



Heat Transfer Laboratory

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Preface

The purpose of this manual is to make it easy for students to perform simple experiments in heat transfer.

The manual presents detailed descriptions of experiments. The arrangement and organization provide a convenient means of giving instruction on handling the equipments. The use of the equipments is not limited to the experiments described; the instructor can feel free to make variations. Moreover, the manual presents guidelines for preparation of laboratory reports.

For further information regarding any experiment, please contact me.

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Nablus, August 25, 2013

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I. Guidelines for Preparation of Laboratory Reports

The report should be typewritten with the graphs by a computer. Use double spacing with 12 fonts. Spelling and usage should be conventionally correct. Use A4 paper for the entire report. The following sections are to be included in this order:

1. TITLE PAGE

1. Student's name
 2. Course and section Number
 3. Number and title of the experiment
 4. Date the experiment was performed
 5. Names of group members
 6. Date the report is presented
- See attached sample cover page

2. ABSTRACT

This is a stand-alone summary of the report. It should include objective, what was done, results and conclusions. It should be clear, informative, and concise. It should not make any references to the body of the report or to the appendices. An abstract should never be longer than one page. Normally it is written after all other sections of the report have been completed.

3. OBJECTIVE

The objective of the experiment should be stated on a separate sheet of paper with the heading OBJECTIVE. State the objective clearly. A few explanatory sentences may be included, if needed.

4. INTRODUCTION

In this section, explain the purpose of the experiment. It puts the experimental work into perspective. Mention the relevance of the experiment to field of engineering. It can form a natural transition into the THEORY, METHODS, RESULTS, and CONCLUSIONS sections of the report.

5. THEORY

In this section state and explain any equations or theoretical principles and assumptions that were used in the experiment and the analysis. Define all parameters used. To find this information refer to textbooks, notes etc. Refer the reader to a numerical listing of sources in the appendix. Write equations using equation writer in the word processor.

6. EXPERIMENTAL METHODS

Give a detailed description of how you accomplished the experimentation. This should include equipment used in the experiment as well as how it was used. The description should have sufficient detail so that another experimenter could duplicate your efforts. Use sketches, diagrams, or photos to describe the experimental set-up. Label the main components. Provide dimensions and material of test samples where applicable. VISIO Technical, AutoCAD or

another CAD package that is suitable can be used to develop and plot your sketches, and spreadsheet programs like EXCEL can be used for graphs. The equipment listing in the Appendices is the appropriate place for model numbers and serial numbers. In the methods section, use generic names for the equipment, e.g., the fluid network apparatus.

7. RESULTS

Summarize your results in an introductory sentence. Relate your results to your objective. Present the results in the easiest way for your reader to understand:

graphs, tables, figures, etc. Spreadsheets are often a good approach. See section on preparation of graphs. All tables and figures must be referenced in the text, use a numbering system for identification of each one.

Explain the results of the experiment; comment on the shapes of the curves; compare results with expected results; give probable reasons for discrepancies from the theory; answer any questions outlined in the instructions and solve any problems that may have been presented. Tell why things happened, not only that they did happen. Comparisons should include numerical values and corresponding error percentages where relevant.

Do not present calculations and formulas in this section. Your calculations should be detailed in the Appendices under SAMPLE CALCULATIONS. Formulas should be discussed in the THEORY section.

8. CONCLUSIONS

State your discoveries, judgments and opinions from the results of this experiment. Summarize your primary results in comparison with theory in two or three sentences. These should answer the objective of the experiment. Make recommendations for further study. Suggest ways to improve the experiment.

Consider that in the real world, information like that in the RESULTS and CONCLUSIONS will be all that upper management will want to receive. Beyond that, figures may be skimmed. Make the most of these sections.

9. APPENDICES

A. DATA TABLES

Data tables are for the convenience of the extremely interested reader. These tables may contain any additional comparisons or calculations that you have prepared and were not included in the RESULTS section which may contain only summaries of your work. Data Tables are the place to show everything that you did.

B. SAMPLE CALCULATIONS

Demonstrate how you performed the calculation made in the experiment. Include tabular results of computations where such were made. Show the generic calculations to support all your work. Provide any computer or calculator program listings, along with sample input and output.

C. EQUIPMENT LIST

List every piece of equipment used in the experiment. Provide unique identification numbers, when possible. State the accuracy and/or the readability of the instruments.

D. RAW DATA SHEETS

Data sheets must be completed in ink and signed by the instructor at the completion of the laboratory period.

In the case of an error, line through the mistake, initial the mistake, and continue. Record the name of the recorder and the group members on the raw data sheets.

10. REFERENCES

List any books or publication that you referenced in compiling your report. Provide titles, authors, publisher, date of publication, page number, Website addresses etc.

II. Preparation of Graphs

ORIENTATION OF GRAPHS

Plan the graph in so that the binding margin of the graph paper is at the left or at the top.

COORDINATE AXES

Draw the axes of coordinates on the cross-sectioned part of the sheet, far enough in from the margin to leave room for inserting the scales and their identifications between the edges of the cross-sectioning and the axes, except when using log-log paper.

SCALES

Start all linear scales at (0,0) unless such a procedure would obscure the presentation of data. Of course, this is not possible when using log scales. The units on the major divisions of log scales should be powers of 10. Choose scales of 1, 2, 4, or 5 units per centimeter, or any decimal multiples, such as 0.1, .002, and 400. Proper choice of scales is important. Guiding principles are:

1. Utilize a good portion of the graph sheet area. DO not squeeze curves into one corner.
2. Do not unduly extend the scales. Have the scales readable to the precision of the instruments from which data was taken. Further extension of the scales only scatters the data points, emphasizing the experimental error.
3. Keep in mind the purpose of the graph. Avoid using scales that hide the real meaning or fail to show the intended relationships.
4. Letter in the scale numerals along the axes, putting the abscissa scale beneath the horizontal axis at appropriate intervals. Set all numerals on either axis in a vertical position as viewed from the bottom of the page.

SCALE LEGEND

Letter in the abscissa legend beneath the abscissa scale so as to be read from the bottom of the page. Letter in the ordinate legend to the left of the ordinate scale so as to be read from the right hand of the page. If more than one ordinate scale is used, place each ordinate legend immediately adjacent to the corresponding scale. Use descriptive titles followed by dimensional units, e.g., CAPACITOR CURRENT (MILLIAMPS).

OTHER LETTERING

Use capitals for all lettering on the graph paper. Arrange all except scale legends to be read from the bottom of the page and to run in horizontal lines.

TITLE

Letter in a concise descriptive title on each graph sheet, preferably in the bottom center. Do not list the legends in the title.

DATA POINTS

Indicate data points by small circles or appropriate geometric symbols, except in the case of correction curves for instruments where the plotted points are not emphasized.

CURVES

With EXCEL Software, draw smooth curves whose positions are governed by the plotted points. The curves should not necessarily pass through every point but should traverse the combined center of gravity of all the points. Only in the case of perfectly smooth data will all the points lie on the curve. One exception to the smooth curve rule: For instrument correction curves, join the plotted points by straight-line sections and break the curve where it reaches the data points. Draw curves with ink or with computer printer and software such as EXCEL.

When more than one curve is drawn on the same set axes, carefully identify each curve, preferable with a legend lettered immediately adjacent to the curve. Other (less desirable) methods are to use horizontal legends, each with an arrow pointing to the appropriate curve, or to number the curves and provide a table of titles. Data points for the different curves should use different geometric symbols.

INDEPENDENT VERSUS DEPENDENT VARIABLES

Plot the independent variable horizontally along bottom of the graph. Plot the dependent variable vertically. The dependent variable is usually mentioned first, e.g., "PRESSURE VERSUS TEMPERATURE" where pressure is the ordinate.

Sample Cover Page

Heat Transfer Laboratory

Boiling Heat Transfer

(Experiment no. 1, Performed on: February 20, 2004)

Prepared by:

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February 26, 2004

III. Criteria for Evaluating Laboratory Reports and Grading Policy

TECHNICAL FORMAT (90%)

Abstract (10%):

- Does it stand alone?
- Is it understandable?
- Does it include a summary of the following- objective, introduction, Theory, Methods and Conclusions?

Objective (5%):

- Is the objective stated clearly and concisely?

Introduction (5%):

- Does the introduction explain the relevance of the experiment to the field of engineering?

Theory (10%):

- Is the theory explained?
- Are all the necessary formulas stated and variables defined?

Experimental Methods (10%):

- Can the experiment be reconstructed from the description given?
- Is there a diagram of the experimental set-up?

Results (40%):

- Is presentation clear and concise? Are all the relevant Tables, Graphs, explanations included? Are the pertinent Sample calculations, References, etc. included in the Appendices?

Conclusion (10%):

- Are the conclusions derived from the results of the experiment? Were there any discrepancies from expected results? Is the objective of the experiment accomplished?

WRITING QUALITY (10%)

- Does the report follow the prescribed format?
- Is the language of the report easy to read? Is it precise? Does it conform to the conventional standards?

Grading System

Component	Details	Max. Mark	Student Mark	Grade
General	Letter of transmittal	1		
	Title page	1		
	Table of contents, figures and tables	3		
	References	2		
	Report quality	3		
Introduction	Summary	3		
	Introduction	5		
	Theory	5		
	Description of apparatus	3		
	Experimental procedure	4		
	Nomenclature	2		
Results	Raw data	5		
	Treatment of data (tables and figures)	12		
	Sample calculations	10		
Discussion	Discussion of obtained results	15		
	Compared with correlated values	5		
	Compared with other group	5		
	Error analysis and possible sources of error	5		
Conclusion	Conclusions	7		
	Recommendations	3		
	Appendix: "original" data sheets and sample calculations	1		
Total				

IV. Laboratory Safety Requirements

Before conducting any experiments, in the first lab students are instructed by the laboratory technician and teaching assistants to abide by safety rules and take all necessary precautions to ensure a safe work environment in order to safeguard their health, and the health of their co-workers. This lab deals with boiling water hot surfaces, which can cause serious burns. All lab instruments have been designed such that all exposed surfaces are well-insulated and not hot to touch. The safety precautions that the students are asked to follow include:

- (i) Food, drinks, and related utensils are prohibited from being brought, stored or consumed in the laboratory. Smoking is strictly prohibited in laboratories. Unauthorized individuals must not be allowed in the laboratory. Laboratory must remain locked when unoccupied.
- (ii) Appropriate personal clothing, laboratory coats, gloves and personal protective equipment (such as safety glasses) must be worn in the laboratory. Shoes must provide full coverage of the feet. Laboratory coats must be removed and hands must be washed before leaving the laboratory.
- (iii) All occupants should be familiar with the locations and operation of safety and emergency equipment such as fire extinguisher, first aid kits, emergency eye wash stations and emergency showers, fire alarm pull stations, emergency telephone, and emergency exits.

1. Linear and Radial Heat Conduction

1.1 Objective

The primary aim of this experiment is to study the Fourier's Law on linear and radial conduction heat transfer.

1.2 Introduction

Generally, heat is defined as energy transfer due to the temperature gradients or difference between two points. Heat energy can be transferred in three modes, which are conduction, convection, and radiation. One of the most common heat transfer modes, which is conduction heat transfer, is defined as heat transferred by molecules that travel a very short distance ($\sim 0.65\mu\text{m}$) before colliding with another molecule and exchanging energy.

In this experiment, both *linear* and *radial* conduction heat transfer methods are studied. The entire system (insulated heater/specimen, air and laboratory enclosure) are at room temperature initially ($t = 0$). The heater generates uniform heat flux as switched on.

1.2.1 Linear Conduction

For linear conduction, an electrical heating element is bonded to one end of a metal rod (heat source). Another end of the rod is exposed to heat discharge (heat sink). The outer surface of the cylindrical rod is well insulated; thus yielding one-dimensional linear heat conduction in the rod once the heating element is switched on. Thermocouples are embedded in the rod, along its centerline, at $x = 0, 10,$ and 20 mm from the heating element. A simple sketch for heat conduction along a well-insulated cylindrical rod is shown on Figure 1.1. Three types of 30 mm length metal species will be tested, namely brass which has a diameter of 25 mm and 13 mm. These sections allow the study of effect of a reduction in the cross-section of heat conduction path. The third piece of metal is stainless, which has a diameter of 25 mm. this section allows the study of the effect of a change in material while maintaining a constant cross-section.

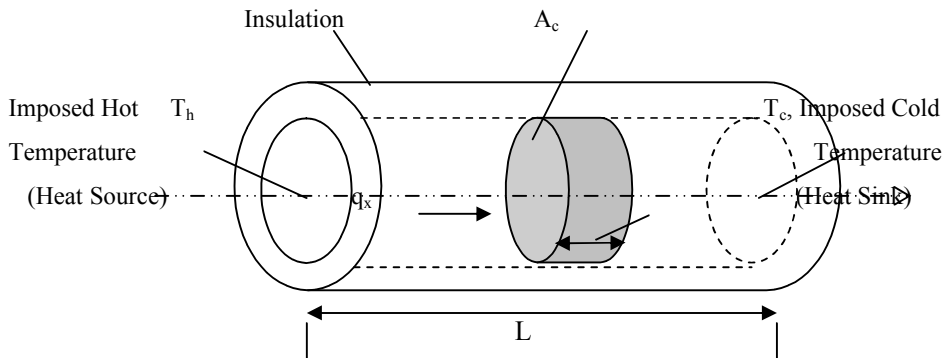


Figure 1.1 A simple sketch for heat conduction along a well-insulated cylindrical rod

1.2.2 Radial Conduction

For radial conduction, the electrical heating element is bonded to the center part of a circular brass plate (heat source). The cooling water flows through the edge of the plate that acts as a heat sink for heat discharge. The other surfaces of the plate are well insulated to simulate radial heat conduction from the plate center to its edge when the heating element is switched on. The brass plate has a radius, $r_{\text{plate}} = 55 \text{ mm}$ and thickness, $t = 3.2 \text{ mm}$. Thermocouples are embedded in the circular plate, at $r = 0, 10, 20, 30, 40,$ and 50 mm . A simple sketch for heat conduction along a well-insulated cylindrical rod is shown in Figure 1.2.

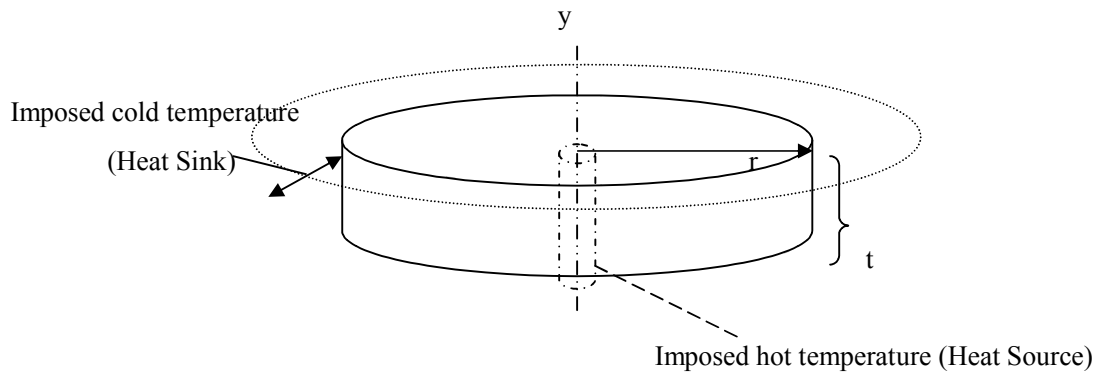


Figure 1.2 A simple sketch for heat conduction along a well-insulated cylindrical rod

1.3 Apparatus

The apparatus that will be using in this experiment is the H940 Heat Conduction Unit. There are four items to this unit.

1.3.1 The First Item

It is the transformer with a circuit breaker attached. The transformer consists of two cords, one of which plugs into an AC outlet and the other into the calibration unit (Figure 1.3).

1.3.2 The Second Item

It is the calibration unit. The calibration unit has two basic functions.

1. It delivers heater power to the heater element within the test unit,
2. It calibrates the temperatures at each of the nine positions so they can be read by the digital meter.

The far right knob adjusts the amount of power delivered to the heater. The knob to the left is the temperature selector switch, which will give the temperature at any of the nine positions (Figure 1.4).

1.3.3 The Third Item

This is the test unit. The test unit consists two test geometries:

1. An insulated brass bar for which samples can be placed between the two ends.
2. An insulated disk.

Both of these test geometries have a hose running through the cold end for which cold water from the sink can be passed through (Figure 1.4). *The purpose of having cold water running through the end of the bar or disk is to remove heat that is produced from the other end.* Once the rate at which heat is generated is equal to the rate at which heat is removed, *steady state equilibrium conditions* will exist. At this point the temperatures will be constant throughout the bar or disk and readings can be taken. There are two heater cords, one from the test bar and the other from the test disk. The cord for the desired test connects into the heater plug located in the lower right hand corner of the calibration unit.

1.3.4 The Sample Box

The last item of the conduction unit is a box that contains the samples, thermocouples, and conducting paste. The samples can be placed in the bar test unit by releasing the clamps and sliding the cold bar end out. The samples fit in only one way. The thermocouples must be placed in order from 1 to 9 as shown in Figure 1.4. There is a label on both the calibration unit and the test unit letting you know where the number 1 thermocouple starts. The conducting paste is a highly conductive compound which is designed to decrease contact resistance when applied to the ends of the connecting bars.

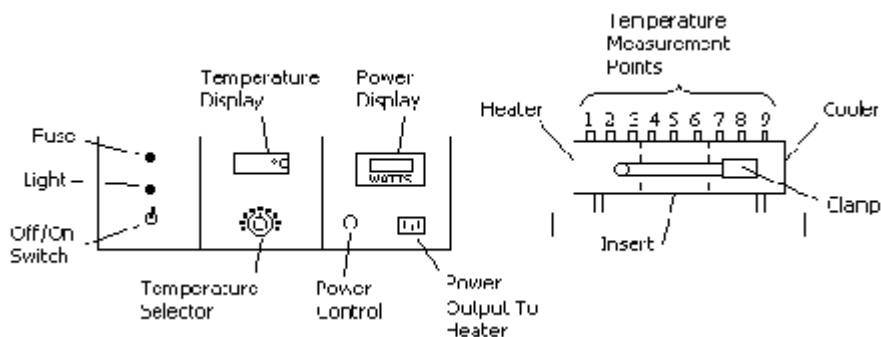


Figure 1.3 Front view of the calibration and test units

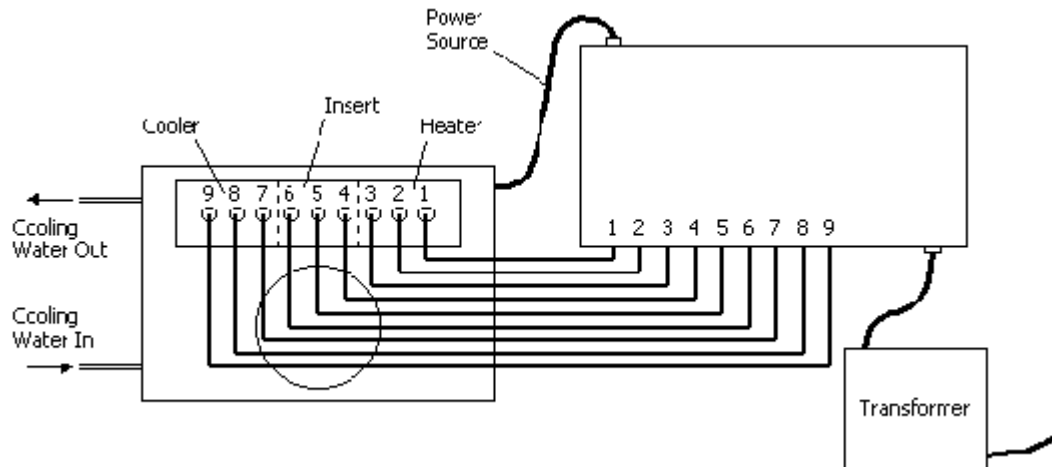


Figure 1.4 Top view of the calibration and test units

1.4 Procedures

1.4.1 Linear conduction along cylindrical metal rod

1. Install the brass specimen to the test unit.
2. Insert the probe in the holes provided along the specimen, making sure that each one is touching the rod. Take note of the distance for each thermocouple (x values).
3. Make sure there is water supply to the unit for simulating heat sink.
4. Turn on the heater with 10-Watt power input and record the temperatures after the readings reach steady state, which is about 20 to 30, minutes. Also, record the corresponding heater power input.
5. Record the measured temperature at each point.

1.4.2 Radial conduction along circular metal plate

1. Insert the thermocouples in the holes provided on the specimen, making sure that each one is operating properly. Take note of the distance for each thermocouple (r -values).
2. Make sure there is water supply to the unit for simulating heat sink.
3. Turn on the heater with 20 W power input and record the temperatures after the readings reach steady state, which is about 20 to 30, minutes. Also, record the corresponding heater power input.
4. Record the measured temperature at each point.

1.5 Report Requirement

1. Plot the temperature profile for both models as a function of distance for the both method of data collected. Select the best method and comment.
2. For the radial and linear conduction model, derive a general equation for the temperature reading as a function of distance, x for linear conduction, $T(x)$, and r for radial conduction, $T(r)$, using the parameters of k , t , A , T_1 , L , and R . State the boundary conditions applied.
3. Plot the temperature profile for both models as a function of distance and obtain the slope dT/dx for linear conduction and dT/dr for radial conduction.
4. By using the slope of the graph plotted, calculate the thermal conductivity for each specimen used.
5. Compare and discuss the thermal conductivity obtained from the two methods and the typical values contained in tables of published data/Literature.
6. Discuss the characteristics of your plots and compare against the expected profile by the theory. Also discuss the validity of the Fourier Law and all the assumptions made as well as the source of errors.

1.6 Raw Data and Result Tables

PART I

Record your reading as follows:

Table 1.1 Raw Data for Experiment #1 (Part I)

<i>Test</i>	<i>Wattmeter r Q (W)</i>	<i>T₁ (°C)</i>	<i>T₂ (°C)</i>	<i>T₃ (°C)</i>	<i>T₄ (°C)</i>	<i>T₅ (°C)</i>	<i>T₆ (°C)</i>	<i>T₇ (°C)</i>	<i>T₈ (°C)</i>	<i>T₉ (°C)</i>
A										
B										
C										

The final results should be reported in the following format

Table 1.2 Processed Data for Experiment #1 (Part I)

<i>Test</i>	<i>Wattmeter Q (W)</i>	<i>A (mm²)</i>	<i>dT/dx (°C/mm)</i>	<i>dx/dT (mm/°C)</i>
A				
B				
C				

$k_{\text{exp}} =$ W/mm.K,

$k_{\text{ref}} =$ W/mm.K,

% diff. = %

Part II

Record your reading as follows:

Table 1.3 Raw Data for Experiment #1 (Part II)

<i>Wattmeter Q (W)</i>	<i>T₁ (°C)</i>	<i>T₂ (°C)</i>	<i>T₃ (°C)</i>	<i>T₄ (°C)</i>	<i>T₅ (°C)</i>	<i>T₆ (°C)</i>	<i>T₇ (°C)</i>	<i>T₈ (°C)</i>	<i>T₉ (°C)</i>

2. Conduction Along a Composite Bar

2.1 Objectives

The objective of this experiment is to study the conduction of heat along a composite bar, as well as to evaluate the overall heat transfer coefficient.

2.2 Introduction

Experiment 1 has indicated how heat is transferred through a simple bar. Now this experiment must extend our knowledge to a bar made up of different materials. As stated in Experiment 1, there is an analogy between the conduction of electricity and the conduction of heat. Since electrical resistance is associated with the conductance of electricity, there is also a thermal resistance associated with the conductance of heat. Composite fluids and solids behave much like series and parallel combination of resistors in an electrical circuit. Using this approach one can add up the thermal resistances to find the overall resistance and heat transfer coefficient.

2.3 Theory

Assume that we have a combination of different materials put together to form a composite structure like the composite wall in Figure 2.1. Also assume that the cross sectional area normal to the flow of heat transfer is constant and that heat flows in a one dimensional direction. Taking only one of the slabs for now, we learned from Experiment 1 that the heat transfer is governed by Fourier's Law, given by

$$q_x = -kA \frac{dT}{dx} = \frac{kA}{L} (T_{s,1} - T_{s,2}) \quad (2.1)$$

Regarding the concept of thermal resistance for conduction. Resistance in general is defined as the ratio of driving potential over the transfer rate. As transfer rate goes to zero, the resistance becomes infinite and, similarly, as the driving potential goes to zero, resistance fails to exist. By using Fourier's Law and the definition of resistance, one can derive the thermal resistance for all the modes of heat transfer:

$$R_{t,cond} = \frac{T_{s,1} - T_{s,2}}{q_x} = \frac{L}{kA} \quad (2.2)$$

$$R_{t,conv} = \frac{T_s - T_{Fluid}}{q} = \frac{1}{hA} \quad (2.3)$$

$$R_{t,rad} = \frac{T_s - T_{sur}}{q_{rad}} = \frac{1}{h_r A} \quad (2.4)$$

where R is the resistance for each mode. Symbols T_s , T_{Fluid} , and T_{sur} are the temperatures for the surface, fluid, and surroundings, respectively. The symbols h_r and h are the heat transfer coefficients for radiation and convection, respectively.

If we sum up all the individual heat transfers, the intermediate temperatures cancel and we get:

$$q_x = \frac{T_{s,1} - T_{s,n}}{\sum R_t} = \frac{T_{s,1} - T_{s,2}}{\left(\frac{L_1}{k_1 A}\right) + \left(\frac{L_2}{k_2 A}\right) + \left(\frac{L_n}{k_n A}\right)} \quad (2.5)$$

To simplify Equation 2.5, combine everything that does not change across the composite, like the initial and final temperature and the area A , and call the rest that does change from material to material the overall heat transfer coefficient U . Therefore

$$q_x = UA\Delta T \quad (2.6)$$

and the overall heat transfer coefficient is:

$$U = \frac{1}{R_{tot} A} = \frac{1}{\left(\frac{L_1}{k_1}\right) + \left(\frac{L_2}{k_2}\right) + \left(\frac{L_n}{k_n}\right)} \quad (2.7)$$

There are two ways to find the overall heat transfer coefficient by finding R_{tot} .

1. The first way is to find all the individual k 's using Equation 2.1 for each section of bar, and using these values in Equation 2.7.
2. The second way is to use Equation 2.6 with the ΔT of the entire bar.

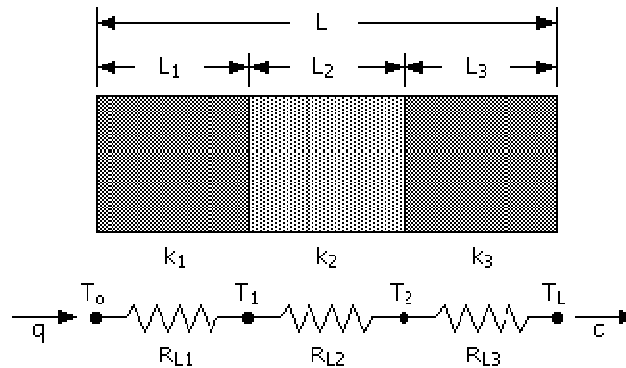


Figure 2.1 Composite Wall

2.4 Apparatus

H940 Heat Conduction Unit

2.5 Procedures

1. Take a stainless steel sample (30 mm long) and insert the steel sample to the test unit.
2. Allow cold water to flow through the test unit.
3. Select an intermediate position for the heater power control and allow sufficient time for a steady state condition to be achieved.
4. Record the temperature (T) at all six sensor points and the input power reading on the wattmeter (Q) in Table 2.1.
5. Repeat the procedure, for other input powers up the maximum setting of the control. After each change, allow sufficient time to achieve steady state conditions (Up to 10 min).

2.6 Report Requirement

1. Plot the temperature profile along the length of the core as in Figure 2.2, and obtain the outer surface temperature T_{hs} and T_{cs} .
2. Calculate the overall heat transfer coefficient (U) using both methods. For the first method, use Equation 2.7 and the individual k 's found from Equation 2.1. For the second method, use Equation 2.6 and the extreme temperatures. Record the results in Table 2.2.
3. Compare the two experimental values of (U). If they disagree significantly, explain why.
4. Calculate (U) using Equation 2.7 and k 's values from literature (published data).
5. Compare the experimental (U) by the second method with the (U) calculated from Equation 2.7 and using the k 's from the literature.
6. Discuss sources of error from equipment and assumptions.

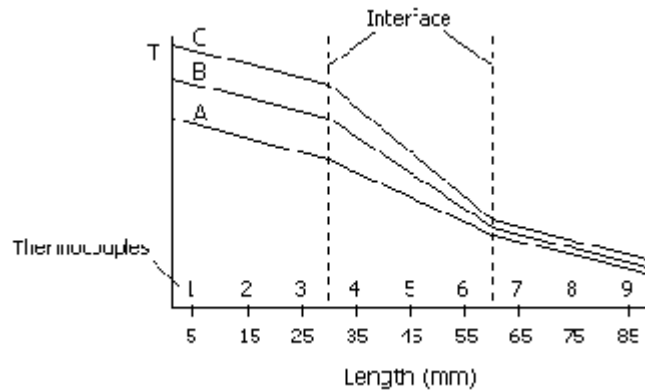


Figure 2.2 Temperature Distributions Along the Composite Bar

2.7 Raw Data and Result Tables

Record your reading as follows:

Table 2.1 Raw Data for Experiment #2

<i>Test</i>	<i>Wattmeter Q (Watts)</i>	T_1 ($^{\circ}\text{C}$)	T_2 ($^{\circ}\text{C}$)	T_3 ($^{\circ}\text{C}$)	T_7 ($^{\circ}\text{C}$)	T_8 ($^{\circ}\text{C}$)	T_9 ($^{\circ}\text{C}$)
A							
B							
C							

The final results should be reported in the following format

Table 2.2 Processed Data for Experiment #2

<i>Test</i>	A (mm^2)	$(dx/dT)_h$ ($\text{mm}/^{\circ}\text{C}$)	$(dx/dT)_s$ ($\text{mm}/^{\circ}\text{C}$)	$(dx/dT)_c$ ($\text{mm}/^{\circ}\text{C}$)	k_{hot}	$k_{specimen}$	k_{cold}
A							
B							
C							
Average	-----						

Table 2.3 Processed Data for Experiment #2

<i>Test</i>	T_{hot} ($^{\circ}\text{C}$)	T_{cold} ($^{\circ}\text{C}$)	U_{exp1} ($\text{W}/\text{mm}\cdot\text{K}$)	U_{exp2} ($\text{W}/\text{mm}\cdot\text{K}$)	$U_{reference}$ ($\text{W}/\text{mm}\cdot\text{K}$)	% diff. 1 vs. 2	% diff. exp. vs. ref.
Average							

3. Effect of Cross-Sectional Area

3.1 Objectives

The objective of this experiment is to understand how variable cross-section affects heat transfer.

3.2 Introduction

Experiment #2 showed how different materials affect heat flow, now this experiment shows how changes in cross-sectional area affect heat flow. In this experiment the same brass bar will be used, but instead of using the 25 mm diameter cross-section sample, a sample with a much smaller cross-section with a diameter of 13 mm will be used.

3.3 Theory

Fourier's Law states that,

$$q = -kA \frac{dT}{dx} \quad (3.1)$$

The heat flow rate (q) is the same for each section of the conductor. Also the thermal conductivity (k) is assumed to be constant. If this is the case then,

$$A_h \left(\frac{dT}{dx} \right)_h = A_s \left(\frac{dT}{dx} \right)_s = A_c \left(\frac{dT}{dx} \right)_c \quad (3.2)$$

In other words, the temperature gradient is inversely proportional to the cross-sectional area. Take Equation 3.2 and solve for the temperature gradient ratio, which is the ratio of the sample temperature gradient over the hot or cold temperature gradient, it can be seen that it is equal to the inverse of the ratio of the two different cross-sectional areas.

$$\frac{\left(\frac{dT}{dx} \right)_s}{\left(\frac{dT}{dx} \right)_{h/c}} = \frac{A_{h/c}}{A_s} \quad (3.3)$$

In this experiment you are to compare the gradient ratio obtained from the plot of temperature versus distance with the inverse ratio of the two different areas.

3.4 Apparatus

H940 Heat Conduction Unit

3.5 Procedures

1. Take the brass sample (30 mm long) with 15 mm.
2. Insert the brass sample to the test unit.
3. Allow cold water to flow through the test unit.
4. Select between 5-10 Watts for the heater power control and allow sufficient time (20 min) for a steady state condition to be achieved (no more than 20 minutes).
5. Record the temperature (T) at all six sensor points and the input power reading on the wattmeter (Q) in Table 3.1.

3.6 Report Requirement

1. Plot the temperature profile along the length of the core as in Figure 3.1, and obtain the temperature gradient ratio. Compare this value with the theoretical value.
2. Discuss possible sources of error within the equipment or the assumptions made in the theory.

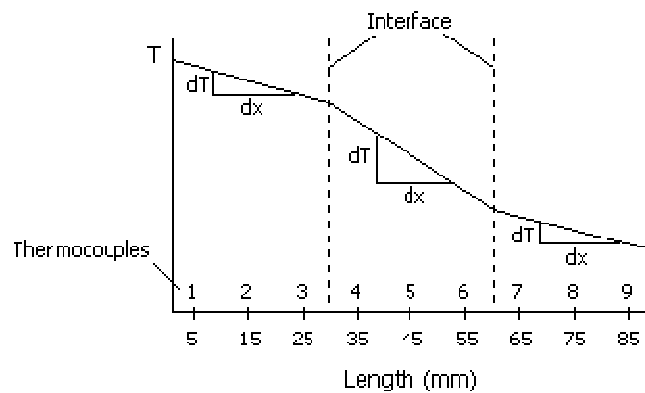


Figure 3.1 Typical Temperature Distributions

3.7 Raw Data and Result Tables

Table 3.1 Data for Experiment #3

<i>Wattmeter</i> <i>Q (W)</i>	<i>T₁</i> <i>(°C)</i>	<i>T₂</i> <i>(°C)</i>	<i>T₃</i> <i>(°C)</i>	<i>T₇</i> <i>(°C)</i>	<i>T₈</i> <i>(°C)</i>	<i>T₉</i> <i>(°C)</i>

Table 3.2 Processed Data for Experiment #3

<i>Area</i> <i>sample</i> <i>(mm²)</i>	<i>Area</i> <i>h/c</i> <i>(mm²)</i>	<i>(dx/dT)_h</i> <i>(mm/°C)</i>	<i>(dx/dT)_s</i> <i>(mm/°C)</i>	<i>(dx/dT)_c</i> <i>(mm/°C)</i>	<i>Area</i> <i>ratio</i> <i>(h/c)/s</i>	<i>Gradient</i> <i>ratio</i> <i>exp.</i>	<i>%</i> <i>error</i>

4. Effect of Insulation

4.1 Objective

The objective of this experiment is to study the effects of an insulating material such as paper by finding the thermal conduction coefficient (k) for that material.

4.2 Introduction

It is very important today in certain engineering applications, such as heating and air conditioning, to limit heat transfer to a minimum. In that respect engineers look for materials that do not conduct heat well or have a very small heat transfer conduction coefficient.

In this experiment you will calculate the conduction coefficient for paper or any other materials and compare it with values from the literature.

4.3 Theory

Using Fourier's Law and solving for the conduction coefficient,

$$k = \frac{q}{A} \left(\frac{\Delta x}{\Delta T} \right)_{Insulator} \quad (4.1)$$

4.4 Apparatus

H940 Heat Conduction Unit

4.5 Procedures

1. Measure and record the paper thickness.
2. Insert the paper concentrically within the two metal bars of the apparatus and clamp (if possible). Do not use conducting compound.
3. Control the input power to approximately 10-15 Watts and allow around 20 min. to reach steady state making sure T_1 does not exceed 100°C .
4. Record temperatures at all six sensor points and record in Table 4.1.

4.6 Report Requirement

1. Plot temperature vs. distance as in Figure 4.1.
2. Calculate the heat transfer coefficient. Record the results in Table 4.2.
3. Compare experimental value with values from the literature.
4. Discuss sources of error that might cause discrepancy.
5. Is this a good experiment to find the thermal conductivity of unknown material such as a circuit board?

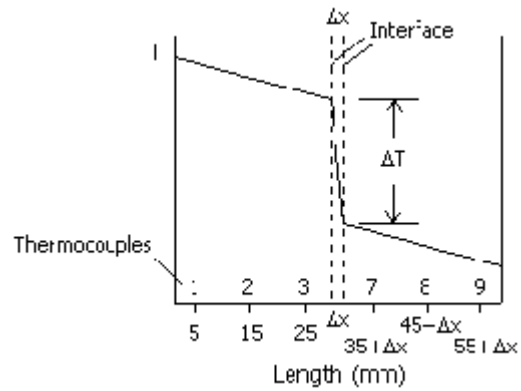


Figure 4.1 Temperature distribution along the cork

4.7 Raw Data and Result Tables

Record your reading as follows:

Table 4.1 Raw Data for Experiment #4.

<i>Wattmeter</i> <i>Q (W)</i>	<i>T₁</i> <i>(°C)</i>	<i>T₂</i> <i>(°C)</i>	<i>T₃</i> <i>(°C)</i>	<i>T₇</i> <i>(°C)</i>	<i>T₈</i> <i>(°C)</i>	<i>T₉</i> <i>(°C)</i>

The final results should be reported in the following format:

Table 4.2 Processed Data for Experiment #4

<i>Sample</i>	<i>Area (mm²)</i>	<i>Width</i> <i>(mm)</i>	<i>Q</i> <i>(W)</i>	<i>ΔT</i> <i>(°C)</i>	<i>k_{exp}</i> <i>(W/mm·K)</i>	<i>k_{ref}</i> <i>(W/mm·K)</i>	<i>% error</i>

5. Heat Conduction in Fluids

5.1 Objective

The objective of this experiment is to study heat conduction in fluids by using Fourier's law. In this experiment the thermal conductivity of water will be determined and the results will be compared with known values.

5.2 Introduction

Conduction does take place in fluids as well as solids. Usually the most common mode of heat transferred in a fluid is convection because of the bulk motion created by buoyancy forces due to density gradients throughout the liquid. However, as the space occupied by the fluid becomes very small, density gradients become negligible. Since there is negligible bulk motion, heat transfer is primarily due to conduction. In this experiment we will use an apparatus, shown in Figure 5.1 that will enable us to neglect density gradients and allow us to study conduction in the fluids air and water.

5.3 Theory

To find the thermal conduction coefficient we must use Fourier's Law. Solving for k we get,

$$k = \frac{q_c \, dx}{A \, dT} \quad (5.1)$$

For radial heat conduction in a cylinder, dx becomes dr and area A is the cross sectional area of the conducting path. Now for measurements made at steady state conditions across the small radial gap, dr becomes Δr , and dT becomes ΔT so we can obtain,

$$k = \frac{q_c \, \Delta x}{A \, \Delta T} \quad (5.2)$$

In order to find the heat by conduction (q_c) we must make use of conservation of energy. When applied to this system we get,

$$q_c = q_{gen} - q_{lost} = \frac{V^2}{R} - q_{lost} \quad (5.3)$$

Substituting Equation 5.2 into Equation 5.3 we get the following expression for q_{lost} .

$$q_{lost} = q_{gen} - q_c = \left(\frac{V^2}{R} \right) - kA \frac{\Delta T}{\Delta r} \quad (5.4)$$

The symbols V and R are the voltage and resistance of the heater element which generates electrical heat (Figure 5.1). In this mechanism there are heat transfers other than that transferred by conduction through the fluid under test. These heat "losses" are defined as *incidental* heat transfer. The heat losses can be a result of:

1. Heat conduction through the O-ring seals
2. Heat radiated from the plug
3. Heat losses to the surroundings by radiation and convection from the exposed ends of the plug.

From a simple understanding of heat transfer, we may assume q_{lost} to be proportional to the temperature difference between the plug and the jacket. q_{lost} can be estimated from the calibration graph of incidental heat transfer versus the plug and jacket temperature difference (see Figure 5.2). For this analysis you will use the known thermal conductivity of air (Figure 5.3). The thermal conduction coefficient can then be calculated for other fluids by the temperature difference across the fluid.

In other words, the data from the air calibration test is used to calculate q_c from Equation 5.2, using the known tabulated thermal conductivity of air, k_{air} . The value for q_{gen} is then calculated and Equation 5.3 solved for q_{lost} . The graph of the three q_{lost} vs. ΔT values is the calibration curve, from which the values of q_{lost} for the water test will be found (it is assumed that heat loss is directly related to temperature difference). The q_{lost} from the graph and the calculated value of q_{gen} for the water tests are then put into Equation 5.3 to find q_c . Finally, the value of q_c is put into Equation 5.2 to give the experimental thermal conductivity of water.

5.4 Apparatus

H470 Heat Conduction Unit, the apparatus used in this experiment consists of three items.

5.4.1 The first item

Is the transformer used to convert 110 to 220 volts.

5.4.2 The second item

Is the plug jacket assembly, which consists of two cylinders. *The smaller cylinder* or plug is machined from aluminum (to reduce thermal inertial and temperature variation) and contains a cylindrical heating element whose resistance at the working temperature is accurately measured. A thermocouple is inserted into the plug close to its external surface, and the plug also has ports for the introduction and venting of the fluid under test.

The second cylinder or water cooled jacket fits concentricity around the plug. The fluid whose thermal conductivity is to be determined fills the small radial clearance between the heated plug and the water cooled jacket. The clearance is small enough to prevent natural convection in the fluid. Due to the positioning of the thermocouples and the high thermal conductivities of the materials involved, the temperatures measured are effectively the temperatures of the hot and cold faces of the fluid surface.

5.4.3 The Third Item

The console, which is connected by flexible cables to the plug/jacket assembly and provides for the control of the voltage supplied to the heating element. An analog voltmeter enables the power input to be determined and a digital temperature indicator with 0.1K resolution displays the temperatures of the plug and jacket surfaces. The features of the console are shown in Figure 5.1.

The following are specifications of the apparatus needed for calculations.

1. Nominal resistance of heating element, $R = 55 \Omega$
2. Nominal radial clearance between plug and jacket, $\Delta r = 0.30 \text{ mm} *$
3. Effective area of conducting path through fluid, $A = 0.0133 \text{ m}^2$

***The values to be used are engraved on the head of the plug!**

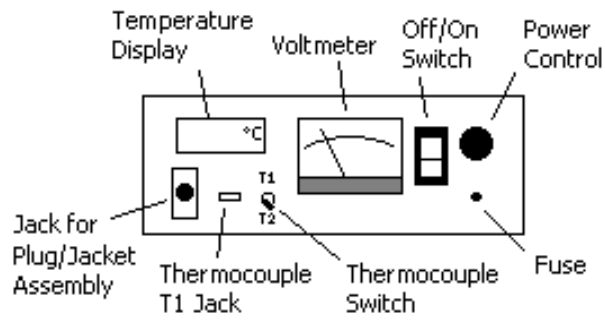


Figure 5.1 Schematic of Console Unit

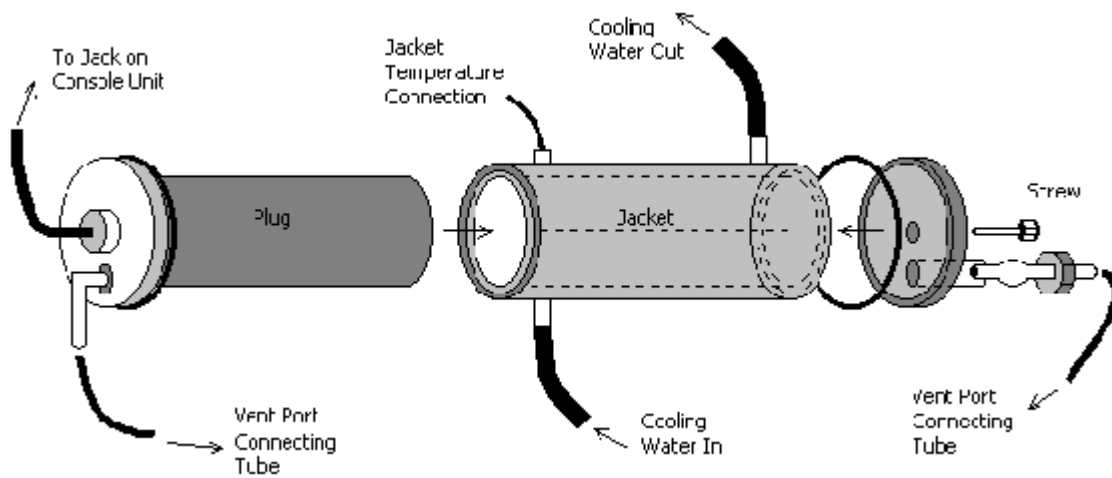


Figure 5.2a Schematic of Plug/Jacket Assembly

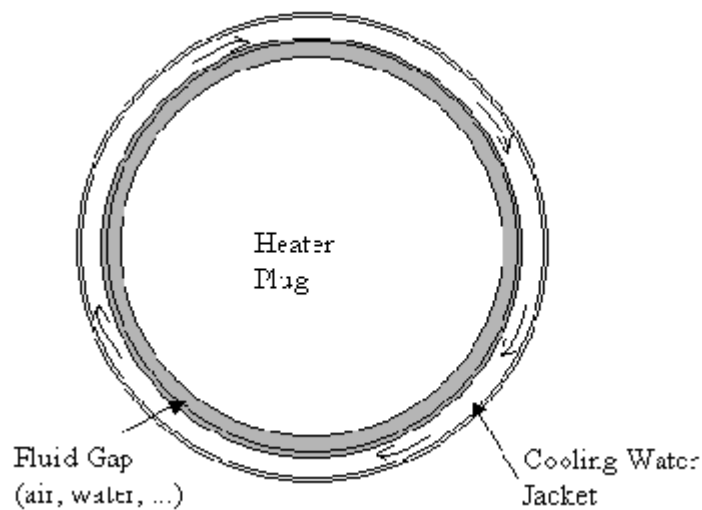


Figure 5.2b Cross-Sectional View of Plug/Jacket Assembly

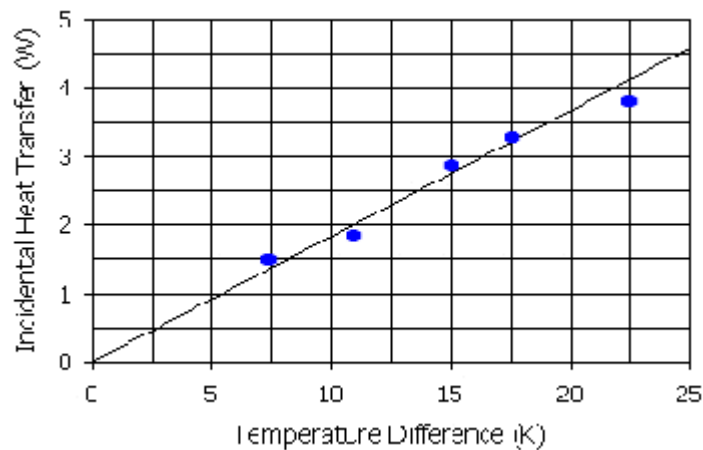


Figure 5.3 Example Graph of Incidental Heat Transfer

5.5 Procedure

5.1 Preparation

1. Ensure the main switch is off.
2. Connect the thermocouple from the jacket to the hand held thermocouple measuring device. Connect the main power cord from the test apparatus to the main control box. Note that the core temperature can be taken from the main control box, and the water jacket temperature is taken from the hand held thermocouple meter. Make sure that the

toggle switch is in the down (T_2) position. Please leave the switch alone during the remainder of the experiment.

3. Pass water through the jacket at about 3 liters per minute (the actual quantity is unimportant but a copious supply is necessary so the jacket will operate at a sensibly constant temperature). The space between the plug and the jacket will remain occupied by air.

5.2 Calibrating the device by heat loss estimation with air in the gap

1. Connect the small flexible tubes to the charging and vent unions at either end of the plug and jacket to close off the chamber. Note: Air is now trapped in the radial chamber.
2. Switch on the electrical supply.
3. Adjust the variable transformer to about 15 V.
4. Observe the plug and jacket temperatures and when they are stable, enter their values and the voltage in Table 5.1.
5. Increase the electrical input to about 30 V and when stable repeat the step above.
6. Repeat again for 45 V.
7. Calculate the incidental heat loss and plot the heat loss as a function of the temperature difference. Calculate the best fit line using linear regression. This will be your preliminary calibration curve for estimating heat loss (see Figure 5.3)
8. Repeat the experiment three more times to improve the heat loss estimate and study the error in the estimate of heat loss. Adjust the transformer to about 40 V, and measure the temperatures and voltage when stable.
9. Repeat again for 25 V, and 10 V.
10. Calculate and plot the heat loss for all six data measurements together on the graph and repeat the linear regression analysis. This will be your final calibration curve for heat loss.

5.6 Raw Data and Result Tables

Table 5.1 Raw Data for Air

<i>Voltage</i> (V)	T_p (°C)	T_j (°C)	ΔT (°C)	q_{gen} (W)	q_c (W)	q_{lost} (W)	k_{air} (ref.)

Table 5.2 Raw Data for Water

<i>Voltage</i> (V)	T_p (°C)	T_j (°C)	ΔT (°C)	q_{gen} (W)	q_{lost} (W)	q_c (W)

$k_{exp} =$ W/mm.K,

$k_{ref} =$ W/mm.K,

% diff. = %

6. Boiling Heat Transfer

- **Suggestion:** Study Chapter 10 in (F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 5th ed., John Wiley and Sons, 2001) or others where boiling and condensation are discussed.

6.1 Objective

The objective of this experiment is to study the effects of phase change on convection by observing the three modes of boiling and determining the heat flux and surface heat transfer coefficient at constant pressure.

6.2 Introduction

The previous experiments have dealt with heat transfer by convection to single phase fluids, or simply pure liquids or pure gases. But what happens when this heat transfer takes place with a fluid that is undergoing a phase change? Thermodynamics says that there will be an exchange of latent heat associated with the phase change. Secondly, there will be a density difference between the two phases, and thirdly, there will be surface tension between the liquid vapor interfaces. All of these parameters will significantly affect heat transfer rates and coefficients during a phase change. Since boiling and condensation are the most important phase changes for heat transfer studies, this experiment deals only with these two for now.

There are basically two major modes of condensation and boiling. For boiling they are film and nucleate boiling, and for condensation they are film and dropwise condensation. Film boiling and condensation are primarily driven by the density difference ($\rho_f - \rho_g$), where the subscripts denote liquid and gas. Dropwise condensation and nucleate boiling are controlled by both density and surface tension.

In this experiment we will look at the boiling of 1,1-Dichloro-1-fluoroethane (R141b) $\text{CCl}_2\text{F-CH}_3$ fluid in great detail and observe how the heat transfer rate and coefficient change throughout each stage of the boiling process.

6.3 Theory

Recall from previous experiments Newton's Law of Cooling,

$$q_s = h(T_s - T_{sat}) = h\Delta T_e \quad (6.1)$$

where ΔT_e is called the excess temperature defined as the temperature difference between heat source and saturation temperature of the fluid.

As it can be seen in Figure 6.1, which shows the stages of pool boiling, when the excess temperature lies between 0.2 and 4 degrees Celsius, only free convection can be observed. When excess temperature is between 4 and 20 degrees there is nucleate boiling. In this region isolated bubbles and or columns or slugs of bubbles will exist. At point P in this region, the heat transfer coefficient starts to decrease due to increased bubbles, which lessen the total surface-liquid contact. However, the heat rate continues to rise because of the rising excess temperature until point C where the maximum heat transfer is reached. After this point the decrease in the coefficient surpasses the increase in excess temperature and the heat transfer rate begins to decrease. Between points C and D is the transition region between nucleate and film boiling. In this region there is a combination of both types of boiling. Because the surface is now primarily in contact with a combination of bubbles and a vapor film, the heat transfer coefficient is reduced drastically; and therefore, the heat transfer rate will continue to decrease until point D. From the point D on there is only film boiling where the surface is covered by a vapor blanket. In this region there is no longer any surface to liquid contact; however, the heat transfer rate continues to increase as excess temperature increases because heat transfer by radiation becomes significant.

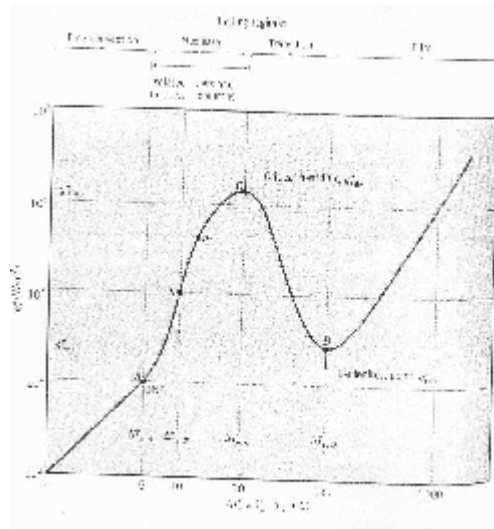


Figure 6.1 Typical Boiling Curve for Water at 1 atm: Surface Heat Flux q_s as a Function of Excess Temperature, $\Delta T_e = \Delta T_s - \Delta T_{sat}$. (Ref. 1).

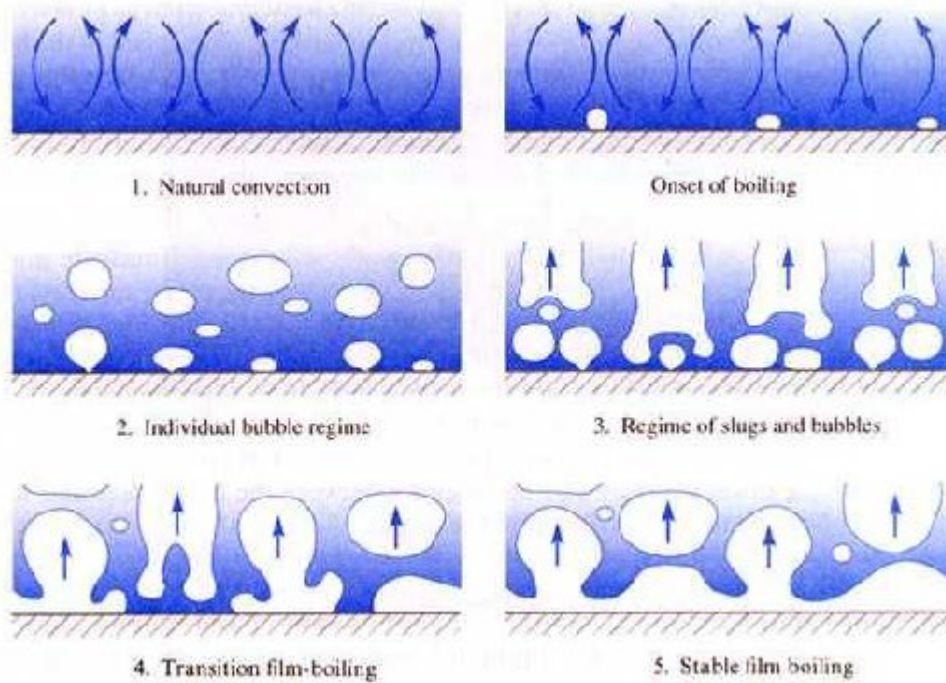


Figure 6.2 Four Regimes of Pool Boiling in Water at 1 atm (Ref. 2).

6.4 Apparatus

The apparatus for this experiment is the Boiling Heat Transfer Unit H655. This unit is a very simple to understand. Study the diagram attached to the equipment to gain an understanding of the operation of the unit.

Data:

Fluid: 1,1-Dichloro-1-fluoroethane (R141b) $\text{C Cl}_2 \text{F-CH}_3$

Quantity: 0.55 Litre

Heat transfer to surroundings: approx. 0.8 W/K

Specific heat of water: 4.18 kJ/kgK

Dimensions of heating surface (fin)

Length: 42 mm

Diameter: 12.7 mm

Surface Area (total): 0.0018 m²

Condenser Surface Area: 0.0320 m²

GlassChamber

Nominal Internal Diameter: 80 mm

Length: 300 mm

Volume: 0.0015 m³

6.5 Procedure

A. Visual Demonstration of the Modes of Boiling

1. Turn on the electrical heater and cooling water and adjust both to low settings. Allow the digital thermometer to stabilize. Observe this and the liquid temperature at frequent intervals. Carefully watch the liquid surrounding the heater. Convection currents will be observed, and at the same time liquid will be seen to collect and drip on the condenser coils, indicating that evaporation is proceeding although at a low rate.
2. Increase the wattage in increments, keeping the vapor pressure at any desired constant value by adjusting the cooling water flow rate. Nucleate boiling will soon start and will increase until vigorous boiling is seen, the temperature difference between the liquid and metal is still quite moderate (< 20 K).
3. Increase the power input to a level between 300 and 400 Watts. The nature of the boiling will be seen to change dramatically and at the same time the metal-liquid temperature difference will rise quickly. The rate of evaporation falls to a low level and the water flow rate must be reduced to maintain a steady pressure. The electrical input should now be reduced to about 60 Watts. Careful examination of the heater surface will show that it is now enveloped in an almost unbroken film of vapor and this is the cause of the reduced heat transfer rate.
4. The electrical power input should now be reduced to zero. It will be found that as the metal-liquid temperature difference falls to about 40 K the boiling suddenly becomes vigorous as film boiling reverts to nucleate boiling.
5. Record your observation in Table 6.1.

B. Determination of Heat Flux and Surface Heat Transfer Coefficient at Constant Pressure

1. Adjust the electric heater to about 30 Watts and adjust the water flow rate until the desired pressure is about 50 kN/m^2 . Note the voltage, current, vapor pressure, liquid temperature and metal temperature.

2. Increase the power to say 50 Watts, adjust the cooling water flow rate to give the desired pressure and when steady, repeat the observation. Try to keep the pressure from changing too much.
3. Repeat in similar increments until the transition from nucleate to film boiling is reached. By careful adjustment of voltage near this condition it is possible to make an accurate assessment of critical conditions.
4. When film boiling is established the voltage should be reduced carefully so that film boiling still remains. If you reduce the voltage too much the system will go out of film boiling, and if the voltage is too high the temperature will rise above the automatic kick-out value and the power will kick on and off making it difficult to accurately measure the heat flux. Reduce the voltage in very small increments so that the temperature finally stabilizes and the voltage ceases to kick on and off.
5. Record your observation in Table 6.2

C. Effect of Pressure on Critical Heat Flux

The Method is similar to that performed in Part A and B, but by careful adjustment of the power and water flow rate, the heat flux at transition from nucleate to film boiling at a variety of pressures may be established.

1. Increase the voltage close to the transition from nucleate to film boiling while keeping the flow rate off. The pressure will rise steadily. When the pressure reaches a desired level turn on the flow rate ever so slightly. Increase the flow rate in small increments until the pressure stabilizes. Continue to increase the voltage until the transition from nucleate to film boiling is evident. Transition is evident when just a slight increase in voltage causes the temperature to increase steadily which would normally stabilize.
2. Repeat the above for various flow rates to get a good variety of pressures similar to the example results below (your results may differ).
3. Record your data in Table 6.3

Note: Effective heating surface area of fin is 0.0018 m^2 .

Pressure (kN/m ²)	75	108	130	172	206
Voltage (Volts)	121	124	127	131	136
Current (Amps)	1.8	1.92	1.96	2.01	2.06

From which:

Critical Heat Flux (kW/m ²)	168	175	184	195	207
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D. Filmwise Condensation

The filmwise condensation, which occurs with R141b, can be clearly seen and the resistance to heat transfer offered by the liquid film is readily appreciated. In this part you will observe the filmwise and dropwise condensation on the cooling coils. The overall heat transfer coefficient between the condensing vapor and the cooling water maybe found as follows:

1. Adjust the voltage to a low setting so that nucleate boiling is evident and adjust the water flow rate to about 10 g/sec. Keep adjusting the voltage so that a pressure of about 60 kN is reached.
2. When conditions are stable, record the water inlet and outlet temperatures and the saturation temperature (vapor temperature) of the R141b. Record all other data as well. Notice droplet condensation on the upper coils and the small amount of film condensation on the bottom coils.
3. Increase the flow rate to about 40 g/s and adjust the voltage to maintain constant pressure of 60 kN. Repeat step 2. Notice the increased amount of film condensation on the lower coils.
4. Record your data in Table 6.4

6.6 References

1. F. P. Incropera and D. P. DeWitt, "*Fundamentals of Heat and Mass Transfer*", 5th ed., John Wiley and Sons, 2001
2. Kreith and Bohn, "*Principles of Heat Transfer*", West Pub. Co., 1993

6.7 Raw Data and Result Tables

PART A

1. Record in your report (Table 6.1) what you observe including wattage, flow rates etc. No calculations are required for this part.
2. Discuss why the surface temperature of the fin begins to rise as the mode of boiling changed from nucleate to film.
3. What do you suppose happened to the value of the convection coefficient during this transition? Please explain your reasoning.

Table 6.1 Data for Boiling Heat Transfer Part A

<i>Heater temp. (°C)</i>	<i>R-141b temp. (°C)</i>	<i>Delta temp. (°C)</i>	<i>R-141b press. (kN/m²)</i>	<i>Volts (V)</i>	<i>Power (W)</i>	<i>h (W/m²K)</i>	<i>Water flow (gram/s)</i>	<i>Boiling Condition</i>

PART B

1. Record your data in Table 6.2
2. From the data in Table 6.2 calculate the heat transfer rate (kW), the heat transfer coefficient h (kW/m²K) between liquid and metal.
3. Make a plot of heat flux verses excess temperature difference and compare qualitatively this plot with Figure 6.1.
4. Make a plot of the heat transfer coefficient as a function of the excess temperature.
5. Discuss your results. Are they reasonable?
6. Discuss any errors that might occur within the equipment or methodology of the experiment.

Table 6.2 Data for Part B

<i>Heater temp. (°C)</i>	<i>R-141b temp. (°C)</i>	<i>Delta temp. (°C)</i>	<i>R-141b press. (kN/m²)</i>	<i>Volts (V)</i>	<i>Power (W)</i>	<i>h (W/m²K)</i>	<i>Water flow (gram/s)</i>	<i>Boiling Condition</i>

PART C

1. Record your data in Table 6.3
2. Using the data you obtain, make a plot of critical heat flux vs. absolute pressure (kN/m^2).
3. Comment on your results

Table 6.3 Data for Part C

<i>R-141b pressure</i> (kN/m^2)	<i>Volts</i> (V)	<i>Power</i> (W)	<i>Power flux</i> (kW/m^2)	<i>Water Flow</i> (g/s)

PART D

For each run calculate:

1. Heat transfer rate to cooling water ($mC_p\Delta T$) (Watts)
2. Log mean temperature difference (see text for equation)
3. Overall heat transfer coefficient (W/m^2K) ($q=UA\Delta T_{lm}$), where

q is the heat transferred to the cooling water

A is the surface area of the condensing coils

ΔT_{lm} is the log mean temperature difference

U is the overall heat transfer coefficient.

4. Discuss the effect of droplet versus film condensation on the overall heat transfer coefficient and the heat transfer to the cooling water.

(Hint: Consider the increased amount of film condensation and decreased amount of droplet condensation from the first run to the second when discussing the above).

Table 6.4 Data for Part D

<i>R-141b pressure (kN/m²)</i>	<i>Voltage (V)</i>	<i>Flow rate (g/s)</i>	<i>Inlet water Temp. (°C)</i>	<i>Outlet water Temp. (°C)</i>	<i>q_{wate r} (W)</i>	<i>ΔT_{l m} (K)</i>	<i>U (W/m²K)</i>

7. Film and Dropwise Condensation

7.1 Objective

The objective of this experiment is to study the effects of condensing surfaces by observing the modes of condensation and determining the heat flux and surface heat transfer coefficient at constant pressure.

7.2 Introduction

The previous experiments have dealt with the boiling of 1,1-Dichloro-1-fluoroethane (R141b) $\text{CCl}_2\text{F-CH}_3$ fluid in great detail and observed how the heat transfer rate and coefficient change throughout each stage of the boiling process. So, that experiments focus on the boiling process of the fluid as well as the heating element. This experiments focus on the condensation processes as well as on the condensing surface. The fluid that will be used in this experiment is water.

There are basically two major modes of condensation. They are film and dropwise condensation.

In this experiment we will look at the condensation of water in great detail and observe how the heat transfer rate and coefficient change throughout each stage of the condensation process.

7.3 Theory

- A. Filmwise Condensation
- B. Dropwise Condensation.

7.3.1 Filmwise Condensation

As briefly described, during filmwise condensation a layer of condensation covers the cool surface and this offers resistance to the transfer of heat. Depending upon the height of the condensing surface, the rate of condensation and the local vapour velocity, flow in this layer, which is flowing in a generally downward direction, may be laminar, or mildly turbulent with a "rippled surface". When flow is laminar as in the Hilton Film and Dropwise Condensation

Unite, the rate of heat transfer can be determined from theoretical considerations provided a number of assumptions are made. These include,

- i. Flow in the condensate film is entirely laminar.
- ii. Heat is transmitted through the layer by conduction only.
- iii. The temperature in the layer falls uniformly from the saturation temperature of the vapour on the outside to the temperature of the cooling surface on inside.
- iv. The condensate flows under the action of gravity only.

Using these assumptions Nusselt derived the following equation for vertical surfaces with film wise condensation.

$$h_{mean} = \frac{2}{3} \sqrt{2} \left[\frac{k_f^3 \rho_f^2 h_{fg} g}{x \mu_f (t_{sat} - t_{sur})} \right]^{1/4} \quad (7.1)$$

$$h_{mean} = 0.943 \left[\frac{k_f^3 \rho_f^2 h_{fg} g}{x \mu_f (t_{sat} - t_{sur})} \right]^{1/4} \quad (7.2)$$

It will be noted that the properties k , ρ , and μ used are at saturated liquid conditions , although within the layer of condensate , the liquid will be slightly sub-cooled. The derivation of this equation and descriptions of more recent work which have resulted in slightly different expressions are given in reference (1).

7.3.1 Dropwise Condensation

The surface heat transfer coefficient achieved during dropwise condensation is usually between 5 and 10 times greater than with filmwise condensation under the same conditions. Dropwise condensation does not provide the same opportunity for theoretical analysis as does filmwise, but a considerable amount of experimental data has been accumulated. This has related to both heat transfer coefficients and to methods of promoting dropwise condensation in practical plants. Unfortunately common drpwise condensation promoters are effective for a relatively short time and at present suitable permanent surface treatments are either too expensive or impractical.

If dropwise condensation can be reliably achieved in practical plants, the heat transfer surface area required in steam to water heat exchangers can be reduced to about 60% of the present size. It therefore seems probable that efforts to achieve this will continue.

7.4 Apparatus

The apparatus for this experiment is the Film and Dropwise Condensation Unit H910. This unit is a very simple to understand. Study the diagram attached to the equipment to gain an understanding of the operation of the unit.

Data:

Fluid: Distilled Water

Quantity: 500 cm^3

Heat transfer to surroundings: approx. 2.5 W/K

Specific heat of water: 4.18 kJ/kgK

Dimensions of heating surface (fin)

Surface Area of heating element: $14.4 \times 10^{-3} \text{ m}^2$

Condenser Surface Area: $3.7 \times 10^{-3} \text{ m}^2$

Diameter: 12.7 mm

Length: 90 mm

Temperature drop across copper shell of condenser: $2 \times 10^{-6} \phi \text{ (K)}$, where ϕ is in W/m^2

Glass Chamber

Nominal Internal Diameter: 76 mm

7.5 Procedure

A. Visual Demonstration of the Modes of Condensations

1. Turn on the electrical heater and cooling water and adjust both to low settings. Allow the digital thermometer to stabilize, the water temperature $t_1 = 80^\circ\text{C}$
2. Carry out the air extraction procedure and then carry on heating until t_1 reaches the desired value (100°C).

3. Adjust the condenser flow rates until the surface temperatures of the dropwise, t_2 and the filmwise, t_5 are equal and about 8 to 10 K less than t_1 .
4. Compare the condensation processes. By keeping one flow rate constant and changing the other.

B. Measurement of Heat Flux and Surface Heat Transfer Coefficient During Filmwise and Dropwise Condensation

1. Run the unit for about five minutes with a saturation (steam) temperature t_1 of 100°C and low condenser water flow rate. This is to warm all the components and to reduce condensation on the glass.
2. Select the steam temperature (t_1) which is to be constant for the test (this may be anywhere between about 50°C and 100°C)
3. Circulate water through the **dropwise** condenser at a low rate (say 5 gm s⁻¹) and adjust the heater input to maintain the selected value of t_1 .
4. Note the steam temperature t_1 , the surface temperature t_2 , the cooling water inlet temperature t_3 , the water outlet temperature t_4 , and the water flow rate m_d .
5. Increase the water flow rate (to say 10 gm s⁻¹) and gain adjust the heater input to bring the steam temperature (t_1) to the selected value.
6. A gain note t_1 , t_2 , t_3 , and m_d .
7. Repeat at other water flow rates up to the maximum.
8. Record your data in Table 7.1
9. Repeat in a similar manner but using the **filmwise** condenser with appropriate water flow rates, observing t_1 , t_5 , t_6 , t_7 and m_c .
10. Record your data in Table 7.2
11. Repeat both tests at other constant values of t_1 .

Table 7.1 Raw Data for Dropwise Condenser

Test No.	1	2	3	4	5	6
Chamber Pressure (P_{sat} kN.g/m ²)						
Saturation Temperature, t_1 (°C)						
Indicated Surface Temperature, t_2 (°C)						
Water Inlet Temperature, t_3 (°C)						
Water Outlet Temperature, t_4 (°C)						
Water Flow Rate, m_d 10 ⁻³ kg/s						

Table 7.1 Raw Data for Filmwise Condenser

Test No.	1	2	3	4	5	6
Chamber Pressure (P_{sat} kN.g/m ²)						
Saturation Temperature, t_1 (°C)						
Indicated Surface Temperature, t_5 (°C)						
Water Inlet Temperature, t_6 (°C)						
Water Outlet Temperature, t_7 (°C)						
Water Flow Rate, m_d 10 ⁻³ kg/s						

C. Investigation of the Saturation Pressure Temperature Relationship for H₂O

1. Ensure that the water level in the chamber is correct.
2. Carry out the air extraction procedure.
3. With a small flow of cooling water through the condenser, bring the saturation temperature (t_1) to 100°C and allow the unit to warm through for about five minutes.
4. Observe t_1 to, say, 95°C by increasing the condenser cooling water flow and reducing the heat input.
5. Again observe the gauge pressure and t_1 .
6. Repeat in similar decrements of t_1 until the lowest value possible is obtained.
7. Increase the value of t_1 in the same steps as used previously and again observe the gauge pressures.
8. Record you data in Table 7.3
9. Compare average results with accepted values in thermodynamic property tables.

Table 7.3 Raw Data for Part C

Saturation Temperature, t_1 (°C)	Gauge Pressure (kN/m ²)	Absolute Pressure (kN/m ²)

7.5 References

1. F. P. Incropera and D. P. DeWitt, “*Fundamentals of Heat and Mass Transfer*”, 5th ed., John Wiley and Sons, 2001

8. Fluidization and Fluid Bed Heat Transfer

8.1 Objectives

- To investigate the behavior of a fluidized bed regarding its fluidization phenomena and its heat transfer properties.
- Examine the relationship between bed height, bed pressure drop, and upward air velocity through a bed of granular material.
- Investigate the effects of:
 1. Superficial air velocity.
 2. What is the effect of superficial velocity of the air on the convective heat transfer coefficient at the heater surface? What is the convective heat transfer coefficient for natural convection to the ambient air surrounding the fluidized bed glass vessel?

8.2 Introduction

Many important industrial processes rely upon intimate contact between a fluid and a granular material. These processes vary widely from grain drying, to a wide range of chemical reactions including combustion.

In early applications, the fluid flowed through a static bed of granules supported on a suitable grid.

Provided the material is suitable, great improvement in mixing and contact is achieved if the granule size is matched to the upward velocity of the fluid, so that the particles of material are supported by the drag forces. In this condition the fluid is said to be *fluidized*.

A gas fluidized bed may have the appearance of a boiling liquid, having bubbles with rise and appear to burst, vigorous mixing, and a generally horizontal free surface.

The motion of the bed varies with the fluid flow rate, and at high velocities, particles may become entrained and transported by the fluid.

Due to the very thorough mixing and large contact area between the gas and particles, a fully fluidized bed has little temperature variation, and the gas leaves at a temperature which is close to that of the bed. A body immersed in a fluidized bed at a different temperature to itself will experience a rate of heat transfer many times greater than would be experienced between the body and gas alone. This is because the boundary layer, which normally impedes heat transfer, is penetrated by a succession of hot (or cold) particles which make physical contact with the immersed body and enhance the heat transfer.

The attractive heat transfer properties of a fluidized bed, coupled with its ability to burn a wide range of “difficult” fuels has encouraged the development of many compact fuel burning appliance.

In this experiment we will investigate the behaviour of a fluidized bed regarding its fluidization phenomena and its heat transfer properties.

8.3 Theory

When a fluid flows through a bed of particles in a tube, it will exert a drag force upon the particles resulting in a pressure drop across the bed. As the fluid’s superficial velocity is increased, pressure drop is magnified. In an unrestrained bed that has fluid flowing upwardly through it, a condition will be reached where, with increasing fluid velocity, the drag forces will cause the bed to expand. This expansion allows the particles to offer less resistance to the fluid flow. When the drag force is sufficient to support the weight of the particles in the bed, the bed is said to be fluidized. The fluid/solid system shows fluid-like properties, and the bed can be made to flow from one vessel to another. The pressure drop across the bed, Δp , then remains constant (even with further increase in the fluid velocity) and equal to the effective weight of the bed per unit area:

$$\Delta p = \frac{m}{\rho_p S_b} (\rho_p - \rho_f) \quad (8.1)$$

m - mass of particles

ρ_p - density of particles

S_b - cross-sectional area of the bed

ρ_f - fluid density

g - gravitational acceleration

In the Fluidization and Fluid Bed Heat Transfer Unit, the fluid is air. The unit is operated at pressures comparable to atmospheric, therefore ρ_f is negligible compared with ρ_p . The particles supplied to form the bed are alumina of density 3700 kg m^{-3} , with average sizes between $125 \text{ }\mu\text{m}$ and $320 \text{ }\mu\text{m}$. These will illustrate one type of gas fluidized bed behavior [1, 2, 3]. As the gas velocity, U , is raised beyond that required to bring the bed to a fluidized condition, i.e. beyond the minimum fluidization velocity, U_{mf} , the bed will begin to bubble. This condition is called *aggregative fluidization*. Cavities looking like vapor bubbles in a boiling fluid will form and generate particle circulation within the bed. The gas flow between

the particles (the interstitial gas flow) remains practically constant; the gas flowing through the bubble phase accounts for any increase in superficial velocity. If the gas velocity were increased excessively, the bubbles would grow so large that they would nearly or completely fill the cross-section of the tube pushing slugs of particles ahead of the. A slugging bed would ensue. Under such high gas flow conditions, energy is used to accelerate slugs of particles, resulting in a pressure drop across the bed that may exceed the given weight per unit area that is lost through particle/wall interactions.

If the fluid were more dense, (e.g. a gas at the high static pressure of a liquid), or if the particles were finer (20 to 100 μm) and less dense ($<1400 \text{ kg m}^{-3}$), the bed would be able to sustain a degree of stable expansion, also known as particulate fluidization. The bed would remain stable until the U_{mf} had been exceeded by a factor of 2 or 3. In contrast, when using gas to fluidize a bed, the bed would collapse and reinitiate bubbling with further increase in gas velocity. A liquid fluidized bed usually continues to expand stably with increasing velocity resulting in a non-bubbling fluidized condition known as a quiescent bed.

With finer, less dense and cohesive powders, it is very difficult to fluidize the bed at all, because the interparticle forces are then greater than the gravitational ones. The particles tend to stick together, and the gas passes through the bed by blowing *channels* through it. Also, when fluidizing particles that are generally larger than 600 μm and/or denser than 4000 kg m^{-3} , the bed fluidizes less stably than that which will be seen with the alumina, and the bubbling behavior is different. Quite often, unwarranted generalities are made from particular observations because of a lack of appreciation for the extraordinarily wide range of behavior that can occur depending on operating conditions and bed material properties.

8.3.1 Advantages and Drawbacks of the Fluidization Technique

The advantages of the technique of fluidization are:

1. The large surface area between particles and fluid promotes heat transfer operations.
2. The ease with which fluidized solids can be transported.
3. The excellent heat transfer properties of the gas-fluidized bed. The bubble generated mixing keeps the bulk of the bed isothermal, and high heat transfer rates are obtainable between the bed and immersed surfaces.

Fluidized bed reactors are most often used in the temperature regulation of highly exothermic reactions and in continuously recycling a catalyst between a reactor and regenerator. Currently, there is much interest in the potential advantages of fluidized bed combustors [3].

The disadvantages are:

1. Fluid throughput rates are limited to the range over which the bed is fluidized. If the velocity is much higher than U_{mf} , there can be excessive loss of material carried out from the bed and there may also be unacceptable particle damage due to excessive operating velocity.
2. The pumping power supplied to fluidize the bed can be excessive for very large, deep beds.
3. Size and type of particles which can be handled by this technique are limited.
4. Due to the complexity of fluidized bed behavior, there are often difficulties in attempting to scale-up smaller scale to industrial units.

8.3.2 Determination of Minimum Fluidizing Velocity

Ergun [4] derived a correlation for the prediction of U_{mf} by equating a correlation for pressure drop through a packed bed at the voidage corresponding to that at minimum fluidization, ϵ_{mf} , to the weight of the bed per unit area [following equation (8.1)] and obtained the following form:

$$Ar = 150 \frac{1 - \epsilon_{mf}}{\phi^2 \epsilon_{mf}^3} Re_{mf} + \frac{1.75}{\phi \epsilon_{mf}} Re_{mf}^2 \quad (8.2)$$

Ar - Archimedes number

Re_{mf} - Reynolds number in terms of U_{mf}

ϵ_{mf} - Voidage at minimum fluidization

ϕ - Particle shape factor

The first term of the correlation in Re_{mf} tends to dominate under laminar flow conditions, whereas, the second term in Re_{mf}^2 dominates in beds of very large particles for which the interstitial flow is turbulent. Under transitional conditions, the contributions of both terms are important. The correlation is obviously very sensitive to the value of ϵ_{mf} used. To use the correlation for predictive purposes, ϵ_{mf} may be estimated from measurements on a loosely packed bed, but it has been shown that ϵ_{mf} varies with operating temperature under some conditions [5]. It is also difficult to estimate the particle shape factor, ϕ , so large errors in the estimation of U_{mf} are likely (typically $\pm 30\%$).

8.3.2.1 Estimation of Voidage

For materials which have no internal porosity, the voidage can be estimated from the density of the solid ρ_p and the density of the bed ρ_b :

$$\rho = 1 - \frac{\rho_b}{\rho_p} \quad (8.3)$$

$$\varepsilon_{mf} = 1 - \frac{\rho_{bmf}}{\rho_b} \quad (8.4)$$

$$\rho_{bmf} = \frac{\text{Mass.of .particles.in.bed}}{\text{Volume.of .bed.at } U_{mf}} \quad (8.5)$$

8.3.2.2 Shape Factor

The shape factor (ϕ) is a ratio of surface area:

$$\phi = \frac{\text{(Surface area of sphere of given volume)}}{\text{(Surface area of particle of same volume)}} \quad (8.6)$$

This is easily calculated for regular geometric shapes but is more difficult to assess for irregular particles. The shape factor for the granular material supplied with this unit is about 0.73.

8.3.3 Observation of General Bed Behavior

A. Measurement of Minimum Fluidization Velocity, U_{mf}

If the value of U_{mf} required is that found under ambient conditions, it is best to measure it directly. To do this, charge a sufficient quantity of particles into the container to form a bed, then fluidize the bed vigorously for a few minutes to break down any particle interlocking. Make measurements of the pressure drop across the bed as the fluidizing gas velocity is reduced in stages. Plot the results in the form of bed pressure drop against superficial gas velocity. At the higher gas flow rates the pressure drop is expected to have a value equal to that of the weight of the bed per unit area, but it may be less than this because some of the weight of the bed is being supported by the column wall through particle/wall interactions.

At low gas flow rates, the pressure drop across the bed should increase from zero (with zero gas flow rate) linearly, with increase in superficial gas velocity, until the bed approaches the conditions of fluidization. This is because the gas flow through the bed will be laminar.

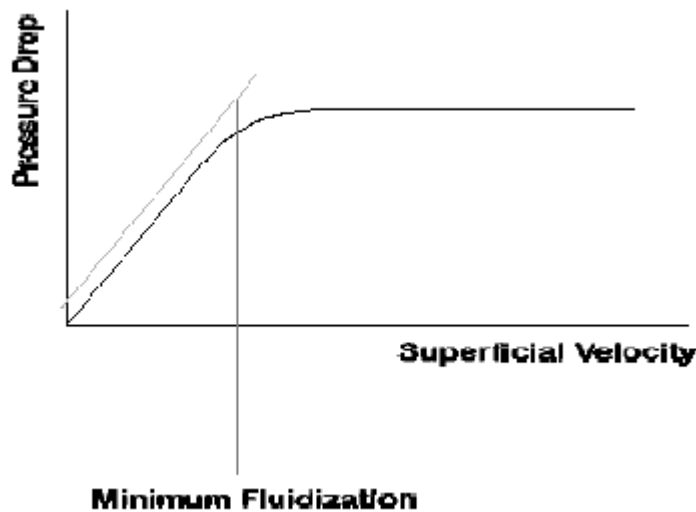


Figure 8.1 Superficial Velocity (Decreasing) versus Bed Pressure Drop

Figure 8.1 illustrates a typical plot of bed pressure drop against superficial gas velocity. The minimum fluidizing velocity corresponds to the velocity at the point of intersection between the rising and flat portions of the curve. If the experiment is performed with beds of much larger/denser particles, e.g. alumina of mean diameter ~ 1 mm, the increase in pressure drop will increase more rapidly because the flow conditions will be changing from laminar to transitional to turbulent.

If the experiment is repeated in the reverse direction by incrementally increasing the gas velocity from zero and noting the corresponding bed pressure drops, it may not follow the earlier curve, and it certainly will not do so if the bed has been tapped. Tapping encourages the bed to compact into the static condition with gas flow through it. This condition is because the bed voidage, ϵ , is reduced to below that of its condition at minimum fluidization, ϵ_{mf} . A measurement under these conditions will lead to an underestimate of the minimum fluidizing velocity. Also, when making incremental measurements from the packed bed condition, the bed pressure drop may initially exceed that of the weight of the bed per unit area as the bed begins fluidization, because the drag force has first to increase to break down the particle interlocking within the bed (Figure 8.2).

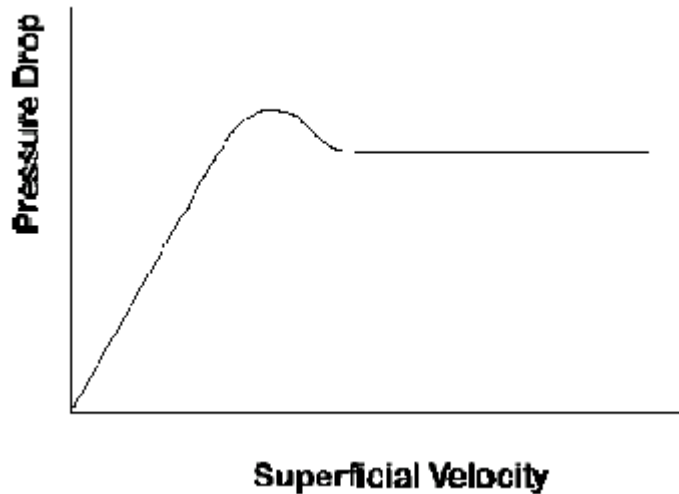


Figure 8.2 Increasing Superficial Velocity

The transition from packed to fluidized conditions will be sharper if the bed material is closely sized than if the bed consists of wide particle size distribution. In the latter instance, as the gas flow rate is increased, there will be a tendency for the finer particles to become fluidized first, and the approach to the fluidized condition will be more gradual. Under such conditions where the fines tend to fluidize and come to the top of the bed, segregation is occurring. If there is a wide particle size distribution, beds should be fluidized vigorously to produce a bubbling bed thus, quickly reaching a well mixed condition and reducing the tendency for segregation to occur.

Once segregation has occurred, it is much more difficult to remix the bed material. These properties will be seen in Experiment.

B. Bed Height

In these experiments the bed height should be measured as a function of superficial gas velocity. At higher velocities this can only be measured approximately, because the surface will fluctuate rapidly as bubbles burst through the surface. The degree of bed expansion beyond that seen at U_{mf} is due to the flow of bubbles through the bed. (Note: Although the bubbling bed may look turbulent, the interstitial gas flow between the particles is laminar except when fluidizing beds of large/dense particles.)

C. Bubble Behavior

It is instructive to look at the bubbling behavior. Bubbles usually grow as they rise through the bed. Partly this is a spontaneous process, but mostly it occurs by larger bubbles, rising more quickly than a smaller. They overtake the smaller bubbles and coalesce with them. With beds of large/dense particles, however, this coalescence behavior is different. These bubbles will tend to grow by cross-wise coalescence [2]. The rising bubbles draw a streak of particles after them and carry some particles in their wake. This is the mechanism by which solids circulation is generated.

The influence of the wall surface, makes the bubbles tend to move inwards into the bed. One can plainly see the return flow of solids descending at the wall in stick/slip flow to replace those which have been carried upward within the bulk of the bed by the rising bubbles.

Again, with beds of larger/denser particles, the bubbling action that occurs is not so effective in generating particle mixing as with the other bubbling beds. The higher the fluidizing velocity, the larger and more numerous the bubbles, because most of the excess gas flows as bubbles.

8.4 Apparatus

A. Description of Equipment

A schematic of the experimental apparatus is depicted in Figure 8.3. A bed of chosen granular material approximately 70 mm deep is contained in a vertical glass cylinder. At the lower end of the cylinder is a distribution chamber and an air distributor which supports the bed when defluidized. This distributor has been designed to ensure uniform air flow into the bed without causing excessive pressure drop and is suitable for the granular material supplied.

Upon leaving the bed, the air passes through the chamber and escapes to the atmosphere through the filter. The chamber, filter and distributor assembly are suspended from a bracket mounted on the panel. Installed in this bracket are probes for temperature and pressure measurement, and a horizontal cylindrical heating element. All of which may be moved vertically to any level in the bed chamber. Air from the local compressed air supply is delivered through a filter/pressure regulator, an air flow meter fitted with a control valve, and an orifice plate (to measure higher flow rates) to the distribution chamber.

When in use, the heat transfer rate from the heating element is controlled by a variable transformer, and the voltage and current are displayed on the panel. Two thermocouples are embedded in the surface of the heater element. One of these indicates the surface temperature, and the other, in conjunction with a controller, prevents the element temperature from exceeding a set value (up to 200°C). A digital temperature indicator with a selector displays the temperatures of the element, the air supplied to the distributor, and the moveable probe in the bed chamber. Also, the fluidization unit is equipped with a metal indicator (welded to the moveable probe). It is used to distinguish heights within the chamber.

Two liquid filled manometers are fitted to the apparatus. One displays the pressure of the air at any level in the bed chamber, and the other displays the orifice differential pressure, from which the higher air flow rates can be determined.

If the pressure in the distribution chamber rises above about 300 mm H₂O above atmospheric, (e.g. due to a blocked filter), an excess pressure relief device will discharge air into the atmosphere. This device will re-set automatically when the blockage is cleared.

An important feature of this unit is the ease with which the bed material may be changed. After unscrewing two union nuts to remove the air connections to the distribution chamber, three knurled nuts are removed from the mounting bracket. The chamber, filter and distribution assembly may now be removed and the bed material tipped out. Another bed material may now be poured into the cylinder. Once reassembling the components in reverse order, the unit can be operational within two or three minutes.

Three grades of Fused Alumina (Aluminum Oxide) Loose Grain are supplied with the unit. These grains are suitable for a wide range of fluidization and heat transfer experiments. In addition to the supplied materials, any dry and free flowing granular material of a suitable density and size may be introduced to the chamber creating many interesting demonstrations.

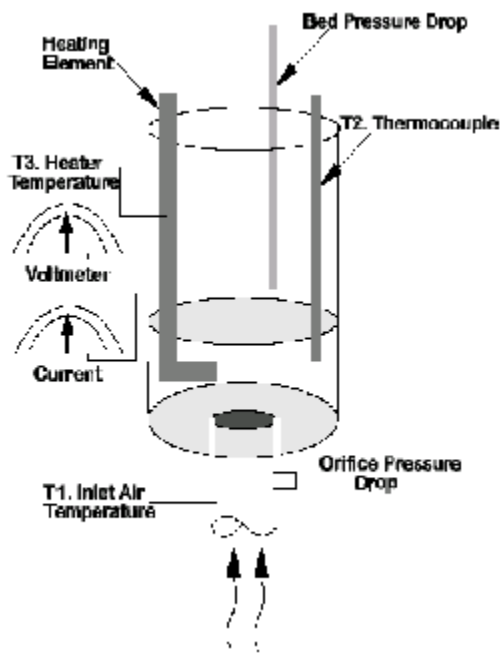


Figure 8.3 Experimental Set-up

B. Specifications

Panel	One piece G.R.P. Molding on which all components are mounted.
Bed Chamber	Strong Glass Cylinder Approx. 105 mm internal dia. x 220 mm long , closed at lower end by an air distribution system and at the upper end by a filter assembly.
Cylinder Mounting	Stainless steel bracket from which the chamber assembly is suspended. The bracket carries a heating element, a thermocouple and a pressure probe. All of which may be moved vertically within the chamber.
Heating Elements	Cylindrical, copper sleeved resistance heater fitted with two surface thermocouples. Surface area equals 16cm² .
Variable Transformer	To vary the heater power input. Allows for a constant heater temperature.
Air Filter/Regulator	To supply a clean and stable air supply.
Bed	Three containers of different fused alumina loose granules are supplied. These have average particles sizes ranging from approximately 125 to 350µm .

C. Instrument

Air Flow	From 0.15 to 1.7 liter per second by variable area flow meter fitted with a control valve. From 1.7 to 3.5 liter per second by an orifice and a 300 mm H ₂ O manometer for differential pressure measurement.
Temperature	Digital temperature indicator with a selector to indicate element, surface, air inlet and probe temperatures. Resolution is 1 degree.
Pressure	Fluid filled manometer (Range 300 mm H ₂ O) to indicate pressure in bed chamber.
Electrical Power	Voltmeter (0 to 250V) and ammeter (0 to 3A) to indicate heater power input.

8.4 Procedure

A. Observation of the Behaviour of Particles in a Bed with Upward Air Flow

1. Start up the Fluid Bed Unit with a moderate air flow and without heating.
2. Observe the air flow rate, orifice pressure drop, bed height, bed pressure drop, etc.

B. Investigation of the Relationship between Bed Height, Bed Pressure Drop, and Superficial Velocity through a Bed of Granular Material

1. Turn on the air flow to a high value and allow the bed to mix thoroughly for two or three minutes. Without changing the air flow, record the following:
 - i) The air inlet temperature, T_3
 - ii) The bed inlet temperature, T_2
 - iii) The bed height
 - iv) The pressure drop across the bed
2. Reduce the air flow rate in steps and repeat the observations at each setting.
3. Repeat all the observations as the air flow is increased in similar steps.
4. Record your data in Table 8.1

C. Investigation of the Effect of Superficial Velocity and Depth of Immersion on the Surface Heat Transfer Coefficient for a Hot Surface in an Air Fluidized Bed

1. Set up the heater to a convenient height above the distributor (say 40 mm)
2. Turn on the air flow to a high value and allow the bed to mix thoroughly
3. Adjust the variable transformer until the desired heater surface temperature (T_1) is attained (about 150°C)
4. Allow conditions to stable, then record:
 - i) Heater surface temperature, T_1
 - ii) Bed temperature, T_2
 - iii) Air temperature, T_3
 - iv) Heater Voltage, V
 - v) Heater Current, A
 - vi) Air flow rate (Orifice differential), V

5. Reduce the air flow, reset the variable transformer to obtain the desired value of T_1 then repeat the observations.
6. Repeat in convenient steps until the air control valve is closed.
7. Record your observations in Table 8.2.
8. Record your derived results in Table 8.3.

8.5 Raw Data and Result Tables

PART A

1. Record in your report what you observe including bed height, air flow rates, etc. No calculations are required for this part.

PART B

1. Record your observations in Table 8.1.
2. Make notes about the behaviour of the bed.
3. Make a graph between pressure drop across bed (ΔP) versus superficial velocity (U) for both velocity increasing and velocity decreasing. From the two curves, you can estimate the minimum fluidizing velocity for each process.
4. Similar graph can be performed between bed height versus superficial velocity (U).
5. Comment on your results and explain the differences in the minimum fluidizing velocity.

Table 8.1a Raw Data for Fluidization Bed (Part B, Air Flow: **Decreasing**)

	1	2	3	4	5	6	7	8	9
Orifice Differential Pressure, x (mm H ₂ O)									
Air Flow Rate, V_m (Liter/s)									
Air Inlet Temperature, T_3 (°C)									
Bed Temperature, T_2 (°C)									
Air Flow through Bed $\dot{V}_b = \dot{V}_m \frac{T_2}{T_3}$ (Liter/s)									
Superficial Velocity $U = 10^{-3} \frac{\dot{V}_b}{S_b}$ (m/s)									
Pressure Drop Across Bed, ΔP (mm H ₂ O)									
Bed Height (mm)									

Table 8.1b Raw Data for Fluidization Bed (Part B, Air Flow: **Increasing**)

	1	2	3	4	5	6	7	8	9
Orifice Differential Pressure, x (mm H ₂ O)									
Air Flow Rate, V_m (Liter/s)									
Air Inlet Temperature, T_3 (°C)									
Bed Temperature, T_2 (°C)									
Air Flow through Bed $\dot{V}_b = \dot{V}_m \frac{T_2}{T_3}$ (Liter/s)									
Superficial Velocity $U = 10^{-3} \frac{\dot{V}_b}{S_b}$ (m/s)									
Pressure Drop Across Bed, ΔP (mm H ₂ O)									
Bed Height (mm)									

PART C

1. Record your raw data in Table 8.2
2. Record your derived results in Table 8.3
3. Make a plot between bed pressure drop (ΔP) versus superficial velocity (U) for both with heating and without heating. From the two curves, you can estimate the minimum fluidizing velocity for each process.
4. Plot heat transfer coefficient (h) versus superficial velocity. h can be calculated as follow:
$$h = \frac{Q}{A(T_1 - T_2)}$$
Where A is the surface area of the heater = $1.6 \times 10^{-3} \text{ m}^2$
5. Explain your results.

Note: 1. Regarding (Air flow measurement)

You should focus on Charles law, $\dot{V}_b = \dot{V}_m \frac{T_2}{T_3}$

Where, V_b is air flow through bed

V_m is air flow rate

T_2 is the bed temperature

T_3 is the air flow temperature.

2. *For the calibration of the orifice*

You know that the maximum flow rate we can measure from the air flow meter is 1.7 L/s.

Thus, if the flow rate exceeds 1.7 we need to make a calibration curve to estimate its value.

The following equation is used in case the flow rate exceeds 1.7

$V_m = kx^{1/2}$, where k can be estimated from known flow rate.

Table 8.2 Raw Data for Fluidization Bed (Part C, Air Flow: **Decreasing**)

	1	2	3	4	5	6	7	8	9
Height of Heater above Distributor (mm)	40								
Orifice Differential Pressure, x (mm H ₂ O)									
Air Flow Rate, V _m (Liter/s)									
Heater Surface Temperature, T ₁ (°C)									
Bed Temperature, T ₂ (°C)									
Air Inlet Temperature, T ₃ (°C)									
Heater e. m. f., E (Volts)									
Heater Current, I (Amps)									

Table 8.3 Derived Results for Part C

	1	2	3	4	5	6	7	8	9
Air Flow through Bed $\dot{V}_b = \dot{V}_m \frac{T_2}{T_3}$ (Liter/s)									
Superficial Velocity $U = 10^{-3} \frac{\dot{V}_b}{S_b}$ (m/s)									
Heat Transfer Rate, Q = EI (W)									
Surface Heat Transfer Coefficient, $h = \frac{Q}{A(T_1 - T_2)}$ (W/m ² .K)									

8.5 References

1. Botterill, "Fluid-Bed Heat Transfer", Academic Press, London, 1973.
2. Geldart, "Powder Technology" 7 (1972) 285.
3. Howard (Ed.), "Fluidized Beds - Combustion and Applications", Applied Science Publishers,
London, 1983.
4. Ergun, "Chem. Eng. Prog." 48 (1952) 89.
5. Botterill, Y. Teoman and K.R. Yuregir, "Powder Technology" 31 (1982) 101
6. McCabe, Warren L. and Julian C. Smith. "Unit Operations of Chemical Engineering." Page 341.
7. Van Swaaij, Afgan, "Heat and Mass Transfer in Fixed and Fluidized Beds", pages 143 to 157.

9. Air Conditioning

9.1 Objective

To understand air conditioning process and able to determine the energy and mass balances of the process.

9.2 Introduction

Air conditioning, which may be described as the control of the atmosphere so that a desired temperature, humidity, distribution and movement are achieved, is a rapidly expanding activity throughout the world. Other than providing human comfort, there are numerous application of air conditioning including computer laboratories, pharmaceutical industries, inspection and storage of sensitive equipment, horticulture, animal husbandry, food storage, and etc.

Generally, the air conditioning unit draws air from the environment into the duct. The air flows through the humidifier, and then the evaporator of the refrigeration plant where it is cooled and dehumidified under certain conditions. The water supply to the water heater is assumed to be at a temperature of 25°C. Whereas, the fan used in this air conditioning unit has the power output of approximately 72 W at normal operating conditions.

9.3 Procedures

1. Turn on the computer and startup the computer-interfacing program of the air conditioning unit by clicking the DOS Prompt icon and type CD 575 ↵ and RUN↵.
2. At the screen prompt, type **CHAIN“575COLF”**.
3. Turn on the water supply to the boiler and check the water level in the gauge glass stabilizes at a depth, which will cover all the heater elements.
4. Switch on the main supply to the unit and turn on the main switch on the panel. The fan will start to ensure air flow through the duct.
5. Return to the computer program. No data is needed to be read or stored.
6. Make sure the Interface Status lamp is on indicating both the computer and interface are in communication.
7. Enter the following information when prompted:
 - i. R134a Flowmeter Calibration Factor : 12.69
 - ii. Atmospheric Pressure : 760 mmHg
 - iii. Heater Resistance:

- a) Boiler 2 kW R1 (ohms) : 25.3
 - b) Boiler 2 kW R2 (ohms) : 24.4
 - c) Boiler 1 kW R3 (ohms) : 47.7
 - d) Pre-Heater R4 (ohms) : 46.0
 - e) Pre-Heater R5 (ohms) : 43.9
 - f) Re-Heater R6 (ohms) : 90.2
 - g) Re-Heater R7 (ohms) : 90.7
- iv. Electrical frequency used (Hz) : 50

9. Select No. 1 from the program menu and observe the data displayed on the screen.
10. Set the fan speed to a moderate speed and leave all heaters and the compressor off. Have the fan running a short while until the four dry bulb temperatures stabilize at same readings. Whereas, the four wet bulb temperatures also read similar values. Record the eight dry and wet bulb temperatures.
11. Switch on a 1 kW pre-heater. Record at least 3 readings of the dry and wet bulb temperatures at location A and B. (typically a reading is taken every minute when the data sampling indicator is lighted up.)
12. Switch on all three water heaters and allow the boiler to generate steam. Once water droplets are seen to appear on the intake pipe, after about 3 minutes the heaters are switched on, reduce the input to 3 kW. Let the unit to stabilize for about 3 minutes.
13. Switch on the compressor and let the unit to stabilize for about 3 minutes.
14. Apply 1 kW of reheat and let the unit to stabilize for about 3 minutes.
15. Record at least 3 readings of all the measured values from the result screen. Label the temperature readings with appropriate subscripts to their respective locations accordingly.

Note: Group members should be cooperative in taking the measured results, as the values will be changed every minute.

9.4 Report Requirements

1. Determine the heat input due to pre-heater to the system, **before switching on the boiler**, by using the energy balance equation. Discuss any discrepancy between the calculated value and the measured value.
2. After switching on the boiler, determine the moisture flow rate.

3. Develop the steady flow energy balance equation for a control volume between location **A** (ambient air inlet) and **B** (after steam inlet). State all assumptions made. Determine the heat input from the boiler and compare it to the measured value.
4. Draw the refrigerant cycle involved on the $P-h$ diagram of R-134a provided when the compressor is switched on. Label all states with corresponding temperatures and pressures recorded.
5. Determine the rate of condensation between location **B** and **C**.
6. Develop the steady flow energy balance equation for a control volume between location **B** and **C**. State all assumptions made.
7. Develop the steady flow energy balance equation for a control volume between location **C** and **D**. State all assumptions made. Determine the heat input from the re-heater and compare it to the measured value.
8. Develop the steady flow energy balance equation for the overall air conditioning process (between **A** and **D**). State all assumptions made.
9. Discuss the purpose of pre-heater, boiler, and re-heater in this air conditioning process.

10. Cooling Tower

10.1 Objectives

1. To understand the concepts of the construction, design and operational characteristics of a modern evaporative cooling system.
2. To investigate the effects of air flow rate, water flow rate, water temperature, and cooling load on the performance of a cooling tower.

10.2 Introduction

Many chemical processes require utility cooling water to lower the temperature of process streams. As it passes through a heat exchanger, the temperature of the cooling water is elevated. Before this water can be used as cooling utility again, its temperature must be lowered. The most common unit used to accomplish this goal is a cooling tower.

In counter-current cooling towers the liquid water stream is introduced at the top of the tower and falls over packing material and is exposed to air that is flowing upward through the tower. Once in contact, the water at the gas-liquid interface evaporates into the air stream. Latent heat of evaporation is carried into the bulk air by the water vapor. Thus, the temperature of the water is lowered. Therefore, the water flow rate and the water temperature decreases as the humidity of the air increases. This process also known as humidification involves the simultaneous transfer of mass and heat.

The cooling tower in the lab provides an excellent tool for studying this process. The tall tower is equipped with several thermocouples strategically located along the column. These thermocouples measure the temperature of the water and the dry and wet bulb temperatures of the air at specific heights in the column. The humidity of the air can then be determined from the recorded wet and dry bulb air temperatures using a humidity chart.

10.3 Theory

10.4 Experimental Apparatus

10.4.1 Water Circuit

Water, which is regulated by a flowmeter, is pumped from the load tank up to the distribution cap where the temperature is taken and the water is evenly distributed over the packing. The water flows over the plates which increases the surface area exposed to the air stream. The water is then cooled by evaporation into the air stream as stated above. The temperature of the water can be taken at various points along the length of the column using the thermocouples attached. At the bottom of the column the water falls past one last thermometer and into the load tank where it can be reheated and recirculated through the column.

The make-up tank is equipped with a float operated needle valve that will open and transfer water into the load tank as required. This happens as a result of the evaporation of water across the column. When the column is running in a steady state, the rate of the water being evaporated is the same as the rate at which water is being transferred into the load tank. Also the wattage of the heater should correspond to the sensible heat change of the water, Figure 10.1.

10.4.2 Air Circuit

Air is pulled from the atmosphere and passes through a fan into the column. A damper can be adjusted to change the flow rate of the air. The wet and dry bulb temperatures of the air are taken at various points along the length of the column. The air then passes through a droplet arrestor and the temperatures are taken again before exiting to the atmosphere through an orifice. The pressure drop through the orifice can be used to estimate the air flow rate.

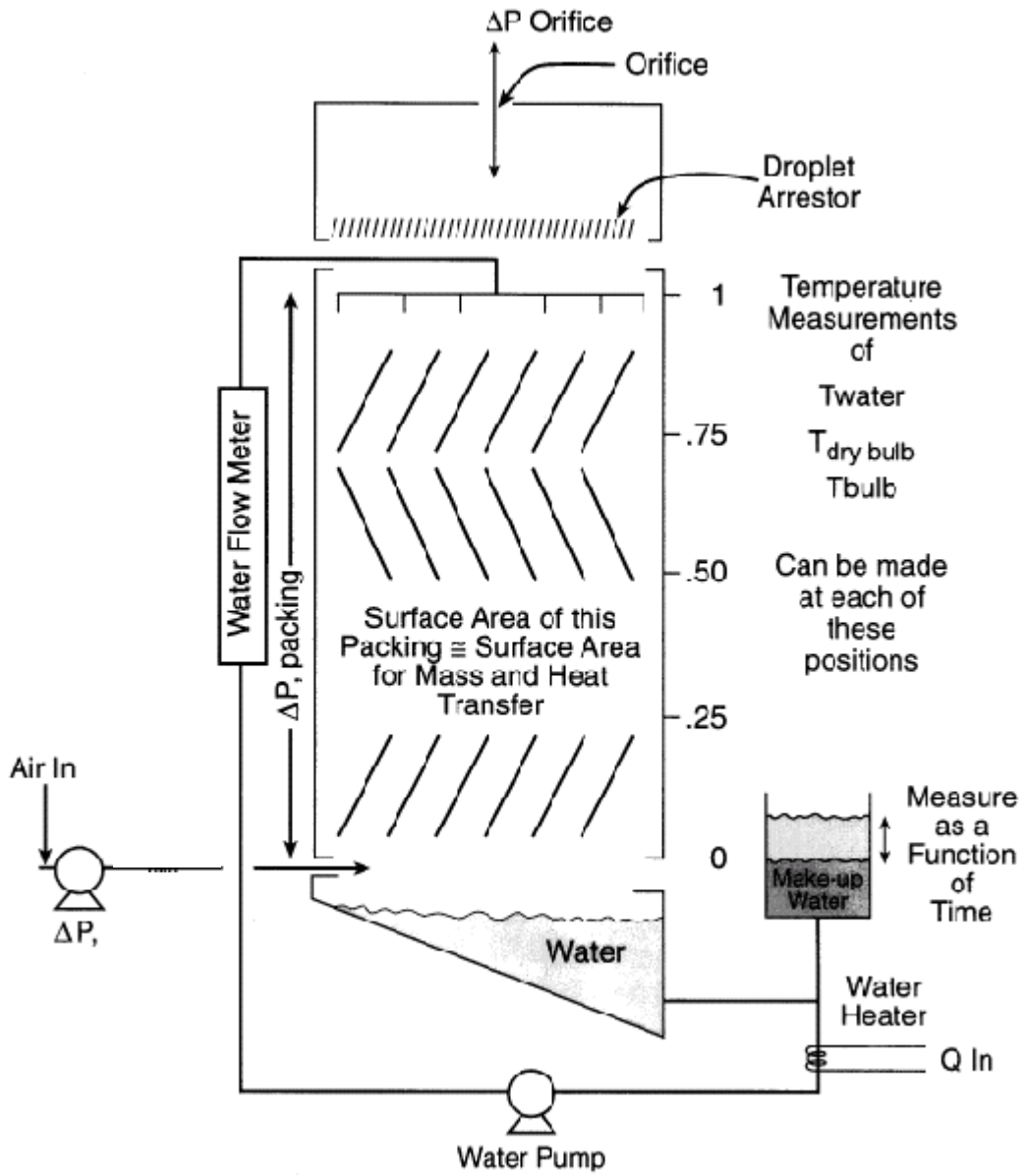


Figure 10.1 Experimental Set-up

10.7 Procedure

A. Observation of the Processes within a Forced Draught Cooling Tower

1. Start up the Top Cooling Tower with a moderate air and water and water flows and with either 1.0 or 1.5 cooling load
2. Observe the water and the air systems

B. Determination of All “End State” Properties of the Air and H₂O from Charts and Tables, and the Application of the Steady Flow Equation to Selected Systems to Draw up Energy and Mass Balances

1. Start the Top Cooling Tower under the following conditions

Orifice Differential	16 mm H ₂ O
Water Flow Rate	40 gm s ⁻¹
Cooling Load	1.0 kW

2. Record your data in Table 10.1

C. Effect of Cooling Load on “Wet Bulb Approach”

1. Start up the Top Cooling Tower under the following conditions

Water Flow Rate	40 gm s ⁻¹
Air Flow Manometer Differential	16 mm H ₂ O
Cooling Load	1.0 kW

2. Test should be repeated with cooling load of 0, 0.5, and 1.5 kW, but without changing the water flow rate and the air flow rate
3. Record your data in Table 10.2
4. Record your derived results in Table 10.3

**D. Relationship between Air Velocity and: 1. Wet Bulb Approach
2. Packing Pressure Drop**

1. Start up the Top Cooling Tower under the following conditions

Water Flow Rate	40 gm s ⁻¹
Air Flow	Maximum
Cooling Load	1.0 kW

2. Test should be repeated with orifice pressure drops of 10, 4, and 1.0 mm H₂O, but without changing the water flow rate and cooling load
3. Record your data in Table 10.4
4. Record your derived results in Table 10.5

E. Relationship between Cooling Load and Cooling Range

1. Start up the Top Cooling Tower under the following conditions

Water Flow Rate	40 gm s ⁻¹
Air Flow Manometer Differential	16 mm H ₂ O
Cooling Load	0

2. Test should be repeated with cooling load of 0.5, 1.0, and 1.5 kW, but without changing the water flow rate and the air flow rate
3. Record your data in Table 10.6

10.8 Raw Data and Result Tables

PART A

1. Record in your report (Table 10.1) what you observe including wattage, flow rates etc.
No calculations are required for this part

PART B

1. Record in your report (Table 10.1) what you observe including wattage, flow rates etc.
2. Apply the steady flow energy equation on the system as follow:
 - a. Assume it is a system G
 - b. Assume it is a system F
3. Discuss your results

Table 10.1 Data for Cooling Tower (Part B)

Packing Installed	B
Packing Density (m^{-1})	110
Air Inlet, Dry Bulb t_1 ($^{\circ}\text{C}$)	
Air Inlet, Wet Bulb t_2 ($^{\circ}\text{C}$)	
Air Outlet, Dry Bulb t_3 ($^{\circ}\text{C}$)	
Air Outlet, Wet Bulb t_4 ($^{\circ}\text{C}$)	
Water Inlet, t_5 ($^{\circ}\text{C}$)	
Water Outlet, t_6 ($^{\circ}\text{C}$)	
Water Make-up, t_7 ($^{\circ}\text{C}$)	
Orifice Differential, x (mm H_2O)	
Water Flow Rate, m_w (gm s^{-1})	
Cooling Load, Q (kW)	
Make-up Quantity, m_E (kg)	
Time Interval, y (s)	

Part C

1. Record your observations in Table 10.2
2. Estimate the Air Flow per Unit Area, Total Cooling Load, and Approach to Wet Bulb and record the results in Table 10.3
3. Plot the Approach to Wet Bulb (K) versus Total Cooling Load (kW)
4. Discuss your Results

Table 10.2 Data for Cooling Tower (Part C)

Test No.	1	2	3	4
Packing Installed	B	B	B	B
Packing Density (m^{-1})	110	110	110	110
Air Inlet, Dry Bulb t_1 ($^{\circ}\text{C}$)				
Water Outlet, t_2 ($^{\circ}\text{C}$)				
Water Outlet, t_6 ($^{\circ}\text{C}$)				
Orifice Differential, x (mm H_2O)				
Water Flow Rate, m_w (gm s^{-1})				
Cooling Load, Q (kW)				

Table 10.3 Derived Results for Cooling Tower (Part C)

	1	2	3	4
Packing Density (m^{-1})				
Air Flow per Unit Area ($\text{kg s}^{-1} \text{m}^{-2}$)				
Total Cooling Load, kW				
Approach to Wet Bulb				

Part D

1. Record your observations in Table 10.4
2. Estimate the Nominal Velocity of Air, Wet Bulb Approach, and Pressure Drop. Record the results in Table 10.5
3. In one Graph, plot Approach to Wet Bulb and Packing Pressure Drop Versus Nominal Air Velocity
4. Discuss your results

Table 10.4 Data for Cooling Tower (Part D)

Test No.	1	2	3	4
Packing Installed	B	B	B	B
Packing Density (m^{-1})	110	110	110	110
Air Inlet, Dry Bulb t_1 ($^{\circ}\text{C}$)				
Air Inlet, Wet Bulb t_2 ($^{\circ}\text{C}$)				
Air Outlet, Dry Bulb t_3 ($^{\circ}\text{C}$)				
Air Outlet, Wet Bulb t_4 ($^{\circ}\text{C}$)				
Water Inlet, t_5 ($^{\circ}\text{C}$)				
Water Outlet, t_6 ($^{\circ}\text{C}$)				
Orifice Differential, x (mm H_2O)				
Water Flow Rate, m_w (gm s^{-1})				
Cooling Load, Q (kW)				
Pressure Drop Across Packing, ΔP (mm H_2O)				

Table 10.5 Derived Results for Cooling Tower (Part D)

	1	2	3	4
Nominal Velocity of Air (m s^{-1})				
Wet Bulb Approach (K)				
Pressure Drop (mm H_2O)				

Part E

1. Record your observations in Table 10.6
2. In one Graph, Water Inlet Temperature and Water Outlet Temperature versus Cooling Load
3. Discuss your results

Table 10.6 Data for Cooling Tower (Part E)

Test No.	1	2	3	4
Packing Installed	B	B	B	B
Packing Density (m^{-1})	110	110	110	110
Air Inlet, Dry Bulb t_1 ($^{\circ}\text{C}$)				
Air Inlet, Wet Bulb t_2 ($^{\circ}\text{C}$)				
Air Outlet, Dry Bulb t_3 ($^{\circ}\text{C}$)				
Air Outlet, Wet Bulb t_4 ($^{\circ}\text{C}$)				
Water Inlet, t_5 ($^{\circ}\text{C}$)				
Water Outlet, t_6 ($^{\circ}\text{C}$)				
Orifice Differential, x (mm H_2O)				
Water Flow Rate, m_w (gm s^{-1})				
Cooling Load, Q (kW)				

10.9 References

1. Foust, Alan S., Principles of Unit Operations, 2nd Edition, John Wiley & Sons, NY, NY(1980), Chapter 17.
2. McCabe, Warren L. and Smith, Julian C., Unit Operations of Chemical Engineering, 3rd Edition, McGraw-Hill Book Company, NY, NY(1976), Humidification Operations Section.