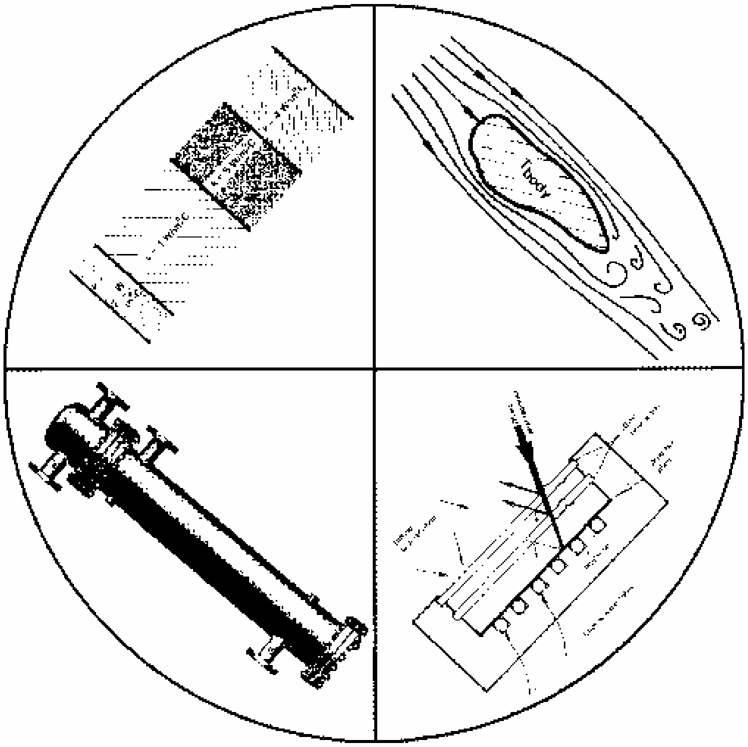
ME 412

Heat Transfer Laboratory

Summer 2005



Department of Mechanical Engineering
Michigan State University
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Craig W. Somerton, Associate Professor
Andre Bénard, Assistant Professor

ME 412
Heat Transfer Laboratory

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Teaching Assistants
Kaci Adkins and Jeremy Metternich

COURSE OBJECTIVES

1. Teach the use of instrumentation and apparatus that are unique and/or special to the field of heat transfer.

2. Demonstrate the fundamental aspects of heat transfer.

3. Employ experimental principles and thought processes to solve engineering problems.

STRUCTURE AND FORMAT

This course is divided into two parts. For the first nine weeks the students will run basic experiments on thermocouples, error estimation, conduction, radiation, convection, power plants, heat exchangers, and refrigeration systems. Every week a lecture will be given on the experiment to be conducted. The second half of the course will involve a project competition for which the students will be asked to design, analyze, build, and test a heat transfer device.

EXPERIMENTAL GROUPS

For the basic experiments (lab sessions 1-9) students will work in groups of six determined by section enrollment. For every two hour lab session there will be two groups assigned by the TA as group A or group B. Each week, with the exception of session 1, these lab groups will be divided into subgroups of two which will produce independent technical memos. This pairing will change every week, so that every member of the group will write a technical memo with every other member of the group.

For the project competition students will work in teams of three of their own choosing Each week the project team will be scheduled to meet with the instructor either during the regular lab lecture time or some other convenient time.

LAB SCHEDULE

Lab Lecture meets in 2243 EB
Lab Sessions meet in 3547 West EB

Lab Session	Lecture Date & Duration	Lecture Subject	Group A Experiment	Group B Experiment
1(week of 5/16)	Mon 5/16 (4:10-5)	Thermocouple	Thermocouple	Thermocouple
2(week of 5/23)	Mon 5/21 (4:10-6)	Team Building Error Estimation	Team Building	Team Building
3(week of 5/30)	Tue 5/31(5-6:30) Wed 6/01(4-5:30)	Power Plant Chiller Plant	Error Estimation	Error Estimation
4(week of 6/6)	Mon 6/06 (4:10-6)	Conduction Convection	Conduction Power Plant Simulation	Convection
5(week of 6/13)	Mon 6/13 (4:10-6)	Heat Exchanger Radiation	Convection	Conduction Power Plant Simulation
6(week of 6/20)	Power Plant Tour		No Lab	No Lab
7(week of 6/27)	No Lecture		Heat Exchanger	Radiation
8(week of 7/4)	No Lecture		Radiation	Heat Exchanger
9(week of 7/11)	20 minute project team meetings with TAs			
10(week of 7/18)	No Lecture		Chiller Plant Tour	Chiller Plant Tour
11-13 (7/25-8/8)	20 minute project team meetings with TAs			
14(week of 8/15)	Project Competition, Mon August 15, 4:10-6 in 3547 EB			

REPORT REQUIREMENTS

Each student will write an individual memo for the thermocouple experiment. This memo will be evaluated on the basis of English usage, in addition to technical content. Drafts of this memo will be submitted to Craig Gunn, who will review them for English usage. The student will then revise the draft accordingly and submit it to their TA for technical grading. A technical memo from each subgroup of two students is required for the other experiments. Data analysis may be done by the group as a whole. A format for the technical memo and an example of a technical memo are included in the lab manual. Memos are due at the beginning of the next lab session. Memos should be typed.

For the project a formal, typed report is required. A general format for the report is provided in the lab manual. The report will be graded for English usage and this will count 25% towards the final grade for the project.

GRADING

The technical memos from the first half of the course will count 60%. The project will count 40%. On all memos and the project report each member of the group will be graded with due consideration given to the participation of each member. Grading will be done by your section TA on a form similar to that shown below. Project grading will be done by Mr. Kharazi. Several of the experiments will have pre-lab assignments that will be due at either the beginning of lecture or the beginning of lab and will count 5-10 points on the technical memo.

Grading Sheet

Basic Grade	/70
Discussion	/±20
Memo, Data, & Graph Quality -8 → Very poor 0 → Mediocre +8 → Outstanding	/±8
Above & Beyond ______ Library work ______ Additional discussion ______ Additional insight	/2
Total	/100

Comments:

The basic grade score is determined upon having correct results and the data analysis requested in the experimental handout. The discussion score is divided into two parts. The first part deals with a general discussion of the results which includes identifying trends and convincing the reader that the results are physically consistent. The second part deals with addressing the suggestions for discussion provided in the handout. Communication skills are evaluated under the memo, data, & graph quality score.

The course grade is assigned on the basis of a distribution. That is, the class's numerical scores are plotted and grade divisions are drawn based on how students group themselves. A straight scale is used to **guide** the setting of these grade divisions. That is

90 or higher	4.0
85-89	3.5
80-84	3.0
75-79	2.5
70-74	2.0
65-69	1.5
60-64	1.0
less than 60	0.0

A student will never receive a course grade less than what a straight scale would predict.

LABORATORY MAKE-UP POLICY

During the term a student enrolled in ME 412 may miss and make-up no more than two laboratory sessions. If a student will be missing a laboratory session and wishes to make it up, the following procedure must be followed.

(i) Inform your laboratory session instructor AND Amir Kharazi about your situation as soon as possible, but it must be prior to your regular lab session.
(ii) The student must submit an individual technical memo for the lab session missed and then made up.
(iii) The lab session make-up can occur by either participating in another regular lab session or attending a make-up lab session on at a time to be arranged by the instructor

Failure to follow this procedure may result in the assignment of a zero for the missed lab session.

ATTENDANCE AT LAB LECTURES

Attendance at the weekly lab lectures is required. Failure to attend lab lecture will lead to a 10 point deduction from the student's grade for that week's laboratory

SAFETY

Each student shall read, sign, and follow the Student Informed Consent Statement

Plagiarism Policy
Department of Mechanical Engineering

Plagiarism is not tolerated in the Department of Mechanical Engineering. It shall be punished according to the student conduct code of the University. Integrity and honesty are essential to maintain society's trust in the engineering profession. This policy is intended to reinforce these values.

For the purpose of this policy, plagiarism means presenting, as one's own, without proper citation, the words, work or opinions of someone else.

A. You commit plagiarism if you submit as your own work:

1. Part or all of an assignment copied from another person's assignment, including reports, drawings, web sites, computer files, or hardware.

2. Part or all of an assignment copied or paraphrased from a source, such as a book, magazine, pamphlet, web site, or web posting, without proper citation

3. The sequence of ideas, arrangement of material, pattern or thought of someone else, even though you express them in your own words. Plagiarism occurs when such a sequence of ideas is transferred from a source to a paper without the process of digestion, integration and reorganization in the writer's mind, and without acknowledgement in the paper.

B. You are an accomplice in plagiarism and equally guilty if you:

1. Knowingly allow your work, in preliminary or finished form, to be copied and submitted as the work of another.

2. Prepare an assignment for another student, and allow it to be submitted as his or her own work.

3. Keep or contribute to a file of assignments with the clear intent that these assignments will be copied and submitted as the work of anyone other than the originator of the assignment. (The student who knows that his or her work is being copied is presumed to consent to its being copied.)

(based upon the MSU English Department's policy on plagiarism at:
http://www.msu.edu/unit/engdept/undergrad/plagiarism.html

Format for Technical Memo

A technical memo is a concise presentation of results, with a logical progression from the principles which are core to the experiment towards the conclusions that were drawn from the results. It is written to an informed audience so regurgitation of the fundamentals of heat transfer is not necessary. It is, however, important to provide the relevant equations on which your experiment is based.

An example technical memo is provided below for reference. Further clarification of what should be contained in each section also follows.

Introduction: This section should begin with the motivation for the study and end with a clear statement of the question you are answering with your experiment. The introduction should flow in a manner similar to the following:

This is why I did this work…{motivation}
This is what I did…{describe your experiment}
Which is based on…{give the fundamental principle/s}
This is the question I answered … {what was concluded}

The introduction is a preview of what is to come and should not be lengthy. You will go into further detail in the body of the report.

Results and Discussion: The material presented in this section should proceed in a step-by-step logical format. It should begin with a brief synopsis of the fundamental theory that is most relevant to your experiment, lead up to the equations that contain the variables that you are measuring, and then proceed into the experimental portion, which discusses how the measurements were taken. This section should also contain any results that were obtained and the conclusions drawn from these results. An error analysis and discussion of the validity of the results will also belong in this section. Often it may be advisable to break this down into two or three parts depending on the nature of the information being presented, for example:

Materials and Methods
Results
Discussion

Appendix: Information that is too bulky or cumbersome to be contained in the body of the report should be included here. For example it may contain procedures, computer code, sample calculations, or large data sets.

Notes on **Graphs**:

- These should be uncluttered and easy to interpret.
- Avoid shaded backgrounds, they obscure the data you are presenting.
- If a legend is included make sure it is not cryptic. For example, instead of TC_T_w use welded T-type thermocouple
- The labels on the axis should be equally descriptive and include the appropriate units when relevant.
- Titles should describe the data and not be generic title such as Graph 1.
- Experimental data should be represented by plotting symbols with error bars, not by solid, continuous lines.
- If needed, use a dashed line through data points to clarify trends.

Perhaps the most important thing to remember about graphs is that they should tell a story even if they are removed from the supporting text.

Tables should include headings, units, and have a title describing the data presented.

Example of Technical Memo

MEMORANDUM

TO: Engineering Foundation

FROM: Craig W. Somerton, Associate Professor
Mechanical Engineering, MSU

DATE: May 3, 1997

SUBJECT: Experiments on Permeability Effects on Heat Transfer in Porous Media

Introduction

Several experiments have been conducted to determine the effect of variable permeability on heat transfer in porous media. A porous medium was formed by using two different size glass beads, 3 mm in diameter and 5 mm in diameter. Each size was constrained in a single layer, so one could study the interactions between homogeneous porous layers of different permeabilities. The experiments were conducted in a cylindrical convection cell composed of a Plexiglas cylinder bounded on top and bottom by heat meters. Through the heat meters a constant temperature fluid would flow so that a temperature gradient could be established. From the temperature and heat flux measurements a convective heat transfer coefficient and Nusselt number can be determined.

Results and Discussion

Two sets of experiments were conducted. In the first set the lower porous layer had a higher permeability than the upper layer while in the second set this situation was reversed. The results, in terms of Rayleigh number versus Nusselt number plots, are shown in Figure 1. The most striking trend from this figure is that at low Rayleigh numbers the data fall on similar curves, but at a Rayleigh number of 80, there is a sudden shift upwards in the Nusselt number for the case of low permeability over high permeability. Often a sudden shift in a Rayleigh number - Nusselt number curve would indicate a change in the fluid mechanics. It is proposed that when the lower layer is a high permeability layer, convection at low Rayleigh numbers occurs only in the lower layer, the upper layer being in conduction mode. Then at a Rayleigh number of about 80, convection begins in the upper layer. Apparently, the low permeability upper layer nearly acts as a solid surface. Evidence of this proposition is shown in Figs. 2 and 3 which show the Rayleigh number - Nusselt number relationship for both the upper layer and the lower layer. In Fig. 2 we see nice smooth curves which indicate very little. However, in Fig. 3, where we connected the data points in terms of increasing overall Rayleigh number, we see a discontinuity. This further indicates that the onset of convection in the upper layer is delayed until that point. Since in the experiment energy is supplied to the lower layer first, the lower layer must be driven first to convection. Hence, for the case of a low permeability lower layer the entire two layer system moves into convection at the same Rayleigh number. All pertinent raw data and calculations are provided in the appendix.

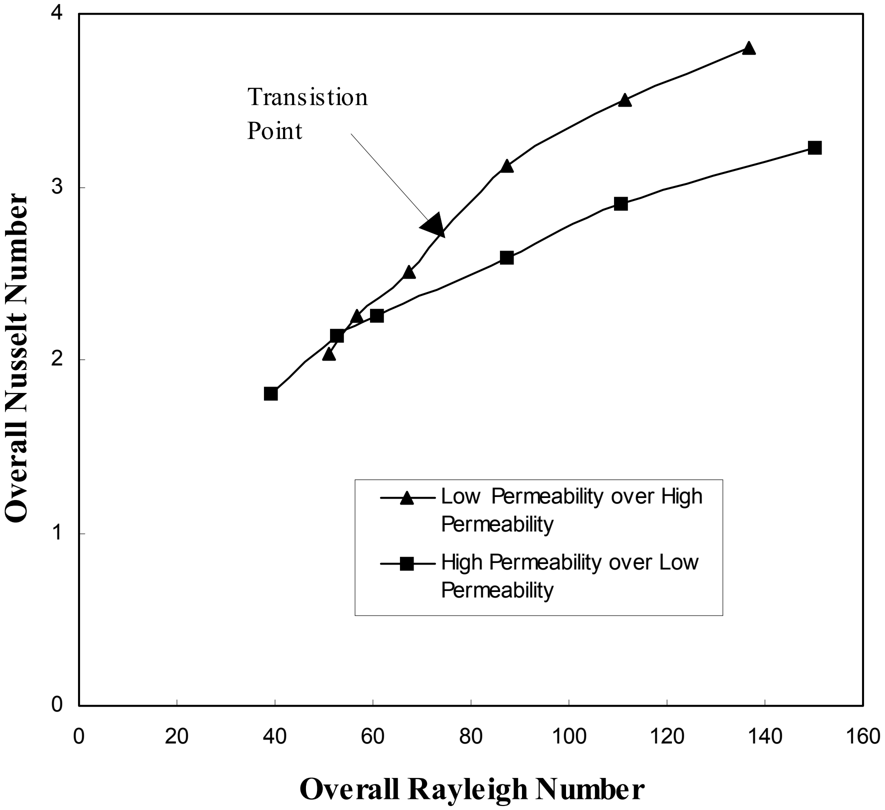


Figure 1. Experimental Heat Transfer Results

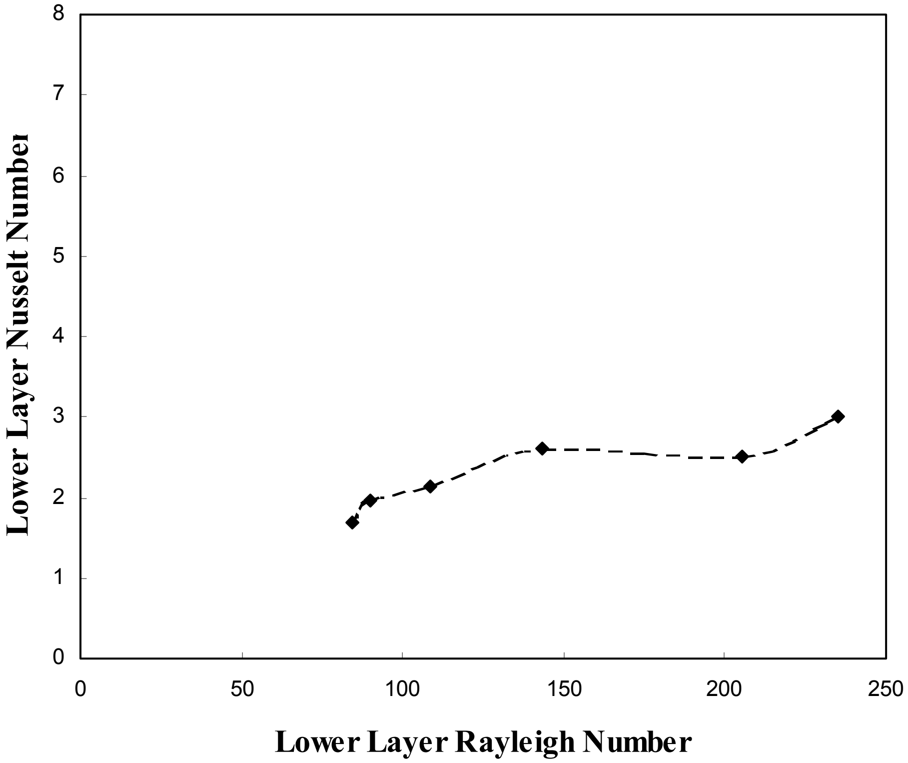


Figure 2. Lower Layer Heat Transfer

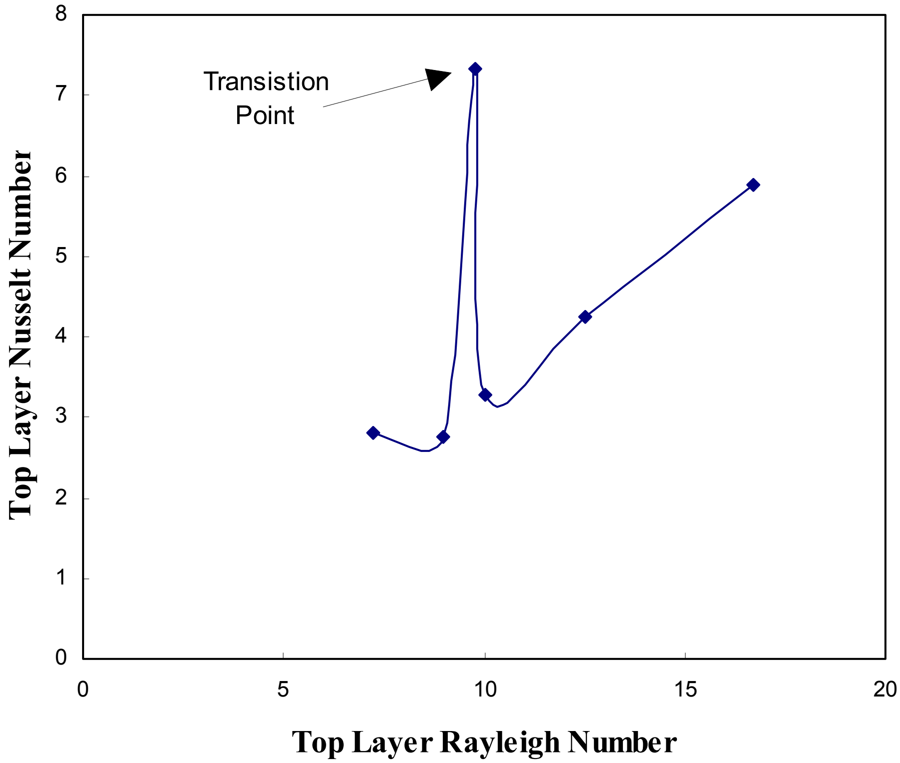


Figure 3. Upper Layer Heat Transfer

Safety Information

In order to avoid personal injuries and injuries to fellow students while performing experiments in your laboratory courses, it is required that you read and understand the following regulations before performing any experiments. Please indicate that you have done so by signing the consent form provided by your laboratory instructor.

I. PERSONAL PROTECTION

1. Safety goggles (not sunglasses) must be worn when handling concentrated acids and bases in the laboratory. These goggles will be provided by the department.

2. If you get foreign material in your eye, immediate and extensive washing with water only is absolutely essential to minimize damage. Use the eye wash fountain in the lab at once. If you spill any chemical on yourself, immediately wash with large amounts of water; then notify your instructor. Report to the health center if unusual symptoms develop after leaving the lab. Take your lab manual and notebook to aid the physician to make a quick accurate diagnosis. Do not use organic solvents to remove organic compounds from the skin; they will only spread the damage over a wider area. Solvents also tend to penetrate skin, carrying other chemicals along. Soap and water are more effective.

3. Do not apply ointments to chemical or thermal burns. Use only cold water.

4. Do not taste anything in the laboratory. Do not use mouth suction in filling pipettes with chemical reagents. (Use a suction bulb.)

5. To minimize hazard, confine hair securely when in the laboratory. Shoes or sneakers must be worn in labs.

6. Exercise great care in noting the odor of fumes and whenever possible avoid breathing fumes of any kind. See also III-6.

7. No smoking in lab.

8. No eating or drinking in lab.

9. You must obtain medical attention for cuts, burns, inhalation of fumes, or any other laboratory incurred accident. If needed, your laboratory instructor will arrange transportation to Olin Health Center. An accident report must be completed by your laboratory instructor. You should take a copy of this with you when you go to Olin Health Center.

II. PROPERTY PROTECTION

1. In case of fire, call the instructor at once. If you are near an extinguisher, bring the extinguisher to the fire, but let the instructor use it.

2. Know the location of all safety equipment: fire extinguishers, safety showers, fire blankets, eye washes (any water hose works in an emergency) and exits.

3. Treat all liquids as extremely flammable unless you know them to be otherwise.

4. Clean all spills promptly with water (except water reactive substances) and paper towels. If you have any doubts about the proper clean-up procedure, ask your instructor.

III. LABORATORY TECHNIQUE

1. Read the experiment before coming into the lab. This will allow you to plan ahead so that you can make best use of your time. The more you rush at the end of a lab, the greater your chance of having an accident.

2. Do not perform unauthorized experiments. Do not remove any chemicals or equipment from the laboratories. You alone will bear the consequences of "unauthorized experimentation".

3. Never work in any laboratory alone.

4. Do not force glass tubing into rubber stoppers. (Protect your hands with a towel when inserting tubing into stoppers, and use a lubricant.)

5. When working with electrical equipment observe caution in handling loose wires and make sure that all equipment is electrically grounded before touching it.

6. Use hood facilities. Odors and gases from chemicals and chemical reactions are usually unpleasant and in many cases toxic.

7. View reactions horizontally, keeping glass and safety glasses between you and the reactants. Do not look into the open mouth of a test tub or reaction flask. Point the open end of the tube away from you and other laboratory workers.

8. Be a good housekeeper. Order and neatness will minimize accidents.

9. Laboratory safety is the personal responsibility of each and every individual in the laboratory. Report unsafe practices.

10. Treat all chemicals as corrosive and toxic and all chemical reactions as hazardous unless you know them to be otherwise.

Thermocouple Experiment

OBJECTIVE

To understand the operation and use of thermocouples to measure temperature.

BACKGROUND

Certainly, one of the most important activities in experimental heat transfer is the measurement of temperature. The temperature of a surface, fluid, or solid body will provide much of the information concerning the heat transfer processes at work. There are many ways to measure temperature. These include, to mention only a few, thermocouples, thermometers, and thermistors. In this experiment we will work with the thermocouple.

A thermocouple consists of two wires of two different materials that are joined at each end. When these two junctions are kept at different temperatures a small electric current is induced. Due to the flow of current a voltage drop occurs. This voltage drop depends on the temperature difference between the two junctions. The measurement of the voltage drop can then be correlated to this temperature difference. It is extremely important to note that a thermocouple does not measure the temperature, but rather the temperature difference between the two junctions. In order to use a thermocouple to measure temperature directly, one junction must be maintained at a known temperature. This junction is commonly called the reference junction and its temperature is the reference temperature. The other junction, which is normally placed in contact with the body of unknown temperature, is called the measurement junction.

In experimental heat transfer we often encounter problems in which the temperature of the environs of a thermocouple is changing. Since a thermocouple has finite mass and thus finite heat capacity, it cannot respond instantaneously to a temperature change. The conservation of energy for this process can be represented by the following differential equation (assuming a lumped capacitance model),

$$m\, c_p \frac{dT}{dt} = h\, A \left(T_o - T\right) \tag{1}$$

where

m: mass of thermocouple (measurement junction)
c_p: specific heat of thermocouple (measurement junction)
h: heat transfer coefficient

A: surface area of thermocouple
T: measurement junction temperature
T_o: environs temperature

If we let

$$\theta = \frac{T - T_o}{T_i - T_o} \tag{2}$$

where T_i is the initial measurement junction temperature, then the solution is

$$\theta = e^{-t/\tau} \tag{3}$$

where we have defined the time constant for this process as

$$\tau = \frac{m\, c_p}{h\, A}. \tag{4}$$

The time response of a thermocouple can be quantified by this time constant.

Finally, there are three additional laws dealing with thermocouples.

1. Law of Homogeneous Metals**:** A thermoelectric circuit cannot be sustained in a circuit of a single homogeneous material, however varying in cross section, by the application of heat alone. That is, two different materials are required for any thermocouple circuit.

2. Law of Intermediate Metals: A third homogeneous material can always be added in a thermocouple circuit with no effect on the net emf of the circuit provided that the extremities of the third material are at the same temperature.

3. Law of Successive or Intermediate Temperatures: If two dissimilar homogeneous metals produce a thermal emf of E_1, when the junctions are at temperatures T_1 and T_2, and a thermal emf of E_2, when the junctions are at T_2 and T_3, the emf generated when the junctions are at T_1 and T_3, will be $E_1 + E_2$.

PROCEDURE

The experiment you will be conducting in laboratory consists of three parts:

A. fabrication of thermocouples
B. calibration of thermocouples
C. time response of thermocouples.

A. Thermocouple Fabrication

Thermocouples can be composed of many different pairs of metals and the junctions can be formed in many different ways. For a variety of reasons, different pairs of metal are used for different applications. For our experiment we will use the following two types of thermocouples:

Copper/Constantan or Type T
(copper has blue insulation and is the positive lead)
(constantan has red insulation and is the negative lead)
Chromel/Alumel or Type K
(chromel has yellow insulation and is the positive lead)
(alumel has red insulation and is the negative lead)

We will fabricate thermocouples by

1. Mechanical tying
2. Soldering
3. Spot welding

Each experimental group will construct six thermocouples:

4 - Type K	2 by mechanical tying 1 by soldering 1 by spot welding
2 - Type T	1 by mechanical tying 1 by soldering

The step by step procedure is outlined below.

1. Check out thermocouple wire, a pair of pliers, and wire strippers from your instructor.

2. Bare approximately 1/2 inch of the leads from both ends of the wire.

3. For two chromel/alumel wire pairs and one copper/constantan pair twist together the wires at one end. You have now made your mechanically tied thermocouples.

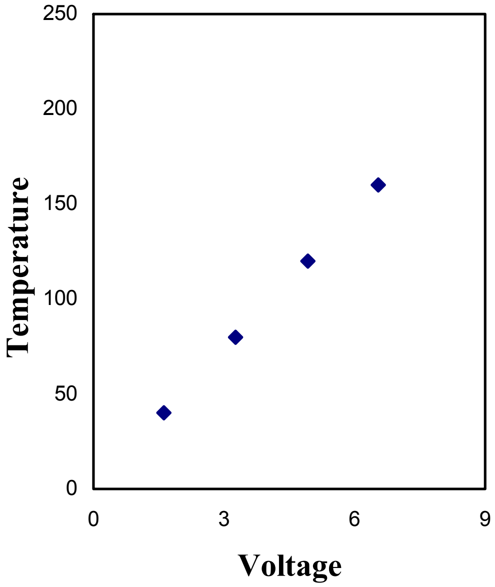
4. For the soldered thermocouples form the wires at one end into an oval shape so that the two wires nearly touch at a point. Next, form a small pool of solder on the soldering plate. Keeping the pool liquid with the soldering iron, dip the thermocouple into the pool so that the solder will form a bridge between the two wires.

5. For the spot welded thermocouple, overlap the two wires at one end and flatten the wires at their point of crossing. Place the this junction on the welding plate. Turn the spot welder on and set the power and timing switches. Carefully take the electrode end of the welder and press it to the junction until the welder fires. You may have to attempt this several times, varying the power and time until a good weld is achieved.

B. Calibration of Thermocouples

The thermocouples you have constructed must now be calibrated. To calibrate, we measure the thermocouple voltage at various known temperatures, so as to develop a correlation between thermocouple voltage and thermocouple temperature. This correlation may be represented by a graph similar to that shown below.

Figure 1. Sample of Thermocouple Calibration Curve



The calibration is achieved with the use of a small block furnace which serves as the constant temperature heat reservoir. The operation of this device will be described by your lab instructor.

1. Attach the loose end of each thermocouple to the rotary selection switch. When attaching the thermocouples, note the polarity of the poles on the rotary selection switch. Since this is the first point in the circuit where the thermocouple will "see" dissimilar metal, it will serve as the reference junction. Hence the temperature of the rotary selection switch must be measured for each thermocouple reading. To determine this temperature, a mechanically tied thermocouple of each type is employed. These thermocouples are inserted into an ice point calibration cell which maintains the temperature at 0°C, ±0.1°C. Thus, for these two thermocouples (called the ice point thermocouples), the reference junction is in the ice point calibration cell, and the measurement junction is at the rotary selection switch (which is the reference junction for the other four thermocouples).

2. With the furnace set at approximately 50°C, insert the remaining four thermocouples (called the calibration thermocouples) into the core and record the readings from the digital multi-meter. You also need to record the readings for the ice point thermocouples. Repeat this procedure at approximately 100°C and 150°C. At 150°C the calibration procedure is suspended and the time response tests are then conducted. After the time response tests, the temperature of the furnace is increased to 180°C and the final calibration point is taken.

3. It will prove useful to record the data on an Excel spreadsheet. Setup a spreadsheet of the form shown below.

Table 1. Form of Excel Spreadsheet for Data

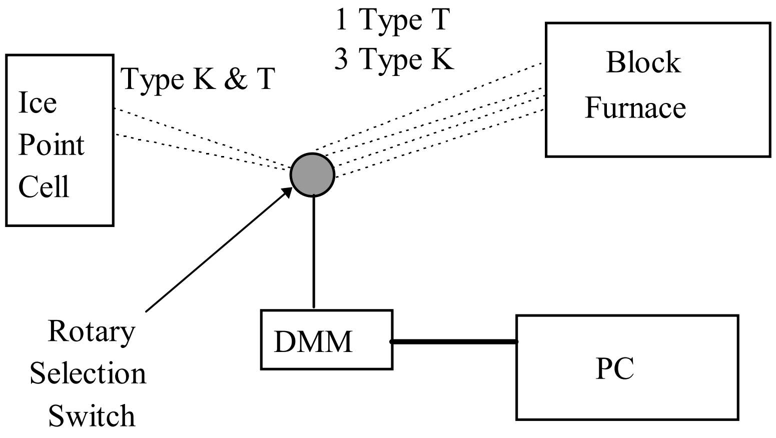
ME 412
Thermocouple Experiment: Calibration Data

	Calibration Thermocouples (raw data)				Ice Point Thermocouples		Calibration Thermocouples (ice point correction)			
T(C)	TC#1 (mv)	TC#2 (mv)	TC#3 (mv)	TC#4 (mv)	TC#5 (mv)	TC#6 (mv)	TC#1 (mv)	TC#2 (mv)	TC#3 (mv)	TC#4 (mv)
▨	▨	▨	▨	▨	▨	▨				
▨	▨	▨	▨	▨	▨	▨				
▨	▨	▨	▨	▨	▨	▨				
▨	▨	▨	▨	▨	▨	▨				

The shaded regions on the spreadsheet indicate cells where the students will make entries, while blank cells require an equation to be inputted. In this case the equation will be the subtraction of the voltage of the appropriate ice point thermocouple, either TC#5 or TC#6, from the measured voltage of the calibration thermocouple.

To obtain an overall perspective of the calibration apparatus a layout is provided below.

Figure 2. Layout of Experimental Apparatus



You will be comparing your calibration to standard tables, which are determined for a reference junction at 0°C. Subtract the voltage reading of the appropriate ice point junction thermocouple from the calibration thermocouple reading to compare our calibration to the standard tables. Say our ice point thermocouple has a voltage reading of -0.935 millivolts. Let the furnace be set at 150°C and we record a voltage reading for a calibration thermocouple in the furnace as 5.134 millivolts. Then for a reference junction at 0°C and a measurement junction at 150°C the corresponding voltage would be the difference of these two readings, or 6.069 mV.

C. Time Response of Thermocouples

When the surrounds of a thermocouple change in temperature the thermocouple reading will show a response to this change. The speed of this response can be quantified in terms of a time constant. You will determine the time constant for each calibration thermocouple using the following procedure.

1. Have the calibration thermocouples in the block calibration furnace at a steady state temperature of approximately 150°C.

2. Initialize the data acquisition system. Your laboratory instructor will assist you with this setup.

3. Start the data acquisition system and remove a calibration thermocouple from the furnace core. Allow the data acquisition system to record temperature data as the thermocouple cools in still air until the thermocouple approaches ambient temperature. Once a steady state is reached the data acquisition may be stopped.

4. The data acquisition system will write the temperature/time data to an Excel spreadsheet file which is named during setup. We first note that the temperature recorded by the data acquisition system is actually the temperature difference between the thermocouple and the environs or $T-T_o$, which we note as the numerator of θ in Eqn.(2). To utilize this data for the prediction of a time constant, it will probably be necessary to edit the file. Since the data acquisition system is turned on prior to removal of the thermocouple from the furnace, the first few data points will be at the constant temperature of the block furnace. We will want to delete all of these except for the very last one. Similarly, the same is true at the end of the experiment, where we may need to delete some of the steady state temperature data. After these deletions, we will also want to correct the time, so that it begins at zero for the first data point retained. To calculate θ at every time step we will need to take our measured temperature, $T-T_o$, and divide it by T_i-T_o. Of course T_i-T_o is simply the measured temperature at the first time step.

5. Repeat steps 2 and 3 for the remaining three calibration thermocouples.

To determine the time constant from experimental measurements of time and temperature we can take two approaches. One method is to plot $\ln(\theta)$ versus t. This should be a straight line with slope $-1/\tau$. This approach allows us to confirm the lumped capacitance model presented in the background. A second way is to note that when the time is equal to the time constant, we have

$$\theta = e^{-1} \approx 0.37 \qquad \text{or} \qquad \ln\theta = -1 \tag{5}$$

We can then scan our data and find the experimental temperature which will give this value. The corresponding time must be the time constant. You should use both approaches, and compare the results.

DATA ANALYSIS

1. On a single graph plot the calibration curves for the three type K calibration thermocouples and compare them to the standard calibration data provided in the attached table. On a second graph repeat this plot for the type T calibration thermocouple. For discussion purposes, it may also prove useful to graph the calibration data for the two soldered thermocouples on a third graph.

2. Plot the semi-log temperature history for at least one of the calibration thermocouples. Use a linear curve fit of this plot to determine the time constant by the first method above. Estimate the time constant of each calibration thermocouple using the second method above (the e^{-1} method). Provide a table of the time constants for the four calibration thermocouples.

3. To what precision (in millivolts) are you reading the temperature?

SUGGESTIONS FOR DISCUSSION

1. What effect does the method of junction have on the thermocouple calibration and time constant? What effect does theory tell us it should have?

2. What differences do we see between the chromel/alumel and the copper/constantan thermocouples? Why?

3. Compare the two methods of estimating the time constant. Which one is better, and why?

4. What errors may be introduced by measuring temperature with a thermocouple? You may wish to consider the heat transfer modes acting on the thermocouple.

5. What role does the reference junction play in thermocouple readings?

NOTE

The technical memo for the thermocouple experiment will be done on an individual basis. It will be reviewed by Craig Gunn prior to turning the memo in to your TA. The following dates will be followed for this memo:

	Tues. Lab	Thur. Lab
Drafts due to Craig Gunn	Fri. 5/20	Mon. 5/23
Students pick-up from Craig Gunn	Mon. 5/23	Wed. 5/25
Turned in to TA's	Tues. 5/24	Wed. 5/26
Returned to Students	Tues. 5/31	Thur. 6/2

Type T Thermocouple Table[1]

Voltages are in mV

Temperature (°C)	0	1	2	3	4	5	6	7	8	9
0	0.0000	0.0388	0.0776	0.1165	0.1555	0.1946	0.2337	0.2729	0.3122	0.3516
10	0.3910	0.4305	0.4701	0.5097	0.5495	0.5893	0.6292	0.6692	0.7092	0.7494
20	0.7896	0.8299	0.8703	0.9108	0.9513	0.9920	1.0327	1.0735	1.1144	1.1554
30	1.1964	1.2376	1.2788	1.3201	1.3616	1.4030	1.4446	1.4863	1.5280	1.5699
40	1.6118	1.6538	1.6959	1.7381	1.7803	1.8227	1.8651	1.9076	1.9503	1.9929
50	2.0357	2.0786	2.1215	2.1646	2.2077	2.2509	2.2942	2.3375	2.3810	2.4245
60	2.4682	2.5119	2.5556	2.5995	2.6435	2.6875	2.7316	2.7758	2.8201	2.8645
70	2.9089	2.9534	2.9980	3.0427	3.0875	3.1323	3.1772	3.2222	3.2673	3.3125
80	3.3577	3.4030	3.4484	3.4939	3.5394	3.5851	3.6308	3.6766	3.7224	3.7683
90	3.8143	3.8604	3.9066	3.9528	3.9991	4.0455	4.0920	4.1385	4.1851	4.2318
100	4.2785	4.3253	4.3722	4.4192	4.4662	4.5133	4.5605	4.6078	4.6551	4.7025
110	4.7500	4.7975	4.8451	4.8928	4.9405	4.9883	5.0362	5.0842	5.1322	5.1803
120	5.2284	5.2767	5.3250	5.3733	5.4218	5.4703	5.5188	5.5675	5.6162	5.6649
130	5.7138	5.7627	5.8116	5.8606	5.9097	5.9589	6.0081	6.0574	6.1068	6.1562
140	6.2057	6.2552	6.3049	6.3545	6.4043	6.4541	6.5040	6.5539	6.6039	6.6540
150	6.7041	6.7543	6.8045	6.8548	6.9052	6.9557	7.0062	7.0567	7.1074	7.1580
160	7.2088	7.2596	7.3105	7.3614	7.4124	7.4635	7.5146	7.5658	7.6170	7.6683
170	7.7197	7.7711	7.8226	7.8741	7.9257	7.9774	8.0291	8.0809	8.1327	8.1846
180	8.2366	8.2886	8.3407	8.3928	8.4450	8.4973	8.5496	8.6020	8.6544	8.7069
190	8.7595	8.8121	8.8647	8.9174	8.9702	9.0231	9.0760	9.1289	9.1819	9.2350
200	9.2881	9.3413	9.3945	9.4478	9.5012	9.5546	9.6080	9.6615	9.7151	9.7687
210	9.8224	9.8761	9.9299	9.9838	10.038	10.092	10.146	10.200	10.254	10.308
220	10.362	10.417	10.471	10.525	10.580	10.634	10.689	10.743	10.798	10.853
230	10.907	10.962	11.017	11.072	11.127	11.182	11.237	11.292	11.347	11.403
240	11.458	11.513	11.569	11.624	11.680	11.735	11.791	11.846	11.902	11.958
250	12.013	12.069	12.125	12.181	12.237	12.293	12.349	12.405	12.461	12.518
260	12.574	12.630	12.687	12.743	12.799	12.856	12.912	12.969	13.026	13.082
270	13.139	13.196	13.253	13.310	13.366	13.423	13.480	13.537	13.595	13.652
280	13.709	13.766	13.823	13.881	13.938	13.995	14.053	14.110	14.168	14.226
290	14.283	14.341	14.399	14.456	14.514	14.572	14.630	14.688	14.746	14.804
300	14.862	14.920	14.978	15.036	15.095	15.153	15.211	15.270	15.328	15.386

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[1] From Omega, Thermocouple Reference Tables, 1993.

Type K Thermocouple Table[2]

Voltages are in mV

Temperature (°C)	0	1	2	3	4	5	6	7	8	9
0	0.0000	0.0395	0.0790	0.1186	0.1582	0.1979	0.2376	0.2773	0.3171	0.3570
10	0.3969	0.4368	0.4768	0.5168	0.5569	0.5970	0.6371	0.6773	0.7175	0.7578
20	0.7981	0.8385	0.8789	0.9193	0.9597	1.0002	1.0408	1.0814	1.1220	1.1626
30	1.2033	1.2440	1.2847	1.3255	1.3663	1.4072	1.4480	1.4889	1.5299	1.5708
40	1.6118	1.6528	1.6939	1.7349	1.7760	1.8171	1.8583	1.8994	1.9406	1.9818
50	2.0231	2.0643	2.1056	2.1469	2.1882	2.2296	2.2709	2.3123	2.3537	2.3951
60	2.4365	2.4779	2.5193	2.5608	2.6023	2.6437	2.6852	2.7267	2.7682	2.8097
70	2.8513	2.8928	2.9343	2.9758	3.0174	3.0589	3.1005	3.1420	3.1836	3.2251
80	3.2666	3.3082	3.3497	3.3913	3.4328	3.4743	3.5159	3.5574	3.5989	3.6404
90	3.6819	3.7234	3.7649	3.8063	3.8478	3.8892	3.9306	3.9721	4.0135	4.0549
100	4.0962	4.1376	4.1789	4.2203	4.2616	4.3029	4.3442	4.3854	4.4267	4.4679
110	4.5091	4.5502	4.5914	4.6325	4.6737	4.7148	4.7558	4.7969	4.8379	4.8789
120	4.9199	4.9609	5.0018	5.0427	5.0836	5.1244	5.1653	5.2061	5.2469	5.2877
130	5.3284	5.3691	5.4098	5.4505	5.4911	5.5318	5.5724	5.6129	5.6535	5.6940
140	5.7345	5.7750	5.8155	5.8559	5.8963	5.9367	5.9771	6.0174	6.0578	6.0981
150	6.1384	6.1786	6.2189	6.2591	6.2993	6.3395	6.3797	6.4198	6.4600	6.5001
160	6.5402	6.5803	6.6204	6.6605	6.7005	6.7406	6.7806	6.8206	6.8606	6.9006
170	6.9406	6.9806	7.0205	7.0605	7.1005	7.1404	7.1803	7.2203	7.2602	7.3001
180	7.3400	7.3800	7.4199	7.4598	7.4997	7.5396	7.5795	7.6194	7.6593	7.6992
190	7.7391	7.7791	7.8190	7.8589	7.8988	7.9388	7.9787	8.0186	8.0586	8.0985
200	8.1385	8.1785	8.2184	8.2584	8.2984	8.3384	8.3784	8.4185	8.4585	8.4985
210	8.5386	8.5787	8.6188	8.6589	8.6990	8.7391	8.7792	8.8194	8.8595	8.8997
220	8.9399	8.9801	9.0203	9.0606	9.1008	9.1411	9.1814	9.2217	9.2620	9.3024
230	9.3427	9.3831	9.4235	9.4639	9.5043	9.5447	9.5852	9.6257	9.6661	9.7066
240	9.7472	9.7877	9.8283	9.8689	9.9094	9.9501	9.9907	10.031	10.072	10.113
250	10.153	10.194	10.235	10.276	10.316	10.357	10.398	10.439	10.480	10.520
260	10.561	10.602	10.643	10.684	10.725	10.766	10.807	10.848	10.889	10.930
270	10.971	11.012	11.053	11.094	11.135	11.176	11.217	11.259	11.300	11.341
280	11.382	11.423	11.465	11.506	11.547	11.588	11.630	11.671	11.712	11.753
290	11.795	11.836	11.877	11.919	11.960	12.002	12.043	12.084	12.126	12.167
300	12.209	12.250	12.292	12.333	12.374	12.416	12.457	12.499	12.541	12.582

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[2] From Omega, Thermocouple Reference Tables, 1993.

Team Building Experiment

What is a team?

A collection of individuals brought together to address or achieve an objective or set of objectives. When functioning properly team members will have some individual responsibilities in helping the team achieve its goals.

Why teams?

The world has become sufficiently complicated that one individual can not have the knowledge needed to achieve the specified objectives

Team Operation

Team selection: Normally done by superiors. Should be done carefully with the team objective dictating the choices.

Setting an objective: Normally done by the superiors. Must be thoroughly communicated to the team. Team should have opportunity to modify when appropriate.

Developing camaraderie: Depends greatly on members chosen for the team and attitude set by superiors. True empowerment by superiors can be very important. A part of leadership responsibilities.

Evaluating individual strengths and weaknesses: See exercise.

Evaluating team strengths and weaknesses: See exercise.

Leadership: Crucial component to effective teams. Must not be dictatorial. Must enforce agreed upon team rules, including decision making process. May be appointed by superiors, elected by team, or evolved from team members. Not to be confused with a facilitator.

Brainstorming: A method to generate ideas. See exercise

Running an effective team meeting: Set an agenda. Set and keep to a talking policy. Set specific goals. Need to have a positive environment.

Strengths/Weakness Identification

Individual Evaluation

Three most positive traits you bring to the team (Your Strengths)
1.
2.
3.

Three most negative traits you bring to the team (Your Weaknesses)
1.
2.
3.

Team Evaluation

Team's Three Greatest Strengths
1.
2.
3.

Team's Three Greatest Weaknesses
1.
2.
3.

Brainstorming

1. Appoint a moderator and a recorder.
2. Record all ideas suggested.
3. During the session there should be no comments on the appropriateness of the ideas.
4. Let the session runs its course. Normally after 20-25 minute the ideas will run out.
5. Plant some seeds to get the session going or continuing
6. Immediately after the session evaluate ideas to identify those that are functional and satisfactory with respect to the team's objective.

Team Building Exercise

(To be passed out in class)

Error Estimation Experiment

OBJECTIVE

To develop basic working knowledge involving error assessment in experimentation.

BACKGROUND

The experimental determination of any parameter is based upon measurements which by their nature contain errors. In general, errors fall into two categories: uncertainty or random errors and systematic errors. Uncertainty errors are due to the inability to read a measurement device exactly. For example, the finest division on a ruler is normally 1 mm, so that in using a ruler to measure length one has an uncertainty of ± 0.5 mm. Consider that an experimental determination will be made for the parameter B. Say that this determination is based upon measurements x_1, x_2,..., x_N. Then mathematically we have

$$B = \mathrm{fn}(x_1, x_2, \ldots, x_N) \tag{1}$$

The uncertainty in B, denoted by dB, can then be related to the uncertainty in the measured values, dx_i, by

$$dB = \sum_{i=1}^{N} \left| \left(\frac{\partial B}{\partial x_i} \right) \right| dx_i \tag{2}$$

It is useful to utilize a specific example. We are provided with a perfect parallelepiped of dimensions a x b x c of an unknown material. It is desired to determine the density of the material and also the uncertainty in this experimental determination of the density. We will determine the density by measuring the dimensions of the parallelepiped with a ruler, measuring its mass with a scale, and using the definition

$$\rho = \frac{m}{V} = \frac{m}{a \cdot b \cdot c} \tag{3}$$

Then the uncertainty becomes

$$d\rho = \left|\left(\frac{\partial \rho}{\partial\, m}\right)\right| dm + \left|\left(\frac{\partial \rho}{\partial\, a}\right)\right| da + \left|\left(\frac{\partial \rho}{\partial\, b}\right)\right| db + \left|\left(\frac{\partial \rho}{\partial\, c}\right)\right| dc \tag{4}$$

Evaluating the partial derivatives

$$\frac{\partial \rho}{\partial\, m} = \frac{\partial}{\partial\, m}\left(\frac{m}{a \cdot b \cdot c}\right) = \frac{1}{a \cdot b \cdot c} \tag{5a}$$

$$\frac{\partial \rho}{\partial\, a} = \frac{\partial}{\partial\, a}\left(\frac{m}{a \cdot b \cdot c}\right) = -\frac{m}{a^2 \cdot b \cdot c} \tag{5b}$$

and similarly for b and c. Now substituting

$$d\rho = \frac{1}{a \cdot b \cdot c} dm + \frac{m}{a^2 \cdot b \cdot c} da + \frac{m}{a \cdot b^2 \cdot c} db + \frac{m}{a \cdot b \cdot c^2} dc \tag{6}$$

We note that

$$\frac{m}{a \cdot b \cdot c} = \rho \tag{7}$$

and rearrange to get

$$d\rho = \rho\left(\frac{dm}{m} + \frac{da}{a} + \frac{db}{b} + \frac{dc}{c}\right) \tag{8}$$

Next, we specify the uncertainty in our measurements. For example

$dm = \pm\, 0.5\ gm = \pm\, 5 \times 10^{-4}\ kg$
$da = db = dc = \pm\, 0.5\ mm = \pm\, 5 \times 10^{-4}\ m$

Finally, using our measurements, say

m = 100 gm = 0.1 kg
a = 10 cm = 0.1 m
b = 5 cm = 0.05 m
c = 5 cm = 0.05 cm

with

$$\rho = \frac{0.1}{(0.1)(.05)(.05)} = 400\ \mathrm{kg/m^3}$$

we determine the numerical value of the uncertainty

$$d\rho = (400)\left(\frac{5\ \mathrm{x}\ 10^{-4}}{0.1} + \frac{5\ \mathrm{x}\ 10^{-4}}{0.1} + \frac{5\ \mathrm{x}\ 10^{-4}}{0.05} + \frac{5\ \mathrm{x}\ 10^{-4}}{0.05}\right)$$

$$d\rho = (400)\left(.005 + .005 + .01 + .01\right)$$

$$d\rho = \pm 12\ \mathrm{kg/m^3}$$

One of the ways in which this uncertainty error appears in our density measurement would involve running the experiment a number of times and obtaining a number of density values. We rarely will obtain the same value, 400 $\mathrm{kg/m^3}$, but if all we have is uncertainty errors all the values should be within ± 12 $\mathrm{kg/m^3}$. If this is not the case, chances are we have systematic errors involved in our experimental determination.

Systematic errors fall into one of three classes:

1. Calibration errors in the measurement device
2. Incorrect assumptions in the physical model
3. Neglecting significant outside influences.

Indications of systematic errors include: differences between results greater than the uncertainty error, bias in the data (all above or below the anticipated value), and unrealistic results. A possible systematic error from our density example involving a calibration error would be using a ruler whose divisions were actually 1.2 mm rather than 1.0 mm. A solution to this error would be to calibrate the ruler. An example of the second class of systematic errors might deal with the solid not being a true parallelepiped. If all of the corners were not at right angles then assuming that the volume is the product of the dimensions is incorrect and some other method of volume determination must be employed, such as a displacement method. Finally, it is difficult to find an example of the third class of systematic error for our density measurement. An example from a different experiment might involve the heat loss to the surrounds during a test to determine specific heat. This error can be addressed by calculating the heat loss and including it in the physical model. In fact the third class of systematic error can always be attributed to the first or second case errors.

In this experiment we will address the issue of experimental errors by considering a very simple system. We wish to determine the efficiency of an immersion heater. This efficiency will be defined as

$$\eta = \frac{E_{th}}{E_{el}} = \frac{\text{thermal energy out}}{\text{electrical energy in}} \tag{9}$$

The electrical energy supplied will be given by

$$E_{el} = P_{el} \cdot \tau = V \cdot I \cdot \tau \tag{10}$$

where τ is the time over which the experiment is run. The thermal energy out is estimated by the internal energy change of the water and beaker in which the immersion heater is placed or

$$E_{th} = (m\, c_p\, \Delta T)_{beaker} + (m\, c_p\, \Delta T)_{water} \tag{11}$$

Substituting

$$\eta = \frac{(m\, c_p\, \Delta T)_{beaker} + (m\, c_p\, \Delta T)_{water}}{V \cdot I \cdot \tau} \tag{12}$$

To determine the uncertainty in the efficiency, we would now apply Eq.(2) to our expression given in Eq.(12). In trying to apply Eq.(2) directly, we run into the problem of having eleven "measurable" quantities with uncertainties which leads to eleven different partial derivatives, and a whole host of possible algebraic errors. Further the very long, extensive equation that would result from this is to large for a cell in an Excel spreadsheet. An alternative is to cascade our uncertainties as follows. We begin by letting the efficiency be a function of the thermal energy and the electrical energy so that

$$\eta = \text{fn}(E_{th}, E_{el}) \tag{13}$$

Then for the uncertainty in the efficiency we have

$$d\eta = \left|\frac{\partial \eta}{\partial E_{th}}\right| dE_{th} + \left|\frac{\partial \eta}{\partial E_{el}}\right| dE_{el} \tag{14}$$

The two partial derivatives can be evaluated from Eq.(9). The two new differentials, dE_{th} and dE_{el}, must be evaluated. For the uncertainty in the electrical energy we note that

$$E_{el} = fn(V, I, \tau) \tag{15}$$

So that via Eq.(2), we have

$$dE_{el} = \left|\frac{\partial E_{el}}{\partial V}\right| dV + \left|\frac{\partial E_{el}}{\partial I}\right| dI + \left|\frac{\partial E_{el}}{\partial \tau}\right| d\tau \tag{16}$$

Once again Eq.(10) can be used to evaluate the partial derivatives. A similar manipulation may be done for dE_{th}. However, since E_{th} is calculated from eight measured values it may prove useful to break it into two parts, one dealing with the beaker energy, $E_{th,bk}$, and a second term dealing with the water energy, $E_{th,H2O}$. Then

$$E_{th} = E_{th,bk} + E_{th,H_2O} \tag{17}$$

where

$$E_{th,bk} = (m\, c_p\, \Delta T)_{beaker} \tag{18}$$

$$E_{th,H_2O} = (m\, c_p\, \Delta T)_{water} \tag{19}$$

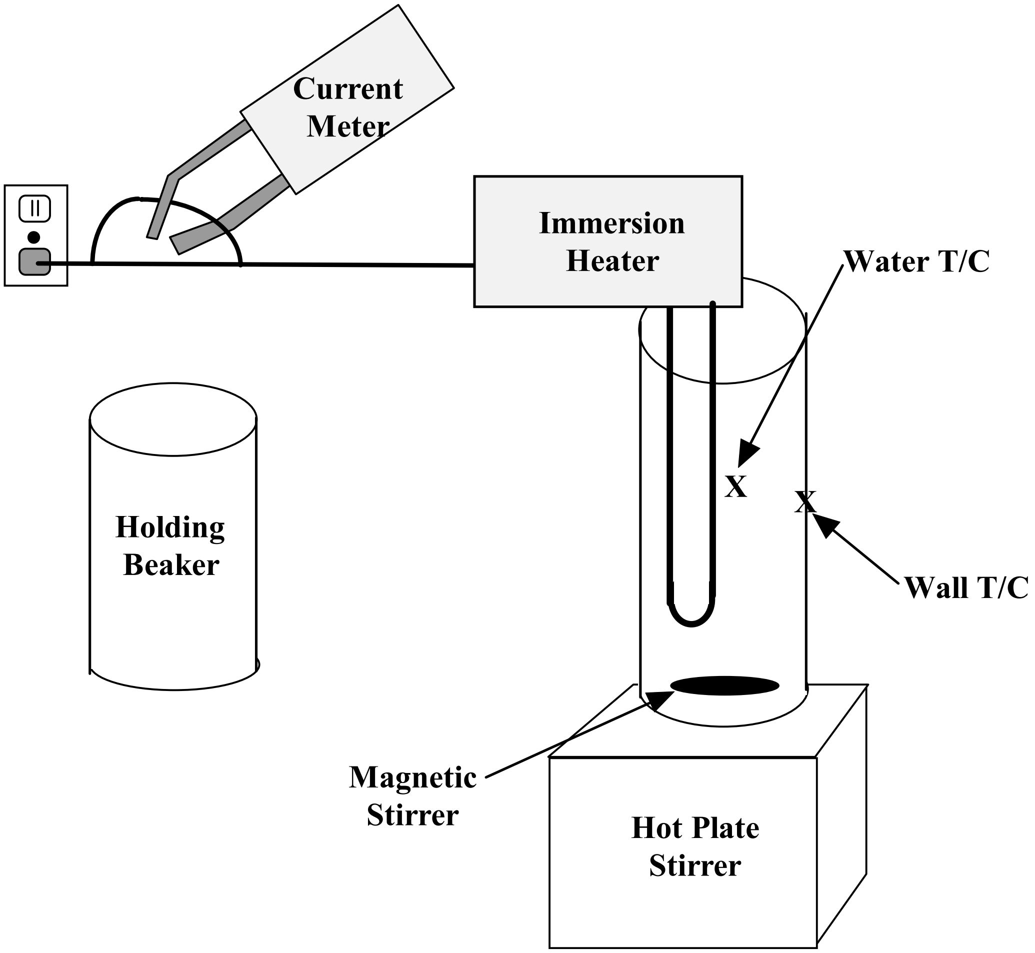
We may then apply Eq.(2) to Eq.(17) to obtain dE_{th} and to Eqs.(18) and (19) to obtain $dE_{th,bk}$ and $dE_{th,H2O}$. Then the expressions for $dE_{th,bk}$ and $dE_{th,H2O}$ will only contain uncertainties of measured parameters.

Each student is responsible for attempting the algebraic evaluation of dη prior to their lab period. This attempt will be reviewed by your TA. **Failure to submit this formulation to your TA at the beginning of your lab period will result in a 10 point deduction on your technical memo.**

PROCEDURE

A layout of the experimental apparatus is shown below.

Figure 1. Experimental Setup



1. Measure the mass of the 1000 ml beaker provided. Record the uncertainty in this measurement.

2. Add approximately 1000 ml of water to the beaker. Measure the mass of the water filled beaker. Record the uncertainty in this measurement and then place this beaker on the magnetic stirrer.

3. Fill the other beaker provided with water. This is the holding beaker depicted in Figure 1.

4. Measure the wall plug voltage using the digital multi-meter by inserting the probes into the wall plug. Record the uncertainty in this measurement.

5. Place the immersion heater into the second beaker. Turn it on to the highest setting and allow it to heat up.

6. Measure the temperature of the water in the 1000 ml beaker and the outside wall of the beaker with the digital thermometer. Record the uncertainty in these measurements.

7. After the immersion heater has warmed up, place it into the 1000 ml beaker until an appreciable temperature rise is observed. Begin the stop watch to measure the time of the run, τ.

8. Using the current meter, measure the current being supplied to the heater during the experiment. Record the uncertainty in this measurement.

9. Remove the heater and quickly measure the temperature of the water and the outside wall of the beaker. Also stop the stop watch and record the time of the run. Record the uncertainty in these measurements.

10. Measure the wall voltage again. Record the uncertainty in this measurement.

11. Repeat the experiment as many times as time will allow. Refill the 1000 ml beaker with fresh cold water before every run.

DATA ANALYSIS

1. Determine the efficiency for each run. Assume that the temperature of the beaker is the average of the outside wall temperature and the water temperature. You will need to look-up the specific heats for water and Pyrex from your heat transfer text book.

2. Determine the experimental uncertainty of the efficiency both algebraically and numerically.

3. Provide a table with run number, efficiency, and uncertainty in the efficiency.

4. Graph the efficiency versus run number with error bars to indicate the uncertainty in the efficiency. Draw a line on this graph to represent the average efficiency

SUGGESTIONS FOR DISCUSSION

1. Are the values for the efficiency within the uncertainty as compared to the average efficiency?

2. Could there be systematic errors present?

3. Assess possible calibration type systematic errors.

4. Are there systematic errors of class two or three present? Estimate their impact on the results. How could they be eliminated or accounted for?

Steam Power Plant Experiment

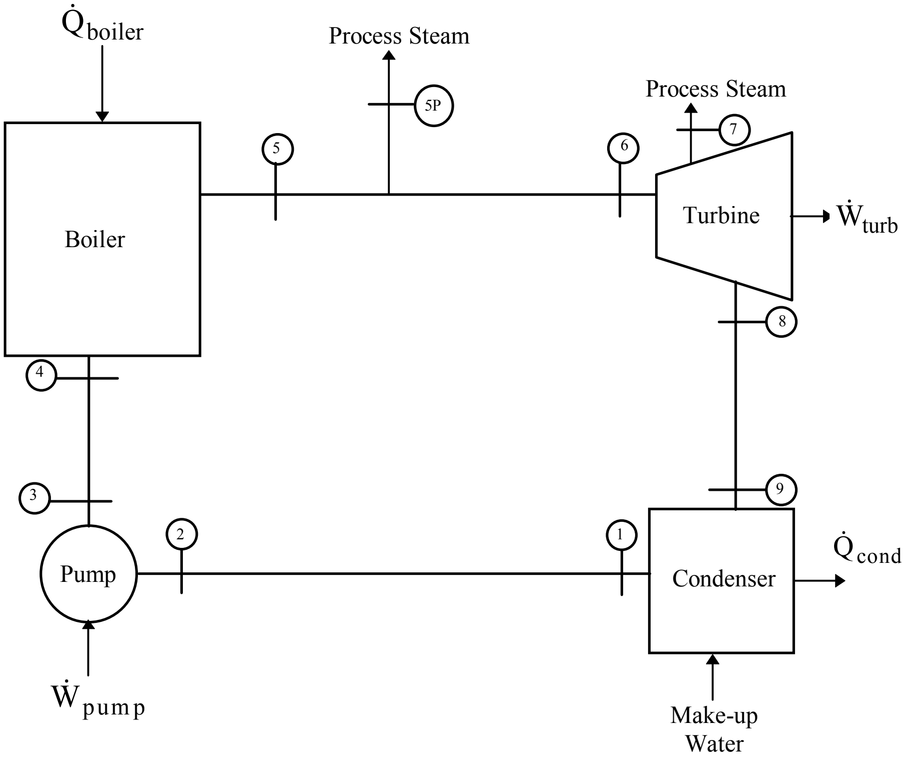
OBJECTIVE

1. To gain exposure to actual steam power plant systems and operation by touring the campus power plant.

2. To explore the effect of operating conditions and configuration on steam power plant performance by conducting a computer simulation.

BACKGROUND

All steam power systems are based upon the simple ideal Rankine cycle which is shown below.



To improve the operation and efficiency of these systems a number of other components are added which include reheaters, additional turbines, open feedwater heaters, and closed feedwater heaters. During the tour of the T.B. Simon Power Plant at MSU, the student will note the power plant layout and operating conditions. With this information, the student will use the software package RANKINE V3.0 to model the power plant and investigate additional optimization of operating conditions. A copy of the RANKINE V3.0 Users Guide is included with this handout. The program itself is available on the Heat Transfer Lab computers.

PROCEDURE

1. Tour the power plant and complete Worksheet I. This is to be done on an individual basis.

2. During your regular lab session your TA will introduce you to the RANKINE program. Complete Worksheet II. This is to be done with your regular sub-group.

Worksheet I Power Plant Tour

Student Name ____

1. Signature of TA to verify attendance ____________________________________

2. Answer the following questions concerning the T.B. Simon Power Plant.

   a. Describe the coal processing system.

   b. Provide two methods that are employed to reduce SO_X emissions in a coal fired power plant.

   c. What is the temperature of the flue gas leaving the stack?

   d. Describe how the "bag house" works in the Simon Power Plant.

   e. Why is water quality so important in the plant?

   f. Describe the steam (pressure, temperature, fluid phase) that is sent to campus for heating.

   g. What percent of the energy provided by the coal is transformed into electricity? Into usable steam? Provide a calculation using the data from a monthly report.

Worksheet II Computer Simulation
Due one week following your lab

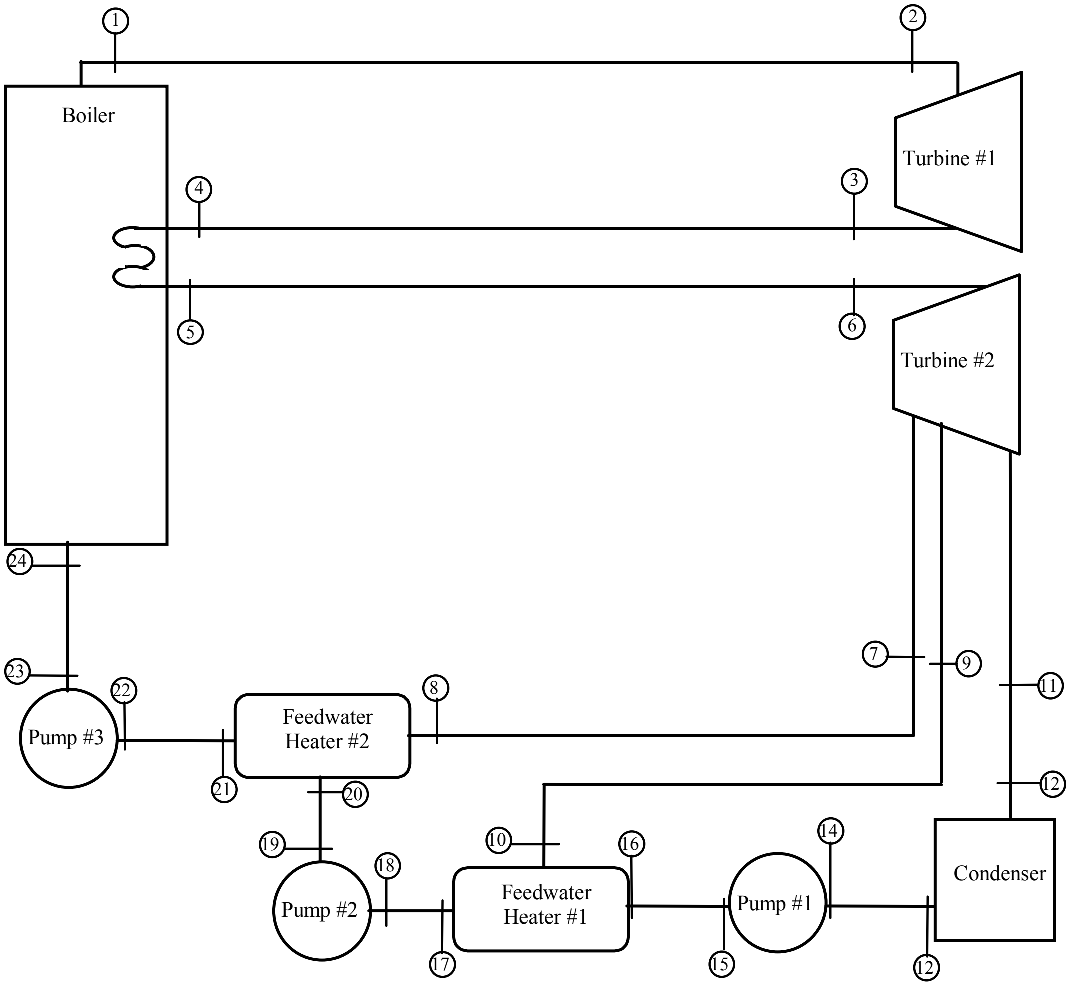
Student Names ____________________________

____

____

1) Using Rankine V3.0, investigate the relationship between system thermal efficiency and reheater operating pressure. For this study, consider a system which includes one boiler with one reheat leg, two turbines, one condenser, three pumps, and two open feed water heaters operating near the critical point. A schematic of this system is included in Fig. 1 and the input file has been provided on the PC's in the Heat Transfer Lab. It is suggested that the reheater operating pressure (controlled by node 4 on device number 1) be varied from about 1.0 MPA to 19.0 MPA. It is suggested that thermal efficiency as a function of reheater operating pressure be plotted to illustrate this relationship. For grading, provide your graph and a tabular listing of thermal efficiency, reheater operating pressure, and turbine #1 exit quality.

Figure 1. Configuration for Item #1

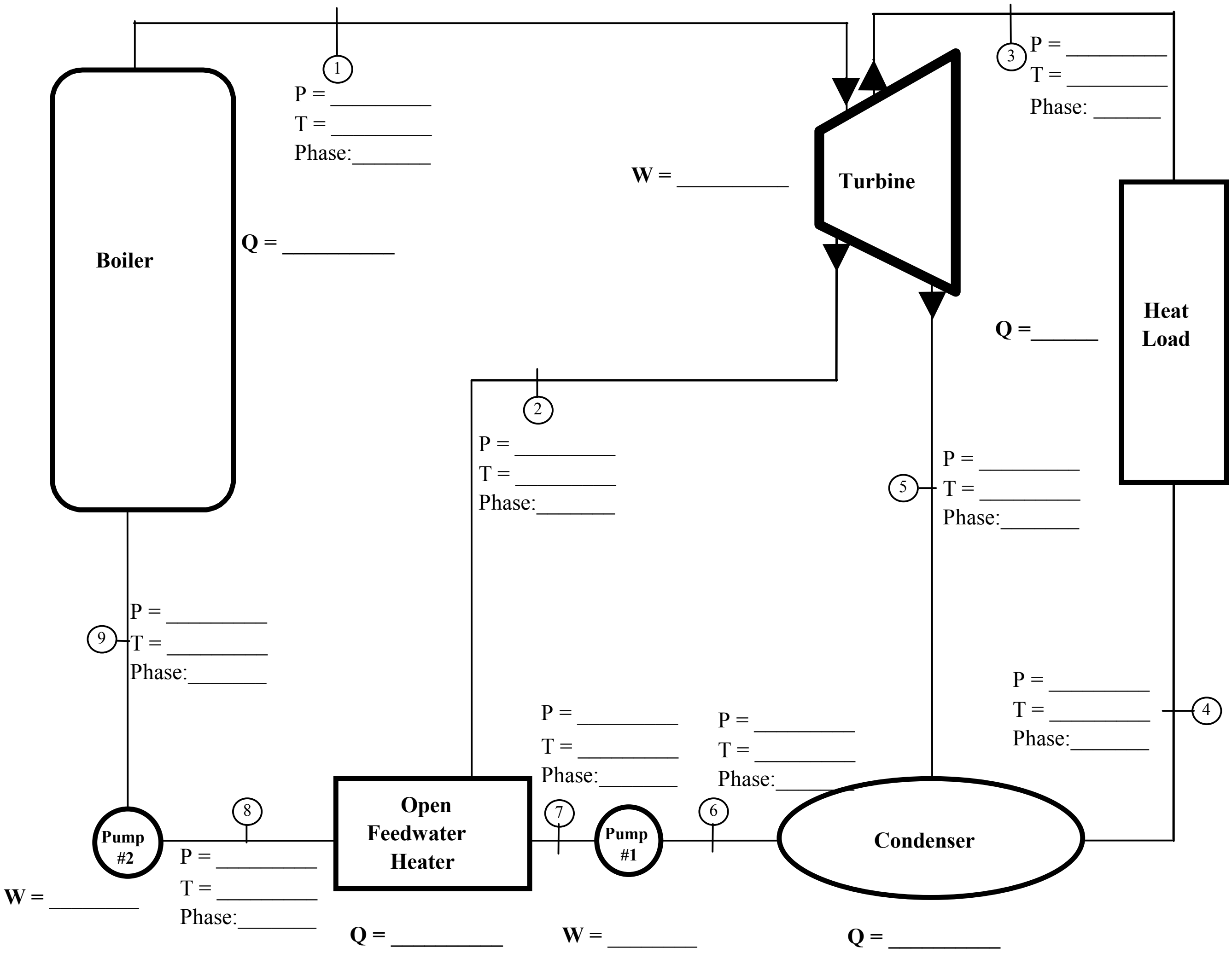


2.) Using the data provided in Table 1 for the T.B. Simon Power Plant, construct an input deck for RANKINE V3.0 which best represents the operation of the T.B. Simon Power Plant. Figure 2 is a sketch of the major thermal devices and a node network which should assist in construction of the input deck. After Rankine V3.0 has been used to model the T.B. Simon power plant, fill in all unknown information on Fig. 2, including the system temperatures, pressures, fluid phases, device work, and device heat rejected as requested on this figure. In addition, using standard sign convention, place arrows on all work and heat vectors. The correct system thermal efficiency will be provided in lecture. Grading will be based upon a hard copy of your input file, the Rankine V3.0 output file, and your completed Fig. 2.

Table 1. Data for T.B. Simon Power Plant

Turbine Data		
Turbine Stage Efficiency	84%	best estimate
Extraction #1 Pressure	178 psig	to feedwater heater
Extraction #2 Pressure	92 psig	to building heat load
Extraction #3 Pressure	-18.3 in of Hg gauge	to condenser
Extraction #2 Mass Flow	165,000 lb_m/hr	to campus buildings
Pump Data		
Pump Efficiencies	78%	best estimate
Heat Load Data		
Exit Temperature	47°C	
Boiler Data		
Boiler Exit Pressure	870 psig	
Boiler Exit Temperature	870°F	
Boiler Exit Mass Flow Rate	300,000 lb_m/hr	

Figure 2. Layout of T.B. Simon Power Plant



Plant Thermal Efficiency: ____________

Numerical Transient Heat Conduction Experiment

OBJECTIVE

1. To demonstrate the basic principles of conduction heat transfer.
2. To show how the thermal conductivity of a solid can be measured.
3. To demonstrate the use of finite difference to solve transient heat conduction problems.

BACKGROUND

The primary law that describes conduction heat transfer is Fourier's Law of Heat Conduction. Fourier's Law is based upon the observation that the conductive heat flux is directly proportional to the negative of the temperature gradient or

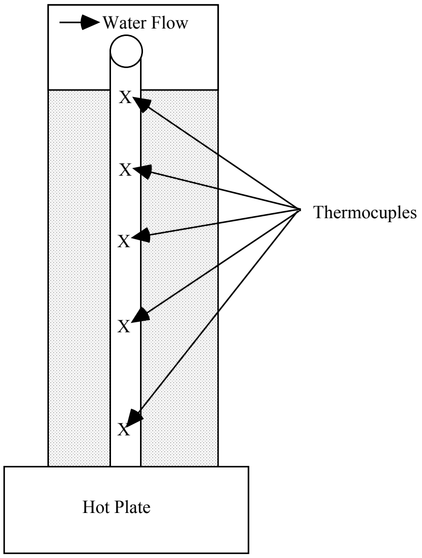
$$\dot{q}_x'' \propto -\frac{\partial T}{\partial x} \tag{1}$$

Introducing the thermal conductivity as the constant of proportionality, we then have the equation

$$\dot{q}_x'' = -k\frac{\partial T}{\partial x} \tag{2}$$

In this experiment we will utilize Fourier's Law to study the problem of transient, one dimensional heat conduction in a cylinder and to use the law in determining the thermal conductivity of a solid. A cylindrical element which is embedded with several thermocouples is heated at one end by an electric hot plate and cooled at the other end by flowing water. The side of the cylinder is very well insulated so that the heat conduction is assumed to be one dimensional. A schematic of the apparatus is shown below.

Figure 1. Experimental Apparatus for Cylindrical Element



We consider the transient problem in which the cylinder begins at some constant, uniform temperature and then suddenly the hot plate is turned on so that a heat flux is imposed at the lower boundary. Our describing equation for conservation of energy balances the internal energy change with the axial heat conduction. Hence, in differential form we write

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \tag{3}$$

where α is the thermal diffusivity of the cylinder material. One way to solve this equation is to discretize the space domain, write it in finite difference form, and solve the subsequent system of algebraic equations for the discritized temperatures. If we use a second order correct approximation, the finite difference form of Eq. (3) becomes

$$\frac{T_i^{(j)} - T_i^{(j-1)}}{\Delta t} = \alpha \frac{T_{i+1}^{(?)} + 2T_i^{(?)} - T_{i-1}^{(?)}}{(\Delta z)^2} \tag{4}$$

The subscript on the T represents the space (or z) discetization while the superscript represents the time discetization. Note that in Eq. (4) we have not specified the time discretization (j or j-1) for the spatial derivative. There are two choices for the time discretization for the temperatures in the spatial derivative. They could be evaluated at the previous time step, j-1, or at the current time step, j. The algorithm is called explicit if the temperatures are evaluated at the previous time step, and clearly this makes the algebraic system very easy to solve since Eq. (4) can be solved directly for

$T_i^{(j)}$ with no coupling to the other spatial nodes (i+1 and i-1). However, the explicit approach does not always lead to a stable solution (can you say blow-up) and in fact stability is only guaranteed when

$$\frac{\alpha \cdot \Delta t}{(\Delta z)^2} < 0.5$$

Since for most materials α is of the order of 10^{-5}, this stability criteria often leads to unacceptable time steps or spatial grids. The implicit algorithm, when the spatial derivative is evaluated at the current time step, does not have this stability problem, but does require simultaneous solution of the spatial node equations. Fortunately, Microsoft Excel is a powerful spreadsheet tool that can carry out these simultaneous calculations. Hence, for a spatial domain with N spatial nodes, we would have N simultaneous equations of the form

$$\frac{T_i^{(j)} - T_i^{(j-1)}}{\Delta t} = \alpha \frac{T_{i+1}^{(j)} + 2T_i^{(j)} - T_{i-1}^{(j)}}{(\Delta z)^2} \tag{5}$$

to be solved for the $T_i^{(j)}$'s.

In steady state the axial temperature profile should be linear which confirms Fourier's Law. The steady state heat transfer is determined by measuring the mass flow rate and temperature change of a coolant stream which passes over one end of the element, or

$$\dot{q} = \dot{m}\, c_p \left(T_{out} - T_{in}\right)_{coolant} \tag{6}$$

Then the thermal conductivity can be calculated by

$$k = \frac{\dot{q}/A_{\text{cross-section,element}}}{\text{slope of T vs z graph}} \tag{7}$$

PROCEDURE

1. Making sure that all coolant sample valves are closed turn on the water supply to the apparatus table.
2. Open the valves to provide cooling to the hot plate assemblies. Valves should be turned so as to point at either coolant in or coolant out.

3. Check to make sure all panel switches and the hot plate switches are in the off position. Plug in the cable and turn on the power to the apparatus table.

4. Turn the panel switch for the hot plates (3 UNIT 4) to the on position .

5. Record the temperatures for the ten thermocouples for Unit 4. These will serve as your initial temperatures for the transient conduction process.

6. Immediately set the hot plate switch for Unit 4 to approximately 250°C and start the stop watch.

7. At ten minute intervals record the temperatures for the ten thermocouples for Unit 4. Also record the time required to record these temperatures. After one hour the system should have reached steady state, which can be confirmed by the linearity of the temperature data with position or little change in the slope calculation.

8. At steady state the energy delivered to the cooling water will be determined. Place the empty beaker on the scale and zero the scale. Using the coolant sample valve allow water to flow into the beaker, measuring the time with a stop watch. When the beaker is nearly full turn the coolant sample valve to off. Record the time. Place the filled beaker on the scale and record the mass.

9. At steady state record thermocouple readings from channels 4&5 on unit 5.

Your data will be entered on an Excel spreadsheet similar to that shown below.

ME 412	One Dimensional, Transient Heat Conduction Experiment						
Material Thermal Diffusivity :			1.17E-04	m^2/s	T/C Distance:	0.0246	m
	Temperature				Temperature		
Location	Experimental	Numerical		Location	Experimental	Numerical	
1				1			
2				2			
3				3			
4				4			
5				5			
6				6			
7				7			
8				8			
9				9			
10				10			
Time =	0	sec.		Time =	600	sec.	
	dT/dx=				dT/dx=		

Steady State Calculation of Thermal Conductivity

Coolant Mass:		gm		Coolant Tin:		C
Time:		sec		Coolant Tout:		C
Mass Flow:		kg/sec		Coolant Tavg:		C
				Water Cp:		J/kg K
				Heat Flow:		W
	Thermal Conductivity:		W/m K			

White cells indicate data input by the student. Lightly shaded cells have calculation equations supplied.

DATA ANALYSIS

1. Graph both the experimental temperature and the numerical temperature versus position at three different times (early time, moderate time, and steady state)

2. Show a sample calculation for the heat supplied at steady state by the hot plate to the element.

3. Show a sample calculation for the thermal conductivity of the element.

SUGGESTIONS FOR DISCUSSION

1. How do the numerical and experimental temperatures compare? Explain any differences or trends in the comparison.

2. What sort of shape does the temperature distribution have at early times? How does this compare with what is predicted by analytical solutions?

3. Based on the thermal conductivity, what would you suppose the element to be made of?

4. How could you check the one-dimensionality of the experiment?

Table 1

	Cylindrical Element Unit 4
Diameter (in.)	2
Length (in.)	$11\frac{3}{8}$
Position of first thermocouple from hot plate (in.)	$1\frac{15}{16}$
Distance between thermocouples (in.)	$\frac{31}{32}$

Unit 5 Thermocouple Channels

Coolant in: Channel 5
Coolant out: Channel 4

Double Pipe Heat Exchanger Experiment

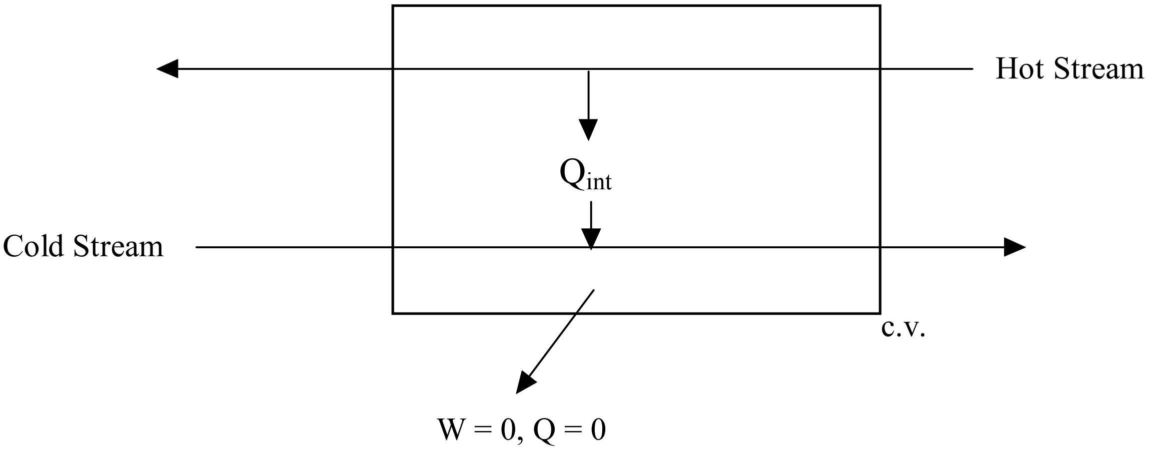
OBJECTIVE

1. To understand the basic operation of heat exchangers.
2. To demonstrate the basic equations of heat exchanger operation.

BACKGROUND

A heat exchanger is a heat transfer device whose purpose is the transfer of energy from one moving fluid stream to another moving fluid stream. It is the most common of heat transfer devices and examples include your car radiator and the condenser units on air conditioning systems. The overall energy transfer is dictated by thermodynamics and the First Law. To perform the thermodynamic analysis on a heat exchanger, we consider the control volume shown in Figure 1.

Figure 1. Control Volume Model



Note that although there is heat transfer from the hot fluid stream to the cold fluid stream, there is no work or heat transfer from the control volume (c.v.) to the surrounds. The first law for this control volume is then written as

$$\dot{H}_{in} = \dot{H}_{out} \tag{1}$$

Considering that we have two flows into the control volume and two flows out of the control volume, we may write a more specific form of the first law as

$$\dot{m}_H \hat{h}_{H,in} + \dot{m}_C \hat{h}_{C,in} = \dot{m}_H \hat{h}_{H,out} + \dot{m}_C \hat{h}_{C,out} \qquad (2)$$

or rearranging by grouping the streams

$$\dot{m}_H \left(\hat{h}_{H,in} - \hat{h}_{H,out}\right) = \dot{m}_C \left(\hat{h}_{C,out} - \hat{h}_{C,in}\right) \qquad (3)$$

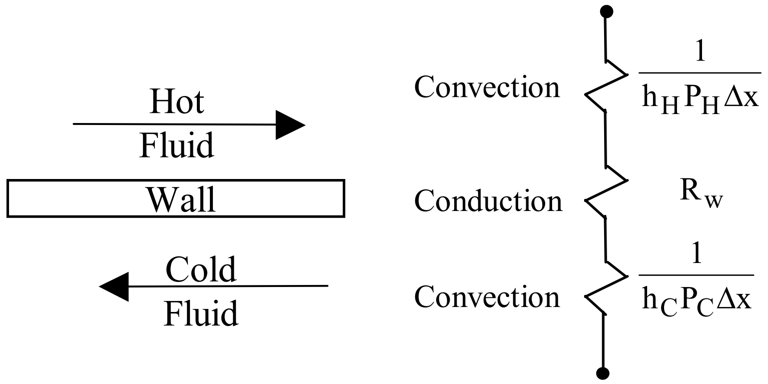
This, then, is the most general form of the First Law for a heat exchanger. However, for many heat exchangers there is not a phase change occurring for either fluid stream and the fluids are either incompressible liquids or ideal gases. Under these two conditions, we may represent the enthalpies in terms of temperature (a much more measurable quantity) by using the appropriate equation of state ($d\hat{h} = c_p dT$), which will introduce the specific heat. Then our First Law becomes in final form

$$\left(\dot{m}c_p\right)_H \left(T_{H,in} - T_{H,out}\right) = \left(\dot{m}c_p\right)_C \left(T_{C,out} - T_{C,in}\right) \qquad (4)$$

Recall that in this transformation from enthalpies to temperatures, we have assumed constant specific heats. To be consistent, we evaluate the specific heat of each fluid at the linear average between its inlet and outlet temperature, $\left(\frac{T_{in} + T_{out}}{2}\right)$.

Unfortunately, thermodynamics does not tell the whole story of a heat exchanger's performance. To achieve the energy transfer predicted by the First Law the principles of convection and conduction heat transfer must be applied. To apply these principles we consider a very small length of the heat exchanger, Δx, as shown Fig. 2.

Figure 2. Thermal Circuit Model



We note that the following heat transfer processes are at work. First, there is convective heat transfer from the hot fluid to the wall surface, next there is conduction through the wall, and finally there is convection from the wall surface into the cold fluid. This series of heat transfer process is ideally modeled by the thermal circuit model, which is shown in the above figure. The total thermal resistance is then given as

$$R_{tot} = \frac{1}{h_H \Delta A_H} + R_{wall} + \frac{1}{h_C \Delta A_C} \tag{5}$$

Utilizing this, our heat transfer between the two fluid streams over this small length segment Δx is

$$\delta \dot{q} = \frac{\left(T_H(x) - T_C(x)\right)}{R_{tot}} \tag{6}$$

Introducing the concept of an overall heat transfer coefficient, U, so that U times the heat transfer surface area is equal to the thermal conductance (one over the thermal resistance), we write

$$\delta \dot{q} = UP\left(T_H(x) - T_C(x)\right)dx \tag{7}$$

where P is the perimeter such that Pdx is the differential heat transfer surface area (ΔA). To obtain the total heat transfer between the two fluids inside the heat exchanger, the above expression is integrated from 0 to L (the length of the heat exchanger),

$$\dot{q} = \int_0^L UP\big(T_H(x) - T_C(x)\big)dx \tag{7}$$

which from our thermodynamics is also equal to

$$\begin{aligned}\dot{q} = \int_0^L UP\big(T_H(x) - T_C(x)\big)dx &= (\dot{m}c_p)_H\big(T_{H,in} - T_{H,out}\big)\\ &= (\dot{m}c_p)_C\big(T_{C,out} - T_{C,in}\big)\end{aligned} \tag{8}$$

We now have a relationship between the heat transfer and thermodynamics. The difficulty with utilizing Eq. (7) lies in evaluating the integral. In order to evaluate the integral, we must know the functional forms of the temperatures, T_H and T_C. The only way to do this is to write the appropriate differential energy equation for both fluid streams and solve these coupled equations for the temperatures. It proves convenient at this juncture to introduce the concept of an average temperature difference between the two fluid streams. We modify Eq. (7) by noting that by definition

$$\begin{aligned}&\frac{1}{L}\int_0^L \big(T_H(x) - T_C(x)\big)dx = \Delta T_{avg}\\ &\int_0^L UP\big(T_H(x) - T_C(x)\big)dx = UPL\Delta T_{avg} = UA\Delta T_{avg}\end{aligned} \tag{9}$$

where ΔT_{avg} is the average temperature difference between the hot and cold fluids as they pass through the heat exchanger. Then our heat transfer is given by

$$\dot{q} = UA\Delta T_{avg} \tag{10}$$

The functional form of ΔT_{avg} can be extracted from the temperature solutions for the differential energy equations noted above. For the simple concentric tube heat exchanger of this experiment, we find that

$$\Delta T_{avg} = \frac{\Delta T_2 - \Delta T_1}{\ln\left\{\dfrac{\Delta T_2}{\Delta T_1}\right\}} \tag{11}$$

where ΔT_2 is the temperature difference between the two fluid streams at one physical end of the heat exchanger and ΔT_1 is the temperature difference between the two fluid streams at the other physical end of the heat exchanger. For a counterflow heat exchanger, the hot fluid enters at one physical end and the cold fluid enters at the other physical end so that ΔT_2 and ΔT_1 can be related to hot and cold fluid inlet and outlet temperatures by

$$\begin{aligned} \Delta T_1 &= T_{H,in} - T_{C,out} \\ \Delta T_2 &= T_{H,out} - T_{C,in} \end{aligned} \qquad (12)$$

Similar expressions may be obtained for a parallel flow heat exchanger.

Unfortunately, the flow in most heat exchangers is so complicated that a simple solution to the differential equation is not possible and we are forced to take another approach. This second approach is based upon the dynamic scaling and dimensionless parameter work you saw in your fluid mechanics course. We begin with some definitions:

<u>Flow Heat Capacity</u> $C = \dot{m}c_p$, e.g., $C_H = \left(\dot{m}c_p\right)_H$ (13)

<u>Minimum Heat Capacity</u> C_{min}, the smaller of C_H and C_C

<u>Maximum Heat Capacity</u> C_{max}, the larger of C_H and C_C

<u>Heat Capacity Ratio</u> $C_R = \frac{C_{min}}{C_{max}}, \left(0 \le C_R \le 1\right)$ (14)

<u>Effectiveness</u>

$$\begin{aligned} \varepsilon &= \frac{\dot{q}_{actual}}{\dot{q}_{maximum\ possible}} \\ &= \frac{C_H\left(T_{H,in} - T_{H,out}\right)}{C_{min}\left(T_{H,in} - T_{C,in}\right)} \\ &= \frac{C_C\left(T_{C,out} - T_{C,in}\right)}{C_{min}\left(T_{H,in} - T_{C,in}\right)} \end{aligned} \qquad (15)$$

<u>Number of Transfer Units</u> $NTU = \frac{UA}{C_{min}}$ (16)

Our next step would be to employ dynamic similarity to obtain a relationship among our three dimensionless parameters, C_R, ε, and NTU. We can partially show this by beginning with Eq. (10), where our heat transfer is given by

$$\dot{q} = UA\Delta T_{avg} \qquad (17)$$

Considering that our flow is sufficiently complicated that we do not know ΔT_{avg}, let us assume that it depends linearly on the maximum possible temperature difference, $\left(T_{H,in} - T_{C,in}\right)$, and that the constant or proportionality is really a function of UA, C_{min}, and C_{max}. Then we may write

$$\dot{q} = UA \cdot fn\left(UA, C_{min}, C_{max}\right) \cdot \left(T_{H,in} - T_{C,in}\right) \tag{18}$$

We would now like to normalize this heat flow, bound it between zero and one, which we can do by dividing Eq. (18) by the maximum possible heat transfer (which will give us the effectiveness) to obtain

$$\varepsilon = \frac{\dot{q}}{\dot{q}_{max}} = \frac{UA \cdot fn\left(UA, C_{min}, C_{max}\right) \cdot \left(T_{H,in} - T_{C,in}\right)}{C_{min}\left(T_{H,in} - T_{C,in}\right)} \tag{19}$$

which after simplification can be rewritten

$$\varepsilon = \frac{UA}{C_{min}} \cdot fn\left(UA, C_{min}, C_{max}\right) \tag{20}$$

We recognize UA/C_{min} as the NTU and that the function can be written equivalently in terms of NTU and C_R, rather than the three parameters stated. Then we have

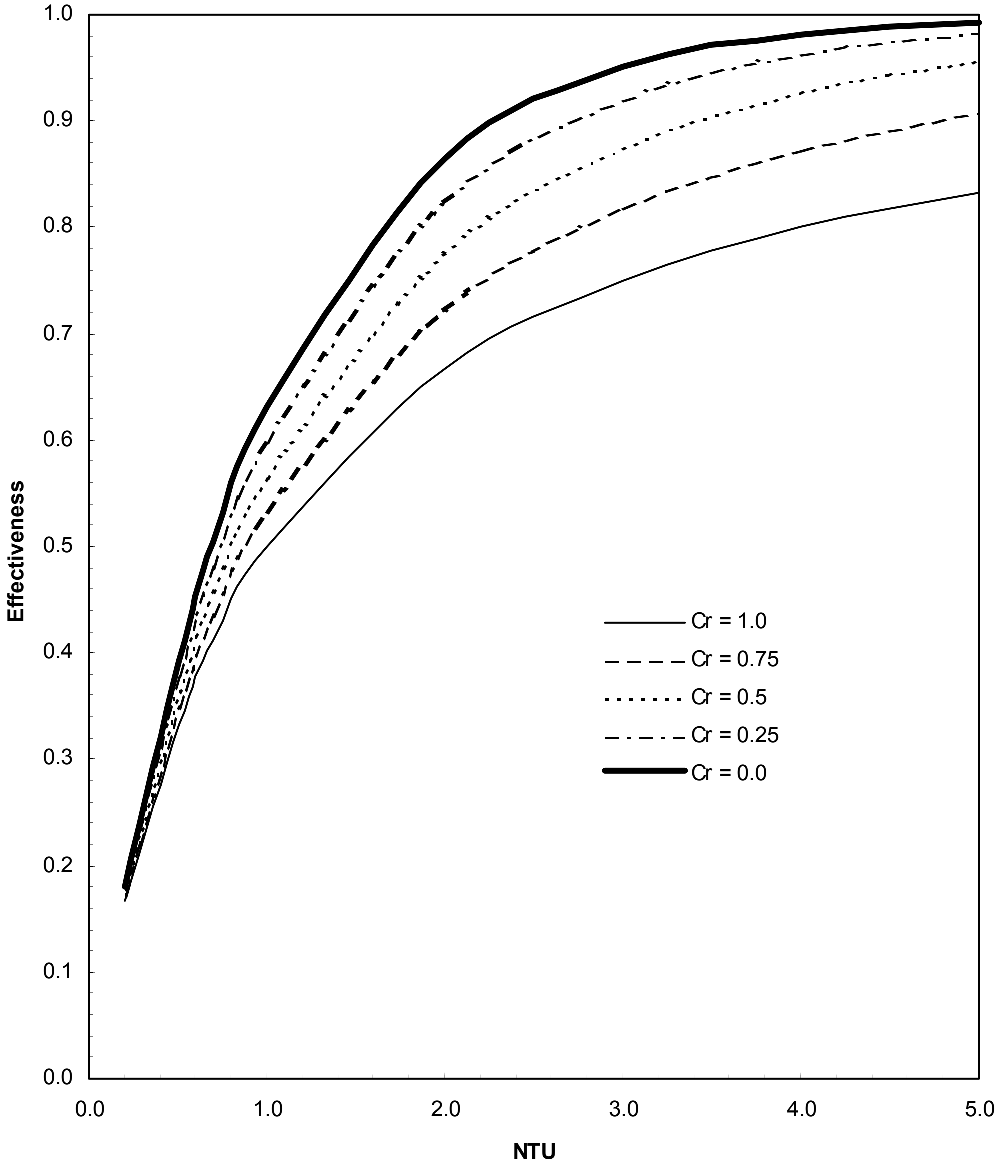
$$\varepsilon = NTU \cdot fn\left(NTU, C_R\right) \tag{21}$$

but since NTU appears in the function, it is redundant to have it out in front, so that we may finally write

$$\varepsilon = fn\left(NTU, C_R\right) \tag{22}$$

This is the basis for one of the most powerful tools in heat exchanger analysis, the effectiveness-NTU approach. In your heat transfer text book you will find these effectiveness-NTU relationships for a variety of heat exchangers in both equation form and graphically. A typical graphical relationship is shown in Fig. 3 for a counterflow, concentric tube heat exchanger.

Figure 3. Effectiveness - NTU Relationship for Counterflow Heat Exchanger



A concentric tube or double pipe heat exchanger is one that is composed of two circular tubes. One fluid flows in the inner tube, while the other fluid flows in the annular space between the two tubes. In counterflow, the two fluids flow in parallel, but opposite directions. In parallel flow the two fluids flow in parallel and in the same direction. The above graph may also be represented by an equation as

$$\varepsilon = \frac{1 - \exp\{- \mathrm{NTU}(1 - \mathrm{C_R})\}}{1 - \mathrm{C_R} \cdot \exp\{- \mathrm{NTU}(1 - \mathrm{C_R})\}} \tag{20}$$

A final note about this equation and its corresponding graph concerns effectiveness behavior when the NTU is small. When the NTU is less that 0.5, all of the C_R curves collapse. Since the graph has a $C_R = 0$ curve, one could take the effectiveness values at

$C_R = 0$ to be valid for all C_R's when NTU is small. This yields a much simpler equation for cases when $C_R = 0$ or NTU < 0.5 of the form

$$\varepsilon = 1 - \exp\{-\mathrm{NTU}\} \qquad (21)$$

PROCEDURE

1. Make the appropriate length measurements on the heat exchanger so you can calculate the heat transfer area.

2. With the help of your lab instructor turn on the system and set it up for parallel flow.

3. Allow the system to come to steady state and record inlet, outlet, and intermediate temperatures of the cold and hot water .

4. Repeat the experiment for at least five different flow rates of hot and cold water while maintaining the same C_{min}/C_{max} ratio.

5. Repeat steps 3-5 with the exchanger in counter-flow configuration.

DATA ANALYSIS

1. Each case should be recorded on the Excel spread sheets provided.

2. From the experimental data calculate the overall heat transfer coefficient. Plot it versus water velocity.

3. Plot the effectiveness versus number of transfer units for this exchanger and compare it to the theoretical relationship.

4. Calculate the uncertainty error in your parameters.

5. Provide one sample hand calculation of your data processing.

SUGGESTIONS FOR DISCUSSION

1. How does the experimental value of the overall heat transfer coefficient compare with expected values for this type of heat exchanger? (See Table 11.1 in your text book, Incropera and DeWitt or Table 10-1 in Çengel)

2. How does the effectiveness - NTU relationships compare with theory?

3. Discuss the differences in performance for the parallel flow and counter flow heat exchangers.

4. What errors may be present in your experimental analysis?

Natural Convection Experiment
Measurements from a Vertical Surface

OBJECTIVE

1. To demonstrate the basic principles of natural convection heat transfer including determination of the convective heat transfer coefficient.

2. To demonstrate the boundary layer character of external natural convection.

BACKGROUND

Since the density of most fluids vary with temperature, temperature gradients within a fluid medium will give rise to density gradients. If these density gradients are such that the fluid is in an unstable situation, heavy fluid on top of light fluid, the fluid will begin to move. This motion is termed natural convection. Newton's law of cooling governs this physical process which states that the heat transfer from the surface is directly proportional to the temperature difference between the surface and the fluid far away from the surface or

$$\dot{q}'' \propto \left(T_{surface} - T_{fluid}\right) \tag{1}$$

Introducing the convective heat transfer coefficient as the constant of proportionality, we have

$$\dot{q}'' = h_c \left(T_{surface} - T_{fluid}\right) \tag{2}$$

It is clear that the major obstacle in utilizing Eq. (2) for convective heat transfer calculations is the evaluation of the convective heat transfer coefficient. There are three standard methods used to evaluate h_c. The first involves a mathematical solution to the conservation equations in differential form. For problems where these equations are too complicated to be solved analytically, we can employ the second method, a computational solution. Finally for problems that are so complicated that we cannot even write the appropriate conservation equations, we must go into the laboratory and make measurements in employing an experimental solution. Before we contemplate employing one of these solution methods, it is useful to use our intuition to figure out upon what the convective heat transfer coefficient depends. Our intuition tells us that the three major factors associated with the calculation of h_c should be

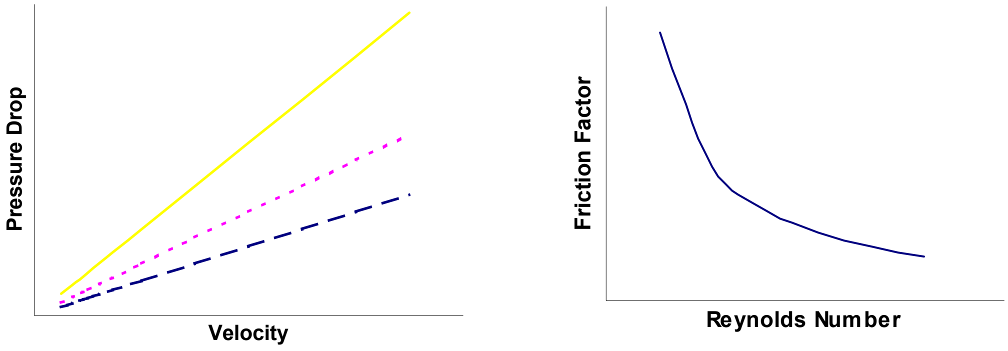
(i) fluid mechanics

(ii) fluid transport properties
(iii) geometry

Starting with the fluid mechanics, we recognize there are a variety of ways to characterize the flow. We can consider what is driving the flow and classify it as forced or natural convection. Next, we consider how many boundaries the fluid flow interacts with and classify it as external or internal flow. Recall that the difference between internal flows and external flows is often one of perspective. A third way to characterize the flow is by the presence or absence of turbulence.

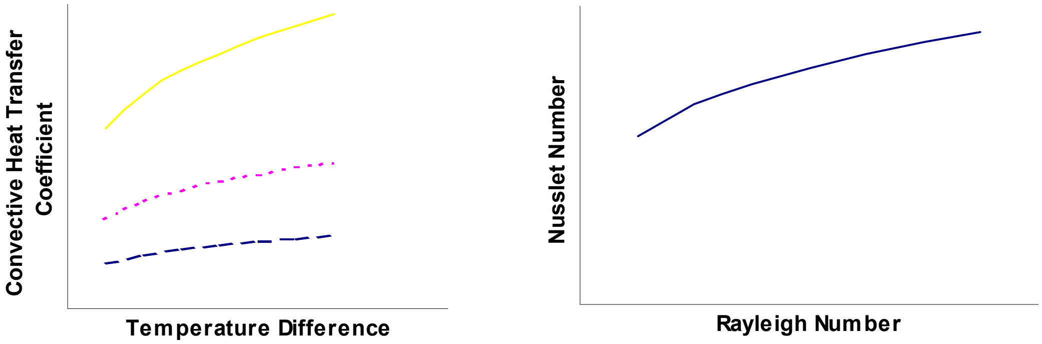
An important consideration in the handling of convective heat transfer coefficients is the notion of dynamic similarity. It is found that certain systems in fluid mechanics or heat transfer are found to have similar behaviors even though the physical situations may be quite different. Recall the fluid mechanics of flow in a pipe. What we are able to do is to take data as shown in Fig. 1 for different fluids and pipe diameters and by appropriately scaling collapse these curves into one curve.

Figure 1. Dynamic Similarity for Pipe Flow



In convective heat transfer we may apply dynamics scaling to make a parallel transformation.

Figure 2. Dynamic Similarity for Convective Heat Transfer



We have defined a dimensionless convective heat transfer coefficient called the Nusselt number as

$$\mathrm{Nu} = \frac{h_c L}{k} \tag{3}$$

where

h_c: convective heat transfer coefficient
L: characteristic length
k: thermal conductivity of the **fluid**.

The characteristic length is chosen as the system length that most affects the fluid flow. For flow along a flat plate our characteristic length is the plate length, L, and we write

$$\mathrm{Nu}_D = \frac{h_c L}{k} \tag{4}$$

The Rayleigh number is indicative of the buoyancy force that is driving the flow and is given by

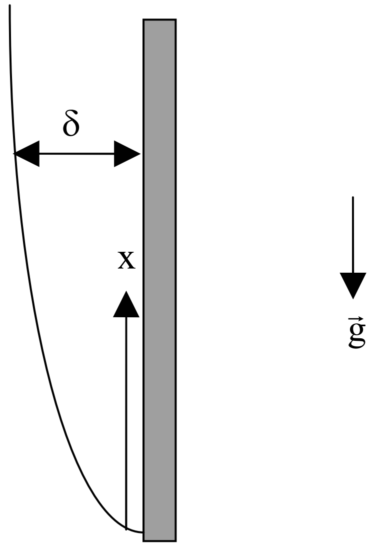
$$\mathrm{Ra} = \frac{g\beta |T_s - T_f| L^3}{\nu\alpha} \tag{5}$$

where

g: acceleration due to gravity
β: fluid thermal expansion coefficient
T_s: surface temperature
T_f: fluid temperature
L: characteristic length
ν: fluid kinematic viscosity
α: fluid thermal diffusivity.

Another important feature introduced by the fluid mechanics is the local nature of the convective heat transfer coefficient. If as the fluid flows over different regions of the surface, the fluid mechanics change, then the convective heat transfer coefficient will change. For natural convection over a vertical flat plate we will have the boundary layer flow shown in Fig. 3.

Figure 3. Flat Plate Boundary Layer Development



As the boundary layer thickness grows, the fluid mechanics change significantly, so that the convective heat transfer coefficient will vary along the length of plate and we will have a local convective heat transfer coefficient, $h_c(x)$. Then we may also define local Nusselt and Rayleigh numbers as

$$Nu_x = \frac{h_c(x) \cdot x}{k} \tag{6}$$

$$\mathrm{Ra} = \frac{g\beta |T_s(x) - T_f| x^3}{\nu\alpha} \tag{7}$$

Though local heat transfer conditions can be extremely important, an average heat transfer coefficient over the entire surface length is often desirable. By definition we have

$$h_{c,avg} = \frac{1}{L}\int_0^l h_c(x)\, dx \tag{8}$$

with an average Nusselt Number given as

$$\mathrm{Nu}_{L,avg} = \frac{h_{c,avg} \cdot L}{k} \tag{9}$$

The dimensionless parameter which is used to represent the affect of fluid properties is the Prandtl number

$$\mathrm{Pr} = \frac{\nu}{\alpha} \tag{10}$$

The influence of geometry may be seen in a couple of ways. First, for those configurations that have two length dimensions, such as a cylinder, we introduce a dimensionless geometric parameter

$$X = \frac{D}{L} \tag{11}$$

The second way in which we see geometrical influences is through the functional form of the Nusselt number correlation. In general we may write

$$\mathrm{Nu} = \mathrm{fn}(\mathrm{Ra},\mathrm{Pr},X) \tag{12}$$

For simple situations these may often be written as power law relationships

$$\mathrm{Nu} = a\, \mathrm{Ra}^n\, \mathrm{Pr}^m \tag{13}$$

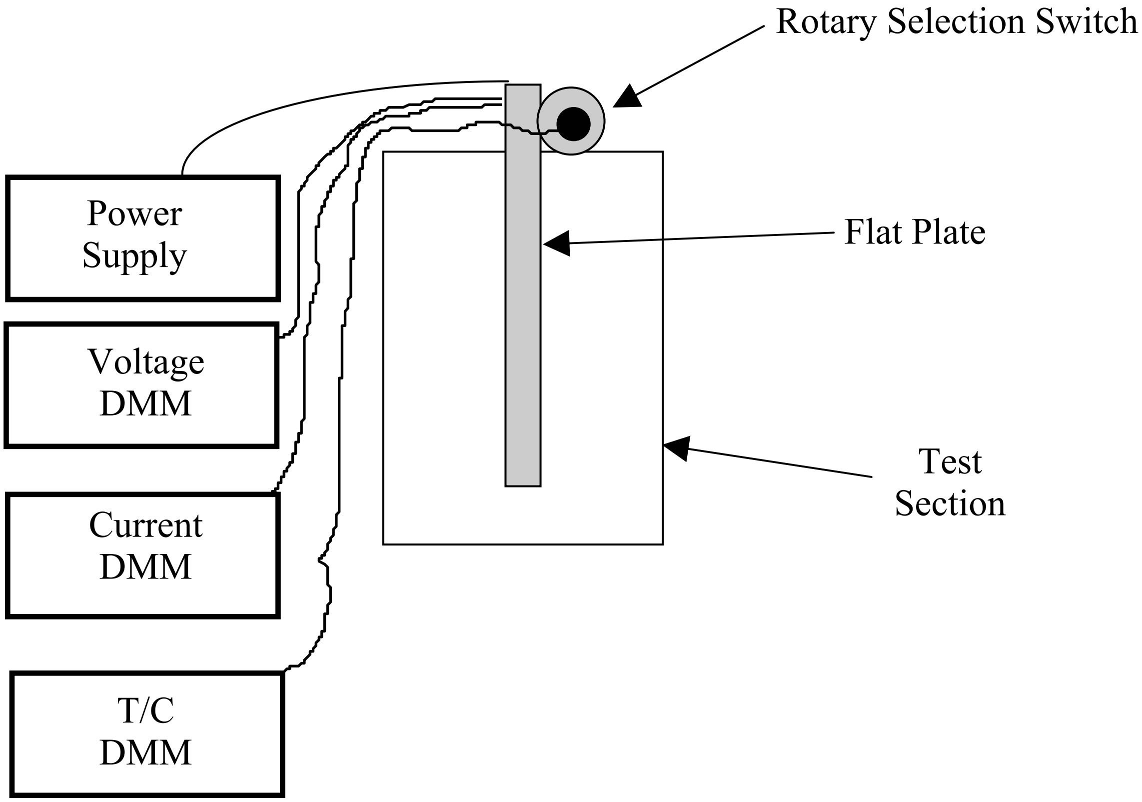
where the constants a, m, and n will change for different geometries.

In this experiment the student will develop the relationship among the Nusselt number and other dimensionless parameters for natural convection from a vertical flat surface.

The students will determine local heat transfer coefficients which are indicative of a boundary layer phenomena. These local measurements will then be averaged and compared to published correlations.

Natural convection heat transfer from a vertical surface will be investigated using an electrically heated flat plate. A schematic of the apparatus is shown in Figure 4.

Figure 4. Schematic of Experimental Apparatus



Assuming the heating is uniform, the heat flux at any location on the plate is given by,

$$\dot{q}'' = \frac{V \cdot I}{2 \cdot w \cdot L} \tag{14}$$

where V and I are the electric voltage and current supplied to the plate and w and L are the width and length of the heated surface. Temperature measurements are made along the length of the plate with thermocouple embedded beneath the heated surface. The local heat transfer coefficient (the heat transfer coefficient at a certain distance from the leading edge) is then calculated as

$$h_c(x) = \frac{\dot{q}''}{T_s(x) - T_f} \tag{15}$$

Since in most engineering applications the interest would be in an average heat transfer coefficient for the entire surface, we use the mathematical definition

$$\overline{h}_c = \frac{1}{L}\int_0^L h_c(x)\,dx \tag{16}$$

Now substituting and recognizing that the thermocouple is designed to read the temperature difference directly, we have

$$\overline{h}_c = \frac{\dot{q}''}{L}\int_0^L \frac{dx}{\Delta T(x)} \tag{17}$$

We now apply a trapezoidal rule integration to obtain

$$\overline{h}_c = \frac{\dot{q}''}{L}\sum_{i=1}^{N-1} 0.5\left(\frac{1}{\Delta T_i} + \frac{1}{\Delta T_{i-1}}\right)\cdot\left(x_i - x_{i-1}\right) \tag{18}$$

where N is the number of temperature data points along the plate and i=0 corresponds to the point at the leading edge. The average Nusslet number can then calculated.

PROCEDURE

1. Check that the power supply is unplugged and that the transformer is set at zero.

2. Plug in the power supply and turn on the transformer.

3. Plug in the power supply and set the current to 2 amps.

4. Read and record the voltage measurements associated with the electrical voltage and current supplied for heating and the thermocouples.

5. Increase the current, allow the system to stabilize, and record appropriate measurements. Repeat the experiment as needed

6. Turn the current down to 0 amps and turn off the power supply.

DATA ANALYSIS

1. Each case should be recorded on the Excel spread sheets provided in the lab.

2. From the experimentally determined values of the local heat transfer coefficient calculate the average heat transfer coefficient and surface temperature for each power setting.

3. Plot the local heat transfer coefficient versus distance from the leading edge.

4. Calculate the average Nusselt number and Rayleigh number for each power setting.

5. Plot the Nusselt number versus Rayleigh number for each case along with the published correlations.

6. Estimate the uncertainty error in your experimentally determined Nusselt number and Rayleigh number.

7. Provide one sample hand calculation of your data processing.

SUGGESTIONS FOR DISCUSSION

1. How does the experimental data compare to the published correlations?

2. What are some possible errors in the experiment?

3. What can you tell about the structure of the boundary layer from the local heat transfer coefficient?

4. Can you identify a transition from laminar to turbulent flow?

Design of a Radiation Transmissivity Experiment

OBJECTIVES

1. To review the basic principles of radiation heat transfer.
2. To reexamine the basic tenets of the Scientific Method as related to research design.
3. To design an experiment and develop an experimental procedure.

BACKGROUND

The Rhino Thermal Engineering Company has been hired by the Jupiter automobile company to do thermal system modeling for a climate control system. In thermal environmental engineering for automobiles it is found that the largest factor in the heating and cooling loads is the solar radiation coming into the passenger compartment. Thus knowledge of the transmissivity of the windows is of critical importance for the thermal design. As an engineer for the Rhino Consulting Corporation it is your job to design an experiment to measure the transmissivity of various materials. As is the case with any design project it is a good idea to reacquaint oneself with the important physics involved. So go to your desk, blow the dust off an old heat transfer text, and begin to read the chapters dealing with radiation heat transfer. Sections of your ME 410 textbook [Incropera and DeWitt, **Introduction to Heat Transfer**, 3rd edition] of particular interest are:

12.1, 12.3.0, 12.3.3, 12.5, 12.7, 12.8

There are many circumstances where we are concerned with radiation passing through a medium, such as sunlight passing through a window. In these cases only some fraction of the radiation will pass through the medium, while some fraction is absorbed by the medium and some fraction is reflected. We define the fraction of radiation transmitted through the medium as the transmissivity, τ. We may mathematically define τ as the ratio of radiation heat flow leaving the medium to the radiation heat flow entering the medium, or

$$\tau = \frac{\dot{q}''_{\text{rad,out}}}{\dot{q}''_{\text{rad,in}}} \tag{1}$$

Having refreshed the basic concepts of radiation heat transfer you wonder how you can implement these ideas into an useful experiment. One of the best references to guide the development of an experiment is the ASTM Standards. The book of ASTM standards is a collection of published experiments that have been used for a considerable period of time and which have gained wide acceptance in the scientific/engineering community as an acceptable method for evaluating the parameter of interest. It is available in the engineering library and is a very good place to begin when attempting to measure a material property. There is guide to the ASTM standards included at the end of this write-up. You will be required to provide a summary of an applicable ASTM standard for this experiment.

A basic literature review on the subject can also be effective. There is a variety of information available in the library on possible search strategies and the databases available. You will be required to submit a list of three papers that are relevant to the determination of transmissivity. (NOTE: you are not required to formally review these papers, however you do need to examine them enough to determine whether or not they are relevant to the topic.)

TASK

The student team is to design an experiment that will permit the determination of transmissivity of several non-opaque materials.

This experiment will be conducted in an open lab format. This means that you will not need to attend your normal two hour lab session, but will need to spend some time in the lab during the week of the experiment. Much of the work involved can be performed outside of the lab. The lab lecture will review some basic research strategies, and will introduce you to the equipment that may be utilized. It will be the student's responsibility to review the fundamentals of radiation theory and how it relates to the determination of material properties such as transmissivity, and to subsequently develop an experiment that can adequately measure this property. A worksheet is included that must be completed and turned in at the **START** of lab lecture. The student will also be expected to justify the merits and validity of this experiment using collected data which might include reproducibility studies, comparison to standards, and sensitivity to other variables. An error analysis will be required to indicate the accuracy of your experiment. These tests will be conducted in small groups during the week of lab lecture, at the student's discretion. T.A.'s will be available during the regular lab-time to answer questions about equipment, however the development of the experiment will be the charge of the student.

Some equipment in the lab that may prove useful include:

1. various square metal plates with attached thermocouple
2. A thermopile
3. An electronic ice point
4. A hot plate
5. An infrared thermometer

6. A heat flux plate heater

Along with these instruments is documentation that may be helpful in designing your experiment.

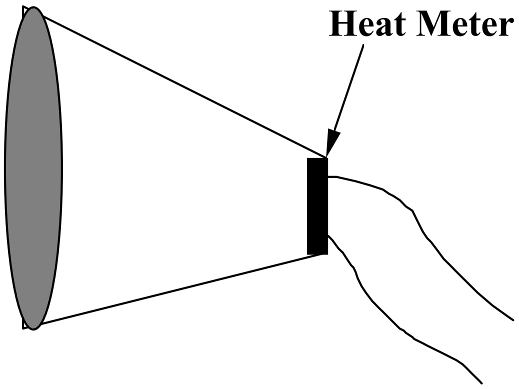
Various Metal Plates:
These square plates are comprised of different textures and colors. These plates have a thermocouple attached to one side to allow for temperature measurement. The reference end of the thermocouple can be attached to an electronic ice point to make the conversion from voltage to temperature easier.

Electronic Ice Point:
This device is easily used in conjunction with the existing thermocouple configuration. The prongs from the thermocouple are inserted into the appropriate slots in the ice point and the ice point is turned on. To test the battery the switch can be turned to "test" and a small ring pressed down. If at this point a light goes off then the battery is good and this device can be used. To measure voltage drop across the thermocouple the leads coming off the ice point are put into a digital multimeter. It is important to have the leads put into the DMM correctly. To assure this is the case the DMM should record a positive voltage at room temperature (assuming the ice point is correctly used).

Hot Plate:
This device is simply a flat heater. The temperature of the hot plate can be set and the plates placed on top. This is the simplest way to raise the temperature of the plate. A good starting point for the temperature setting would be 200°C . The draw back to using this method is that once the plate is removed it begins to cool, resulting is a transient effect which may or may not add complications to designing an experiment.

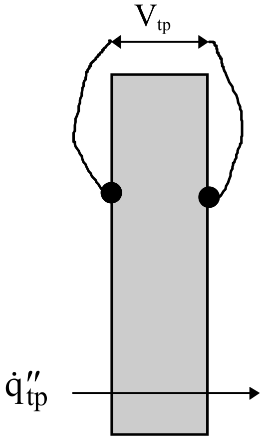
Thermopile:
The thermopile is conical in shape (as shown in the Fig. 1) and has a heat meter situated at the back end of the cone.

Figure 1. Sketch of Thermopile



Simplistically, the heat meter consists of a thin slab of material with thermocouples attached to either side. In steady state, Fourier's law of heat conduction can be used to show that a linear relationship exists between the temperature difference (or voltage difference which can be measured by a multi-meter) across the slab and the heat flux through the slab. This is shown in Fig. 2.

Figure 2. Schematic of Heat Meter



$$\dot{q}''_{tp} = \frac{k_{hm}\Delta T}{\delta_{hm}}$$

but

$$\Delta T \propto V_{tp}$$

so that

$$\dot{q}''_{tp} \propto V_{tp}$$

Hence, the voltage reading from the thermopile is proportional to the heat flux delivered to the back end of the cone. By utilizing a cone, we have eliminated the possibilities of convection and conduction and thus any heat flux which reaches the heat meter must be radiation.

Infrared Thermometer:

The infrared thermometer is a measurement device which allows the emissivity of a surface to be calculated. This device will work on any surface, but is most reliable for surfaces with high emissivities, greater than 0.9. This thermometer works by measuring the radiation heat flux from a surface. It assumes that this surface is a gray surface completely surrounded by black surrounds with the infared thermometer part of the surrounds. By using the gray surface radiation expression

$$\dot{q}''_{rad} = \varepsilon\sigma\left(T^4_{surface} - T^4_{surrounds}\right) \tag{2}$$

The temperature reading displayed by the infrared thermometer is calculated from this equation using the emissivity set on the device. By separately measuring the temperature of the surface (say with a thermocouple), the emissivity of the surface can be estimated by adjusting the emissivity setting on the infrared thermometer until the temperature reading of the infrared thermometer is equal to the true temperature of the surface. Similarly, if the emissivity of the surface is knwon then the radiation heat flux may be calculated from equation (2) using the temperature reading displayed by the infrared thermometer when the emissivity setting is at the true value. It is important that the infrared thermometer be aligned to approximately the same spot the surface temperature was recorded. To re-iterate this device should only be used for surfaces with emissivities greater than 0.9 to obtain accurate results.

Heat Flux Plate Heater:

This device supplies a constant heat flux from a 6"x 6" heating unit. To operate this device one must turn the "powerstat" switch and the "plate heater" switch to "on". Now the heater is online and can be set to the desired flux level by simply turning the powerstat dial to the left of the switches. This dial ranges from 0 to 100, with the setting reflecting a percentage of the maximum heat flux. In this case the maximum heat supplied from the heater is 350 watts.

During lab lecture, the equipment available for use will be reviewed and the procedure for operating these devices discussed. You should take the opportunity to familiarize yourself with the equipment during this time. The operating manuals will be provided for review. They should not leave the lab.

You will also be provided with several non-opaque materials with previously determined transmissivity values to guide the development of your experiment.

PROCEDURE

1. Before lab lecture read through the experiment write up, the sections of the ME 412 textbook indicated above, and complete the radiation worksheet. The radiation worksheet is to be turned in at the beginning of lab lecture. **The worksheet will count for a maximum of ten points on the technical memo.** Lab lecture for this experiment will be held in the Heat Transfer Teaching Lab, 3547 EB.

2. Review the use of the ASTM Standards that are attached. Using online literature search resources, identify three papers associated with the measurement and determination of transmissivity. Record these three citations.

3. Go to the library and identify one ASTM standard that is relevant to the measurement of transmissivity. You are to provide a brief summary (no more than two paragraphs) in your own words of the standard.

4. After reviewing the literature and equipment available, design an experimental procedure that can be used to determine the transmissivity of non-opaque materials. You should draft this procedure prior to experimentation.

5. Go to the lab and try out your experimental procedure and compare your results to the transmissivity values provided.

6. Record all uncertainties associated with your measurements and perform an error analysis.

SUGGESTIONS FOR DISCUSSIONS

1. Evaluate your experimental design.

2. What were the flaws in your experiment?

3. What sort of reproducibility does your experimental procedure yield?

4. How might you reduce the uncertainty in the determined transmissivities?

ME 412
Heat Transfer Laboratory
Radiation Transmissivity Experiment
Grading Sheet

Name: ____

Name: ____

Worksheet	/10
Discussion of basic theory Definition of radiative heat transfer, transmissivity. Clear statement of the problem	/10
Procedure Clearly written procedure for conducting the experiment	/20
Analytical/Experimental Results for test run Reproducibility Error analysis Control observations Justification of experimental method chosen	/30
Library Search Summary of ASTM Standard Mini literature review (3 citations)	/20
Overall Quality	/10
Total	/100

Comments:

Radiation Worksheet

To Be Completed and Turned In at the Beginning of Lab Lecture (will count for maximum of ten points on the technical memo)

Student Name: ____________________________

1. What is a photon? (1 pt)

2. Under what conditions is radiation heat transfer important? (1 pt)

3. Write an equation that represents the Stefan-Boltzman law. (1 pt)

4. What is transmissivity? (1 pt)

5. A radiant heater may be considered a gray surface and the room it is occupying may be considered black surrounds. If the heater is at 200°C with emissivity 0.85 and the room walls are at 22°C, determine the radiative heat flux away from the heater. (2 pts)

6. Solar radiation of 300 $W/m^2 \cdot K$ is incident the outside surface of a window with solar transmissivity of 0.78. What is the value of the radiation heat flux the leaves the inside surface of the window? (2 pts)

7. What types of measurements will need to be made to determine the transmissivity of a non-opaque material? (2 pts)

Finding ASTM Standards

Tom Volkening
Engineering Library
Michigan State University

The American Society for Testing and Material (ASTM) publishes the Annual Book of ASTM Standards which is kept in the Engineering Library. The most recent addition of the Annual Book of ASTM Standards is kept in the Reference area of the Library and the older years are kept in the regular book stacks. The call number of for the Annual Book of ASTM Standards is TA 401 . A653.

ASTM documents published as part of the Annual Book include classifications of materials and products, practices, product and materials specifications, test methods, and number of other types of documents. About 30% of the ASTM documents in the volumes are new or revised each year.

The first volume, v. 00.01, is the index for the entire set. It includes a subject index and an alphanumeric index of the ASTM standards.

Below is a sample entry from the subject index.

Transmissivity and reflectivity

[1] transmissivity of transparent part, test, [2] F 1316 (15.03)[3]

1. This is the title of the ASTM standard.
2. This is the ASTM standard number.
3. This is volume number where the ASTM standard will be found.
   Within the volume standards are arranged in alphanumerical order. For example the standard, F1316 would be found in volume 15.03.

Refrigeration Experiment
MSU Chilled Water Plant Tour

Worksheet

Name: ____

Signature of TA to Verify Attendance: __________________________________

1. What devices in an absorption refrigeration system replace the compressor of a conventional vapor/compression refrigeration system?
2. Describe the four (4) fluid streams within a Trane absorption unit.
3. How does a cooling tower operate?
4. What is the rated capacity of the chilled water plant in tons of refrigeration, Btu/hr, and kW?
5. Given the chilled water flow rate (from the pump) and the entering and exiting temperatures of the chilled water stream for one of the absorption units, calculate the actual cooling load (in tons of refrigeration) the unit is providing.
6. Determine the Carnot cycle COP for the absorption cycle used at the MSU chilled water plant.
7. Using the Carnot cycle COP and assuming a cooling load of 1250 tons, determine the required mass flow rate of steam.

Figure 1. Outside View of Trane Absorption Unit

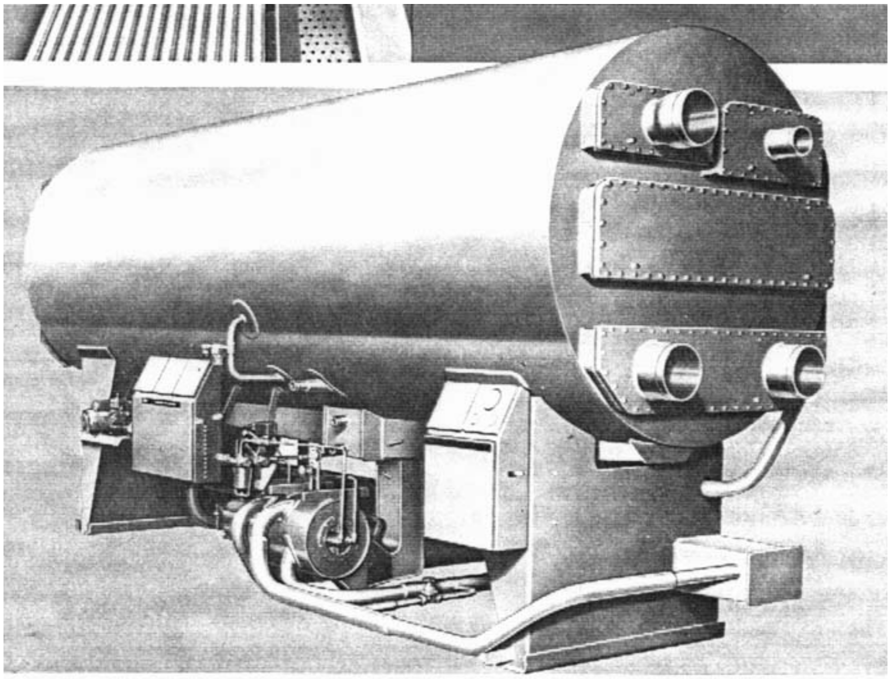


Figure 2. Schematic View of Trane Absorption Unit

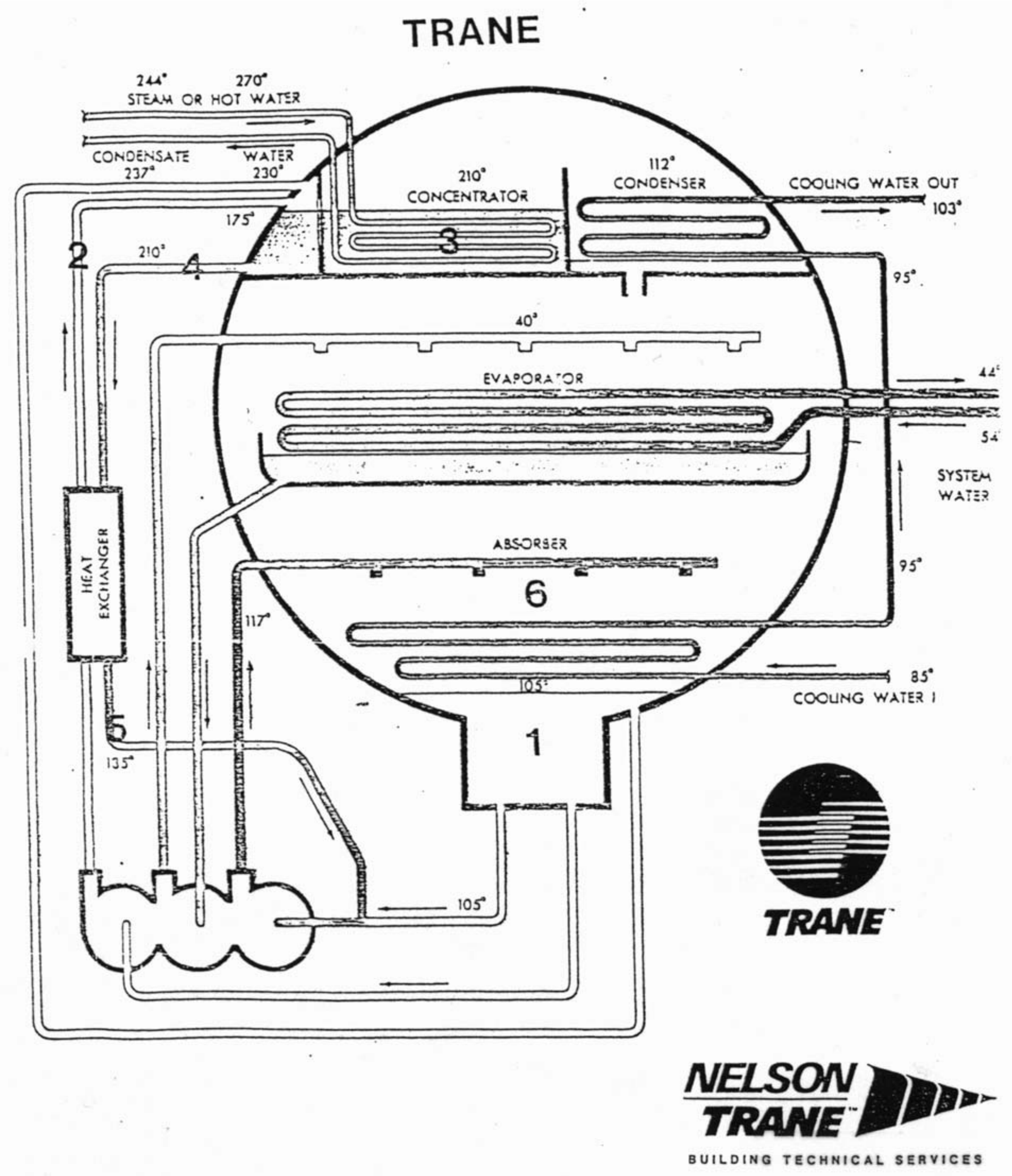


Figure 3. Block Diagram of Absorption Refrigeration System

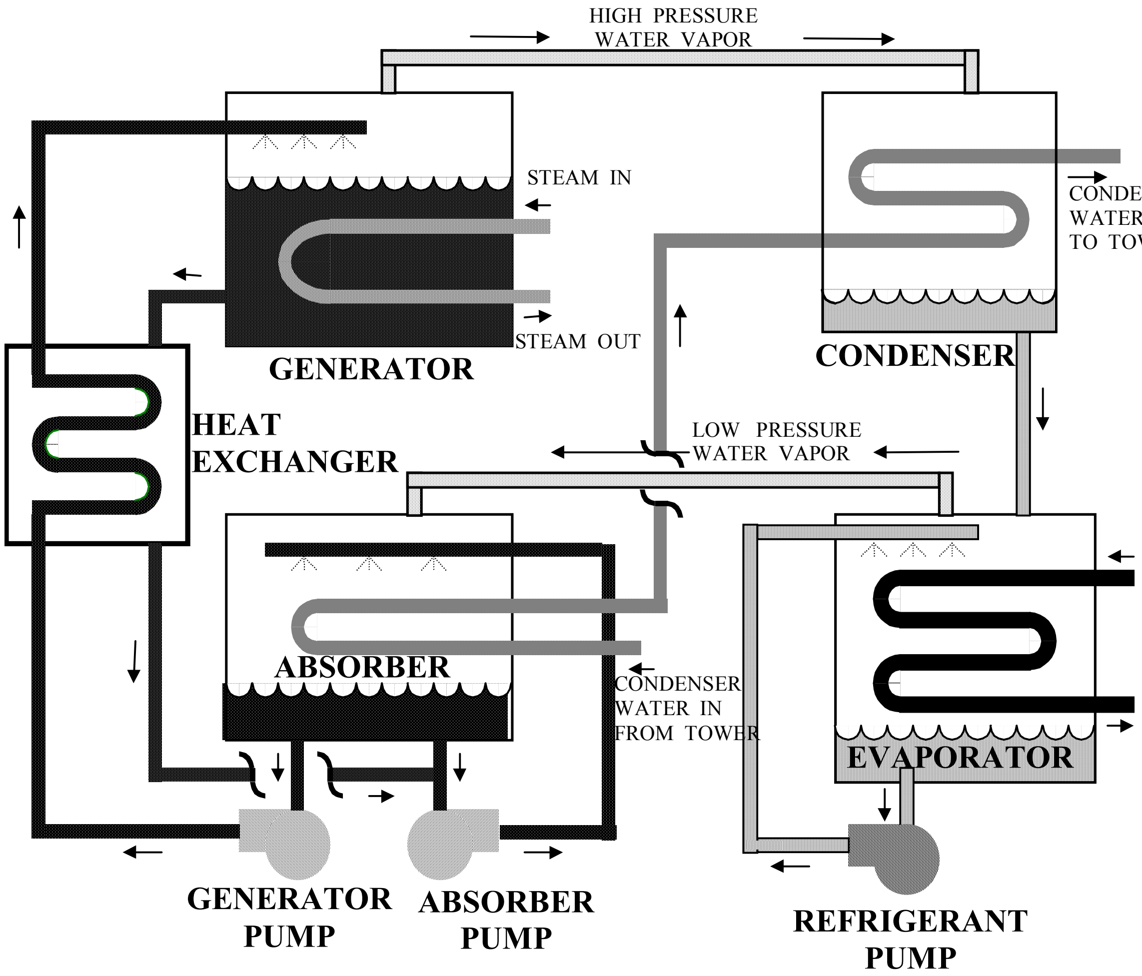


Table 1. MSU Central Chilled Water Plant Facilities

Chiller #	Capacity (tons)	Pump Flow Rate (gpm) at design ΔT	Pump Flow Rate (gpm) at ΔT=14°F
1-Carrier 16JA054	475	1150@10°F	814
2-Carrier 16JA054	475	1150@10°F	814
3-Trane C12A-2	1170	2900@10°F	2006
4-Trane C12A-2	1170	2900@10°F	2006
5-Trane ABSC-12A4	1250	2143@14°F	2143
6-Trane ABSC-12A4	1250	2143@14°F	2143
7-Trane ABSC-12A4	1250	2143@14°F	2143
8-Trane ABSC-12A4	1250	2143@14°F	2143
9-Trane ABSC-12A4	1250	2143@14°F	2143
10-Trane ABSC-12A4	1250	2143@14°F	2143

ME 412
Project Sign-up

GROUP MEMBERS	EMAIL	PHONE #
1.		
2.		
3.		
4.		

MEETING TIMES
Groups will be scheduled to meet on Mondays from 4:00-5:00 at 15 minute intervals.

<u>ALL GROUPS WILL MEET IN 3547 West EB</u>

Project Competition
"Hot Air Solar Balloon"

Prelude

The possibility of flight has always been fascinating and is of great practical importance. The creation of a flying device powered only by sunlight would be very useful but there must be little cloud cover and plenty of sunlight.

Balloons are amongst the very first flying devices invented (Montgolfiere) and very recently the first attempt to circumnavigate the globe using a balloon with someone inside was realized by Bertran Piccard of Switzerland and Brian Jones of Britain.

Balloons are not very effective flying devices but they are useful to lift a payload that requires little control/guidance high in the atmosphere (e.g. weather balloons). Such balloons often use an inert gas to become buoyant. Very recent successful flights have been made with solar montgolfiere balloons. Such balloons are for very high altitude (longest flight 69 days). They might be used on Mars by NASA.

The ME 412 design project will look at efficient ways of converting solar energy into heated air that will then provide buoyancy.

Project Statement

The project team is to design, *analyze*, build, and test a hot air balloon that will float with the assistance of sunlight only (or an equivalent source). The device will begin at room temperature and there are no restrictions on size. The objective will be to maximize the weight of a payload that can be lifted by the balloon, as well as to minimize the time to become airborne. A device must be manufactured by the project team. To test the device, four infrared lamps that provide approximately 300 W will be used.

Design Report

The design report shall consist of the following sections:

> Abstract: The abstract is a very short summary of the project report. A brief paragraph should include a problem statement, the method of solution, and solution statement.
>
> Background: In this section the heat transfer principles involved in the process should be defined. Appropriate equations modeling the physical process should

be provided. These equations should be solved to produce an analytical model for the process.

Design Analysis: Design alternatives should be presented and evaluated in this section. The criteria used in selecting the preferred design should be stated. The details of the fabrication of the device should also be included. This will include detailed drawings of the device, material specifications, and manufacturing processes. The material cost of the device must be provided in a documented fashion. That is, a receipt must be provided for each material component of the device. Only the cost of materials and not fabrication costs need to be provided, and only the material cost will be used in the evaluation of the device.

Testing and Verification: In this section the testing procedures and results will be presented. Several tests should be conducted with the device. The data collected should be compared to results generated from the analytical model and any difference between the two should be noted and explained. Presentation of the testing data should include an uncertainty analysis.

Recommendations: If you were to do this project again, what would you do differently? If you had another semester to work on the project, what additional things would you do?

Project Competition

On Monday, August 16, the competition for the project will be conducted.. At 4:10 pm the device will be logged in. The payload mass will be measured, and the material cost recorded. Once all of the devices have gone through this procedure, its time to liftoff and maximum payload (if needed) will be determined. The design team will be allowed to prep their device. After liftoff, the payload must be added at some point.

Each team's device will be ranked from 1 to N (N being the number of teams) for each event (material cost, time for liftoff, and payload weight). For time for liftoff and device cost the ranking will be from low to high, while for the payload mass the ranking will be from high to low.

In each event the team ranked number one will receive N points, the team ranked second will receive N-1 points, and so on to the last place team which will receive one point. If a tie exists for a position, the two teams will equally share the sum of the points for that position and the next position. That is, if two teams tie for fourth in the cost event each team would receive one half the combined points for fourth and fifth place. The next ranked team would receive the points for sixth place. An overall champion will be determined by summing the time for liftoff event points with the cost event points with two times the payload mass points. That is, Total Pts = Cost Pts + Time for Liftoff Pts + 2 x (Payload Mass Pts)

Grading

The grade for the project will be based on the following weighting:

Report	50%
Device	40%
Competition	10%

The project report will be graded out of 100 points (similar to the technical memos) with regards to the items requested in the above Project Report section and its quality. The device will be graded out of 100 points with 75 points awarded for a functional device. The remaining 25 points will be distributed on the basis of quality and creativity of the design. The project competition will be graded out of 100 points. The project team with the overall highest score will receive 100 points. The second place overall team will receive 95 points, and so forth through the final rankings at five point intervals.

Cost Information

To be consistent all design teams should use the following cost data.

copper $\$2.00/\text{lb}_\text{m}$
bronze or brass $\$1.75/\text{lb}_\text{m}$
aluminum $\$1.50/\text{lb}_\text{m}$
stainless steel $\$3.00/\text{lb}_\text{m}$
galvanized steel $\$0.75/\text{lb}_\text{m}$
steel $\$0.50/\text{lb}_\text{m}$
paper or cardboard $\$0.55/\text{lb}_\text{m}$
generic plastic $\$0.30/\text{lb}_\text{m}$
wood $\$0.25/\text{lb}_\text{m}$
Styrofoam $\$10/\text{lb}_\text{m}$
rubber $\$4.50/\text{lb}_\text{m}$
fiberglass $\$5.00/\text{lb}_\text{m}$
water: $\$\ 0.13/\text{kg}$