions) the condensing temperature and pressure will rise. As this happens, the rate of condensation is again seen to fall, principally due to the reduction of volumetric efficiency as the compressor pressure ratio increases.

2. PRESSURE TEMPERATURE RELATIONSHIP

Start the unit. Ensure that there is no air in the system and allow it to "warm up".

Operate the unit through a range of evaporating and condensing pressures (by variation of the water flow rates) noting the values as soon as conditions are stable.

Convert all gauge pressures to absolute pressure, then draw a graph of evaporating and condensing temperatures, i.e. saturation temperatures, against pressure.

The results may be compared with the curve shown in Page 36.

Discrepancies may be attributed to lack of stability, instrument errors* and air or other gases in the system.

*It is worth noting that a small error occurs in the indicated evaporator pressure due to the hydrostatic pressure of the liquid in the gauge connecting pipe. The gauge may read a maximum of 4kN m^{-2} lower than the evaporator pressure.

3. DEMONSTRATION OF "PUMPING OVER" INTO THE CONDENSER

During maintenance of refrigeration plants~ particularly when replacement of components is involved, it is convenient to transfer the refrigerant to the condenser. This has the advantage of saving the refrigerant for further use and also may avoid the need of evacuation prior to recharging.

To demonstrate this, the following procedure may be followed.

Turn on the water to the evaporator and condenser and start the compressor.

Close the isolating valve at the bottom of the condenser thus stopping the flow from the expansion valve to the evaporator. The refrigerant will now be transferred from the evaporator and will appear as liquid in the condenser.

Note: In an industrial plant, isolating valves are usually fitted between all major components. As soon as the refrigerant has been transferred to the condenser (or liquid receiver) the valves may be closed, trapping the liquid. The defective component can then be serviced or replaced without losing the refrigerant charge.

At the end of the demonstration, the isolating valve should be opened. The refrigerant will then return to its normal position.

4. DEMONSTRATION OF CHARGING

See Page 17.

5. DEMONSTRATION OF THE EFFECT OF AIR IN A REFRIGERATION SYSTEM

When air is present in a refrigeration plant it will normally be swept from the evaporator by the flow of refrigerant vapour and will become trapped in the condenser.

For a combination of reasons, the air will cause the compressor delivery pressure to rise, reducing the coefficient of performance, and increasing the power input for a given duty.

The increase of pressure is due to

(i) The total pressure in the condenser is approximately equal to the sum of the refrigerant saturation pressure and the pressure of the air present (Dalton's Law).

and

(ii) The air tends to be swept towards the heat transfer surfaces, forming an insulating layer which reduces the heat transfer coefficient. This in turn drives up the temperature difference required for a given heat transfer rate and this results in a higher refrigerant saturation temperature and pressure.

The effect of air in the system may be demonstrated as follows:

Start the unit and adjust the condenser cooling water flow rate to about 30 gm s^{-1}. Adjust the evaporator water flow rate so that the evaporator pressure is at least 20 kN m^{-2} below atmospheric and allow conditions to stabilise.

Note the evaporator and condenser pressures.

Open the charging valve at the base of the evaporator and allow a small quantity of air to enter the evaporator and then close the valve. There will be a transient small increase in evaporator pressure as the air enters and then it will return to normal as the air is transferred to the condenser.

If the condenser coils are examined it will be found that condensation is sluggish due to the insulating layer of air. When the air is released, by pulling on the relief valve spindle, condensation will become vigorous and the condenser pressure will quickly fall to normal.

6. EFFECT OF EVAPORATING AND CONDENSING TEMPERATURES ON THE REFRIGERATION RATE

Start the compressor and adjust the water flow rate through the condenser to 50 gm s^{-1}. Adjust the flow rate through the condenser to about 30 gm s^{-1} and allow the condition to stabilise. Note all flow rates, temperatures, and pressures.

Reduce the condenser water flow rate so that the condenser temperature increases by about 2K and at the same time adjust the evaporator water flow rate to give the same evaporating temperature as initially. Allow conditions to stabilise, then observe all flow rates, temperatures, and pressures.

Repeat with similar increments of condensing pressure and temperature~ while keeping the evaporating temperature constant.

Typical results are shown below.

Observations Room Temperature (t_a) = 21°C Barometer 985 mbar = 98.5 kN m^{-2}					
Test No.	1	2	3	4	5
Evaporator Gage Pressure, p_e, [kN m^{-2}]	-51	-51	-51	-51	-51
Evaporator Temperature, t_e, [°C]	4	4	4	4	4
Evaporator Water Flow Rate, $\dot{m}_e$, [gm s^{-1}]	27	18.25	12	9	6
Evaporator Water Inlet Temp, t_1, [°C]	12.6	12.9	13.1	13.4	13.6
Evaporator Water Outlet Temp, t_2, [°C]	10.8	10.4	9.75	9.5	8.25
Condenser Gage Pressure, p_c, [kN m^{-2}]	-12	-2	7	10	18
Condenser Temperature, t_c, [°C]	17.5	19.5	21.5	23.5	25.8
Condenser Water Flow Rate, $\dot{m}_c$, [gm s^{-1}]	50	17.5	11	7.2	6
Condenser Water Inlet Temp, t_3, [°C]	12.6	12.75	13	13.25	13.7
Condenser Water Outlet Temp, t_4, [°C]	14.1	16.9	19.25	22.25	23.3

SPECIMEN CALCULATIONS FOR TEST NO.2

EVAPORATOR

Rate of Heat Transfer to Water in Evaporator:

$$= m_e C_p (t_1 - t_2)$$

$$= 18.25 \times 10^{-3} \times 4.18(12.9 - 10.4) \text{ kW}$$

$$= \underline{\underline{0.191 \text{ kW}}} \text{ or } \underline{\underline{191 \text{ W}}}$$

Heat Transfer from Surroundings:

$= 0.8(t_a - t_e)$ W *See Page 5

$= 0.8(21 - 4)$ W

$= \underline{\underline{13.6 \text{ W}}}$

<u>Total Refrigerating Effect</u> $Q_e = 191 + 13.6 = \underline{\underline{204.6 \text{ W}}}$

<u>CONDENSER</u>

Rate of Heat Transfer to Water in Condenser:

$= m_c C_p (t_4 - t_3)$

$= 17.5 \times 10^{-3} \times 4.18(16.9 - 12.75)$ kW

$= \underline{\underline{0.304 \text{ kW}}}$ or $\underline{\underline{304 \text{ W}}}$

Heat Transfer from Surroundings:

$= 0.8(t_a - t_c)$ *See Page 3

$= 0.8(21 - 19.5)$

$= \underline{\underline{1.2 \text{ W}}}$

Total Heat Transfer at Condenser $Q_c = 304 - 1.2 = \underline{\underline{303 \text{ W}}}$

Similar calculations yield the following results:

DERIVED RESULTS

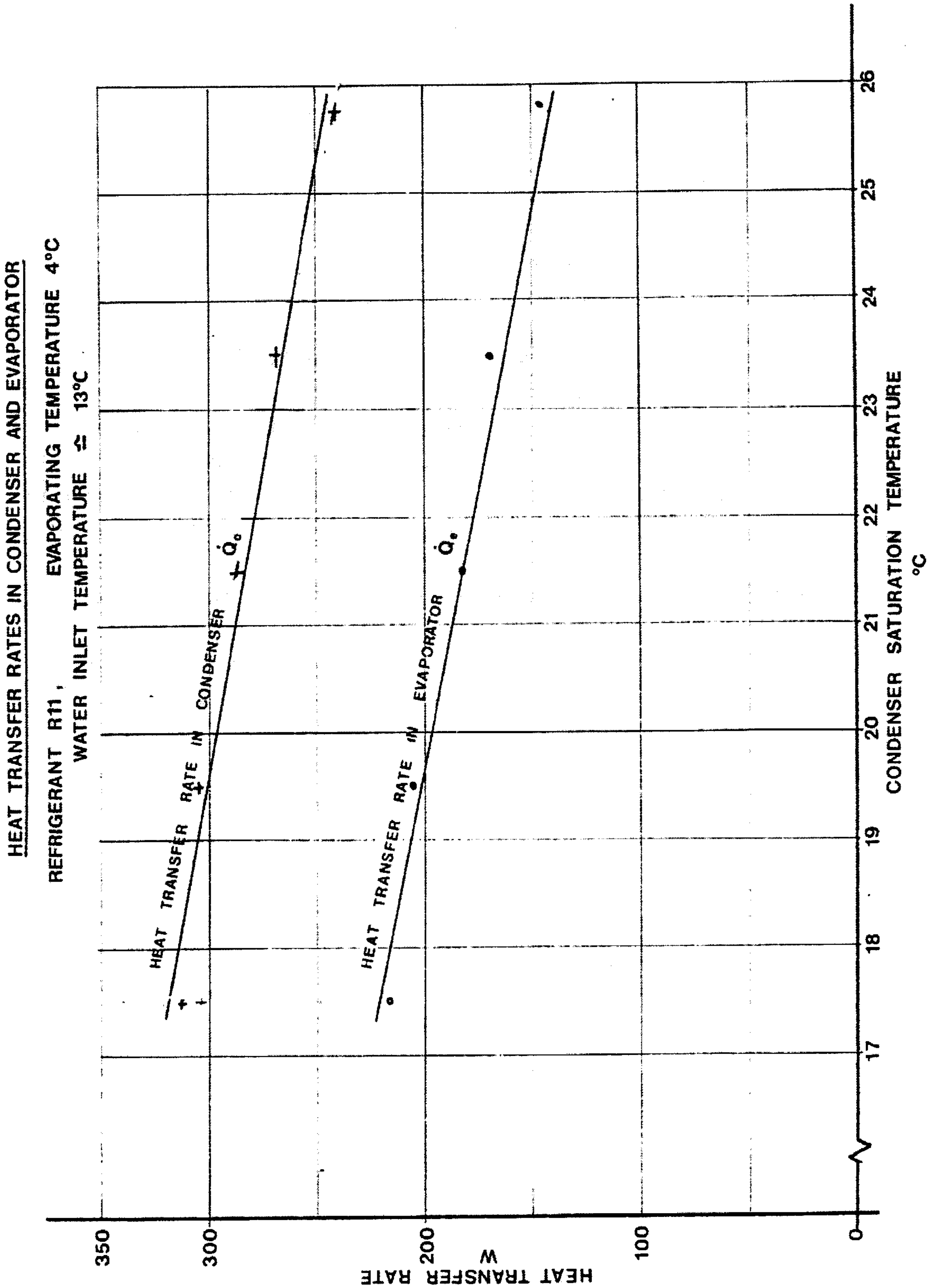
Evaporating Temp	T_e, [°C]	4	4	4	4	4
Condensing Temp	T_c, [°C]	17.5	19.5	21.5	23.5	25.8
Heat Transfer in Evaporator	Q_e, [W]	216	205	182	170	147
Heat Transfer in Condenser	Q_c [W]	313	303	286	269	240

The graph on Page 27 has been drawn from these results.

It will be seen that both the heat transfer at the evaporator and the condenser increase as the condensing temperature decreases. This effect is largely attributed to the reduction of the volumetric efficiency of the compressor as the pressure ratio increases.

The above test may be repeated at other evaporating temperatures.

Note: It may be necessary to supply slightly warmed water to the unit to get a wider range of evaporating temperatures.


HEAT TRANSFER RATES IN CONDENSER AND EVAPORATOR
REFRIGERANT R11, EVAPORATING TEMPERATURE 4°C
WATER INLET TEMPERATURE ≐ 13°C
HEAT TRANSFER RATE IN CONDENSER
$\dot{Q}_c$
HEAT TRANSFER RATE IN EVAPORATOR
$\dot{Q}_e$
HEAT TRANSFER RATE
W
350
300
200
100
0
17
18
19
20
21
22
23
24
25
26
CONDENSER SATURATION TEMPERATURE
°C

7. ESTIMATION OF COEFFICIENT OF PERFORMANCE

Procedure and Observations as on Pages 23 and 24 (i.e. Effect of Evaporating and Condensing Temperatures on the Refrigeration Rate).

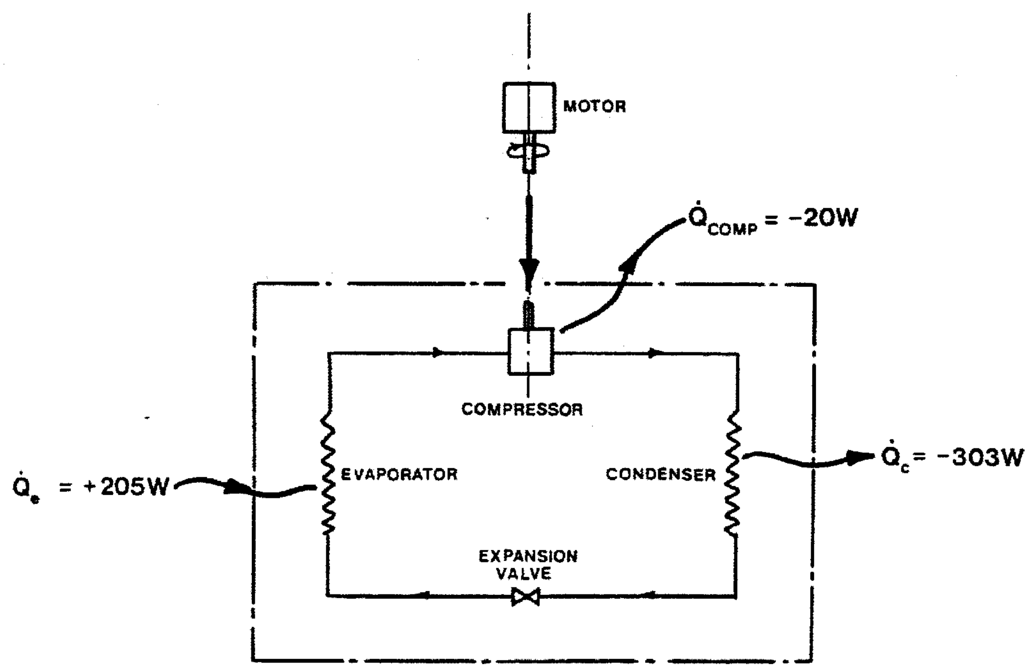
CALCULATIONS – Test No.2

Heat Transfer at Evaporator = 205 W From Page 24

Heat Transfer at Condenser = 303 W

It has been estimated that the heat loss from the compressor is typically 20W (See Page 5).

Considering the plant indicated and using the normal sign convention



For the cycle, the net heat transfer rate = the net work transfer rate

Thus, $P = \dot{Q}_e + \dot{Q}_c + \dot{Q}_{comp}$

$= 205 - 303 - 20$

$= \underline{-118\ W}$

The Coefficient of Performance of a Refrigerator is the ratio

$$\frac{\text{Heat transfer in evaporator}}{\text{Work transfer at compressor}}$$

Thus, $CoP_{\mathrm{Re}f} = \dfrac{205}{118} = 1.74$

The Coefficient of Performance of a Heat Pump is the ratio

$$\frac{\text{Heat transfer in condenser}}{\text{Work transfer at compressor}}$$

Thus, $CoP_{HeatPump} = \dfrac{303}{118} = 2.57$

Similar calculations yield the following derived results:

Evaporating Temp	T_e, [°C]	4	4	4	4	4
Condensing Temp	T_c, [°C]	17.5	19.5	21.5	23.5	25.8
Heat Transfer in Evaporator	Q_e, [W]	216	205	182	170	147
Heat Transfer in Condenser	Q_c [W]	313	303	286	269	240
Power Input to Compressor	P [W]	117	118	124	119	113
CoP_{Ref}	---	1.85	1.74	1.46	1.43	1.3
$CoP_{Heat\ Pump}$	---	2.68	2.57	2.3	2.26	2.12

These results are shown graphically on Page 32.

It will be noted that the Coefficient of Performance in both cases decreases as the condensing temperature increases. This may be largely attributed to the increased specific work as the compressor pressure ratio is raised.

The above test may be repeated at other evaporating temperatures.

Note: It may be necessary to supply the unit with slightly warmed water to obtain a wide range of evaporating temperatures.

It should be noted that this work input has not been measured directly. It has been deduced from the various measured heat transfers and estimated heat transfers to or from the surroundings at the condenser, evaporator and compressor.

Since each of these heat transfers will be subject to some error, the estimated power input at the compressor will be affected by the sum of these errors.

Alternative Method of Estimating Power Input

A watt meter, integrating energy meter, or voltmeter and ammeter may be connected into the electrical supply so that the electrical power input may be measured. (Neither of these instruments are supplied with the unit, but they will be available in most Universities and Colleges.)

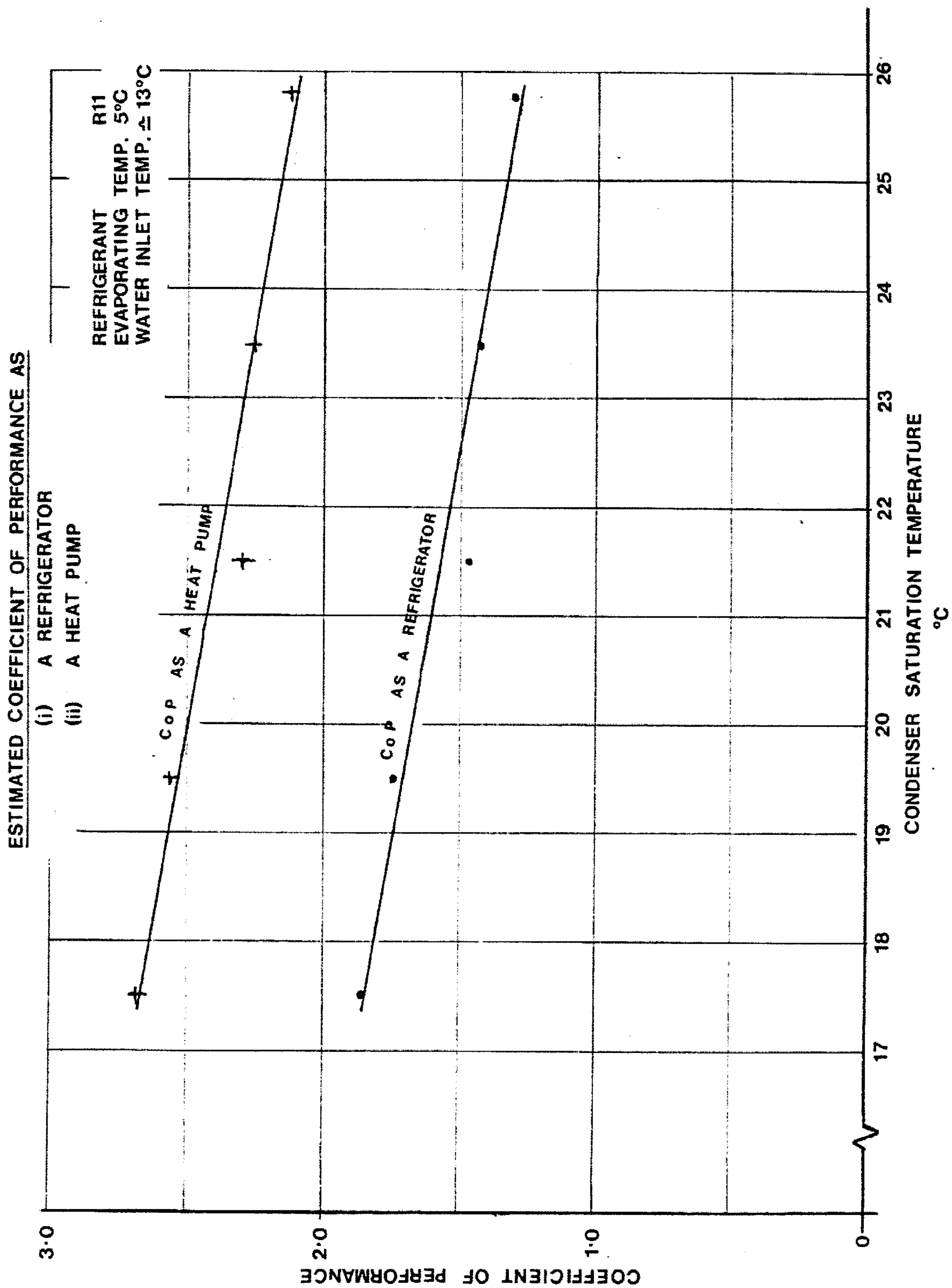
The combined efficiency of the electric motor and compressor may be taken as 50%, so that Compressor Piston Power ~O.5 Electrical Input.

Note: The measured electrical power includes that used by the lamps and an allowance should be made for this. Alternatively, the lamps may be removed for this test.

THE HILTON REFRIGERATION LABORATORY UNIT

When extensive evaluation of the refrigeration cycle with rapid and accurate measurement of all heat and work transfers are required, the Hilton Refrigeration Laboratory Unit is recommended.

P.A. Hilton Limited will be pleased to supply full details about this unit.


ESTIMATED COEFFICIENT OF PERFORMANCE AS
(i) A REFRIGERATOR
(ii) A HEAT PUMP
REFRIGERANT R11
EVAPORATING TEMP. 5°C
WATER INLET TEMP. ± 13°C
CoP AS A HEAT PUMP
CoP AS A REFRIGERATOR
17
18
19
20
21
22
23
24
25
26
CONDENSER SATURATION TEMPERATURE
°C
0
1·0
2·0
3·0
COEFFICIENT OF PERFORMANCE

8. DETERMINATION OF OVERALL HEAT TRANSFER BETWEEN R11 AND WATER IN THE EVAPORATOR AND CONDENSER

The Overall Heat Transfer Coefficient (U) is the heat transfer rate per unit area when a temperature difference of one degree exists between the hot and cold fluids.

In a condenser or evaporator, the refrigerant temperature is sensibly constant, but the water temperature either rises or falls as it passes through the coils.

The temperature difference to be used in this case is the "Logarithmic Mean" which is given by

$$\Theta_{mean} = \frac{\Theta_{inlet} - \Theta_{outlet}}{Ln\frac{\Theta_{inlet}}{\Theta outlet}}$$

where Θ_{inlet} = Temperature difference between the two fluids at inlet,

and Θ_{outlet} = Temperature difference between the two fluids at outlet.

From Test 2, Page 24 and calculations on Page 24.

For the Evaporator

Heat Transfer Rate Q = 191 W

Θ_{inlet} = 12.9 – 4 = 8.9 K

Θ_{outlet} = 10.4 – 4 = 6.4 K

$$\Theta_{mean} = \frac{8.9 - 6.4}{Ln\frac{8.9}{6.4}} = \underline{\underline{7.58K}}$$

$$U = \frac{\dot{Q}}{A\Theta_m}$$

$$U = \frac{191}{0.032 \times 7.58} W \cdot m^{-2} \cdot K^{-1}$$

$$U = 787 W \cdot m^{-2} \cdot K^{-1}$$

<u>For the Condenser</u>

Heat Transfer Rate Q = 304 W

Θ_{inlet} = 19.5 – 12.75 = 6.75 K

Θ_{outlet} = 19.5 – 16.9 = 2.6 K

$$\Theta_{mean} = \frac{6.75 - 2.6}{Ln\frac{6.75}{2.6}} = \underline{\underline{4.35K}}$$

$$U = \frac{\dot{Q}}{A\Theta_m}$$

$$U = \frac{304}{0.032 \times 4.35} W \cdot m^{-2} \cdot K^{-1}$$

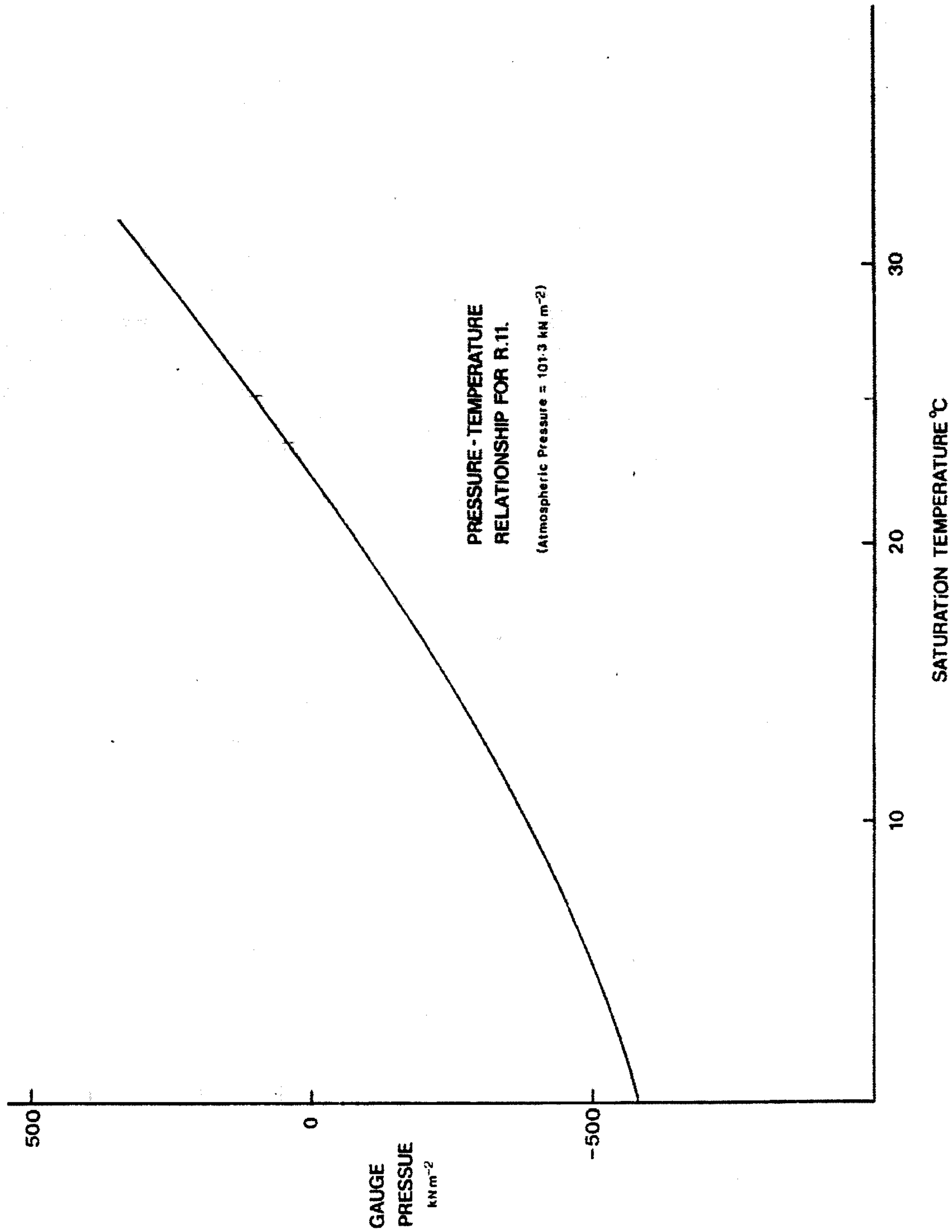
$$U = \underline{\underline{2184 W \cdot m^{-2} \cdot K^{-1}}}$$

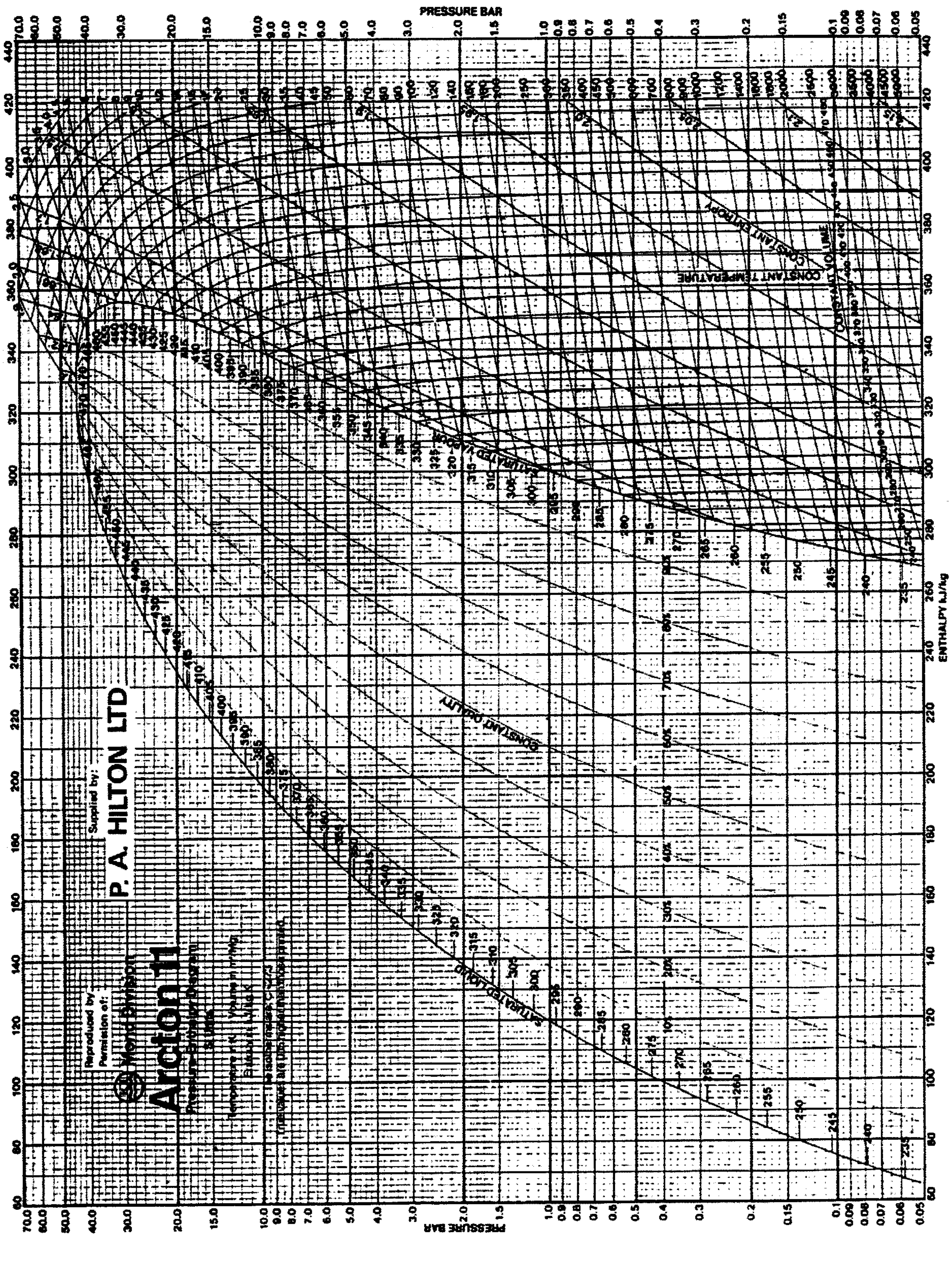
The effect of water flow rate on the overall heat transfer rate forms an interesting investigation for more advanced students.

OBSERVATIONS

Room Temperature (t_a) = °C Barometer mbar = kN m^{-2}

Test No.	1	2	3	4	5
Evaporator Gauge Pressure $\frac{p_e}{kN\ m^{-2}}$					
Evaporator Temperature $\frac{t_e}{°C}$					
Evaporator Water Flow Rate $\frac{\dot{m}_e}{gm\ s^{-1}}$					
Evaporator Water Inlet Temp. $\frac{t_1}{°C}$					
Evaporator Water Outlet Temp. $\frac{t_2}{°C}$					
Condenser Gauge Pressure $\frac{p_c}{kN\ m^{-2}}$					
Condenser Temperature $\frac{t_c}{°C}$					
Condenser Water Flow Rate $\frac{\dot{m}_c}{gm\ s^{-1}}$					
Condenser Water Inlet Temp. $\frac{t_3}{°C}$					
Condenser Water Outlet Temp. $\frac{t_4}{°C}$					

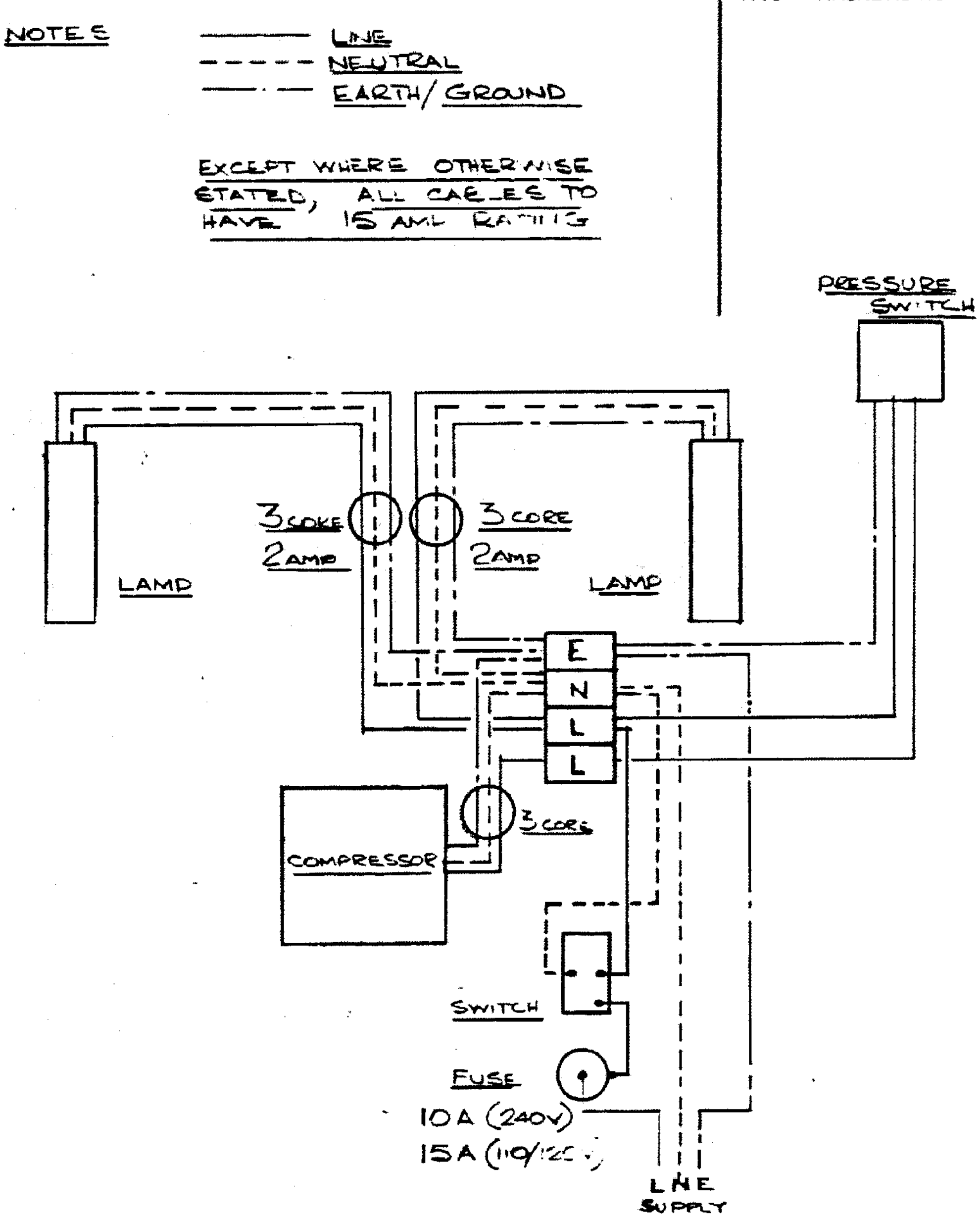

PRESSURE - TEMPERATURE
RELATIONSHIP FOR R.11.
(Atmospheric Pressure = 101·3 kN m^{-2})
GAUGE
PRESSUE
kN m^{-2}
500
0
-500
10
20
30
SATURATION TEMPERATURE °C


PRESSURE BAR
ENTHALPY kJ/kg
Arcton 11
Supplied by:
P. A. HILTON LTD
SATURATED LIQUID
SATURATED VAPOUR
CONSTANT QUALITY
CONSTANT ENTROPY
CONSTANT VOLUME
CONSTANT TEMPERATURE

Physical Data

ARCTON		11	12	22	113
		Trichloro-fluoromethane	Dichlorodi-fluoromethane	Chlorodi-fluoromethane	Trichloro-trifluoroethane
BRITISH UNITS					
Chemical Formula		CCl_3F	CCl_2F_2	$CHClF_2$	$CCl_2F\text{-}CClF_2$
Molecular Weight		137·38	120·93	86·48	187·39
Boiling Point at 1 atm	°F	74·8	−21·62	−41·4	117·6
Freezing Point	°F	−168	−252	−256	−31
Critical Temperature	°F	388·4	233·6	204·8	417·4
Critical Pressure	atm	43·2	40·6	48·7	33·7
	lb/sq in abs	635	596·9	716	495
Critical Volume	cu ft/lb	0·0289	0·0287	0·0305	0·0278
Critical Density	lb/cu ft	34·6	34·84	32·8	36·0
Specific Heat of Liquid at 86°F	B.t.u./lb/°F	0·209	0·236	0·335	0·218
Specific Heat of Vapour at Constant Pressure (1 atm at 36°F)	B.t.u./lb/°F	0·135	0·148	0·152	0·161 (140°F)
Ratio of Specific Heats (Cp/Cv) at 1 atm and 86°F		1·136	1·136	1·184	1·080 (140°F)
Density of Liquid at 86°F	lb/cu ft	91·38	80·67	73·38	96·96
Density of Saturated Vapour at boiling point	lb/cu ft	0·365	0·395	0·301	0·461
Latent Heat of Vaporisation at boiling point	B.t.u./lb	78·31	71·04	100·66	63·12
Thermal Conductivity of Liquid at 68°F	B.t.u./ft/sq ft/h/°F	0·053*	0·042*	0·052*	0·0521 (86°F)
Thermal Conductivity of Vapour at 86°F (1 atm)	B.t.u./ft/sq ft/h/°F	0·0048	0·0059*	0·0068	0·00450 (0·5 atm)
Surface Tension at 77°F	dynes/cm	19	9	9	19
Viscosity of Liquid at 86°F	Centipoise	0·405	0·251	0·229	0·619
Viscosity of Vapour at 1 atm and 86°F	Centipoise	0·0111	0·0127	0·0131	0·0104 (0·1 atm)
Solubility of Water in 'Arcton'	wt % at 86°F	0·013	0·012	0·15	0·013
	32°F	0·0036	0·0026	0·060	0·0036
Solubility of 'Arcton' in Water at 1 atm and 77°F	wt %	0·11	0·028	0·30	0·017 (sat'n press)
Relative di-electric strength at 1 atm and 73·4°F (Nitrogen = 1)		3·1	2·4	1·3	2·6 (0·4 atm)
Di-electric constant, liquid. Temperature in °F		2·28$^{84.2}$	2·13$^{84.2}$	6·11$^{75.2}$	2·44^{88}
Di-electric constant, vapour (0·5 atm). Temperature in °F		1·0019$^{75.2}$	1·0016$^{84.2}$	1·0035$^{77.7}$	1·0024$^{81.5}$
METRIC UNITS					
Chemical Formula		CCl_3F	CCl_2F_2	$CHClF_2$	$CCl_2F\text{-}CClF_2$
Molecular Weight		137·38	120·93	86·48	187·39
Boiling Point at 1 atm	°C	23·3	−29·8	−40·8	47·57
Freezing Point	°C	−111	−158	−160	−35
Critical Temperature	°C	198	112	96	214·1
Critical Pressure	atm	43·2	40·6	48·7	33·7
	kg/sq cm abs	44·6	42·0	50·3	34·9
Critical Volume	cc/mol	247	217	164	325
Critical Density	g/cc	0·554	0·558	0·525	0·576
Specific Heat of Liquid at 30°C	cal/g/°C	0·209	0·236	0·335	0·218
Specific Heat of Vapour at Constant Pressure (1 atm at 30°C)	cal/g/°C	0·135	0·148	0·152	0·161 (60°C)
Ratio of Specific Heats (Cp/Cv) at 1 atm and 30°C		1·136	1·136	1·184	1·080 (60°C)
Density of Liquid at 30°C	g/cc	1·464	1·292	1·175	1·553
Density of Saturated Vapour at boiling point	g/l	5·85	6·33	4·82	7·38
Latent Heat of Vaporisation at boiling point	cal/g	43·51	39·47	55·92	35·07
Thermal Conductivity of Liquid at 20°C	J/cm/sq cm/s/°C	0·000911*	0·000725*	0·000901*	0·00090 (30°C)
Thermal Conductivity of Vapour at 30°C (1 atm)	J/cm/sq cm/s/°C	0·000083	0·000102*	0·000117	0·000078 (0·5 atm)
Surface Tension at 25°C	dynes/cm	19	9	9	19
Viscosity of Liquid at 30°C	Centipoise	0·405	0·251	0·229	0·619
Viscosity of Vapour at 1 atm and 30°C	Centipoise	0·0111	0·0127	0·0131	0·0104 (0·1 atm)
Solubility of Water in 'Arcton'	wt % at 30°C	0·013	0·012	0·15	0·013
	0°C	0·0036	0·0026	0·060	0·0036
Solubility of 'Arcton' in Water at 1 atm and 25°C	wt %	0·11	0·028	0·30	0·017 (sat'n press)
Relative di-electric strength at 1 atm and 23°C (Nitrogen = 1)		3·1	2·4	1·3	2·6 (0·4 atm)
Di-electric constant, liquid. Temperature in °C		2·28^{29}	2·13^{29}	6·11^{24}	2·44^{29}
Di-electric constant, vapour (0·5 atm). Temperature in °C		1·0019^{24}	1·0016^{29}	1·0035$^{25.4}$	1·0024$^{27.5}$

ISSUE AMENDMENTS



The supplier is required to deliver goods strictly according to drawing. Component inspection is the suppliers responsibility. Remove all sharp edges and burrs.	Drawn by : D C F
	Dimensions : —
Limits unless otherwise stated : Fractions ± 1/5 mm (1/64") Decimals ± 0·25 mm (0·01")	Projection :
	Issue : /
TITLE: WIRING DIAGRAM . R632	Date : 13.10.83 — DRG. No. 63272
MTL:	Scale : -
FINISH:	no/rig : -

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2 Dr. Kim's (Revised) Expectations for Analysis and Discussion for the Refrigeration Performance lab

Aside from organized data in tables (including wattage, measured with a "Watts-Up Meter"), Dr. Kim wanted students to calculate the following:

- $\dot{m}_{\text{coolant}} = (\dot{m}_{\text{evap, water}} C_p \Delta T_{\text{evap, water}})/(h_1 - h_4)$
- $W_{\text{comp}} = \dot{m}_{\text{coolant}}(h_2 - h_1)$
- $\nu_{\text{mech}} = \dot{W}_{\text{comp}}/\dot{W}_{\text{elec}}$
- $\text{COP} = \dot{Q}_L/\dot{W}_{\text{comp}}$

In addition, discuss:

- How can COP be improved?
- Why is COP a function of refrigerator load?
- How does the actual COP compare with the ideal COP?

THERMODYNAMIC PROPERTIES OF SATURATED TRICHLOROFLUOROMETHANE (R-11)

Temp	Pressure		Volume		Density		Enthalpy			Entropy		Temp
			Liquid	Vapor	Liquid	Vapor	Liquid	Latent	Vapor	Liquid	Vapor	
°F	psia	psig	ft³/lbm	ft³/lbm	lbm/ft³	lbm/ft³	Btu/lbm	Btu/lbm	Btu/lbm	Btu/lbm-R	Btu/lbm-R	°F
-94	0.08234	29.754*	0.0094936	346.72	105.33	0.0028841	-6.0915	86.879	80.788	-0.015323	0.22318	-94
-92	0.09052	29.737*	0.0095077	317.12	105.18	0.0031534	-6.0237	87.037	81.014	-0.015138	0.22243	-92
-90	0.09939	29.719*	0.0095219	290.38	105.02	0.0034438	-5.9384	87.179	81.240	-0.014906	0.22169	-90
-88	0.10900	29.699*	0.0095360	266.19	104.87	0.0037567	-5.8363	87.304	81.467	-0.014631	0.22097	-88
-86	0.11940	29.678*	0.0095502	244.29	104.71	0.0040935	-5.7184	87.413	81.695	-0.014315	0.22026	-86
-84	0.13065	29.655*	0.0095643	224.43	104.56	0.0044556	-5.5853	87.509	81.923	-0.013960	0.21957	-84
-82	0.14280	29.630*	0.0095785	206.42	104.40	0.0048446	-5.4378	87.590	82.152	-0.013568	0.21889	-82
-80	0.15592	29.604*	0.0095927	190.04	104.25	0.0052619	-5.2767	87.658	82.382	-0.013143	0.21823	-80
-78	0.17005	29.575*	0.0096068	175.15	104.09	0.0057093	-5.1025	87.714	82.612	-0.012685	0.21758	-78
-76	0.18528	29.544*	0.0096210	161.59	103.94	0.0061884	-4.9160	87.758	82.842	-0.012198	0.21694	-76
-74	0.20165	29.511*	0.0096352	149.23	103.79	0.0067010	-4.7176	87.791	83.073	-0.011682	0.21632	-74
-72	0.21925	29.475*	0.0096494	137.95	103.63	0.0072489	-4.5080	87.813	83.305	-0.011140	0.21571	-72
-70	0.23815	29.436*	0.0096636	127.65	103.48	0.0078341	-4.2878	87.825	83.537	-0.010574	0.21511	-70
-68	0.25843	29.395*	0.0096779	118.23	103.33	0.0084584	-4.0573	87.827	83.770	-0.009984	0.21453	-68
-66	0.28016	29.351*	0.0096921	109.60	103.18	0.0091239	-3.8172	87.820	84.003	-0.009373	0.21395	-66
-64	0.30343	29.303*	0.0097064	101.70	103.02	0.0098328	-3.5679	87.805	84.237	-0.008741	0.21339	-64
-62	0.32832	29.253*	0.0097207	94.454	102.87	0.010587	-3.3098	87.781	84.471	-0.008091	0.21285	-62
-60	0.35493	29.199*	0.0097350	87.802	102.72	0.011389	-3.0434	87.749	84.705	-0.007422	0.21231	-60
-58	0.38335	29.141*	0.0097494	81.689	102.57	0.012242	-2.7690	87.710	84.941	-0.006738	0.21178	-58
-56	0.41368	29.079*	0.0097637	76.068	102.42	0.013146	-2.4871	87.663	85.176	-0.006038	0.21127	-56
-54	0.44602	29.013*	0.0097781	70.893	102.27	0.014106	-2.1980	87.610	85.412	-0.005324	0.21077	-54
-52	0.48047	28.943*	0.0097926	66.125	102.12	0.015123	-1.9020	87.551	85.649	-0.004596	0.21027	-52
-50	0.51715	28.868*	0.0098070	61.728	101.97	0.016200	-1.5996	87.485	85.886	-0.003856	0.20979	-50
-48	0.55616	28.789*	0.0098215	57.670	101.82	0.017340	-1.2909	87.414	86.123	-0.003105	0.20932	-48
-46	0.59762	28.704*	0.0098361	53.921	101.67	0.018546	-0.9763	87.337	86.361	-0.002342	0.20886	-46
-44	0.64165	28.615*	0.0098506	50.455	101.52	0.019820	-0.6562	87.255	86.599	-0.001571	0.20841	-44
-42	0.68838	28.520*	0.0098652	47.248	101.37	0.021165	-0.3306	87.168	86.838	-0.000789	0.20797	-42
-40	0.73794	28.419*	0.0098799	44.278	101.22	0.022584	0.0	87.077	87.077	0.0	0.20754	-40
-38	0.79046	28.312*	0.0098946	41.526	101.07	0.024081	0.3355	86.981	87.316	0.000797	0.20711	-38
-36	0.84607	28.199*	0.0099093	38.973	100.92	0.025659	0.6755	86.880	87.556	0.001602	0.20670	-36
-34	0.90491	28.079*	0.0099241	36.603	100.77	0.027320	1.0200	86.776	87.796	0.002412	0.20630	-34
-32	0.96714	27.952*	0.0099389	34.401	100.62	0.029069	1.3687	86.668	88.037	0.003229	0.20590	-32
-30	1.0329	27.818*	0.0099537	32.355	100.46	0.030907	1.7213	86.556	88.278	0.004052	0.20552	-30
-28	1.1023	27.677*	0.0099686	30.450	100.31	0.032840	2.0777	86.441	88.519	0.004879	0.20514	-28
-26	1.1756	27.528*	0.0099836	28.678	100.16	0.034870	2.4377	86.323	88.761	0.005711	0.20477	-26
-24	1.2529	27.370*	0.0099986	27.026	100.01	0.037002	2.8011	86.201	89.003	0.006546	0.20441	-24
-22	1.3344	27.204*	0.010014	25.486	99.864	0.039238	3.1678	86.077	89.245	0.007386	0.20406	-22
-20	1.4202	27.030*	0.010029	24.049	99.713	0.041582	3.5377	85.950	89.487	0.008229	0.20372	-20
-18	1.5106	26.846*	0.010044	22.707	99.563	0.044039	3.9105	85.820	89.730	0.009074	0.20338	-18
-16	1.6056	26.652*	0.010059	21.454	99.412	0.046612	4.2861	85.687	89.974	0.009922	0.20305	-16
-14	1.7055	26.449*	0.010074	20.282	99.261	0.049305	4.6644	85.553	90.217	0.010773	0.20273	-14
-12	1.8105	26.235*	0.010090	19.185	99.110	0.052123	5.0452	85.416	90.461	0.011625	0.20242	-12
-10	1.9208	26.010*	0.010105	18.159	98.959	0.055069	5.4285	85.276	90.705	0.012479	0.20212	-10
-8	2.0365	25.775*	0.010121	17.197	98.808	0.058148	5.8141	85.135	90.949	0.013334	0.20182	-8
-6	2.1579	25.528*	0.010136	16.296	98.657	0.061364	6.2019	84.992	91.194	0.014190	0.20153	-6
-4	2.2852	25.268*	0.010152	15.451	98.505	0.064721	6.5919	84.847	91.439	0.015047	0.20124	-4
-2	2.4186	24.997*	0.010167	14.658	98.354	0.068224	6.9838	84.700	91.684	0.015905	0.20097	-2
0	2.5583	24.713*	0.010183	13.912	98.202	0.071878	7.3776	84.551	91.929	0.016763	0.20070	0
2	2.7045	24.415*	0.010199	13.212	98.050	0.075686	7.7733	84.401	92.174	0.017621	0.20043	2
4	2.8575	24.103*	0.010215	12.554	97.898	0.079654	8.1707	84.249	92.420	0.018480	0.20017	4
6	3.0174	23.778*	0.010231	11.935	97.746	0.083786	8.5698	84.096	92.666	0.019338	0.19992	6
8	3.1846	23.437*	0.010247	11.352	97.593	0.088088	8.9705	83.941	92.912	0.020196	0.19968	8
10	3.3592	23.082*	0.010263	10.803	97.440	0.092563	9.3727	83.785	93.158	0.021053	0.19944	10
12	3.5415	22.711*	0.010279	10.286	97.287	0.097218	9.7763	83.628	93.404	0.021910	0.19921	12
14	3.7318	22.323*	0.010295	9.7985	97.134	0.10206	10.181	83.470	93.651	0.022766	0.19898	14
16	3.9303	21.919*	0.010311	9.3385	96.981	0.10708	10.588	83.310	93.898	0.023621	0.19876	16
18	4.1372	21.498*	0.010328	8.9042	96.827	0.11231	10.995	83.149	94.144	0.024475	0.19854	18
20	4.3529	21.059*	0.010344	8.4942	96.673	0.11773	11.404	82.987	94.391	0.025328	0.19833	20
22	4.5776	20.601*	0.010361	8.1067	96.519	0.12335	11.814	82.824	94.638	0.026180	0.19813	22
24	4.8115	20.125*	0.010377	7.7405	96.365	0.12919	12.225	82.661	94.885	0.027031	0.19793	24
26	5.0549	19.629*	0.010394	7.3941	96.210	0.13524	12.637	82.496	95.133	0.027880	0.19774	26
28	5.3081	19.114*	0.010411	7.0663	96.055	0.14152	13.050	82.330	95.380	0.028728	0.19755	28
30	5.5715	18.578*	0.010428	6.7559	95.900	0.14802	13.464	82.163	95.627	0.029574	0.19737	30
32	5.8452	18.020*	0.010444	6.4620	95.744	0.15475	13.879	81.996	95.875	0.030419	0.19719	32
34	6.1296	17.441*	0.010462	6.1834	95.589	0.16172	14.295	81.827	96.122	0.031262	0.19701	34
36	6.4249	16.840*	0.010479	5.9193	95.432	0.16894	14.712	81.658	96.370	0.032103	0.19685	36
38	6.7315	16.216*	0.010496	5.6688	95.276	0.17640	15.129	81.488	96.617	0.032942	0.19668	38
40	7.0497	15.568*	0.010513	5.4311	95.119	0.18413	15.547	81.317	96.865	0.033780	0.19652	40
42	7.3798	14.896*	0.010531	5.2054	94.962	0.19211	15.966	81.146	97.112	0.034616	0.19637	42
44	7.7220	14.199*	0.010548	4.9910	94.805	0.20036	16.386	80.973	97.360	0.035450	0.19622	44
46	8.0768	13.477*	0.010566	4.7873	94.647	0.20889	16.807	80.801	97.607	0.036282	0.19607	46
48	8.4444	12.728*	0.010583	4.5936	94.489	0.21769	17.228	80.627	97.855	0.037111	0.19593	48

Problem:

[15 pts] I have constructed an instrument to measure the thermal conductivity of a sample of solid material. My instrument consists of: a hot plate and cold plate which I can use to maintain specific surface temperatures; thermistors which will tell me what those surface temperatures are at any given time; a thermopile which produces a voltage proportional to the heat flux through the sample. For a particular sample, I record the following information at equilibrium conditions:

$$T_{hot} = 40°C$$
$$T_{cold} = 10°C$$
$$thickness = 2cm$$
$$emf_{thermopile} = 145 \times 10^{-6} V$$

If the calibration factor for the thermopile is $1.75 \frac{\mu V}{W/m^2}$, what is the k-factor of the sample tested?

Solution:

1st determine the heat flux from the thermopile output:

$$q' = q/A = \frac{145 \times 10^{-6} V}{\left(1.75 \times 10^{-6} \frac{V}{W/m^2}\right)} = \underline{82.86 W/m^2}$$

Next, apply Fourier's Law of Heat Conduction to find the thermal conductivity:

$$q' = \frac{k}{t} \Delta T$$

$$\Rightarrow 82.86 W/m^2 = \frac{k}{(0.02m)}(40 - 10)K$$

$$\Rightarrow \underline{\underline{k = 0.055 W/m \cdot K}} \longleftarrow \boxed{\text{Ans}}$$

Item	Qty	Room	Location In Room	Comments
600 mL beakers (for oil)	4	103	Green countertop	At least one is mislabeled w.r.t. oils.
Boiler w/ hoses, gloves & specifications sheet	-	103	Front wall	
Box of thermocouple plugs	-	231	Beige ME 415 equip. locker, 2nd shelf	Male and Female, big and small, T and K, plus some random wires.
"Centrifugal Pump Performance" apparatus	-	231	Right-side wall	
Diesel can, 5 gal. capacity	1	103	Green countertop	Empty.
"Diesel Engine Performance" apparatus	-	103	Right-side wall	Recall that the shop water flow meter is broken.
Digital calipers	1	231	Beige ME 415 equip. locker, 2nd shelf	
DV-1 viscometer	-	231	Beige ME 415 equip. locker, top shelf	Black box includes everything but the "Factor Finder."
Earplugs, box of	1	103	Green countertop	
"Factor Finder"	-	231	Beige ME 415 equip. locker, 2nd shelf	Goes with the DV-1 viscometer.
Funnel	1	103	Green countertop	
Garden hoses	6	103	Back wall	At least one of these hoses leaks. Also, hose count is approximate.
"Gas Turbine Performance" apparatus	-	103	Right-side wall	If I recall correctly, one of the hoses has a minor leak.
"Heat Exchanger Performance" apparatus	-	231	Right-side wall	
Hot plate	1	231	Beige ME 415 equip. locker, 2nd shelf	Probably belongs to Dr. Das. His grad students might ask for it back.
Laptop	-	337	Dr. Kim's office	
Motor oils	4	103	Green countertop	
Needle probe alternative apparatus	-	230	--	Does not belong to ME 415, but Rorik and/or the graduate student using the equipment may be willing to lend it.
NI USB-6218 DAQ device	-	337	Dr. Kim's office	
"Refrigerator Performance" apparatus	-	103	Corner table	
Ring stand	1	231	Beige ME 415 equip. locker, 2nd shelf	
Stopwatch	1	231	Beige ME 415 equip. locker, 2nd shelf	Dr. Bargar used to keep it locked in a different cabinet to keep it from "walking off." This is not a bad idea.
"Temperature in Rods" apparatus	-	103	Corner table	
"Thermal Conductivity Measurement" apparatus	-	231	Back wall	Broken, probably beyond reasonable repair
Thermistor measurement devices	3	231	Beige ME 415 equip. locker, 2nd shelf	
Thermocouple measurement device	1	231	Beige ME 415 equip. locker, 2nd shelf	
"Transient Temperature Measurement" spheres	2	231	Beige ME 415 equip. locker, 2nd shelf	
Viscometer stand	-	231	Beige ME 415 equip. locker, 2nd shelf	

libtsl2

What's this?

Remember this gem?* Well, I'm the TA for that class now. Libtsl2, instead of being my homework, will consist of tools and goodies used to actually *run* the labs.

What's in it?

/transient_convection/

/transient_convection.cmbl:

We used Logger Pro to do the first lab. It's pretty trivial to set up in terms of computers, so I just went and did it. Basically, we're just recording one (two for extra fun) temperature(s) with a type-K thermocouple (we also have the apparatus for a type-T but the Vernier sensors don't roll that way) every fifteen seconds over the course of 1.5—2 hours.

Perhaps interestingly, the cmbl format is "just" xml.

/low-temp_viscosity/

/factor_finder.xlsx :

Our viscometer gives a non-united number, and in order to get the actual viscosity (in centiPoise), one needs to use a "factor finder," which is a glorified lookup table. The factor is a function of spindle model (either RV- or LV-, then a number 1–7—for example, LV–2) and set RPM.

Last year, I implemented a lookup table using python. However, engineers looove Excel, so I made an analogous lookup table with Excel. The magic is in a function that looks like this:

```
=vlookup(A2,'Factor Finder'!A4:K14,hlookup(B2,'Factor Finder'!B2:K3,2,FALSE)+1,FALSE)
```

The basic API for *vlookup* is like this:

```
=vlookup(look_for_this_in_first_column, range_of_your_table, output_column_no, exact_nume
```

hlookup is analogous, except it searches by row and not by column. The "lookup" family of functions can't look for two things at once, so we use an intermediate hlookup to get the correct column number.

Alternately, just use the cardboard slidey-thing. It's your time. ;)

* http://github.com/jesusabdullah/libtsl
(Detritus from my student reports, Spr. 2010)

/temp_rods/

/temp_rods.vi :

This is a LabVIEW VI that takes measurements from 10 thermocouples using our National Instruments USB DAQ box. Essentially, this is all it does. It has a lot of bells and whistles, but could definitely use some fine-tuning. Note that the box doesn't have a cold-junction compensator built-in, so we simply use a constant for room temperature and hope that the inaccuracy this introduces isn't important.

It should be noted that this lab had issues with the DAQ box returning garbage values after roughly two minutes of use. This may be solved by grounding at least one of the thermocouples with the "AI_GND" plug on the NI DAQ box, as later shown to work in the case of the generator lab.

/temp_rods.pdf :

This is a print-out of the associated VI.

/boiler_directions/ :

This folder contains a LaTeX document describing how to use the boiler required for this experiment. It includes a picture!

/needle_probes/ :

I ran out of time to fix the Guarded Hot Plate apparatus. Reportedly, it has a busted flux sensor. It actually has three of them, so one should be able to fix it by disconnecting them and reconnecting them until some combination of 2/3 of them behaves as expected. Alternately, one could dig up a replacement HFS somewhere and use that.

Anyways: The measurement stuff for my thesis is pretty much ready to go, so we're going to have students do the isotropic version of this instead.

The code used to actually run the experiment is *not* included, because it's not mine. Look into Matthew Sturm's research if you are interested. Some details: It uses a Campbell CR10X data logger, a hand-made needle, some D-cell batteries and a relay switch to heat the needle, and a thermocouple or two and a voltmeter for measurements. The original code used for analysis was written for IGOR Pro, but the stuff I wrote uses python, and I expect that the students will just use Excel.

/equations.tex :

This is the source code for the corresponding pdf file that describes the equations necessary to use with this lab.

/equations.pdf :

This is the compiled version of the corresponding LaTeX file that describes the equations nessary to use with this lab.

/pump/

/rpm_meter.vi

Only one of the transducers for the pump performance lab was measured with LabVIEW. This VI reads in voltage over an overkill sampling window, finds the fundamental frequency, and converts the result to GPM.

/transducers.md

This document details some research I did on the transducers used for this lab, for future reference. It includes important information about gross inaccuracy in one of the sensors, so if you are doing this lab, *please* read it.

/generator/

/generator.vi

This is the VI that gathers all the data from the generator. There is a lot of stuff to measure!

/generator.pdf

I was proud of the front panel, so I made a .pdf printout to share this VI with my friends!

/transducers.md

This document details most of what's known about the transducers used for this lab. It includes which wires are which, the conversion factors, and more.

/manual/

This folder (if all goes as planned) contains the pdf version of the Unofficial Expanded, Annotated & Revised 2011 Edition of the UAF Mechanical Engineering ME 415: Thermal Systems Laboratory Manual.

/manual.pdf

The manual in question.

/src/

This folder contains a few markdown documents written to update and support the latest edition of the unofficial manual.

/inventory.xls

This is an Excel spreadsheet detailing what equipment we have and where it is located/stored.

/extras/

This folder contains some sub-VIs written for various labs. They tend to be the sort of VIs that should have room for reuse.

/range.vi

This VI implements the range function as seen in such languages as python. It looks something like this:

```
                                 ----------------
                                |                |
0---[from (default 0)]-->|   R A N G E     |
0---[to (required)]------>|----------------|
                                |                |0==[1-D array (from, from+every...to-1)]==>
0---[every (default 1)]->|    *   *   *    |
                                |________________|
```

and is roughly equivalent to range(from, to, every).

/push.vi

This VI makes pushing data to the end of an array easy:

```
                              ----------------
                             |                |
0===[Original Array]====>|     *PUSH*     |
                             |                |0==[New array w/ pushed element]==>
0---[New element]-------->|                |
                             |________________|
```

Note that, unlike many things called "push," in LabVIEW you hardly ever modify an actual variable in-place. This is no exception; it's pretty much a new array coming out.

/pop.vi

push.vi's brother:

```
                          ---------------
                         |               |
                         |               |
                         |     *POP*     |O==[New array w/ missing element]==>
O===[Original Array]====>|               |
                         |               |
                         |               |O---[Popped element]------->
                         |_______________|
```

Like push.vi, this doesn't really modify the original array in-place; it just gives you the last element of the array, plus an array without that last element.

THERMODYNAMIC PROPERTIES OF SATURATED TRICHLOROFLUOROMETHANE (R-11)

Temp	Pressure		Volume		Density		Enthalpy			Entropy		Temp
			Liquid	Vapor	Liquid	Vapor	Liquid	Latent	Vapor	Liquid	Vapor	
°F	psia	psig	ft³/lbm	ft³/lbm	lbm/ft³	lbm/ft³	Btu/lbm	Btu/lbm	Btu/lbm	Btu/lbm-R	Btu/lbm-R	°F
50	8.8251	11.953*	0.010601	4.4094	94.330	0.22679	17.650	80.452	98.102	0.037939	0.19579	50
52	9.2193	11.151*	0.010619	4.2342	94.172	0.23617	18.072	80.277	98.350	0.038765	0.19566	52
54	9.6273	10.320*	0.010637	4.0673	94.012	0.24586	18.495	80.102	98.597	0.039589	0.19553	54
56	10.049	9.4604*	0.010655	3.9085	93.853	0.25585	18.919	79.925	98.844	0.040410	0.19541	56
58	10.486	8.5714*	0.010673	3.7571	93.693	0.26616	19.343	79.748	99.091	0.041230	0.19529	58
60	10.938	7.6522*	0.010691	3.6129	93.533	0.27678	19.768	79.570	99.339	0.042047	0.19517	60
62	11.404	6.7022*	0.010710	3.4754	93.372	0.28774	20.194	79.392	99.585	0.042863	0.19505	62
64	11.886	5.7205*	0.010728	3.3443	93.211	0.29902	20.620	79.213	99.832	0.043676	0.19494	64
66	12.384	4.7065*	0.010747	3.2191	93.049	0.31065	21.046	79.033	100.08	0.044487	0.19484	66
68	12.899	3.6595*	0.010766	3.0997	92.888	0.32262	21.473	78.853	100.33	0.045295	0.19474	68
70	13.429	2.5787*	0.010785	2.9856	92.725	0.33494	21.901	78.672	100.57	0.046102	0.19464	70
72	13.977	1.4634*	0.010804	2.8766	92.563	0.34763	22.329	78.490	100.82	0.046906	0.19454	72
74	14.542	0.3129*	0.010823	2.7725	92.399	0.36068	22.757	78.308	101.06	0.047709	0.19445	74
74.53	14.696	0.0	0.010828	2.7455	92.356	0.36423	22.871	78.259	101.13	0.047922	0.19442	74.
76	15.125	0.4291	0.010842	2.6730	92.236	0.37412	23.186	78.125	101.31	0.048509	0.19436	76
78	15.726	1.0300	0.010861	2.5778	92.072	0.38793	23.615	77.941	101.56	0.049306	0.19427	78
80	16.345	1.6493	0.010881	2.4867	91.907	0.40214	24.045	77.756	101.80	0.050102	0.19419	80
82	16.983	2.2874	0.010900	2.3996	91.742	0.41674	24.475	77.571	102.05	0.050896	0.19411	82
84	17.641	2.9447	0.010920	2.3162	91.577	0.43175	24.906	77.386	102.29	0.051687	0.19403	84
86	18.318	3.6216	0.010940	2.2363	91.411	0.44717	25.337	77.199	102.54	0.052476	0.19396	86
88	19.014	4.3185	0.010960	2.1598	91.245	0.46301	25.769	77.012	102.78	0.053263	0.19388	88
90	19.732	5.0357	0.010980	2.0864	91.078	0.47929	26.201	76.824	103.03	0.054048	0.19382	90
92	20.470	5.7738	0.011000	2.0161	90.911	0.49600	26.633	76.636	103.27	0.054830	0.19375	92
94	21.229	6.5329	0.011020	1.9487	90.743	0.51315	27.066	76.447	103.51	0.055611	0.19369	94
96	22.010	7.3137	0.011041	1.8841	90.575	0.53076	27.500	76.257	103.76	0.056389	0.19363	96
98	22.812	8.1164	0.011061	1.8220	90.406	0.54884	27.934	76.066	104.00	0.057166	0.19357	98
100	23.637	8.9414	0.011082	1.7625	90.237	0.56738	28.368	75.874	104.24	0.057940	0.19351	100
102	24.485	9.7893	0.011103	1.7053	90.067	0.58640	28.802	75.682	104.48	0.058712	0.19346	102
104	25.356	10.660	0.011124	1.6504	89.896	0.60591	29.237	75.489	104.73	0.059482	0.19341	104
106	26.251	11.555	0.011145	1.5977	89.725	0.62591	29.673	75.295	104.97	0.060250	0.19336	106
108	27.170	12.474	0.011166	1.5470	89.554	0.64642	30.109	75.101	105.21	0.061016	0.19331	108
110	28.113	13.417	0.011188	1.4983	89.382	0.66744	30.545	74.905	105.45	0.061780	0.19327	110
112	29.081	14.385	0.011210	1.4514	89.209	0.68899	30.982	74.709	105.69	0.062542	0.19323	112
114	30.074	15.378	0.011231	1.4063	89.036	0.71107	31.419	74.511	105.93	0.063301	0.19319	114
116	31.093	16.397	0.011253	1.3630	88.863	0.73369	31.857	74.313	106.17	0.064059	0.19315	116
118	32.138	17.442	0.011275	1.3212	88.688	0.75686	32.295	74.114	106.41	0.064815	0.19311	118
120	33.210	18.514	0.011298	1.2811	88.513	0.78059	32.734	73.914	106.65	0.065569	0.19308	120
122	34.309	19.613	0.011320	1.2424	88.338	0.80489	33.173	73.714	106.89	0.066321	0.19305	122
124	35.435	20.739	0.011343	1.2051	88.162	0.82978	33.612	73.512	107.12	0.067072	0.19302	124
126	36.589	21.893	0.011366	1.1693	87.985	0.85525	34.052	73.309	107.36	0.067820	0.19299	126
128	37.771	23.075	0.011389	1.1347	87.808	0.88132	34.492	73.105	107.60	0.068566	0.19296	128
130	38.983	24.287	0.011412	1.1013	87.630	0.90800	34.933	72.901	107.83	0.069311	0.19294	130
132	40.223	25.527	0.011435	1.0692	87.451	0.93531	35.374	72.695	108.07	0.070053	0.19292	132
134	41.493	26.797	0.011458	1.0382	87.272	0.96324	35.816	72.488	108.30	0.070794	0.19289	134
136	42.793	28.097	0.011482	1.0082	87.092	0.99182	36.259	72.280	108.54	0.071533	0.19287	136
138	44.124	29.428	0.011506	0.97938	86.911	1.0211	36.701	72.071	108.77	0.072271	0.19286	138
140	45.486	30.790	0.011530	0.95152	86.730	1.0509	37.145	71.861	109.01	0.073006	0.19284	140
142	46.879	32.183	0.011554	0.92463	86.548	1.0815	37.588	71.650	109.24	0.073740	0.19282	142
144	48.305	33.609	0.011579	0.89865	86.365	1.1128	38.033	71.438	109.47	0.074472	0.19281	144
146	49.762	35.066	0.011603	0.87357	86.182	1.1447	38.478	71.224	109.70	0.075203	0.19280	146
148	51.253	36.557	0.011628	0.84933	85.997	1.1774	38.923	71.009	109.93	0.075932	0.19278	148
150	52.777	38.081	0.011653	0.82591	85.813	1.2108	39.369	70.793	110.16	0.076659	0.19277	150
152	54.335	39.639	0.011679	0.80327	85.627	1.2449	39.815	70.576	110.39	0.077384	0.19276	152
154	55.927	41.231	0.011704	0.78138	85.440	1.2798	40.262	70.358	110.62	0.078108	0.19276	154
156	57.553	42.857	0.011730	0.76021	85.253	1.3154	40.710	70.138	110.85	0.078831	0.19275	156
158	59.215	44.519	0.011756	0.73974	85.065	1.3518	41.158	69.917	111.07	0.079551	0.19274	158
160	60.913	46.217	0.011782	0.71993	84.876	1.3890	41.606	69.695	111.30	0.080271	0.19274	160
162	62.647	47.951	0.011808	0.70076	84.687	1.4270	42.056	69.471	111.53	0.080988	0.19273	162
164	64.418	49.722	0.011835	0.68221	84.496	1.4658	42.505	69.246	111.75	0.081705	0.19273	164
166	66.225	51.529	0.011862	0.66425	84.305	1.5055	42.956	69.019	111.98	0.082419	0.19273	166
168	68.071	53.375	0.011889	0.64686	84.113	1.5459	43.407	68.791	112.20	0.083133	0.19273	168
170	69.954	55.258	0.011916	0.63001	83.920	1.5873	43.859	68.562	112.42	0.083844	0.19273	170
172	71.876	57.180	0.011944	0.61370	83.726	1.6295	44.311	68.331	112.64	0.084555	0.19273	172
174	73.838	59.142	0.011971	0.59788	83.532	1.6726	44.764	68.098	112.86	0.085264	0.19273	174
176	75.839	61.143	0.012000	0.58256	83.336	1.7166	45.218	67.864	113.08	0.085972	0.19273	176
178	77.880	63.184	0.012028	0.56771	83.140	1.7615	45.672	67.628	113.30	0.086678	0.19273	178

THERMODYNAMIC PROPERTIES OF SATURATED TRICHLOROFLUOROMETHANE (R-11)

Temp	Pressure		Volume Liquid	Volume Vapor	Density Liquid	Density Vapor	Enthalpy Liquid	Enthalpy Latent	Enthalpy Vapor	Entropy Liquid	Entropy Vapor	Temp
°F	psia	psig	ft³/lbm	ft³/lbm	lbm/ft³	lbm/ft³	Btu/lbm	Btu/lbm	Btu/lbm	Btu/lbm-R	Btu/lbm-R	°F
180	79.961	65.265	0.012057	0.55331	82.942	1.8073	46.127	67.391	113.52	0.087383	0.19273	180
182	82.084	67.388	0.012085	0.53934	82.744	1.8541	46.582	67.152	113.73	0.088087	0.19274	182
184	84.248	69.552	0.012115	0.52580	82.544	1.9019	47.039	66.911	113.95	0.088790	0.19274	184
186	86.455	71.759	0.012144	0.51266	82.344	1.9506	47.496	66.669	114.16	0.089491	0.19274	186
188	88.704	74.008	0.012174	0.49991	82.143	2.0004	47.954	66.424	114.38	0.090191	0.19275	188
190	90.996	76.300	0.012204	0.48753	81.940	2.0511	48.412	66.178	114.59	0.090890	0.19275	190
192	93.332	78.636	0.012234	0.47552	81.737	2.1030	48.871	65.931	114.80	0.091588	0.19276	192
194	95.713	81.017	0.012265	0.46386	81.533	2.1558	49.331	65.681	115.01	0.092284	0.19276	194
196	98.137	83.441	0.012296	0.45253	81.327	2.2098	49.792	65.429	115.22	0.092980	0.19277	196
198	100.61	85.912	0.012327	0.44154	81.121	2.2648	50.254	65.176	115.43	0.093674	0.19277	198
200	103.12	88.427	0.012359	0.43085	80.913	2.3210	50.716	64.921	115.64	0.094367	0.19278	200
202	105.69	90.990	0.012391	0.42047	80.704	2.3783	51.179	64.663	115.84	0.095059	0.19278	202
204	108.29	93.599	0.012423	0.41038	80.494	2.4367	51.643	64.404	116.05	0.095751	0.19279	204
206	110.95	96.255	0.012456	0.40058	80.283	2.4964	52.108	64.142	116.25	0.096441	0.19280	206
208	113.66	98.959	0.012489	0.39105	80.071	2.5572	52.574	63.878	116.45	0.097130	0.19280	208
210	116.41	101.71	0.012522	0.38178	79.858	2.6193	53.041	63.612	116.65	0.097818	0.19281	210
212	119.21	104.51	0.012556	0.37277	79.643	2.6826	53.508	63.344	116.85	0.098506	0.19281	212
214	122.06	107.36	0.012590	0.36400	79.427	2.7472	53.977	63.074	117.05	0.099192	0.19282	214
216	124.96	110.27	0.012625	0.35547	79.210	2.8132	54.446	62.801	117.25	0.099878	0.19282	216
218	127.91	113.22	0.012660	0.34717	78.992	2.8804	54.916	62.526	117.44	0.10056	0.19283	218
220	130.92	116.22	0.012695	0.33910	78.772	2.9490	55.387	62.249	117.64	0.10125	0.19283	220
222	133.97	119.28	0.012731	0.33124	78.551	3.0190	55.860	61.969	117.83	0.10193	0.19284	222
224	137.08	122.38	0.012767	0.32359	78.328	3.0903	56.333	61.687	118.02	0.10261	0.19284	224
226	140.24	125.54	0.012803	0.31614	78.104	3.1632	56.807	61.402	118.21	0.10329	0.19284	226
228	143.45	128.76	0.012840	0.30888	77.879	3.2375	57.282	61.115	118.40	0.10397	0.19285	228
230	146.72	132.02	0.012878	0.30182	77.652	3.3132	57.759	60.825	118.58	0.10466	0.19285	230
232	150.04	135.35	0.012916	0.29494	77.424	3.3906	58.236	60.532	118.77	0.10533	0.19285	232
234	153.42	138.72	0.012954	0.28823	77.194	3.4695	58.714	60.236	118.95	0.10601	0.19285	234
236	156.85	142.16	0.012993	0.28169	76.963	3.5499	59.194	59.938	119.13	0.10669	0.19285	236
238	160.34	145.65	0.013033	0.27532	76.730	3.6321	59.675	59.637	119.31	0.10737	0.19285	238
240	163.89	149.19	0.013073	0.26912	76.496	3.7159	60.156	59.333	119.49	0.10805	0.19285	240
242	167.49	152.80	0.013113	0.26306	76.259	3.8014	60.640	59.026	119.67	0.10872	0.19285	242
244	171.15	156.46	0.013154	0.25716	76.022	3.8886	61.124	58.715	119.84	0.10940	0.19284	244
246	174.87	160.18	0.013196	0.25140	75.782	3.9777	61.609	58.402	120.01	0.11008	0.19284	246
248	178.65	163.96	0.013238	0.24579	75.541	4.0685	62.096	58.086	120.18	0.11075	0.19283	248
250	182.49	167.80	0.013281	0.24031	75.298	4.1613	62.584	57.766	120.35	0.11143	0.19283	250
252	186.39	171.70	0.013324	0.23497	75.053	4.2559	63.073	57.443	120.52	0.11210	0.19282	252
254	190.36	175.66	0.013368	0.22975	74.806	4.3526	63.564	57.116	120.68	0.11278	0.19281	254
256	194.38	179.68	0.013412	0.22466	74.557	4.4512	64.056	56.786	120.84	0.11345	0.19280	256
258	198.47	183.77	0.013458	0.21969	74.307	4.5519	64.549	56.452	121.00	0.11413	0.19279	258
260	202.62	187.92	0.013504	0.21484	74.054	4.6547	65.044	56.115	121.16	0.11480	0.19278	260
262	206.83	192.13	0.013550	0.21010	73.799	4.7597	65.540	55.774	121.31	0.11547	0.19276	262
264	211.11	196.41	0.013598	0.20547	73.542	4.8669	66.038	55.429	121.47	0.11615	0.19275	264
266	215.45	200.75	0.013646	0.20095	73.283	4.9764	66.537	55.081	121.62	0.11682	0.19273	266
268	219.86	205.16	0.013694	0.19653	73.022	5.0882	67.038	54.728	121.77	0.11750	0.19271	268
270	224.33	209.64	0.013744	0.19222	72.759	5.2024	67.541	54.371	121.91	0.11817	0.19269	270
272	228.88	214.18	0.013794	0.18800	72.493	5.3191	68.045	54.010	122.05	0.11884	0.19266	272
274	233.48	218.79	0.013846	0.18388	72.225	5.4384	68.550	53.644	122.19	0.11952	0.19264	274
276	238.16	223.47	0.013898	0.17985	71.954	5.5602	69.058	53.274	122.33	0.12019	0.19261	276
278	242.91	228.21	0.013951	0.17591	71.680	5.6848	69.567	52.900	122.47	0.12087	0.19258	278
280	247.73	233.03	0.014005	0.17205	71.405	5.8121	70.078	52.520	122.60	0.12154	0.19255	280
282	252.62	237.92	0.014060	0.16829	71.126	5.9423	70.591	52.136	122.73	0.12222	0.19252	282
284	257.57	242.88	0.014115	0.16460	70.845	6.0754	71.106	51.747	122.85	0.12289	0.19248	284
286	262.61	247.91	0.014172	0.16099	70.560	6.2115	71.622	51.353	122.98	0.12357	0.19244	286
288	267.71	253.01	0.014230	0.15746	70.273	6.3509	72.141	50.954	123.09	0.12425	0.19240	288
290	272.89	258.19	0.014289	0.15400	69.983	6.4934	72.662	50.549	123.21	0.12492	0.19235	290
292	278.14	263.44	0.014349	0.15062	69.690	6.6392	73.185	50.138	123.32	0.12560	0.19231	292
294	283.46	268.77	0.014411	0.14731	69.393	6.7885	73.710	49.722	123.43	0.12628	0.19226	294
296	288.87	274.17	0.014473	0.14406	69.093	6.9413	74.238	49.300	123.54	0.12696	0.19220	296
298	294.34	279.65	0.014537	0.14089	68.789	7.0979	74.767	48.872	123.64	0.12764	0.19215	298
300	299.90	285.20	0.014602	0.13778	68.482	7.2582	75.300	48.438	123.74	0.12832	0.19209	300
302	305.53	290.84	0.014669	0.13473	68.172	7.4225	75.834	47.997	123.83	0.12901	0.19202	302
304	311.24	296.55	0.014737	0.13174	67.857	7.5908	76.371	47.549	123.92	0.12969	0.19196	304
306	317.04	302.34	0.014806	0.12881	67.538	7.7635	76.911	47.095	124.01	0.13037	0.19188	306
308	322.91	308.21	0.014877	0.12594	67.216	7.9405	77.454	46.633	124.09	0.13106	0.19181	308
310	328.86	314.17	0.014950	0.12312	66.888	8.1222	78.000	46.163	124.16	0.13175	0.19173	310
312	334.90	320.20	0.015025	0.12036	66.557	8.3086	78.548	45.686	124.23	0.13244	0.19165	312
314	341.01	326.32	0.015101	0.11765	66.220	8.5000	79.100	45.201	124.30	0.13313	0.19156	314
316	347.21	332.52	0.015179	0.11499	65.879	8.6967	79.655	44.707	124.36	0.13383	0.19146	316
318	353.50	338.80	0.015260	0.11238	65.532	8.8987	80.213	44.205	124.42	0.13452	0.19137	318

THERMODYNAMIC PROPERTIES OF SATURATED TRICHLOROFLUOROMETHANE (R-11)

Temp	Pressure		Volume		Density		Enthalpy			Entropy		Temp
			Liquid	Vapor	Liquid	Vapor	Liquid	Latent	Vapor	Liquid	Vapor	
°F	psia	psig	ft³/lbm	ft³/lbm	lbm/ft³	lbm/ft³	Btu/lbm	Btu/lbm	Btu/lbm	Btu/lbm-R	Btu/lbm-R	°F
320	359.87	345.17	0.015342	0.10981	65.181	9.1064	80.775	43.694	124.47	0.13522	0.19126	320
322	366.33	351.63	0.015427	0.10730	64.823	9.3201	81.340	43.173	124.51	0.13592	0.19115	322
324	372.87	358.17	0.015514	0.10482	64.459	9.5399	81.909	42.642	124.55	0.13662	0.19104	324
326	379.50	364.80	0.015603	0.10239	64.090	9.7663	82.482	42.101	124.58	0.13733	0.19092	326
328	386.22	371.52	0.015695	0.10000	63.713	9.9996	83.060	41.548	124.61	0.13804	0.19079	328
330	393.03	378.33	0.015790	0.097655	63.330	10.240	83.642	40.985	124.63	0.13875	0.19065	330
332	399.93	385.23	0.015888	0.095345	62.939	10.488	84.228	40.409	124.64	0.13947	0.19051	332
334	406.92	392.22	0.015990	0.093071	62.540	10.744	84.820	39.821	124.64	0.14019	0.19036	334
336	414.00	399.30	0.016094	0.090833	62.133	11.009	85.417	39.219	124.64	0.14091	0.19020	336
338	421.17	406.48	0.016203	0.088629	61.717	11.283	86.019	38.603	124.62	0.14164	0.19004	338
340	428.44	413.74	0.016315	0.086456	61.291	11.567	86.627	37.972	124.60	0.14238	0.18986	340
342	435.80	421.10	0.016432	0.084315	60.856	11.860	87.242	37.325	124.57	0.14312	0.18967	342
344	443.26	428.56	0.016554	0.082202	60.409	12.165	87.863	36.661	124.52	0.14386	0.18948	344
346	450.81	436.11	0.016681	0.080117	59.950	12.482	88.492	35.978	124.47	0.14461	0.18927	346
348	458.46	443.76	0.016813	0.078057	59.478	12.811	89.129	35.276	124.41	0.14537	0.18905	348
350	466.21	451.51	0.016951	0.076020	58.992	13.154	89.774	34.553	124.33	0.14614	0.18882	350
352	474.05	459.36	0.017097	0.074005	58.490	13.513	90.429	33.806	124.24	0.14692	0.18857	352
354	482.00	467.30	0.017250	0.072009	57.972	13.887	91.094	33.034	124.13	0.14771	0.18831	354
356	490.05	475.35	0.017411	0.070029	57.434	14.280	91.771	32.234	124.01	0.14851	0.18803	356
358	498.19	483.50	0.017582	0.068063	56.875	14.692	92.461	31.404	123.86	0.14932	0.18773	358
360	506.44	491.75	0.017765	0.066107	56.292	15.127	93.164	30.540	123.70	0.15014	0.18740	360
362	514.79	500.10	0.017959	0.064158	55.681	15.586	93.884	29.637	123.52	0.15099	0.18706	362
364	523.25	508.55	0.018169	0.062212	55.039	16.074	94.623	28.691	123.31	0.15185	0.18669	364
366	531.81	517.11	0.018396	0.060262	54.360	16.594	95.383	27.695	123.08	0.15274	0.18628	366
368	540.47	525.78	0.018644	0.058303	53.637	17.152	96.170	26.641	122.81	0.15365	0.18584	368
370	549.25	534.55	0.018918	0.056325	52.861	17.754	96.987	25.517	122.50	0.15460	0.18536	370
372	558.13	543.44	0.019224	0.054317	52.019	18.410	97.843	24.309	122.15	0.15560	0.18483	372
374	567.13	552.43	0.019573	0.052265	51.091	19.133	98.749	22.994	121.74	0.15665	0.18423	374
376	576.24	561.55	0.019980	0.050143	50.049	19.943	99.721	21.541	121.26	0.15777	0.18355	376
378	585.48	570.78	0.020474	0.047918	48.842	20.869	100.79	19.894	120.68	0.15901	0.18276	378
380	594.85	580.16	0.021088	0.045537	47.420	21.960	101.98	17.988	119.97	0.16039	0.18181	380
382	604.39	589.69	0.022012	0.042828	45.430	23.349	103.51	15.506	119.02	0.16216	0.18058	382
**388.4	639.6	624.9	0.02876	0.02876	34.77	34.77	111.2	0.0	111.2	0.1711	0.1711	388.4

**Critical Point
* In. Hg. Vacuum

THERMODYNAMIC PROPERTIES OF TRICHLOROFLUOROMETHANE (R-11)

Temp °F	Pressure 1 psia (27.9 in. vac) (Sat'n Temp −30.99°F)			Pressure 2 psia (25.8 in. vac) (Sat'n Temp −8.62°F)			Pressure 4 psia (21.8 in. vac) (Sat'n Temp 16.68°F)			Pressure 6 psia (17.7 in. vac) (Sat'n Temp 33.10°F)		
	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R
Sat'n (Liquid)	(100.54)	(1.547)	(0.00365)	(98.855)	(5.694)	(0.01307)	(96.929)	(10.727)	(0.02391)	(95.659)	(14.107)	(0.03088)
(Vapor)	(0.029988)	(88.159)	(0.20571)	(0.057178)	(90.873)	(0.20191)	(0.10885)	(93.982)	(0.19869)	(0.15855)	(96.011)	(0.19709)
−10	0.028572	90.774	0.21166									
0	0.027943	92.041	0.21445	0.056082	91.969	0.20432						
10	0.027342	93.319	0.21720	0.054863	93.251	0.20708						
20	0.026767	94.610	0.21992	0.053697	94.546	0.20980	0.10806	94.415	0.19959			
30	0.026215	95.913	0.22261	0.052581	95.851	0.21250	0.10578	95.727	0.20230			
40	0.025686	97.227	0.22527	0.051511	97.169	0.21516	0.10359	97.050	0.20497	0.15625	96.929	0.19894
50	0.025178	98.553	0.22789	0.050484	98.497	0.21779	0.10149	98.384	0.20762	0.15303	98.268	0.20160
60	0.024690	99.890	0.23049	0.049498	99.836	0.22040	0.099475	99.728	0.21023	0.14995	99.618	0.20422
70	0.024221	101.24	0.23306	0.048551	101.19	0.22297	0.097545	101.08	0.21281	0.14700	100.98	0.20681
80	0.023769	102.60	0.23560	0.047640	102.55	0.22551	0.095689	102.45	0.21536	0.14416	102.35	0.20937
90	0.023334	103.97	0.23811	0.046762	103.92	0.22803	0.093905	103.82	0.21789	0.14144	103.73	0.21190
100	0.022915	105.34	0.24060	0.045917	105.30	0.23052	0.092188	105.21	0.22038	0.13882	105.11	0.21440
110	0.022510	106.73	0.24306	0.045102	106.69	0.23298	0.090533	106.60	0.22285	0.13630	106.51	0.21688
120	0.022120	108.13	0.24549	0.044316	108.09	0.23542	0.088939	108.00	0.22529	0.13388	107.92	0.21933
130	0.021743	109.54	0.24790	0.043557	109.50	0.23783	0.087400	109.42	0.22771	0.13154	109.33	0.22175
140	0.021379	110.96	0.25029	0.042824	110.92	0.24021	0.085915	110.84	0.23010	0.12928	110.76	0.22414
150	0.021027	112.38	0.25264	0.042115	112.35	0.24258	0.084481	112.27	0.23246	0.12710	112.19	0.22651
160	0.020686	113.82	0.25498	0.041430	113.78	0.24491	0.083094	113.71	0.23480	0.12500	113.63	0.22886
170	0.020356	115.26	0.25729	0.040766	115.23	0.24723	0.081753	115.15	0.23712	0.12296	115.08	0.23118
180	0.020037	116.72	0.25958	0.040124	116.68	0.24952	0.080455	116.61	0.23941	0.12099	116.54	0.23348
190	0.019727	118.18	0.26184	0.039502	118.14	0.25178	0.079198	118.07	0.24169	0.11909	118.00	0.23575
200	0.019427	119.64	0.26409	0.038899	119.61	0.25403	0.077980	119.54	0.24393	0.11725	119.48	0.23800
220	0.018853	122.60	0.26851	0.037747	122.57	0.25845	0.075655	122.51	0.24836	0.11373	122.45	0.24243
240	0.018313	125.60	0.27285	0.036661	125.57	0.26279	0.073466	125.51	0.25271	0.11042	125.45	0.24678
260	0.017803	128.61	0.27710	0.035637	128.59	0.26705	0.071402	128.53	0.25697	0.10730	128.47	0.25105
280	0.017320	131.66	0.28128	0.034668	131.63	0.27122	0.069451	131.58	0.26115	0.10435	131.53	0.25523
300	0.016863	134.73	0.28538	0.033751	134.71	0.27533	0.067605	134.66	0.26525	0.10156	134.61	0.25934
320	0.016429	137.83	0.28940	0.032882	137.81	0.27935	0.065855	137.76	0.26928	0.098921	137.71	0.26337
340	0.016018	140.95	0.29335	0.032056	140.93	0.28331	0.064194	140.88	0.27324	0.096416	140.84	0.26733
360	0.015626	144.10	0.29724	0.031271	144.08	0.28719	0.062616	144.03	0.27713	0.094036	143.99	0.27122
380	0.015253	147.26	0.30105	0.030523	147.24	0.29101	0.061113	147.20	0.28095	0.091771	147.16	0.27504
400	0.014898	150.45	0.30480	0.029810	150.43	0.29476	0.059682	150.39	0.28470	0.089615	150.35	0.27880
420	0.014558	153.66	0.30849	0.029130	153.64	0.29845	0.058316	153.60	0.28839	0.087557	153.56	0.28249
440	0.014234	156.88	0.31212	0.028481	156.86	0.30207	0.057012	156.83	0.29202	0.085593	156.79	0.28612
460	0.013924	160.13	0.31568	0.027860	160.11	0.30564	0.055765	160.07	0.29559	0.083716	160.03	0.28969

Temp °F	Pressure 8 psia (13.6 in. vac) (Sat'n Temp 45.57°F)			Pressure 10 psia (9.6 in. vac) (Sat'n Temp 55.77°F)			Pressure 12 psia (5.5 in. vac) (Sat'n Temp 64.46°F)			Pressure 14 psia (1.4 in. vac) (Sat'n Temp 72.08°F)		
	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R
Sat'n (Liquid)	(94.681)	(16.717)	(0.03610)	(93.871)	(18.870)	(0.04032)	(93.174)	(20.718)	(0.04386)	(92.556)	(22.346)	(0.04694)
(Vapor)	(0.20704)	(97.555)	(0.19610)	(0.25468)	(98.816)	(0.19542)	(0.30168)	(99.889)	(0.19492)	(0.34816)	(100.83)	(0.19454)
50	0.20513	98.151	0.19728	94.332	17.651	0.03794	94.334	17.653	0.03793	94.336	17.656	0.03793
60	0.20093	99.506	0.19991	0.25245	99.392	0.19654	93.534	19.770	0.04205	93.536	19.772	0.04204
70	0.19692	100.87	0.20251	0.24733	100.76	0.19915	0.29824	100.65	0.19637	92.726	21.901	0.04610
80	0.19307	102.24	0.20508	0.24242	102.14	0.20172	0.29224	102.04	0.19895	0.34253	101.93	0.19659
90	0.18937	103.63	0.20762	0.23772	103.53	0.20427	0.28650	103.43	0.20151	0.33571	103.33	0.19915
100	0.18583	105.02	0.21013	0.23321	104.92	0.20679	0.28099	104.83	0.20403	0.32918	104.73	0.20168
110	0.18242	106.42	0.21261	0.22888	106.33	0.20927	0.27571	106.24	0.20653	0.32291	106.14	0.20419
120	0.17913	107.83	0.21506	0.22472	107.74	0.21173	0.27064	107.65	0.20899	0.31690	107.56	0.20666
130	0.17597	109.25	0.21749	0.22071	109.16	0.21417	0.26576	109.08	0.21143	0.31113	108.99	0.20910
140	0.17292	110.68	0.21989	0.21685	110.59	0.21657	0.26106	110.51	0.21384	0.30557	110.43	0.21152
150	0.16998	112.11	0.22226	0.21312	112.03	0.21895	0.25654	111.95	0.21622	0.30023	111.87	0.21391
160	0.16714	113.56	0.22461	0.20953	113.48	0.22130	0.25218	113.40	0.21858	0.29508	113.32	0.21627
170	0.16440	115.01	0.22694	0.20607	114.93	0.22363	0.24797	114.86	0.22091	0.29011	114.78	0.21860
180	0.16175	116.47	0.22924	0.20271	116.40	0.22594	0.24390	116.32	0.22322	0.28531	116.25	0.22092
190	0.15918	117.93	0.23152	0.19948	117.87	0.22822	0.23997	117.80	0.22551	0.28068	117.72	0.22320
200	0.15670	119.41	0.23377	0.19634	119.34	0.23047	0.23618	119.27	0.22777	0.27621	119.21	0.22547
220	0.15196	122.38	0.23821	0.19037	122.32	0.23492	0.22894	122.26	0.23222	0.26769	122.19	0.22992
240	0.14751	125.39	0.24256	0.18476	125.33	0.23928	0.22215	125.27	0.23658	0.25970	125.20	0.23429
260	0.14332	128.42	0.24683	0.17948	128.36	0.24355	0.21577	128.30	0.24086	0.25219	128.24	0.23858
280	0.13936	131.47	0.25102	0.17450	131.42	0.24774	0.20975	131.36	0.24506	0.24512	131.31	0.24278
300	0.13562	134.55	0.25513	0.16979	134.50	0.25186	0.20406	134.45	0.24917	0.23844	134.40	0.24690
320	0.13208	137.66	0.25917	0.16533	137.61	0.25590	0.19868	137.56	0.25322	0.23213	137.51	0.25094
340	0.12872	140.79	0.26313	0.16111	140.74	0.25986	0.19359	140.69	0.25718	0.22615	140.65	0.25491
360	0.12553	143.94	0.26702	0.15710	143.89	0.26376	0.18875	143.85	0.26108	0.22048	143.80	0.25881
380	0.12250	147.11	0.27085	0.15329	147.07	0.26758	0.18416	147.03	0.26491	0.21509	146.98	0.26264
400	0.11961	150.31	0.27460	0.14967	150.26	0.27134	0.17978	150.22	0.26867	0.20996	150.18	0.26641
420	0.11685	153.52	0.27830	0.14621	153.48	0.27504	0.17562	153.44	0.27237	0.20508	153.40	0.27011
440	0.11423	156.75	0.28193	0.14291	156.71	0.27867	0.17164	156.67	0.27600	0.20042	156.63	0.27374
460	0.11171	160.00	0.28550	0.13976	159.96	0.28224	0.16784	159.92	0.27958	0.19598	159.88	0.27732

THERMODYNAMIC PROPERTIES OF TRICHLOROFLUOROMETHANE (R-11)

Temp °F	Pressure 14.70 psia (0 psig) (Sat'n Temp 74.53°F)			Pressure 16 psia (1.3 psig) (Sat'n Temp 78.89°F)			Pressure 18 psia (3.3 psig) (Sat'n Temp 85.07°F)			Pressure 20 psia (5.3 psig) (Sat'n Temp 90.73°F)		
	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R
Sat'n (Liquid)	(92.356)	(22.871)	(0.04792)	(91.999)	(23.807)	(0.04966)	(91.489)	(25.137)	(0.05211)	(91.017)	(26.360)	(0.05434)
(Vapor)	(0.36423)	(101.13)	(0.19442)	(0.39422)	(101.67)	(0.19423)	(0.43994)	(102.42)	(0.19399)	(0.48537)	(103.12)	(0.19379)
50	94.336	17.656	0.03793	94.338	17.658	0.03793	94.340	17.660	0.03792	94.342	17.662	0.03792
60	93.537	19.772	0.04204	93.538	19.774	0.04204	93.540	19.776	0.04204	93.542	19.778	0.04203
70	92.727	21.902	0.04610	92.728	21.903	0.04610	92.730	21.905	0.04609	92.733	21.908	0.04609
80	0.36015	101.89	0.19584	0.39332	101.82	0.19452	91.909	24.047	0.05010	91.912	24.049	0.05010
90	0.35294	103.29	0.19841	0.38537	103.22	0.19709	0.43550	103.12	0.19526	91.078	26.201	0.05405
100	0.34604	104.70	0.20094	0.37777	104.63	0.19963	0.42680	104.53	0.19781	0.47625	104.43	0.19616
110	0.33943	106.11	0.20345	0.37050	106.05	0.20214	0.41847	105.95	0.20032	0.46685	105.85	0.19868
120	0.33309	107.53	0.20592	0.36352	107.47	0.20462	0.41050	107.38	0.20281	0.45785	107.29	0.20118
130	0.32699	108.96	0.20836	0.35682	108.90	0.20707	0.40285	108.82	0.20526	0.44922	108.73	0.20364
140	0.32113	110.40	0.21078	0.35039	110.34	0.20949	0.39551	110.26	0.20769	0.44095	110.17	0.20607
150	0.31550	111.84	0.21317	0.34420	111.79	0.21188	0.38845	111.71	0.21009	0.43300	111.63	0.20847
160	0.31007	113.30	0.21554	0.33824	113.25	0.21425	0.38166	113.17	0.21246	0.42536	113.09	0.21085
170	0.30483	114.76	0.21787	0.33249	114.71	0.21659	0.37512	114.63	0.21481	0.41801	114.55	0.21320
180	0.29978	116.22	0.22019	0.32695	116.18	0.21891	0.36882	116.10	0.21713	0.41092	116.03	0.21552
190	0.29490	117.70	0.22248	0.32160	117.65	0.22120	0.36274	117.58	0.21942	0.40409	117.51	0.21782
200	0.29018	119.18	0.22474	0.31643	119.14	0.22346	0.35686	119.07	0.22169	0.39750	119.00	0.22009
220	0.28121	122.17	0.22920	0.30661	122.13	0.22793	0.34570	122.06	0.22616	0.38498	122.00	0.22457
240	0.27280	125.18	0.23357	0.29740	125.14	0.23230	0.33525	125.08	0.23054	0.37327	125.02	0.22895
260	0.26490	128.22	0.23785	0.28875	128.19	0.23659	0.32545	128.13	0.23483	0.36228	128.07	0.23325
280	0.25745	131.29	0.24206	0.28061	131.25	0.24079	0.31622	131.20	0.23904	0.35196	131.14	0.23746
300	0.25043	134.38	0.24618	0.27293	134.35	0.24492	0.30752	134.29	0.24317	0.34223	134.24	0.24160
320	0.24379	137.49	0.25023	0.26567	137.46	0.24897	0.29930	137.41	0.24722	0.33304	137.36	0.24565
340	0.23750	140.63	0.25420	0.25880	140.60	0.25294	0.29153	140.55	0.25120	0.32435	140.50	0.24963
360	0.23153	143.79	0.25810	0.25228	143.76	0.25684	0.28416	143.71	0.25510	0.31612	143.67	0.25354
380	0.22587	146.97	0.26193	0.24609	146.94	0.26068	0.27716	146.89	0.25894	0.30831	146.85	0.25737
400	0.22048	150.17	0.26569	0.24021	150.14	0.26444	0.27051	150.10	0.26270	0.30088	150.05	0.26115
420	0.21535	153.38	0.26939	0.23460	153.36	0.26814	0.26418	153.32	0.26641	0.29382	153.28	0.26485
440	0.21045	156.62	0.27303	0.22926	156.59	0.27178	0.25815	156.55	0.27005	0.28708	156.52	0.26849
460	0.20578	159.87	0.27661	0.22416	159.85	0.27536	0.25239	159.81	0.27363	0.28066	159.77	0.27207

Temp °F	Pressure 25 psia (10.3 psig) (Sat'n Temp 103.19°F)			Pressure 30 psia (15.3 psig) (Sat'n Temp 113.85°F)			Pressure 35 psia (20.3 psig) (Sat'n Temp 123.23°F)			Pressure 40 psia (25.3 psig) (Sat'n Temp 131.64°F)		
	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R
Sat'n (Liquid)	(89.966)	(29.061)	(0.05917)	(89.049)	(31.387)	(0.06325)	(88.229)	(33.444)	(0.06678)	(87.483)	(35.296)	(0.06992)
(Vapor)	(0.59793)	(104.63)	(0.19343)	(0.70942)	(105.91)	(0.19319)	(0.82017)	(107.03)	(0.19303)	(0.93040)	(108.03)	(0.19292)
50	94.347	17.668	0.03791	94.352	17.674	0.03790	94.357	17.679	0.03790	94.362	17.685	0.03789
60	93.548	19.784	0.04202	93.553	19.789	0.04201	93.558	19.795	0.04201	93.564	19.800	0.04200
70	92.738	21.913	0.04608	92.744	21.918	0.04607	92.750	21.924	0.04606	92.755	21.929	0.04606
80	91.918	24.054	0.05009	91.924	24.059	0.05008	91.929	24.064	0.05007	91.935	24.070	0.05006
90	91.085	26.206	0.05404	91.091	26.211	0.05403	91.097	26.216	0.05402	91.103	26.221	0.05401
100	90.238	28.369	0.05794	90.245	28.374	0.05793	90.252	28.379	0.05792	90.258	28.384	0.05791
110	0.58962	105.61	0.19516	89.385	30.547	0.06178	89.392	30.552	0.06177	89.399	30.556	0.06176
120	0.57790	107.05	0.19767	0.70047	106.81	0.19474	88.516	32.735	0.06557	88.524	32.740	0.06556
130	0.56669	108.50	0.20015	0.68648	108.27	0.19724	0.80874	108.03	0.19473	87.631	34.934	0.06931
140	0.55597	109.95	0.20259	0.67312	109.73	0.19970	0.79253	109.50	0.19721	0.91434	109.27	0.19501
150	0.54569	111.42	0.20501	0.66034	111.20	0.20213	0.77706	110.98	0.19966	0.89598	110.76	0.19747
160	0.53582	112.88	0.20740	0.64810	112.68	0.20454	0.76228	112.47	0.20207	0.87848	112.25	0.19990
170	0.52634	114.36	0.20976	0.63636	114.16	0.20691	0.74814	113.96	0.20446	0.86177	113.75	0.20230
180	0.51723	115.84	0.21210	0.62509	115.65	0.20925	0.73459	115.46	0.20682	0.84579	115.26	0.20467
190	0.50845	117.33	0.21440	0.61426	117.14	0.21157	0.72158	116.96	0.20914	0.83047	116.77	0.20701
200	0.50000	118.82	0.21669	0.60384	118.64	0.21386	0.70908	118.46	0.21145	0.81579	118.28	0.20932
220	0.48396	121.83	0.22118	0.58412	121.66	0.21837	0.68549	121.49	0.21597	0.78811	121.32	0.21387
240	0.46900	124.86	0.22558	0.56576	124.71	0.22279	0.66357	124.55	0.22040	0.76247	124.39	0.21831
260	0.45499	127.92	0.22988	0.54860	127.77	0.22711	0.64313	127.62	0.22473	0.73862	127.47	0.22266
280	0.44184	131.00	0.23411	0.53252	130.86	0.23134	0.62402	130.72	0.22898	0.71636	130.58	0.22691
300	0.42947	134.11	0.23825	0.51742	133.97	0.23549	0.60610	133.84	0.23314	0.69551	133.70	0.23108
320	0.41781	137.23	0.24231	0.50321	137.11	0.23956	0.58924	136.98	0.23722	0.67593	136.85	0.23517
340	0.40679	140.38	0.24630	0.48979	140.26	0.24356	0.57336	140.14	0.24122	0.65751	140.02	0.23918
360	0.39636	143.55	0.25021	0.47711	143.44	0.24748	0.55836	143.32	0.24515	0.64013	143.20	0.24312
380	0.38648	146.74	0.25406	0.46509	146.63	0.25133	0.54417	146.52	0.24900	0.62370	146.41	0.24698
400	0.37709	149.95	0.25783	0.45369	149.84	0.25511	0.53071	149.73	0.25279	0.60814	149.63	0.25077
420	0.36816	153.17	0.26154	0.44287	153.07	0.25882	0.51794	152.97	0.25651	0.59338	152.87	0.25450
440	0.35966	156.42	0.26519	0.43256	156.32	0.26247	0.50579	156.22	0.26016	0.57936	156.12	0.25816
460	0.35155	159.68	0.26877	0.42274	159.58	0.26606	0.49422	159.49	0.26376	0.56601	159.39	0.26175

THERMODYNAMIC PROPERTIES OF TRICHLOROFLUOROMETHANE (R-11)

Temp °F	Pressure 50 psia (35.3 psig) (Sat'n Temp 146.32°F)			Pressure 60 psia (45.3 psig) (Sat'n Temp 158.93°F)			Pressure 70 psia (55.3 psig) (Sat'n Temp 170.05°F)			Pressure 80 psia (65.3 psig) (Sat'n Temp 180.04°F)		
	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R
Sat'n (Liquid) (Vapor)	(86.152) (1.1499)	(38.549) (109.74)	(0.07532) (0.19279)	(84.978) (1.3690)	(41.366) (111.18)	(0.07989) (0.19274)	(83.916) (1.5883)	(43.870) (112.43)	(0.08386) (0.19273)	(82.939) (1.8082)	(46.135) (113.52)	(0.08740) (0.19273)
50	94.372	17.696	0.03787	94.382	17.707	0.03785	94.392	17.718	0.03784	94.402	17.730	0.03782
60	93.574	19.811	0.04198	93.585	19.822	0.04196	93.595	19.833	0.04195	93.606	19.844	0.04193
70	92.766	21.940	0.04604	92.777	21.950	0.04602	92.789	21.961	0.04600	92.800	21.972	0.04599
80	91.947	24.080	0.05004	91.959	24.090	0.05002	91.971	24.101	0.05001	91.982	24.111	0.04999
90	91.116	26.231	0.05399	91.128	26.241	0.05397	91.141	26.252	0.05395	91.153	26.262	0.05394
100	90.271	28.393	0.05789	90.285	28.403	0.05787	90.298	28.413	0.05785	90.311	28.422	0.05783
110	89.413	30.566	0.06174	89.427	30.575	0.06172	89.441	30.584	0.06170	89.454	30.593	0.06168
120	88.538	32.748	0.06553	88.553	32.757	0.06551	88.568	32.766	0.06549	88.583	32.775	0.06547
130	87.647	34.942	0.06929	87.663	34.951	0.06927	87.679	34.959	0.06924	87.694	34.967	0.06922
140	86.737	37.148	0.07300	86.754	37.156	0.07297	86.771	37.164	0.07295	86.788	37.172	0.07293
150	1.1409	110.30	0.19371	85.826	39.374	0.07664	85.843	39.381	0.07662	85.861	39.388	0.07659
160	1.1174	111.81	0.19617	1.3658	111.35	0.19301	84.894	41.612	0.08025	84.913	41.619	0.08022
170	1.0950	113.33	0.19860	1.3368	112.88	0.19547	83.920	43.859	0.08384	83.941	43.865	0.08382
180	1.0736	114.85	0.20100	1.3094	114.42	0.19790	1.5539	113.98	0.19518	82.942	46.127	0.08738
190	1.0533	116.37	0.20336	1.2833	115.97	0.20029	1.5213	115.54	0.19760	1.7682	115.10	0.19518
200	1.0338	117.90	0.20570	1.2585	117.51	0.20265	1.4904	117.10	0.19999	1.7303	116.68	0.19760
220	0.99733	120.97	0.21028	1.2122	120.61	0.20727	1.4331	120.23	0.20466	1.6606	119.85	0.20233
240	0.96370	124.06	0.21476	1.1698	123.72	0.21179	1.3810	123.37	0.20921	1.5977	123.02	0.20692
260	0.93257	127.16	0.21913	1.1307	126.85	0.21619	1.3332	126.52	0.21365	1.5405	126.19	0.21139
280	0.90362	130.29	0.22341	1.0945	129.99	0.22050	1.2892	129.68	0.21798	1.4880	129.38	0.21576
300	0.87661	133.43	0.22761	1.0609	133.15	0.22471	1.2485	132.86	0.22222	1.4395	132.57	0.22002
320	0.85132	136.59	0.23171	1.0295	136.32	0.22884	1.2106	136.05	0.22637	1.3947	135.78	0.22419
340	0.82760	139.77	0.23574	1.0001	139.52	0.23288	1.1752	139.26	0.23043	1.3530	139.00	0.22827
360	0.80526	142.96	0.23969	0.97257	142.72	0.23685	1.1421	142.48	0.23441	1.3140	142.24	0.23227
380	0.78419	146.18	0.24356	0.94661	145.95	0.24073	1.1110	145.72	0.23831	1.2775	145.49	0.23618
400	0.76428	149.41	0.24737	0.92213	149.19	0.24455	1.0818	148.97	0.24214	1.2432	148.75	0.24002
420	0.74541	152.66	0.25110	0.89898	152.45	0.24830	1.0541	152.24	0.24590	1.2109	152.03	0.24379
440	0.72751	155.92	0.25477	0.87706	155.72	0.25197	1.0280	155.52	0.24958	1.1804	155.32	0.24749
460	0.71050	159.20	0.25838	0.85625	159.01	0.25559	1.0033	158.82	0.25321	1.1516	158.62	0.25112

Temp °F	Pressure 90 psia (75.3 psig) (Sat'n Temp 189.14°F)			Pressure 100 psia (85.3 psig) (Sat'n Temp 197.51°F)			Pressure 110 psia (95.3 psig) (Sat'n Temp 205.29°F)			Pressure 120 psia (105.3 psig) (Sat'n Temp 212.56°F)		
Sat'n (Liquid) (Vapor)	(82.028) (2.0291)	(48.214) (114.50)	(0.09059) (0.19275)	(81.171) (2.2513)	(50.141) (115.38)	(0.09350) (0.19277)	(80.359) (2.4750)	(51.943) (116.18)	(0.09620) (0.19279)	(79.583) (2.7005)	(53.639) (116.91)	(0.09870) (0.19282)
50	94.412	17.741	0.03781	94.422	17.752	0.03779	94.432	17.763	0.03777	94.442	17.775	0.03776
60	93.617	19.855	0.04191	93.627	19.866	0.04190	93.638	19.877	0.04188	93.648	19.888	0.04186
70	92.811	21.982	0.04597	92.822	21.993	0.04595	92.833	22.004	0.04593	92.844	22.015	0.04592
80	91.994	24.122	0.04997	92.006	24.132	0.04995	92.018	24.143	0.04993	92.029	24.153	0.04992
90	91.166	26.272	0.05392	91.178	26.282	0.05390	91.190	26.292	0.05388	91.203	26.302	0.05386
100	90.324	28.432	0.05781	90.337	28.442	0.05779	90.350	28.452	0.05777	90.363	28.461	0.05775
110	89.468	30.603	0.06166	89.482	30.612	0.06164	89.496	30.621	0.06162	89.510	30.631	0.06160
120	88.597	32.784	0.06545	88.612	32.793	0.06543	88.627	32.802	0.06541	88.641	32.811	0.06539
130	87.710	34.976	0.06920	87.726	34.984	0.06918	87.741	34.993	0.06916	87.757	35.001	0.06914
140	86.804	37.179	0.07291	86.821	37.187	0.07288	86.838	37.195	0.07286	86.854	37.203	0.07284
150	85.879	39.396	0.07657	85.897	39.403	0.07655	85.915	39.410	0.07652	85.932	39.417	0.07650
160	84.932	41.625	0.08020	84.951	41.632	0.08017	84.970	41.639	0.08015	84.989	41.645	0.08013
170	83.961	43.870	0.08379	83.982	43.876	0.08377	84.002	43.882	0.08374	84.023	43.888	0.08372
180	82.964	46.132	0.08736	82.986	46.137	0.08733	83.008	46.142	0.08730	83.030	46.147	0.08727
190	2.0250	114.64	0.19296	81.962	48.416	0.09086	81.986	48.420	0.09084	82.009	48.424	0.09081
200	1.9792	116.24	0.19542	2.2379	115.79	0.19339	80.931	50.718	0.09435	80.957	50.721	0.09432
220	1.8954	119.45	0.20020	2.1382	119.03	0.19824	2.3897	118.60	0.19640	2.6511	118.15	0.19465
240	1.8205	122.65	0.20484	2.0498	122.27	0.20293	2.2861	121.88	0.20115	2.5302	121.47	0.19947
260	1.7527	125.85	0.20936	1.9704	125.50	0.20749	2.1939	125.14	0.20575	2.4237	124.77	0.20412
280	1.6910	129.06	0.21375	1.8985	128.73	0.21192	2.1109	128.40	0.21022	2.3285	128.06	0.20863
300	1.6343	132.27	0.21804	1.8329	131.97	0.21624	2.0356	131.66	0.21457	2.2426	131.35	0.21301
320	1.5820	135.50	0.22223	1.7726	135.22	0.22045	1.9667	134.93	0.21881	2.1644	134.64	0.21728
340	1.5335	138.74	0.22633	1.7169	138.47	0.22457	1.9032	138.20	0.22295	2.0928	137.93	0.22145
360	1.4883	141.99	0.23035	1.6651	141.74	0.22861	1.8445	141.48	0.22701	2.0267	141.22	0.22552
380	1.4461	145.25	0.23428	1.6169	145.01	0.23255	1.7900	144.77	0.23097	1.9654	144.52	0.22950
400	1.4066	148.53	0.23813	1.5718	148.30	0.23642	1.7391	148.07	0.23485	1.9084	147.84	0.23340
420	1.3694	151.81	0.24191	1.5295	151.60	0.24021	1.6914	151.38	0.23866	1.8551	151.16	0.23722
440	1.3343	155.11	0.24562	1.4897	154.91	0.24394	1.6466	154.70	0.24239	1.8052	154.49	0.24096
460	1.3012	158.43	0.24927	1.4521	158.23	0.24759	1.6045	158.03	0.24605	1.7582	157.83	0.24464

THERMODYNAMIC PROPERTIES OF TRICHLOROFLUOROMETHANE (R-11)

Temp °F	Pressure 130 psia (115.3 psig) (Sat'n Temp 219.39°F)			Pressure 140 psia (125.3 psig) (Sat'n Temp 225.85°F)			Pressure 150 psia (135.3 psig) (Sat'n Temp 231.98°F)			Pressure 160 psia (145.3 psig) (Sat'n Temp 237.81°F)		
	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R
Sat'n (Liquid)	(78.839)	(55.245)	(0.10104)	(78.121)	(56.772)	(0.10324)	(77.427)	(58.230)	(0.10533)	(76.753)	(59.628)	(0.10730)
Sat'n (Vapor)	(2.9280)	(117.58)	(0.19283)	(3.1577)	(118.20)	(0.19284)	(3.3896)	(118.77)	(0.19285)	(3.6240)	(119.29)	(0.19285)
50	94.452	17.786	0.03774	94.462	17.797	0.03772	94.472	17.808	0.03771	94.482	17.820	0.03769
60	93.659	19.899	0.04185	93.669	19.910	0.04183	93.680	19.921	0.04181	93.690	19.932	0.04180
70	92.855	22.025	0.04590	92.866	22.036	0.04588	92.878	22.047	0.04586	92.889	22.058	0.04585
80	92.041	24.163	0.04990	92.053	24.174	0.04988	92.064	24.184	0.04986	92.076	24.195	0.04984
90	91.215	26.312	0.05384	91.227	26.322	0.05382	91.240	26.332	0.05381	91.252	26.343	0.05379
100	90.376	28.471	0.05773	90.389	28.481	0.05772	90.402	28.491	0.05770	90.415	28.500	0.05768
110	89.524	30.640	0.06158	89.537	30.649	0.06156	89.551	30.659	0.06154	89.565	30.668	0.06152
120	88.656	32.819	0.06537	88.671	32.828	0.06535	88.685	32.837	0.06533	88.700	32.846	0.06531
130	87.772	35.009	0.06911	87.788	35.018	0.06909	87.803	35.026	0.06907	87.819	35.035	0.06905
140	86.871	37.211	0.07282	86.887	37.219	0.07279	86.904	37.227	0.07277	86.920	37.235	0.07275
150	85.950	39.425	0.07648	85.968	39.432	0.07645	85.985	39.439	0.07643	86.003	39.447	0.07641
160	85.008	41.652	0.08010	85.027	41.658	0.08008	85.046	41.665	0.08005	85.064	41.672	0.08003
170	84.043	43.894	0.08369	84.063	43.900	0.08366	84.083	43.906	0.08364	84.103	43.911	0.08361
180	83.052	46.152	0.08725	83.074	46.157	0.08722	83.096	46.162	0.08719	83.117	46.167	0.08717
190	82.033	48.428	0.09078	82.057	48.432	0.09075	82.080	48.436	0.09072	82.103	48.440	0.09069
200	80.982	50.724	0.09429	81.008	50.727	0.09426	81.033	50.730	0.09423	81.059	50.733	0.09420
220	2.9234	117.68	0.19298	78.800	55.388	0.10122	78.830	55.388	0.10118	78.860	55.388	0.10115
240	2.7828	121.05	0.19787	3.0448	120.61	0.19634	3.3174	120.16	0.19485	3.6018	119.68	0.19340
260	2.6602	124.39	0.20258	2.9042	124.00	0.20111	3.1562	123.59	0.19969	3.4171	123.17	0.19832
280	2.5516	127.71	0.20713	2.7807	127.36	0.20571	3.0161	126.99	0.20434	3.2585	126.61	0.20303
300	2.4542	131.03	0.21155	2.6707	130.70	0.21017	2.8924	130.36	0.20884	3.1196	130.01	0.20758
320	2.3660	134.34	0.21585	2.5717	134.03	0.21450	2.7817	133.72	0.21321	2.9962	133.40	0.21198
340	2.2855	137.65	0.22004	2.4818	137.36	0.21871	2.6816	137.07	0.21745	2.8851	136.78	0.21625
360	2.2116	140.96	0.22413	2.3994	140.69	0.22283	2.5903	140.42	0.22159	2.7844	140.15	0.22042
380	2.1432	144.28	0.22813	2.3236	144.03	0.22685	2.5065	143.77	0.22563	2.6922	143.51	0.22447
400	2.0798	147.60	0.23205	2.2534	147.36	0.23078	2.4292	147.13	0.22958	2.6074	146.88	0.22844
420	2.0207	150.94	0.23588	2.1881	150.71	0.23462	2.3575	150.48	0.23344	2.5289	150.25	0.23232
440	1.9653	154.28	0.23964	2.1272	154.06	0.23839	2.2907	153.85	0.23722	2.4560	153.63	0.23611
460	1.9134	157.63	0.24332	2.0701	157.42	0.24209	2.2282	157.22	0.24093	2.3879	157.01	0.23983

Temp °F	Pressure 170 psia (155.3 psig) (Sat'n Temp 243.37°F)			Pressure 180 psia (165.3 psig) (Sat'n Temp 248.70°F)			Pressure 190 psia (175.3 psig) (Sat'n Temp 253.82°F)			Pressure 200 psia (185.3 psig) (Sat'n Temp 258.74°F)		
Sat'n (Liquid)	(76.096)	(60.972)	(0.10919)	(75.455)	(62.268)	(0.11099)	(74.828)	(63.520)	(0.11272)	(74.213)	(64.733)	(0.11438)
Sat'n (Vapor)	(3.8611)	(119.79)	(0.19285)	(4.1010)	(120.24)	(0.19283)	(4.3438)	(120.67)	(0.19281)	(4.5898)	(121.06)	(0.19278)
50	94.492	17.831	0.03767	94.502	17.842	0.03766	94.512	17.854	0.03764	94.522	17.865	0.03763
60	93.701	19.943	0.04178	93.711	19.954	0.04176	93.722	19.965	0.04174	93.732	19.976	0.04173
70	92.900	22.068	0.04583	92.911	22.079	0.04581	92.922	22.090	0.04579	92.933	22.101	0.04578
80	92.088	24.205	0.04983	92.099	24.216	0.04981	92.111	24.226	0.04979	92.123	24.237	0.04977
90	91.264	26.353	0.05377	91.277	26.363	0.05375	91.289	26.373	0.05373	91.301	26.383	0.05371
100	90.428	28.510	0.05766	90.441	28.520	0.05764	90.454	28.530	0.05762	90.467	28.540	0.05760
110	89.579	30.678	0.06150	89.592	30.687	0.06148	89.606	30.696	0.06146	89.620	30.706	0.06144
120	88.714	32.855	0.06529	88.729	32.864	0.06527	88.743	32.873	0.06525	88.758	32.882	0.06522
130	87.834	35.043	0.06903	87.850	35.052	0.06901	87.865	35.060	0.06899	87.880	35.069	0.06896
140	86.937	37.243	0.07273	86.953	37.251	0.07271	86.969	37.259	0.07268	86.986	37.267	0.07266
150	86.020	39.454	0.07638	86.038	39.461	0.07636	86.055	39.469	0.07634	86.072	39.476	0.07632
160	85.083	41.679	0.08000	85.102	41.685	0.07998	85.120	41.692	0.07996	85.139	41.699	0.07993
170	84.123	43.917	0.08359	84.143	43.923	0.08356	84.163	43.930	0.08354	84.183	43.936	0.08351
180	83.139	46.172	0.08714	83.160	46.177	0.08711	83.182	46.183	0.08709	83.203	46.188	0.08706
190	82.127	48.444	0.09067	82.150	48.449	0.09064	82.173	48.453	0.09061	82.196	48.457	0.09058
200	81.084	50.736	0.09417	81.109	50.740	0.09414	81.134	50.743	0.09411	81.159	50.746	0.09408
220	78.890	55.389	0.10111	78.920	55.389	0.10108	78.950	55.390	0.10105	78.980	55.391	0.10101
240	76.518	60.155	0.10802	76.555	60.151	0.10798	76.591	60.148	0.10795	76.627	60.145	0.10791
260	3.6878	122.73	0.19699	3.9696	122.27	0.19568	4.2636	121.80	0.19439	4.5716	121.29	0.19311
280	3.5084	126.22	0.20176	3.7665	125.81	0.20053	4.0337	125.39	0.19932	4.3108	124.96	0.19813
300	3.3528	129.66	0.20636	3.5924	129.29	0.20517	3.8388	128.92	0.20402	4.0927	128.53	0.20290
320	3.2155	133.08	0.21080	3.4399	132.74	0.20966	3.6697	132.40	0.20855	3.9054	132.06	0.20748
340	3.0927	136.48	0.21510	3.3044	136.17	0.21400	3.5205	135.86	0.21293	3.7413	135.54	0.21189
360	2.9817	139.87	0.21929	3.1826	139.58	0.21821	3.3870	139.30	0.21717	3.5953	139.00	0.21617
380	2.8806	143.25	0.22337	3.0721	142.99	0.22232	3.2665	142.72	0.22130	3.4641	142.45	0.22032
400	2.7880	146.64	0.22735	2.9710	146.39	0.22632	3.1566	146.14	0.22532	3.3449	145.88	0.22436
420	2.7024	150.02	0.23125	2.8780	149.79	0.23023	3.0558	149.55	0.22925	3.2359	149.31	0.22831
440	2.6231	153.41	0.23506	2.7920	153.19	0.23405	2.9628	152.97	0.23309	3.1355	152.74	0.23216
460	2.5492	156.80	0.23879	2.7120	156.59	0.23779	2.8765	156.38	0.23684	3.0427	156.17	0.23593

THERMODYNAMIC PROPERTIES OF TRICHLOROFLUOROMETHANE (R-11)

Temp °F	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R
	Pressure 210 psia (195.3 psig) (Sat'n Temp 263.49°F)			Pressure 220 psia (205.3 psig) (Sat'n Temp 268.06°F)			Pressure 230 psia (215.3 psig) (Sat'n Temp 272.49°F)			Pressure 240 psia (225.3 psig) (Sat'n Temp 276.78°F)		
Sat'n (Liquid)	(73.609)	(65.910)	(0.11598)	(73.014)	(67.054)	(0.11752)	(72.427)	(68.169)	(0.11901)	(71.848)	(69.256)	(0.12046)
(Vapor)	(4.8391)	(121.43)	(0.19275)	(5.0918)	(121.77)	(0.19271)	(5.3481)	(122.09)	(0.19266)	(5.6083)	(122.39)	(0.19260)
50	94.532	17.876	0.03761	94.542	17.887	0.03759	94.552	17.899	0.03758	94.562	17.910	0.03756
60	93.743	19.987	0.04171	93.753	19.998	0.04169	93.764	20.009	0.04168	93.774	20.021	0.04166
70	92.944	22.112	0.04576	92.955	22.122	0.04574	92.966	22.133	0.04573	92.977	22.144	0.04571
80	92.134	24.247	0.04975	92.146	24.258	0.04974	92.157	24.268	0.04972	92.169	24.279	0.04970
90	91.313	26.393	0.05369	91.325	26.404	0.05368	91.338	26.414	0.05366	91.350	26.424	0.05364
100	90.480	28.549	0.05758	90.493	28.559	0.05756	90.506	28.569	0.05754	90.519	28.579	0.05753
110	89.633	30.715	0.06142	89.647	30.725	0.06140	89.661	30.734	0.06138	89.674	30.744	0.06136
120	88.772	32.891	0.06520	88.787	32.900	0.06518	88.801	32.909	0.06516	88.815	32.918	0.06514
130	87.896	35.078	0.06894	87.911	35.086	0.06892	87.926	35.095	0.06890	87.941	35.103	0.06888
140	87.002	37.275	0.07264	87.018	37.283	0.07262	87.034	37.291	0.07259	87.051	37.299	0.07257
150	86.090	39.484	0.07629	86.107	39.491	0.07627	86.124	39.499	0.07625	86.142	39.506	0.07622
160	85.158	41.706	0.07991	85.176	41.713	0.07988	85.195	41.719	0.07986	85.213	41.726	0.07983
170	84.203	43.942	0.08349	84.223	43.948	0.08346	84.243	43.954	0.08344	84.263	43.960	0.08341
180	83.225	46.193	0.08703	83.246	46.198	0.08701	83.267	46.204	0.08698	83.288	46.209	0.08695
190	82.219	48.462	0.09055	82.242	48.466	0.09052	82.265	48.471	0.09050	82.288	48.475	0.09047
200	81.184	50.749	0.09405	81.209	50.753	0.09402	81.234	50.756	0.09399	81.258	50.760	0.09396
220	79.010	55.391	0.10098	79.039	55.392	0.10095	79.068	55.393	0.10091	79.098	55.394	0.10088
240	76.663	60.142	0.10787	76.699	60.140	0.10783	76.735	60.137	0.10779	76.770	60.134	0.10775
260	74.088	65.038	0.11477	74.133	65.030	0.11472	74.177	65.022	0.11468	74.222	65.015	0.11463
280	4.5989	124.50	0.19696	4.8994	124.03	0.19579	5.2139	123.54	0.19463	5.5444	123.02	0.19346
300	4.3548	128.14	0.20180	4.6257	127.72	0.20071	4.9064	127.30	0.19964	5.1978	126.85	0.19858
320	4.1473	131.70	0.20643	4.3959	131.33	0.20540	4.6517	130.95	0.20439	4.9153	130.57	0.20340
340	3.9670	135.22	0.21088	4.1979	134.88	0.20990	4.4344	134.54	0.20894	4.6768	134.20	0.20800
360	3.8076	138.70	0.21519	4.0241	138.40	0.21424	4.2449	138.09	0.21332	4.4705	137.77	0.21242
380	3.6649	142.17	0.21937	3.8692	141.89	0.21845	4.0771	141.61	0.21756	4.2887	141.32	0.21668
400	3.5359	145.63	0.22344	3.7298	145.36	0.22254	3.9266	145.10	0.22167	4.1265	144.83	0.22082
420	3.4183	149.07	0.22740	3.6031	148.83	0.22652	3.7903	148.58	0.22567	3.9802	148.33	0.22485
440	3.3103	152.51	0.23127	3.4871	152.28	0.23041	3.6660	152.05	0.22958	3.8470	151.82	0.22877
460	3.2106	155.95	0.23505	3.3802	155.74	0.23420	3.5517	155.52	0.23339	3.7249	155.30	0.23259

Temp °F	Pressure 250 psia (235.3 psig) (Sat'n Temp 280.93°F)			Pressure 260 psia (245.3 psig) (Sat'n Temp 284.97°F)			Pressure 280 psia (265.3 psig) (Sat'n Temp 292.70°F)			Pressure 300 psia (285.3 psig) (Sat'n Temp 300.04°F)		
Sat'n (Liquid)	(71.275)	(70.318)	(0.12186)	(70.707)	(71.356)	(0.12322)	(69.586)	(73.370)	(0.12584)	(68.477)	(75.309)	(0.12834)
(Vapor)	(5.8725)	(122.66)	(0.19253)	(6.1409)	(122.91)	(0.19246)	(6.6912)	(123.36)	(0.19229)	(7.2611)	(123.74)	(0.19209)
50	94.572	17.921	0.03754	94.582	17.933	0.03753	94.602	17.955	0.03750	94.621	17.978	0.03746
60	93.785	20.032	0.04164	93.795	20.043	0.04163	93.816	20.065	0.04159	93.837	20.087	0.04156
70	92.988	22.155	0.04569	92.999	22.166	0.04567	93.020	22.187	0.04564	93.042	22.209	0.04561
80	92.180	24.289	0.04968	92.192	24.300	0.04967	92.215	24.321	0.04963	92.238	24.342	0.04960
90	91.362	26.434	0.05362	91.374	26.444	0.05360	91.398	26.465	0.05357	91.422	26.485	0.05353
100	90.531	28.589	0.05751	90.544	28.599	0.05749	90.570	28.619	0.05745	90.595	28.638	0.05741
110	89.688	30.753	0.06134	89.701	30.763	0.06132	89.728	30.782	0.06128	89.755	30.801	0.06124
120	88.830	32.927	0.06512	88.844	32.937	0.06510	88.873	32.955	0.06506	88.901	32.973	0.06502
130	87.957	35.112	0.06886	87.972	35.120	0.06884	88.002	35.138	0.06880	88.032	35.155	0.06875
140	87.067	37.307	0.07255	87.083	37.315	0.07253	87.115	37.331	0.07248	87.147	37.348	0.07244
150	86.159	39.514	0.07620	86.176	39.521	0.07618	86.210	39.537	0.07613	86.245	39.552	0.07609
160	85.231	41.733	0.07981	85.250	41.740	0.07979	85.286	41.754	0.07974	85.323	41.768	0.07969
170	84.282	43.966	0.08339	84.302	43.973	0.08336	84.341	43.985	0.08331	84.380	43.998	0.08326
180	83.310	46.215	0.08693	83.331	46.220	0.08690	83.373	46.231	0.08685	83.414	46.242	0.08680
190	82.311	48.479	0.09044	82.333	48.484	0.09041	82.379	48.493	0.09036	82.423	48.502	0.09030
200	81.283	50.763	0.09393	81.307	50.767	0.09390	81.356	50.774	0.09384	81.405	50.781	0.09378
220	79.127	55.395	0.10085	79.156	55.396	0.10081	79.214	55.398	0.10075	79.271	55.400	0.10068
240	76.806	60.132	0.10772	76.841	60.129	0.10768	76.911	60.125	0.10760	76.980	60.121	0.10753
260	74.266	65.007	0.11459	74.310	65.000	0.11454	74.396	64.986	0.11445	74.482	64.972	0.11436
280	71.418	70.075	0.12153	71.475	70.060	0.12147	71.588	70.031	0.12137	71.699	70.003	0.12126
300	5.5012	126.39	0.19751	5.8181	125.91	0.19645	6.4996	124.88	0.19430	68.483	75.299	0.12832
320	5.1874	130.17	0.20241	5.4688	129.75	0.20144	6.0630	128.88	0.19949	6.7071	127.94	0.19754
340	4.9256	133.84	0.20707	5.1811	133.48	0.20615	5.7147	132.71	0.20435	6.2825	131.91	0.20257
360	4.7009	137.45	0.21153	4.9366	137.12	0.21066	5.4248	136.44	0.20896	5.9380	135.73	0.20730
380	4.5043	141.02	0.21583	4.7240	140.72	0.21500	5.1765	140.11	0.21337	5.6482	139.47	0.21180
400	4.3296	144.56	0.22000	4.5361	144.28	0.21919	4.9595	143.72	0.21763	5.3980	143.14	0.21612
420	4.1727	148.08	0.22404	4.3679	147.82	0.22326	4.7670	147.30	0.22174	5.1783	146.77	0.22029
440	4.0303	151.58	0.22798	4.2159	151.34	0.22722	4.5942	150.86	0.22574	4.9825	150.36	0.22433
460	3.9001	155.08	0.23182	4.0772	154.85	0.23107	4.4375	154.40	0.22963	4.8061	153.93	0.22826

THERMODYNAMIC PROPERTIES OF TRICHLOROFLUOROMETHANE (R-11)

Temp °F	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R
	Pressure 350 psia (335.3 psig) (Sat'n Temp 316.89°F)			Pressure 400 psia (385.3 psig) (Sat'n Temp 332.02°F)			Pressure 500 psia (485.3 psig) (Sat'n Temp 358.44°F)			Pressure 600 psia (585.3 psig) (Sat'n Temp 381.08°F)		
Sat'n (Liquid)	(65.725)	(79.903)	(0.13414)	(62.935)	(84.235)	(0.13948)	(56.748)	(92.615)	(0.14950)	(46.395)	(102.78)	(0.16131)
(Vapor)	(8.7858)	(124.39)	(0.19142)	(10.491)	(124.64)	(0.19051)	(14.786)	(123.83)	(0.18766)	(34.785)	(109.79)	(0.16964)
50	94.671	18.035	0.03738	94.720	18.092	0.03730	94.817	18.206	0.03714	94.914	18.320	0.03698
60	93.888	20.143	0.04148	93.940	20.198	0.04140	94.042	20.310	0.04123	94.143	20.423	0.04107
70	93.097	22.263	0.04552	93.151	22.318	0.04544	93.258	22.427	0.04527	93.364	22.537	0.04510
80	92.295	24.395	0.04951	92.352	24.448	0.04942	92.465	24.555	0.04925	92.576	24.662	0.04907
90	91.483	26.537	0.05344	91.543	26.588	0.05335	91.661	26.692	0.05317	91.778	26.796	0.05299
100	90.659	28.688	0.05732	90.722	28.738	0.05722	90.847	28.838	0.05704	90.970	28.940	0.05686
110	89.822	30.849	0.06114	89.889	30.897	0.06105	90.020	30.994	0.06086	90.150	31.091	0.06067
120	88.972	33.019	0.06492	89.042	33.065	0.06482	89.182	33.158	0.06462	89.319	33.252	0.06443
130	88.107	35.199	0.06865	88.182	35.243	0.06855	88.329	35.331	0.06834	88.474	35.421	0.06814
140	87.227	37.389	0.07233	87.306	37.430	0.07222	87.462	37.514	0.07201	87.615	37.600	0.07180
150	86.329	39.590	0.07597	86.413	39.629	0.07586	86.579	39.708	0.07564	86.741	39.788	0.07542
160	85.413	41.803	0.07957	85.502	41.839	0.07946	85.678	41.912	0.07923	85.851	41.987	0.07900
170	84.476	44.030	0.08314	84.572	44.062	0.08302	84.759	44.129	0.08277	84.943	44.197	0.08254
180	83.518	46.270	0.08667	83.620	46.299	0.08654	83.820	46.358	0.08629	84.016	46.420	0.08604
190	82.535	48.526	0.09017	82.644	48.551	0.09003	82.859	48.602	0.08977	83.069	48.657	0.08951
200	81.525	50.800	0.09364	81.643	50.820	0.09350	81.874	50.862	0.09322	82.099	50.908	0.09295
220	79.412	55.407	0.10052	79.551	55.416	0.10036	79.821	55.436	0.10005	80.082	55.462	0.09975
240	77.150	60.112	0.10734	77.316	60.105	0.10716	77.637	60.097	0.10681	77.944	60.096	0.10647
260	74.692	64.941	0.11415	74.896	64.913	0.11394	75.286	64.865	0.11353	75.657	64.828	0.11314
280	71.968	69.938	0.12100	72.228	69.878	0.12074	72.718	69.773	0.12025	73.176	69.687	0.11979
300	68.853	75.177	0.12798	69.202	75.066	0.12766	69.848	74.873	0.12706	70.436	74.711	0.12650
320	8.6417	125.14	0.19238	65.596	80.608	0.13486	66.520	80.255	0.13405	67.325	79.969	0.13333
340	7.9005	129.63	0.19807	9.9777	126.75	0.19317	62.380	86.129	0.14149	63.616	85.594	0.14045
360	7.3569	133.79	0.20321	9.0484	131.50	0.19903	14.501	124.47	0.18844	58.712	91.937	0.14828
380	6.9265	137.75	0.20799	8.3886	135.82	0.20424	12.300	130.82	0.19610	48.329	101.47	0.15975
400	6.5702	141.60	0.21252	7.8753	139.91	0.20905	11.094	135.86	0.20203	16.085	129.98	0.19355
420	6.2663	145.36	0.21685	7.4552	143.85	0.21359	10.252	140.39	0.20724	13.996	135.98	0.20046
440	6.0016	149.07	0.22102	7.0999	147.70	0.21791	9.6039	144.65	0.21203	12.716	141.02	0.20612
460	5.7673	152.74	0.22505	6.7922	151.48	0.22207	9.0778	148.74	0.21652	11.790	145.60	0.21117

Temp °F	Pressure 700 psia (685.3 psig)			Pressure 800 psia (785.3 psig)			Pressure 900 psia (885.3 psig)			Pressure 1000 psia (985.3 psig)		
60	94.244	20.535	0.04091	94.344	20.649	0.04075	94.442	20.762	0.04059	94.541	20.877	0.04043
70	93.470	22.647	0.04493	93.574	22.758	0.04477	93.678	22.870	0.04461	93.780	22.982	0.04444
80	92.687	24.770	0.04890	92.796	24.878	0.04873	92.905	24.987	0.04857	93.012	25.097	0.04840
90	91.895	26.901	0.05282	92.009	27.007	0.05264	92.123	27.113	0.05247	92.235	27.220	0.05230
100	91.092	29.042	0.05668	91.213	29.144	0.05650	91.332	29.248	0.05632	91.449	29.352	0.05614
110	90.279	31.190	0.06048	90.405	31.290	0.06030	90.530	31.390	0.06011	90.654	31.491	0.05993
120	89.454	33.347	0.06423	89.587	33.443	0.06404	89.718	33.540	0.06385	89.848	33.638	0.06367
130	88.616	35.512	0.06794	88.757	35.604	0.06774	88.895	35.698	0.06754	89.032	35.792	0.06735
140	87.766	37.686	0.07159	87.914	37.774	0.07139	88.060	37.863	0.07119	88.203	37.954	0.07099
150	86.900	39.870	0.07520	87.057	39.953	0.07499	87.211	40.038	0.07478	87.362	40.124	0.07458
160	86.020	42.064	0.07877	86.186	42.142	0.07855	86.348	42.222	0.07834	86.508	42.303	0.07812
170	85.123	44.268	0.08230	85.298	44.341	0.08207	85.471	44.415	0.08185	85.640	44.492	0.08162
180	84.207	46.485	0.08580	84.394	46.551	0.08556	84.577	46.620	0.08532	84.757	46.690	0.08509
190	83.273	48.714	0.08925	83.472	48.774	0.08900	83.667	48.836	0.08876	83.857	48.900	0.08852
200	82.317	50.957	0.09268	82.530	51.010	0.09242	82.737	51.064	0.09216	82.940	51.122	0.09191
220	80.334	55.492	0.09945	80.579	55.526	0.09916	80.816	55.564	0.09888	81.047	55.605	0.09861
240	78.240	60.101	0.10614	78.525	60.112	0.10581	78.800	60.129	0.10550	79.065	60.150	0.10520
260	76.009	64.801	0.11276	76.346	64.782	0.11239	76.669	64.771	0.11204	76.978	64.767	0.11170
280	73.606	69.615	0.11936	74.013	69.556	0.11894	74.398	69.509	0.11854	74.765	69.471	0.11815
300	70.979	74.574	0.12597	71.482	74.459	0.12548	71.953	74.362	0.12501	72.395	74.281	0.12457
320	68.041	79.732	0.13267	68.688	79.533	0.13207	69.281	79.364	0.13151	69.829	79.221	0.13098
340	64.641	85.178	0.13957	65.524	84.841	0.13879	66.304	84.563	0.13809	67.005	84.329	0.13745
360	60.448	91.108	0.14689	61.783	90.507	0.14579	62.885	90.040	0.14486	63.830	89.662	0.14404
380	54.432	98.126	0.15535	56.996	96.810	0.15338	58.763	95.951	0.15198	60.143	95.317	0.15085
400	35.788	112.84	0.17262	49.586	104.68	0.16264	53.341	102.65	0.15987	55.646	101.47	0.15810
420	20.160	129.38	0.19168	34.609	117.51	0.17737	45.144	111.06	0.16952	49.781	108.47	0.16614
440	16.941	136.38	0.19956	23.727	129.78	0.19118	34.219	121.61	0.18139	42.075	116.68	0.17537
460	15.165	141.89	0.20562	19.688	137.28	0.19944	26.212	131.42	0.19217	33.996	125.58	0.18515

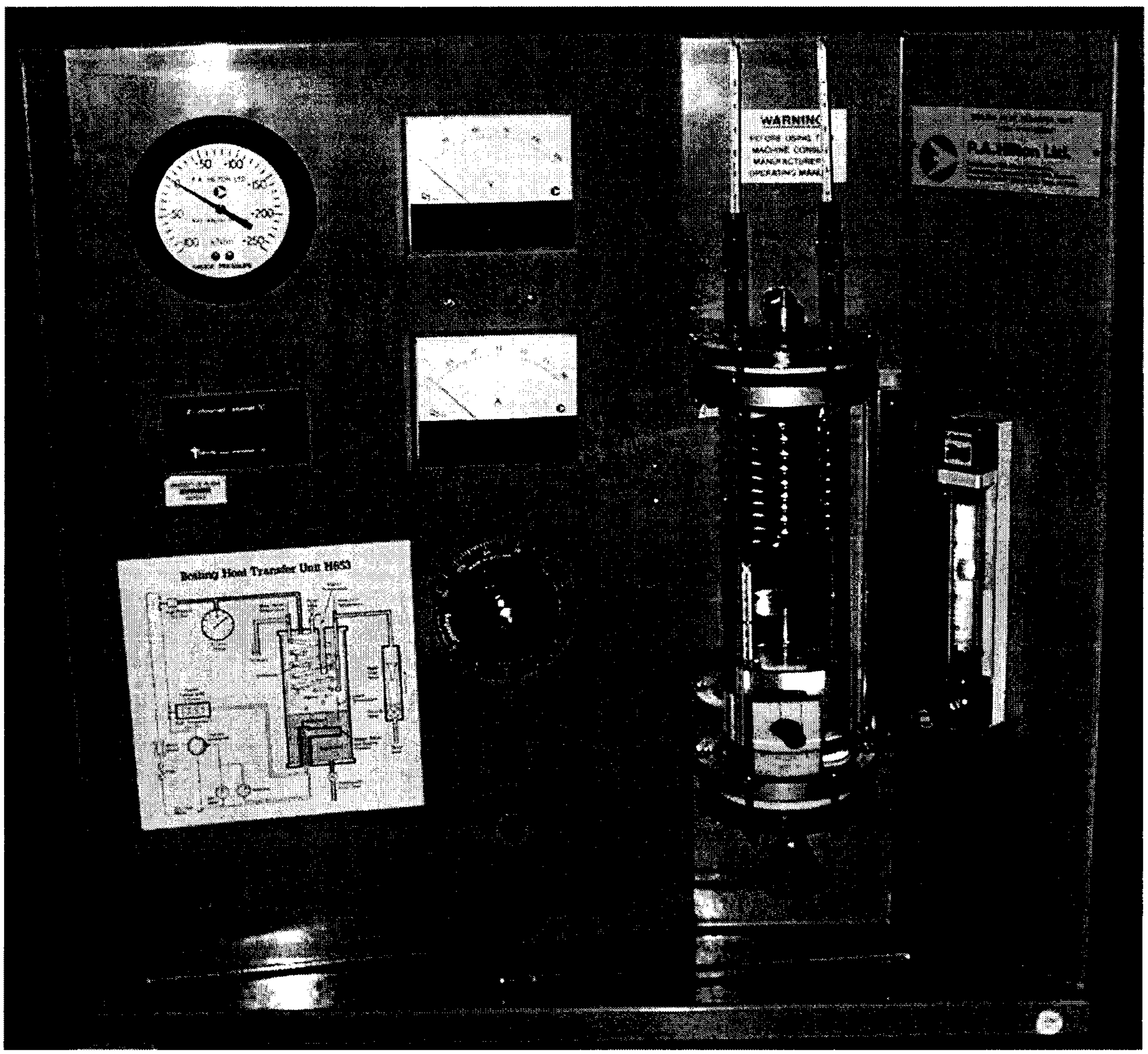
Temp °F	Pressure 1500 psia (1485 psig)			Pressure 2000 psia (1985 psig)			Pressure 2500 psia (2485 psig)			Pressure 3000 psia (2985 psig)		
70	94.280	23.549	0.04366	94.762	24.126	0.04290						
80	93.534	25.652	0.04759	94.035	26.220	0.04681	94.517	26.796	0.04606	94.984	27.382	0.04534
90	92.781	27.764	0.05147	93.302	28.320	0.05067	93.803	28.888	0.04990	94.285	29.464	0.04916
100	92.020	29.883	0.05529	92.563	30.427	0.05447	93.083	30.984	0.05368	93.582	31.552	0.05292
110	91.251	32.008	0.05905	91.817	32.540	0.05821	92.357	33.086	0.05740	92.874	33.643	0.05663
120	90.473	34.139	0.06276	91.064	34.658	0.06190	91.625	35.192	0.06107	92.161	35.739	0.06027
130	89.687	36.277	0.06642	90.303	36.781	0.06553	90.887	37.303	0.06468	91.443	37.839	0.06387
140	88.891	38.421	0.07002	89.535	38.910	0.06911	90.143	39.418	0.06824	90.720	39.942	0.06740

THERMODYNAMIC PROPERTIES OF TRICHLOROFLUOROMETHANE (R-11)

Temp °F	Pressure 1500 psia (1485 psig)			Pressure 2000 psia (1985 psig)			Pressure 2500 psia (2485 psig)			Pressure 3000 psia (2985 psig)		
	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R	Density lbm/ft³	Enthalpy Btu/lbm	Entropy Btu/lbm-R
150	88.085	40.572	0.07358	88.759	41.045	0.07264	89.392	41.538	0.07174	89.991	42.050	0.07089
160	87.269	42.730	0.07709	87.975	43.185	0.07612	88.635	43.663	0.07520	89.257	44.161	0.07432
170	86.442	44.895	0.08056	87.181	45.331	0.07956	87.870	45.793	0.07861	88.517	46.277	0.07771
180	85.603	47.069	0.08398	86.378	47.484	0.08295	87.098	47.929	0.08197	87.771	48.397	0.08105
190	84.751	49.252	0.08737	85.566	49.645	0.08630	86.318	50.070	0.08530	87.018	50.523	0.08435
200	83.886	51.444	0.09072	84.743	51.812	0.08961	85.530	52.218	0.08858	86.260	52.653	0.08760
220	82.114	55.858	0.09731	83.066	56.172	0.09612	83.929	56.533	0.09502	84.723	56.930	0.09399
240	80.278	60.319	0.10378	81.341	60.568	0.10250	82.293	60.877	0.10132	83.159	61.231	0.10023
260	78.370	64.832	0.11014	79.564	65.004	0.10875	80.618	65.252	0.10749	81.566	65.558	0.10632
280	76.379	69.406	0.11641	77.730	69.485	0.11489	78.901	69.663	0.11353	79.942	69.913	0.11229
300	74.293	74.049	0.12260	75.832	74.016	0.12093	77.141	74.111	0.11946	78.287	74.298	0.11814
320	72.095	78.770	0.12873	73.864	78.600	0.12689	75.332	78.599	0.12530	76.598	78.713	0.12388
340	69.768	83.583	0.13483	71.818	83.243	0.13277	73.473	83.129	0.13103	74.875	83.160	0.12951
360	67.289	88.500	0.14090	69.687	87.950	0.13858	71.562	87.702	0.13668	73.118	87.639	0.13504
380	64.628	93.541	0.14698	67.464	92.724	0.14434	69.596	92.319	0.14225	71.326	92.149	0.14048
400	61.754	98.724	0.15308	65.142	97.570	0.15004	67.575	96.980	0.14773	69.501	96.689	0.14582
420	58.630	104.07	0.15922	62.717	102.49	0.15570	65.500	101.68	0.15314	67.645	101.26	0.15108
440	55.234	109.60	0.16544	60.190	107.48	0.16131	63.376	106.43	0.15847	65.763	105.85	0.15624
460	51.575	115.31	0.17171	57.570	112.54	0.16687	61.208	111.21	0.16373	63.858	110.47	0.16131

Boiling Heat Transfer

BOILING HEAT TRANSFER



Boiling Heat Transfer Experiment

D.K. Das

Purpose: Demonstration of the three modes of boiling and determination of heat flux and heat transfer coefficient for a boiling liquid.

Apparatus: Hilton Boiling Heat Transfer Unit

Introduction: When a liquid at saturation temperature is in contact with the surface of a solid at a higher temperature, boiling occurs with a change in phase. When the heating surface is slightly hotter than the saturation temperature, convection currents carry the warmed liquid to the liquid-vapor interface where evaporation takes place. This is the convective boiling mode and, no bubble formation is observed during this process. If the surface temperature is increased further, bubbles are formed on the surface and are carried up due to buoyancy. This is the nucleate boiling mode which is characterized by vigorous bubble formation and turbulence. Exceptionally high heat transfer rates and heat transfer coefficients with moderate temperature differences occur in nucleate boiling. In practical applications, such as steam generators, boiling is usually in this mode. Above a critical surface-liquid temperature difference the surface gets covered with a vapor blanket and film boiling ensues. In this mode the temperature of the surface can rise until a failure or "burn out" occurs. Many tube failures in the radiant section of advanced power plant boilers are attributed to this cause.

Procedure: From the Hilton Boiling Heat Transfer Unit the following measurements should be taken. Refer to the attached schematic diagram of the apparatus.

1. Liquid temperature, T.
2. Metal temperature, T_m.
3. Voltage, V.
4. Current, I.

To produce a complete boiling curve, maintain a constant chamber pressure (P saturation) anywhere in the range of 75 – 200 KN/m^2. By adjusting the heater and water flow rate, the pressure can be maintained constant. Repeat in small increments for accurate results near the transition from nucleate to film boiling. When film boiling is established the voltage should be reduced along with the water flow to maintain a steady pressure.

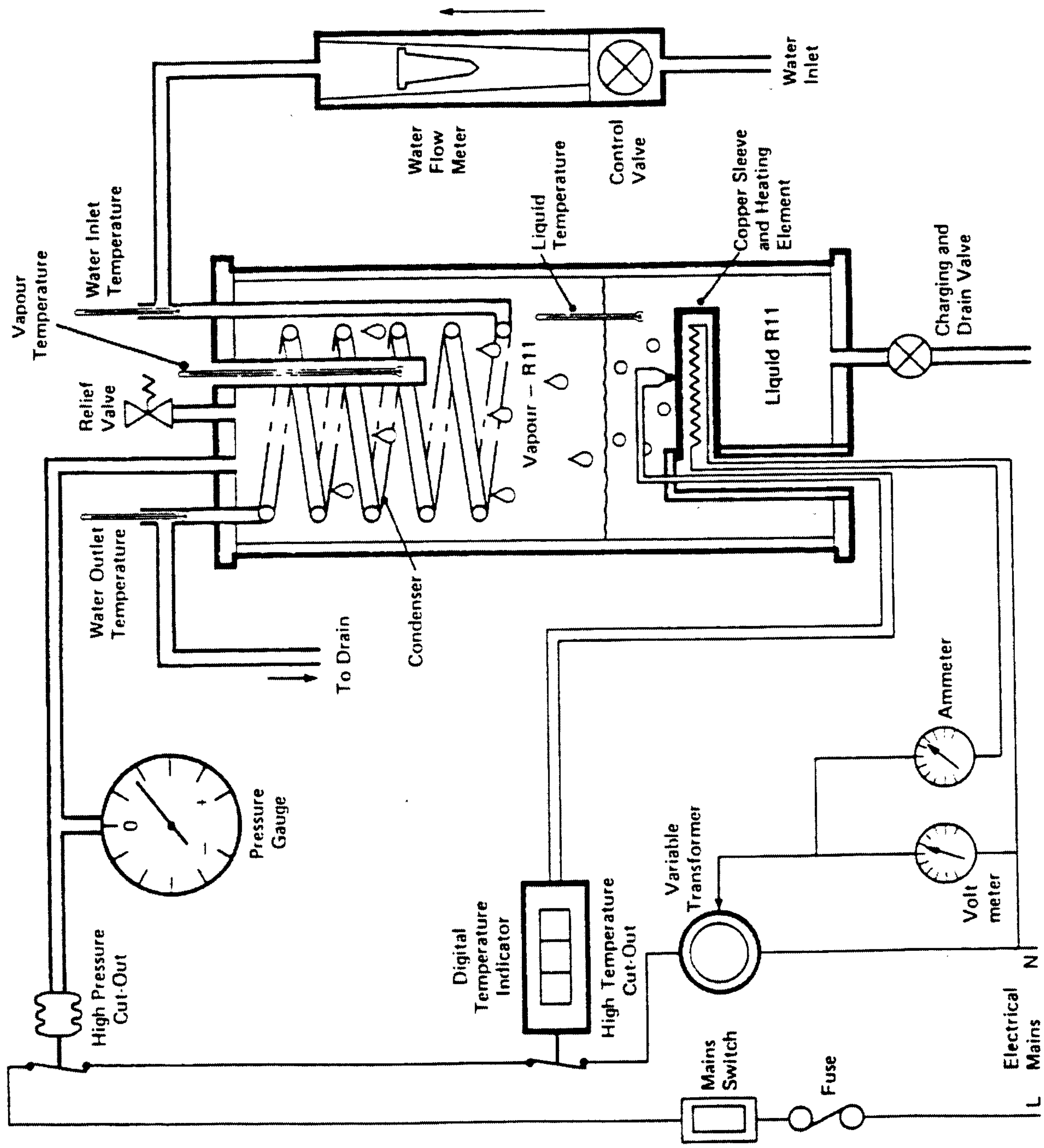
Equations:

Heat transfer rate from the heater: $\dot{Q} = EI$

$HeatFlux = \dfrac{\dot{Q}}{A}$; where the heat transfer surface $A = 1.3 \times 10^{-3} m^2$

Heat transfer coefficient: $h = \dfrac{\dot{Q}}{A(T_m - T)}$

Results: Plot heat flux versus (T_m – T) and h versus (T_m – T) on log-log plots and discuss your results with regards to the three modes of boiling and the critical heat flux.


Water Inlet
Water Flow Meter
Control Valve
Liquid Temperature
Copper Sleeve and Heating Element
Charging and Drain Valve
Liquid R11
Vapour – R11
Vapour Temperature
Water Inlet Temperature
Relief Valve
Water Outlet Temperature
Condenser
To Drain
Ammeter
Pressure Gauge
Variable Transformer
Volt meter
Digital Temperature Indicator
High Temperature Cut-Out
High Pressure Cut-Out
Mains Switch
Fuse
Electrical Mains
L
N

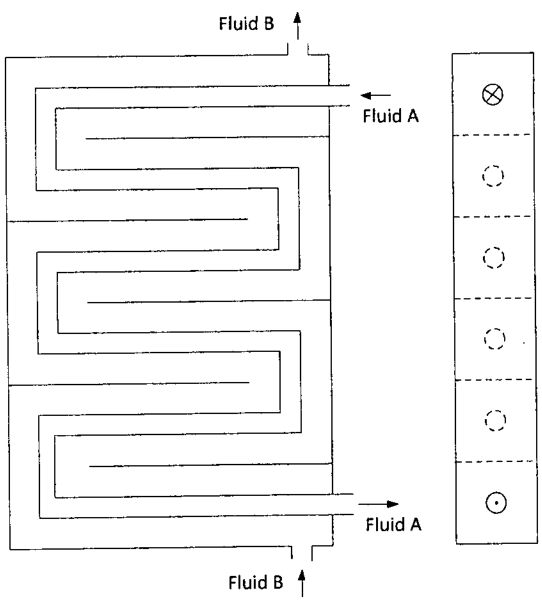
Heat Exchanger Design Project

Design Project: Oil-to-Water Heat Exchanger

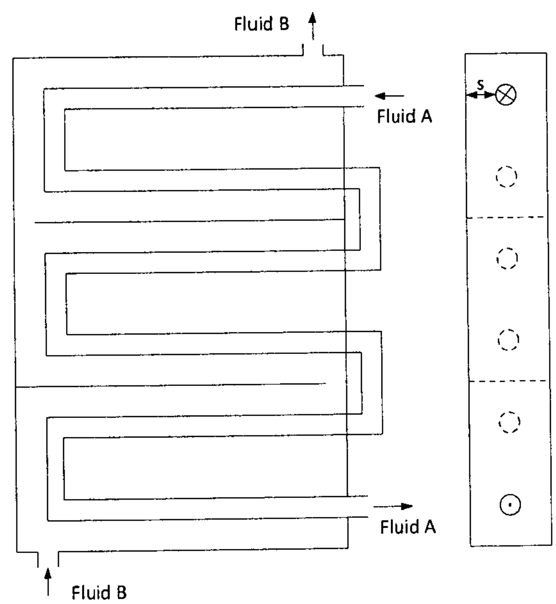
ME 415 (Thermal Systems Laboratory) 2011 Fall

In this project you are asked to design an effective oil-to-water heat exchanger. You become a mechanical engineer who is in charge of drawing and specifying a heat exchanger that utilizes high-temperature oil from waste heat of a diesel power plant. Water from the heat exchanger is to be used for heating buildings or for other applications of your interest.

Your heat exchanger should create maximum heat transfer rate and maximum water flow rate with an acceptable outlet temperature. Depending on where the hot water is used, you may focus either on the maximum flow rate or on the highest outlet temperature. The oil is supplied at 150 °C with a flow rate of 1.2 kg/s while the water temperature at the inlet is 23 °C. You can choose type of heat exchanger from double-pipe, cross-flow and shell-and-tube. However, you must use one piece of circular copper tube, which separates the two fluids. The total volume of the copper tube is limited to 0.01 m^3. Although you can pick the tube diameter, the tube wall thickness is specified to be 3 mm. The wall that houses the fluid flowing over the outside of the copper tube is flat surfaces as in Figure 1. Thus, from the cross-section view the heat exchanger has tube-in-box configuration, instead of tube-in-tube. The space, s, between wall and the tube must keep equal to or larger than 10% of outer diameter of the tube, $s \geq 0.1D_o$. Each tube pass occupies a square space $(2s + D_o) \times (2s + D_o)$.



(a) 6-shell-pass 6-tube-pass heat exchanger



(b) 3-shell-pass 6-tube-pass heat exchanger

Figure 1: Example configurations, side-view and cross-section view

1. Optimize your heat exchanger to produce a maximum heat transfer rate. At the same time, you must have a good water flow rate (must be equal to or greater than 0.3 kg/s) and outlet temperature. Maximum available pumping work for each fluid is 500 W. Assume that there is no heat loss to the

ambient. However, attempt to minimize the outer surface area in order to save the cost of insulation. Use a fouling factor $R_f = 0.0003\ m^2K/W$ for both inner and outer surface of the tube. And surface roughness e is assumed to be 0.1 mm for all surfaces.

2. Discuss a new technology utilizing waste heat and how your heat exchanger works for the technology.

Your project paper should consist of

Title

Objective

Design of Heat Exchanger

Sub-sections:

a. selection of type and flow configuration,

b. selection of flow rate and diameter,

c. calculation to find the heat transfer coefficients h_i and h_o, the overall heat transfer coefficient U, the number of transfer unit (NTU), effectiveness ε, the heat transfer rate $\dot{Q}$, outlet temperatures $T_{C,out}$, T_{H_out}, LMTD, and pumping work for both fluids,

d. optimization,

e. optimized design including figures, and

f. discussion.

Introduction of new technology utilizing waste heat (1/2 ~ 1 page)

References

Appendix

3. Others

Maximum length of paper: **10 pages** excluding Appendix.

Use SI Units

Submit your paper in DOC or PDF by 5 pm May 2 (Mon) tinyurl.com/radiatorstuff

ENGINE COOLANT

Deg C	Deg F	Deg C	Deg F	Deg C	Deg F
Cooling Water inlet	Cooling Water inlet	Cooling Water outlet	Cooling Water outlet	Intake manifold	Intake manifold
62.3	144.2	89.6	193.4	45.5	114.0
62.8	145.0	89.7	193.5	45.6	114.1
62.4	144.3	89.7	193.4	45.6	114.0
62.5	144.4	89.5	193.[illegible]	45.5	114.0
62.6	144.6	89.8	193.6	45.5	114.0
62.4	144.3	89.7	193.4	45.6	114.0
62.3	144.2	89.7	193.5	45.5	113.9
63.1	145.5	89.6	193.4	45.5	114.0
62.3	144.2	89.8	193.6	45.7	114.2
62.5	144.5	89.7	193.4	45.5	113.8
62.6	144.7	89.7	193.1	45.4	113.8
62.6	144.6	89.6	193.4	[illegible]	114.2
62.1	[illegible]	89.3	193.2	45.6	114.0
62.6	[illegible]	89.[illegible]	193.4	45.6	114.0
62.5	[illegible]	89.6	193.4	45.5	114.0
62.7	143.9	89.[illegible]	193.4	45.6	114.0
62.3	144.1	89.8	193.6	45.7	114.2
62.2	143.9	89.7	193.5	45.6	114.1
62.5	144.5	89.7	193.5	45.6	114.1
62.5	144.5	89.7	193.4	45.6	114.0
62.5	144.5	89.8	193.7	45.6	114.1
63.0	145.4	89.8	193.6	45.7	114.2
62.[illegible]	144.1	89.8	193.7	45.6	114.1
62.[illegible]	[illegible]	89.7	193.5	45.5	113.9
62.8	[illegible]	89.8	193.7	45.6	114.[illegible]
62.6	[illegible]	89.7	193.5	45.6	114.[illegible]
62.9	[illegible]	89.7	193.5	45.7	114.[illegible]

Engine Coolant

GPM	in WC	CFM	milli bar	in of Hg		
Vol Flow of coolant	Diffpress	Air Flow	Barometric Pressure	Barometric Pressure	Viscosity (AIR)	TempAvs (CF
10.5	3.0	378.5	974.0	28.8	190.4	0.9
10.5	3.0	378.0	974.0	28.8	190.4	0.9
10.6	3.0	379.0	973.9	28.8	190.4	0.9
10.5	3.0	378.3	974.0	28.8	190.4	0.9
10.5	3.0	378.8	974.0	28.8	190.4	0.9
10.5	3.0	377.7	973.9	28.8	190.4	0.9
10.7	3.0	378.2	973.9	28.8	190.4	0.9
10.5	3.0	378.8	973.9	28.8	190.4	0.9
10.5	3.0	378.2	973.9	28.8	190.4	0.9
10.7	3.0	378.8	974.0	28.8	190.4	0.9
[illegible]	3.0	378.8	973.9	28.8	190.4	0.9
10.6	3.0	379.6	973.9	28.8	190.4	0.9
10.6	3.0	379.7	973.9	28.8	190.5	0.9
10.6	3.0	379.9	973.9	28.8	190.5	0.9
10.6	3.0	379.1	973.9	28.8	190.5	0.9
10.3	3.0	378.5	973.9	28.8	190.5	0.9
10.5	3.0	379.0	973.9	28.8	190.5	0.9
10.5	3.0	379.1	973.9	28.8	190.5	0.9
10.6	3.0	379.9	973.9	28.8	190.5	0.9
10.3	3.0	379.0	973.9	28.8	190.5	0.9
10.2	3.0	379.3	974.0	28.8	190.5	0.9
[illegible]	3.0	378.8	973.9	28.8	190.5	0.9
[illegible]	3.0	379.0	973.9	28.8	190.5	0.9
10.5	3.0	378.6	973.9	28.8	190.5	0.9
10.5	3.0	378.3	973.9	28.8	190.5	0.9
10.1	3.0	379.0	973.8	28.8	190.5	0.9
10.1	3.0	379.4	973.9	28.8	190.5	0.9

Table 8 Thermal Conductivity of Aqueous Solutions of Ethylene Glycol

	Concentrations in Volume Percent Ethylene Glycol								
Temperature, °F	10%	20%	30%	40%	50%	60%	70%	80%	90%
–30					0.187	0.173	0.161	0.151	
–20					0.190	0.175	0.163	0.153	0.145
–10				0.209	0.192	0.178	0.165	0.154	0.146
0				0.213	0.195	0.180	0.166	0.155	0.147
10			0.236	0.216	0.198	0.182	0.168	0.156	0.148
20		0.263	0.240	0.219	0.200	0.184	0.169	0.158	0.148
30	0.294	0.268	0.244	0.222	0.203	0.186	0.171	0.159	0.149
40	0.300	0.273	0.248	0.225	0.205	0.188	0.172	0.160	0.150
50	0.305	0.277	0.251	0.228	0.208	0.190	0.174	0.161	0.151
60	0.310	0.281	0.255	0.231	0.210	0.191	0.175	0.162	0.151
70	0.314	0.285	0.258	0.234	0.212	0.193	0.177	0.163	0.152
80	0.319	0.289	0.261	0.236	0.214	0.195	0.178	0.164	0.153
90	0.323	0.292	0.264	0.239	0.216	0.196	0.179	0.164	0.153
100	0.327	0.296	0.267	0.241	0.218	0.198	0.180	0.165	0.154
110	0.331	0.299	0.269	0.243	0.220	0.199	0.181	0.166	0.154
120	0.334	0.301	0.272	0.245	0.221	0.200	0.182	0.167	0.155
130	0.337	0.304	0.274	0.247	0.223	0.201	0.183	0.167	0.155
140	0.340	0.306	0.276	0.248	0.224	0.202	0.183	0.168	0.156
150	0.342	0.309	0.277	0.250	0.225	0.203	0.184	0.168	0.156
160	0.345	0.310	0.279	0.251	0.226	0.204	0.185	0.169	0.156
170	0.347	0.312	0.280	0.252	0.227	0.204	0.185	0.169	0.157
180	0.349	0.314	0.282	0.253	0.228	0.205	0.186	0.169	0.157
190	0.350	0.315	0.283	0.254	0.228	0.206	0.186	0.170	0.157
200	0.351	0.316	0.284	0.255	0.229	0.206	0.186	0.170	0.157
210	0.352	0.317	0.284	0.255	0.229	0.206	0.186	0.170	0.157
220	0.353	0.318	0.285	0.256	0.230	0.207	0.187	0.170	0.157
230	0.354	0.318	0.285	0.256	0.230	0.207	0.187	0.170	0.157
240	0.355	0.319	0.286	0.256	0.230	0.207	0.187	0.170	0.157
250	0.355	0.319	0.286	0.257	0.230	0.207	0.187	0.170	0.157

Source: Dow Chemical (2001b)

Note: Thermal conductivity in Btu·ft/h·ft^2·°F.

Table 9 Viscosity of Aqueous Solutions of Ethylene Glycol

	Concentrations in Volume Percent Ethylene Glycol								
Temperature, °F	10%	20%	30%	40%	50%	60%	70%	80%	90%
–30					154.07	216.92	311.55	448.06	
–20					97.68	146.26	217.55	317.67	688.18
–10				47.37	65.97	101.72	153.61	222.27	410.83
0				33.29	46.79	72.77	110.26	157.34	260.71
10			16.52	24.51	34.50	53.37	80.58	113.43	173.86
20		9.43	13.01	18.72	26.25	40.06	59.97	83.41	120.81
30	5.23	7.60	10.47	14.73	20.51	30.67	45.41	62.51	86.87
40	4.40	6.27	8.56	11.88	16.38	23.95	34.96	47.68	64.32
50	3.77	5.27	7.14	9.77	13.30	18.99	27.36	36.99	48.82
60	3.27	4.50	6.02	8.18	11.01	15.31	21.70	29.15	37.86
70	2.85	3.89	5.15	6.94	9.22	12.51	17.47	23.27	29.92
80	2.52	3.41	4.45	5.95	7.81	10.35	14.22	18.84	24.02
90	2.25	3.00	3.87	5.15	6.68	8.66	11.73	15.43	19.59
100	2.01	2.69	3.41	4.52	5.78	7.33	9.77	12.77	16.16
110	1.81	2.39	3.02	3.97	5.03	6.24	8.22	10.67	13.50
120	1.64	2.18	2.69	3.53	4.40	5.39	6.97	9.02	11.39
130	1.50	1.96	2.42	3.14	3.89	4.67	5.98	7.67	9.70
140	1.38	1.79	2.18	2.83	3.46	4.09	5.15	6.58	8.35
150	1.28	1.64	1.98	2.54	3.10	3.60	4.50	5.68	7.21
160	1.19	1.52	1.81	2.30	2.78	3.19	3.94	4.96	6.29
170	1.11	1.40	1.64	2.10	2.52	2.85	3.46	4.35	5.52
180	1.04	1.31	1.52	1.91	2.27	2.56	3.07	3.82	4.86
190	0.97	1.21	1.40	1.77	2.06	2.30	2.76	3.39	4.33
200	0.90	1.14	1.31	1.62	1.89	2.08	2.47	3.02	3.87
210	0.85	1.04	1.21	1.48	1.72	1.89	2.23	2.71	3.46
220	0.80	0.99	1.11	1.38	1.60	1.74	2.01	2.44	3.12
230	0.77	0.92	1.04	1.28	1.45	1.60	1.84	2.20	2.81
240	0.73	0.87	0.97	1.19	1.35	1.48	1.67	2.01	2.56
250	0.70	0.82	0.92	1.09	1.26	1.35	1.52	1.81	2.32

Source: Dow Chemical (2001b)

Note: Viscosity in ft/lb·h.

~~whups~~ okay?

Table 6 Density of Aqueous Solutions of Ethylene Glycol

Temperature, °F	Concentrations in Volume Percent Ethylene Glycol								
	10%	20%	30%	40%	50%	60%	70%	80%	90%
−30					68.12	69.03	69.90	70.75	
−20					68.05	68.96	69.82	70.65	71.45
−10				67.04	67.98	68.87	69.72	70.54	71.33
0				66.97	67.90	68.78	69.62	70.43	71.20
10			65.93	66.89	67.80	68.67	69.50	70.30	71.06
20		64.83	65.85	66.80	67.70	68.56	69.38	70.16	70.92
30	63.69	64.75	65.76	66.70	67.59	68.44	69.25	70.02	70.76
40	63.61	64.66	65.66	66.59	67.47	68.31	69.10	69.86	70.59
50	63.52	64.56	65.55	66.47	67.34	68.17	68.95	69.70	70.42
60	63.42	64.45	65.43	66.34	67.20	68.02	68.79	69.53	70.23
70	63.31	64.33	65.30	66.20	67.05	67.86	68.62	69.35	70.04
80	63.19	64.21	65.17	66.05	66.90	67.69	68.44	69.15	69.83
90	63.07	64.07	65.02	65.90	66.73	67.51	68.25	68.95	69.62
100	62.93	63.93	64.86	65.73	66.55	67.32	68.05	68.74	69.40
110	62.79	63.77	64.70	65.56	66.37	67.13	67.84	68.52	69.17
120	62.63	63.61	64.52	65.37	66.17	66.92	67.63	68.29	68.92
130	62.47	63.43	64.34	65.18	65.97	66.71	67.40	68.05	68.67
140	62.30	63.25	64.15	64.98	65.75	66.48	67.16	67.81	68.41
150	62.11	63.06	63.95	64.76	65.53	66.25	66.92	67.55	68.14
160	61.92	62.86	63.73	64.54	65.30	66.00	66.66	67.28	67.86
170	61.72	62.64	63.51	64.31	65.05	65.75	66.40	67.01	67.58
180	61.51	62.42	63.28	64.07	64.80	65.49	66.12	66.72	67.28
190	61.29	62.19	63.04	63.82	64.54	65.21	65.84	66.42	66.97
200	61.06	61.95	62.79	63.56	64.27	64.93	65.55	66.12	66.65
210	60.82	61.71	62.53	63.29	63.99	64.64	65.24	65.81	66.33
220	60.57	61.45	62.27	63.01	63.70	64.34	64.93	65.48	65.99
230	60.31	61.18	61.99	62.72	63.40	64.03	64.61	65.15	65.65
240	60.05	60.90	61.70	62.43	63.10	63.71	64.28	64.81	65.29
250	59.77	60.62	61.40	62.12	62.78	63.39	63.94	64.46	64.93

Source: Dow Chemical (2001b) *Note*: Density in lb/ft^3.

Table 7 Specific Heat of Aqueous Solutions of Ethylene Glycol

Temperature, °F	Concentrations in Volume Percent Ethylene Glycol								
	10%	20%	30%	40%	50%	60%	70%	80%	90%
−30					0.734	0.680	0.625	0.567	
−20					0.739	0.686	0.631	0.574	0.515
−10				0.794	0.744	0.692	0.638	0.581	0.523
0				0.799	0.749	0.698	0.644	0.588	0.530
10			0.849	0.803	0.754	0.703	0.651	0.595	0.538
20		0.897	0.853	0.808	0.759	0.709	0.657	0.603	0.546
30	0.940	0.900	0.857	0.812	0.765	0.715	0.664	0.610	0.553
40	0.943	0.903	0.861	0.816	0.770	0.721	0.670	0.617	0.561
50	0.945	0.906	0.864	0.821	0.775	0.727	0.676	0.624	0.569
60	0.947	0.909	0.868	0.825	0.780	0.732	0.683	0.631	0.576
70	0.950	0.912	0.872	0.830	0.785	0.738	0.689	0.638	0.584
80	0.952	0.915	0.876	0.834	0.790	0.744	0.696	0.645	0.592
90	0.954	0.918	0.880	0.839	0.795	0.750	0.702	0.652	0.600
100	0.957	0.922	0.883	0.843	0.800	0.756	0.709	0.659	0.607
110	0.959	0.925	0.887	0.848	0.806	0.761	0.715	0.666	0.615
120	0.961	0.928	0.891	0.852	0.811	0.767	0.721	0.673	0.623
130	0.964	0.931	0.895	0.857	0.816	0.773	0.728	0.680	0.630
140	0.966	0.934	0.898	0.861	0.821	0.779	0.734	0.687	0.638
150	0.968	0.937	0.902	0.865	0.826	0.785	0.741	0.694	0.646
160	0.971	0.940	0.906	0.870	0.831	0.790	0.747	0.702	0.654
170	0.973	0.943	0.910	0.874	0.836	0.796	0.754	0.709	0.661
180	0.975	0.946	0.913	0.879	0.842	0.802	0.760	0.716	0.669
190	0.978	0.949	0.917	0.883	0.847	0.808	0.766	0.723	0.677
200	0.980	0.952	0.921	0.888	0.852	0.813	0.773	0.730	0.684
210	0.982	0.955	0.925	0.892	0.857	0.819	0.779	0.737	0.692
220	0.985	0.958	0.929	0.897	0.862	0.825	0.786	0.744	0.700
230	0.987	0.961	0.932	0.901	0.867	0.831	0.792	0.751	0.708
240	0.989	0.964	0.936	0.905	0.872	0.837	0.799	0.758	0.715
250	0.992	0.967	0.940	0.910	0.877	0.842	0.805	0.765	0.723

Source: Dow Chemical (2001b) *Note*: Specific heat in Btu/lb·°F.

Introduction & Background

For this exercise, we are presented with the following scenario: A rural Alaskan village has a large diesel generator. Because diesel fuel is at a premium, the operators wish to reuse the waste heat from the generator to heat a small building, namely a laundromat. Our task, then, is to design a heat exchanger to dump the waste heat from the generator into a glycol heating system. The temperature differential for the building heat is specified to be $> 20^oF$, the minimum coolant temperature for the generator is specified at 140^oF, and typical operating temperatures and flow rates for the generator are given in a table. The fluids for both sides of the heat exchanger are assumed to be 50% by volume ethylene glycol.

Mathematics & Approach

The basis of this analysis is the Log Mean Temperature Difference method, or LMTD method, which relies on the relation in equations 1, 2 and 3, where T_i is the ith temperature, A_s is the surface area over which heat transfer is occuring, and U is the total heat transfer coefficient for the apparatus.

$$\dot{Q} = UA_sF(\text{LMTD}) \tag{1}$$
$$= \dot{m}c_P\Delta T_{\text{hot}} \tag{2}$$

$$\text{LMTD} = \frac{(T_{\text{hot, in}} - T_{\text{cold, out}}) - (T_{\text{cold, in}} - T_{\text{hot, out}})}{\log\left((T_{\text{hot, in}} - T_{\text{cold, out}})/(T_{\text{cold, in}} - T_{\text{hot, out}})\right)} \tag{3}$$

In this case, the LMTD is defined as with the case of a counter-flow heat exchanger. In this analysis, however, I am assuming a cross-flow heat exchanger, which requires a correction factor F to be used. This correction factor is a function of all four inlet/outlet temperatures, as well as the particular geometry of the heat exchanger. For this analysis, the relations encoded in Cengel's Heat and Mass Transfer's graphs assuming unmixed flow were used, as seen in figure .

From the constraints and assumptions for this heat exchanger design, both the LMTD and F may be found. In addition, based on the constraints for the hot side of the heat exchanger, $\dot{Q}$ may also be calculated. With these pieces of information, we may find what the product UA_s must be in order to meet the constraints for the heat exchanger design.

The tough part, naturally, is finding good values for U and A_s. A_s is a function of the heat exchanger's geometry. U relates to the geometry and the materials involved as in equation 4, for the case of a brazed plate heat exchanger.

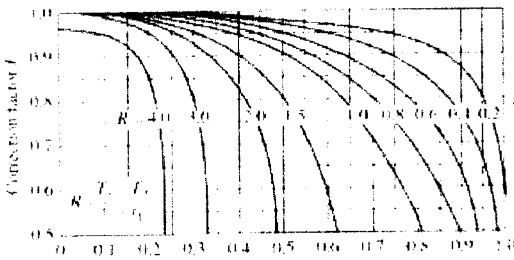


Figure 1: This graph shows the correction factor as a function of the derived parameters R and P. Despite the low quality of the scan, the graph was still usable.

$$U = \left(\frac{2}{h} + \frac{A_{s,\text{plate}} t_{\text{plate}}}{k_{\text{solid}}}\right)^{-1} \tag{4}$$

This means that not only must A_s be known, but so must the thickness of the plates, the material the exchanger is made of, and the convective heat transfer coefficient across the plates, which is in turn a function of the geometry of the heat exchanger, the material properties of the fluid, and the velocity of the fluids through the exchanger.

For this design, I decided to start with pre-fabricated plates designed for brazed plate heat exchangers. This gives a good starting point for the design of the heat exchanger, removing a lot of the design variables, while still requiring the basic calculations required to actually design a heat exchanger. Moreover, while the plates might be already-designed in real life, specifications on them detailed enough to base the entire design are not easily-obtained. Therefore, basic released knowledge of plate designs will be used to make reasonable calculations for this purpose.

Due to their prominence on the Google search page, I chose to work with Schmidt's line of brazed plate heat exchangers. Figure, which depicts a table from Schmidt's literature, mostly concerns itself with dimensions. Otherwise, Schmidt reveals that the primary material for their plates is 316 stainless steel. Looking up the properties of 316 stainless steel reveals a density of 0.29 lbm/in^3 and a heat conductivity of 9.4 $\text{Btu/hr/ft}^2\text{/ft/}^\circ\text{F}$.

The average thickness of each plate may be roughly calculated as in equation 5, where t_{plate} is the thickness of the plate, ΔW is the change in weight per added plate, A_s is the surface area of one side of the plate, and ρ is the density of 316 stainless steel.

$$t_{\text{plate}} = \frac{\Delta W}{\rho A_s} \tag{5}$$

From this, the space between plates may also be calculated as in equation 6, where Δl_z is the

Schmidt Model Type	Dimensions in Inches (millimeters)					Max Number of Plates	Surface per Plate sq. ft. (sq. m.)	Max Flow gpm (m³/h)	Weight Empty lbs (KG)
	A	B	C	D	F				
SB1, SBN1	2.88 (73)	8 (203)	1.63 (40)	6.56 (170)	0.47+ (.09 x N) (7+(2.3 x N))	50	.13 (.012)	20 (4.5)	1.65+(.11 x N) (.75+(.05 x N))
SB2, SBN2	3.5 (89)	9.06 (230)	1.69 (43)	7.19 (182)	0.47+ (.09 x N) (7+(2.3 x N))	50	.15 (.014)	20 (4.5)	2.42+(.13 x N) (1.3+(.08 x N))
SB22, SBN22	3.5 (89)	12.8 (325)	1.69 (43)	10.98 (279)	0.47+ (.09 x N) (7+(2.3 x N))	50	.24 (.022)	20 (4.5)	3.14+(.18 x N) (1.3+(.08 x N))
SB24, SBN24	3.5 (89)	18.15 (461)	1.69 (43)	16.34 (415)	0.47+ (.095 x N) (7+(2.4 x N))	50	.37 (.033)	20 (4.5)	4.2+(.33 x N) (1.7+(.15 x N))
SBG24	3.5 (89)	18.15 (461)	1.69 (43)	16.34 (415)	0.47+ (.112 x N) (7+(2.9 x N))	50	.37 (.033)	20 (4.5)	4.2+(.33 x N) (1.7+(.15 x N))
SB3, SBN3	4.88 (124)	6.73 (171)	2.88 (73)	4.72 (120)	0.47+ (.09 x N) (7+(2.3 x N))	50	.16 (.015)	50 (11)	2.64+(.13 x N) (1.2+(.06 x N))
SB4, SBE4, SBN4	4.88 (124)	13.07 (332)	2.88 (73)	11.06 (281)	0.47+ (.09 x N) (7+(2.3 x N))	100	.32 (.03)	50 (11)	3.52+(.26 x N) (1.6+(.12 x N))
SB5, SBE5, SBN5, SBD5	4.88 (124)	20.83 (529)	2.88 (73)	18.81 (478)	0.47+ (.09 x N) (7+(2.3 x N))	100	.53 (.049)	50 (11)	4.4+(.53 x N) (2.0+(.24 x N))
SB7, SBE7	10.59 (269)	20.83 (529)	7.88 (200)	18.13 (460)	0.47+ (.09 x N) (7+(2.3 x N))	200	1.46 (.136)	175 (40)	12.1+(1.32 x N) (5.5+(.6 x N))
SB8,SBE8	10.59 (269)	20.83 (529)	6.34 (161)	16.57 (421)	0.88+(.09 x N) (7+(2.3 x N))	200	1.29 (.120)	385 (88)	12.1+(1.32 x N) (5.5+(.6 x N))
SB9,SBE9	10.59 (269)	31.41 (798)	6.34 (161)	27.16 (690)	0.47+ (.095 x N) (7+(2.4 x N))	200	2.15 (.20)	385 (88)	23.15+(1.76 x N) (10.5+(.8 x N))
SB10,SBE10	15.08 (383)	34.25 (870)	9.33 (237)	28.46 (723)	0.88+(.095 x N) (13+(2.4 x N))	200	2.69 (.25)	385 (88)	86.90+(2.66 x N) (39+(1.2 x N))

*N=Number of Plates

Figure 2: Schmidt Brazed Heat Exchanger Properties

change in the depth of the heat exchanger per added plate.

$$t_{\text{gap}} = \Delta l_z - t_{\text{plate}} \tag{6}$$

The real-life plates are ribbed, which increases the convective heat transfer coefficients for heat transfer through the device. Unfortunately, finding these coefficients for such a complicated geometry would require computational fluid dynamics and heat transfer using a finite element method, which is out of the scope of this analysis. Therefore, we will assume that the plates are flat, and know that the real-life convective heat transfer coefficients are significantly higher.

Assuming a flat plate, one may calculate the heat transfer coefficient using the empirical formula in equation 7, where all physical properties are with respect to the fluid:

$$h = \frac{k_f}{t_{\text{gap}}} 0.037 \text{Re}^{0.8} \text{Pr}^{1/3} \tag{7}$$

$$\text{Re} = \frac{\rho v t_{\text{gap}}}{\mu} \tag{8}$$

$$\text{Pr} = \frac{\mu c_P}{k} \tag{9}$$

As mentioned previously, finding Re requires knowing the velocity of the fluids through the heat exchanger. The volumetric flow rate of the hot fluid, in gallons per minute, is supplied, and may be used to find the average velocity through the heat exchanger through the relation in equation 10.

$$v = \frac{2\dot{V}}{l_x l_z} \tag{10}$$

However, the volumetric flow rate for the building heating system is unknown. However, the flow rate necessary to meet the given design constraints may be calculated, from which the velocity for the cold side may be found in a similar manner.

Due to the first law of thermodynamics and assuming adiabatic heat transfer (which I do throughout), equation 11 must be satisfied.

$$(\dot{m} c_P \Delta T)_{\text{hot}} = (\dot{m} c_P \Delta T)_{\text{cold}} \tag{11}$$

Since all the ΔTs are known, $\dot{m}_{\text{hot}}$ may be calculated by dividing $\dot{Q}_{\text{hot}}$ by ρ, and c_P is a function of temperature, one may solve for $\dot{m}_{\text{hot}}$, which may be converted back to $\dot{Q}_{\text{cold}}$ and consequently to v.

(Not that, assuming equal c_P values for both fluids, the outgoing volumetric flow rate should be roughly 25 and consequently plate sizes 1, 2, 22 and 24 may be safely ruled out.)

Referring back to equation 10, notice that l_z is a function of N, or the number of plates on the heat exchanger as can be seen in figure . This means that, ultimately, U and A_s are both functions of N, and due to the functional nature of the material properties of the brines used, finding an analytical solution to this problem is nearly impossible. Instead, this may be solved as a zero-finding problem. In other words, the N which satisfies this equation is the solution to equation 12.

$$0 = (UA_s)_{\text{required}} - U(N)A_s(N) \tag{12}$$

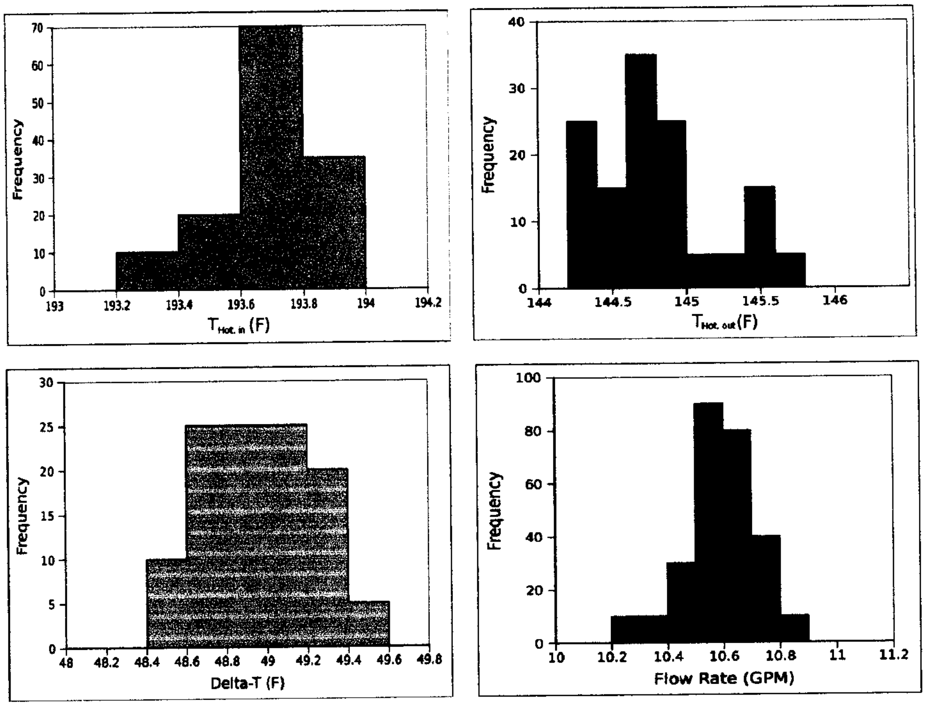


Figure 3: Histograms of the generator's run data. From the top left: The "hot side" of the generator loop, the "cold side" of the generator loop, the temperature difference between them, and the volumetric flow rate.

Hence, given dimensions of a plate heat exchanger (with dimensions l_x and l_y) and the inlet and outlet temperatures of both the hot and the cold side, the number of plates required to achieve the required heat exchanger performance may be calculated.

Data Tables

There are four sets of data associated with this design strategy.

Engine Coolant Data Points

This data set consists of a series of temperature and volumetric flow rate readings from the original generator/radiator configuration. From this data, approximate probability distributions for $T_{H,\text{in}}$, $T_{H,\text{out}}$ and $\dot{V}_H$ can be found (see figure), and based on these sensible values may be assumed for the temperatures for use in heat exchanger calculations.

Another, more sophisticated approach would be to attempt some sort of stochastic approach. For example, calculations could be ran for all combinations of $\bar{T}_i \pm \sigma_i$. Alternately, finding

uncertainty equations based on those we have may be the best bet, since they could potentially decrease computer crunch time significantly. Unfortunately, such treatments of data seem to be rare enough that finding information on them is difficult. Moreover, it's a lot of effort for values that, in the case of the temperatures, tend to vary by less than a degree either way.

50% by volume Ethylene Glycol Property Table

"ASHRAE 2005 Fundamentals" contains property tables for ethylene glycol at a number of by-volume mixtures relating temperature to density, heat capacity at constant pressure, heat conductivity and dynamic viscosity all at standard pressure. For calculations, it's easiest to pick a representative temperature for the entire system at which to pull constant values for ρ, c_P, k and μ, but this is (of course) not technically correct. Instead, I chose the approach of looking up these values at average temperatures for the hot and cold side of the heat exchanger, respectively.

LMTD Correction Factors

"Heat and Mass Transfer," by Yunus Cengel, contains graphs relating the four inlet/outlet temperatures of a cross-flow, non-mixing heat exchanger (amongst a few other configurations) to the correction factor F. Unfortunately, these values were not in table form. I converted them to table form by using a piece of open-source software called Engauge Digitizer, which is designed to convert scans of graphs into tabular form.

Heat Exchanger Specifications Table

Finally, the data in figure , which contains the specifications for each model of heat exchanger, was to be used for its dimension and weight values, as functions of N where applicable.

Software Implementation

The software implementation of this design, while complete enough to be worthy of discussion, is unfinished due to the complexity of the problem as posed.

As it stands, three classes were implemented to handle tabular data in .csv format:

1. `2dtable()` was designed to handle the correction factor tables from Cengel, which were functions of the derived values R and P, both functions of the four inlet/outlet temperatures. The correction factor instance of this class allows returns F when called with R and P as arguments.
2. `Continuoustable()` was designed with the properties tables from "ASHRAE 2005 Fundamentals" in mind, and instances of this class return interpolated values for requested properties at a given value for the left-most property (in this case, temperature).

3. `Discretetable()`, in contrast, was designed for tables where interpolation wouldn't make sense—in particular, the engine coolant datapoints and heat exchanger parameters table. Other than the lack of value interpolation, this class has a similar structure to `Continuoustable()`.

In addition, two other classes have been implemented:

1. `Tparams()` takes the four inlet/outlet temperatures as inputs and has methods returning values for $\mathrm{LMTD}_{\mathrm{CF}}$, $\bar{T}_H$, $\bar{T}_C$, ΔT_H, ΔT_C, R and P.
2. `Htxrparams` takes heat exchanger parameter information, with the density of steel, as inputs. It has methods returning t_{plate}, t_{gap} and $l_z(N)$.

These two classes, supply most of the variables required to complete the rest of the mathematical calculations as explained previously

Outcomes & Conclusions

Unfortunately, N was never actually calculated. However, this experience has delivered a number of significant outcomes. First, the method for designing a plate heat exchanger has been outlined—this is arguably the most important part conceptually. Having never approached such a problem previously, I ended up learning quite a bit about the LMTD method and how it may be used in the real world.

Second, implementation has been explored, and while one hasn't been completed the structure of an implementation has been mostly fleshed out. In addition, the use of tabular (and graphical) data with software has been studied, leading to the beginnings of what may end up being a publically-available python module (tabular.py).

In fact, not completing the calculations necessary to find N can be seen as a cautionary tale regarding simplifying assumptions (or lack thereof). For this project, I chose to make as few simplifying assumptions as I could get away with. This has the advantage of (hopefully) higher accuracy, but suffers from increased complexity. Had I made more simplifying assumptions (constant fluid properties and one model for the plates for example), I should've easily been able to calculate a value for N. The moral of this project, if it has one, is this: Make as many simplifying assumptions as you can get away with.

Thermal Systems Laboratory (ME 415) University of Alaska Fairbanks

Mid-Term Exam Mar. 9 (Wed), 2011

Instructor: Prof. Sunwoo Kim

Name: Jeremy Sparger Student ID: 30853915

1. (8 points) The Brookfield DV-1 viscometer we used for the viscosity lab can be modeled as described in Figure 1. It has a cylindrical spindle of height L and radius r_1, which rotates in a concentric, confined space (the beaker of r_2) that is filled with a sample fluid. According to Newton's law of viscosity, the shear stress is $\tau_{r\theta} = \mu r \frac{d}{dr}\left(\frac{v_\theta}{r}\right)$. On the other hand, the torque is $T = \tau_{r\theta}(2\pi L)r$. Using these two relations we can derive the following relation between the torque T and the spindle surface speed V:

$$\frac{V}{r_1} = \frac{T}{4\pi\mu L}\left(\frac{1}{r_1^2} - \frac{1}{r_2^2}\right)$$

Compute the viscosity of the sample when the spindle angular speed is set at 60 rpm, the height and radius of the spindle used are L = 50 mm and r_1 = 3 mm, and when the viscometer indicates that the torque T = 1.2 x 10^{-5} N-m. Please note that we can say r_2 = infinity because $r_2 >> r_1$ and that we can ignore the shear stress on the bottom side of the spindle because L >> r_1.

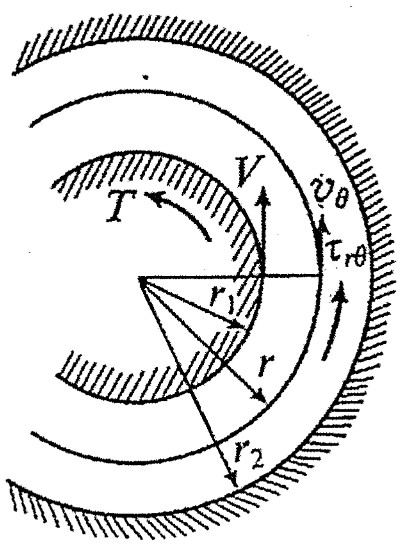


Figure 1: Analytical model of the Brookfield DV-1 viscometer, cross-sectional view of the spindle and the beaker with a sample fluid.

2. An engineer considered a comparative method for measuring the thermal conductivity of a newly developed alloy. Figures 2a and 2b show a schematic diagram (side view and cross-section view) of her apparatus. She supplied cooling water to the cooling jacket and turned on the electric heater. Most of heat supplied by the heater flows through the lower copper bar, the alloy sample, and the upper copper bar, and the cooling water rejects the heat. She recorded the temperatures at points 1, 3, and 4 when a steady-state was reached. She wrote a note as follows.

x_{12} = 30 mm, x_{23} = 30 mm, x_{34} = 12 mm, k_{cu} = 395 W/m·K (thermal conductivity of copper)
T_1 = 103.3 °C, T_3 = 92.5 °C, T_4 = 54.2 °C, Room temperature = 23.2 °C

(a) (6 points) Assuming that all heat supplied reaches the cooling jacket, determine the thermal conductivity of sample.

(b) (3 points) She measured another sample under the same conditions. She took a note on her experiment notebook as follows. Choose the most proper answer in parenthesis and justify your answer.

The assumption that I made for the first sample could be wrong this time because the temperature of insulator surface T_{2s} was much (higher / lower) than when I measured the first sample, which is an indication of heat loss to the insulator. I tried to minimize the error that the heat loss might cause by using a (thinner, thicker) sample. I learned from the experiments that this method may not be accurate when the thermal conductivity of sample is close to ($k_{insulator}$, k_{cu}).

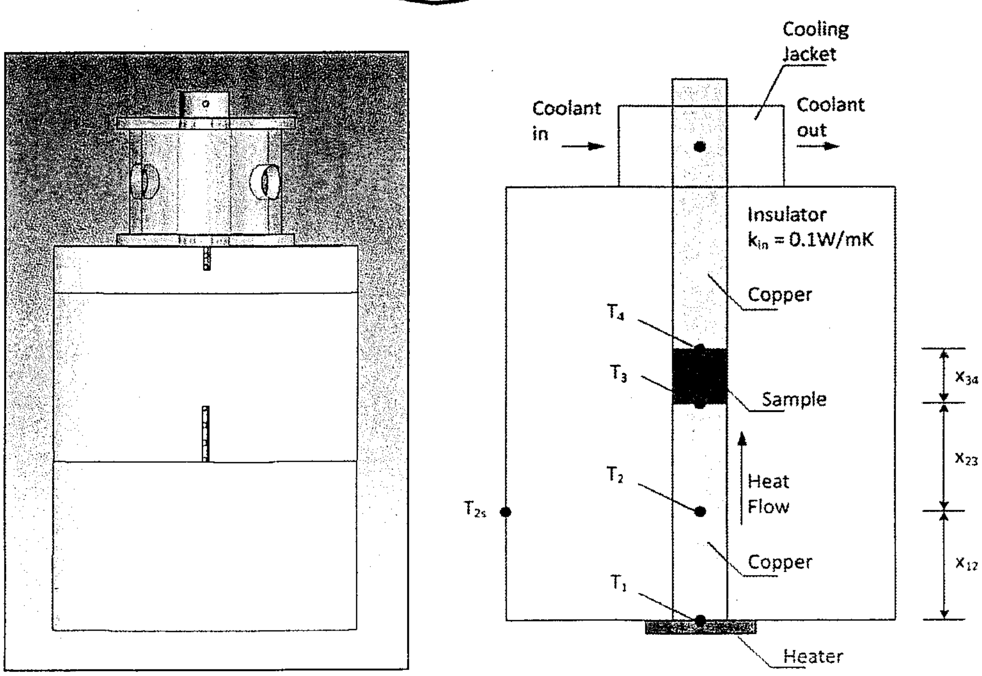


Figure 2: Schematic diagram of thermal conductivity measurement apparatus (a) side view, (b) cross-sectional veiw.

3. (8 points) We purchased two new thermocouples to replace the old ones whose accuracy is questionable. Currently five thermal couples are installed in the aluminum rod of our "Temperature Profiles in Rods" apparatus. The steam temperature at the steam chest is 250°F and the temperature readings from the thermocouples at a steady-state are tabulated in Table 1. Please choose the two thermocouples you must replace after filling the blanks in Table 1.

Table 1: computed and measured temperatures along the aluminum rod.

TC #	x [in]	Computed Temperature [°F]	Measured Temperature °F	Difference [°F]
1	0.5	242.4	241.03	1.37
2	3.5	202.8	186.52	16.28
3	9.0	152.4	154.85	2.45
4	18.0	107.7	112.74	-5.04
5	30.0	83.3	108.33	25.03

x is the distance between the heat source and a thermocouple.

Diameter of the rod d = 1 in = 1/12 ft
Thermal conductivity of aluminum k = 96.5 Btu/h·ft·R
Heat transfer coefficient of the rod h = 2.0 Btu/h·ft^2·R

Room temperature T_a = 70°F

The T/C's to replace are 2 and 5

① Jeremy Spargur

$$\frac{V}{r_1} = \frac{T}{4\pi\mu L}\left(\frac{1}{r_1^2} - \cancel{\frac{1}{r_2^2}}\right) \rightarrow 0$$

$V = \omega r_1 = 2\pi \times 0.003 = 0.006\pi$ m/s

(−2)

$$60\,\frac{\text{rev}}{\text{min}}\left(\frac{1\text{ min}}{60\text{ sec}}\right)\left(\frac{2\pi\text{ rad}}{1\text{ rev}}\right) =$$

360 rad/s

$$\frac{V}{r_1} = \frac{T}{4\pi\mu L r_1^2}$$

$$\frac{V 4\pi L r_1^{\cancel{2}}}{\cancel{r_1}} = \frac{T}{\mu} \Rightarrow \mu = \frac{T}{V 4\pi L r_1}$$

Computation error (−1)

$$= \frac{1.2\times10^{-5}}{(2\pi)(4)\pi(0.05)(0.003)} = \boxed{3.18\times10^{-3}\ \text{N}\cdot\text{s}/\text{m}^2}$$

$$= \frac{\text{N}\cdot\text{m}}{\frac{\text{rad}}{\text{s}}(\text{m})(\text{m})} = \text{N}\cdot\text{s}/\text{m}^2$$

5/8

(2) $\dot{q} = K_{cu} \dfrac{T_1 - T_3}{X_{12} + X_{23}} = 395 \left(\dfrac{103.3 - 54.2}{(0.03 + 0.03)} \right)$ Jeremy Sparger

$= 323242 \ W/m^2$

$$\boxed{K = 395 \left(\frac{103.3 - 92.5}{92.5 - 54.2} \right) \left(\frac{0.06}{0.012} \right) = 557 \ W/m \cdot K}$$

$\dfrac{0.012}{0.06} = 22.28 \ W/mK$ (-2)

(b) Higher - The experiment has already been run which raises heat. (Wrong justification) (-0.5)

thinner - Thick plate will cause more heat to escape through insulation. ✓

Kins - If they are near the same heat is not controlled in one direction. ✓

6.5/9

Jeremy Sprague

(3) $\frac{T(x)-T_\infty}{T_b - T_\infty} = e^{-x\sqrt{hp/kA_c}}$

$A_c = \frac{\pi}{4}\left(\frac{1}{12}\right)^2 = 0.005\ ft^2$

$P = 2\pi\left(\frac{1/12}{2}\right) = 0.262\ ft$

$m = \sqrt{\frac{hp}{kA_c}} = \sqrt{\frac{(2)(0.262)}{(96.5)(0.005)}}$

$= 1.042$ = 0.9948 exactly but ok.

$T_b - T_\infty = 250 - 70 = 180$

$T(x) = 70 + 180e^{-1.042x}$

$T(0.042) = 242.4$

$T(0.292) = 202.8$

$T(0.75) = 152.4$

$T(1.5) = 107.7$

$T(2.5) = 83.3$

8/8

Problem:
[30 pts] Newton's equation says that the shear stress on a fluid is related to the deformation on the fluid within the boundary layer by a certain proportionality constant that Newton called the absolute viscosity, a property, of the fluid. In equation form:

$$\tau = \mu \frac{dv}{dy}$$

Noting the parameters of this equation (stress, velocity gradient, etc.), explain how the design of the Brookfield DV-I viscometer and the values you recorded from its operation allowed you to calculate the viscosity of the oils tested.

Solution:

The DV-I employed a motor to turn a spindle that was immersed in the fluid. The motor, in combination with a helical spring, developed a certain torque (force times a moment arm) on the spindle which was displayed by the viscometer. The surface area of the spindle was also known. It was reflected by the factors used which were functions of the spindle being used. In this way, the shear force and resulting shear stress of the fluid in contact with the spindle was determined.

The container was large enough that the boundary layer of the fluid was contained within the container. In essence, there existed some point at a distance away from the spindle where the fluid was not in motion (the definition of the boundary layer). The DV-I also measured the rotational speed of the spindle thus "measuring" the velocity of the fluid at the spindle. The velocity of the fluid "far" from the spindle was at rest. This provided information on the velocity gradient of the fluid.

Thus, the viscometer "knew" the shear stress and velocity gradient characteristics of the fluid by how much torque was applied by the motor, the speed of the spindle's rotation, and the surface area of the spindle. From this, it provided the information needed to calculate the proportionality constant (absolute viscosity).

Problem:

[30 pts] A temperature measuring instrument has been designed using a thermistor that has a tip that can be approximated as a small sphere. The manufacturer informs us that the time constant for this sensor is 3 s. We'll assume that this system may be treated as a lumped heat transfer problem. I place the temperature sensor in an environment that has an ambient temperature of 475°F. The sensor was originally at room temperature (~70°F). (a) What temperature does my instrument read after 15 s? (b) How long must we wait to obtain a temperature reading that is at least 99.5% of the actual temperature?

Solution:

The governing equation for transient, lumped capacitance, heat transfer is:

$$\frac{T(t)-T_\infty}{T_1-T_\infty}=e^{-bt}$$

$$\tau=\frac{1}{b}$$

Plugging in the information for part (a) of this problem:

$$\frac{T(15s)-475°F}{70°F-475°F}=e^{\frac{-(15s)}{3s}}$$

$$\Rightarrow \underline{\underline{T(15s)=472.3°F}}$$

Ans (a)

For part (b):

$$\frac{(0.995)(475°F)-475°F}{70°F-475°F}=e^{\frac{-(t)}{3s}}$$

$$\Rightarrow 5.864\times10^{-3}=e^{\frac{-(t)}{3s}}$$

$$\Rightarrow \underline{\underline{t=15.42s\approx15s}}$$

Ans (b)

Problem:

[40 pts] Heat is being conducted into the end of a segment of 316 stainless steel rod with a circular cross-section and diameter of 3.5 cm. Heat flows out of this rod segment via conduction to the next segment of the rod and via natural convection to the surrounding air (radiant losses can be assumed to be negligible). The rod segment is 5 cm in length. Assume a thermal conductivity of $k = 13.4 \, W/_{m \cdot K}$ and a convective coefficient of $h = 6.15 \, W/_{m^2 \cdot K}$. The upstream segment temperature is 135°C, downstream segment temperature is 110°C, segment under analysis temperature is 115°C, and the ambient temperature is 20°C. Is this heat transfer system in transient or steady-state mode? Prove your answer using the 1st Law of Thermodynamics.

Solution:

The 1st Law of Thermodynamics states that energy must be conserved. In this case, we are interested in conserving heat. We analyze the heat transferring into the segment via conduction and the heat transferring out of the segment via conduction and convection. If they are equal, then the system is in steady-state. Otherwise, the system is in transient mode.

The heat in from conduction from the upstream rod segment:

Assume the "thickness" of the segment for Fourier's Equation is from segment center-to-center. That is, $t = 5cm$.

$$q_{in} = \frac{k}{t} A(\Delta T) = \frac{\left(13.4 \, W/_{m \cdot K}\right)}{(0.05m)} \left[\left(\frac{\pi}{4}\right)(0.035m)^2\right](135 - 115)K = \underline{5.157W}$$

The heat out is made up of conduction to the downstream segment and convection to the ambient surroundings.

Heat conduction to the downstream segment:

$$q_{out,cond} = \frac{k}{t} A(\Delta T) = \frac{\left(13.4 \, W/_{m \cdot K}\right)}{(0.05m)} \left[\left(\frac{\pi}{4}\right)(0.035m)^2\right](115 - 110)K = \underline{1.289W}$$

Heat convection to the surroundings:

$$q_{out,conv} = hA(\Delta T) = \left(6.15 \, W/_{m^2 \cdot K}\right)\left[(\pi)(0.035m)(0.05m)\right](115 - 20)K = \underline{3.212W}$$

So, the energy balance on our segment is:

$$q_{in} - q_{out} = 5.157W - (1.289W + 3.212W) = \underline{0.656W}$$

Therefore, the system is in transient mode. More heat is entering than leaving. Actually it is in a state of flux and will eventually reach equilibrium at some higher segment temperature.