Experiment 3 Heat Transfer

Overview

Humanity's energy system has an average power of almost 16 Terawatts, and most of this involves some transfer of thermal energy due to a temperature difference: heat transfer. Moreover, heat transfer has a central role in natural phenomena: weather, temperature regulation of animals, and radiation from stars.

Heat transfer mechanisms are conventionally divided into 3 categories: conduction, convection and radiation. In real physical phenomena, it is very common that more than one mechanism is involved. In this lab you will use your knowledge of conduction to gain knowledge about convection or radiation.

11 MWe solar power plant in Spain
By afloresm (SOLUCAR PS10) [CC BY 2.0 (http://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons

Objectives

In the first period, you will gain some confidence in common measurement methods used in heat transfer, mainly by measuring things that are readily known from textbooks. This is the normal first step in experimentation; in the second period you will tackle some more complex measurements involving multi-mode heat transfer and you will need to be confident that you can measure the relevant quantities.

Background

Engineering design and the interpretation of thermal measurements both require an understanding of heat transfer theory. Starting with the simplest situations, the theory needed for this lab is reviewed below. If this is not a review for you, then you will probably need to consult your heat transfer textbook.

Steady 1-Dimensional Conduction

Fourier's law relates the spatial gradient of temperature dT/dx and the *thermal conductivity* k to the local heat flux q [W/m^2] in the positive x direction:

$$q = -k\frac{dT}{dx} \qquad [1]$$

This relation is itself useful in modelling 1-D steady heat transfer; Fourier's law is easily integrated to determine, for example, the heat flow Q [W] through a uniform wall (thickness Δx, area A) with inside and outside temperatures T_i and T_o:

$$Q = kA\frac{T_i - T_o}{\Delta x} \qquad [2]$$

This is often a good approximation for heat flow in building walls; an N-layer wall can be modelled by appliction of equation [2] to each layer, matching temperatures at the interface of each layer. This is equivalent to adding thermal resistances R_j in series:

$$Q = \frac{T_i - T_o}{\sum_{j=1}^{N} R_j} \qquad [3]$$

$$R_j = \frac{\Delta x_j}{k_j A} \qquad [4]$$

Here Δx_j is the thickness of layer j. When the temperature varies with multple coordinates (eg, x and y), the solution to Fourier's Law becomes complicated. A surprising exception to this is steady conduction in cylindrically symmetric objects, such as cylinders and pipes. The analog of equation [2] is

$$Q = 2\pi Lk\frac{T_i - T_o}{ln\left(^{r_o}/_{r_i}\right)} \qquad [5]$$

In equation [5], the cylinder length is L and the inner and outer radii of the pipe are r_i, r_o.

Unsteady 1-Dimensional Conduction

Implicit in the relations above is the idea that the temperature at every location in the object remains constant in time (but not constant in space). When temperatures change with time, the problem is "unsteady", and the key change to the physics is that energy can be stored or released from the mass. In a steady problem, the *net* heat transfer through a control surface *must* be zero, but in an unsteady problem, a net postitive heat transfer is simply balanced by an increase in the energy contained in the object. For objects without phase change, this change in energy corresponds to a change in temperature. Applying the First Law of Thermodynamics to a control volume of length *dx*, one can find the relation between the rate of temperature change and the heat flux through the surface.

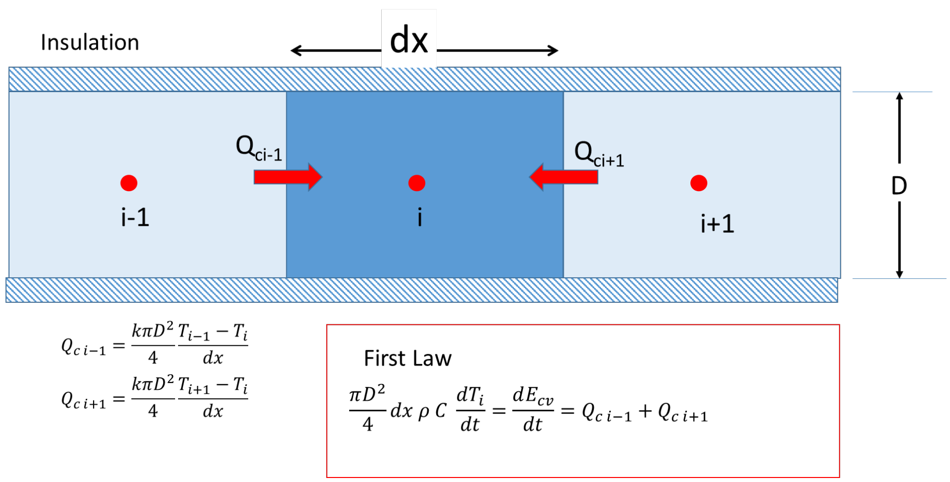


Figure 1. Unsteady heat balance for an insulated rod.

In Figure 1, the conduction heat flux is expressed as a finited difference ratio, but taking the limit for dx→0, one obtains an exact result:

$$\rho C \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \qquad [6]$$

The grouping $k/\rho C = \alpha$ [m²/s] is the *thermal diffusivity*. A well-posed problem would consist of this partial differential equation (Eq. 6),appropriate boundary conditions and initial conditions. For the 1-D rod, we most commonly know the initial temperature $T_i(x)$, as well as a boundary

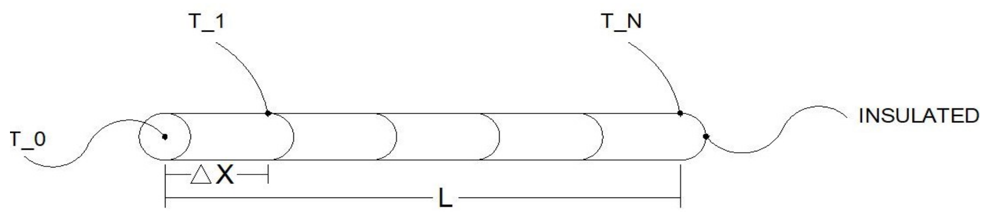


Figure 1 - Discretization of a Rod for the Finite Difference Method

condition (specified *T, dT/dx*, or a combination) at each end. Many ways of solving this problem have been developed, but there is no closed-form analytical solution for a finite-length rod. However, for a semi-infinite solid, there is a nice solution. In this experiment, one end (x=0) of a rod (initial temperature T_i) is suddenly cooled to temperature T_s, and for a short time, the temperature solution as a function of position x and time *t* is the same as for a semi-infinite solid:

$$\frac{T(x,t)-T_i}{T_s-T_i} = 1 - \operatorname{erf}\left(\frac{x}{2\sqrt{\alpha t}}\right) \qquad [7]$$

The errror function erf(x) is well described on Wikipedia https://en.wikipedia.org/wiki/Error_function .

Convection Heat Transfer

Generally, when a gas or liquid flows over a solid object, there will be a heat flux from the surface *q* [W/m²]:

$$q = h(T_s - T_f) \qquad [8]$$

Here *h* is the heat transfer coefficient, T_s the temperature of the solid surface and T_f the temperature of the fluid far from the object. The heat transfer coefficient depends on the *fluid properties and the nature of the flow* (geometry, Reynolds number, effect of buoancy, velocity). This lab will involve mainly forced convection from a cylinder (diameter *d*) at laminar or transition conditions. A simple correlation that covers the relevant regime ($1<Re<10^5$; $0.67<Pr< 300$) was given by Whitaker[1]. Reynolds number is based on the cylinder diameter, free stream (a.k.a far field) viscosity and velocity. Prandtl number $Pr = \frac{\nu}{\alpha}$; $\nu = \mu/\rho$ and the subscripts "f" and "w" refer to properties evaluated at the far field and wall conditions respectively.

$$Nu = \frac{hd}{k} = \left(0.4\, Re^{.5} + 0.06\, Re^{2/3}\right) Pr^{0.4} \left[\frac{\mu_f}{\mu_w}\right]^{0.25} \qquad [9]$$

Note that from the definition of the Nusselt number Nu, we can calculate the desired heat transfer coefficient as $h=k\,Nu/d$. The term d/Nu can be thought of as the thickness of a stagnant fluid layer yielding the same heat transfer as the actual value.

Radiation Heat Transfer

Radiation heat transfer arises from the thermal motion of the electric charges within matter – photons are emitted from any object at temperatures above absolute zero. Radiation heat transfer problems can become incredibly complex. For example, imagine the path of photons from the sun, through the atmosphere, into your house, and reflecting from a table onto your face. However, thermal radiation from a solid object (surface temperature T_s)in surroundings with a uniform temperature T_∞, the heat flux [W/m^2] is relatively easy to model:

$$q = \epsilon\sigma(T_s^4 - T_\infty^4) \qquad [10]$$

Equation (10) is valid for a "grey body", which is one with constant emissivity ε. The Stefan-Boltzmann constant is $\sigma = 5.67 \times 10^{-8}$ W/m^2/K^4.

Lumped Heat Capacity Analysis (0-Dimensional Transient Problem)

When one object (say, an aluminum rod) is surrounded by insulation or other large heat transfer resistance, heat transfer within the first object is much faster than heat transfer to/from the object. In this case, temperatures in the object are spatially uniform, but may vary slowly with time. That is, a single temperature *T(t)* can characterize the highly-conductive object. Application of the First Law yields Newton's Law of Cooling:

---

[1] S. Whitaker, "Forced convection heat transfer calculations for flow in pipes, past flat plate, single cylinder, and for flow in packed beds and tube bundles", *AIChE J.* 18 (1972) 361–371, reviewed and discussed in a more recent good paper, S.Sanitjai and R.J.Goldstein "Forced convection heat transfer from a circular cylinder in crossflow to air and liquids" *International Journal of Heat and Mass Transfer*, 47:4795-4805 (2004).

$$mC\frac{dT}{dt} = \frac{T_{sur} - T}{R} \qquad [11]$$

Where R is the thermal resistance defined earlier for conduction and T_{sur} is the temperature of the surroundings. The heat capacity is C [kJ/kg/K]. In practice, R could be dominated by the convection resistance or radiation resistance. The body approaches the temperature of the surroundings exponentionally with a time constant of mCR.

Experimental Equipment

You have available the equipment detailled in Appendix A and summarized here:

1. Data acquisition system to record temperatures as a function of time.
2. Cartridge heater, power supply, voltmeter and ammeter.
3. Various metal test pieces.
4. Insulation
5. Ice bath (blender and ice)
6. Fan and hot film air speed probe
7. Matlab simulation from last week, modified to include transverse heat loss by convection or radiation.
8. Additional thermocouple probes and an infrared temperature sensor.

Assignment for Part a Familiarization

In the familiarization experiment you will determine the thermal diffusivity of a known material using a transient conduction model of your measurements. By comparing this result with the known diffusivity, you will get an idea of how accurate the method is.

Lab Procedure

1. Assemble the lab apparatus consisting of the insulated, instrumented rod, DAQ and ice container.
2. Initialize the data acquisition system and begin recording data.
3. Allow the system to warm up (approximately 5 minutes). Before applying the ice boundary condition, note that the thermocouples *should* be reading the same values. Are they? Record any offsets in your lab notebook.
4. Apply the ice boundary condition to the end of the rod. Ensure that the boundary condition remains constant during the experiment by slowly and continually moving the ice.
5. After all thermocouples read less than 5 ^{o}C, remove the ice boundary condition and place the rod on a piece of foam insulation. Record data for another 10 minutes.

Analysis and Reporting

i) Make a spreadsheet (or Matlab code) that plots the experimental temperatures and the theoretical temperatures predicted for a semi-infinite slab, for assumed values of α. Adjust α to get the best fit you can. On Canvas, you will upload this graph, the value of α, and you will comment on the results.

ii) From the last part of the experiment, estimate the overall thermal resistance R_i of the insulation around the rod. To do this, plot the spatially averaged rod temperature as a function of time, and determine R_i using a lumped heat capacity model of the process. Again, go to Canvas to report your results.

iii) Read the Part b assignment and outline a procedure to experimentally answer the questions posed there.

Assignment for Part b Exploration

Experimental Questions

Using some cleverness, your knowledge of heat transfer, and the materials available in this lab, **determine the emissivity of polished aluminum, black-painted aluminum, and the convection heat transfer coefficient for a cylinder in cross flow.** Compare your experimentally-determined heat transfer coefficients with the prediction of the Whitaker correlation. As a broad hint: radiation and convection heat transfer will be present in all experiments, but you can vary conditions to change the relative importance of the two mechanism. In order to design your experiment, and to analyze the results afterwards, you need to have some understanding of how the experimental variables affect convection and radiation heat transfer. The data analysis is quite imporant in this lab, and you should consider carefully what factors should influence the emissivity and the heat transfer coefficient. For example, the surface colour should affect ε but not h.

Laboratory Procedure

This is up to you, but most groups will use the electrically heated cylinders, run at different power levels, with different convective velocities blowing over the cylinder.

Analysis and Reporting

Use the template for Introductory Experiment reports, addressing the experimental questions above clearly.

Appendix A Equipment Data

You will have the following equipment available for your experiment.

Item	Part Number	Description
Cartridge Heater	OMEGA HDC19102	Max 50W @120V
Infrared Temperature Gauge	OMEGA OS-418-LS	-60 degrees C to 500 degrees C Adjustable emissivity
Infrared Temperature Gauge	OMEGA OS-PEN9	-30 degrees C to 500 degrees C
Variac	3PN221B	Variable output 0-120VAC 330 watts maximum output
Aluminum Rods		2 painted flat black, 2 polished 6” length 3/8” diameter 8 thermocouple locations Drilled end for cartridge heater
Fan		No heat, low heat, high heat
Multimeter		Current,Voltage,Resistance
Thermocouple Probes		K type, quantity 8
Air velocity probe		Propellor type, approximately 5 cm diameter.
Data Acquisition System (DAQ)	Omega OMB-DAQ-2416	See Appendix B for details

Appendix B DAQ Software Installation Guide

The following procedure allows for data acquisition using the Omega OMB-DAQ-2416.

<u>Installation</u>

1. Download “Lab 3 software.zip” from the class webpage and extract the files.
2. Open the folder “Omega Software” and run “Install”.
3. Follow the prompts to install the software.

    Note: You do not need to install “Tracer DAQ” or “ULx for NI LabVIEW”.

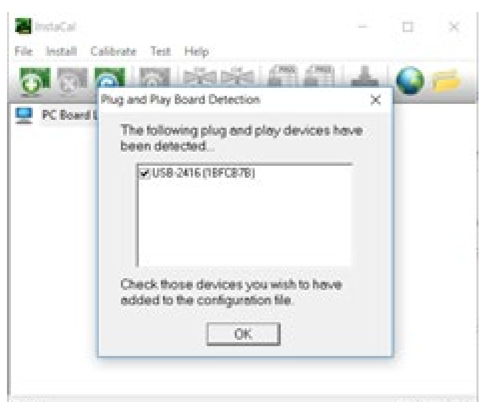
4. In “Lab 3 software” run “daqamisetup”.
5. Follow the prompts to install the software.

<u>Setup</u>

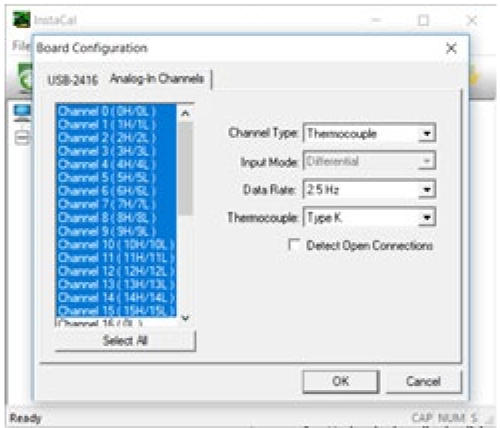
This procedure should be completed with the OMB-DAQ-2416 connected and powered on.

<u>Instacal Setup</u>

1. Start the Instacal software.
2. A popup window should appear as below indicating that the OMB-DAQ-2416 is available. Click OK.



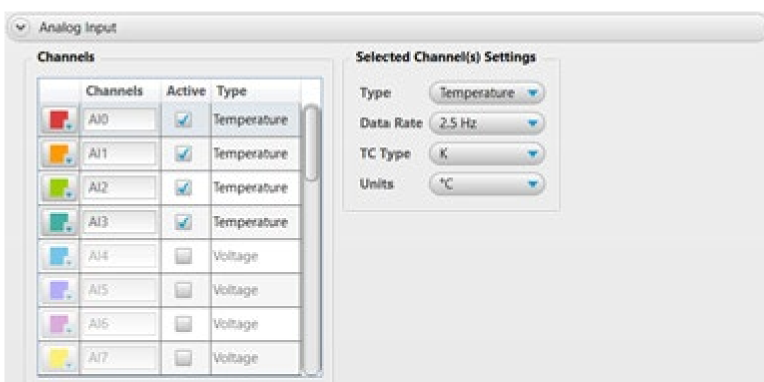
3. Under the install tab, click configure. Check the temperature units and change as required.
4. Select the Analog-In Channels tab.
    a. Select Channels 0-15 and set up the channels as shown below.



5. Click OK to accept the changes and close the Board Configuration popup window.
6. Close Instacal.

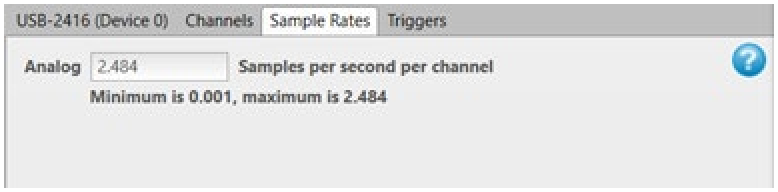
<u>DAQami Setup</u>

7. Run DAQami.
8. Choose to start a new manual configuration.
9. In the top left corner of the window click .
10. Select USB-2416 and add to the workspace.
11. Open the channels tab. Configure thermocouple inputs as below.



12. Open the sample rates tab. Set the sample rate manually as desired.

Note: This sample rate does not need to be equal to the sample rate set in Instacal.



13. Switch to the Display Panel by clicking  in the top left corner of the window.
14. Click  to add a display.
15. Drag channels into the display from the active channels list.
16. Click run to start the data acquisition.
17. When data acquisition is complete, export the data by clicking  and selecting Export.

<u>Post Processing</u>

The time data column is not in an appropriate format for MATLAB. Replace the data in the Date/Time column with a decimal value of seconds elapsed from 0 for each scan.