MEEG346 Thermal Laboratory

Laboratory Problem X5 –Compare Convection and Radiant Heat Transfer

Objectives

To measure and compare relative heat transfer rates from a heated surface with free convection, forced external convection, and radiant heat transfer.

To apply combined heat transfer modes in a practical problem.

LAB INSTRUCTIONS

As shown in Figure 1, the system to be tested has a simple cylindrical heater element located near the top end of a tube. The element is instrumented with a thermocouple measuring its surface temperature. Power input is also measured. Airflow velocity in the tube is given. Thermocouples measure inlet and exit air temperatures. Radiant heat transfer is measured with a separate instrument.

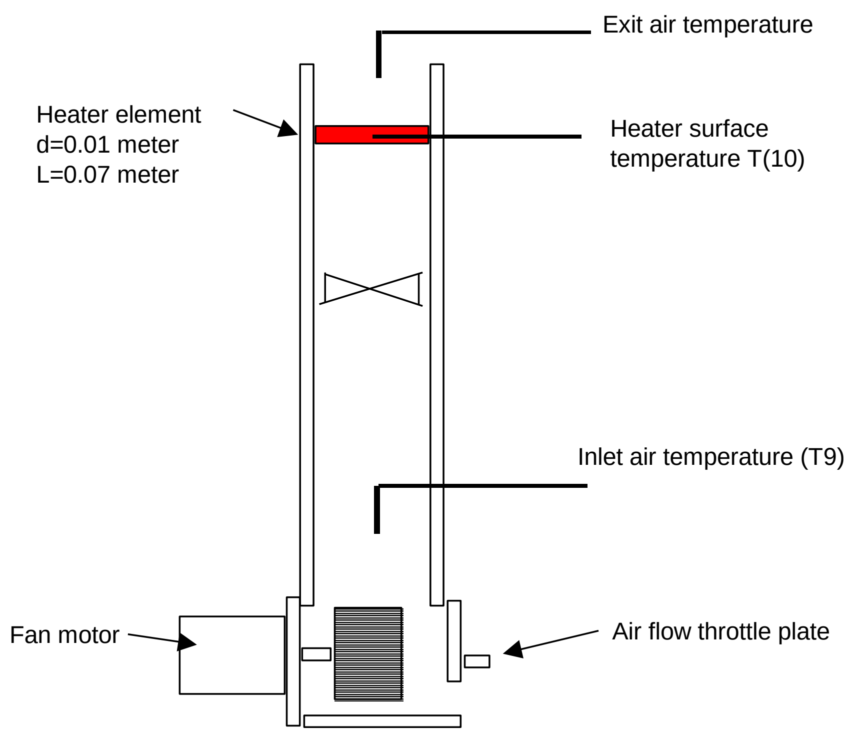

Figure 1 – The heater radiates and convects (by free convection with fan off, or forced with the fan on

For reference if needed:

$$Q = m\, c_p\, (T_{out} - T_{in}) \qquad (1)$$

$$m = \rho\, A_c\, V \qquad (2)$$

All three modes of heat transfer are present in this apparatus: natural (or free) convection, forced convection, and radiant.

The fundamental relationships for convection are:

Natural convection $\quad q_{nc} = h_{nc}\, A_s\, (T_s - T_{amb}) \qquad (3)$

Forced convection $\quad q_{fc} = h_{fc}\, A_s\, (T_s - T_{amb}) \qquad (4)$

<u>We will not measure h_{nc} and h_{fc} in this experiment, but instead use commonly accepted correlations that you have seen in class</u>. (This is what you would usually do in practice, unless the geometry of interest did not match the correlation. Then you would do an X1 type of experiment).

Radiant heat transfer has an entirely different physics from conduction and convection. You are or will be introduced to its complexities in MEEG342. It is fascinating and challenging. But for now in this experiment, we will simply use the basic relations without exploring the origins in depth.

The fundamental relationship for radiant heat transfer between objects at two temperatures is

$$Q_{rad} = A_s \varepsilon\, \sigma\, F\, (\, T_s^4 - T_{sur}^4\,) \qquad (5)$$

where ε = surface emissivity (0< ε < 1, dimensionless)*
α = surface absorptivity (0<α<1, dimensionless)*
σ = Stefan-Boltzmann constant = $5.67\text{x}10^{-8}$ W/m^2-K
F= shape or configuration factor (0<F<1)
A_s = surface area of heater, m^2
T_s = Hot surface temperature, ^{o}K.
T_{surr} = Temperature of surroundings, ^{o}K

*For a surface emitting radiant heat, use ε. For receiving radiant heat, use α. A surface can do both at the same time if wavelengths are different. Important: ε is an empirical factor that is very difficult to measure (we have tried in this lab in other years). We will use a value from a table, and vary to see the effect.

An important property of radiant heat transfer is that it is independent of the convection modes. That is, a surface can both convect and radiate at the same time, <u>in parallel</u>.

$$Q_{total} = h_{fc}\, A_s\, (T_s - T_{amb}) + A_s\, \varepsilon\, \sigma\, F\, (T_s^{\,4} - T_{sur}^{\,4}) \quad (6)$$

The challenge in this experiment is to separate the different modes. And, observe when one or the other dominates. For example at lower temperatures, the radiant component is very small and might be ignored (but watch out! It can get big fast).

Procedure

CONVECTION APPARATUS (See Figure 1)

Examine the equipment and with the help of the TA get acquainted with the different parts of the apparatus and the controls. Take particular note of the following:

IMPORTANT

1. **This equipment is capable of reaching quite high temperatures (@500 C heater surface temperature, > 200 C exit air temperatures. Keep hands away from the top end area of the tube where the heater element is. It's tall for a reason.**

2. **The apparatus does not have a built-in limit switch on temperatures or power. Therefore conditions must be continuously monitored to prevent damage to the heater. A team member should be appointed to monitor these conditions.**

   Maximum applied voltage = 20 volts
   Maximum heater temperature = 500 C

   If the system starts to go beyond these, immediately reduce voltage and increase airflow to bring back within these limits.

3. **The Air Flow throttle plate on the blower must ALWAYS be at least partially open to allow some cooling air flow. Otherwise the heater element can rapidly overheat. For the Natural Convection part of the experiment, open it all the way.**

Part 1 – Measurement of Natural Convection and Radiant heat transfer

In this part of the work we will vary heater power with no forced flow, and measure surface temperature, and air temperatures.

1. Be sure that the air flow throttle plate is wide open. The blower motor is turned off.

2. Set the heater voltage to 12 volts with the voltage control potentiometer.

3. Allow the heater temperature to stabilize. Record T8, T9, T10, V and I.

4. Repeat these measurements for Heater Voltages of 16 and 20 volts.

Voltage	Amps	T9(inlet)	T10 (htr)	T8 (outlet)

Part 2 – Measurement of Forced Convection

(Note: The anemometer sensor is not working. New part on order. Use the throttle plate opening stick to adjust airflow, calibrated to value given by TA).

In this part, we will hold the <u>heater power constant and vary the airflow</u>. The radiant heat transfer will still be present, but we expect from the results of Part 1 to be able to subtract it out.

1. Start the blower first.

2. Adjust the throttle plate on the fan by closing the throttle plate to give a reading of 1.6 meter/sec air velocity.

3. Set the heater voltage to 20 volts. (keep watch on the heater temperature. If it goes above 500 C, reduce the voltage to bring it within limits.

4. When temperatures are stable, record the following:

5. Repeat these measurements for 2.1 m/sec

Flow	Voltage	Amps	T9(inlet)	T10 (htr)	T8 (outlet)

Basic data applicable to all steps:

Heater element diameter d = 0.01 meters
Heater element length L = 0.07 meters
Heater surface area = π d L
Tube inside diameter D = L approximately
Velocity correction factor = 1.22 (for heater blocking tube)
Tube exit nozzle diameter = 0.03 meters

Analysis:

Part 1. Natural Convection and Radiant

Calculate the heat transferred by natural convection for each power level. Use eqn 3 in this document along with the correlation for h_{nc} given in the textbook equation 9.33:

$$Nu_d = h_{nc}d/k = C\ Ra^n \qquad (7)$$

Values for C and n are given in Table 9.1 depending on the value you calculate for the Rayleigh Number, Ra. You could also use Eqn 9.34.You may not have seen the Rayleigh number yet, but you will. It is sort of the Reynolds number for natural convection. It is defined in your textbook, eqn 9.23. Table A.4 in your textbook gives values for the air properties to use. That table does not give the value of β, which is the coefficient of volume expansion. It can be shown that for a perfect gas, which air nearly is, $\beta = 1/T$, where T is in ^oK. Also, note that the thermal properties of air vary considerably with temperature. (Eqn references are for 6^{th} ed.)

In using complex correlations, great care must be taken with the units of the parameters. Look at the top of the columns in the table for the correct units.

Calculate the heat transferred by radiant heat transfer using equation (5) with an emissivity value from table for oxidized copper and an F-value of 1 (implies all radiated heat was absorbed inside the tube). Different tables will give different values!

Compare the sum of calculated natural convection and radiant heat transfer to the measured power input to the heater. In principle, it should be the same value at all power levels. If the measured heater power is greater than the sum of calculated convective and radiant heat transfer, consider the possibility that some of the heater power is being lost by conduction to the structure, and not transferred to the air or radiated out. Discuss the difference.

Plot heat transferred by natural convection and by radiant together on a graph with Heater surface temperature as the abscissa.

Part 2. Forced Convection

Calculate the heat transferred by forced convection using Eqn 4 of this document and one of the three cylinder correlations for h_{fc} given in Table 7.7 of your textbook for cylinders. Note carefully the conditions for each relating to the values of the Reynolds Number and the Prandtl number. Use the one that fits. If they all fit, use the simplest one.

You have seen the Reynolds number before in fluid dynamics. This is the same, but taking care to evaluate the properties at the average temperature. For this experiment, the calculation of velocity requires adjustment, because the heater element partially blocks the air flow channel, requiring the air to speed up going around it (recall Bernoulli's equation). The manufacturer says that the adjustment factor is 1.22. That is, the velocity to use in the calculation of Reynolds number is 1.22 x Velocity Measured.

Calculate the heat transferred to the air using equation (1) of this document.

A suitable tabulation of results could be something like this (or more):

Power to heater	(same for all)
Heat transfer area	(same for all)
Ambient temperature	(same for all)

For each air flow value:

Air velocity
Air mass flow rate
Corrected air velocity
Heat transfer coefficient h_{fc}
Surface temperature
Air outlet temperature
Heat transfer by forced convection
Heat transfer by radiant
Heat transfer by eqn (1)

Plot on the same graph the heat transfer by radiant and by forced convection. Also plot the total heat transfer from calculation of radiant plus convection and from Equation (1) from measuring airflow rate and overall increase in temperature.

Discussion& Conclusions

Comment on the relative values of the different modes of heat transfer.

1. Which one dominates under what circumstances?
2. When does radiant become important in terms of heater surface temperature?
3. Is free convection truly insignificant in a forced convection circumstance?
4. Does the radiant contribute directly to heating the air?

We calculated heat transfer in different ways. We used handbook correlations and coefficient values, we measured power to the heater, and we calculated Flow*Delta T (equation (1). If results varied, comment on which are most reliable in your opinion.

Uncertainty

The heat transfer was measured in several different ways, each with uncertainties in measurement or in correlations used. We will only analyze the uncertainty in the radiant heat transfer rigorously, using the Propagation of Statistical Error methodology.

Analyze Equation (5) of this document using that method, with values for parameters typical of Part 1 of this lab. Note that the Stefan-Boltzmann constant σ is a physical value of long standing and is not uncertain. The other parameters measured or assumed do have uncertainties. The shape factor F in principle is constant for a fixed geometry. Calculation of F is the most difficult part of radiant heat transfer analysis, and we are not attempting it here. Use $\Delta F = 0.1$. Temperatures – your call.

Design Objective: A instrument package is being designed to be lifted to a high altitude over the Antarctic by a NASA balloon. (You were shown in Discussion pictures and movie of flight in spring 2018 in Arctic from Sweden to Canada).

Instruments will measure various properties of cosmic radiation as concentrated by the polar magnetic fields. It is required that the instruments be maintained at approximately 10 – 30 C both at launch and at altitude. Your engineering team is asked (1) to calculate the size (Q-gen,watts) of an electrical resistance heater to maintain temperature if needed, by estimating the heat transfer from the package at altitude (heating by sun and cooling by radiation to deep space). (2) Calculate convective heat loss on the ground before launch. Compare to (1) and advise NASA if greater than resistance heater you found in part (1).

Data:

Package dimensions: A cylinder 1.1 meter tall, outside diameter 1 meter. Assume heat transfer is from the cylinder sides, not the ends, which are shielded.

The electronic instruments inside generate 50 watts continuous (additive to a heater).

Ground conditions at launch: Air temperature 7 C. Wind speed 5 knots.

Conditions at altitude (45,000 m): Solar flux qs =1385 watts/m^2.

**(You can neglect conduction and convection at altitude – why?
Also neglect radiation from sunlight reflected from the earth surface, and radiation from the earth below)**

Heat loss at altitude can be found by equating the incoming solar radiation in the ultraviolet to the outgoing radiation in the infrared to deep space, plus energy added by the heater. The Ts (deg K) in the equation below is literally the package surface temperature. Tsp = effective temperature of deep space. Assume Ts approximates the internal package temperature. Tsp is very low, and can be assumed =0 K. The emissivity ε is not given. Determine a value ε to recommend. It can be changed by surface treatment.

Solar energy absorbed = surface radiation out + internal heat generation.

α*(A*Fs)*qs = ε*A*σ*(Ts^4 – Tsp^4) + Qgen

where ε = emissivity of package surface to space = ?
A= surface area of package
σ= Stephan-Boltzman constant 5.67x10^{-8} W/m^2-K
α= absorptivity of package surface to solar flux = 0.2
Fs= shape factor of a cylinder to unidirectional flux = 0.32
qs= solar flux at altitude = 1385 w/m^2

Heat loss on the ground during setup for launch can be estimated by finding a suitable correlation for the cylinder surface heat transfer coefficient as you are doing in the lab experiment. Do not include ground level solar radiation (night time=worst case).

You sized the internal heater to maintain instrument function at altitude. If heat loss on ground is greater, then suggest ways to keep package warm temporarily.

The Report SUMMARY is a letter reporting your recommendations to:

James Roth
Bartol Institute
Dept of Physics
University of Delaware
