This manual contains all relevant material necessary to complete Florida International University Mechanical and Materials Engineering's Mechanical Lab I

EML 4906L

Laboratory Guide

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Laboratory Safety

What YOU should know

You need to develop the habit of asking yourself whether an operation is safe and ensuring that you have the adequate knowledge and training about the equipment/ experiment you are using and safe working practices for that equipment/ experiment. Tidiness and thinking ahead are important aspects of a safe working environment.

For your work in the undergraduate teaching laboratories the following rules apply; but you must use common sense and ask an instructor if you have any doubts about safety or a particular situation.

General Laboratory Safety

1. Students are not permitted to work in the laboratories outside the specified times of laboratory classes unless they have been given specific permission to do so by the Department Lab Manager, who will then supervise the work.
2. Smoking and the consumption of food and drink are not permitted in the laboratories.
3. Apparatuses should be disconnected at the end of a session, unless you have asked for and been given permission by the Department Lab Manager to leave it assembled.
4. All accidents or breakages, however small, should be reported immediately to the Department Lab Manager.
5. Any dangerous incident or anything which is suspected to be an unsafe situation must be reported immediately to the Department Lab Manager or to the MME Department.
6. Bags and other personal items are not allowed to obstruct exits or pathways.
7. Solvents (propanol, acetone etc.) should only be used in a well-ventilated environment. They are highly flammable and should be kept away from ignition sources.
8. Students should be aware of the dangers of loose clothing or long hair when working with machinery or chemicals.
    a. Sandals or open toed shoes are not allowed to be worn in the lab. Doing so, will not allow you entrance to the lab.

Electricity

Electricity is potentially lethal. Under normal circumstances, any voltage over 55V is to be treated as hazardous unless it is incapable of delivering a current in excess of 1mA.

1. Students are not permitted to work with exposed electrical mains or to perform any kind of maintenance work on the electrical mains or any of its circuitry, including plugs. Equipment requiring repair should be brought to the attention of the Department Lab Manager.
2. Before connecting any equipment/ experiment, a check should be made that all instruments and apparatuses are of a suitable rating for the experiment to be performed.
   a. Check also that all wires are of a suitable current capacity.
   b. All supply switches should be in the "**OFF"** position whilst connections are made (during disconnection as well).
   c. All power supplies should be switched off before changing any components.
3. Before switching on check that all connections are correct (if in doubt, ask).
4. Place apparatus so that short circuits cannot occur.

Laboratory Rules:

1. No one is allowed to use the laboratory facilities without permission of the Department Lab Manager.
2. In order to use the laboratory facilities, you must schedule it at least 5 business days prior to the day of intended use.
3. No one is allowed to take out any equipment, devices and/or tools from the MME laboratories without permission of the Department Lab Manager.
4. Written permission or documentation is necessary when borrowing any equipment, devices and/or tools from the MME laboratories. The documentation must include the reason, usage, return date and signature of the Department Lab Manager. Return of the equipment must be punctual and without any damage.
5. Everyone must sign in before using the MME laboratories, and sign out when leaving.
6. No food, drink (except water), or gum is permitted in the laboratory.
7. Everyone must follow the instructions during any experiments.

8. When finishing with the experiments, everyone is responsible for putting back what was used to its original place and for shutting off the power.

9. Everyone is responsible for his or her own safety.

10. Everyone who uses the MME laboratory facilities is responsible to provide experimental documentation (with certain exemptions).

Lab Report Format and Guide

Required Format for Lab Reports

1. All laboratory reports must be done on a computer using a word processing software program.
    a. All mechanical engineering students have access to the computer laboratory, where all the computers have the software required to comply with this requirement.
2. Reports must be in Adobe PDF format.
3. Allow for a one inch margin on each edge of the paper.
4. The major headings in the report should be on the left-hand side and underlined.
5. Number all pages, including plots and appendices, at the bottom right-hand corner of the page.
6. The report (PDF) must be named in the following manner: **Class_Section_Experiemnt#_Group#_.pdf**
7. Remember, laboratory report grades are unduly influenced by the quality of the presentation of the report.

Report Sections

All reports should contain the following sections:

1. **Title Page**
    a. The title page should include the experiment's title, group number, names of the members of your group, and the date of the experiment.
2. **Table of Contents, List of Tables, and List of Figures**
    a. A table of contents should be provided for ease of locating the desired material of the report. The table of contents gives page numbers for easy reference to the individual sections of the report, and provides an outline of the topics to be covered in the report.
    b. All tables in a report should be numbered and titled. The list of tables is the index to all tables in the report.

c. All figures in a report should be numbered and titled. The list of figures is the index to all figures in the report. All graphs and sketches are to be given figure numbers and titles.

3. Nomenclature

a. A list of all mathematical symbols with their respective units and description.

4. Abstract

a. The abstract is the last section that is written and the first section that is read of a technical report. All technical reports should begin with an abstract. The abstract is a summary or synopsis of the experiment written for the reader who wants to know whether or not he/she would be interested in reading the full text of the report. Therefore, the abstract should be self-contained and independent of the rest of the report.

b. The abstract should **not** exceed a full page in length; **and for the typical length of a lab report, the abstract is generally 3-4 sentences**.

c. The purpose of the abstract is to inform the reader of the important aspects of the work. Any new equipment or unusual procedures used to perform the work and the significance of the results obtained should be briefly presented in the abstract.

5. Body of report

a. The body of the report will contain eight (8) sub sections:

i. Introduction

An introduction is not always necessary, but it is usually desirable to spend a few paragraphs describing the background of the project and the reasons for undertaking it. References to previous works of a similar nature are often cited, and the differences between those projects and the current study are presented. Any important notation or mathematical preliminaries can also be briefly given in the introduction.

ii. Objective(s)

Briefly state the nature and purpose(s) of the experiment in a concise manner.

iii. Procedure

This section should contain a brief description of the specimen, component, or structure used in the experiment (including its geometrical shape and significant dimensions), the material used in the experiment (including significant material properties, if applicable), and a general description of the equipment used. Then briefly describe the methods employed in obtaining the experimental results.

iv. Data, Results and Analysis

Experimental data and results should be presented in this section in a suitable fashion; i.e., tables and figures, following the outline given in the lab handout. If analytical (theoretical or predicted) values are also being calculated tabulated, and/or plotted, it should be done in this section (but comparison with the experimental results should be made in the discussion section). The original data sheet(s) and sample calculations, however, should be in the Appendices.

v. Discussion

This section presents the theoretical and practical evaluation of the results reported in the previous section. The discussion should include the extent to which the objectives of the experiment have been achieved. The reliability, meaning, evaluation, and application of the results should be considered in this section. Compare the results with those which might be expected in practice, theory, or both. An important consideration when writing the discussion, is that any part of it that could have been written without doing the experiment, is not an evaluation of the work done, nor is it a conclusion drawn from the experiment.

vi. Conclusions and Recommendations

In this section the writer should summarize the findings of the report and draw attention to the significance of these results. Any deviations from accepted theory should be noted and their statistical significance discussed. Conclusions are to be drawn with reference to the previously stated objectives of the project. Each conclusion should be supported by reference to data and results, and should follow directly from the numerical results obtained.

Recommendations are often more important than conclusions. Recommendations should be made in this section on changes in the procedure or instrumentation of the experiment, which could make the experiment more accurate or effective. Few experimental projects are an end in themselves. Either the results are to be used for a purpose, or at least the experimenter sees more work that could be done to adequately accomplish the original project.

vii. References

List any books, reports, etc., cited in the previous sections of the report. The references should be listed according to the order in which they were annotated in the report. References should be formatted according to MLA or IEEE guidelines.

viii. Appendices

All information important to the completeness of the report, but either too detailed or cumbersome to include in the smooth flow of the report should be put in an appendix. This would include information such as original data collected, sample calculations, calibration data, computer programs, etc. For the laboratory reports on the experiments at least the following appendices must be present:

1. Appendix A: Apparatus

   A sketch or schematic of the experimental apparatus showing all instrumentation and control stations should be provided. A schematic diagram is adequate, but it must be neat and complete. Describe the experimental setup and the instruments used including limitations and relative accuracy. Full and accurate identification of all instrumentation should be given, including model and serial numbers or other unique identification.

2. Appendix B: Procedure

   A write-up of how the experiment was conducted should be provided. This write-up should be of sufficient detail that anyone, with the proper equipment and your report, could reconstruct the experiment and achieve the same results. This write-up should be factual, almost a log of the steps you went through in performing the experiment to the point of reporting the errors made, and later discovered, in conducting the study. Changes which you would recommend be made to the experimental procedures should be noted in the conclusions and recommendations section of the report. Preliminary tests, equalizing periods, duration of runs, and frequency of readings, should be recorded. Special precautions for obtaining accuracy and means for controlling conditions should be described. Independent variables and reasons for their selection should be given. This section is in much more detail than that of the “Procedure” section in the body of the report.

3. Appendix C: Calibration Data

   The calibration procedure and the results of the calibration process for all equipment should be included in this appendix section. Calibration plots may often be included in the body of the report to support the results of the experiment, however all the supporting material used to develop those charts or tables should be detailed here.

4. Appendix D: Experimental Data

   Scanned images of the original data sheets from an engineering laboratory notebook or from a plotter should be included. Along with all raw data obtained by other means (i.e. a data acquisition device).

5. Appendix E: Sample Calculations

   Examples of calculations used in the experiment should be included in this appendix section. Mathematical developments of special equations should also be included here.

Introduction to Data Analysis

In the following, “Error”, does not mean mistake but rather refers to the uncertainty in a measurement. All measurements in practice and even in principle have some error associated with them; no measured quantity can be determined with infinite precision.

Statistical Errors (also known as Random Errors)

Most measurements involve reading a scale. The fineness of the scale markings (how close together the markings are) is limited and the width of the scale lines is nonzero. In every case, the final reading must be estimated and is therefore uncertain. This kind of scale-reading error is random; since we expect that half of the time the estimate will be too small, and the other half of the time the estimate will be too large. We expect that random errors should cancel on average, that is, many measurements of the same quantity should produce a more reliable estimate. Statistical errors can be controlled by performing a sufficiently large number of measurements. The error estimate on a single scale reading can be taken as half of the scale width. For example, if you were measuring length with a scale marked in millimeters, you might quote the reading as 17.0 mm ± 0.5 mm. If you measured the same length many times, you would expect the error on the measurement to decrease. This is indeed the case. The best estimate of the measured quantity is the mean or average of all the measurements. Simply add all the individual measurements together and divide by the number of measurements. The best estimate of the error associated with the mean value is called the "error on the mean" and is given by (the error on a single measurement) divided by (the square root of the number of measurements). Obviously, this will decrease as the number of measurements increases. The final reading for a quantity should be quoted as: (mean) ± (error on the mean).

Error Propagation

Addition and Subtraction

If several quantities with associated random errors are given by: $\pm\Delta x$, $y \pm \Delta y$, …, $z \pm \Delta z$, then the sum or difference is given by $q \pm \Delta q$ where $\boldsymbol{q}$ might be

$$q = x + y - z$$

and the error on ***q*** is propagated from the errors on ***x***, ***y***, ... , and ***z*** as follows:

$$\Delta q = \sqrt{(\Delta x)^2 + (\Delta y)^2 + \cdots + (\Delta z)^2}$$

Notice that the errors are added in quadrature, even when the quantities are being subtracted. The error always increases when adding or subtracting quantities.

Multiplication and Division

If several quantities with associated random errors are given by: $\pm\Delta x$, $y \pm \Delta y$, …, $z \pm \Delta z$, then the product or quotient is given by $q \pm \Delta q$ where ***q*** might be

$$q = \frac{x * y}{z}$$

and the error on ***q*** is propagated from the errors on ***x***, ***y***, ... , and ***z*** as follows:

$$\frac{\Delta q}{q} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2 + \cdots + \left(\frac{\Delta z}{z}\right)^2}$$

Systematic Errors

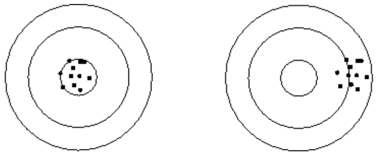
These errors are more insidious than statistical errors. Systematic errors are difficult to detect, and the sizes of systematic errors are difficult to estimate. Increasing the number of measurements has no effect on systematic errors because the error is always in the same direction (all measurements too high, or all measurements too low). Careful instrument calibration and an understanding of the measurements being made, aid in prevention of these errors.

For example, suppose that you are using a stopwatch to time runners in the 100-meter dash. You are quite adept at making the measurement; but, unknown to you, the watch runs 5% fast. All times will be 5% too high. There will be no immediately obvious indication of a problem. If you happen to be familiar with the runners' normal times, you might notice that everyone seems to be having a slow day. To prevent such problems, one should calibrate the stopwatch with a known standard such as the Nation Institute of Standards and Technology's standard time service on short wave radio.

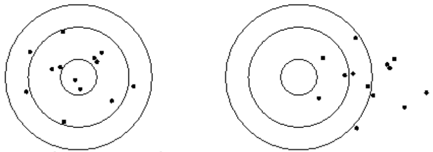
The guidelines for data recording are:

1. The error should have one significant figure

2. The number of decimal places in the measurement should be the same as the number of decimal places in the error.
3. Always remember: There is no such thing as "human error".
4. Try to find the deeper cause for any uncertainty or variation in the data.



Precise and accurate	Precise, but not accurate



Accurate, but not precise	Neither precise nor accurate

Figure 1: Difference between Precision and Accuracy

Statistics and Error

The second method of estimating error on measured quantities uses statistics as a tool. Now that we have some idea about the types of error found in the lab, random and systematic, we can discuss how statistics are used to describe them. Statistics can only be used to describe random error. All systematic error should have been eliminated from the experimental setup. On the other hand, random errors are made to order for a statistical description. If your balance reading is being influence by air current, sometimes your readings will be high, and sometimes low.

Whether or not the reading is high or low is pretty much a random thing. Statistics excel at describing these kinds of events. So, if you are sure all systematic errors have been eliminated, the rest, the random error, can be estimated statistically.

We make several assumptions in using statistics to describe errors. The main assumption is that the errors are normally distributed. The normal distribution, also called the Gaussian distribution or the bell-shaped curve, is one of the most common probability distributions. A probability distribution tells us about the probability of randomly selecting different values. For instance, if you roll a fair die (singular of dice); the probability that you get a two is 1/6. There are six possible outcomes, all equally likely. The probability that any one of the six faces will be up is 1/6. This type of probability distribution, in the continuous case, is call a uniform distribution and is graphed as a straight flat line. All values are equally likely. If you think about it for a moment, you will realize that all values aren’t equally likely when it comes to errors. If your experiment is correctly set up, you should get only small errors. A value near the “correct” value is more likely than a value far from it. This is exactly the type of probability described by the normal distribution.

In Figure 2, one example of the distribution is plotted with values on the x-axis vs. the probability of those values on the y-axis. In the figure, the curve is centered at zero and has a standard deviation of one. Both of these values can be adjusted to be most any value and will depend on the specific system being modeled; zero and one are just a convenient example.

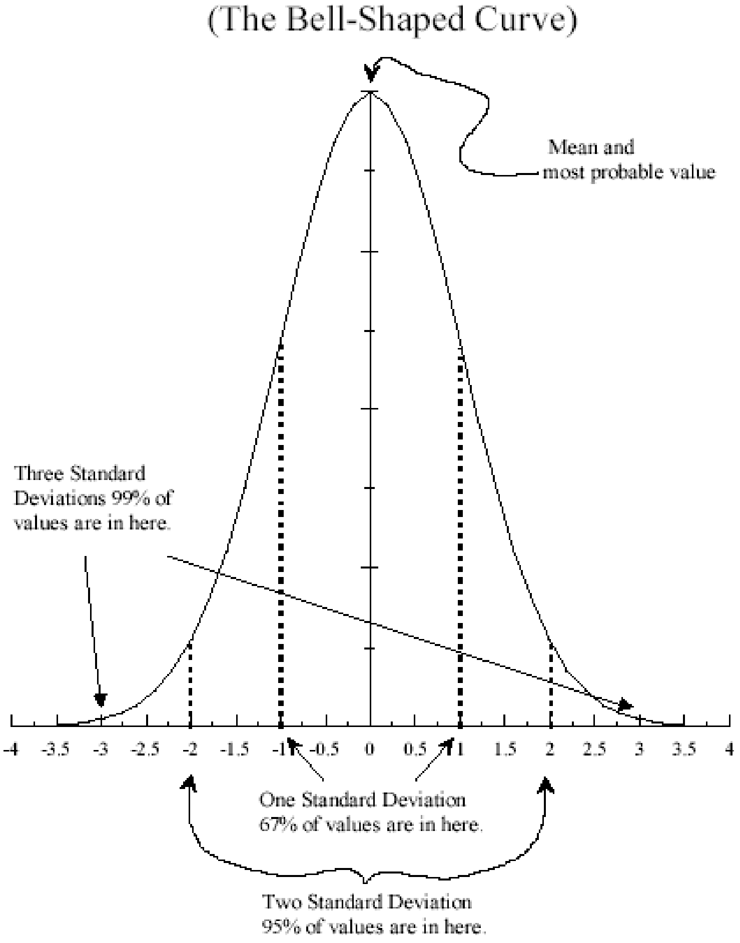


Figure 2: Normal Probability Distribution

The normal distribution has a maximum probability in the middle, where the curve is the highest. This spot corresponds to the mean value of the random variable being measured. Also, we see that the probability drops off quickly away from the mean. How quickly? In other words, just how closely packed in toward the mean are the values. A measure of this is the standard deviation, σ. The standard deviation gives the width of the curve or the probability of finding a value far from the mean. In Figure 2, the standard deviation was selected to be one. For the normal distribution, 67% of randomly selected values will fall within one standard deviation of the mean, which is within -1σ and +1σ. 95% of the randomly selected values will fall between -2 σ and +2 σ and 99% between +3 σ and -3 σ.

For the example distribution shown in Figure 2, 67% of the values will be between +1 and -1 (σ = 1), 95% between +2 and -2, and 99% between +3 and -3.

The formula for the mean is the same as always:

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_n}{n}$$

(In MS Excel: use function AVERAGE)

As with all measured quantities, we need to associate an error with the mean: The standard deviation can be found by:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

(Excel: use function STDEV)

However, the standard deviation isn't quite right. It tells us about the probability of a given value being a certain distance from the true mean. What we want to know is, given the number of trials, what is the probability that out mean reflects the true mean? Such a quantity is given by the standard error,

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{n}}$$

(Excel: use function STEYX or simply $\frac{STDEV}{n^{0.5}}$)

For measured data, the values used in calculations or the estimates in the results are:

Estimated Value = Average ± (factor*standard error)

When using statistics to estimate the error on your measurements; use the average value with the standard error as the uncertainty. The following table gives the factor values with the corresponding confidence level.

Confidence Level	Factor
50 %	0.67
67 %	1.0
95 %	2.0
99 %	2.6

Table 1: Confidence Level and Factor Correlation

Rejection of Data

Many scientists believe that data points should never be rejected since some important scientific discoveries have come from data that initially appeared "strange data". If an experimental result appears to be flawed the experiment should be repeated to check the particular data point(s). However, in a student lab with limited time it may not be practical to repeat an experiment. In this case we can sometimes reject a data point based on a consideration of the mean and standard deviation of the particular quantity being measured. Suppose we measure the acceleration of gravity 10 times, obtaining a mean value of $9.72\frac{m}{s^2}$ with a standard deviation of $0.2\frac{m}{s^2}$. Suppose we have one data point that has a value of $9.32\frac{m}{s^2}$, which is two standard deviations from our mean. The probability of getting a data point this far from the mean (or worse) in a single trial is 5% (making the usual statistical assumptions concerning the data distribution). Therefore, in ten measurements the probability of obtaining at least one data point this bad (or worse) would be ten times 5% or 50%. Chauvenet's Criterion states that if this calculated probability turns out to be less than 50% the data point can be rejected. Without this data point the standard deviation of the remaining points will be much less of course.

For example, let's say we make six measurements of the period of a pendulum and come up with 3.8, 3.5, 3.9, 3.9, 3.4, and 1.8 seconds. The 1.8 looks like it might be bad.

The standard deviation of this set of measurements is 0.8 seconds, and the mean is 3.4 seconds. The 1.8 therefore is two standard deviations away from the mean. The probability of getting a value deviant by 2 σ or more, on a single measurement, is 5% (recall the definition of the 2 σ confidence level). The probability of finding a single value this bad in six measurements, then, is 30%.

This is certainly not inconceivable; it may even seem reasonable to you now that this point should have come up. If this point is bad, however, then the standard deviation we used to calculate the probability has been contaminated. The true standard deviation is likely to be much smaller, and for this reason people commonly set the lower limit of probability to be 50%. If a point comes up to be less than 50%, which is likely to occur using this method, it can be thrown out.

In the example above, the point does indeed get thrown out, leaving us with a set of five measurements. The mean of this set is 3.7, and the standard deviation is 0.2; which is significantly smaller! In other words, the measurement we discarded was approximately 9 σ and the total probability of its occurrence was really astronomically small. Even if it were only 5 σ, the probability would only be about 4 in a million. Of course, to be rigorous you should check each point in your data set using this method, and after throwing out the first round of bad points, start all over again on the new set.

Graphs

Your graph is intended to present your data and results in an easily interpreted manner. The experimental results are contained in the plotted data points. In a sense, the data points are the heart of your graph. They are to contain as much information as possible and still be easily examined. Along with the data you recorded, you can also present the error or uncertainty on the data. These uncertainties are indicated by using error bars on your data points.

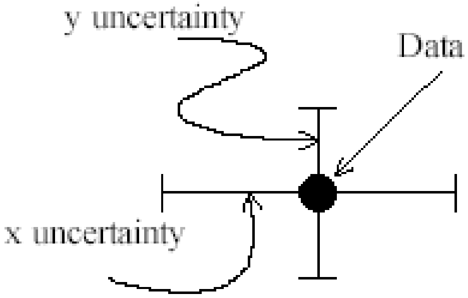


Figure 3: Data Point with X and Y Uncertainties

Curve Fitting: Least Squares Fit (linear regression)

A mathematical technique allows one to ‘fit’ a straight line to a set of data points. If you suspect that a set of data points lie on a straight line, then you need to be able to fit those points on that line. The equation for a straight line is given by:

$$y = mx + b$$

Where ***m*** is the slope of the straight line and ***b*** is the y-intercept (where the line crosses the y-axis). Given these two quantities the line can be drawn by selecting a set of x-values, inserting them into the equation for the line, and plotting the result. The *least squares method* allows us to find ***m*** and ***b***.

In the laboratory you will have collected a set of data points, (x1, y1), (x2, y2), (x3, y3)… and wish to find the “best” straight line through them. Before we can do anything else, we must decide what is meant by the “best” line. By “best” we could mean the line that passes through the most points; we could also mean the line that clips the most error bars. We need a definition of “best”. A simple and sufficient definition turns out to be that the “best” line through the data points is the line that minimizes the sum of the squares of the distances from the data points to the line. Minimization is a straight forward calculus problem. If the procedure is carried out, one finds:

$$m = \frac{\overline{XY} - \bar{X}\bar{Y}}{\overline{X^2} - \bar{X}\bar{X}} \qquad\qquad b = \bar{Y} - m\bar{X}$$

(Excel: uses the function SLOPE for the calculation of ***m*** and the function INTERCEPT for the calculation of ***b***)

Where, the *over-bar* indicates the average of the values. Note that the average of x squared (X X) is not the same as the average of X^2. One difference is that the two averages treat negative values differently. Try calculating X X and X^2 for the two values 1 and -1.

Sample graph:

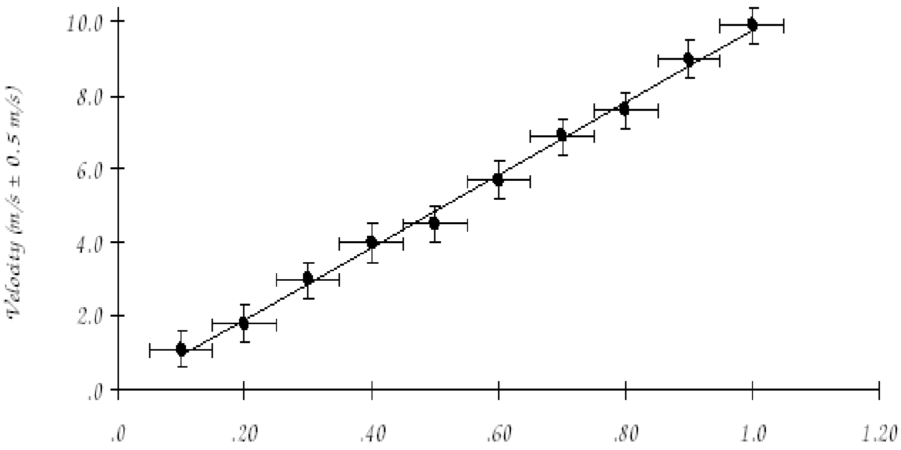


Figure 4: Example of Line Fitting

In case of an exponential relationship (for example, = ax^n), the linear least squares method should be applied to the log-log plot of the results. For example, given:

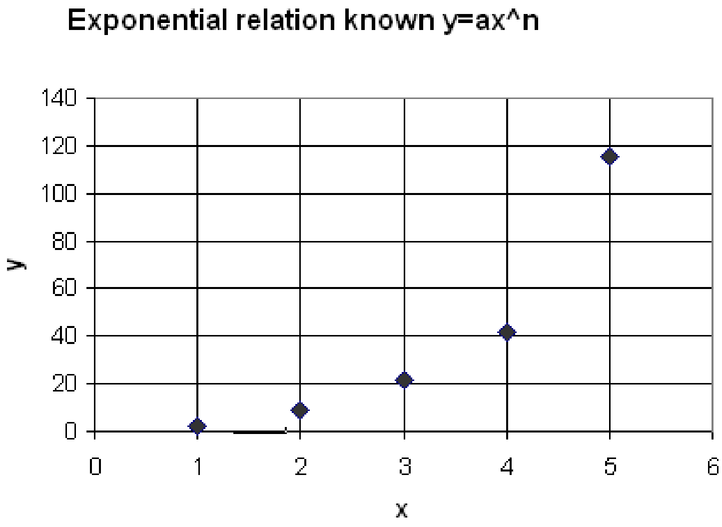


Figure 5: Example Data Points

Then the log-log plot with curve fitting would be:

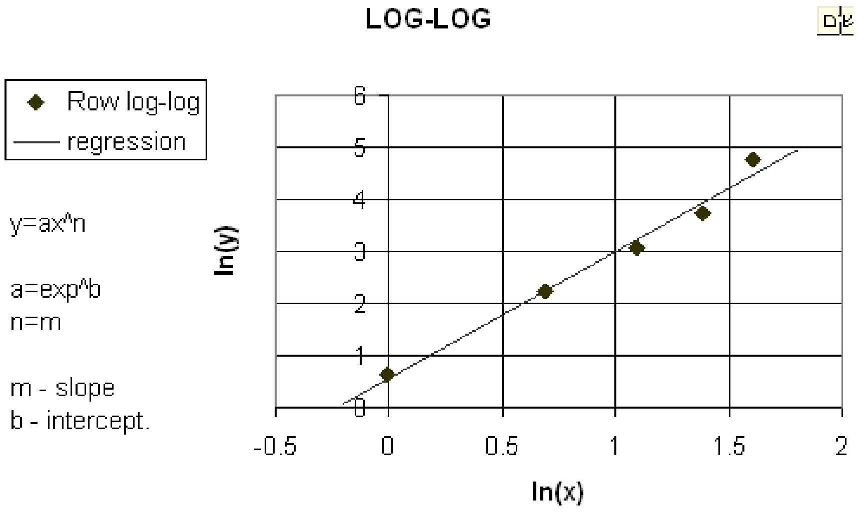


Figure 6: Log-Log Curve Fitting Plot

Experiment 1: Cross Flow Heat Exchanger

Objective

This laboratory exercise is used to investigate convection heat transfer in a cross flow heat exchanger. The performance of a cross flow heat exchanger is largely dependent on the configuration of the tubes across the duct and the speed of the cooling air flowing within the duct. The heat transfer is not uniform throughout the tube array, and hence, it is necessary to find an effective value for the entire heat exchanger over a range of airflow rates. Additionally, the overall performance of any heat exchanger must involve a determination of the static pressure drop through the apparatus. Upon successful completion of the experiment you should be able:

1. To understand convection heat transfer in a cross flow heat exchanger.
2. To investigate the cross flow heat exchanger at different speeds of the cooling air flow and at different positions of the air duct.
3. To determine the convection heat transfer coefficients for the tested conditions.

Nomenclature

Symbol	**Description**	**SI Unit**
A_s	Surface Area	m^2
c	Specific Heat of the Rod	$\frac{J}{kg \cdot K}$
d or D	Diameter	m
Δh	Difference between the Stagnation pressure head and the static pressure head; read from the manometer	in_{H_2O}
h	Convection Heat Transfer Coefficient	$\frac{W}{m^2 \cdot K}$
k	Thermal Conductivity	$\frac{W}{m \cdot K}$
l or L	Length	m
m	Mass	kg
Nu	Nusselt Number	-
P	Pressure	Pa
ΔP	Differential Pressure	Pa
Pr	Prandlt Number	-
Q	Rate of Heat Transfer	W
Re	Reynolds Number	-
T	Temperature	°C or K
t	Time	s
v	Velocity	$\frac{m}{s}$
ρ	Density	$\frac{kg}{m^3}$
µ	Viscosity	$\frac{kg}{m \cdot s}$
V	Volume	m^3

Introduction

A Plint & Partners cross flow heat exchanger apparatus is used for this experiment, as depicted below:

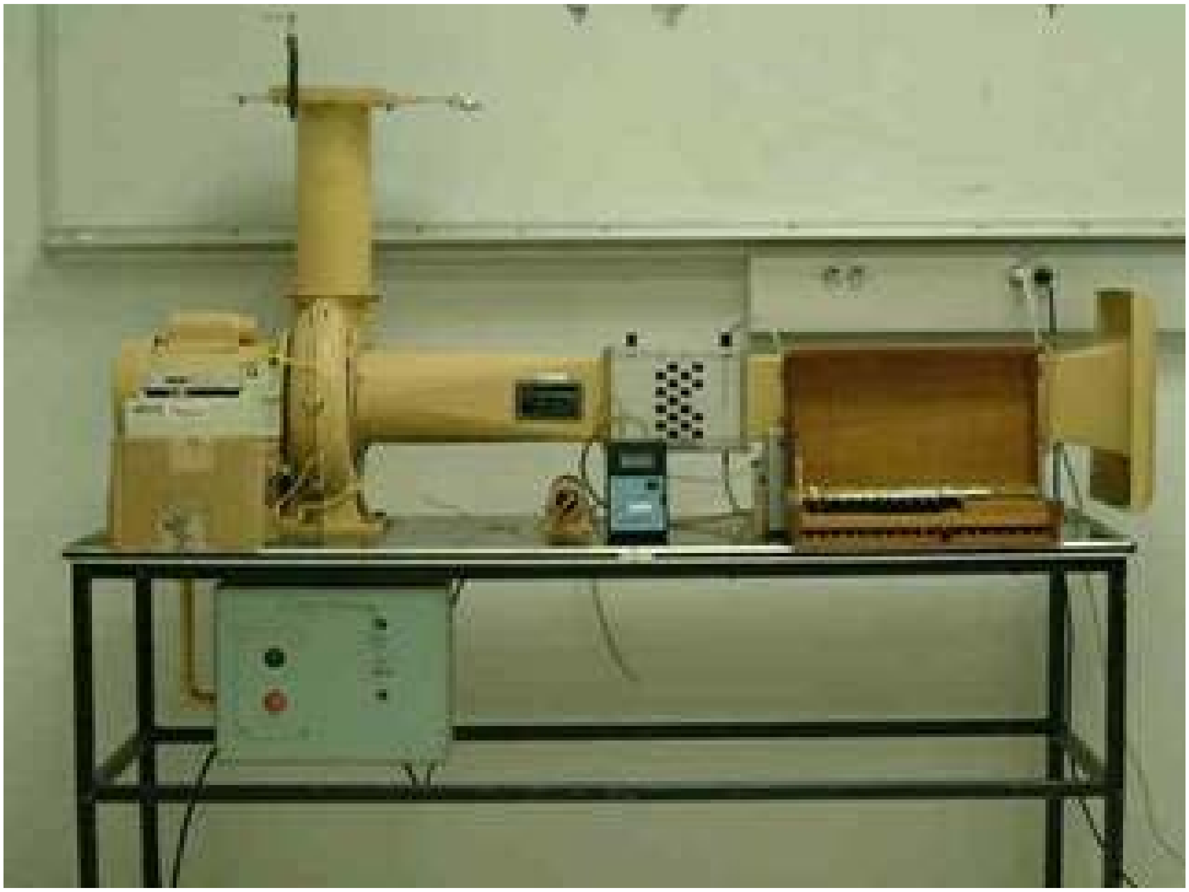


Figure 7: The Cross Flow Heat Exchanger Apparatus.

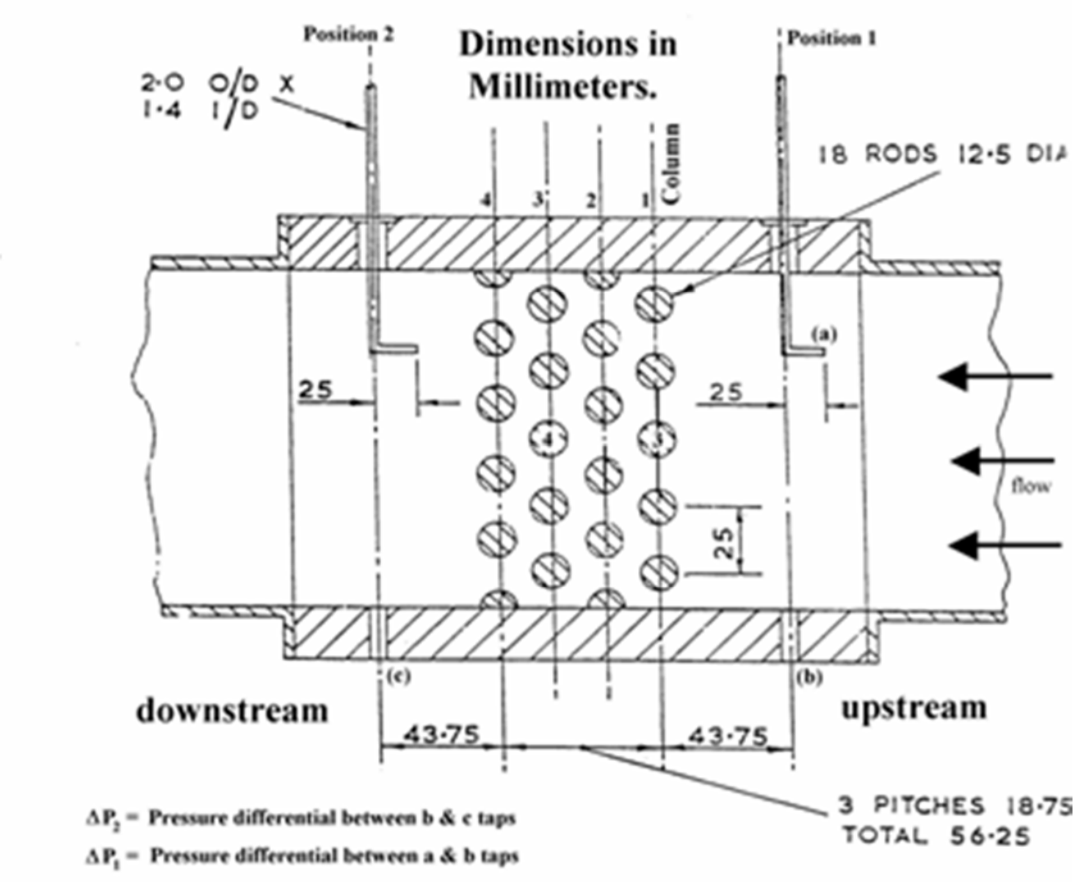


Figure 8: Schematic Diagram of the Cross Flow Heat Exchanger Test Section.

It consists of a centrifugal fan and a *125 x 125 mm* duct assembly mounted on a frame. The centrifugal fan draws air into the duct through a flared entry and exhausts upward through the vertical duct above the fan unit. The air speed through the duct is varied by the position of a sliding throttle plate at the top of the vertical duct. The air speed in the duct is determined by measuring the difference between the stagnation pressure and the static pressure of the air flow. A Pitot tube and a digital manometer are used for measurement, and the air speed can be calculated by the following formula:

$$v = \sqrt{\frac{2 \cdot \Delta h \cdot \rho_{water} \cdot g}{\rho_{air}}}$$

There is a copper cylindrical rod with a length of 94.9 mm, a diameter of 12.5 mm, and a weight of 106.9 g, that is used for the experiment. After heating to a certain temperature (maximum), the rod is put into the test section, and then cooled down by the air flow. The test rod can be set at different positions in the test section of the duct. An Omega single chart recorder is used for displaying and recording the temperature changes during the cooling. The convection heat transfer of the rod can be described by using the law of energy conservation as the following:

$$-hA_s\theta(x) = c\rho V\frac{d\theta(t)}{\partial t}$$

$$\theta(t) = T(t) - T_a$$

The radiation is neglected because the experiment is at a relatively low temperature. With an initial condition of $\theta(0) = T_0 - T_a$ or $T(t) = T_0$, $t = 0$ (T_0 is the initial temperature of the rod). The solution then becomes:

$$\theta(t) = \theta(0)e^{-\frac{t}{\frac{c\rho V}{kA_s}}}$$

Or

$$ln\frac{T(t) - T_a}{T_0 - T_a} = -\left(\frac{hA_s}{c\rho V}\right)t$$

Procedures

1. Setup the measurement unit and pre-heat the test rod.

    Step 1. Use the black plugs to seal unused holes in the test section of the apparatus, place the sliding throttle plate at the top of the vertical duct to the full open position.

    Step 2. Connect the thermocouple of the test rod to the signal recorder, and place the test rod into the heater.

    Step 3. Connect the power of the signal recorder and turn on the recorder. Record the ambient air temperature.

    Step 4. Connect the power of the apparatus, turn on the heater, and wait until the temperature of the test rod reaches $80°C$.

2. Measure and record the temperatures during the test rod cooling in different conditions.

    Step 1. When the temperature of the test rod reaches $80°C$, turn on the fan and allow the air flow to stabilize.

    Step 2. Turn on the paper feed button of the signal recorder, insure a proper setting.

    Step 3. Place the heated rod into the middle hole of the third column in the test section. Record the temperature changes during the cooling and stop the recorder when the rod temperature is approximately that of the ambient air temperature.

    Step 4. Place the Pitot tube in the middle of the test section. Use the digital manometer to measure the difference between the stagnation pressure head and the static pressure head of the air flow. When done, turn off the fan.

    Step 5. Close the sliding throttle plate to the half open position. Heat the test rod again to $80°C$. Repeat Steps 1 thru 4.

    Step 6. Close the sliding throttle plate to a position that is less than half open. Heat the test rod again to $80°C$. Repeat Steps 1 thru 4.

    Step 7. Repeat Steps 1 thru 6 (entire experiment), but use a lower hole in the column for the test rod.

    Step 8. Repeat Steps 1 thru 6 (entire experiment), but use the lowest hole in the column for the test rod.

Analysis and Discussions

1. Plot a temperature, $\left\{ \ln\left(\frac{T(t) - T_a}{T_0 - T_a} \right) \right\}$, vs. time, (*t*), graphic for three different air test cases.
2. Use the least-square method to find a linear line for each case.
3. Calculate the convection heat transfer coefficient, *h*, for each case.
4. Plot a convection coefficient, (*h*), vs. air speed, (*v*), graphic; and obtain a quadric curve.
5. Use three different position test cases to calculate the convection heat transfer coefficient, *h*, as above.
6. Plot a convection coefficient, (*h*), vs. position, (*y*), graphic, and obtain a quadric curve.

Report Requirement

1. The report must follow the lab report format.
2. The report must be submitted electronically (**PDF**) by the due date.
3. The electronic file must have a file name of: EML4906L_section#_Exp#_Group#.pdf

   Example: EML4906L_U01_Exp1_Grp1.pdf

Experiment 2: Extended Surface Heat Transfer

Objectives

When it is required to cool a surface by convection, the rate of heat removal can be improved by increasing the area of the surface. This is usually achieved by adding extended surfaces called fins or pins. A temperature gradient exists along each fin or pin due to the combination of the conductivity of the material and heat loss to the surroundings (greater at the root and less at the tip). The temperature distribution along the fin or pin must be known to determine the heat transfer from the surface to its surroundings. Since radiation and natural convection from the surface occur simultaneously, both of these effects must also be included in the analysis. After completion of this experiment you should be able to:

1. Understand one-dimensional conduction heat transfer.
2. Understand natural convection heat transfer.
3. Investigate the temperature distribution along an extended rod with combined heat conduction and heat convection during steady-state conditions.
4. Determine the convection heat transfer coefficients for the extended rod.

Nomenclature

Symbol	Description	SI Unit
α	Diffusivity $\left(\frac{k}{c_p \rho}\right)$	$\frac{m^2}{s \cdot K}$
c	Specific Heat	$\frac{J}{kg \cdot K}$
d or D	Diameter of the Rod	$0.010\ m$
ρ	Density of the Rod	$\frac{kg}{m^3}$
h	Convection Heat Transfer Coefficient	$\frac{W}{m^2 \cdot K}$
k	Thermal Conductivity of the Rod	$\frac{W}{m \cdot K}$
l or L	Length of the Rod	$0.350\ m$
P	Cross-section perimeter of the rod	m
A	Cross-section Area of the Rod	m^2
T_a	Ambient Air Temperature	K
t	Time	s
x	Distance	m
$T(x,t)$	Temperature at the Position **x** and time **t**	K
Q	Rate of Heat Transfer	W

Introduction

An Armfield HT15 experiment apparatus and an Armfield HT10X measurement unit are used for this experiment. Figure 9, below, depicts the Armfield HT15 experiment apparatus that will be used during the experiment.

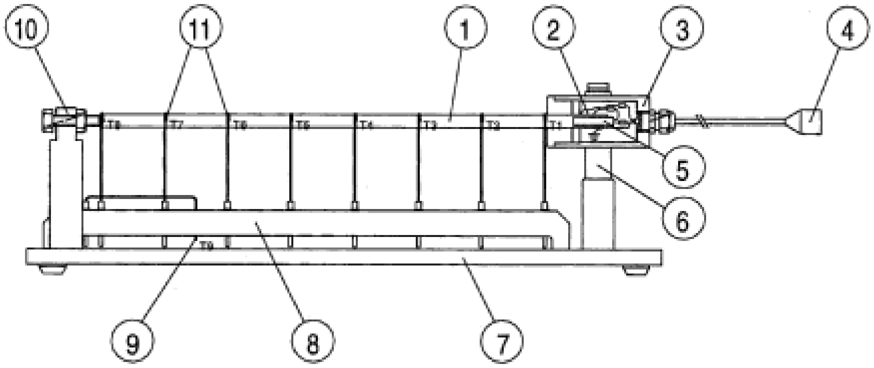


Figure 9: Armfield HT15 Experiment Apparatus

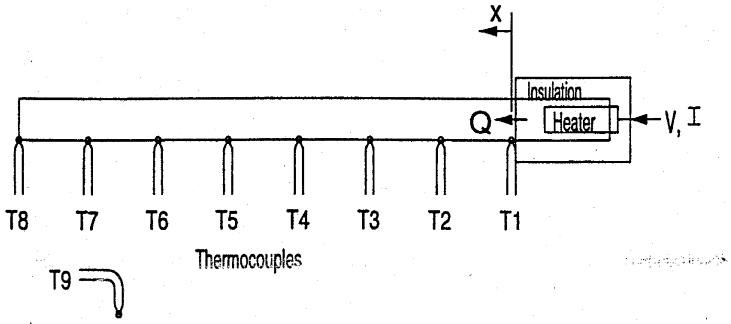


Figure 10: Schematic of the HT15

Figure 10 depicts the schematic of the Armfield HT15. In the experiment apparatus there are eight thermocouples (T1 to T8) installed along the surface of a brass cylindrical rod with an even distance (0.050 m). They provide a distribution temperature measurement along the surface of the rod. The ambient air temperature is measured by thermocouple T9. A heater is set on one end of the rod, where the temperature is T1, and its heat flux can be changed by adjusting the input voltage.

When the system reaches steady-state, the conduction heat transfer through the cross-section of the rod and convection heat transfer around the surface of the rod can be described by using the law of energy conservation; as follows:

$$\frac{\partial^2\theta(x,t)}{\partial x^2} - m^2\theta(x,t) = \frac{1}{\alpha}\frac{\partial\theta(x,t)}{\partial t}$$

Where:

$$\theta(x,t) = T(x,t) - T_a$$

Note that radiation is being neglected.

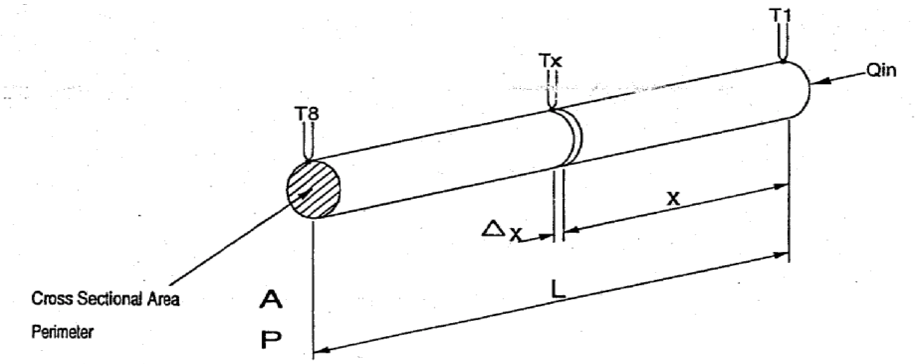


Figure 11: Free Body Diagram of the Extended Surface

When the heat transfer in the rod reaches steady-state, the above equation can be simplified to the following:

$$\frac{d^2\theta(x)}{dx^2} - m^2\theta(x) = 0$$

With boundary conditions:

$\theta(0) = T_1 - T_a$ or $T(x) = T_1$, $x = 0$ (T_1 is the temperature at the end of the heater)

$\frac{d\theta(L)}{dx} = 0$ or $\frac{dT(x)}{dx} = 0$, $x = L$ (L is the length of the rod. *0.350* m)

The solution then becomes:

$$\theta(x) = \theta(0)\,\frac{cosh[m(L-x)]}{cosh(mL)} \qquad \text{or} \qquad \frac{T(x)-T_a}{T_1-T_a} = \frac{cosh[m(L-x)]}{cosh(mL)}$$

Procedures

1) Setup the measurement unit and pre-heat the experimental apparatus

    Step 1) Connect the power of the HT15 apparatus to the HT10X measurement unit at the rear.

    Step 2) Connect the nine thermocouples of the apparatus to the nine channels in the front of the HT10X unit

    Step 3) Check if all switches at the rear of the unit are up.

    Step 4) Turn the **OPERATE SELECTOR SWITCH** to the manual position, and set the input voltage to minimum by turning the **VOLTAGE CONTROL** potentiometer in the counter-clockwise direction.

    Step 5) Turn on the power switch in front of the unit.

    Step 6) Set the **FUNCTION SELECTOR** switch to the **VOLTAGE** position, then adjust the **VOLTAGE CONTROL** potentiometer to set the heater voltage to **20 Volts**.

    Step 7) Set the **TEMPERATURE SELECTOR** switch to the **T1** position, and wait until the temperature reaches 80°C.

2) Measure the temperatures along the extended rod at the first steady-state condition

    Step 1) When thermocouple **T1** reaches 80°C, reduce the **VOLTAGE CONTROL** potentiometer to **9 Volts**. The temperatures will drop; wait until all temperature readings stabilize (steady-state).

    Step 2) Record the heater voltage and current by switching the **FUNCTION SELECTOR** switch.

    Step 3) Record the eight temperatures along the extended rod (**T1** to **T8**) and ambient air temperature, **T9**, by switching the **TEMPERATURE SELECTOR** switch.

3) Measure the temperatures along the extended rod at the second steady-state condition.

    Step 1) Increase the **VOLTAGE CONTROL** potentiometer to **16 Volts**. The temperatures will rise; wait until all temperature readings stabilize (steady-state).

    Step 2) Repeat Steps 2 & 3 from 2 (above).

        i) If time permits, set the heater voltage to **12 Volts** and repeat the experiment. Then set the heater to **14 Volts** and repeat the experiment again.

    Step 3) When finished and before leaving, turn off the unit and set the **VOLTAGE CONTROL** to zero.

Analysis and Discussions

1. Calculate the input power of the heater for each test case.
2. Plot a temperature (T) vs. distance (x) graphic for each of the tested steady-state conditions.
3. Find the convection heat transfer coefficients (h) for each measured position; and plot a convection heat transfer coefficient (h) vs. distance (x) graphic for each of the tested steady-state conditions.
4. Use the least-squares method to determine a constant for the convection heat transfer coefficient for each of the tested steady-state conditions. Also calculate the errors associated with the determination.

Report Requirement

1. The report must follow the lab report format.
2. The report must be submitted electronically (**PDF**) by the due date.
3. The electronic file must have a file name of: EML4906L_section#_Exp#_Group#.pdf

   Example: EML4906L_U01_Exp2_Grp1.pdf

Experiment 3: Transient Heat Transfer

Objectives

This laboratory exercises is used to investigate the heat transfer response of simple geometrical shapes that are suddenly exposed to convection with a fluid at a constant temperature. This configuration can be extended to many practical applications by using the lumped capacitance method to model the transient heat transfer. It is the overall objective of this experiment to investigate how shape and material selection affects the transient heat transfer response of the system. Additionally, the non-dimensional parameters related to transient heat transfer are used to analyze the response when different materials are used. After completion of this experiment you should be able to:

1. Understand transient heat transfer.
2. Investigate the effect of shape, size and material properties on unsteady heat flow.
3. Determine the Biot Number (Bi) and the convection heat transfer coefficient (h) for the tested cases using different shape, size, and material specimens.

Nomenclature

Symbol	**Description**	**SI Unit**
α	Diffusivity $\left(\frac{k}{c_p\rho}\right)$	$\frac{m^2}{s \cdot K}$
c_p	Heat Capacity of the Material (Isobaric)	$\frac{J}{kg \cdot K}$
ρ	Density of the Material	$\frac{kg}{m^3}$
h	Convection Heat Transfer Coefficient	$\frac{W}{m^2 \cdot K}$
k	Thermal Conductivity of the Material	$\frac{W}{m \cdot K}$
L_c	Characteristic Length $\left(\frac{V}{A_s}\right)$	m
V	Volume	m^3
A_s	Surface Area	m^2
T_a	Ambient Temperature	K
t	Time	s
T_0	Initial Temperature at time $t = 0$	K
$T(t)$	Temperature of the Solid at time $\boldsymbol{t}$	K
$\tau = \frac{c_p\rho V}{hA_s} = \frac{c_p\rho A}{hP}$	Thermal Time Constant	s
$\frac{t}{\tau} = \frac{hA_s t}{c_p\rho V} = Bi \cdot Fo$	Biot-Fourier Number	-
Bi	Biot Number $\left(\frac{hL_c}{k}\right)$	-
Fo	Fourier Number $\left(\frac{\alpha t}{L_c^2}\right)$	-

Introduction

This experiment is qualitative only and intended to show the transient/ time-dependent behavior of a system where temperature varies with time and position. The unsteady-state condition exits when a solid shape is immersed in the hot water and continues until the whole specimen reaches equilibrium with the temperature of the water.

An Armfield HT17 experiment apparatus, a HT10X measurement unit, and Solid shapes of different sizes, forms, and construction material are used for this experiment. The specimen will be allowed to stabilize at room temperature, then placed into a bath of hot water. The temperature changes at the center of the specimen during transient heat transfer are recorded by a signal recorder.

Equipment Overview

The apparatus is a large insulated water bath with a volume of approximately 30 Liters, depicted in Figure 12. At the bottom of the bath is a 3 kW electric heater controlled by a thermostat in order to maintain a constant bath temperature. The water temperature is controlled by a rotary switch located on the front of the bath. The cover assembly for the water bath is designed to allow for rapid insertion of the test specimen into the bath; while keeping the flow conditions similar for various samples. The test samples are attached to the carrier assembly as shown in Figure 12. A small pump is located near the side of the experimental chamber and is used to circulate the water inside the bath. The pump speed is controlled by setting the voltage (0-24 V) on the HT-10X control console. There is no measurement of flow rate inside the bath. The bath is constructed so that the water flow pattern is as shown in Figure 12. The circulation of the water in the bath ensures that the temperature of the water in the vicinity of the test specimen is constant. The temperature of the water in the bath is indicated by the thermocouple marked **T1**. Two other thermocouples are used in the experiments. **T2** is used to measure the temperature of the water as it passes over the test specimen, and **T3** is the temperature embedded in the center of the test specimen.

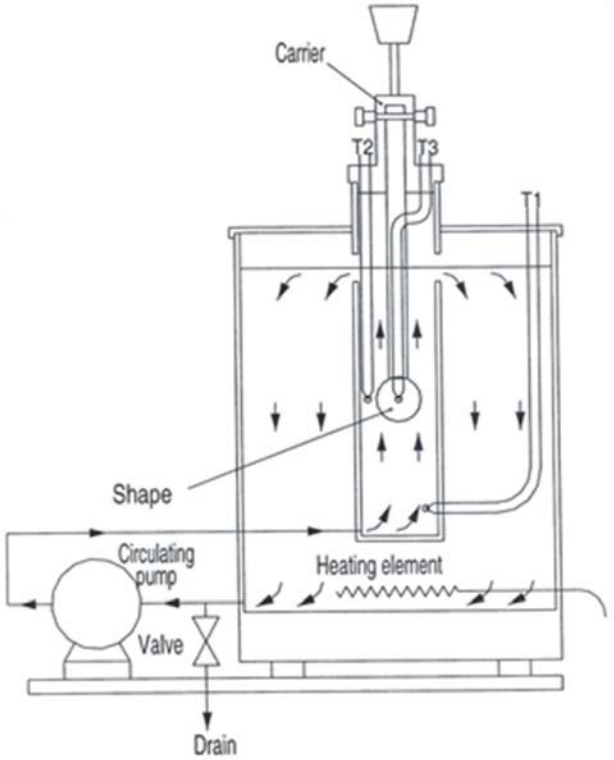


Figure 12: Schematic of HT17 Experiment

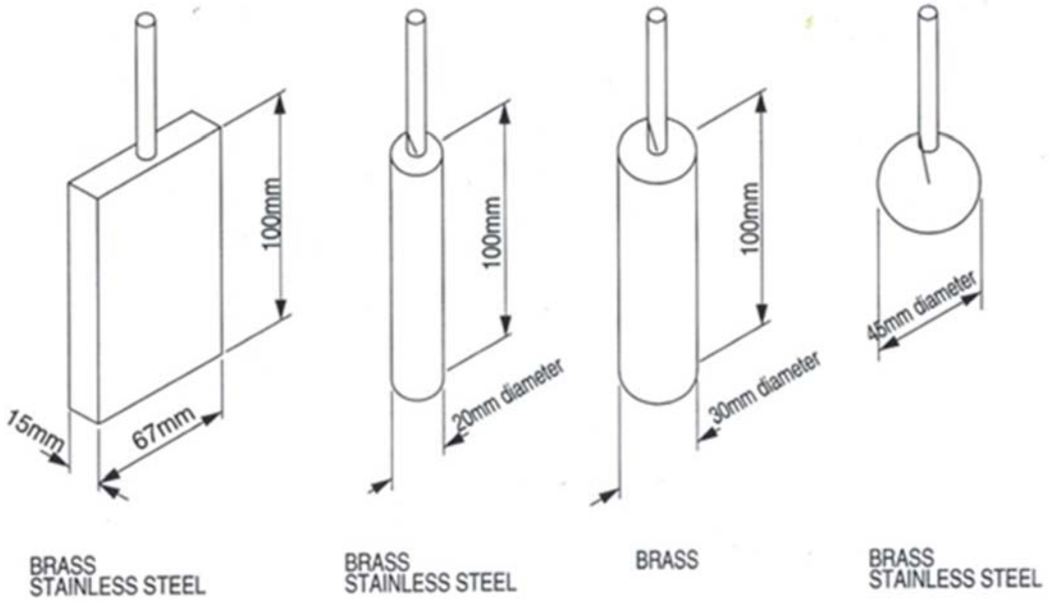


Figure 13: Test Specimens

The HT17 Accessory provides four geometric shapes as shown in the figure above: rectangular plate, large and small diameter cylinder, and sphere. The test specimens are fabricated out of Brass or Stainless Steel as indicated in the figure. Each of the test specimens is mounted to a support rod, which is secured into the carrier assembly for testing and has a thermocouple installed to measure the temperature at the center of the shape.

The apparatus and instrumentation console provide the following data:

Symbol	Description	SI Unit
V	Voltage to the circulating pump	V
I	Current to the circulating pump, I	A
T1	Temperature of water in heated bath	°C
T2	Temperature of air/water carrier	°C
T3	Temperature at center of test specimen	°C

Table 2: Instrument's Data Output

Theoretical Background

When the step change is applied, a temperature gradient exists between the surface of the shape at the water temperature and the center of the shape which is at ambient temperature. Heat flows by conduction through the shape until the whole of the shape is at the same temperature as the water.

According to the lumped analysis approach, the analytical solution is available for temperature distribution and heat flow as a function of time and position for simple solid shapes which are suddenly subjected to convection with a fluid at a constant temperature. Given by:

$$\frac{T(t) - T_a}{T_0 - T_a} = e^{-\frac{t}{\tau}}$$

When $t = \tau$

$$T(\tau) = T_a + 0.368(T_0 - T_a)$$

Or

$$T(\tau) = T_0 + 0.632(T_a - T_0)$$

Material Properties:

Steel: $k = 25 \frac{W}{m \cdot K}$, $\alpha = 0.6 \times 10^{-5} \frac{m^2}{s}$

Brass: $k = 121 \frac{W}{m \cdot K}$, $\alpha = 3.7 \times 10^{-5} \frac{m^2}{s}$

Procedure

1) Setup the measurement unit and pre-heat the experimental apparatus

   Step 1) Connect the power of the apparatus HT17 to the measurement unit HT10X at the rear.

   Step 2) Connect both bath temperature sensor (**T1**) to channel **T1** and carrier sensor (**T2**) to channel 2 in the front of the unit.

   Step 3) Check if all switches at the rear of the unit are up.

   Step 4) Turn the **OPERATE SELECTOR SWITCH** to the manual position, and set the input voltage to minimum by turning the **VOLTAGE CONTROL** potentiometer in the counter-clockwise direction.

   Step 5) Turn on the power switches of both HT-17 and HT-10X units.

   Step 6) Turn on the bath circulator pump by setting the **FUNCTION SELECTOR** switch to the Voltage position; then adjust the **VOLTAGE CONTROL** potentiometer to set the heater voltage to **10 Volts**.

   Step 7) Rotate the black control knob at the base of the water bath to the "**4**" setting. This should heat the water in the bath to approximately **80 °C**.

   Step 8) Set the **TEMPERATURE SELECTOR** switch to the **T1** position, and wait until the temperature reaches approximately **80 °C**.

2) Measure and record the temperatures during transient heat transfer.

   Step 1) Connect the specimen center temperature sensor (**T3**) to the signal recorder, and turn on the signal recorder to record the temperature at the center of the specimen **r = 0** and at time **t = 0**, **T0**.

   Step 2) Turn on the paper feed button of signal recorder with a proper speed setting.

   Step 3) Rapidly insert the specimen into the water bath recording the temperature excursion of the test specimen on the signal recorder paper.

   Step 4) Repeat step 1 to 3 for additional shapes and materials.

Analysis and Discussion

1. Determine the Thermal Time Constant (τ) for each tested case using the recorded plot of the transient response of the specimen.

2. Calculate the characteristic length (L_c), Biot number (Bi), and the convection heat transfer coefficient (h) for each tested case.

3. List the characteristic length (L_c), Biot number (Bi), conductivity (k), and the convection heat transfer coefficient (h) for each tested case in tables (separate the cases of different materials with the same shape from the cases of different shapes with the same material); and discuss the results.

4. Calculate the theoretical temperature by using thermal time constant (τ) obtained from 1. Plot both curves of the experimental temperature vs. time and the theoretical temperature vs. time on a graph.

5. Estimate the surface temperature at $t = 3\tau$.

Report Requirement

1. The report must follow the lab report format.

2. The report must be submitted electronically (**PDF**) by the due date.

3. The electronic file must have a file name of: EML4906L_section#_Exp#_Group#.pdf

   Example: EML4906L_U01_Exp3_Grp1.pdf

Experiment 4: Combined Convection and Radiation

Part A: Heat Transfer at Various Temperatures

Objectives

To compare the contribution of convective heat transfer to that of radiative heat transfer and, from the measurements obtained, show how the convective heat transfer coefficient, h_c, at low surface temperatures is the dominant factor and how the radiative heat transfer coefficient, h_r, is the dominant factor at high surface temperatures. After completion of this experiment you should be able to:

1. Understand natural convection and radiation heat transfer.
2. Investigate how voltage on the heater affects the temperature on the surface of a cylinder in natural convection combined with radiation heat transfer.
3. Determine the effects of different heat fluxes on convective and radiative heat transfer

Nomenclature

Symbol	Description	SI Unit
h	Convection Heat Transfer Coefficient	$\frac{W}{m^2 \cdot K}$
A_s	Surface Area of the Cylinder (πDL)	m^2
V	Input Voltage of the Heater	V
I	Input Current of the Heater	I
T_a	Ambient Temperature	K
T_s	Surface Temperature of the Cylinder	K
σ	Stefan-Boltzmann Constant	$56.7 \times 10^{-9} \frac{W}{m^2 \cdot K^4}$
ε	Emissivity of the Surface	0.95 (for test)
k	Conductivity of the air	$\frac{W}{m \cdot K}$
D or d	Diameter of the cylinder	$0.01\ m$
L	Heated Length of the Cylinder	$0.07\ m$
Q_C	Heat Loss from the Cylinder due to Forced Convection Heat Transfer	W
Q_R	Heat Loss from the Cylinder due to Radiation Heat Transfer	W
Q_{in}	Input power applied onto the cylinder (VI)	W

Introduction

An Armfield experiment apparatus, HT14, and a measurement unit, HT10X, are used for this experiment.

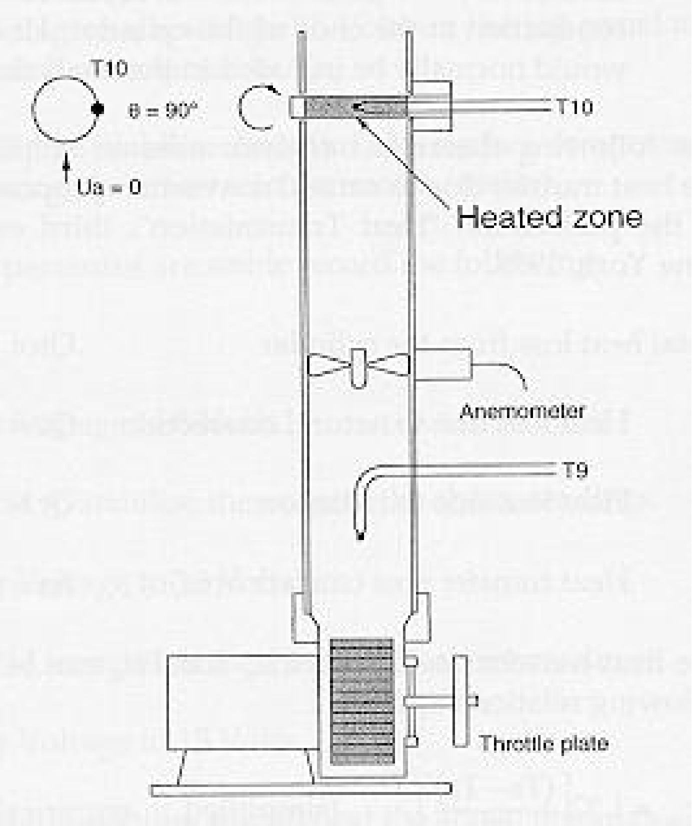


Figure 14: Schematic of the Experimental Setup

If a surface, at a temperature above that of its surroundings, is located in stationary air at the same temperature as the surroundings, then heat will be transferred from the surface to the air and surroundings. This transfer of heat will be a combination of natural convection, to the air, and radiation to the surroundings. A horizontal cylinder is used in this experiment to provide a simple shape from which the heat transfer can be calculated. When the cylinder reaches steady-state, the power of the heater applied onto the cylinder is equal to the heat loss from the cylinder according to energy conservation.

$$Q_{in} = Q_C + Q_R$$

Where

$$Q_{in} = VI$$

And

$$Q_C = h_C A_s (T_s - T_a)$$

$$Q_R = \varepsilon \sigma A_s (T_s^4 - T_a^4) = h_R A_s (T_s - T_a)$$

The free convection heat transfer coefficient, h_C, can be approximately calculated by the following empirical formula,

$$h_C = 1.32 \left(\frac{T_s - T_a}{D} \right)^{0.25}$$

The radiation heat transfer coefficient, h_R, can be approximately calculated by the following empirical formula,

$$h_R = \varepsilon \sigma \frac{(T_s^4 - T_a^4)}{(T_s - T_a)}$$

Procedures

1. Setup the measurement unit and pre-heat the cylinder
   - Step 1. Connect the power of the apparatus, HT14, to the measurement unit, HT10X, at the rear.
   - Step 2. Connect the two thermocouple sensors of the apparatus to the two channels in the front of the unit.
   - Step 3. Check if all the switches in the rear of the unit are up.
   - Step 4. Set the position of the thermocouple on the cylinder to the front (face down), and set the "**Temperature Selector**" switch to the position for monitoring the temperature of the cylinder.
   - Step 5. Turn the "**Operate Selector Switch**" to the manual position, and set the input voltage to minimum by turning the "**Voltage Control**" potentiometer in the counter-clockwise direction.
   - Step 6. Turn on the power to the unit by using the switch on the front of the unit.
   - Step 7. Set the "**Function Selector**" switch to the Voltage position, and then adjust the "**Voltage Control**" potentiometer, to set the heater voltage to **5 Volts**.
2. Measure the temperatures around the surface of the cylinder at the steady-state condition.
   - Step 1. When the temperature on the cylinder stabilizes, record the following:
     - i. The cylinder temperature, *T10*
     - ii. The voltage of the heater, *V*
     - iii. The current of the heater, *I*
   - Step 2. Adjust the voltage to **8 Volts**, allow the temperature to stabilize, and record the data again.
   - Step 3. Repeat Step 2 with voltages of **12**, **15**, and **20 Volts**. Make sure the temperatures stabilized before taking a data sample and moving to the next voltage.
   - Step 4. Before turning off the unit; set the "**Voltage Control**" to zero.

Note: Do not set the heater voltage in excess of 20 Volts when operating the cylinder in natural convection (no forced airflow). The life of the heating element will be considerably reduced if operated at excessive temperature.

Analysis and Discussions

1. Calculate the heater input power for the experiment.
2. Plot a temperature, (T), vs. Voltage, (V), graphic for the experiment.
3. Plot the heat transfer coefficients, h_C and h_R, vs. the temperature of the surface
4. Plot the percentage of the total heat transferred by natural convection and radiation on the same graph. Discuss the trends observed.
5. Compare the calculated heat transfer due to convection, Q_C, with the calculated heat transfer due to radiation, Q_R.
6. Estimate and calculate the experimental errors associate with the experiment.

Report Requirements

1. The report must follow the lab report format.
2. The report must be submitted electronically (**PDF**) by the due date.
3. The electronic file must have a file name of: EML4906L_section#_Exp#_Group#.pdf
   Example: EML4906L_U01_Exp4_Grp1.pdf

Experiment 5: Combined Convection and Radiation

Part B: Forced Convection over a Cylinder in Cross-Flow

Objectives

To determine the effects of forced convection heat transfer on the surface of a cylinder at varying air velocities and surface temperatures. To demonstrate the relationship between air velocity and surface temperature for a cylinder subjected to forced convection. After completion of this experiment you should be able to:

1. Understand forced convection and radiation heat transfer.
2. Investigate the surface temperature of a cylinder in cross flow forced convection combined with radiation heat transfer.
3. Determine the effects of different heat fluxes and airflow velocities on convective and radiative heat transfer.

Nomenclature

Symbol	Description	SI Unit
Re	Reynolds Number $\left(\frac{U_c D}{v}\right)$	-
Pr	Prandtl Number for the Air	-
U_c	Corrected Air Velocity $(1.22U_a)$	$\frac{m}{s}$
v	Viscosity of the Air	$\frac{m^2}{s}$
h	Convection Heat Transfer Coefficient	$\frac{W}{m^2 \cdot K}$
k	Thermal Conductivity of the Material	$\frac{W}{m \cdot K}$
A_s	Surface Area of the Cylinder (πDL)	m^2
V	Input Voltage of the Heater	V
I	Input Current of the Heater	I
T_a	Ambient Temperature	K
T_s	Surface Temperature of the Cylinder	K
σ	Stefan-Boltzmann Constant	$56.7 \times 10^{-9} \frac{W}{m^2 \cdot K^4}$
ε	Emissivity of the Surface	0.95 (for test)
k	Conductivity of the air	$\frac{W}{m \cdot K}$
D or d	Diameter of the cylinder	0.01 m
L	Heated Length of the Cylinder	0.07 m
Nu_{av}	Average Nusselt number	-
Q_C	Heat Loss from the Cylinder due to Forced Convection Heat Transfer	W
Q_R	Heat Loss from the Cylinder due to Radiation Heat Transfer	W
Q_{in}	Input power applied onto the cylinder (VI)	W

Introduction

An Armfield experiment apparatus, HT14, and a measurement unit, HT10X, are used for this experiment.

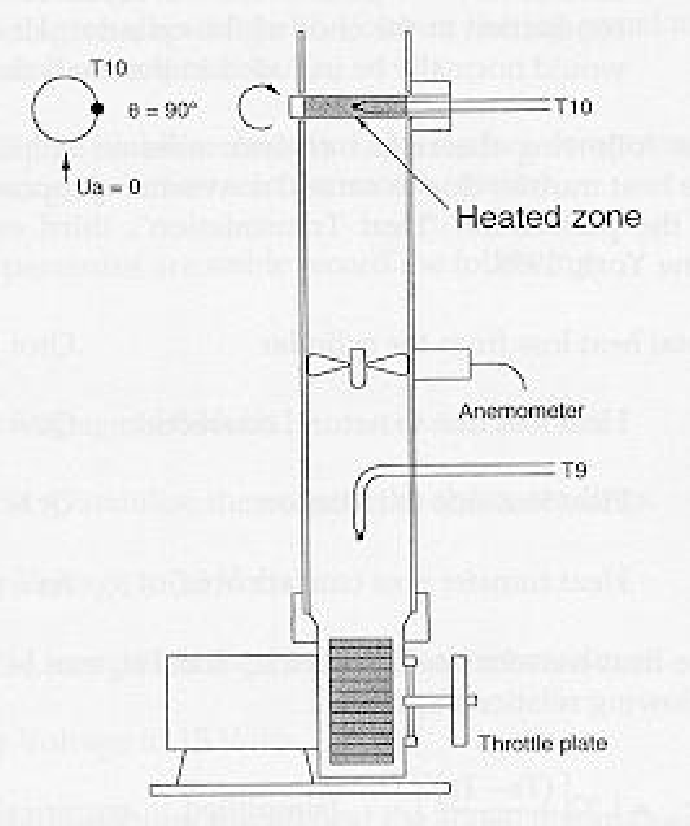


Figure 15: Schematic of the Experimental Setup

In natural convection the heat transfer rate from a surface is limited by the small movements of air which are generated by changes in the density of the air as the air is heated by the surface. In forced convection the air movement can be greatly increased resulting in improved heat transfer rate from a surface. Therefore, a surface subjected to forced convection will have a lower surface temperature than the same surface subjected to free convection, for the same power input.

Heat will be transferred from a surface to the fluid flowing over the surface as long as the fluid is at a lower temperature than that of the surface. This transfer of heat will be a combination of forced convection to the air (heat is transferred to the air passing the surface) and radiation to the surroundings. The horizontal cylinder used in this exercise provides a simple shape from which the heat transfer can be calculated. Cylinders in cross-flow are typical to designs found in heat exchangers. When the cylinder reaches steady-state, the power of the heater applied onto the cylinder is equal to the heat loss from the cylinder according to energy conservation[1].

$$Q_{in} = Q_F + Q_R$$

Where

$$Q_{in} = VI$$

And

$$Q_C = h_F A_s (T_s - T_a)$$

$$Q_R = \varepsilon \sigma A_s (T_s^4 - T_a^4) = h_R A_s (T_s - T_a)$$

The forced convection heat transfer coefficient, h_F, can be approximately calculated by the following empirical formula,

$$h_F = \frac{k_f}{D} Nu_{av}$$

The radiation heat transfer coefficient, h_R, can be approximately calculated by the following empirical formula,

$$h_R = \varepsilon \sigma \frac{(T_s^4 - T_a^4)}{(T_s - T_a)}$$

---

[1] Heat loss due to conduction is minimized by the design of the equipment. Measurements mid- way along the heated section of the cylinder can be assumed to be unaffected by conduction at the ends of the cylinder. Heat loss by conduction would normally be included in the analysis of a real application.

An empirical formula[2] from can be used to calculate the value for the Average Nusselt number as follows:

$$Nu_{av} = 0.3 + \frac{0.62Re^{0.5}Pr^{0.33}}{\left(1+\left(\frac{0.4}{Pr}\right)^{0.66}\right)^{0.25}}\left[1+\left(\frac{Re}{282000}\right)^{0.5}\right]$$

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[2] S Churchill and M Bernstein "A Correlating Equation for Forced Convection from Gases and Liquids to a Circular cylinder in crossflow" Journal of Heat Transfer, 99:300-306 (1977)

Procedures

1. Setup the measurement unit and pre-heat the cylinder
   - Step 1. Connect the power of the apparatus, HT14, to the measurement unit, HT10X, at the rear.
   - Step 2. Connect the two thermocouple sensors of the apparatus to the two channels in the front of the unit.
   - Step 3. Check if all the switches in the rear of the unit are up.
   - Step 4. Set the position of the thermocouple on the cylinder to the front (face down), and set the "**Temperature Selector**" switch to the position for monitoring the temperature of the cylinder.
   - Step 5. Turn the "**Operate Selector Switch**" to the manual position, and set the input voltage to minimum by turning the "**Voltage Control**" potentiometer in the counter-clockwise direction.
   - Step 6. Turn on the power to the unit by using the switch on the front of the unit.
   - Step 7. Set the "**Function Selector**" switch to the Voltage position, and then adjust the "**Voltage Control**" potentiometer, to set the heater voltage to **20 Volts**.
2. Measure the temperatures around the surface of the cylinder at the steady-state condition.
   - Step 1. When the temperature on the cylinder stabilizes, record the following:
     - i. Air Temperature, *T9*
     - ii. Cylinder temperature, *T10*
     - iii. Voltage of the heater, *V*
     - iv. Current of the heater, *I*
   - Step 2. Turn on the fan, and open the throttle plate on the front of the fan by rotating the adjustment knob to give an air velocity, U_a, reading of 1.0 $m/_{s}$. Repeat *Step 1*.
   - Step 3. Repeat *Step 2* with changing the air velocity in 1.0 $m/_{s}$ intervals, until the air velocity is 5.0 $m/_{s}$.
   - Step 4. Before turning off the unit; set the "**Voltage Control**" to zero.

Note: Do not set the heater voltage in excess of 20 Volts when operating the cylinder in natural convection (no forced airflow). The life of the heating element will be considerably reduced if operated at excessive temperature.

Analysis and Discussions

1. Determine the forced convection heat transfer coefficients for each of the tested cases, and compare them to the results obtained from the empirical formula; list them in a table.
2. Plot a Surface Temperature (T) of the cylinder vs. the Air Velocity (U_a) on a graph
3. Generate an approximate empirical formula for the Surface Temperature (T) of the cylinder changing with the air velocity (U_a).
4. Plot the heat transfer coefficients, h_F and h_R, vs. the temperature of the surface
5. Plot the percentage of the total heat transferred by forced convection and radiation on the same graph. Discuss the trends observed.
6. Compare the calculated heat transfer due to forced convection, Q_F, with the calculated heat transfer due to radiation, Q_R.
7. Estimate and calculate the experimental errors associate with the experiment.

Report Requirements

1. The report must follow the lab report format.
2. The report must be submitted electronically (**PDF**) by the due date.
3. The electronic file must have a file name of: EML4906L_section#_Exp#_Group#.pdf
   Example: EML4906L_U01_Exp5_Grp1.pdf

Experiment 6: Combined Convection and Radiation

Part C: Forced Convection over a Cylinder in Cross-Flow

Objectives

To demonstrate that the local heat transfer coefficient varies around the circumference of a horizontal cylinder when subjected to forced convection. This will be accomplished by subjecting a horizontal cylinder to a steady-state condition of forced convection and radiation (constant power input), and then rotate the cylinder and measure the local differences in temperature over the surface of the cylinder (positioning thermocouple T10 at different angular positions to produce a temperature profile). After completion of this experiment you should be able to:

1. Understand forced conduction and radiation heat transfer.
2. Investigate the temperature distribution around the surface of a cylinder in cross flow forced convection combined with radiation heat transfer.
3. Determine the convection heat transfer coefficients for the different positions around the cylinder.

Nomenclature

Symbol	**Description**	**SI Unit**
Re	Reynolds Number $\left(\frac{U_c D}{v}\right)$	-
Pr	Prandtl Number for the Air	-
U_c	Corrected Air Velocity $(1.22U_a)$	$\frac{m}{s}$
v	Viscosity of the Air	$\frac{m^2}{s}$
h	Convection Heat Transfer Coefficient	$\frac{W}{m^2 \cdot K}$
k	Thermal Conductivity of the Material	$\frac{W}{m \cdot K}$
A_s	Surface Area of the Cylinder (πDL)	m^2
V	Input Voltage of the Heater	V
I	Input Current of the Heater	I
T_a	Ambient Temperature	K
T_s	Surface Temperature of the Cylinder	K
σ	Stefan-Boltzmann Constant	$56.7 \times 10^{-9} \frac{W}{m^2 \cdot K^4}$
ε	Emissivity of the Surface	0.95 (for test)
k	Conductivity of the air	$\frac{W}{m \cdot K}$
D or d	Diameter of the cylinder	0.01 m
L	Heated Length of the Cylinder	0.07 m
Nu_{av}	Average Nusselt number	-
Q_C	Heat Loss from the Cylinder due to Forced Convection Heat Transfer	W
Q_R	Heat Loss from the Cylinder due to Radiation Heat Transfer	W
Q_{in}	Input power applied onto the cylinder (VI)	W

Introduction

An Armfield experiment apparatus, HT14, and a measurement unit, HT10X, are used for this experiment.

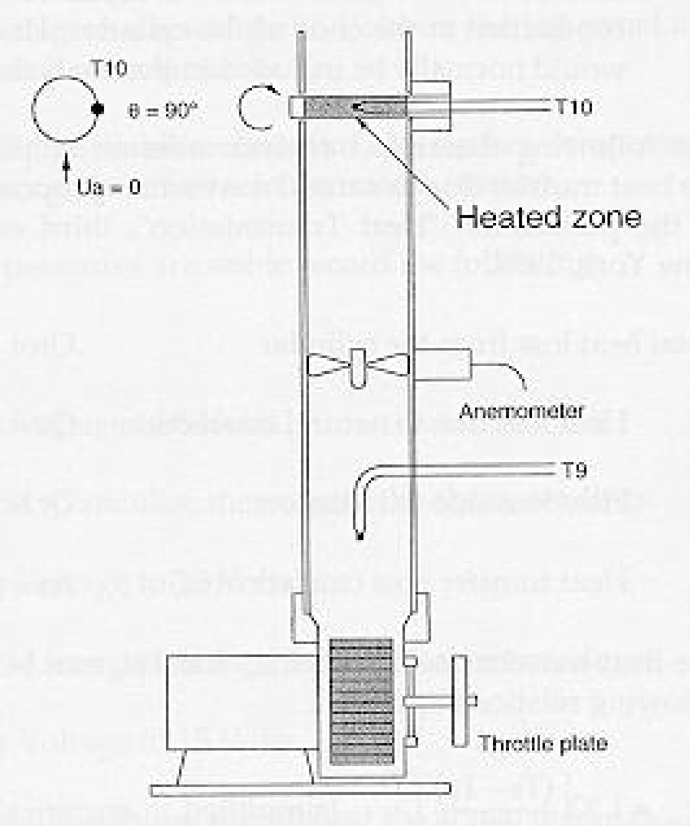

Figure 16: Schematic of the Experimental Setup

The purpose of this apparatus is to demonstrate that the temperature profile around the circumference of the cylinder is not constant. The heat transfer coefficient varies according to the position on the surface of the cylinder. The cylinder is rotated to present the thermocouple at different angular positions; the temperature is recorded at each angular position after allowing the temperature profile of the cylinder to stabilize (steady-state). When the cylinder reaches steady-state, the power of the heater applied onto the cylinder is equal to the heat loss from the cylinder according to the energy conservation.

$$Q_{in} = Q_F + Q_R$$

Where

$$Q_{in} = VI$$

And

$$Q_C = h_F A_s (T_s - T_a)$$

$$Q_R = \varepsilon \sigma A_s (T_s^4 - T_a^4) = h_R A_s (T_s - T_a)$$

The forced convection heat transfer coefficient, h_F, can be approximately calculated by the following empirical formula[3],

$$h_F = \frac{k_f}{D} Nu_{av}$$

The radiation heat transfer coefficient, h_R, can be approximately calculated by the following empirical formula[4],

$$h_R = \varepsilon \sigma \frac{(T_s^4 - T_a^4)}{(T_s - T_a)}$$

An empirical formula from can be used to calculate the value for the Average Nusselt number as follows:

$$Nu_{av} = 0.3 + \frac{0.62 Re^{0.5} Pr^{0.33}}{\left(1 + \left(\frac{0.4}{Pr}\right)^{0.66}\right)^{0.25}} \left[1 + \left(\frac{Re}{282000}\right)^{0.5}\right]$$

Figure 17 depicts the variation of the Nusselt Number with the variation in cylinder angle.

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[3] S Churchill and M Bernstein "A Correlating Equation for Forced Convection from Gases and Liquids to a Circular cylinder in crossflow" Journal of Heat Transfer, 99:300-306 (1977)

[4] S Churchill and M Bernstein "A Correlating Equation for Forced Convection from Gases and Liquids to a Circular cylinder in crossflow" Journal of Heat Transfer, 99:300-306 (1977)

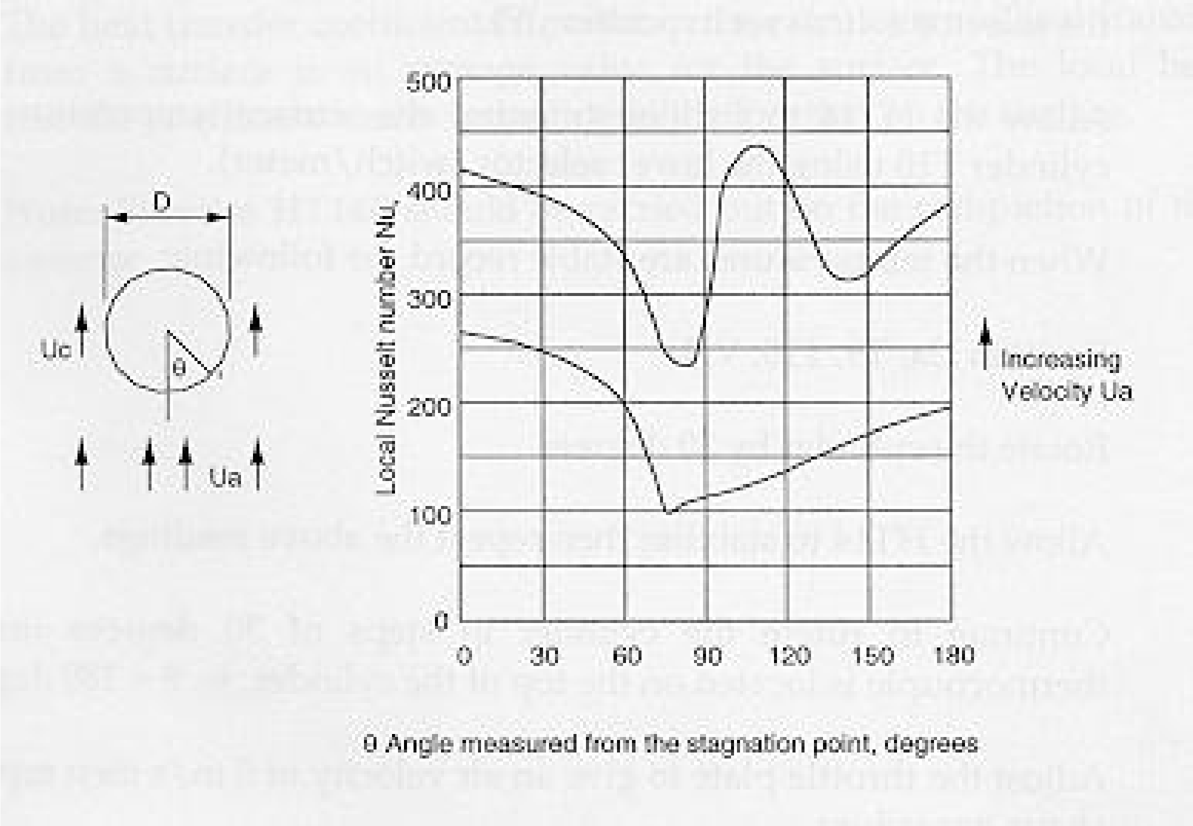

Figure 17: Variation of the Nusselt Number with varying Cylinder Angle

Procedures

1. Setup the measurement unit and pre-heat the cylinder

   Step 1. Connect the power of the apparatus, HT14, to the measurement unit, HT10X, at the rear.

   Step 2. Connect the two thermocouple sensors of the apparatus to the two channels in the front of the unit.

   Step 3. Check if all the switches in the rear of the unit are up.

   Step 4. Set the position of the thermocouple on the cylinder to the front (face down), and set the "**Temperature Selector**" switch to the position for monitoring the temperature of the cylinder.

   Step 5. Turn the "**Operate Selector Switch**" to the manual position, and set the input voltage to minimum by turning the "**Voltage Control**" potentiometer in the counter-clockwise direction.

   Step 6. Turn on the power to the unit by using the switch on the front of the unit.

   Step 7. Set the "**Function Selector**" switch to the Voltage position, and then adjust the "**Voltage Control**" potentiometer, to set the heater voltage to **20 Volts**.

   Step 8. Turn on the fan and open the throttle plate on the front of the fan by rotating the adjustment knob to give an air velocity, U_a, reading of $1.0\, {}^{m}/_{s}$.

2. Measure the temperatures around the surface of the cylinder at the steady-state condition.

   Step 1. When the temperature on the cylinder stabilizes, record the following:

      i. Angle, θ
      ii. Air Flow Temperature, *T9*
      iii. Cylinder temperature, *T10*
      iv. Voltage of the heater, *V*
      v. Current of the heater, *I*

   Step 2. Rotate the cylinder by 30°, allow the temperature to stabilize, and record the data again.

   Step 3. Repeat *Step 2* until the cylinder reaches 180°

   Step 4. Before turning off the fan and unit; set the "**Voltage Control**" to zero.

Analysis and Discussions

1. Calculate the heater input power for the experiment.
2. Plot a Surface Temperature (T) of the cylinder vs. Angular Position (θ) on a graph
3. Determine the local heat transfer coefficients over the surface of the cylinder, and compare them to the results obtained from the empirical formula.

Report Requirements

1. The report must follow the lab report format.
2. The report must be submitted electronically (**PDF**) by the due date.
3. The electronic file must have a file name of: EML4906L_section#_Exp#_Group#.pdf
   Example: EML4906L_U01_Exp6_Grp1.pdf

Appendix

Air Speed Calculation Using a Pitot Tube

In many cases, pressure is indicated in the equivalent column height of a liquid, (sometimes known as a *pressure head*) usually water for gas (air) flow, or mercury for liquid (water) flow. The hydrostatic pressure created in a column of any liquid is given by:

$$P = \rho g H \tag{1}$$

Hence, when a pressure is given in terms of height, [e.g. **inches H_2O** or **mm Hg**], then it can be converted to a pressure using equation (1). This pressure head or liquid height is historically related to the differential height for the two columns of the liquid in a U-Tube manometer.
A *Pitot Tube* measures both the *total* (or *stagnation*) pressure and the *static* pressure in an air flow. The velocity of the air is related to the difference of these two pressures by:

$$V = \sqrt{\frac{2(P_{Total} - P_{Static})}{\rho_{air}}} \tag{2}$$

The pressure in equation (2) is in terms of force over area, so a pressure measured in liquid column height must be converted. For example, if the pressure is given in terms of **inches H_2O** then using equation (1) in equation (2) gives:

$$V = \sqrt{\frac{2(H_{Total} - H_{Static})\rho_{water} g}{\rho_{air}}} \tag{3}$$

To obtain the density of ambient air, use the ambient pressure and temperature and the Ideal Gas Law:

$$V = \sqrt{\frac{2(H_{Total} - H_{Static})\rho_{water} g}{\frac{P_{ambient}}{R_g T_{ambient}}}} \tag{4}$$

where R_g is the Universal Gas Constant and equal to:

$$R_g = 287\,\frac{J}{kg \cdot K} \qquad \text{(for air only!)}$$

Warning: CHECK YOUR UNITS! Pressure heads may need to be converted to standard length dimensions and temperature will need to be converted to Rankine or Kelvin.