T.C.
ANKARA YILDIRIM BEYAZIT UNIVERSITY
FACULTY OF ENGINEERING AND NATURAL SCIENCES
MECHANICAL ENGINEERING DEPARTMENT

MCE - 403 MACHINERY LABORATORY - I LABORATORY MANUAL

2020 - 2021 Fall Semester

October 2020, Ankara

PREFACE

Machinery Laboratory course, due to being a practice of the courses taken by engineering faculty students during their undergraduate studies, has a great importance and differs from other courses from this aspect. Therefore, theoretical subjects learned from other courses can only be deeply understood by attaching importance to laboratory courses. Attending all the laboratories and preparing lab reports will contribute to clear understanding of many subjects that is previously investigated by the students theoretically.

The basic starting point of this laboratory manual is to make our students better educated and equipped, also prevent time waste for the students who need to get laboratory manuals. In addition to this, having an experiment manual would provide a source to our students during their professional lives.

I wish this lab manual will be beneficial for all our students and I sincerely would thank to academic staff of the department who provided the main contribution for this manual to be prepared.

October 2020, Ankara

Prof. Dr. Sadettin ORHAN
Head of The Mechanical Engineering Department

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1. INTRODUCTION

Machinery Laboratory course, due to being a practice of the courses taken by engineering faculty students during their undergraduate studies, has a great importance and differs from other courses in this aspect. Therefore, theoretical subjects of engineering courses can only be deeply understood through giving importance to laboratory courses. Attending all the laboratories and preparing lab reports will contribute to clear understanding of many subjects that is previously investigated by the students theoretically.

1.1 Scope of the Course

As a practical course, Machinery Laboratory course is oriented to demonstrate the validity of many physical laws which students have learned theoretically during their courses in undergraduate study. Through the experiments within the scope of this course, basic principles of many courses from Engineering Materials course to Thermodynamics course, from Strength of Materials course to Heat Transfer course will be practically examined. From this point of view, Machinery Laboratory course is a summary of undergraduate study and gives an important opportunity to the students to understand all the subjects better.

1.2 Importance and Basis of Experimental Studies

It is obvious that experimental studies are useful to comprehend theoretical subjects. However, in order to reach this target, many regulations have to be provided; for instance, experiments have to be conducted patiently and carefully, the equipment used in experiments have to be calibrated, experiments have to be repeated sufficiently, the measurements have to be done after maintaining steady-state conditions. Even after providing all these regulations, experimental studies include errors. Errors occurring in experimental studies and analysis of errors are explained below.

1.2.1 Experimental Errors and Error Analysis Methods

All experimental studies contain errors due to different reasons. The errors in experimental studies can be classified into three groups. The first one is due to lack of attention and experience of the researcher. Improper selection of measurement equipment and inappropriate design of measurement tools can be considered within this group. The second type of errors is called as constant or systematic errors. These errors are seen generally during repeated measurements and mostly the reasons cannot be determined. The third one is random errors. These are occurring due to personal fluctuations, decrease of attention of people who conducts experiments by the time, random electronic fluctuations, and hysteresis of measurement equipment [1].

In order to determine the validity of experimental results, error analysis has to be conducted. A few methods have been practically developed to determine errors belonging to the parameters calculated by using the data obtained from experiments. The most common ones of these methods are Uncertainty Analysis and Commonsense Basis [1]. Uncertainty method which was found by Kline and McClintock, is more sensitive method since it determines the variable causing the greatest error immediately. Thus, to reduce error, the tool which is used for measurement of the related variable can be considered and investigated deeply. The mentioned uncertainty analysis method is explained in the following part and practical application of it is explained shortly.

1.2.2 Uncertainty Analysis Method

A more precise method of estimating uncertainty in experimental results has been presented by Kline and McClintock. The method is based on a careful specification of the uncertainties in the various primary experimental measurements. For example, a certain pressure reading might be expressed as

$$p = 100\ \mathrm{kPa}\ \pm 1\ \mathrm{kPa} \qquad (1.1)$$

When the plus or minus notation is used to designate the uncertainty, the person making this designation is stating the degree of accuracy with which he or she believes the measurement has been made. We may note that this specification is in itself uncertain because the experimenter is naturally uncertain about the accuracy of these measurements. If a very careful calibration of an instrument has been performed recently with standards of very high precision, then the experimentalist will be justified in assigning a much lower uncertainty to measurements than if they were performed with a gage or instrument of unknown calibration history.

To add a further specification of the uncertainty of a particular measurement, Kline and McClintock propose that the experimenter specify certain odds for the uncertainty. The above equation for pressure might thus be written

$$p = 100\ kPa\ \pm 1\ kPa\ (20\ to\ 1) \qquad (1.2)$$

In other words, the experimenter is willing to bet with 20 to 1 odds that the pressure measurement is within ±1 kPa. It is important to note that the specification of such odds can only be made by the experimenter based on the total laboratory experience.

Suppose that the value R is to be measured by using experimental equipment, and n independent variables which have effects on this value are; $x_1, x_2, x_3,.....,x_n$. In this condition, it can be written as;

$$R = R(x_1,\ x_2,\ x_3,.....,x_n\ ) \qquad (1.3)$$

If constant error values for each effective variables are $w_1, w_2, w_3,.....,w_n$ and constant error value of R is w_R, then according to uncertainty analysis method;

$$w_R = \pm\left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}w_2\right)^2 + ...+\left(\frac{\partial R}{\partial x_n}w_n\right)^2\right]^{1/2} \qquad (1.4)$$

The formula above is obtained [2]. We should call the student's attention to the requirement that all the uncertainties in Eq. (1.4) should be expressed with the same odds. As a practical matter, the relation is most often used without regard to a specification of the odds of the uncertainties w_n. The experimentalist conducting the experiments is the person best qualified to estimate such odds, so it not unreasonable to assign responsibility for relaxation of the equal-odds to him or her [2].

1.2.3 An Exemplary Calculation According to Uncertainty Analysis

The uncertainties (constant error values) of measurement tools used in experiments are determined by calibration of these tools. For instance, calibration of measurement tools used in an experiment was done and uncertainties of these tools are given as in Table 1.1. Thus, uncertainties of independent variables are known and by using the Eq. (1.4), uncertainties of dependent variables can be determined.

Table 1.1. Determined Uncertainties of Measurement Tools in an Exemplar Experiment [3]

Measurement Tool	Calibration Range	Uncertainty Values (±*w*)
Thermometers	0 ~ 80 ºC	± 0.092 ºC
Pressure Gauge (Absolute pressure)	0 ~ 12.5 bar	± 0.980 kPa
Pressure Gauge (Differential pressure)	0 ~ 55 kPa	± 0.123 kPa
Flowmeter (Refrigerant)	0 ~ 2.703 g/s	± 0.019 g/s
Rotameter (Cooling water)	0 ~ 21.2 g/s	± 0.316 g/s
After heater	0 ~ 600 W	± 0.300 W

For example[3], in a counter current parallel flow heat exchanger; logarithmic mean temperature difference (*LMTD*) ΔT_{lm}, is defined as below formula, depending on ΔT_1 and ΔT_2 which are temperature differences between fluids in entrance and exit of heat exchanger:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{ln \frac{\Delta T_1}{\Delta T_2}} \tag{1.5}$$

In this condition, if uncertainties of the measurements done during entrance and exit of fluids are known, regarding this point, error values related to ΔT_1 and ΔT_2 temperature differences can be found with the aid of the formulas below:

$$w_{\Delta T_1} = \pm \left[\left(w_{T_{1,g}} \right)^2 + \left(w_{T_{2,ç}} \right)^2 \right]^{1/2} \tag{1.6}$$

$$w_{\Delta T_2} = \pm \left[\left(w_{T_{1,ç}} \right)^2 + \left(w_{T_{2,g}} \right)^2 \right]^{1/2} \tag{1.7}$$

With reference to the mentioned error values, constant error value related to ΔT_{lm} can be found through the Eq. (1.8).

$$w_{\Delta T_{lm}} = \pm\left[\left(\frac{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)-\frac{\Delta T_1-\Delta T_2}{\Delta T_1}}{\left(ln\left(\frac{\Delta T_1}{\Delta T_2}\right)\right)^2} w_{\Delta T_1}\right)^2 + \left(\frac{-ln\left(\frac{\Delta T_1}{\Delta T_2}\right)+\frac{\Delta T_1-\Delta T_2}{\Delta T_2}}{\left(ln\left(\frac{\Delta T_1}{\Delta T_2}\right)\right)^2} w_{\Delta T_2}\right)^2\right]^{1/2} \qquad (1.8)$$

1.3 General Regulations about the Course

For the engineering students to reach the beneficial targets of the laboratory course which is a practical application of the undergraduate courses, students should obey the general regulations explained below and should give sufficient importance to preparing experiment (lab) reports. Thus, the below regulations are to be obeyed.

1.3.1 General Subjects about the Course

The rules below are given in order to maintain lab sessions in an orderly manner;

1) The related experiment manual should be investigated in detail before coming to the labs.
2) The students without experiment manual will not be accepted to the labs.
3) It is compulsory for every student to attend the lab with his/her own group.
4) The students have to attend at least 80% of the labs and submit all the lab reports which s/he has attended. However, the report grades s/he took will be summed up and the average grade will be calculated by dividing the total grade to total number of labs, even s/he would not attend.
5) The cover page shown in App. 1, must be used in the lab reports.
6) The experiment reports must be prepared in a style that they include all the tables needed for the measurements.
7) Experiment reports must be hand written, not prepared in computers. Both sides of the pages should be used except for the cover page.
8) Lab reports must be submitted at most 1 week later after the experiment date. Late submission of reports is not an accepted choice. Late submitted reports will not be evaluated.
9) Experiment reports will be submitted directly to the related instructor and the answers to the questions asked by the instructor will be strongly effective on your grades.
10) No makeup experiment will be held at the end of the semester.

1.3.2 Preparing Experiment (Lab) Report

1) The cover page shown in App. 1, will be used in the lab reports.

2) The lab reports will include a cover page, the aim of the experiment, a schematic demonstration of the experiment installation, the main equipment of the experiment installation and information about the main equipment.

3) Also the experiment reports will include a table for the measurements done in the related lab, calculations done, a table for results, the graphs to be drawn and a “Comments and Conclusion” part.

1.4 Experiment List and Related Instructors

Name of the experiments and the responsible instructors for the related experiments are given in Table 1.2 below.

Table 1.2. Experiment List, the Related Instructors and Labs

Order	Name of the Experiment	Relevant Instructor	Teaching Assistant	Place
1	Bernoulli Experiment	Prof. Dr. Veli ÇELİK	R. Assist. Polat KURT	Online
2	Flow Measurement Experiment	Prof. Dr. Ünal ÇAMDALI	R. Assist. Aysun GÜVEN	Online
3	Hardness Measurement Experiment	Prof. Dr. Adem ÇİÇEK	R. Assist. Necati UÇAK	Online
4	Heat Conduction Experiment	Assist. Prof. Dr. Kemal BİLEN	R. Assist. Halil YILDIRIM	Online
5	Heat Radiation Experiment	Assist. Prof. Dr. Yasin SARIKAVAK	R. Assist. Orçun BİÇER	Online
6	Fluid Machinery and Pelton Turbine Experiment	Prof. Dr. Ahmet PINARBAŞI	R. Assist. Ahmet Emin KILIÇ	Online
7	Mechanical Vibrations Experiment	Prof. Dr. Sadettin ORHAN Prof. Dr. Mehmet SUNAR	R. Assist. M. Cihat YILMAZ	Online
8	Natural and Forced Heat Convection Experiment	Prof. Dr. Erol ARCAKLIOĞLU Assoc. Prof. Dr. Hasan ÖZCAN	R. Assist. Halil YILDIRIM R. Assist. Orçun BİÇER	Online
9	Strain Measurement Experiment	Assist. Prof. Dr. Fatih GÖNCÜ Assist. Prof. Dr. Mete BAKIR	R. Assist. Mustafa YILDIZ	Online
10	Tensile Test Experiment	Prof. Dr. Fahrettin ÖZTÜRK Assoc. Prof. Dr. İhsan TOKTAŞ	R. Assist. Oğuzhan MÜLKOĞLU	Online

1.5 Experiment Weeks

Experiment weeks are announced (for Fall and Spring Semesters) on the department's website.

1.6 Extra Notes about the Semester

1) There will be a laboratory reports grade (50%), and a final exam grade (50%) within the scope of the course.
2) To fulfill the course; at least 80% of laboratory attendance and submitting the reports of attended labs are compulsory. Average report grade is calculated over 10 labs.
3) The students who are repeating the course without attendance obligation do not have to attend the experiments, they can attend only final exam. In this case, their final exam grade will have an effect of 100%.
4) For other regulations of the course, please see Chapter 1.3 "General Regulations about the Course" in the Laboratory Manual.
5) The updated Laboratory Manual of this semester can be obtained from the department's website.
6) For more information about the experiments, you can contact relevant assistant. For general information about the course, you can also contact Assist. Prof. Dr. Yasin SARIKAVAK.

2. EXPERIMENT MANUALS

2.1 Bernoulli Experiment

2.1.1 Objective

The aim of this experiment is to verify Bernoulli Equation by using a venturi meter to observe fluid elevation through the tube with different flow rates and research the reasons of different between theory and practice.

2.1.2 Introduction

The Bernoulli equation is an approximate relation between pressure, velocity, and elevation, and is valid in regions of steady, incompressible flow where net frictional forces are negligible (Fig. 2.1.1). Despite its simplicity, it has proven to be a very powerful tool in fluid mechanics. In this section, we derive the Bernoulli equation by applying the conservation of linear momentum principle, and we demonstrate both its usefulness and its limitations.

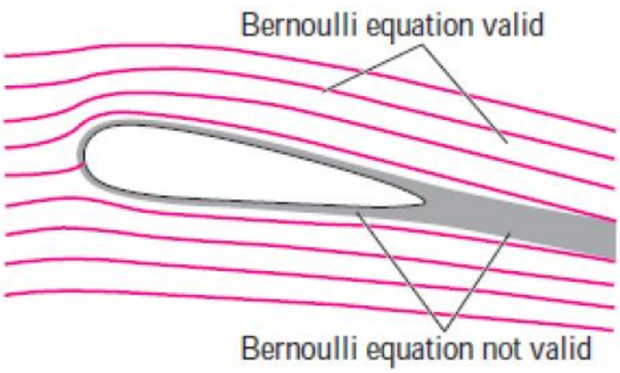


Figure 2.1.1. Practicable regions of Bernoulli equation

2.1.3 Theory

To derive the Bernoulli equation Consider the motion of a fluid particle in a flow field in steady flow.

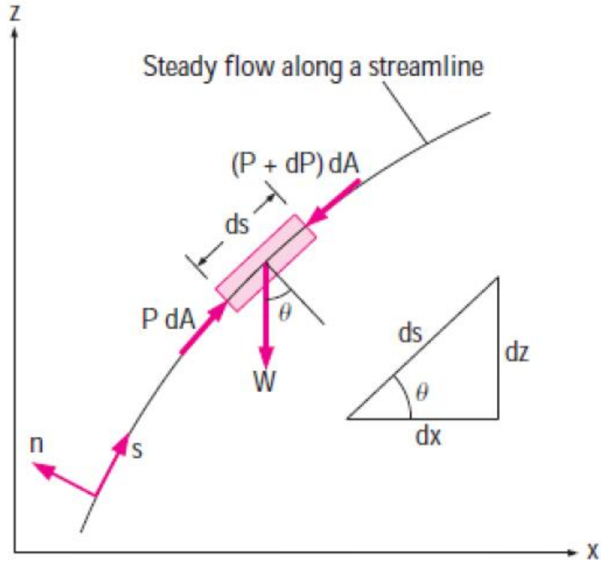


Figure 2.1.2. The forces acting on a fluid particle along a streamline

Applying Newton's second law (which is referred to as the conservation of linear momentum relation in fluid mechanics) in the s-direction on a particle moving along a streamline gives:

$$\sum F_s = m\, a_s \tag{2.1.1}$$

In regions of flow where net frictional forces are negligible, the significant forces acting in the s-direction are the pressure (acting on both sides) and the component of the weight of the particle in the s-direction (Fig. 2.1.2). Therefore, Eq. 2.1.1 becomes:

$$P\, dA - (P + dP)dA - W\, sin\theta = m\, V \frac{dV}{ds} \tag{2.1.2}$$

where θ is the angle between the normal of the streamline and the vertical z-axis at that point, $m = \rho\, V = \rho\, dA\, ds$ is the mass, $W = m\, g = \rho\, g\, dA\, ds$ is the weight of the fluid particle, and $sin\theta = dz/ds$. Substituting;

$$-dP\, dA - \rho\, g\, dA\, ds \frac{dz}{ds} = \rho\, dA\, ds\, V\, \frac{dV}{ds} \tag{2.1.3}$$

Canceling *dA* from each term and simplifying,

$$-dP - \rho\, g\, dz = \rho\, V\, dV \tag{2.1.4}$$

Noting that $V\, dV = 1/2\ \ d(V^2)$ and dividing each term by ρ gives;

$$\frac{dP}{\rho} + \frac{1}{2} d(V^2) + g\, dz = 0 \tag{2.1.5}$$

For steady flow along a streamline equation becomes;

$$\int \frac{dP}{\rho} + \frac{V^2}{2} + g\, z = constant \tag{2.1.6}$$

since the last two terms are exact differentials. In the case of incompressible flow, the first term also becomes an exact differential, and its integration gives;

$$\frac{P}{\rho} + \frac{V^2}{2} + g\, z = constant \tag{2.1.7}$$

The value of the constant can be evaluated at any point on the streamline where the pressure, density, velocity, and elevation are known. The Bernoulli equation can also be written between any two points on the same streamline as;

$$\frac{P_1}{\rho} + \frac{V_1^2}{2} + g\, z_1 = \frac{P_2}{\rho} + \frac{V_2^2}{2} + g\, z_2 \tag{2.1.8}$$

2.1.3.1 Static, Dynamic and Stagnation Pressures

The Bernoulli equation states that the sum of the flow, kinetic, and potential energies of a fluid particle along a streamline is constant. Therefore, the kinetic and potential energies of the fluid can be converted to flow energy (and vice versa) during flow, causing the pressure to change. This phenomenon can be made more visible by multiplying the Bernoulli equation by the density ρ;

$$P + \rho \frac{V^2}{2} + \rho\, g\, z = constant \tag{2.1.9}$$

Each term in this equation has pressure units, and thus each term represents some kind of pressure:

- P is the static pressure (it does not incorporate any dynamic effects); it represents the actual thermodynamic pressure of the fluid. This is the same as the pressure used in thermodynamics and property tables.
- $\rho V^2/2$ is the dynamic pressure; it represents the pressure rise when the fluid in motion is brought to a stop isentropically.
- $\rho\, g\, z$ is the hydrostatic pressure, which is not pressure in a real sense since its value depends on the reference level selected; it accounts for the elevation effects, i.e., of fluid weight on pressure.

The sum of the static, dynamic, and hydrostatic pressures is called the total pressure. Therefore, the Bernoulli equation states that the total pressure along a streamline is constant.

The sum of the static and dynamic pressures is called the stagnation pressure, and it is expressed as:

$$P_{stag} = P + \rho \frac{V^2}{2} \tag{2.1.10}$$

The stagnation pressure represents the pressure at a point where the fluid is brought to a complete stop isentropically. When static and stagnation pressures are measured at a specified location, the fluid velocity at that location can be calculated from:

$$V = \sqrt{\frac{2(P_{stag} - P)}{\rho}} \tag{2.1.11}$$

2.1.4 The Experiment

As seen from Fig. 2.1.3 that there are 11 water columns from inlet to outlet through the main tube in the setup. Diameter and cross section area are not constant (Fig. 2.1.4) and diameter values are given in Table 2.1.1. Also a comprehensive informing will be performed on the experiment day.

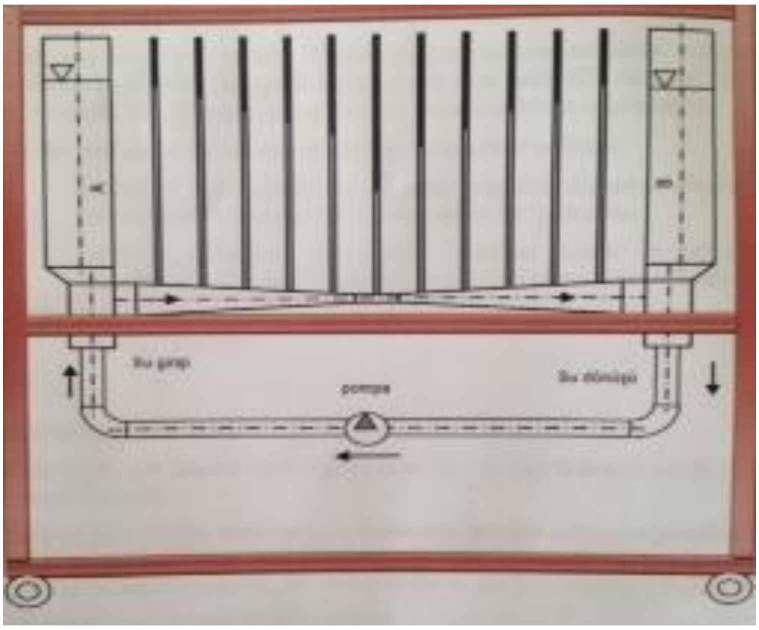


Figure 2.1.3. Experimental setup

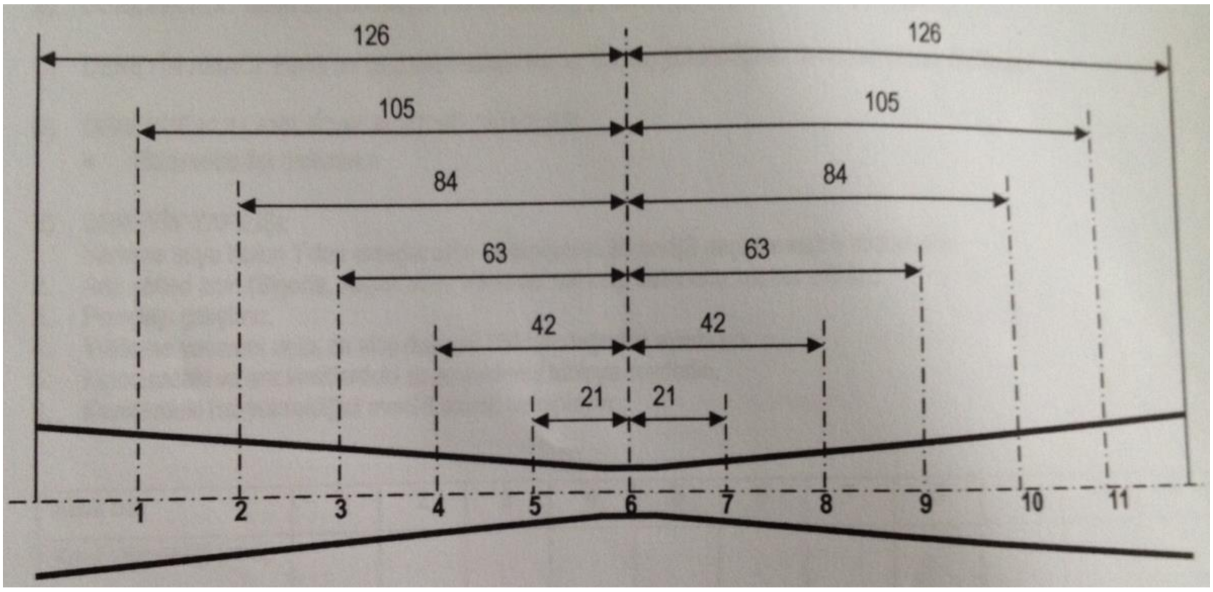


Figure 2.1.4. Front view of main tube

Table 2.1.1. Diameter and cross section areas through the tube

No	1	2	3	4	5	6	7	8	9	10	11
Diameter (mm)	26	24.66	22.49	20.33	18.16	16	18.16	20.33	22.49	24.66	26

Table 2.1.2. Data sheets

Flow Rate:

No	1	2	3	4	5	6	7	8	9	10	11
Height (mm)											
Height at Column A (mm)											
Velocity (m/s)											
Dynamic Pressure (kPa)											
Total Pressure (kPa)											

Flow Rate:

No	1	2	3	4	5	6	7	8	9	10	11
Height (mm)											
Height at Column A (mm)											
Velocity (m/s)											
Dynamic Pressure (kPa)											
Total Pressure (kPa)											

Flow Rate:

No	1	2	3	4	5	6	7	8	9	10	11
Height (mm)											
Height at Column A (mm)											
Velocity (m/s)											
Dynamic Pressure (kPa)											
Total Pressure (kPa)											

2.1.5 Report

Requested measurements and calculations to be done:

a) Do necessary calculations and fill the data sheet.
b) Draw water height distribution through the tube.
c) Draw velocity distribution through the tube.
d) Draw total pressure through the tube.

2.2 Flow Measurement Experiment

2.2.1 Objective

The main objectives of this experiment is to obtain the coefficient of discharge from experimental data by utilizing venture meter and, also the relationship between Reynolds number and the coefficient of discharge.

2.2.2 Introduction

There are many different meters used to measure fluid flow: the turbine-type flow meter, the rotameter, the orifice meter, and the venturi meter are only a few. Each meter works by its ability to alter a certain physical property of the flowing fluid and then allows this alteration to be measured. The measured alteration is then related to the flow. The subject of this experiment is to analyze the features of certain meters.

2.2.3 Theory

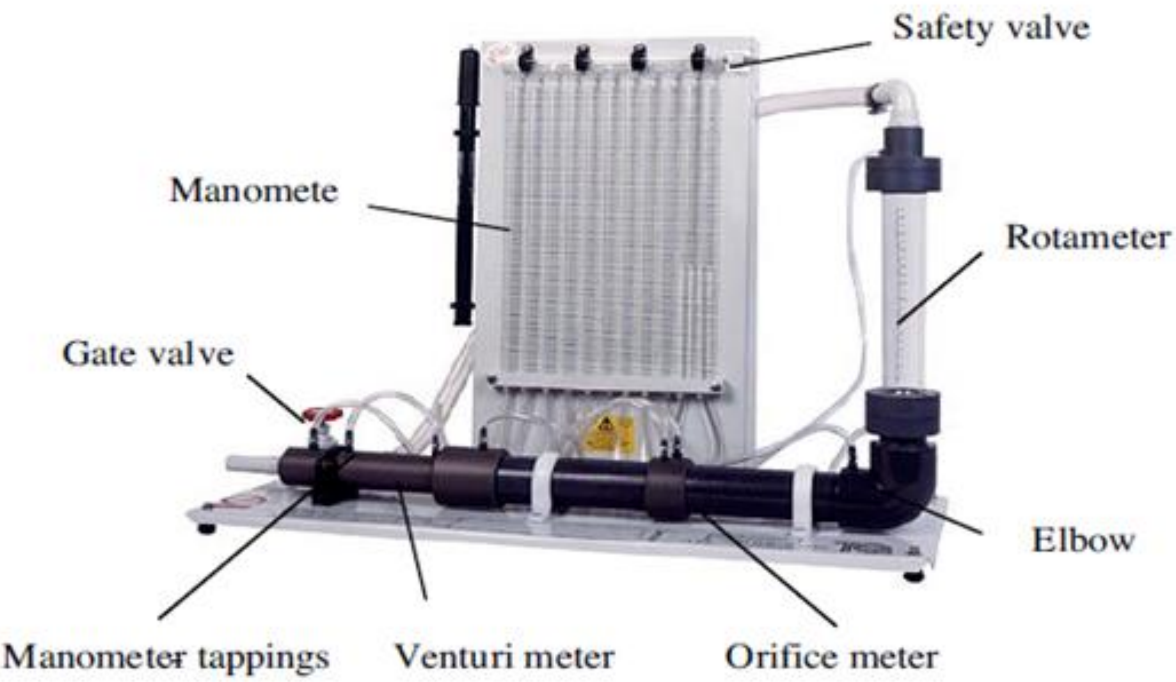


Figure 2.2.1. Flow measurement apparatus

The flow measurement apparatus consists of a water loop as shown above figure. The supple line is connected to a gravimetric hydraulic bench. The flow rate controlled by a gate valve located at the discharge side of the hydraulics bench. A venturi meter, wide-angled diffuser, orifice meter and rotameter are arranged in series. Pressure taps across each device are connected to vertical manometer tubes located on a panel at the rear of the apparatus. The discharge from the apparatus is returned to the hydraulics bench.

2.2.3.1 Venturi Meter

A venturi meter is a measuring or also considered as a meter device that is usually used to measure the flow of a fluid in the pipe. A Venturi meter may also be used to increase the velocity of any type fluid in a pipe at any particular point. It basically works on the principle of Bernoulli's Theorem. The pressure in a fluid moving through a small cross section drops suddenly leading to an increase in velocity of the flow. The fluid of the characteristics of high pressure and low velocity gets converted to the low pressure and high velocity at a particular point and again reaches to high pressure and low velocity. The point where the characteristics become low pressure and high velocity is the place where the venturi flow meter is used.

The Venturi meter is constructed as shown in Figure 2.2.2. It has a constriction within itself. The pressure difference between the upstream and the downstream flow, Δh, can be found as a function of the flow rate. Applying Bernoulli's equation to points ① and ② of the Venturi meter and relating the pressure difference to the flow rate yields.

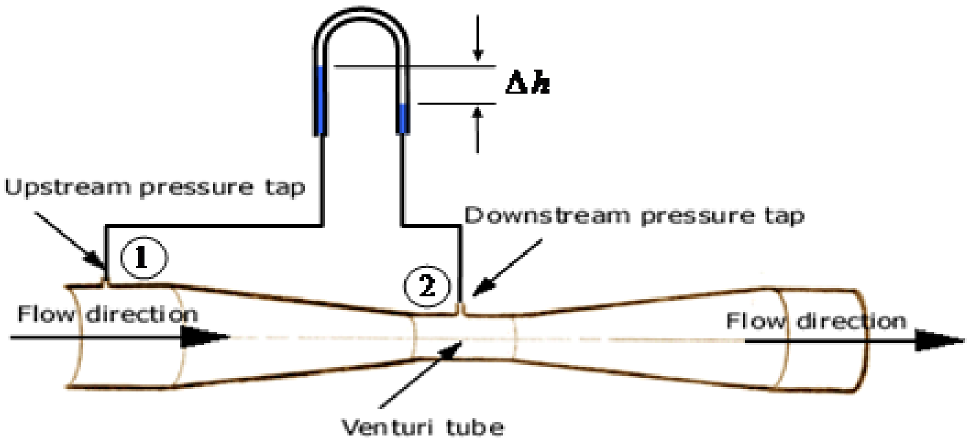


Figure 2.2.2. Venturi meter

Assume incompressible flow and no frictional losses, from Bernoulli's Equation

$$\frac{P_1}{\gamma}+\frac{V_1^2}{2g}+Z_1=\frac{P_2}{\gamma}+\frac{V_2^2}{2g}+Z_2 \qquad (2.2.1)$$

Use of the continuity Equation Q = $A_1V_1 = A_2V_2$, Equation (2.2.1) becomes

$$\frac{P_1-P_2}{\gamma}+Z_1-Z_2=\frac{V_2^2}{2g}\left[1-\left(\frac{A_2}{A_1}\right)^2\right] \qquad (2.2.2)$$

$$V_2=\frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{2g\left(\frac{P-P_2}{\gamma}+(Z_1-Z_2)\right)} \qquad (2.2.3)$$

Theoretical

$$Q_{theo} = A_2\,V_2 = \frac{A_2}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{2g\left(\frac{P_1-P_2}{\gamma}+(Z_1-Z_2)\right)} \tag{2.2.4}$$

The term $\frac{P_1-P_2}{\gamma}+(Z_1-Z_2)$ represents the difference in piezo metric head (Δh) between the two sections 1 and 2. The above expression for V_2 is obtained based on the assumption of one-dimensional frictionless flow. Hence the theoretical flow can be expressed as

$$Q_{theo} = A_2\,V_2 = \frac{A_2}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{2g(\Delta h)} \tag{2.2.5}$$

Thus,

$$Q_{theo} = \sqrt{\frac{2g\Delta h}{\left(\frac{1}{A_2^2}-\frac{1}{A_1^2}\right)}} \tag{2.2.6}$$

Because of the above assumptions, the actual flow rate, Q_{act} differs from Q_{theo} and the ratio between them is called the discharge coefficient, C_d which can be written as

$$C_d = \frac{Q_{act}}{Q_{theo}} \tag{2.2.7}$$

The value of C_d differs from one flowmeter to the other depending on the flowmeter geometry and the Reynolds number. The discharge coefficient is always less than due to various losses(friction losses, area contraction etc.).

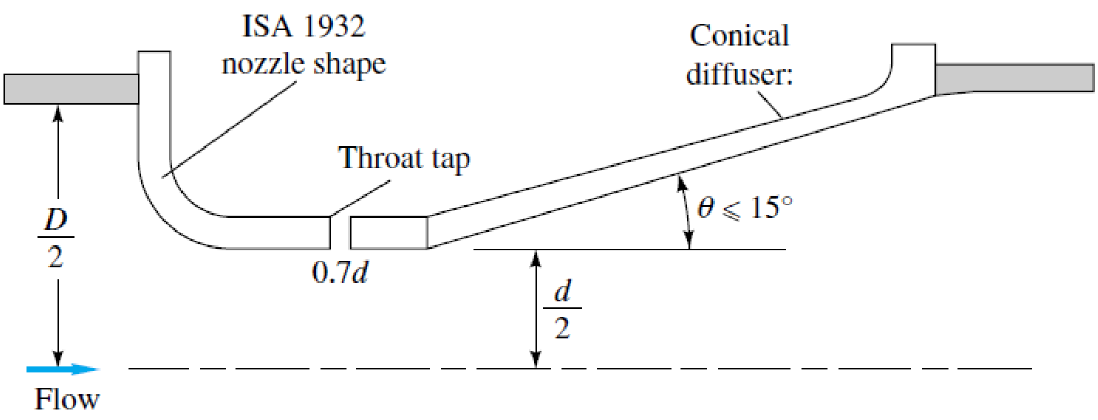


Figure 2.2.3. International standard shapes for venture nozzle

The modern venturi nozzle, Fig. 2.2.3, consists of an ISA 1932 nozzle entrance and a conical expansion of half-angle no greater than 15°. It is intended to be operated in a narrow Reynolds-number range of 1.5 x 10^5 to 2 x 10^6. The co-efficient of discharge is 0.95-0.98 for venturi meter.

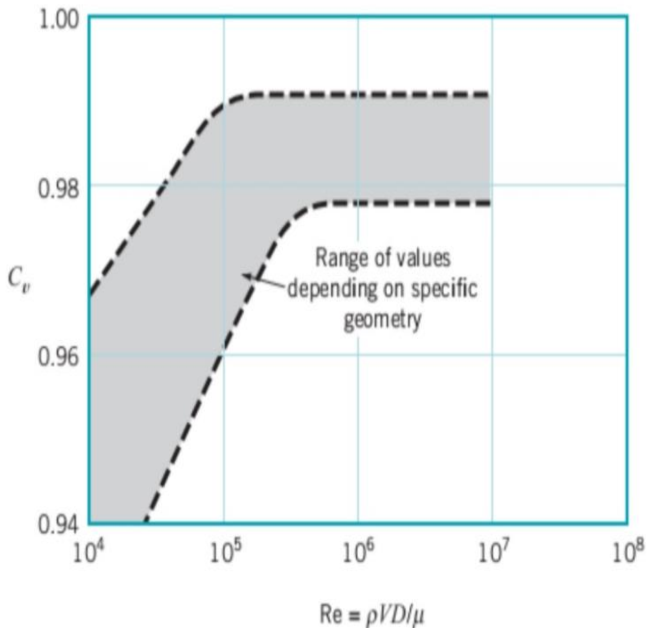


Figure 2.2.4. . The co-efficient of discharge of a venturi meter

2.2.3.2 The Orifice Meter

The orifice meter consists of a throttling device (an orifice plate) inserted in the flow. This orifice plate creates a measurable pressure difference between its upstream and downstream sides. This pressure is then related to the flow rate. Like the Venturi meter, the pressure difference varies directly with the flow rate. The orifice meter is constructed as shown in Figure 2.2.5.

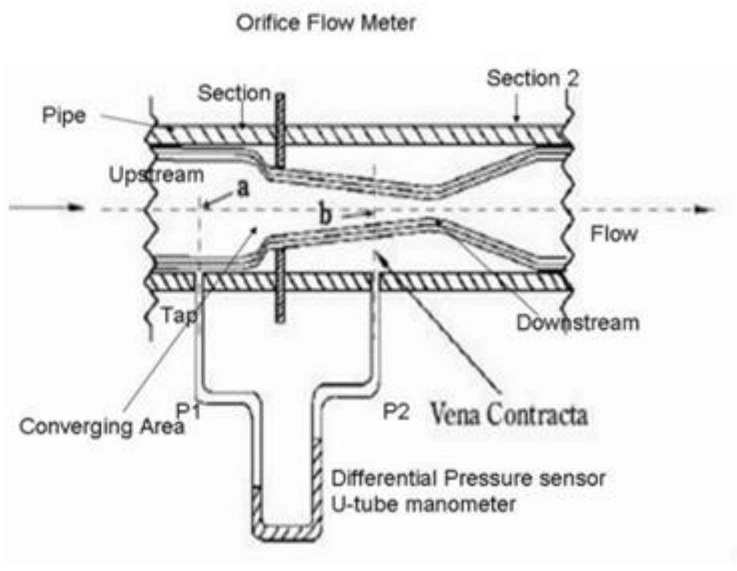


Figure 2.2.5. Cutaway view of the orifice meter

The co-efficient of discharge is 0.62-0.67 for orifice meter.

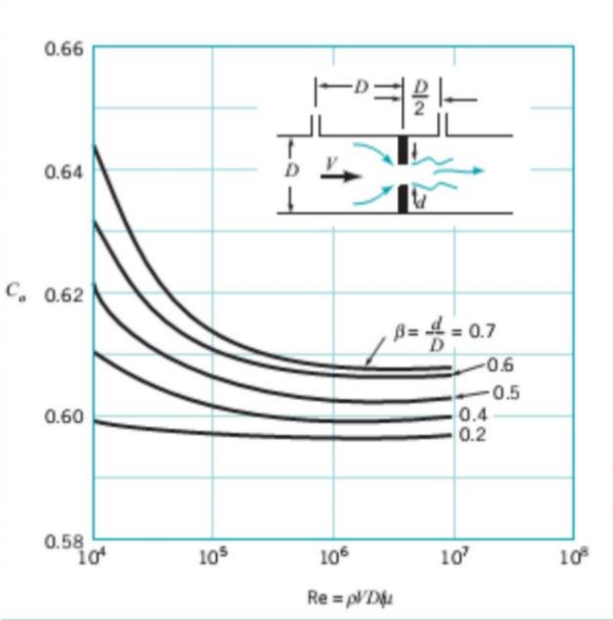


Figure 2.2.6. The co-efficient of discharge of a orifice meter

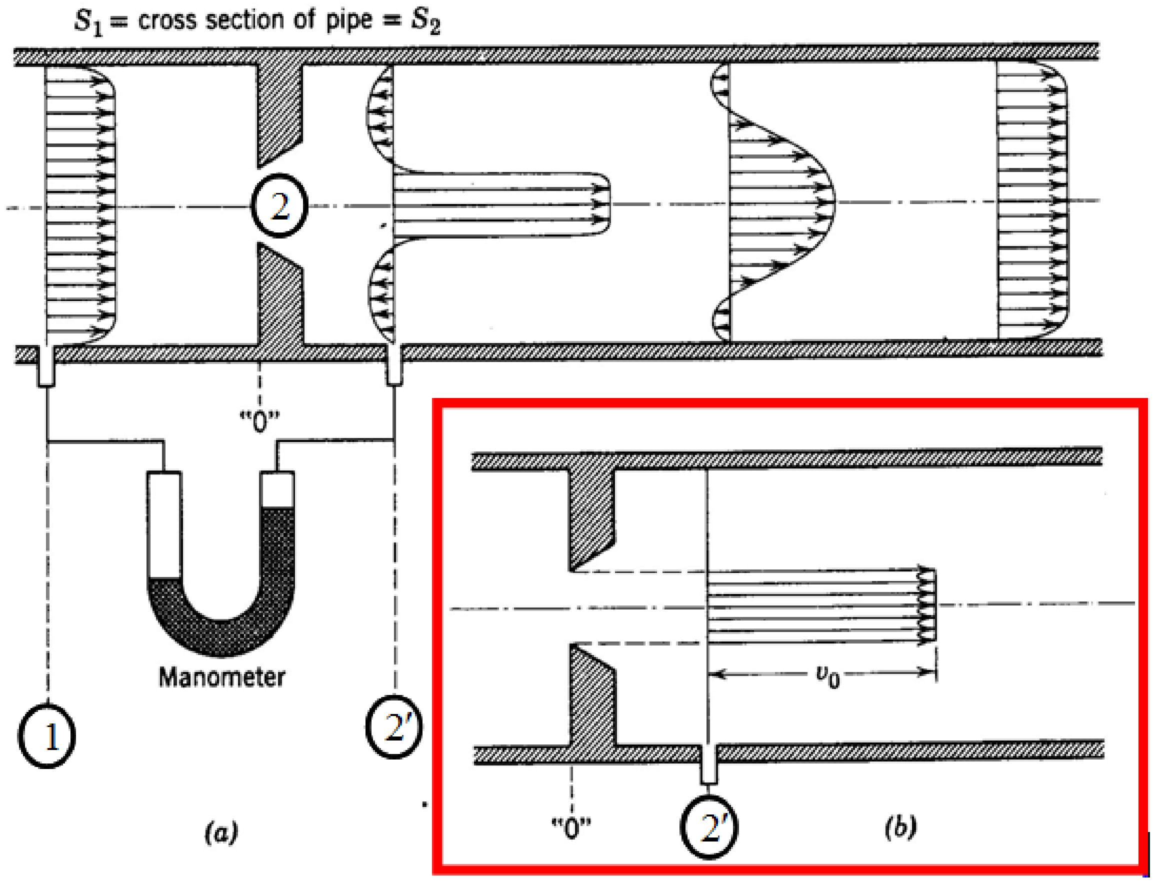
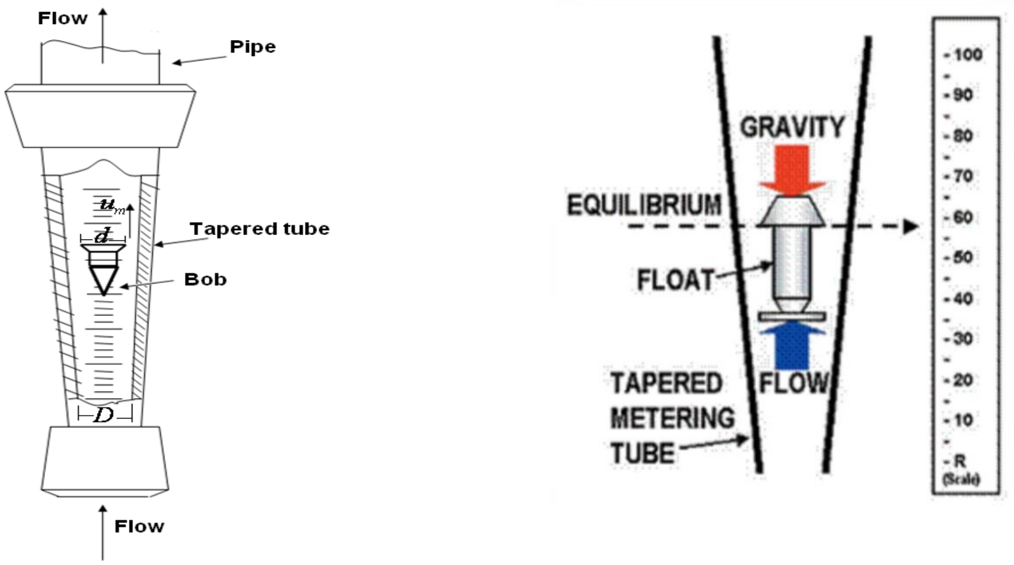


Figure 2.2.7. (a) The approximate velocity profiles at several planes near a sharp-edged orifice plate. Note: the jet emerging from the hole is somewhat smaller than the hole itself; in highly turbulent flow the jet necks down to a minimum cross section at the vena contracta. Note that there is some backflow near the wall. **(b)** It is assumed that the velocity profile at ② is given by the approximate profile shown. It is also assumed that the velocity profile at ① is uniform. From boundary layer theory, the pressure of the plug flow at ② is transmitted across the (assumed stagnate) interval from the plug to the pressure port

2.2.3.3 The Variable Area Meter (Rotameter)

A rotameter consists of a gradually tapered glass tube mounted vertically in a frame with the large end up. Fluid enters the tube from the bottom. As it enters, it causes the float to rise to a position of equilibrium. The position of equilibrium is at the point where the weight of the float is balanced by the weight of the fluid it displaces (the buoyant force exerted on the float by the fluid) and the pressure due to velocity (dynamic pressure).

The higher the float position the greater the flow rate. Note that as the float rises, the annular area formed between the float and the tube increases. Maximum flow is at maximum annular area or when the float is at the top of the tube. Minimum area, of course, represents minimum flow rate and is when the float is at the bottom of the tube.



(a) **(b)**

Figure 2.2.8. **(a,b)** Rotameter

In balance conditions, the flow rate is expressed by the following formula:

$$Q = C_d (A_T - A_F) = \sqrt{\frac{2V_f(\rho_f - \rho)}{A_f \rho}} \quad (2.2.8)$$

where

C_d = coefficient of efflux
A_t = pipe section
A_f = maximum section of the float
V_f = Volume of the float
ρ_f = density of the float
ρ = density of fluid

2.2.4 Experiments

The test unit will be introduced in the laboratory before the experiment by the relevant assistant.

2.2.4.1 Calculation of the coefficient of efflux of the calibrated diaphragm

Aim of the Experiment:

- To find out the relationship between the flow rate and the load loss
- To find the coefficient of efflux

The necessary data for calculations will be recorded to the table given below

Q_{rot}	Q_{vol}	H_1	H_2	$\sqrt{\Delta H_{1,2}}$	H_3	H_4	$\sqrt{\Delta H_{3,4}}$	H_5	H_6	$\sqrt{\Delta H_{5,6}}$

Calculations: Using the equation given below, calculate the coefficient of efflux.

The flow rate is defined as:

$$Q = \frac{C_d A_2}{\sqrt{1-\beta^4}}\sqrt{2g\Delta h} = \left[\frac{C_d A_2}{\sqrt{1-\beta^4}}\sqrt{2g}\right]\sqrt{\Delta h} \qquad (2.2.9)$$

Where:

D=20 mm d=10 mm

$Cd\ =\ coefficient\ of\ discharge$

$\beta\ =\ d/D$

$A_1 =\ pipe\ section$

$A_1 = \frac{\pi D^2}{4}$

$A_2\ =\ restriction\ section$

$A_2 = \frac{\pi d^2}{4}$

$\Delta h\ =\ load\ loss\ in\ m$

- Draw a relationship between the flow rate in y – axis and the load loss in x – axis
- Carry out a linear interpolation and find the coefficient of efflux from the angular coefficient value of the obtained line.

2.2.4.2 Calculation of the coefficient of efflux of the venturi meter

Aim of the Experiment:

- To find out the relationship between the flow rate and the square root of the load loss
- To find the coefficient of efflux

The necessary data for calculations will be recorded to the table given below.

Q_{rot}	Q_{vol}	H_1	H_2	$\sqrt{\Delta H_{1,2}}$	H_3	H_4	$\sqrt{\Delta H_{3,4}}$	H_5	H_6	$\sqrt{\Delta H_{5,6}}$

Calculations: Using the equation given below, calculate the coefficient of efflux.

The flow rate is defined as:

$$Q = \frac{C_d A_2}{\sqrt{1-\beta^4}} \sqrt{2g\Delta h} = \left[\frac{C_d A_2}{\sqrt{1-\beta^4}} \sqrt{2g}\right] \sqrt{\Delta h} \qquad (2.2.10)$$

Where:

$Cd = coefficient\ of\ discharge$
$\beta = d/D$
$A1 = pipe\ section$
$A2 = restriction\ section$
$\Delta h = load\ loss\ in\ m$

- Draw a relationship between the flow rate in y – axis and the square root of the load loss in x – axis
- The slope of the best line is :

$$Slope = C_d A_2 \sqrt{\frac{2g}{1-\left(\frac{A_2}{A_1}\right)^2}} \qquad (2.2.11)$$

- Then , Calculate C_d

2.2.4.3 Calibration of the variable area flowmeter

- Fill a graph with the measured flowrate with the rotameter against the one obtain using the volumetric tank.
- Carry out a linear interpolation; the obtained straight line represents the calibration line of the flow meter

Q_{rot} (l/h)							
V (l)							
T (sec)							
Q_{vol} (l/h)							

2.2.4.4 Measurement methods compression

- Using the coefficients of efflux determined in the exercises 2.2.4.1 and 2.2.4.2, carry out a series of measurements and calculate the measurements error for the flow meters.

2.2.4.5 Comparing the load losses

- Using the data obtained, draw a graph with the load loss as function of the flow for three flow meters.

Volume (l)	Time (sec)	Q (l/h)	Q_{rot} (l/h)	H_1 (m)	H_2 (m)	H_3 (m)	H_4 (m)	H_5 (m)	H_6 (m)

2.2.5 Report

In your laboratory reports must have the followings;

a) Cover
b) A short introduction (only 1 page)
c) All the necessary calculations using measured data.
d) Discussion of your results and a conclusion.

2.3 Hardness Measurement Experiment

2.3.1 Objective

The objectives of this experiment are the demonstration of how a hardness test is conducted, different methods of hardness testing and their selection criteria, and how the test results are interpreted.

2.3.2 Introduction

Hardness may be defined as the resistance of a material to permanent penetration by another material. A hardness test is generally conducted to determine the suitability of a material to fulfill a certain purpose. Conventional types of static indentation hardness tests, such as the Brinell, Vickers, Rockwell, and Knoop hardness, provide a single hardness number as the result, which is most useful as it correlates to other properties of the material, such as strength, wear resistance, and ductility. The correlation of hardness to other physical properties has made it a common tool for industrial quality control, acceptance testing, and selection of materials.

The consequence of material hardness depends on its application in industry. For example, a fracture mechanics engineer may consider a hard material as brittle and less reliable under impact loads; a tribologist may consider high hardness as desirable to reduce plastic deformation and wear in bearing applications. A metallurgist would like to have lower hardness for cold rolling of metals, and a manufacturing engineer would prefer less hard materials for easy and faster machining and increased production. These considerations lead, during component design, to the selection of different types of materials and manufacturing processes to obtain the required material properties of the final product, which are, in many cases, estimated by measuring the hardness of the material.

Hardness tests are performed more frequently than any other mechanical test for several reasons:

- They are simple and inexpensive-typically, no special specimen needs to be prepared, and the testing apparatus is relatively inexpensive.
- The test is nondestructive-the specimen is neither fractured nor excessively deformed; a small indentation is the only deformation.
- Other mechanical properties often may be estimated from hardness data, such as tensile strength.

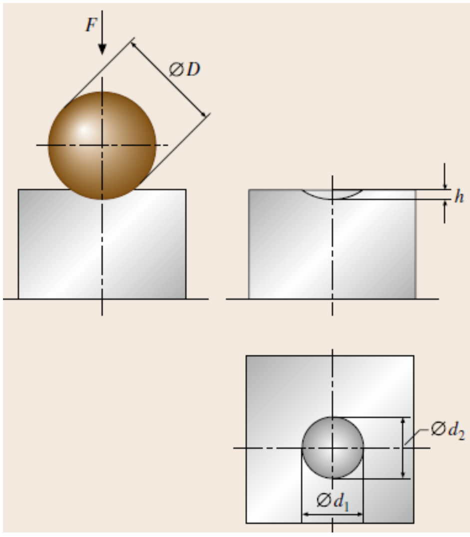
There are many hardness tests currently in use. The necessity for all these different hardness tests is due to the need for categorizing the great range of hardness from soft rubber to hard ceramics.

2.3.3 Theory

Many manufactured products are made of different types of materials, varying in hardness, strength, size and thickness. To accommodate the testing of these diverse products, each conventional hardness method has defined a range of standard force levels to be used in conjunction with several different types of indenters. Each combination of indenter type and applied force level has been designated as a distinct hardness scale of the specific hardness test method. The most commonly used indentation hardness tests used today are the Brinell, Rockwell, Vickers, and Knoop methods.

2.3.3.1 Brinell Hardness Test (HB)

In Brinell hardness test, an indenter (hardmetal ball with diameter D) is forced into the surface of a test piece and the diameter of the indentation d left in the surface after removal of the force F is measured (Figure 2.3.1). The diameter of the hardened steel (or tungsten carbide) indenter is 10.00 mm. Standard loads range between 500 and 3000 kg in 500-kg increments; during a test, the load is maintained constant for a specified time (between 10 and 30 s). Harder materials require greater applied loads. The Brinell hardness number, HB, is a function of both the magnitude of the load and the diameter of the resulting indentation The Brinell hardness is proportional to the quotient obtained by dividing the test force by the curved surface area of the indentation. The indentation is assumed to be spherical with a radius corresponding to half of the diameter of the ball:



$$Brinell\ hardness = \frac{Test\ force}{Surface\ area\ of\ indentation}$$

$$HB = \frac{2F}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$$

HB: Brinell hardness number, (kgf/mm^2)
F: Aplied load, (kgf)
D: Diameter of indenter, (mm)
d: Diameter of indentation, (mm)

Figure 2.3.1. Principle of Brinell hardness test

The Brinell hardness is denoted by HB, followed by numbers representing the ball diameter, applied test force, and the duration time of the test force. (Example: 600 HB 1/30/20). Note that, in cases when a tungsten (wolfram) carbide is used as material of indenter instead of steel ball, the Brinell hardness is denoted by HBW.

Advantages of the Brinell hardness test

- Suitable for hardness tests even under rough workshop conditions if large ball indenters and high test forces are used.
- Suitable for hardness tests on inhomogeneous materials because of the large test indentations, provided that the extent of the inhomogeneity is small in comparison to the test indentation.
- Suitable for hardness tests on large blanks such as forged pieces, castings, hot-rolled or hot-pressed and heat-treated components.
- Relatively little surface preparation is required if large ball indenters and high test forces are used.

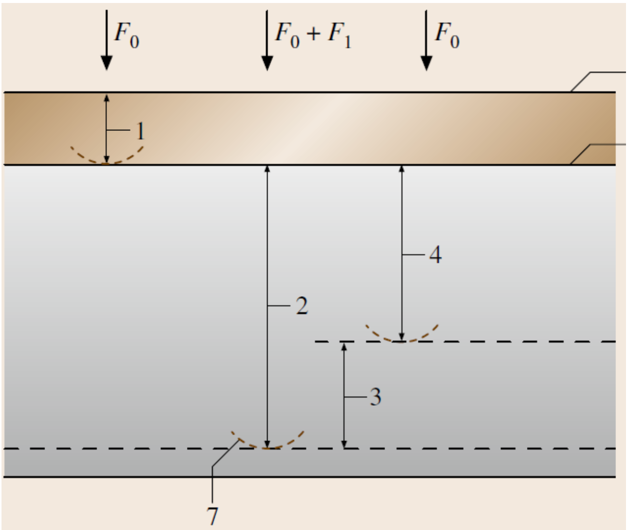
- Measurement is usually not affected by movement of the specimen in the direction in which the test force is acting.
- Simple, robust and low-cost indenters.

Disadvantages of the Brinell hardness test

- Restriction of application range to a maximum Brinell hardness of 650HBW.
- Restriction when testing small and thin-walled specimens.
- Relatively long test time due to the measurement of the indentation diameter.
- Relatively serious damage to the specimen due to the large test indentation.
- Measurement of many indentations can lead to operator fatigue and increased measurement error.

2.3.3.2 Rockwell Hardness Test (HBW)

The Rockwell tests constitute the most common method used to measure hardness because they are so simple to perform and require no special skills. Several different scales may be used from possible combinations of various indenters and different loads a process that permits the testing of virtually all metal alloys (as well as some polymers). Indenters include spherical and hardened steel balls having diameters of $\frac{1}{16}, \frac{1}{8}, \frac{1}{4}$, and $\frac{1}{2}$ in., as well as a conical diamond (Brale) indenter, which is used for the hardest materials.



1-Indentation depth by preliminary force F_0;
2-Indentation depth by additional test force F_1;
3-Elastic recovery just after removal of additional test force F_1;
4-Permanent indentation depth, h;
5-Surface of test piece;
6-Reference plane for measurement;
7-Position of indenter

Figure 2.3.2. Principle of Rockwell hardness test

The general Rockwell test procedure is the same regardless of the Rockwell scale or indenter being used. The indenter is brought into contact with the material to be tested and a preliminary force is applied to the indenter. The preliminary force is held constant for a specified time duration, after which the depth of indentation is measured. An additional force is then applied at a specified rate to increase the applied force to the total force level. The total force is held constant for a specified time duration, after which the additional force is removed, returning to the preliminary force level. After holding the preliminary force constant for a specified time duration, the depth of indentation is measured for a second time, followed by removal of the indenter from the test material (Figure 2.3.2). The difference in the two depth measurements is calculated as *h* in mm and used for calculation of Rockwell hardness number.

The Rockwell hardness is denoted by the symbol HR, followed by a letter indicating the scale, and either an S or W to indicate the type of ball used (S= steel; W= hard metal, tungsten carbide alloy). (Example: 52 HRC W).

For the Rockwell test, the minor load is 10 kg, whereas major loads are 60, 100, and 150 kg. Each scale is represented by a letter of the alphabet; several are listed with the corresponding indenter and load in Table 2.3.1.

Table 2.3.1. Rockwell hardness scales

Rockwell scale (X)	Indenter	Major load (kf)
A	Brale (diamond)	60
B	1/16 in. ball	100
C	Brale (diamond)	150
D	Brale (diamond)	100
E	1/8 in. ball	100
F	1/16 in. ball	60
G	1/16 in. ball	150
H	1/8 in. ball	60
K	1/8 in. ball	150

Advantages of the Rockwell hardness test

- Relatively short test time because the hardness value is automatically displayed immediately following the indentation process.
- The test may be automated.
- Relatively low procurement costs for the testing machine because no optical measuring device is necessary.
- No operator influence of evaluation because the hardness value is displayed directly.
- Relatively short time needed to train operator.

Disadvantages of the Brinell hardness test

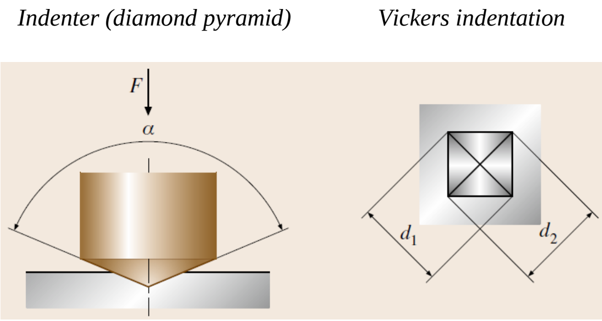
- Possibility of measurement errors due to movement of the test piece and poorly seated or worn machine components during the application of the test forces.
- Less possibility of testing materials with surface layer hardening as a consequence of relatively high test forces.
- Sensitivity of the diamond indenter to damage, thus producing a risk of incorrect measurements.
- Relatively low sensitivity on the difference in hardness.
- Significant influence of the shape of the conical diamond indenter on the test result (especially of the tip).

2.3.3.3 The Vickers and Knoop Hardness Microindentation Hardness Tests

Two other hardness-testing techniques are the Knoop and Vickers tests. For each test, a very small diamond indenter having pyramidal geometry is forced into the surface of the specimen. Applied loads are much smaller than for the Rockwell and Brinell tests, ranging between 1 and 1000 g. The resulting impression is observed under a microscope and measured; this measurement is then converted into a hardness number. Careful specimen surface preparation (grinding and polishing) may be necessary to ensure a well-defined indentation that may be measured accurately.

2.3.3.3.1 Vickers Hardness Test

A diamond indenter in the form of a right pyramid with a square base and with a specified angle between opposite faces at the vertex is forced into the surface of a test piece followed by measurement of the diagonal length of the indentation left in the surface after removal of the test force F (Figure 2.3.3).



$$HV = \frac{2F\sin\left(\frac{136°}{2}\right)}{d^2}$$

HV: $Vickers$ hardness number, (kgf/mm^2)
F: Aplied load, (kgf)
d: Arithmetic mean of the two diagonals, d_1, d_2, (mm)
d: Diameter of indentation, (mm)

Figure 2.3.3. Principle of Vickers hardness test

The Vickers hardness is denoted by the symbol HV followed by numbers representing the applied test force, and the duration time of the test force. (Example: 320 HV 30/10).

Advantages of the Vickers hardness test

- Practically no limit to the use of the method due to the hardness of the test piece.
- Testing thin sheets, small test pieces or test surfaces, thin-walled tubes, thin, hard and plated coatings is possible.
- In most cases, the small indentation has no influence on the function or appearance of tested materials or products.
- The hardness value is usually independent of the test force in the range of HV 0.2 and above.
- No incorrect measurement if the test piece yields to a limited extent in the direction of the test force.
- Can be reported in terms of stress values.

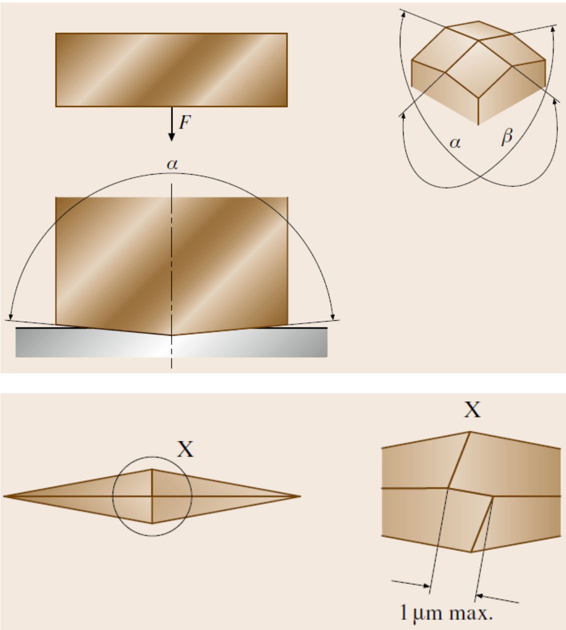
Disadvantages of the Vickers hardness test

- Possibility of measurement errors due to movement of the test piece and poorly seated or worn machine components during the application of the test forces.
- Less possibility of testing materials with surface layer hardening as a consequence of relatively high test forces.
- Sensitivity of the diamond indenter to damage, thus producing a risk of incorrect measurements.
- Relatively low sensitivity on the difference in hardness.

- Significant influence of the shape of the conical diamond indenter on the test result (especially of the tip).

2.3.3.3.2 Knoop Hardness Test (HK)

A diamond indenter, in the form of a rhombic-based pyramid with specified angles between opposite faces at the vertex, is forced into the surface of a test piece followed by measurement of the long diagonal of the indentation remaining in the surface after removal of the test force *F* (Figure 2.3.4).



$$HK = \frac{Test\ force}{Projected\ area\ of\ indentation}$$

$$= \frac{F}{cd^2}$$

HK: Knoop hardness number, (kgf/mm^2)
F: Aplied load, (kgf)
d: Length of the long diagonal, (mm)
c: $Indenter\ constant$, $\mathrm{c} = \dfrac{\tan\frac{\beta}{2}}{2\tan\frac{\alpha}{2}}$

Figure 2.3.4. Principle of Knoop hardness test

The Knoop hardness is denoted by the symbol HK followed by numbers representing the applied test force, and the duration time of the test force. (Example: 640 HK 0.1/20).

Advantages of the Knoop hardness test

- Particularly suitable for narrow test pieces, such as wire, due to the large diagonal length ratio of approximately 7 : 1.
- Better suited to thin test pieces or platings than the Vickers test method because the indentation depth is smaller by a factor of four for the same diagonal length.
- Particularly suitable for brittle materials because of lower tendency to cracking.
- Particularly suited to investigating the anisotropy of a material because the Knoop test is dependent on the direction selected for the long diagonal in such cases.
- In most cases, the small indentation has no influence on the function or appearance of tested materials or products.
- Practically no limit on the application of the method from the hardness of the material tested.

Disadvantages of the Knoop hardness test

- Time effort to achieve a sufficiently fine test surface.
- Considerable dependency of the hardness on the test force, with an especially strong influence of the preparation of the test surface.
- Sensitivity to damage of the diamond indenter.
- Expensive alignment of the test surface to achieve symmetrical test indentations.
- Relatively long test time due to the measurement of the diagonal length.
- Measurement of the diagonal length is more difficult than in the Vickers test method as a consequence of the indenter geometry.

2.3.3.4 Selecting a Conventional Hardness Test Method and Hardness Scale

The selection of a specific hardness testing method is substantially influenced by many factors such as:

- Strength of the test piece,
- Test-piece dimensions and weight,
- Material composition and homogeneity,
- Permissible damage,
- Test surface preparation,
- Permissible measurement uncertainty,
- Economic viability and the availability of machines and equipment.

Unfortunately, there is no one hardness test that meets the optimum conditions for all applications. Although the Brinell, Rockwell, Vickers and Knoop hardness testing methods have been developed to be capable of testing most materials, in many testing circumstances the size or depth of the indentation is generally the primary consideration when choosing the appropriate test forces and type of indenter to be utilized by the hardness test method. The combinations of test forces and indenter types are known as a hardness method's specific hardness scales. The hardness scales have been defined to provide suitable measurement sensitivity and indentation depths that are appropriate for different materials, strengths and dimensions of test pieces. The largest and deepest indentations are generally obtained from the heavy-force Brinell scales, followed by the commonly used heavy-force Rockwell and Vickers scales, while small to extremely small indentations can be obtained from the commonly used lower-force Rockwell, Vickers and Knoop scales.

2.3.3.5 Hardness Conversion

The facility to convert the hardness measured on one scale to that of another is most desirable. However, because hardness is not a well-defined material property, and because of the experimental dissimilarities among the various techniques, a comprehensive conversion scheme has not been devised. Hardness conversion data have been determined experimentally and found to be dependent on material type and characteristics. The most reliable conversion data exist for steels, some of which are presented in Figure 2.3.5 for Knoop, Brinell, and two Rockwell scales; the Mohs scale is also included. Detailed conversion tables for various other metals and alloys are contained in ASTM Standard E140, "Standard Hardness Conversion Tables for Metals."

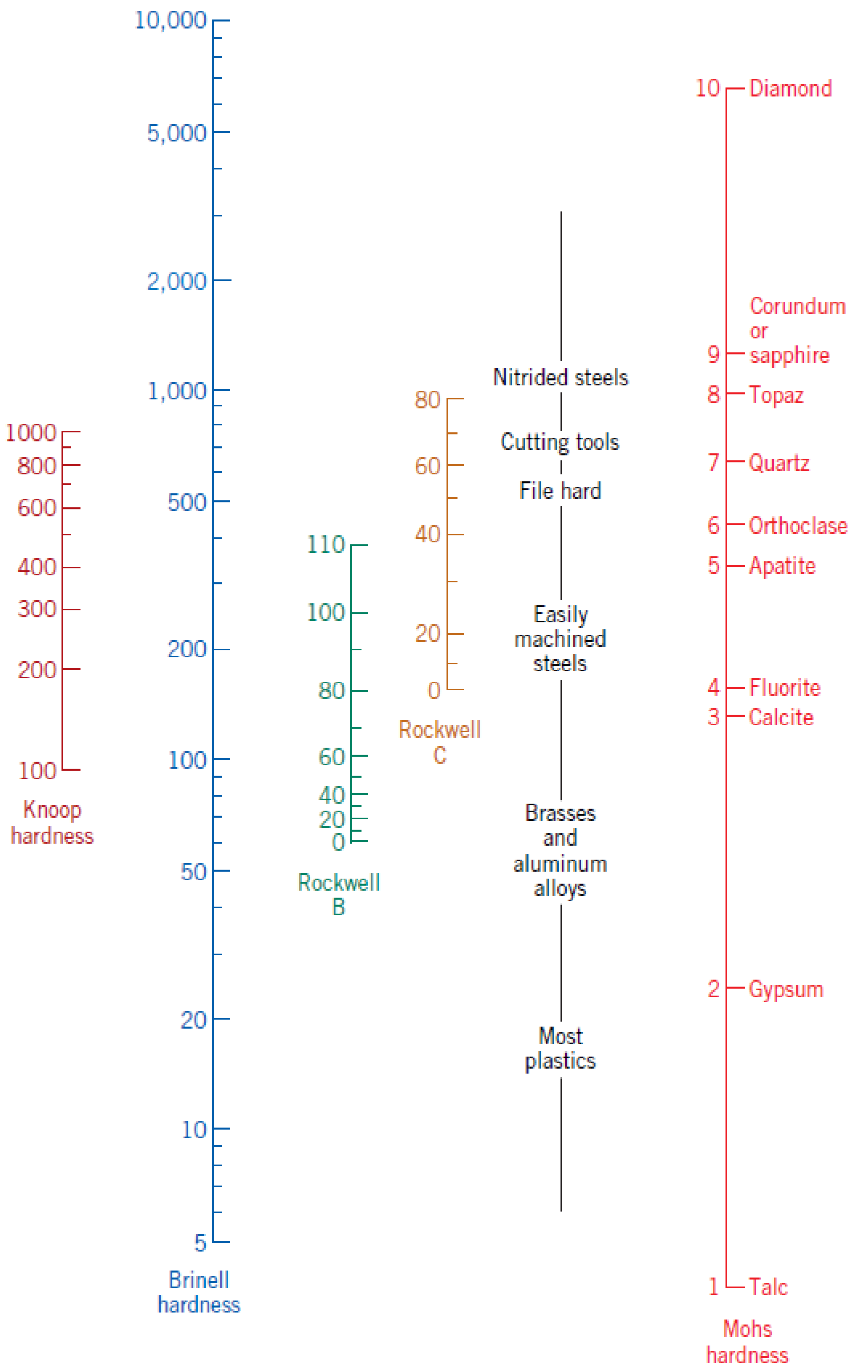


Figure 2.3.5. Comparison of several hardness scales

2.3.4 Experiments

Figure 2.3.6 shows the test equipment in the laboratory. Harness testing of several engineering materials such as aluminum alloy, carbon steel, brass, commercial pure copper, and stainless steel, etc. will be performed using Brinell, Vickers and Rockwell hardness tests.

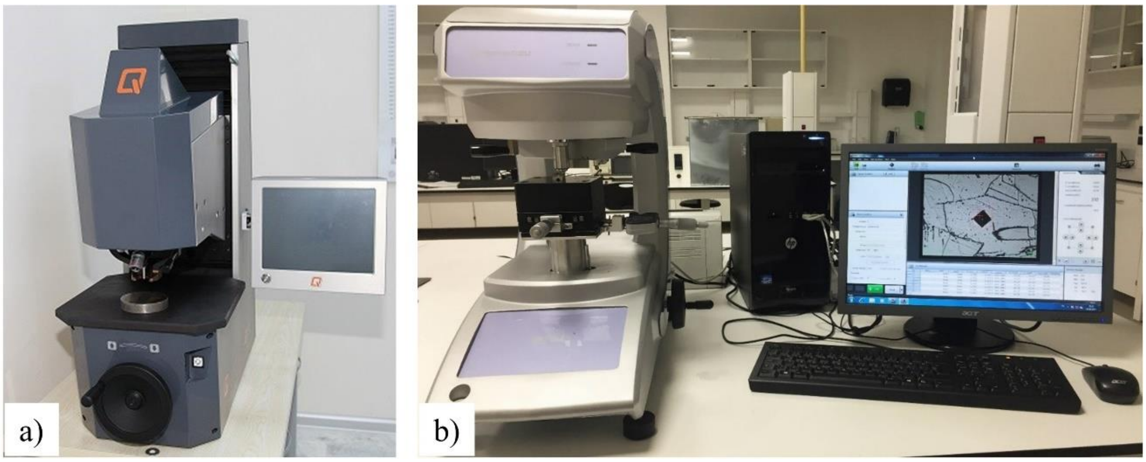


Figure 2.3.6. a) Macro, **b)** micro hardness test equipment

2.3.5 Report

Answer the following questions.

1. What is the purpose of the hardness test? Which factors affect the selecting of the appropriate hardness test method?
2. Compare the Brinell, Rockwell, Vickers, and Knoop hardness measurement methods briefly.
3. Discuss the advantages and disadvantages of the Brinell, Rockwell, Vickers, and Knoop hardness measurement methods separately.
4. According to measured values in experiments calculate the asked values below.

a) According to Brinell test results, calculate the diameter of indentation (*d*) after the test for each material.
b) According to Vickers test results, calculate the arithmetic mean value of two diagonals (*d*) after the test for each material.
c) According to Rockwell test results, calculate the depth of indentation (h) after the test for each material.

5. Discuss the relationship between hardness and tensile properties.

2.4 Heat Conduction Experiment

2.4.1 Objective

The purpose of this experiment is to determine the constant of proportionality (the thermal conductivity *k*) for one-dimensional steady flow of heat, to understand the use of the Fourier's law in determining heat rate through solids, and to demonstrate the effect of contact resistance on thermal conduction between adjacent materials.

2.4.2 Introduction

Thermal conduction is the transfer of heat energy in a material due to the temperature gradient within it. It always takes place from a region of higher temperature to a region of lower temperature. A solid is chosen for the experiment of pure conduction because both liquids and gasses exhibit excessive convective heat transfer. For practical situation, heat conduction occurs in three dimensions, a complexity which often requires extensive computation to analyze. For experiment, a single dimensional approach is required to demonstrate the basic law that relates rate of heat flow to temperature gradient and area.

2.4.3 Theory

2.4.3.1 Linear Heat Conduction

According to Fourier's law of heat conduction: If a plane wall of thickness (ΔL) and area (A) supports a temperature difference (ΔT) then the heat transfer rate per unit time (Q) by conduction through the wall is found as shown in the following formulas.

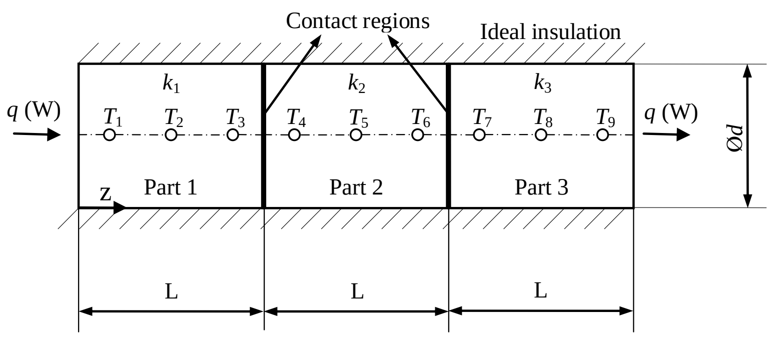


Figure 2.4.1. The Schematic View of Linear Heat Conduction Experiment Setup

The steady-state heat conduction equation in 1-D Cartesian coordinates is

$$\frac{d}{dz}\left(k\frac{dT}{dz}\right) = 0 \tag{2.4.1}$$

Integrate from the left boundary *z* = 0, to some arbitrary location *z* less than the bar length *L*

$$\int_{\mathbf{0}}^{\boldsymbol{z}} \frac{d}{dz}\left(k\frac{dT}{dz}\right) dz = 0 \tag{2.4.2}$$

$$k\frac{dT}{dz}\bigg|_z - k\frac{dT}{dz}\bigg|_0 = 0 \tag{2.4.3}$$

At $z = 0$, the heat flux is known:

$$q''(0) = \frac{q}{A_0} = -k\left.\frac{dT}{dz}\right|_0 \tag{2.4.4}$$

Where $A_0 = \frac{\pi d^2}{4}$, d is the diameter of the bar and q is the input power as you can get them experiment setup's schematic view in Fig.2.4.1. Upon substitution, Equation 2.4.3 becomes:

$$k\left.\frac{dT}{dz}\right|_z + \frac{q}{A_0} = 0 \tag{2.4.5}$$

Integrate between any two thermocouples, e.g. from z_i to z_{i+1}

$$\int_{\boldsymbol{T_i}}^{\boldsymbol{T_{i+1}}} kdT = -\int_{\boldsymbol{z_i}}^{\boldsymbol{z_{i+1}}} \frac{q}{A_0} dz \tag{2.4.6}$$

Assuming the thermal conductivity *(k)* is constant between each thermocouple position, and the cross sectional area is the same, the temperature at any thermocouple location can be related to the temperature at any other thermocouple location by

$$T_{i+1} - T_i = -\frac{q}{k_i A_0}(z_{i+1} - z_i) \tag{2.4.7}$$

or solving for the thermal conductivity

$$k = -\frac{q}{A_0}\frac{z_{i+1} - z_i}{T_{i+1} - T_i} \tag{2.4.8}$$

Equation 2.4.8 may be used to estimate the local thermal conductivity. Linear heat conduction experiment setup can be seen in Fig.2.4.2.

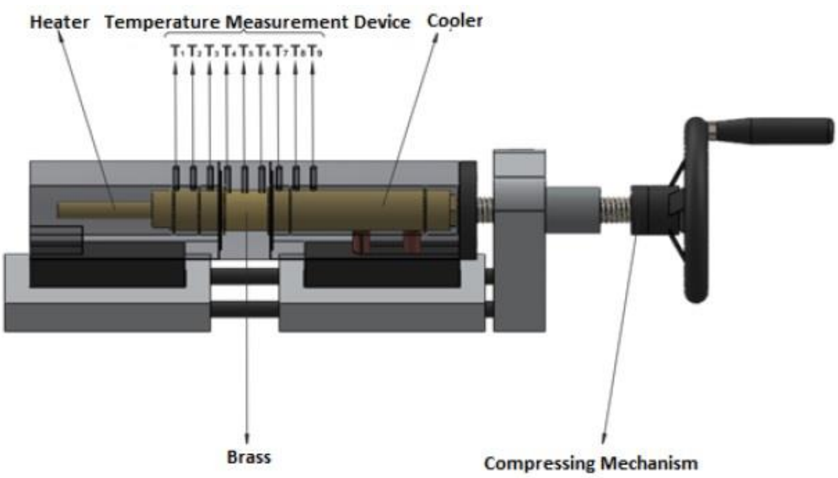


Figure 2.4.2. Linear Heat Conduction Experiment Setup

2.4.3.1.1 Contact Resistance

In the absence of good thermal contact, the temperature distribution will show a drop at the interface between any two sections. However, the heat flux will be the same through both materials at steady-state. We can define the temperature drop across the interface in terms of a *contact resistance* such that:

$$R" = \frac{\Delta T_{gap}}{q"} \tag{2.4.9}$$

In this experiment however, the temperatures are not measured at the interface, and the gap conductance, as well as the thermal conductivity must be inferred from the measured temperature distribution. Consider the diagram of the interface illustrated below, where T_1 and T_2 refer to thermocouple locations on either side of the interface.

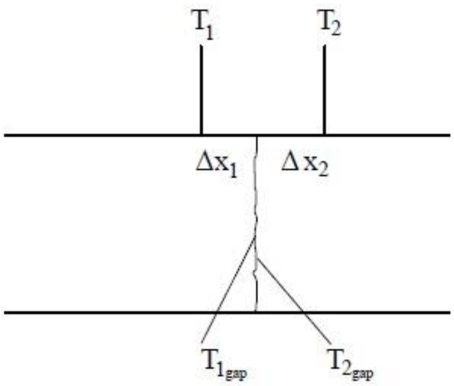


Figure 2.4.3. Contact Regions View

In addition, we define $T_{1,gap}$ as the temperature at location $z_{1,gap}^{(-)}$ on the left hand surface of the interface and $T_{2,gap}$ as the temperature at locationon $z_{1,gap}^{(+)}$ on the right hand surface of the interface. The temperature distribution prior to the interface is obtained from the steady-state heat conduction equation in 1-D Cartesian geometry:

$$\frac{d}{dz}\left(k\frac{dT}{dz}\right) = 0 \tag{2.4.10}$$

Integrate from the first thermocouple location z = z_0, to some arbitrary location z less than $z_{1,gap}$.

$$\int_{z_0}^{z} \frac{d}{dz}\left(k\frac{dT}{dz}\right)dz = 0 \tag{2.4.11}$$

$$k\frac{dT}{dz}\bigg|_z - k\frac{dT}{dz}\bigg|_0 = 0 \tag{2.4.12}$$

Since the cross sectional area is constant, at steady state the heat flux is known:

$$q"(z_0) = q"(0) = \frac{q}{A_0} = -k\left.\frac{dT}{dz}\right|_{z_0} \qquad (2.4.13)$$

Upon substitution, Equation 2.4.12 becomes:

$$k\left.\frac{dT}{dz}\right|_z + \frac{q}{A_0} = 0 \qquad (2.4.14)$$

Integrate from $z=z_0$ to any arbitrary thermocouple location prior to the interface

$$\int_{\boldsymbol{T_0}}^{\boldsymbol{T_n}} kdT = -\int_{\boldsymbol{z_0}}^{\boldsymbol{z_n}} \frac{q}{A_0} dz \qquad (2.4.15)$$

Assuming the thermal conductivity is constant, the temperature at any thermocouple location prior to the interface is

$$T_n - T_0 = -\frac{q}{k_i A_0}(z_n - z_0) \qquad (2.4.16)$$

where T_0 is the first thermocouple location. The temperature on the left hand side of the interface is then simply

$$T_{1,gap} - T_0 = -\frac{q}{k_i A_0}(z_{1,gap} - z_0) \qquad (2.4.17)$$

The temperature drop across the interface is written in terms of the gap conductance as

$$T_{1,gap} - T_{2,gap} = -\frac{q}{A_0} R" \qquad (2.4.18)$$

The temperature distribution after the interface is again obtained by integrating the conduction equation from z $=z_{1,gap}^{(+)}$, to some arbitrary location z less than $z_{2,gap}$, where $z_{2,gap}$ is the second interface location.

$$\int_{\boldsymbol{z_{1,gap}^{(+)}}}^{\boldsymbol{z}} \frac{d}{dz}\left(k\frac{dT}{dz}\right) dz = 0 \qquad (2.4.19)$$

$$k\left.\frac{dT}{dz}\right|_z - k\left.\frac{dT}{dz}\right|_{z_{1,gap}^{(+)}} = 0 \qquad (2.4.20)$$

Since the heat flux across the interface is unchanged:

$$-k\left.\frac{dT}{dz}\right|_{z_{1,gap}^{(+)}} = \frac{q}{A_0} \qquad (2.4.21)$$

Upon substitution, Equation 2.4.20 becomes:

$$k\left.\frac{dT}{dz}\right|_{z}+\frac{q}{A_0}=0 \tag{2.4.22}$$

Integrate again from z = $z_{1,gap}^{(+)}$ to some arbitrary location z less than $z_{2,gap}$.

$$\int_{\boldsymbol{T_{1,gap}}}^{\boldsymbol{T}} kdT=-\int_{\boldsymbol{z_{1,gap}^{(+)}}}^{\boldsymbol{z}} \frac{q}{A_0}dz \tag{2.4.23}$$

Assuming the thermal conductivity is constant, the temperature drop following the interface is

$$T-T_{2,gap}=-\frac{q}{k_iA_0}(z-z_{1,gap}) \tag{2.4.24}$$

We can eliminate the temperature at the gap interface, and write the temperature at any point after the interface by adding equations 2.4.17, 2.4.18 and 2.4.24 to give

$$T-T_0=-\frac{q}{A_0}\left(\frac{z-z_0}{k}+R"\right) \tag{2.4.25}$$

The analysis can be repeated for the second interface, such that the temperature at any thermocouple location can be written as

Prior to interface 1(z_n<$z_{1,gap}$)

$$T_n=T_0-\frac{q}{k_iA_0}(z_n-z_0) \tag{2.4.26}$$

Following interface 1, and prior to interface 2($z_{2,gap}<z_n$<$z_{2,gap}$)

$$T_n=T_0-\frac{q}{A_0}\left(\frac{z-z_0}{k}+R"_1\right) \tag{2.4.27}$$

Following interface 2($z_{2,gap}$<z_n)

$$T_n=T_0-\frac{q}{A_0}\left(\frac{z-z_0}{k}+R"_1+R"_2\right) \tag{2.4.28}$$

2.4.3.2 Radial Heat Conduction

When the inner and outer surfaces of a thick walled cylinder are each at a different uniform temperature, heat flows radially through the cylinder wall. The disk can be considered to be constructed as a series of successive layers. From continuity considerations the radial heat flow through each of the successive layers in the wall must be constant if the flow is steady but since the area of the successive layers increases with radius, the temperature gradient must decrease with radius.

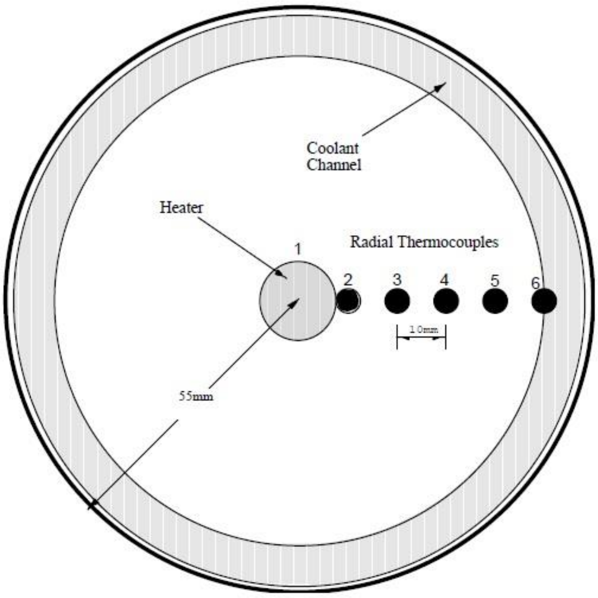


Figure 2.4.4. The Schematic View of Radiation Heat Conduction Experiment Setup

The steady-state heat conduction equation in 1-D cylindrical geometry is

$$\frac{1}{r}\frac{d}{dr}\left(rk\frac{dT}{dr}\right) = 0 \tag{2.4.29}$$

Multiply through by r and integrate from the heater radius r_H to some arbitrary radius r less than the outer radius, r_o

$$\int_{r_H}^{r}\frac{d}{dr}\left(rk\frac{dT}{dr}\right)dr = 0 \tag{2.4.30}$$

$$rk\frac{dT}{dr}\bigg|_{r} - rk\frac{dT}{dr}\bigg|_{r_H} = 0 \tag{2.4.31}$$

At r_H, the heat flux is known:

$$q"(r_H) = \frac{q}{A_H} = -k\frac{dT}{dr}\bigg|_{r_H} \tag{2.4.32}$$

where $A_H = 2\pi r_H L$, L is the thickness of the disk and q is the input power to the heater. Upon substitution, Equation 2.4.31 becomes:

$$rk\frac{dT}{dr}\bigg|_{r} + \frac{q}{2\pi L} = 0 \tag{2.4.33}$$

Divide by r and integrate between two adjacent thermocouples (e.g. from r_i to r_{i+1})

$$\int_{T_i}^{T_{i+1}} k\, dT = -\int_{r_i}^{r_{i+1}}\frac{q}{2\pi L}\frac{dr}{r} \tag{2.4.34}$$

Assuming the thermal conductivity, k, is constant, the temperature at any thermocouple location can be related to the temperature at any other thermocouple location by

$$T_{i+1} - T_i = -\frac{q}{2\pi kL}\ln\left(\frac{r_{i+1}}{r_i}\right) \tag{2.4.35}$$

or solving for the thermal conductivity

$$k = -\frac{q}{2\pi L}\,\frac{1}{T_{i+1} - T_i}\,\ln\left(\frac{r_{i+1}}{r_i}\right) \tag{2.4.36}$$

If we let $r_i = r_H$, then Equation 2.4.35 can be used to relate the temperature at any thermocouple location to the temperature at the heater surface by

$$T_n = T(r_H) - \frac{q}{2\pi kL}\ln\left(\frac{r_n}{r_H}\right) \tag{2.4.37}$$

Equation 2.4.36 may be used to estimate the local thermal conductivity in the radial experiment. Radial heat conduction experiment setup can be seen in Fig.2.4.5.

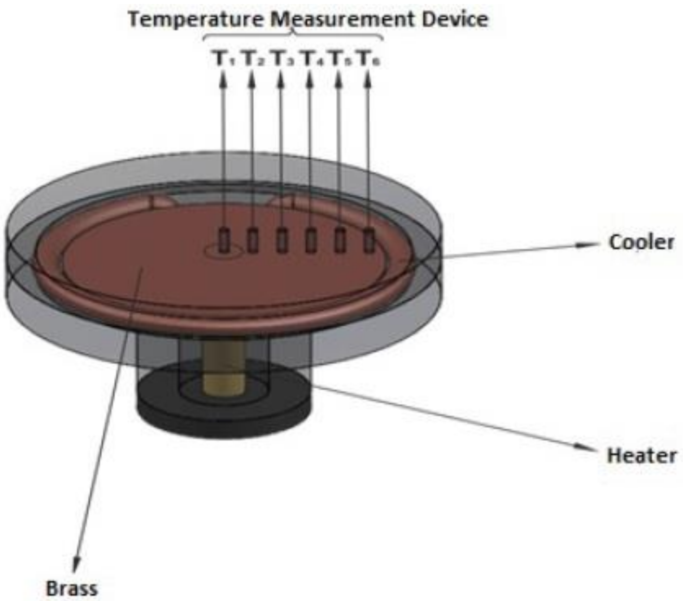


Figure 2.4.5. Radial Heat Conduction Experiment Setup

2.4.4 Experiments

2.4.4.1 Linear Heat Conduction

Aim of the Experiment: To comprehend how to calculate thermal conductivity (k).

The necessary data for calculations will be recorded to the table given below.

Material:									
Power(W)	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9
Distance from T_1 (m)	0,00	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08

Calculations: Using the equation given below, calculate the thermal conductivity.

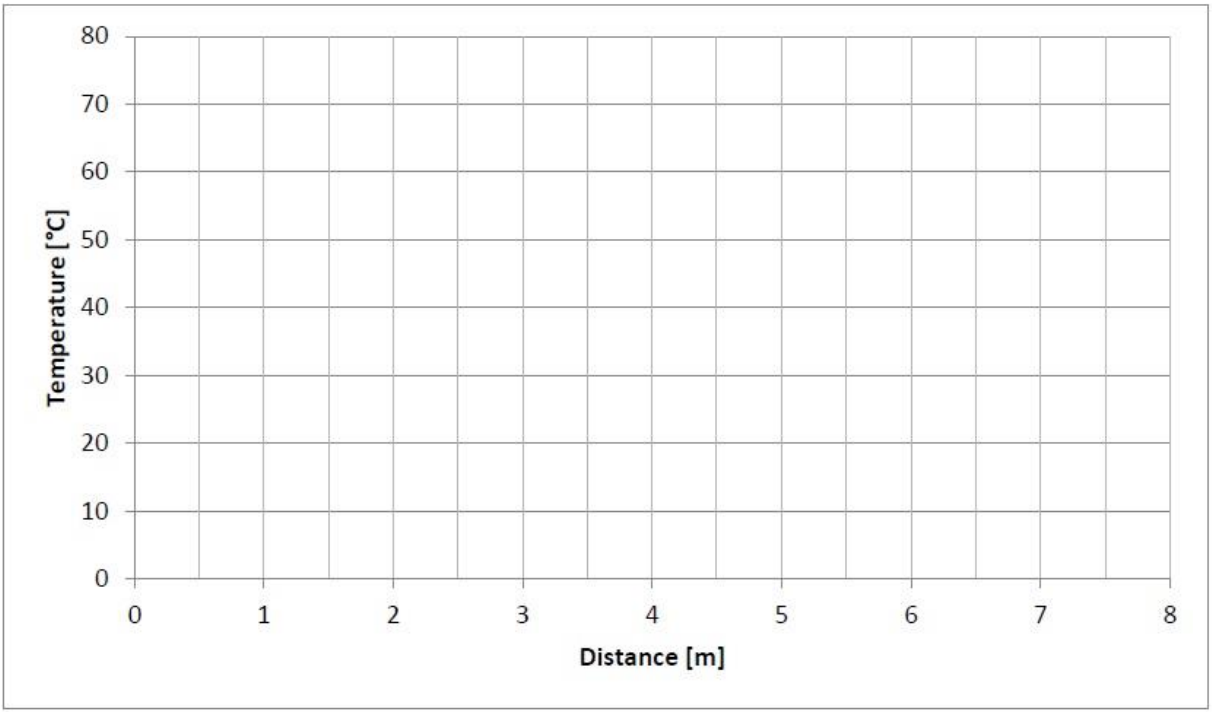
Thermal conductivity is defined as:

$$k = \frac{q\Delta L}{A\Delta T}$$

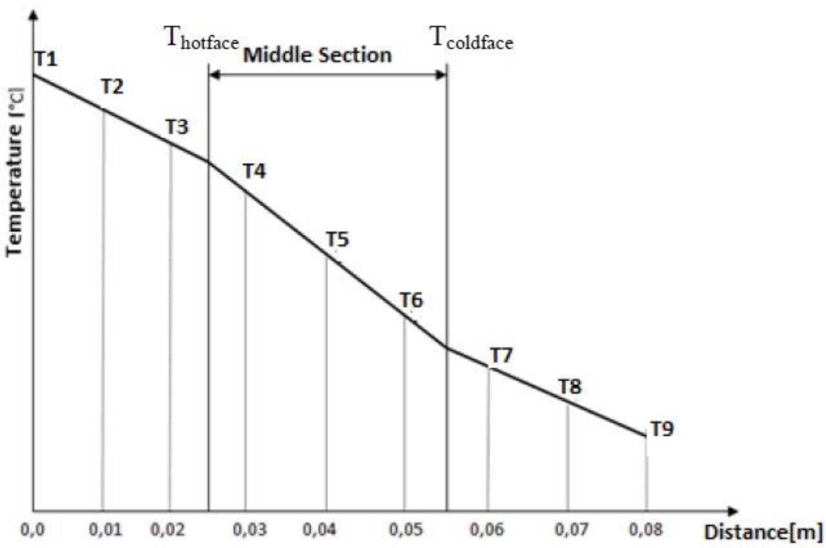
where:

$$A = 7{,}065 \times 10^{-4}\ m^2$$

Plot a graph of temperature against position along the bar and draw the best straight line through the points. Comment on the graph.



A sample graph of temperature against position along the bar can be seen.



Compare your result with Table 2.4.1.

Table 2.4.1. Thermal Conductivities for Different Material Types

Materials in Normal Conditions (298 K, 24.85 °C)		Thermal Conductivity (k) W/m°C
Metals	Pure Aluminium	205-237
	Aluminium Alloy (6082)	170
	Brass (CZ 121)	123
	Brass (63% Copper)	125
	Brass (70% Copper)	109-121
	Pure Copper	353-386
	Copper (C101)	388
	Light Steel	50
	Stainless Steel	16
Gas	Air	0.0234
	Hydrogen	0.172
Others	Asbestos	0.28
	Glass	0.8
	Water	0.6
	Wood	0.07-0.2

2.4.4.2 Radial Heat Conduction

Aim of the Experiment: To comprehend how to calculate thermal conductivity (*k*).

The necessary data for calculations will be recorded to the table given below.

Material:						
Power(W)	$\boldsymbol{T_1}$	$\boldsymbol{T_2}$	$\boldsymbol{T_3}$	$\boldsymbol{T_4}$	$\boldsymbol{T_5}$	$\boldsymbol{T_6}$
Radial Distance from T_1 (m)	0,00	0,01	0,02	0,03	0,04	0,05

Calculations: Using the equation given below, calculate the thermal conductivity.

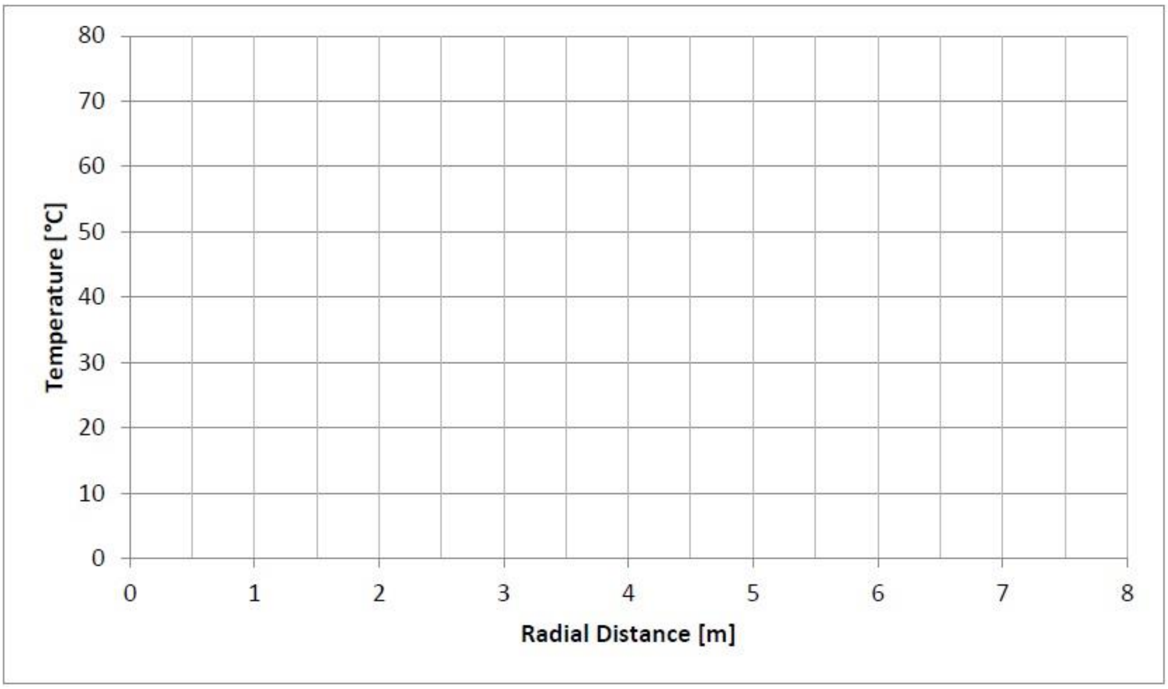
Thermal conductivity is defined as:

$$k = \frac{q \ln \frac{R_b}{R_a}}{2\pi L (T_a - T_a)}$$

where:

$$L = 0{,}012 \text{ m}$$

Plot a graph of temperature against position along the bar and draw the best straight line through the points. Comment on the graph.



2.4.5 Report

In your laboratory reports must have the followings;

a) Cover.
b) A short introduction.
c) All the necessary calculations using measured data.
d) Discussion of your results and a conclusion.

2.5 Heat Radiation Experiment

2.5.1 Objective

The purpose of this experiment is to understand thermal radiation which is one of the heat transfer mechanism. Also, substantial terms concerning with thermal radiation such as emissivity, view factor, and radiation intensity will be perceived through the experiments performed.

2.5.2 Introduction

Thermal radiation has a different characteristic in comparison to conduction and convection in that it does not need any medium. To illustrate, heat transfer between a hot object and a vacuum chamber to which the hot object is placed cannot be occur with conduction or convection due to lack of medium. However, thermal radiation will be responsible for the amount of heat transfer between the object and vacuum chamber. Energy transfer with radiation is transported by electromagnetic waves which travel at the speed of light in a vacuum. From this aspect, energy transfer with radiation is the fastest heat transfer mechanism.

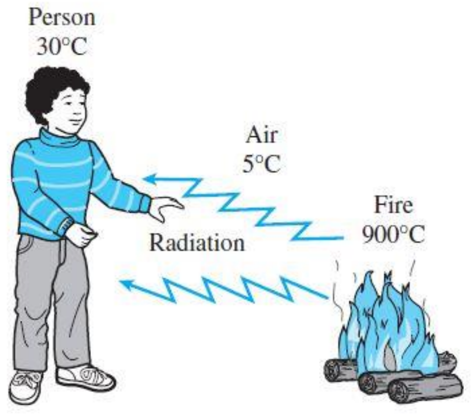


Figure 2.5.1. Heat transfer by radiation when medium is colder than both bodies

The most important example for radiative heat transfer is that the energy of the sun reaches the earth through radiation. Furthermore, we have the knowledge that heat transfer by conduction and convection occurs in the direction of decreasing temperature. The mechanism for the radiative heat transfer is a bit different in that thermal radiation can occur even if temperature of medium is lower than those of two bodies between which energy is transferred as demonstrated in Figure 2.5.1. Thermal radiation emission increases with increasing temperature and all matter with a temperature above absolute zero emits thermal radiation.

2.5.3 Theory

2.5.3.1 Blackbody radiation

Even if their temperatures are the same, different bodies may emit different amounts of radiation per unit surface area. A body that emits maximum radiation is called blackbody.

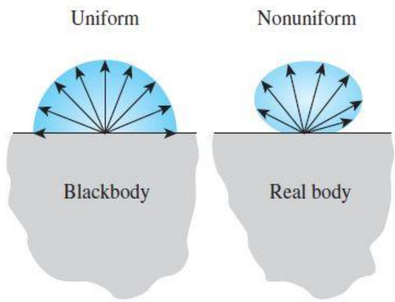


Figure 2.5.2. Radiation emission from blackbody and real surface

A blackbody is defined as a perfect emitter and absorber of radiation. At a specified temperature and wavelength no surface can emit more energy than a blackbody. A blackbody absorbs all coming radiation from other bodies. Besides, as illustrated in Figure 2.5.2, a blackbody emits radiation energy uniformly in all directions unlike real bodies. Therefore, a blackbody is a diffuse emitter which is the term used for emission independence of direction. The radiation energy emitted by a blackbody per unit time and per unit surface is expressed by Equation 2.5.1;

$$E_b = \sigma T^4 \tag{2.5.1}$$

where E_b is the blackbody emissive power, $\sigma = 5.67 \cdot 10^{-8}$ W/(m^2·K^4) is the Stefan-Boltzmann constant and T is the temperature of the surface in terms of Kelvin.

2.5.3.2 Radiation intensity

The radiation is emitted by all parts of a plane surface in all directions and the directional distribution of emitted surface is not uniform if the object is not a blackbody. Therefore, a quantity should be described to determine the magnitude of radiation emitted or incident in a specified direction in space.

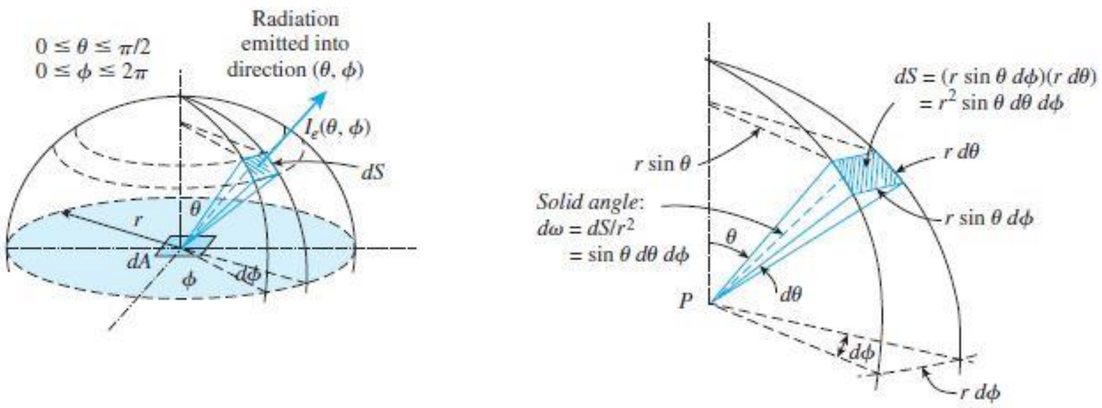


Figure 2.5.3. The emission of radiation from a differential surface element into the surrounding hemispherical space through a differential solid angle

The direction of radiation passing through a point is best described in spherical coordinates in terms of zenith angle θ and the azimuth angle ϕ. The quantity, radiation intensity denoted by I represents how the emitted radiation varies with the zenith and azimuth angles.

As shown in Figure 2.5.3, the angle subtended by an area dS is expressed as differential solid angle, $d\omega$ and it is represented by the following equation;

$$d\omega = \frac{dS}{r^2} = \frac{r^2 sin\theta \ d\theta \ d\phi}{r^2} = sin\theta \ d\theta \ d\phi \tag{2.5.2}$$

by using the foregoing relation, the radiation intensity for emitted radiation $I_e(\theta, \phi)$ can be defined as the rate at which radiation energy dq is emitted in the (θ, ϕ) direction per unit area normal to this direction and per unit solid angle about this direction. The radiation intensity is given as;

$$I_e(\theta, \phi) = \frac{dq}{dAcos\theta \ d\omega} = \frac{dq}{dAcos\theta \ sin\theta \ d\theta \ d\phi} \tag{2.5.3}$$

Also, the intensity of radiation is inversely proportional to the distance from source. This phenomenon is called as Inverse Square law.

2.5.3.3 Radiative properties

The emissivity of a surface represents the ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature. The emissivity of a surface is denoted by ε, and it varies between zero and one. It is a measure of how closely a real surface approximates a blackbody, for which $\varepsilon = 1$.

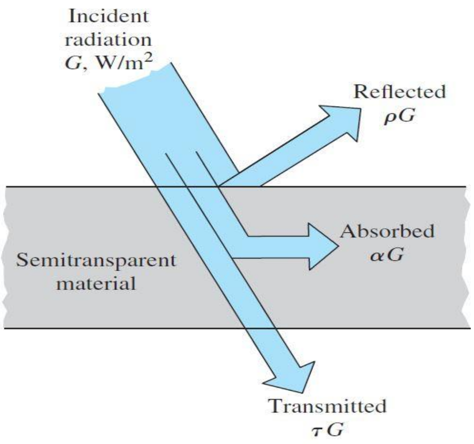


Figure 2.5.4. The absorption, reflection, and transmission of incident radiation by a semitransparent material

Every object is constantly bombarded by radiation coming from all directions over a range of wavelengths as well as emission. Radiation flux incident on a surface is called irradiation and is denoted by G. As shown in Figure 2.5.4, when radiation strikes a surface, part of it is absorbed part of it is reflected and the remaining part, if any, is transmitted. For an opaque medium transmission is not valid and only within a few microns from the surface, a portion of the incident radiation is absorbed. The fraction of irradiation absorbed by the surface is called the absorptivity α, the fraction of reflected by the surface is called reflectivity ρ, and the fraction transmitted is called transmissivity τ.

As expressed in Equation 2.5.4, the summation of these terms will be one.

$$\alpha + \rho + \tau = 1 \tag{2.5.4}$$

For opaque surfaces, since $\tau = 0$, the foregoing relation reduces to

$$\alpha + \rho = 1 \tag{2.5.5}$$

For a body with a gray surface (diffuse and its properties are independent of wavelength), the radiation absorbed and the radiation emitted can be given as the following relations;

$$G_{abs} = \alpha G = \alpha \sigma T^4 \tag{2.5.6}$$

$$E_{emit} = \varepsilon \sigma T^4 \tag{2.5.7}$$

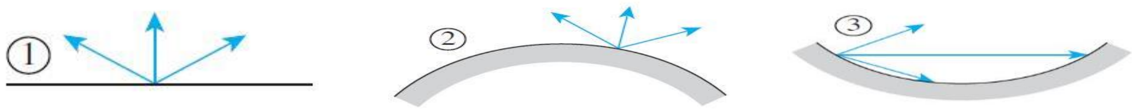
Since the surface is gray, emissivity is equal to absorptivity.

2.5.3.4 The view factor

Radiation heat transfer between surfaces depends on the orientation of the surfaces relative to each other as well as their radiation properties and temperatures. To account for the effects of orientation on radiation heat transfer between two surfaces, we define a new parameter called the view factor, which is a purely geometric quantity and is independent of the surface properties and temperature.

The view factor from a surface i to a surface j is denoted by $F_{i\to j}$ or F_{ij} and defined as the fraction of the radiation leaving surface *i* that strikes surface *j* directly.

The view factor from a surface to itself is zero unless the surface sees itself. Therefore, $F_{ii} = 0$ for plane or convex surfaces and $F_{ii} \neq 0$ for concave surfaces, as illustrated in Figure 2.5.6.



a) **b)** **c)**

Figure 2.5.5. The view factor from a surface to itself for **(a)** plane surface $\boldsymbol{F_{11} = 0}$, **(b)** convex surface $\boldsymbol{F_{22} = 0}$, and **(c)** concave surface $\boldsymbol{F_{33} \neq 0}$

<u>*The Reciprocity Relation*</u>

The view factors F_{ij} and F_{ji} are not equal to each other unless the areas of the two surfaces are. That is, $F_{ij} = F_{ji}$ when $A_i = A_j$, $F_{ij} \neq F_{ji}$ when $A_i \neq A_j$. F_{ij} and F_{ji} are related to each other by;

$$A_i F_{ij} = A_j F_{ji} \tag{2.5.8}$$

This relation is known as reciprocity rule.

The Summation Rule

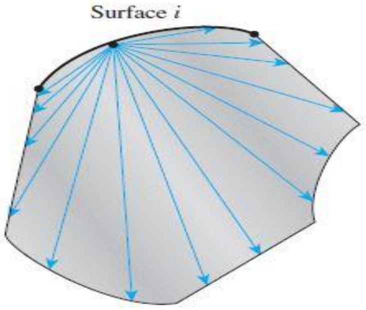


Figure 2.5.6. The radiation leaving any surface i of an enclosure

The conservation of energy principle requires that the entire radiation leaving any surface i of an enclosure be intercepted by the surfaces of the enclosure. Therefore, the sum of the view factors from surface i of an enclosure to all surfaces of the enclosure, including to itself, must equal unity. This is known as the summation rule for an enclosure and is expressed as

$$\sum_{j=1}^{N} F_{i\to j} = 1 \tag{2.5.9}$$

where N is the number of surfaces of enclosure. For example, applying the summation rule to surface 1 of a three surface enclosure yields

$$\sum_{j=1}^{N} F_{1\to j} = F_{1\to 1} + F_{1\to 2} + F_{1\to 3} = 1 \tag{2.5.10}$$

The summation rule can be applied to each surface of an enclosure by varying j from 1 to N.

The Superposition Rule

Sometimes the view factor associated with a given geometry is not available in standard tables and charts. In such cases, it is desirable to express the given geometry as the sum or difference of some geometries with known view factors. This method is known as superposition rule.

As shown in Figure 2.5.8, consider a geometry which is infinitely long in the direction perpendicular to the plane of the paper.

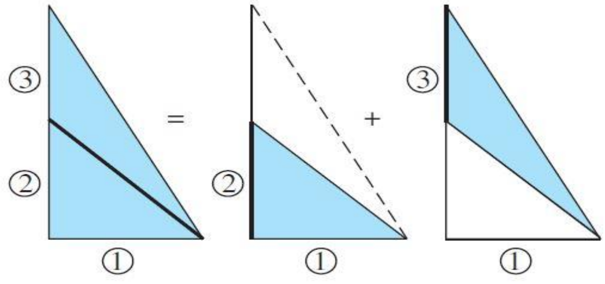


Figure 2.5.7. The view factor from a surface to a composite surface

The radiation that leaves surface 1 and strikes the combined surfaces 2 and 3 is equal to the sum of the radiation that strikes surfaces 2 and 3. Therefore, the view factor from surface 1 to the combined surfaces 2 and 3 is;

$$F_{1\to(2,3)} = F_{1\to 2} + F_{1\to 3} \tag{2.5.11}$$

The Symmetry Rule

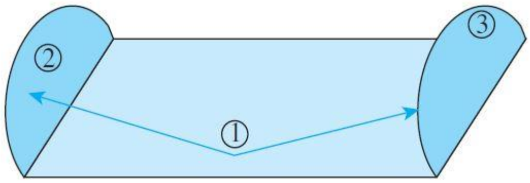


Figure 2.5.8. Two surfaces which are symmetric about a third surface

The symmetry rule can be expressed two (or more) surfaces that possess symmetry a third surface will have identical ciew factors from that surface. If the symmetry rule is applied surfaces as shown in Figure 8, the relation can be stated as

$$F_{12} = F_{13} \; and \; F_{21} = F_{31} \tag{2.5.12}$$

2.5.3.5 Radiation heat transfer

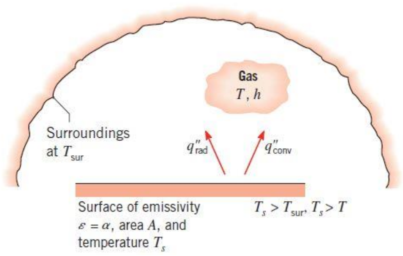


Figure 2.5.9. Radiation heat transfer from a gray surface

When a gray surface of emissivity ε and the surface area A at a thermodynamic temperature T_s is completely enclosed by a surrounding with a temperature of T_{sur}, the net rate of radiation heat transfer between the surface and the surrounding

$$q_{rad} = A(\varepsilon E_b - \alpha G) = \varepsilon \sigma A({T_s}^4 - {T_{sur}}^4) \tag{2.5.13}$$

If the surface is black, then $\varepsilon = 1$.

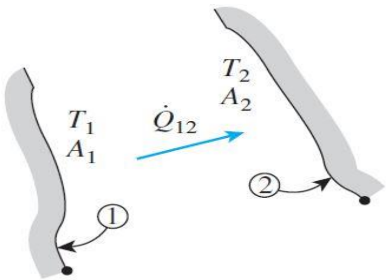


Figure 2.5.10. Two surfaces maintained at uniform temperatures $\boldsymbol{T_1}$ and $\boldsymbol{T_2}$

Consider two surfaces of arbitrary shape maintained at uniform temperatures T_1 and T_2 as shown in Figure 2.5.9. the net rate of radiation heat transfer from surface 1 to surface two can be expressed as the difference between the radiation leaving the entire surface 1 that strikes surface 2 and the radiation leaving the entire surface 2 that strikes surface 1. If the emissivity of the surfaces are the same, the relation can be given as;

$$q_{12} = A_1 \varepsilon E_{b1} F_{12} - A_2 \varepsilon E_{b2} F_{21} \tag{2.5.14}$$

If the reciprocity rule $A_1 F_{12} = A_2 F_{21}$ is applied, Equation 2.5.15 reduces to the following relation;

$$q_{12} = \varepsilon A_1 F_{12} \sigma ({T_1}^4 - {T_2}^4) \tag{2.5.15}$$

2.5.4 Experiments

2.5.4.1 Experimental setup

The experimental setup includes a horizontal support and a heat radiation source as shown in Figure 2.5.8. Radiometer and other devices related to the experiment can be placed to this support. Radiometer and each device must be placed to relevant holder. These holders can be moved through a rail system.

Heat radiation source gains energy through the measurement and control panel. Temperature of metal plates can be read on the measurement and control panel screen through thermocouples. The signals from radiometer are received through socket *D*.

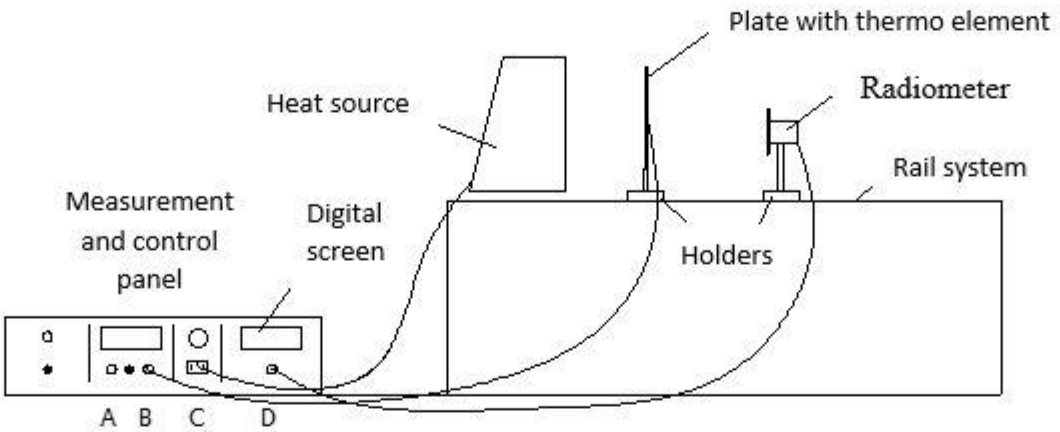


Figure 2.5.11. The experimental setup

2.5.4.2. Determination of Calibration Curve

In order to establish a relationship between a $R\%$ value read from the measurement and control panel and the heat transfer rate received by the radiometer, a calibration curve must be obtained in different heat source temperatures.

Before obtaining the calibration curve, some related terms should be defined. Since the circular plate with a temperature of T_s attached to heat source is black, the heat radiation flux can be obtained by the following formula in case that the surrounding temperature is T_{sur};

$$q_b'' = \sigma({T_s}^4 - {T_{sur}}^4) \tag{2.5.16}$$

and the thermal radiation received by the radiometer which is also at the surrounding temperature is defined as;

$$q_r'' = F\sigma({T_s}^4 - {T_{sur}}^4) \tag{2.5.17}$$

where F is the view factor that represents the fraction of total thermal radiation emitted by circular black plate that received by radiometer or another object. Then the view factor F is defined as;

$$F = \frac{q_r''}{q_b''} \tag{2.5.18}$$

In order to find view factor between circular radiometer and circular black plate, Equation 2.5.19 corresponding to the schematic as illustrated in Figure 2.5.11 can be invoked.

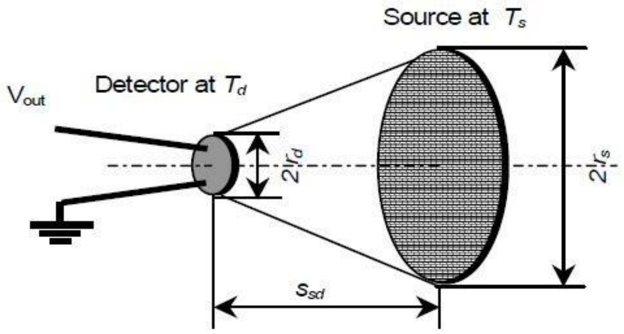


Figure 2.5.12. The circular detector (radiometer) and the circular source

$$F = \frac{2\pi r_d^2}{r_s^2 + r_d^2 + s_{sd}^2 + \sqrt{(r_s^2 + r_d^2 + s_{sd}^2)^2 - 4r_s^2 r_d^2}} \qquad (2.5.19)$$

For $T_{sur} = 25.3$ °C, $r_s = 100$ mm, $r_d = 25$ mm and the length of 20 cm between radiometer and detector, the values obtained are given in Table 2.5.1. The view factor is determined as $F = 0.039$ using Equation 2.5.18.

Table 2.5.1

T_s (K)	q_b'' (W/m^2)	R %	q_r'' (W/m^2)
304.85		2.55	
392.75		17.09	
413.85		24.07	
425.85		29.43	
454.55		45	
495.35		78.01	
515.65		100.52	

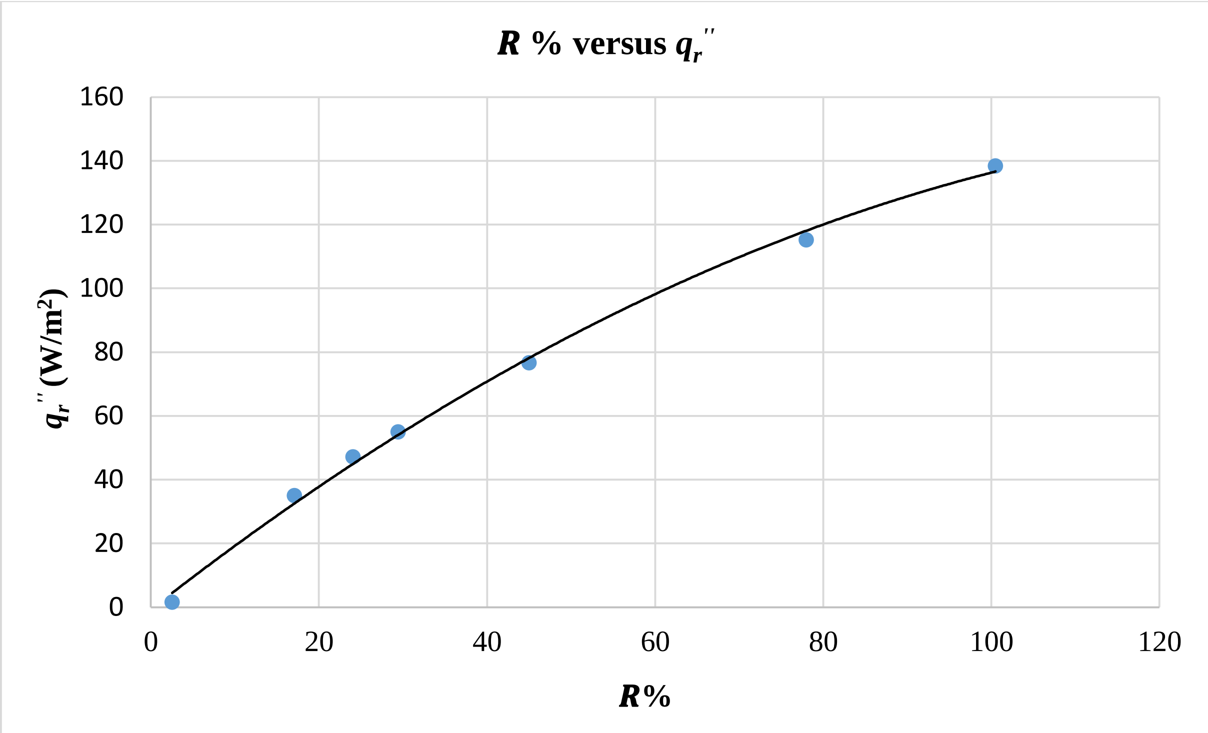


Figure 2.5.13. The relationship between the thermal radiation received by radiometer and R %.

Finally, the relationship between R % and q_r'' (W/m^2) is found as;

$$q_r'' = -0.0069R^2 + 2.0648R - 0.706 \tag{2.5.20}$$

The foregoing relation will be used for all experiments.

2.5.4.3 Experiments

2.5.4.3.1 Determination of View Factor

The distance between radiometer and the plate is $x = 10$ mm
The distance between the black plate and the heat source is $y = 20$ mm

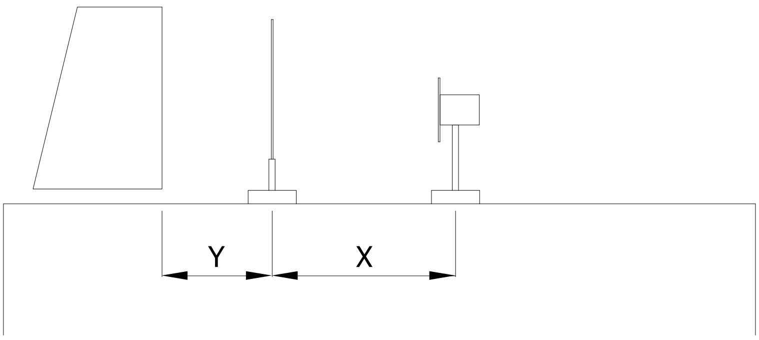


Figure 2.5.14. The positions of the radiometer and the plate

Since the emissivity of a black plate, $\varepsilon = 1$, the view factor between the black plate and radiometer can be obtained through the equations given in the previous sections. The view factor obtained in this experiment can also be used for other plates for the same distance between a plate and the radiometer. Thus, emissivity of another plate can be determined.

T_s (K)	R %	q_b'' (W/m^2)	q_r'' (W/m^2)	F

Here, T_s is the surface temperature of the black plate and q_b'' is the net rate of radiation from the black plate.

2.5.4.3.2 Determination of Emissivity

In this experiment, the emissivity of gray plates will be determined using the view factor obtained in the previous experiment. Since the heat radiation flux leaving the gray plate that received by radiometer, q_s'' will be;

$$q_s'' = \varepsilon\sigma F(T_s{}^4 - T_{sur}{}^4) \tag{2.5.21}$$

the emissivity can be stated as;

$$\varepsilon\sigma F\left(T_s{}^4 - T_{sur}{}^4\right) = q_r'' \implies \varepsilon = \frac{q_r''}{\sigma F(T_s{}^4 - T_{sur}{}^4)} \tag{2.5.22}$$

T_s (K)	R%	$\sigma F(T_s{}^4 - T_{sur}{}^4)$	q_r'' (W/m^2)	$\varepsilon = \frac{q_r''}{q_s''}$

2.5.4.3.3 Radiation intensity

The intensity of radiation inversely proportional to square of the distance from the source.

Distance, x (mm)	100	200	300	400	500	600	700
Radiometer, R%							
q_r'' **(W/m^2)**							
$Log_{10}x$							
$Log_{10}q_r''$							

2.5.4.3.4 Determination of View Factor between Black Plates

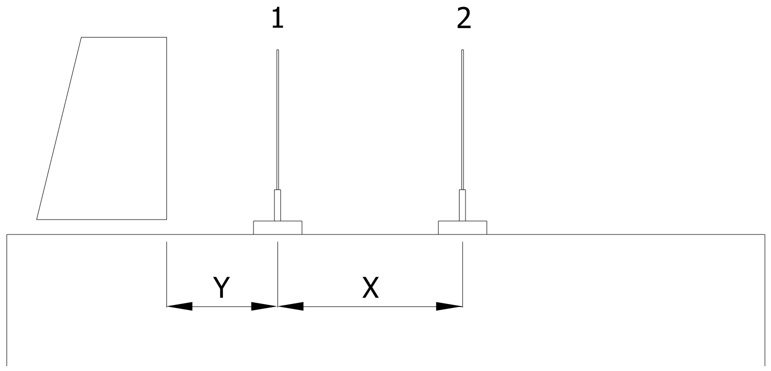


Figure 2.5.15. The positions of the plates for view factor experiment

The distance between two plates x = 10 mm
The distance between first plate and heat source y = 10 mm

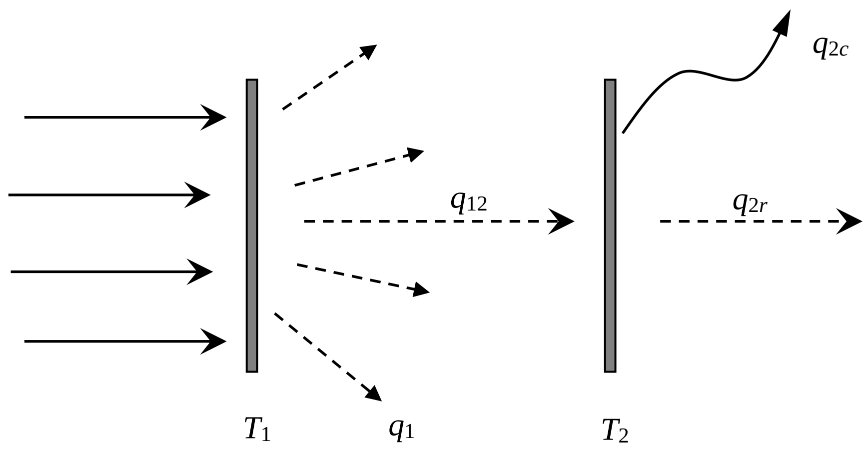


Figure 2.5.16. Heat transfer from plates

Total heat transfer from plate 1 $q_1 = \varepsilon_1 \sigma {T_1}^4 A$
Radiation heat transfer from plate 2 to the surrounding $q_{2r} = \varepsilon_2 \sigma ({T_2}^4 - {T_{sur.}}^4) A$
Heat transfer by convection from plate 2 to the environment $q_{2c} = h(T_2 - T_{sur.}) 2A$
When the system reaches the balance thermodynamically, $q_{12} = q_{2r} + q_{2c}$ and
View factor can be calculated from $F_{12} = q_{12}/q_1$

To be able to calculate heat transfer by natural convection from plate 2 to the environment, we should determine the convection heat transfer coefficient (W/m^2). For this calculation, we will evaluate Rayleigh Number and Nusselt Number respectively. Rayleigh number can be calculated by;

$$Ra = GrPr = \frac{g\beta\Delta T L^3}{\nu\alpha} \tag{2.5.23}$$

In this equation;

g : Gravitational acceleration, (m/s^2)
β : Thermal expansion coefficient, (K^{-1})
ΔT : Temperature difference between surface and the environment, (K *or* °C)
L : Characteristic length, (m)
ν : Kinematic viscosity, (m^2/s)
α : Thermal diffusivity, (m^2/s)

For ideal gases, thermal expansion coefficient can be calculated from $\dfrac{1}{\beta} = T_f = \dfrac{T_2 + T_{sur.}}{2}$

All thermophysical properties must be calculated at the film temperature, T_f. For natural convection heat transfer from horizontal plate, characteristic length must be taken as height of the plate. The height and width of the plates are 100 mm. Nusselt number can be calculated through Equation 2.5.24 by using "*C*" and "*n*" values for related Rayleigh Number given below.

$Ra < 10^9 \quad \Longrightarrow \quad C = 0.59, \quad n = 1/4$ (Laminar)
$Ra \geq 10^9 \quad \Longrightarrow \quad C = 0.15, \quad n = 1/3$ (Turbulent)

$$Nu = CRa^n = \frac{hL}{k} \tag{2.5.24}$$

Using Equation 2.5.24, convective heat transfer coefficient h W/(m^2·K) can be obtained.

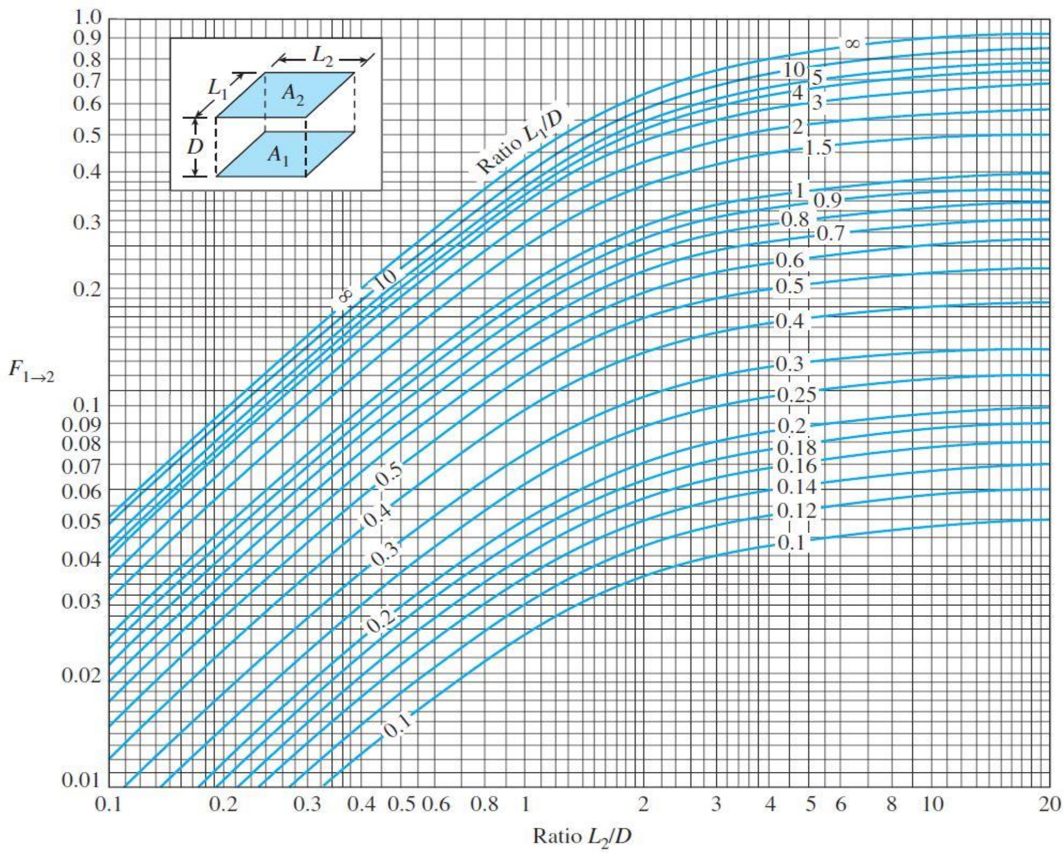


Figure 2.5.17. View factor between two aligned parallel rectangles of equal size.

Also, the view factor between two parallel plates with same dimensions can be determined using Equation 2.5.25.

$$F_{12} = \frac{2}{\pi \bar{a}\bar{b}}\left\{ln\left(\frac{(1+a^{-2})(1+b^{-2})}{1+a^{-2}+b^{-2}}\right)^{1/2} + \bar{a}(1+b^{-2})^{1/2}tan^{-1}\frac{\bar{a}}{(1+b^{-2})^{1/2}} + \bar{b}(1+a^{-2})^{1/2}tan^{-1}\frac{\bar{b}}{(1+a^{-2})^{1/2}} - \bar{a}tan^{-1}\bar{a} - \bar{b}tan^{-1}\bar{b}\right\}, \tag{2.5.25}$$

$$\bar{a} = \frac{a}{c} \text{ and } \bar{b} = \frac{b}{c}$$

where a and b are the dimensions of plates and c is the distance between plates.

2.5.5 Report

First experiment: Calculate the average view factor using the data obtained by four measurements.
Second experiment: Obtain the average emissivity for the gray plate and make a comment about whether the value is reasonable or not.
Third experiment: Draw a graph of change of $Log_{10}q_r''$ with $Log_{10}x$. Fin the related equation. Make a comment about radiation intensity using the slope of the graph.
Fourth experiment: Determine the view factor using the graph and the equation as well as the data obtained with the help of measurements. Make a comment comparing the values you calculated.

2.6 Fluid Machinery and Pelton Turbine Experiment

2.6.1 Objective

The purpose of this experiment is to introduce fluid machinery and to study the constructional details and performance parameters of Pelton Turbines.

2.6.2 Introduction

Energy may exist in various forms. Hydraulic energy is that which may be possessed by a fluid. It may be in the form of kinetic, pressure, potential, strain or thermal energy. Fluid machinery is used to convert hydraulic energy into mechanical energy or mechanical energy into hydraulic energy. This distinction is based on the direction of energy transfer and forms the basis of grouping fluid machinery into two different categories. One is power producing machines which convert hydraulic energy into mechanical energy like turbines and motors, the other is power consuming machines doing the reverse like pumps, fans and compressors. Another classification for fluid machinery can also be done based on the motion of moving parts. These are rotodynamic machines and positive displacement machines. A detailed chart is given below explaining the classifications.

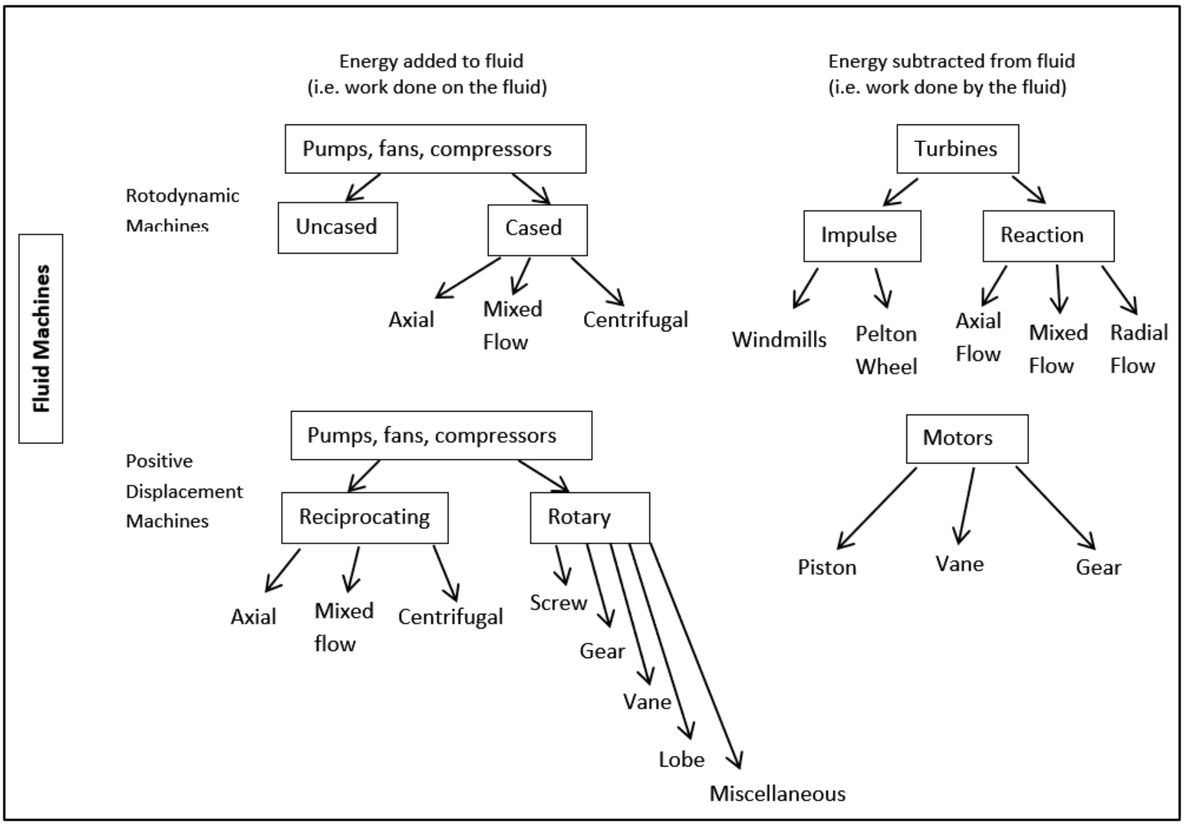


Figure 2.6.1. Classification of Fluid Machines

The turbines, a sub group of rotodynamic machines, are used to produce power by means of converting hydraulic energy into mechanical energy. They are of different types according to their specification. Turbines can be subdivided into two groups, impulse and reaction turbines. Moreover, due to working fluid used, turbines can be named as steam turbines, gas turbines, wind turbines and water turbines.

The water turbines convert the energy possessed by the water to mechanical energy. Pelton turbine (or wheel), an impulse turbine, is one of the well-known types of water turbines.

2.6.3 Theory

In the impulse turbines, the total head available is first converted into the kinetic energy. This is usually accomplished in one or more nozzles. The jets issuing from the nozzles strike vanes attached to the periphery of a rotating wheel. Because of the rate of change of angular momentum and the motion of the vanes, work is done on the runner by the fluid and, thus, energy is transferred. Since the fluid energy which is reduced on passing through the runner is entirely kinetic, it follows that the absolute velocity at outlet is smaller than the absolute velocity at inlet (jet velocity). Furthermore, the fluid pressure is atmospheric throughout and the relative velocity is constant except for a slight reduction due to friction.

The Pelton wheel is an impulse turbine in which vanes, sometimes called buckets, of elliptical shape are attached to the periphery of a rotating wheel, as shown in Fig. 2.6.2. One or two nozzles project a jet of water tangentially to the vane pitch circle. The vanes are of double-outlet section, as shown in Fig. 2.6.3, so that the jet is split and leaves symmetrically on both sides of the vane.

This type of turbine is used for high head and low flow rates. It is named after the American engineer Lester Pelton.

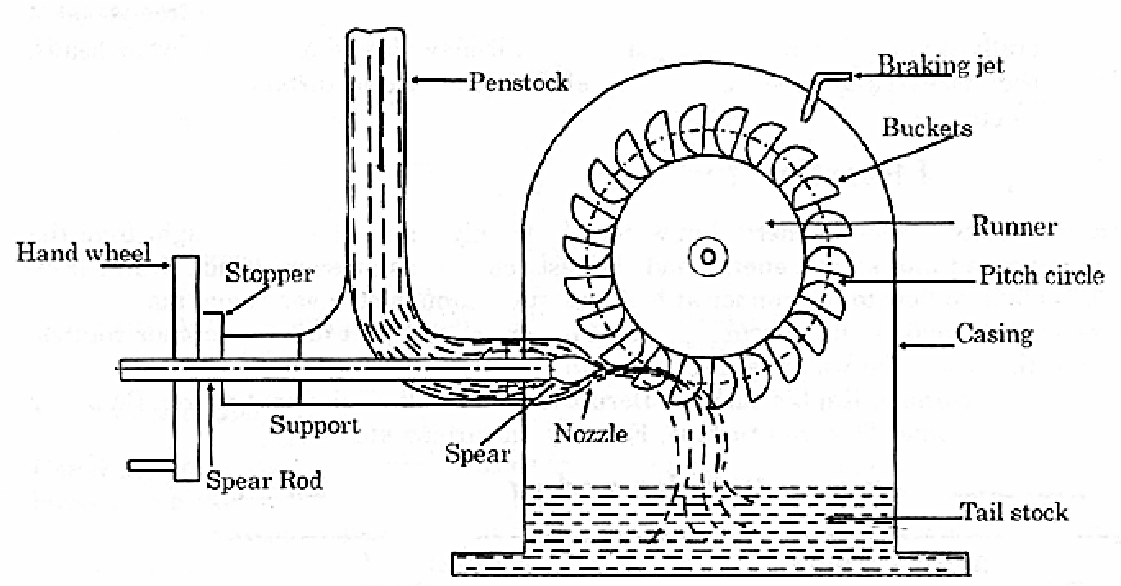


Figure 2.6.2. Schematic diagram of a Pelton Turbine

<u>Components of the Pelton Turbine</u>:

Runner with bucket: Runner of Pelton Turbine consists of a circular disc on the periphery of which a number of buckets are fixed.

Nozzle: The water coming from the reservoir through penstock is accelerated to a certain velocity by means of a nozzle.

Spear: The spear is a conical needle which is operated either by a hand wheel or automatically in an axial direction depending upon the size of the unit. The amount of water striking the buckets of the runner is controlled the spear in the nozzle.

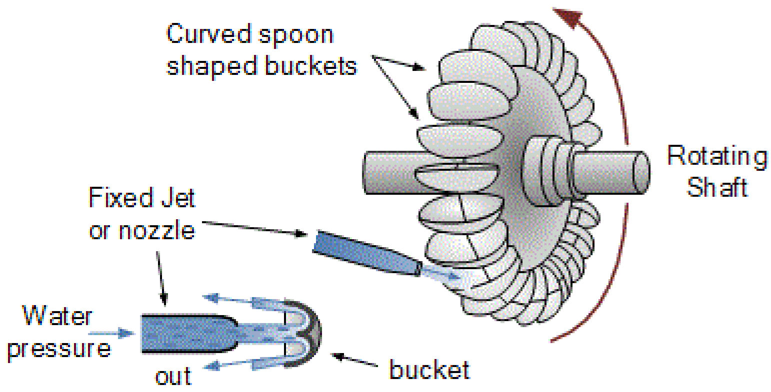


Figure 2.6.3. Configuration of water flow in buckets

Casing: Casing is used to prevent the splashing of the water and to discharge water to tail race. It is made up of cast iron or steel plate.

Breaking jet: When the nozzle is completely closed by moving the spear in the forward direction the amount of water striking the runner reduce to zero. However, the runner due to inertia goes on revolving for a long time. To stop the runner in a short time, a small nozzle is used which directs the jet of water on the back of buckets. This jet of water is called breaking jet.

Governing mechanism: The speed of turbine runner is required to be maintained constant so that electric generator can be coupled directly to turbine. Therefore, a device called governor is used to measure and regulate the speed of turbine runner.

<u>Power, Efficiency and Specific Speed Expressions</u>:

From Newton's second law applied to angular motion,

Angular momentum = (Mass)(Tangential velocity)(Radius)
Torque = Rate of change of angular momentum
Power = (Torque)(Angular velocity)

Considering the water jet striking the runner generates a torque of $T$and rotates the runner with N (rev/m), then power obtained from the runner can be expressed as:

$$\mathcal{P}_{out} = T\omega \quad [W] \tag{2.6.1}$$

$$\omega = \frac{2\pi N}{60} \quad [rad/s] \tag{2.6.2}$$

The total head available at the nozzle is equal to gross head minus losses in the pipeline leading to the nozzle (in the penstock) and denoted by H. Then available power input to the turbine becomes:

$$\mathcal{P}_{in} = \rho g H \dot{V} \tag{2.6.3}$$

where:

$\mathcal{P}_{in}$ → *Power input to turbine [W]*
H → *Total available head [m]*
ρ → *density of water [kg/m^3]*
$\dot{V}$ → *volume flow rate of water [m^3/s]*
g → *gravitational acceleration [m/s^2]*

During conversion of energy (hydraulic energy to mechanic energy or vice versa) there occur some losses. They can be in many form and main causes of them are friction, separation and leakage.

For a turbine:

Fluid Input Power = (Mechanical loss) + (Hydraulic losses) + (Useful shaft power output)

where:

Hydraulic Losses = (Runner loss) + (Casing loss) + (Leakage loss)

Considering all losses in a single term:

$$\mathcal{P}_{in} = \mathcal{P}_{lost} + \mathcal{P}_{out} \tag{2.6.4}$$

Then, overall efficiency of turbine becomes:

$$\eta_o = \frac{\mathcal{P}_{out}}{\mathcal{P}_{in}} = \frac{T\omega}{\rho g H \dot{V}} \tag{2.6.5}$$

Pelton wheel is directly coupled to a generator to produce electricity. Therefore, another efficiency term, namely generator efficiency is used to show how efficiently the mechanical energy is converted to electricity.

$$\eta_{gen.} = \frac{\mathcal{P}_e}{\mathcal{P}_{out}} = \frac{VI}{T\omega} \tag{2.6.6}$$

where:

V → *Generator voltage [V]*
I → *Generator current [A]*

The performance or operating conditions for a turbine handling a particular fluid are usually expressed by the values of N, $\mathcal{P}$ and H. It is important to know the range of these operating parameters covered by a machine of a particular shape at *high efficiency*. Such information enables us to select the type of machine best suited to a particular application, and thus serves as a starting point in its design.

Therefore, a parameter independent of the size of the machine (D-rotor diameter) is required which will be the characteristic of all the machines of a homologous series. A parameter involving N, $\mathcal{P}$ and H but not D is obtained and called as *specific speed*. It is a dimensionless parameter and expressed by the equation:

$$N_{s_T} = \frac{\omega(\mathcal{P}_{out})^{1/2}}{(\rho)^{1/2}\,(gH)^{5/4}} \tag{2.6.7}$$

2.6.4 Experiments

2.6.4.1 Calculation of Pelton Turbine Efficiency

Aim of the Experiment: To comprehend how to calculate Pelton Turbine efficiency

The necessary data for calculations will be recorded to the table given below.

Measurement No:	**1**	**2**
Rotational speed, N [rev/min]		
Force, F [N]		
Water flow rate, $\dot{V}$ [L/h]		
Head, H [m]		

Calculations: Using the appropriate equations, calculate the overall efficiency.

2.6.4.2 Calculation of Pelton Turbine Specific Speed

Aim of the Experiment: To comprehend how Pelton Turbine specific speed is calculated and to study parameters affecting it.

The necessary data for calculations will be recorded to the table given below.

Measurement No:	**1**	**2**	**3**
Rotational speed, N [rev/min]			
Force, F [N]			
Water flow rate, $\dot{V}$ [L/h]			
Head, H [m]			

Calculations: Using the appropriate equations, calculate both the overall efficiency and the specific speed of turbine.

Comment: How does efficiency vary with specific speed for Pelton Turbines? Do you think is it suitable to use Pelton Turbine with the operating conditions given above? Why?

2.6.4.3 Determination of the Change in Overall Efficiency and Power Output with Volume Flow Rate

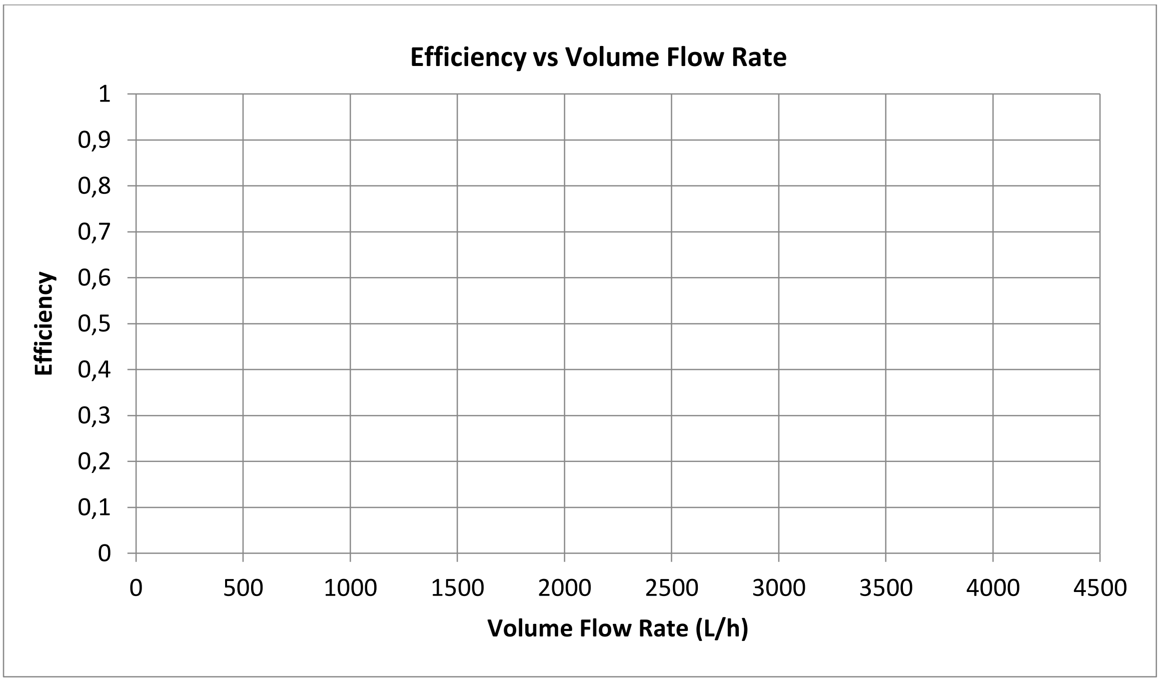
Aim of the Experiment: To understand how efficiency and power output alters with the volume flow rate.

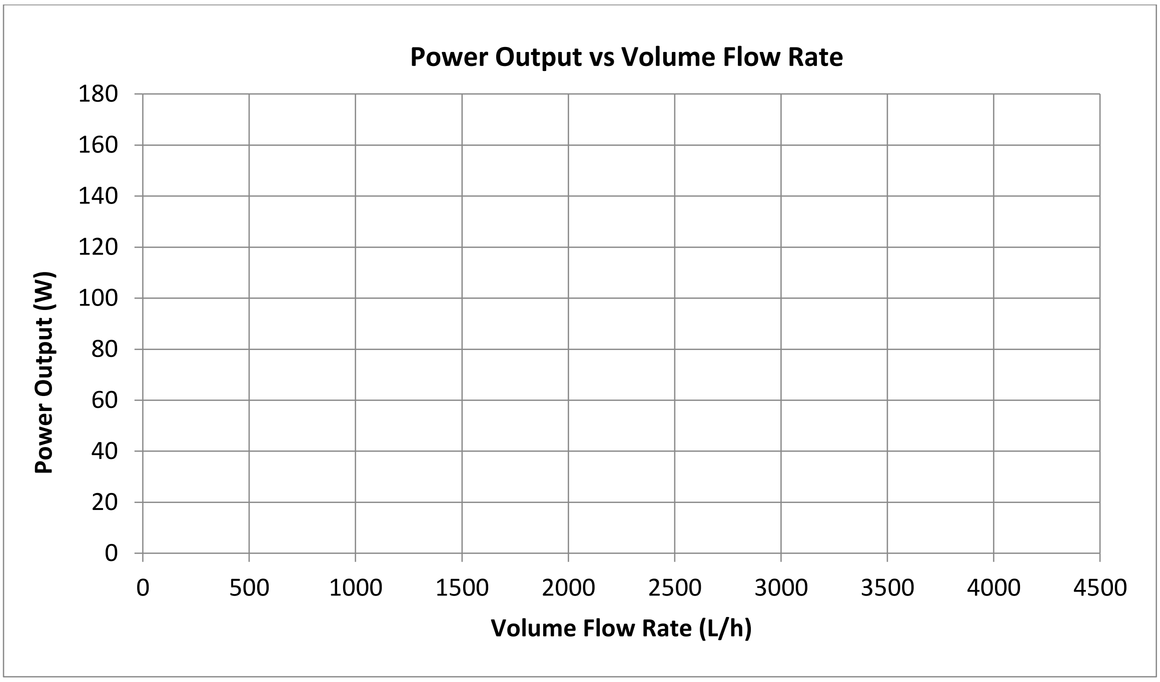
The necessary data for calculations will be recorded to the table given below.

Measurement No:	**1**	**2**	**3**	**4**	**5**	**6**
Rotational speed, N [rev/min]						
Force, F [N]						
Water flow rate, $\dot{V}$ [L/h]						
Head, H [m]						

Calculations: Using the appropriate equations, calculate the efficiency and power output for each measurement. Draw two graphs showing the change in efficiency and power output with volume flow rate, respectively.

Comments: What do you get from the graphs? Explain.





2.6.4.4 Calculation of Generator Efficiency

Aim of the Experiment: To understand the conversion of mechanical energy into electrical energy and to calculate the efficiency of this conversion.

The necessary data for calculations will be recorded to the table given below.

Measurement No:	**1**	**2**
Rotational speed, N [rev/min]		
Force, F [N]		
Voltage, V [V]		
Current, I [A]		

Calculations: Using the appropriate equations, calculate the efficiency of the generator.

2.6.5 Report

In laboratory reports you must have the followings;

a) Cover
b) A short introduction
c) All the necessary calculations using measured data.
d) Discussion of your results and a conclusion.

2.7 Mechanical Vibrations Experiment

2.7.1 Objective

The purpose of this experiment is to give basic information about vibration and to reinforce the knowledge with some applications. The experiment will show how to obtain the natural frequency of a free-floating bar and spring constants of three different spring. Through this experiment, students will be able to practice basic vibration knowledge practically.

2.7.2 Introduction

Vibrations are oscillations of a mechanical or structural system about an equilibrium position. Vibrations are initiated when an inertia element is displaced from its equilibrium position due to an energy imparted to the system through an external source. A restoring force, or a conservative force developed in a potential energy element, pulls the element back toward equilibrium. When work is done on the block of Figure 2.7.1(a) to displace it from its equilibrium position, potential energy is developed in the spring. When the block is released the spring force pulls the block toward equilibrium with the potential energy being converted to kinetic energy. In the absence of non-conservative forces, this transfer of energy is continual, causing the block to oscillate about its equilibrium position. When the pendulum of Figure 2.7.1(b) is released from a position above its equilibrium position the moment of the gravity force pulls the particle, the pendulum bob, back toward equilibrium with potential energy being converted to kinetic energy. In the absence of non-conservative forces, the pendulum will oscillate about the vertical equilibrium position.

(a) When the block is displaced from equilibrium, the force developed in the spring (as a result of the stored potential energy) pulls the block back toward the equilibrium position. (b) When the pendulum is rotated away from the vertical equilibrium position, the moment of the gravity force about the support pulls the pendulum back toward the equilibrium position.

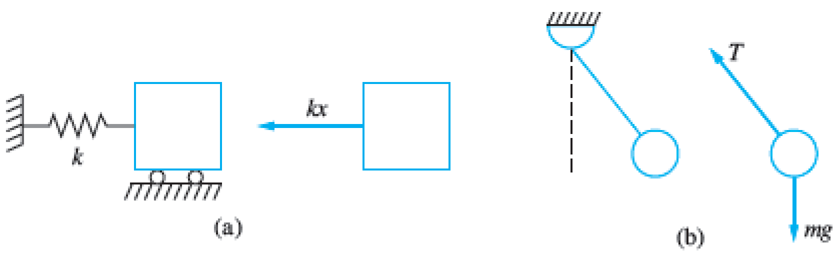


Figure 2.7.1.

Vibrations occur in many mechanical and structural systems. If uncontrolled, vibration can lead to catastrophic situations. Vibrations of machine tools or machine tool chatter can lead to improper machining of parts. Structural failure can occur because of large dynamic stresses developed during earthquakes or even wind-induced vibration. Vibrations induced by an unbalanced helicopter blade while rotating at high speeds can lead to the blade's failure and catastrophe for the helicopter. Excessive vibrations of pumps, compressors, turbo machinery, and other industrial machines can induce vibrations of the surrounding structure, leading to inefficient operation of the machines while the noise produced can cause human discomfort.

Vibrations can be introduced, with beneficial effects, into systems in which they would not naturally occur. Vehicle suspension systems are designed to protect passengers from discomfort when traveling over rough terrain. Vibration isolators are used to protect structures from excessive forces developed in the operation of rotating machinery. Cushioning is used in packaging to protect fragile items from impulsive forces. Energy harvesting takes unwanted vibrations and turns them into stored energy. An energy harvester is a device that is attached to an automobile, a machine, or any system that is undergoing vibrations. The energy harvester has a seismic mass which vibrates when excited, and that energy is captured electronically.

The Tacoma Narrows Bridge collapsed due to wind induced resonance on November 7th, 1940. Resonance is a process in which an object's, in this case a bridge's, natural vibrating frequency is amplified by an identical frequency. In this case the identical frequency was caused by strong wind gusts blowing across the bridge, creating regions of high and low pressure above and below the bridge (Bernoulli's principle). This produced violent oscillations, or waves, in the bridge leading to its collapse. In layman's terms, the wind was forced either above or below the bridge, causing the bridge to be moved up or down. This tensed or relaxed the supporting cables, which acted much like rubber bands, and increased the waves in the bridge. These waves were so intense that a person driving across the bridge often lost sight of the car ahead as it dropped into a trough, low point, of the wave.

The following pictures show the violent twisting waves that the bridge withstood prior to its collapse.

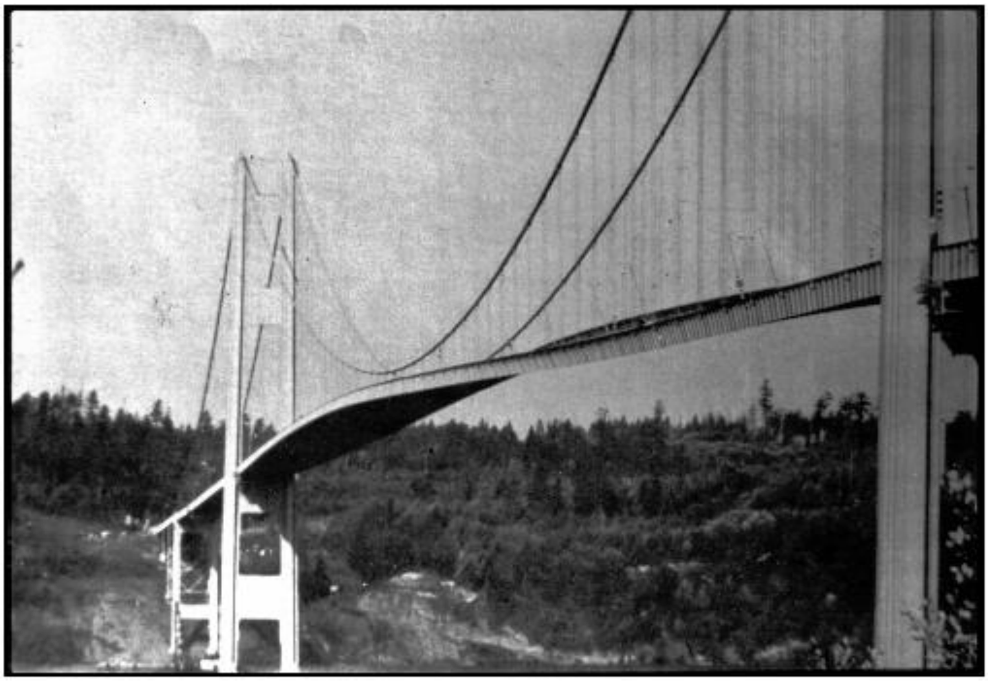


Figure 2.7.2.

2.7.2.1 Importance of the Study of Vibration

- Vibrations can lead to excessive deflections and failure on the machines and structures
- To reduce vibration through proper design of machines and their mountings

- To utilize profitably in several consumer and industrial applications
- To improve the efficiency of certain machining, casting, forging & welding processes
- To stimulate earthquakes for geological research and conduct studies in design of nuclear reactors
- Vibratory System basically consists of:
    - spring or elasticity
    - mass or inertia
    - damper
- Vibration Involves transfer of potential energy to kinetic energy and vice versa

2.7.3 Theory

Degree of Freedom *(d.o.f.)*:

Minimum number of independent coordinates required to determine completely the positions of all parts of a system at any instant of time

- Examples of single degree-of-freedom systems:

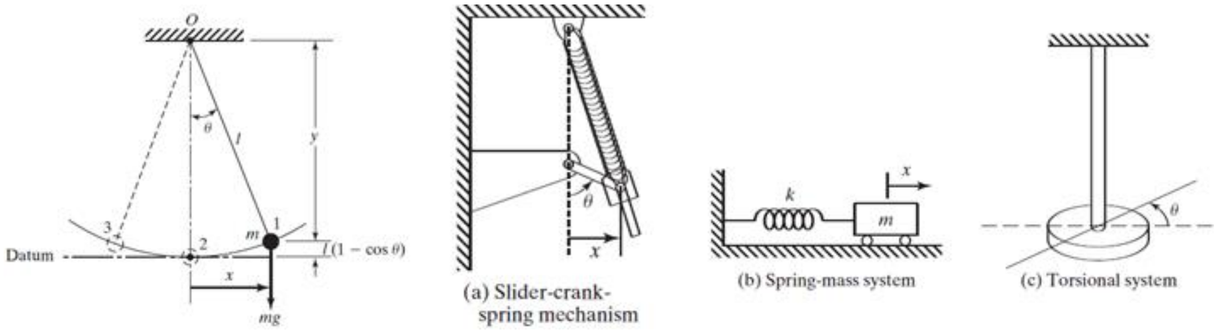


Figure 2.7.3.

- Examples of second degree-of-freedom systems:

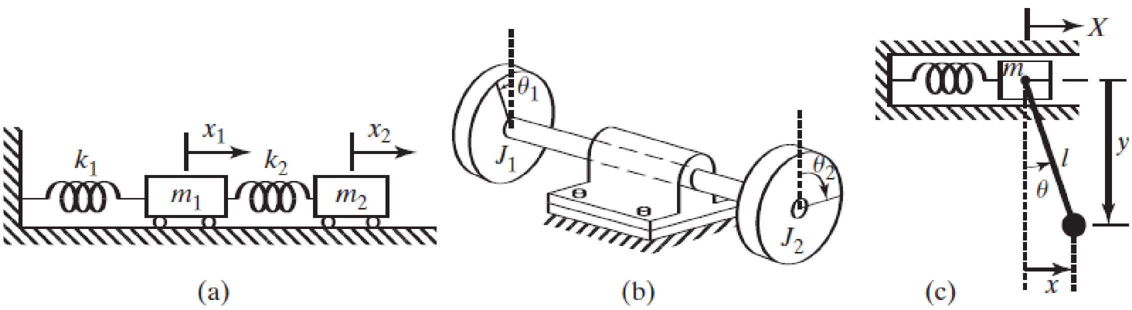


Figure 2.7.4.

- Examples of three degree-of-freedom systems:

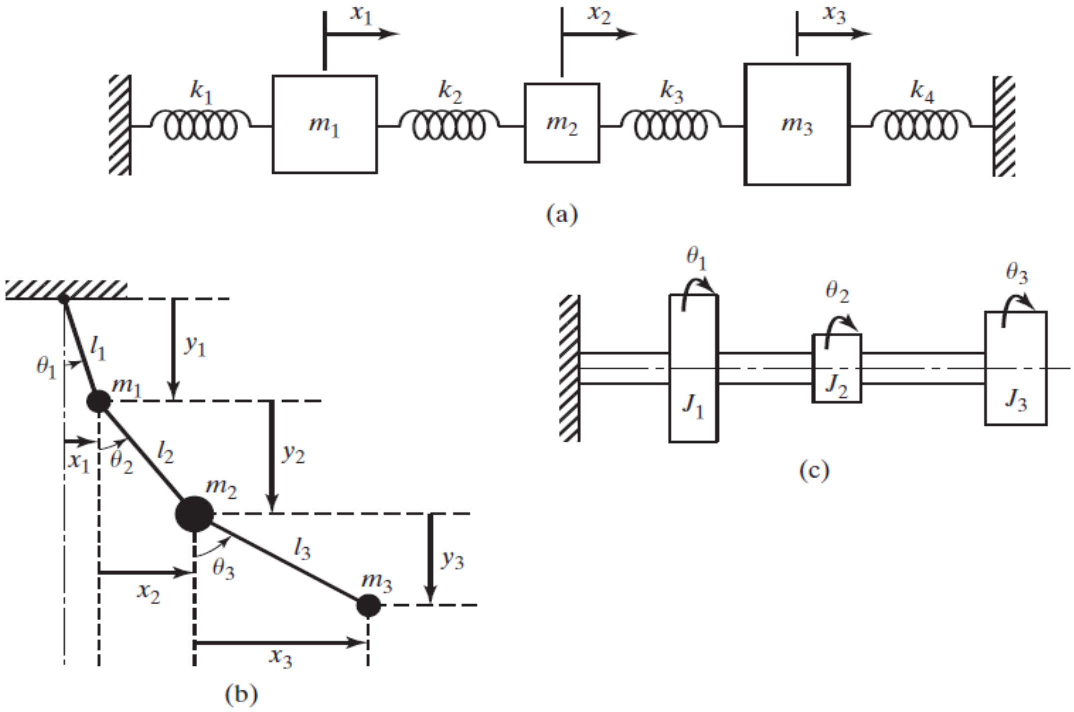


Figure 2.7.5.

- Example of Infinite-number-of-degrees-of-freedom system:

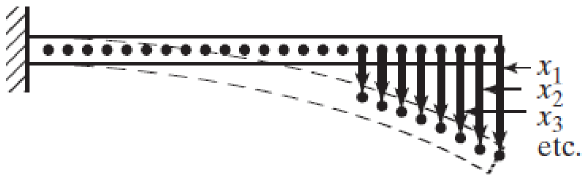


Figure 2.7.6.

- Infinite number of degrees of freedom system are termed *continuous* or *distributed* systems
- Finite number of degrees of freedom are termed *discrete* or *lumped* parameter systems
- More accurate results obtained by increasing number of degrees of freedom

Free Vibration:

A system is left to vibrate on its own after an initial disturbance and no external force acts on the system. E.g. simple pendulum

Forced Vibration:

A system that is subjected to a repeating external force. E.g. oscillation arises from diesel engines.

Resonance:

It occurs when the frequency of the external force coincides with one of the natural frequencies of the system.

Undamped Vibration:

When *no* energy is lost or dissipated in friction or other resistance during oscillations.

Damped Vibration:

When *any* energy is lost or dissipated in friction or other resistance during oscillations.

Linear Vibration:

When *all* basic components of a vibratory system, i.e. the spring, the mass and the damper behave linearly.

Nonlinear Vibration:

If *any* of the components behave nonlinearly.

Deterministic Vibration:

If the value or magnitude of the excitation (force or motion) acting on a vibratory system is known at any given time.

Nondeterministic or random Vibration:

When the value of the excitation at a given time cannot be predicted.

- Examples of deterministic and random excitation:

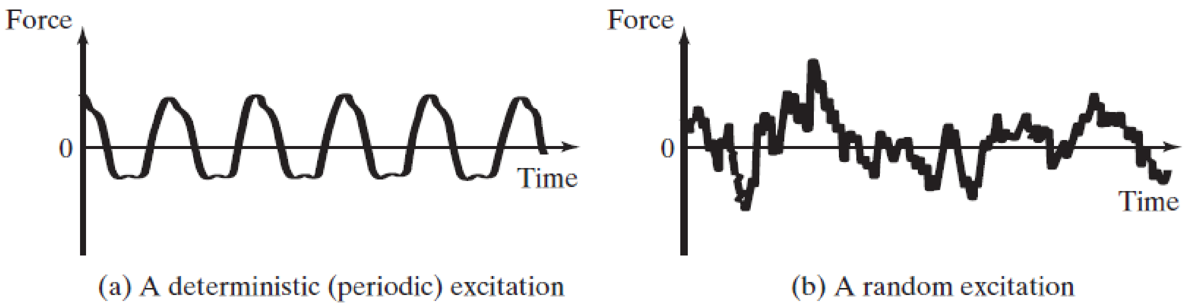
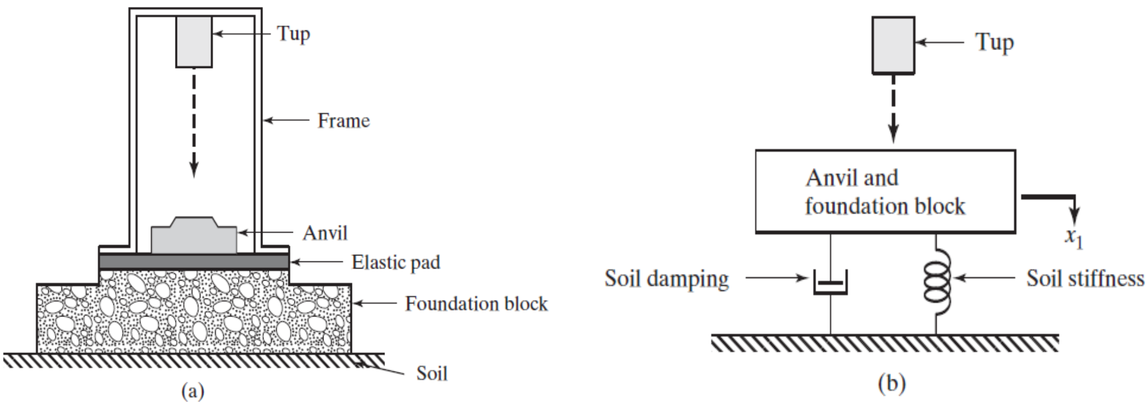


Figure 2.7.7.

2.7.3.1 Modeling of the mechanical systems:

Example: a forging hammer



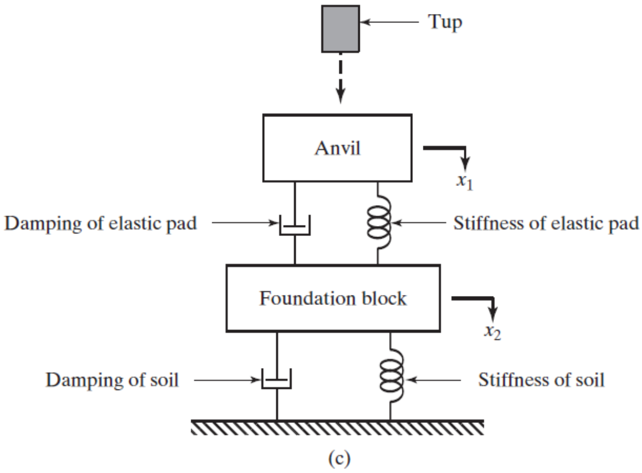


Figure 2.7.8.

Spring Elements:

- Linear spring is a type of mechanical link that is generally assumed to have negligible mass and damping.
- Spring force is given by:

$$F = kx$$

F = spring force
k = spring stiffness or spring constant
x = deformation (displacement of one end with respect to the other)

- Static deflection of a cantilever beam at the free end is given by:

$$\delta_{st} = \frac{Wl^3}{3EI}$$

W = mg is the weight of the mass m,
E = Young's Modulus, and
I = moment of inertia of cross-section of beam

- Spring Constant is given by:

$$k = \frac{W}{\delta_{st}} = \frac{3EI}{l^3}$$

- Combination of Springs:

1) Springs in parallel – if we have n spring constants k_1, k_2, …, k_n in *parallel*, then the equivalent spring constant k_{eq} is:

$$k_{eq} = k_1 + k_2 + \dots + k_n$$

2) Springs in series – if we have n spring constants k_1, k_2, …, k_n in *series*, then the equivalent spring constant k_{eq} is:

$$\frac{1}{k_{eq}} = \frac{1}{k_1} + \frac{1}{k_2} + \ldots + \frac{1}{k_n}$$

Mass or Inertia Elements:

- Using mathematical model to represent the actual vibrating system.

  E.g. In the figure below, the mass and damping of the beam can be disregarded; the system can thus be modeled as a spring-mass system as shown.

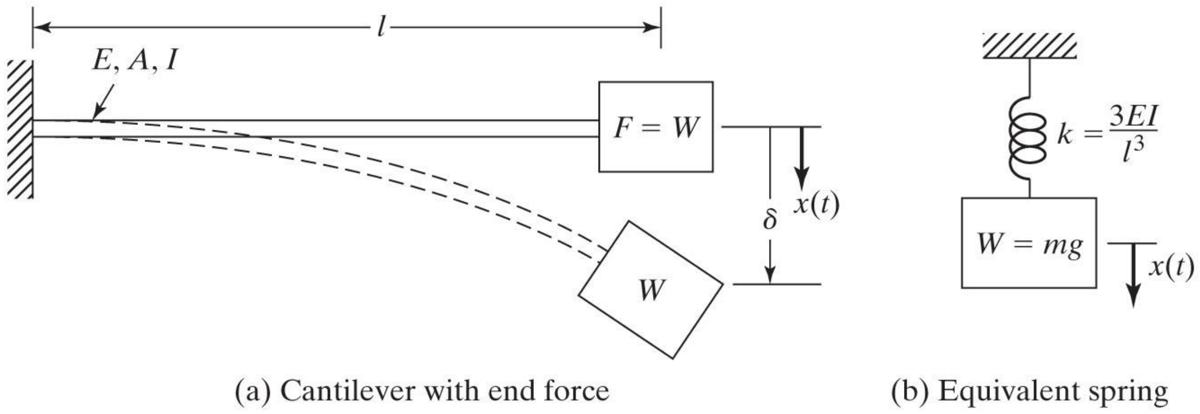


Figure 2.7.9.

Damping Elements:

- Viscous Damping:
  Damping force is proportional to the velocity of the vibrating body in a fluid medium such as air, water, gas, and oil.
- Coulomb or Dry Friction Damping:
  Damping force is constant in magnitude but opposite in direction to that of the motion of the vibrating body between dry surfaces.
- Material or Solid or Hysteretic Damping:
  Energy is absorbed or dissipated by material during deformation due to friction between internal planes.

Harmonic Motion:

- Periodic Motion: motion repeated after equal intervals of time.
- Harmonic Motion: simplest type of periodic motion.
- Displacement (x): *(on horizontal axis)*.

$$x = A\sin\theta = A\sin\omega t$$

- Velocity:

$$\frac{dx}{dt} = \omega A\cos\omega t$$

- Acceleration:

$$\frac{d^2x}{dt^2} = -\omega^2 A\sin\ \omega t = -\omega^2 x$$

2.7.4 Experiments

The Oscillation Training System is housed on a laboratory trolley. As you can see in the figure below, 1 shows the cantilever beam which has a free support that allows to rotation of the beam. Member 2 is representing the spring element and its applying place and stiffness can be changed. Member 3 is damping element that is not used in this experiment. 4th member has a duty of recording the frequency with a pen on it. Finally, member 5 represents the control unit.

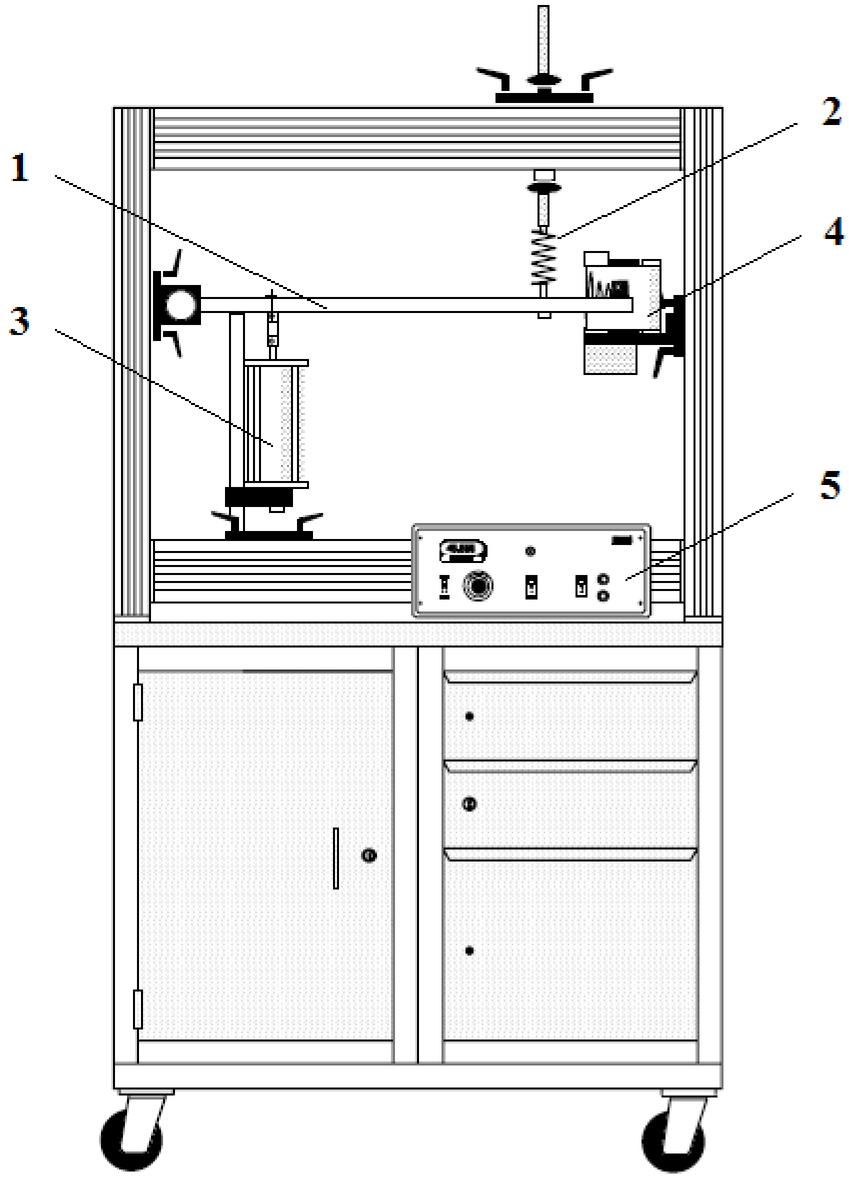


Figure 2.7.10.

Aim of the experiment:

This experiment is designed to observe the change of the natural frequency due to the change of lever arm length. Experimental and calculated natural frequencies will also be compared with each other.

Equation of Motion:

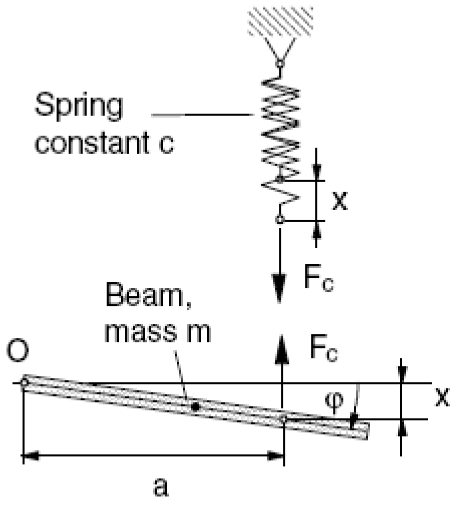


Figure 2.7.11.

After mathematically modeling the system, equation of motion of the vibration is obtained using Newton's laws or Energy method. Positive direction is CCW in this system. First, displacement of the spring should be established.

$$x = a\ sin\theta$$

and for small amplitudes, it can be accepted that:

$$sin\theta = \theta, \qquad cos\theta = 1$$

Establishment of the equation of motion involves forming the moment equilibrium about the fulcrum point O of the beam:

$$\sum M_o = I_o \ddot{\varphi} = -F_c$$

Here, *mg* weight of the beam is not taken into consideration because of measuring the *x* at equilibrium position. The spring force Fc results from the deflection *x* and the spring constant *k*. For a small angle, the deflection can be formed from torsion φ and lever arm *a*

$$F_c = kx = k\,\varphi\, a$$

The mass moment inertia of the beam about the fulcrum point is

$$I_o = \frac{mL^2}{3}$$

The equation of motion is thus the following homogeneous differential equation

$$\ddot{\varphi} + \frac{3ka^2}{mL^2}\varphi = 0$$

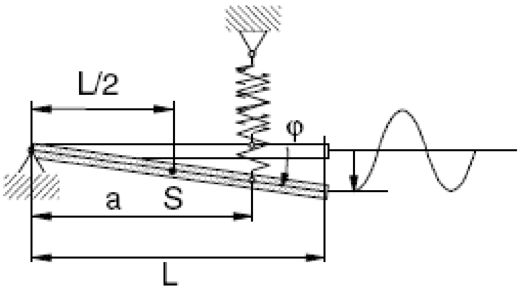


Figure 2.7.12.

The solution produces harmonic oscillations with the natural angular frequency ω_n:

$$w_n^2 = \frac{3ka^2}{mL^2} \text{ , f} = \frac{1}{T}$$

$$\omega_n = \frac{2\pi}{T},$$

$$f = \frac{1}{2\pi}\sqrt{\frac{3ka^2}{mL^2}}$$

The periodic time is

$$T = 2\pi\sqrt{\frac{mL^2}{3ka^2}}$$

As can be seen, the periodic time/natural frequency can easily be set by way of the lever arm *a* of the spring. The natural frequency of the undamped free vibration is:

$$w_n = \sqrt{\frac{k}{m}}$$

Performing Steps of the Experiment:

- Mount spring accordingly and secure with lock nuts
- Horizontally align beam
- Insert pen
- Start plotter
- Deflect beam by hand and let it oscillate
- Stop plotter

Repeat experiment with other springs and lever arms

Mass of beam m = 1.680 kg
Length of beam L = 732 mm
Testing involves the following combinations:

Table 2.7.1.

Influence of spring constant Calculated frequences			
Experiment	Spring no., constant c in N/mm	Lever arm a in mm	Natural frequency f in Hz
1	1, 0.75	350	2.78
2	1, 0.75	650	5.17
3	2, 1.50	350	3.94
4	2, 1.50	650	7.31
5	3, 3.00	650	10.34

Result of Experiment 2:

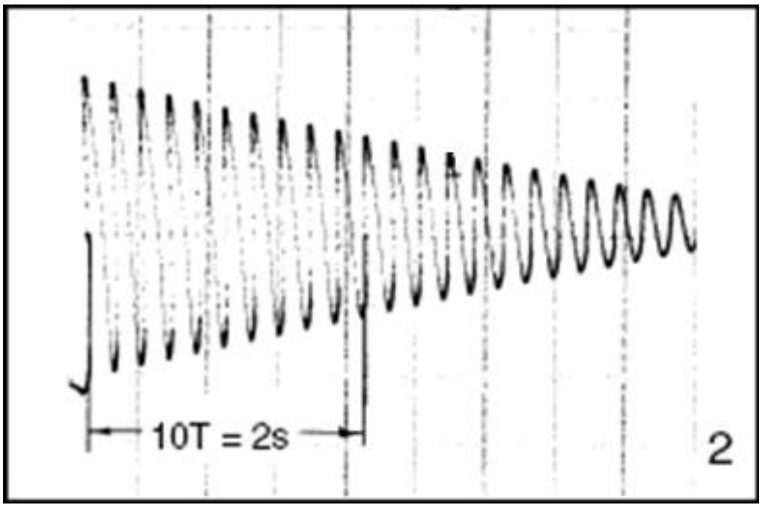


Figure 2.7.13.

2.7.5 Report

Please prepare your report in pdf format and deliver it to mcyilmaz@ybu.edu.tr in one week.

Your report should have the followings;

a) Cover (with names and numbers) (1 page)
b) A short introduction (1 page)
c) All the necessary calculations using measured data.
1. Calculation of stiffness of the spring.
2. Calculation of natural frequencies using formula.
3. Comparing the frequencies with the values that obtained from graphics.
4. Comparing the frequencies with the values from table and calculation of the error rate.

d) Discussion of your results and a conclusion (1/2 page).

2.8 Natural and Forced Heat Convection Experiment

2.8.1 Objective

The objective of this experiment is to compare the heat transfer characteristics of free and forced convection so can the students who participate in the experiment can experience the convection from the first hand.

2.8.2 Introduction

Convection is the mechanism of heat transfer through a fluid in the presence of bulk fluid motion. Convection is classified as natural (or free) and forced convection depending on how the fluid motion is initiated. In natural convection, any fluid motion is caused by natural means such as the buoyancy effect, i.e. the rise of warmer fluid and fall the cooler fluid. Whereas in forced convection, the fluid is forced to flow over a surface or in a tube by external means such as a pump or fan.

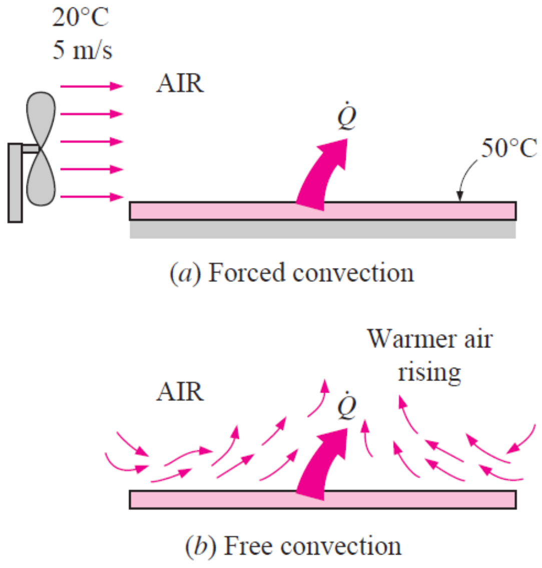


Figure 2.8.1. Heat transfer from a hot surface to the surrounding fluid by convection.

2.8.3 Theory

By applying simple overall energy balance, the heat transfer rate from a heated surface can be calculated as,

$$q = \dot{m} c_p (T_{m,e} - T_{m,i}) \tag{2.8.1}$$

where c_p is the specific heat of the fluid [J/kg·K], T_m is the mean temperature, subscript e and i stands for exit and inlet, and $\dot{m}$ is the mass flow rate [kg/s] which can be written as,

$$\dot{m} = \rho u_m A_c \tag{2.8.2}$$

where ρ is the density of the fluid [kg/m^3], u_m is the mean velocity of the fluid [m/s], and A_c is the cross-sectional area of the flow [m^2]. The average heat transfer coefficient of the system, $\bar{h}$ [W/m^2 K], can be calculated as,

$$\bar{h} = \frac{q}{A\Delta T_{lm}} \tag{2.8.3}$$

where q is the heat transfer rate, A is the area of the heated surface, and ΔT_{lm} is the log-mean temperature difference defined as,

$$\Delta T_{lm} = \frac{\Delta T_{m,i} - \Delta T_{m,e}}{\ln(\Delta T_{m,i}/\Delta T_{m,e})} = \frac{T_{m,o} - T_{m,i}}{\ln\left(\frac{T_s - T_{m,i}}{T_s - T_{m,o}}\right)} \tag{2.8.4}$$

where *Ts* is the surface temperature. The heat transfer characteristics of a system strongly depends on whether the flow is laminar or turbulent. The dimensionless quantities are Rayleigh number (*Ra*) (for free convection) and Reynolds number (*Re*) (for forced convection) that are used to determine the flow characteristics of the system. If they are smaller than a critical value, the flow is assumed to be laminar, otherwise the flow is assumed to be turbulent. The definitions of Ra and Re together with the critical values are given as follows;

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{v\alpha} \qquad \begin{matrix} Ra_L < 10^9 & laminar \\ Ra_L > 10^9 & turbulent \end{matrix} \tag{2.8.5}$$

$$Re = \frac{u_m L}{v} \qquad \begin{matrix} Re_L < 5x10^5 & laminar \\ Re_L > 5x10^5 & turbulent \end{matrix} \tag{2.8.6}$$

where g is the gravitational acceleration [m^2 /s], β is the volumetric thermal expansion coefficient (for an ideal gas, $\beta = 1/T$), T_∞ is the ambient temperature, v is the kinematic viscosity of the fluid [m^2 /s], α is the thermal diffusivity of the fluid [m^2/s], and L is the characteristic length of the flow. The average heat transfer coefficient h can be calculated for a given geometry by using the correlations given in the literature. In the case of free convection from a heated vertical surface, the average value of the Nusselt number ($\overline{Nu}$), which is a dimensionless number and provides a measure of the convective heat transfer, can be determined by using the following correlation,

$$\overline{Nu}_L = \frac{\bar{h}L}{k} = CRa_L^n \tag{2.8.7}$$

where k is the thermal conductivity of the fluid. C and n are the correlation coefficients given as $C = 0.59$, $n = 1/4$ for laminar flow and $C = 0.10$, $n = 1/3$ for turbulent flow case.

In the case of a forced convection from a heated surface, the average Nusselt number can be calculated as,

$$\overline{Nu_L} = \frac{\bar{h}L}{k} = 0.664Re_L^{0.5}Pr^{1/3} \qquad (laminar) \qquad (2.8.8)$$

$$\overline{Nu_L} = \frac{\bar{h}L}{k} = 0.037Re_L^{0.8}Pr^{1/3} \qquad (turbulent) \qquad (2.8.9)$$

where Pr is the Prandtl number ($Pr = v/\alpha$)

2.8.4 Experiments

During the experiments, the power input value, the flow speed of the air inside the duct, the inlet and exit temperatures of air and the temperature of the heater surface are recorded.

Figure 2.8.2. Convection experiment unit

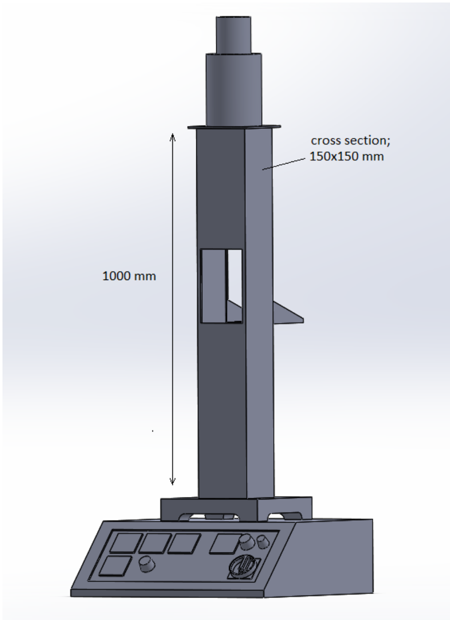


Figure 2.8.3. Schematics of the experimental unit

Procedure

1. Turn on the power and adjust a power input value.
2. Wait until the system reaches the steady-state.
3. Record inlet and exit temperatures of the air.
4. Record the surface temperature of the heater.
5. Turn on the fan.
6. Record the speed of the air, inlet and exit temperatures of the air.
7. Record the surface temperature of the heater.

Table 2.8.1. Natural convection data

	Inlet temperature (℃)	**Exit temperature (℃)**	**Surface temperature (℃)**
Flat plate			
Cylindrical fins			

Table 2.8.2. Forced convection data for plate surface

Speed of air (m/s)	**Inlet temperature (℃)**	**Exit temperature (℃)**	**Surface temperature (℃)**

Table 2.8.3. Forced convection data for cylindrical fins

Speed of air (m/s)	**Inlet temperature (℃)**	**Exit temperature (℃)**	**Surface temperature (℃)**

Analysis For free convection:

1. Calculate the heat transfer rate.
2. Calculate the efficiency (η) of the heat transfer, which is the measure of what fraction of energy input is transferred to the fluid $(\eta = q/P_{el})$.
3. Calculate the log mean temperature difference and the average heat transfer coefficient.
4. Calculate *Ra* and the corresponding *Nu* and the average heat transfer coefficient.
5. Compare the calculated values of heat transfer coefficients by using experimental data with the theoretical values.

For forced convection:

1. Calculate the mass flow rate of the air and the heat transfer rate.
2. Calculate the efficiency $(\eta = q/P_{el})$.
3. Calculate the log mean temperature difference and the average heat transfer coefficient
4. Calculate *Re* and the corresponding *Nu* and the average heat transfer coefficient.
5. Compare the calculated values of heat transfer coefficients by using experimental data with the theoretical values.

Report Questions

• Compare the heat transfer coefficients for free and forced convection. Comment on the results.
• Compare the efficiency values for free and forced convection. Are they different? Is it expected?
• Are the flows for free and forced convection laminar or turbulent? What would be the case if otherwise?
• Compare your results with the theoretical results available in the literature. Comment on the discrepancy between the results if any.

2.8.5 Report

The following should be in your laboratory report;

a) Cover
b) A short introduction
c) All the necessary calculations and answers of the questions which is mentioned above
d) Discussion of your results
e) Conclusion

P.S. (Postscript) Every student should bring their own hard copy of this document to the experiment.

2.9 Strain Measurement Experiment

2.9.1 Objective

The objective of this experiment is to become familiar with the electric resistance strain gauge techniques and utilize such gauges for the determination of unknown quantities (such as strain, stress and young's modulus) at the prescribed conditions of a cantilever beam.

2.9.2 Introduction

Experimental stress analysis is an important tool in the design and testing of many products. Several practical techniques are available including photoelastic, coatings and models, brittle coatings, and electrical resistance strain gauges.

In this experiment, the electrical resistance strain gauge will be utilized. There are three steps in obtaining experimental strain measurements by using a strain gauge:

1. Selecting a strain gauge.
2. Mounting the gauge on the test structure.
3. Measuring strains corresponding to specific loads.

The operation and selection criteria for strain gauges will be discussed. In this experiment, you will mount a strain gauge on a beam and test its accuracy. Measurements will be made with a strain gauge rosette in this experiment to obtain the principal stresses and strains on a cantilevered beam.

What's a Strain Gauge Used For?

The Birdman Contest is an annual event held on Lake Biwa near Kyoto, Japan. In this contest cleverly designed human-powered airplanes and gliders fly several hundred meters across the lake. Aside from the great spectacle of this event, it is a wonderful view of engineering experimentation and competition. Despite the careful designs and well-balanced airframes occasionally the wings of these vehicles fail and crash into the lake. There have been some spectacular crashes but few, if any, injuries to the contestants.

Increasingly, each time a new airplane, automobile, or other vehicle is introduced, the structure of such vehicles is designed to be lighter to attain faster running speeds and less fuel consumption. It is possible to design a lighter and more efficient product by selecting light-weight materials. However, as with all technology, there are plusses and minuses to be balanced. If a structural material is made lighter or thinner the safety of the vehicle is compromised unless the required strength is maintained. By the same token, if only the strength is taken into consideration, the vehicle's weight will increase and its economic feasibility is compromised.

In engineering design the balance between safety and economics is one variable in the equation of creating a successful product. While attempting to design a component or vehicle that provides the appropriate strength it is important to understand the stress borne by the various parts under different conditions. However, there is no technology or test tool that allows direct measurement of stress. Thus, strain on the surface is frequently measured in order to determine internal stress. Strain gauges are the most common instrument to measure surface strain.

2.9.2.1 Strain Gauges:

There are many types of strain gauges. The fundamental structure of a strain gauge consists of a grid-shaped sensing element of thin metallic resistive foil (3 to 6 microns thick) that is sandwiched between a base of thin plastic film (12-16 micron thick) and a covering or lamination of thin film.

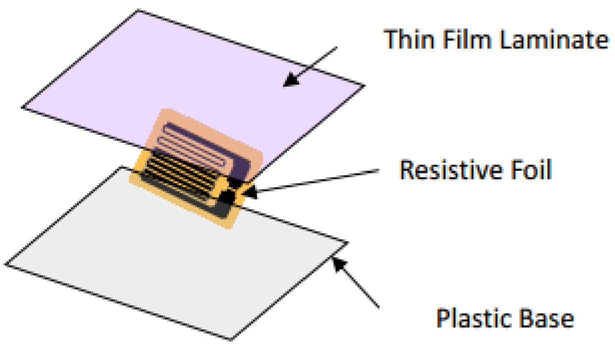


Figure 2.9.1. Strain gauge construction

2.9.2.2 Strain Gauge Operation:

Strain gauge is tightly bonded to the specimen. Therefore, depending that unit deformation on the specimen, the sensing element may elongate or contract. During elongation or contraction, electrical resistance of the metal wire changes. The strain gauge measure the strain on the specimen by means of the principle resistance changes. Generally, sensing element are made of copper-nickel alloy in strain gauge. Depending the strain on the alloy plate, the resistance changes at a fix rate.

$$\frac{\Delta R}{R} = Ks.\varepsilon \qquad (2.9.1)$$

R: The initial resistance of the strain gauge, Ω (ohm)
ΔR: The change of the resistance, Ω (ohm)
Ks: Gauge Factor, Proportional constant
ε : Strain

Gauge factor, Ks, changes according to the material being used in strain gauge. Generally, Gauge factor of copper-nickel alloy strain gauges is approximately 2 or 2.1. Strain gauges, generally have 120 or 350 Ω resistance. It is very difficult to accurately measure such a small resistance change, and also, it is not possible to use an ohmmeter to measure. Thus, Wheatstone bridge electric circuit are used to measure the resistance changes.

2.9.3 Theory

2.9.3.1 Stress:

Stress is simply a distributed force on an external or internal surface of a body. To obtain a physical feeling of this idea, consider being submerged in water at a particular depth. The ‘‘force’’ of the water one feels at this depth is a pressure, which is a compressive stress, and not a finite number of ‘‘concentrated’’ forces. Other types of force distributions (stress) can occur in a liquid or solid. Tensile (pulling rather than pushing) and shear (rubbing or sliding) force distributions can also exist.

Consider a general solid body loaded as shown in Figure 2.9.2 (a). Pi and pi are applied concentrated forces and applied surface force distributions, respectively; and R_i and r_i are possible support reaction force and surface force distributions, respectively. To determine the state of stress at point Q in the body, it is necessary to expose a surface containing the point Q. This is done by making a planar slice, or break, through the body intersecting the point Q. The orientation of this slice is arbitrary, but it is generally made in a convenient plane where the state of stress can be determined easily or where certain geometric relations can be utilized. The first slice, illustrated in Figure 2.9.2 (b), is described by the surface normal oriented along the x axis. This establishes the yz plane. The external forces on the remaining body are shown, as well as the internal force (stress) distribution across the exposed internal surface containing Q. In the general case, this distribution will not be uniform along the surface, and will be neither normal nor tangential to the surface at Q. However, the force distribution at Q will have components in the normal and tangential directions. These components will be tensile or compressive and shear stresses, respectively.

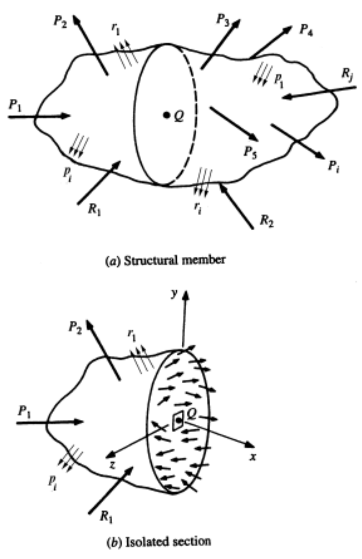


Figure 2.9.2. (a) Structural member and **(b)** Isolated section

Following a right-handed rectangular coordinate system, the y and z axes are defined perpendicular to x, and tangential to the surface. Examine an infinitesimal area $\Delta A_x = \Delta y \Delta z$ surrounding Q, as shown in Figure. 2.9.3 (a). The equivalent concentrated force due to the force distribution across this area is ΔF_x, which in general is neither normal nor tangential to the surface (the subscript x is used to designate the normal to the area). The force ΔF_x has components in the x, y, and z directions, which are labeled ΔF_{xx}, ΔF_{xy}, and ΔF_{xz}, respectively, as shown in Figure 2.9.3 (b). Note that the first subscript denotes the direction normal to the surface and the second gives the actual direction of the force component. The average distributed force per unit area (average stress) in the x direction is

$$\bar{\sigma}_{xx} = \frac{\Delta F_{xx}}{\Delta A_X} \tag{2.9.2}$$

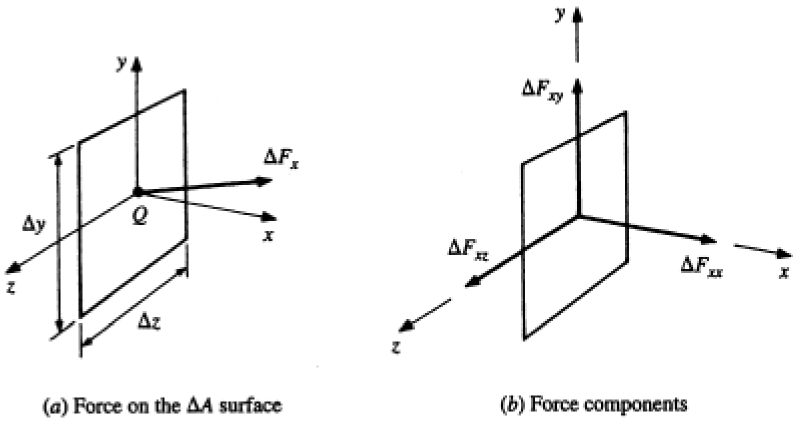


Figure 2.9.3. (a) Force on the ΔA surface, **(b)** Force components

Recalling that stress is actually a point function, we obtain the exact stress in the x direction at point Q by allowing ΔA_x to approach zero. Thus,

$$\sigma_{xx} = \lim_{\Delta A_X \to \infty} \frac{\Delta F_{xx}}{\Delta A_X} \tag{2.9.3}$$

or,

$$\sigma_{xx} = \frac{dF_{xx}}{dA_X} \tag{2.9.4}$$

2.9.3.2 Strain:

As with stresses, two types of strains exist: normal and shear strains, which are denoted by ε and γ, respectively. Normal strain is the rate of change of the length of the stressed element in a particular direction. Let us first consider a bar with a constant cross-sectional area which has the undeformed length *l*. Under the action of tensile forces (Figure 2.2.4) it gets slightly longer. The elongation is denoted by Δl and is assumed to be much smaller than the original length *l*. As a measure of the amount of deformation, it is useful to introduce, in addition to the elongation, the ratio between the elongation and the original (undeformed) length:

$$\varepsilon = \frac{\Delta l}{l} \tag{2.9.5}$$

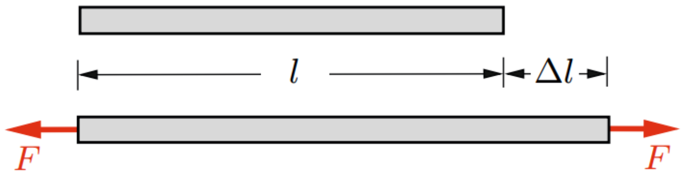


Figure 2.9.4. The undeformed length *l* and the deformed length *l*

The dimensionless quantity ε is called strain.

2.9.3.3. Hook's Law

The strains in a structural member depend on the external loading and therefore on the stresses. For linear elastic behavior, the relation between stresses and strains is given by Hooke's law. In the uniaxial case (bar) it takes the form σ = E ε where E is Young's modulus.

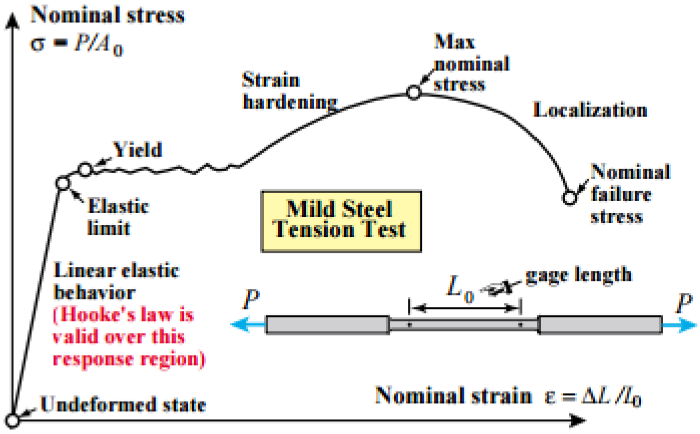


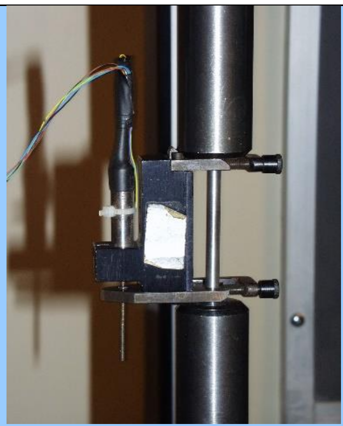
Figure 2.9.5. Stress vs strain diagram

Strain Measurement

It should be noted that there are various types of strain measuring methods available. These may be roughly classified into mechanical, electrical, and even optical techniques.

From a geometric perspective, strain recorded during any test may be regarded as a distance change between two points on a test article. Thus all techniques are simply a way of measuring this change in distance.

If the elastic modulus of the test article's constituent material is known, strain measurement will allow calculation of stress. As you have learned from your studies and prior labs strain measurement is often performed to determine the stress created in a test article by some external force, rather than to simply gain knowledge of the strain value itself.



This **linear variable differential transformer** (LVDT), attached to a tensile specimen, is also a common tool for measuring strain.

2.9.4 Experiments

2.9.4.1. Wheatstone Bridge:

Wheatstone bridge is an electric circuit that is used for measuring the instantaneous change in the instant resistance.

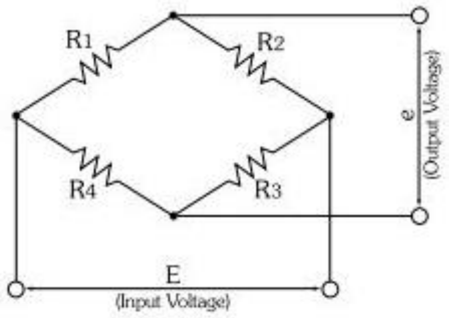


Figure 2.9.6. Wheatstone Bridge

$$R1 = R2 = R3 = R3 \tag{2.9.6}$$

or,

$$R1XR3 = R2XR4 \tag{2.9.7}$$

When applying any voltage to input, the output of the system may be zero "0". In this way, the bridge is in balance. When the any resistance changes, the output will be different than zero.

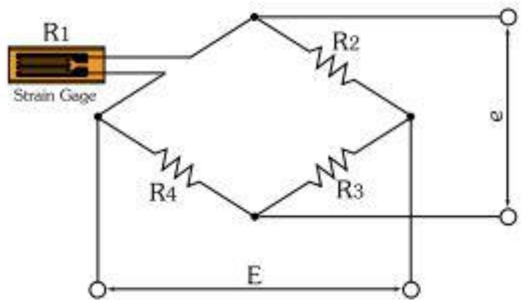


Figure 2.9.7. Quarter Wheatstone Bridge

A strain gauge connects to the circuit in Figure 2.9.7. When strain gauge loads and the resistance changes, the voltage is obtained at the output of the bridge.

$$e = \frac{1}{4}.\frac{\Delta R1}{R1}.E \tag{2.9.8}$$

and,

$$e = \frac{1}{4}.Ks.\varepsilon_1.E \tag{2.9.9}$$

Two strain gauged connect to the circuit in Figure 2.9.8. When strain gauges load and the resistances change, the voltage is obtained at the output of the bridge.

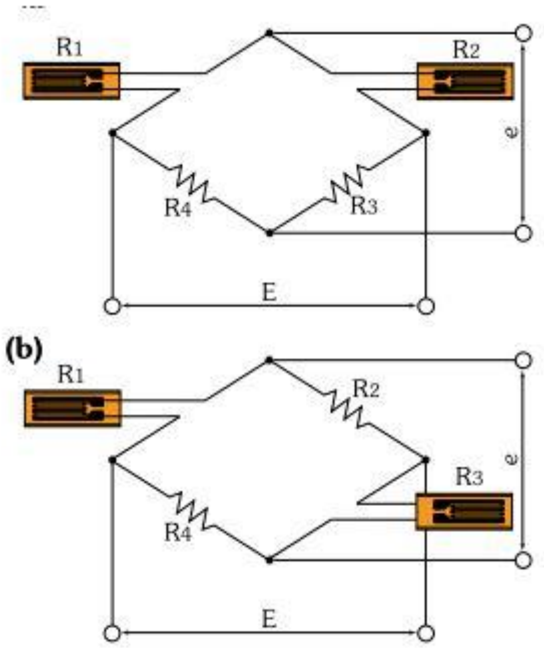


Figure 2.9.8. Half Wheatstone Bridge

$$e = \frac{1}{4}.\left(\frac{\Delta R1}{R1} - \frac{\Delta R2}{R2}\right).E \quad (2.9.10)$$

and,

$$e = \frac{1}{4}.Ks.(\varepsilon_1 - \varepsilon_2).E \quad (2.9.11)$$

or,

$$e = \frac{1}{4}.\left(\frac{\Delta R1}{R1} + \frac{\Delta R3}{R3}\right).E \quad (2.9.12)$$

and,

$$e = \frac{1}{4}.Ks.(\varepsilon_1 + \varepsilon_3).E \quad (2.9.13)$$

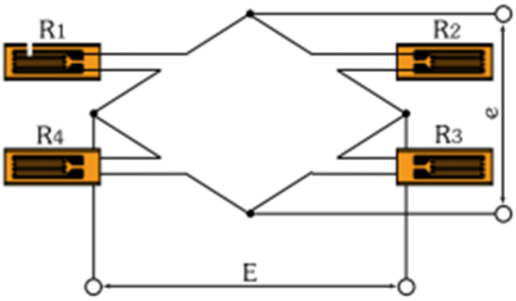


Figure 2.9.9. Full Wheatstone Bridge

$$e = \frac{1}{4}.\left(\frac{\Delta R1}{R1} - \frac{\Delta R2}{R2} + \frac{\Delta R3}{R3} - \frac{\Delta R4}{R4}\right).E \qquad (2.9.14)$$

and,

$$e = \frac{1}{4}.Ks.(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4).E \qquad (2.9.15)$$

A resistance strain gage consists of a thin strain-sensitive wire mounted on a backing that insulates the wire from the test structure. Strain gages are calibrated with a gage factor F, which relates strain to the resistance change in the wire by

$$F = \frac{\Delta R/R}{\Delta L \,/\, L} \qquad (2.9.16)$$

where R is the resistance and L is the length of the wire. The change in resistance corresponding to typical values of strain is usually only a fraction of an ohm.

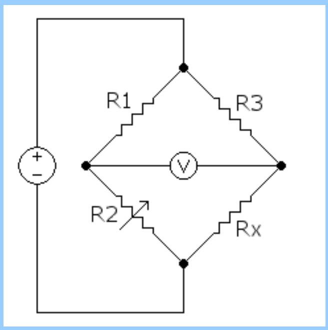
Because conventional ohmmeters are not capable of measuring these small changes in resistance accurately, a Wheatstone bridge is usually employed. It can be operated in either a balanced or unbalanced configuration. For an unbalanced bridge, a change in resistance is measured as a non-zero voltage V_o which, can be calibrated in standard strain units ($\Delta L/L \times 10^{-6}$) or micro strain. A balanced bridge is rebalanced after each load increment so that the output voltage V_o is zero. The appropriate changes in resistance are then noted and strain calculated using the gage factor.

The Wheatstone Bridge

A Wheatstone bridge is a measuring instrument that, despite popular myth, was **not** invented by Sir Charles Wheatstone, but by Samuel H. Christie in 1833. The device was later improved upon and popularized by Wheatstone. The bridge is used to measure an unknown electrical resistance by balancing two legs of a circuit, one leg of which includes the unknown component that is to be measured. The Wheatstone bridge illustrates the concept of a difference measurement, which can be extremely accurate. Variations on the Wheatstone bridge can be used to measure capacitance, inductance, and impedance.

In a typical Wheatstone configuration, Rx is the unknown resistance to be measured; R1, R2 and R3 are resistors of known resistance and the resistance of R2 is adjustable. If the ratio of the two resistances in the known leg (R2/R1) is equal to the ratio of the two in the unknown leg (Rx/R3), then the voltage between the two midpoints will be zero and no current will flow between the midpoints. R2 is varied until this condition is reached. The current direction indicates if R2 is too high or too low. Detecting zero current can be done to extremely high accuracy. Therefore, if R1, R2 and R3 are known to high precision, then Rx can be measured to high precision. Very small changes in Rx disrupt the balance and are readily detected.

Alternatively, if R1, R2, and R3 are known, but R2 is not adjustable, the voltage or current flow through the meter can be used to calculate the value of Rx. This setup is what you will use in strain gauge measurements, as it is usually faster to read a voltage level off a meter than to adjust a resistance to zero the voltage.



Typical Wheatstone Bridge diagram with strain gauge at Rx

2.9.4.2. Cantilever Beam

The beam with the strain gage you have just attached will be placed in the Cantilever Flexure Frame to take strain measurements. The arrangement is schematically shown in Figure 2.9.10.

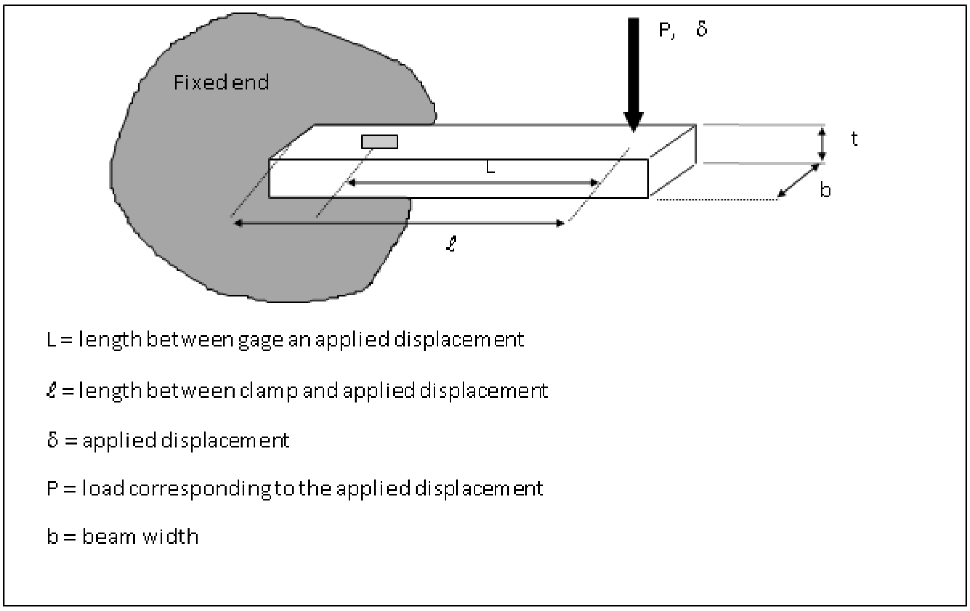


Figure 2.9.10. Beam with Strain Gage in Flexure Fixture

The structure examined in this experiment is the cantilever beam. A beam under bending can be characterized by Equation 2.9.11.

$$\frac{1}{\rho} = \frac{M}{EI} \tag{2.9.17}$$

The radius of curvature is given by Equation 2.9.12

$$\frac{1}{\rho} = \frac{d^2y/_{dx^2}}{\left(1 + \left(^{dy}/_{dx}\right)^2\right)^{3/2}} \tag{2.9.18}$$

where y is the deflection in the y direction at any given point x along the beam. Any expression involving the radius of curvature seems to always have it appear in the denominator. And this is no exception, even when it is a defining equation. The fact that many mechanics applications involve bending, but on a small scale. The beam bending discussed here is no exception. In such cases, the best approach is to define the x-axis along the beam such so that the y deflections, and more importantly the deformed slope, y′, will both be small. If y′<<1, then y′ can be neglected in the above equation. It means that, the deflection is very small for many problems. This means that the denominator can be neglected in most cases.

$$\frac{1}{\rho} \approx d^2y/_{dx^2} \tag{2.9.19}$$

Combining Equations 2.9.17 and 2.9.19 yields.

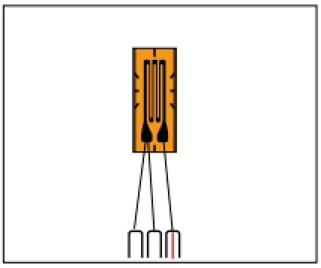
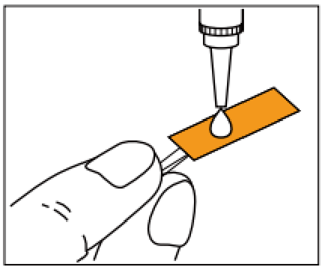
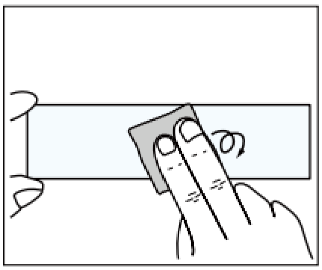
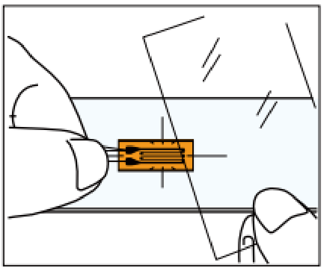
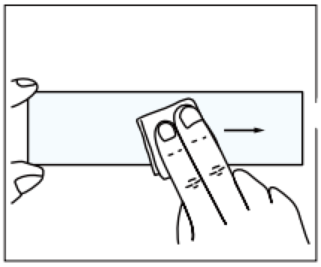
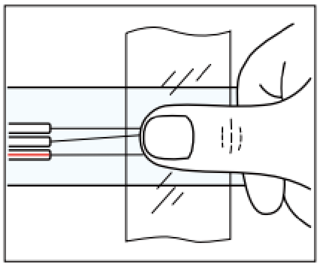
$$\frac{M}{EI} = {d^2y}/{dx^2} \tag{2.9.20}$$

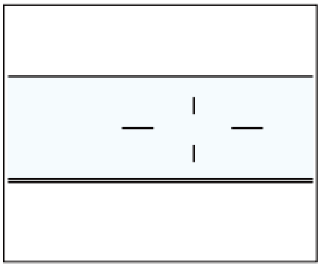
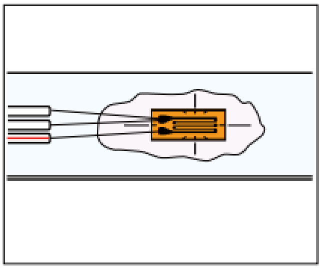
This further reduces to a convenient form of the equation for stress in the cantilever beam.

$$\sigma = \frac{Mc}{I} \tag{2.9.21}$$

Also, there should be some observation about the usability and reliability of the relatively crude instrumentation involved in the experiment. In most cases, strain values differ at most by 5 µstrain from the actual values. In most of the experiments here, that relates to much less than an ounce of resolution. In the laboratory most load cells typically fall within 0.5 % error.

2.9.4.3. Strain Gauge Bonding Procedure

(1) Select strain gage.  Select the strain gauge model and gauge length which meet the requirements of the measuring object and purpose	**(5) Apply adhesive.**  Ascertain the back and front of the strain gauge. Apply a drop of adhesive to the back of the strain gauge. Do not spread the adhesive. If spreading occurs, curing is adversely accelerated, thereby lowering the adhesive strength.
(2) Remove dust and paint.  Using a sand cloth (20 to 300), polish the strain gauge bonding site over a wider area than the strain gauge size. Wipe off paint, rust and plating, if any, with a grinder or sand blast before polishing.	**(6) Bond strain gage to measuring site.**  After applying a drop of the adhesive, put the strain gauge on the measuring site while lining up the center marks with the marking off lines.
(3) Remove grease from bonding surface and clean.  Using an industrial tissue paper (SILBON paper) dipped in acetone, clean the strain gauge bonding site. Strongly wipe the surface in a single direction to collect dust and then remove by wiring in the same direction. Reciprocal wiping causes dust to move back and forth and does not ensure cleaning.	**(7) Press strain gage.**  Cover the strain gauge with the accessory polyethylene sheet and press it over the sheet with a thumb. Quickly perform steps (5) to (7) as a series of actions. Once the strain gauge is placed on the bonding site, do not lift it to adjust the position. The adhesive strength will be extremely lowered.

(4) Decide bonding position.  Using a pencil or marking off pin, mark the measuring site in the strain direction. When using a marking off pin, take care not to deeply scratch the strain gauge bonding surface.	(8) Complete bonding work.  After pressing the strain gauge with a thumb for one minute or so, remove the polyethylene sheet and make sure the strain gauge is securely bonded. The above steps complete the bonding work. However, good measurement results are available after 60 minutes of complete curing of adhesive.

2.9.5 Report

In your laboratory reports must have the followings;

a) Cover
b) A short introduction
c) All the necessary calculations using measured data.
d) Discussion of your results and a conclusion.

2.10 Tensile Test Experiment

2.10.1 Objective

The purpose of this experiment is to understand the uniaxial tensile testing and provide knowledge of the application of the tensile test machine.

2.10.2 Introduction

Tensile testing is one of the simplest and most widely used mechanical tests. By measuring the force required to elongate a specimen to breaking point, material properties can be determined that will allow designers and quality managers to predict how materials and products will behave in application.

2.10.3 Theory

Tensile tests are performed for several reasons. The results of tensile tests are used in selecting materials for engineering applications. Tensile properties frequently are included in material specifications to ensure quality. Tensile properties often are measured during development of new materials and processes, so that different materials and processes can be compared. Finally, tensile properties often are used to predict the behavior of a material under forms of loading other than uniaxial tension.

The strength of a material often is the primary concern. The strength of interest may be measured in terms of either the stress necessary to cause appreciable plastic deformation or the maximum stress that the material can withstand. These measures of strength are used, with appropriate caution (in the form of safety factors), in engineering design. Also of interest is the material's ductility, which is a measure of how much it can be deformed before it fractures. Rarely is ductility incorporated directly in design; rather, it is included in material specifications to ensure quality and toughness. Low ductility in a tensile test often is accompanied by low resistance to fracture under other forms of loading. Elastic properties also may be of interest, but special techniques must be used to measure these properties during tensile testing, and more accurate measurements can be made by ultrasonic techniques.

Engineering Stress is the ratio of applied force P and cross section or force per area.

$$\sigma = \frac{P}{A_0} \tag{2.10.1}$$

is engineering stress.
P is the external axial tensile load
A_0 is the original cross-sectional area
There are three types of stresses as seen in Fig. 2.10.1.

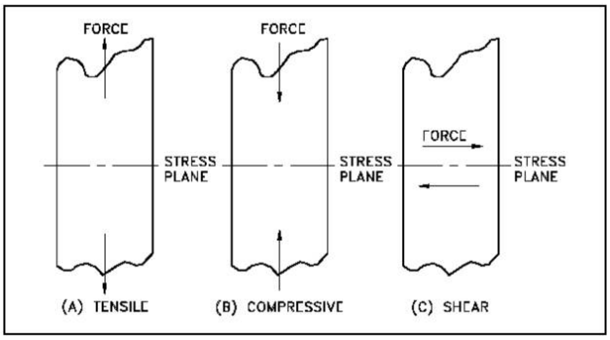


Figure 2.10.1. Types of the stresses

Engineering Strain is defined as extension per unit length.

$$\varepsilon = \frac{\Delta L}{L_0} = \frac{L_f - L_0}{L_0} \qquad \textbf{(2.10.2)}$$

ε is the engineering strain
L_0 is the original length of the specimen
L_f is the final length of the specimen

An example of the engineering stress-strain curve for a typical engineering alloy is shown in Figure 2.10.2. From it some very important properties can be determined. The elastic modulus, the yield strength, the ultimate tensile strength, and the fracture strain are all clearly exhibited in an accurately constructed stress strain curve.

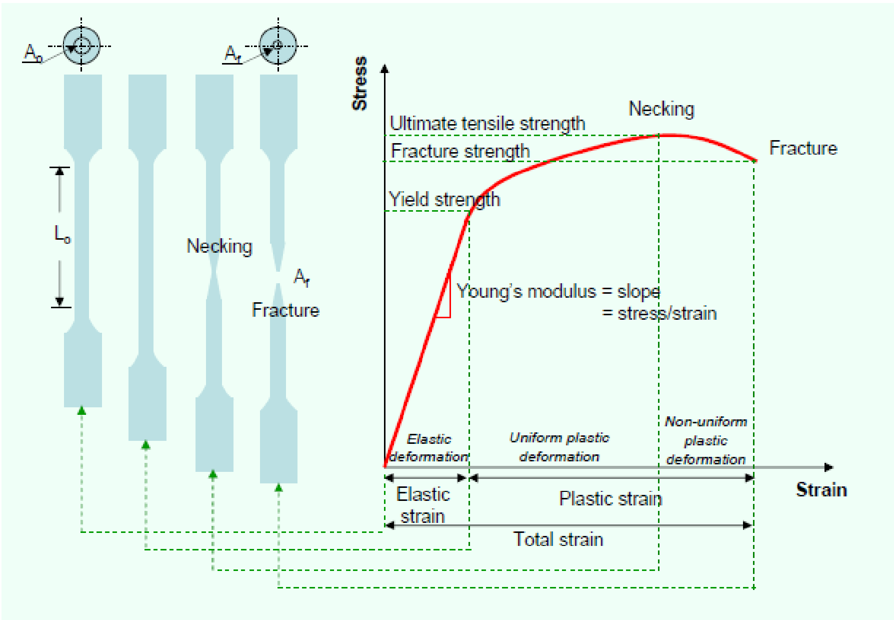


Figure 2.10.2. Stress-strain curve

True stress is the stress determined by the instantaneous load acting on the instantaneous cross-sectional area (Fig. 2.10.3).

$$\sigma_T = P/A_i \qquad (2.10.3)$$

True strain is the rate of instantaneous increase in the instantaneous gauge length (Fig.2.10.3).

$$\varepsilon_T = \ln (l_i/l_o) \tag{2.10.4}$$

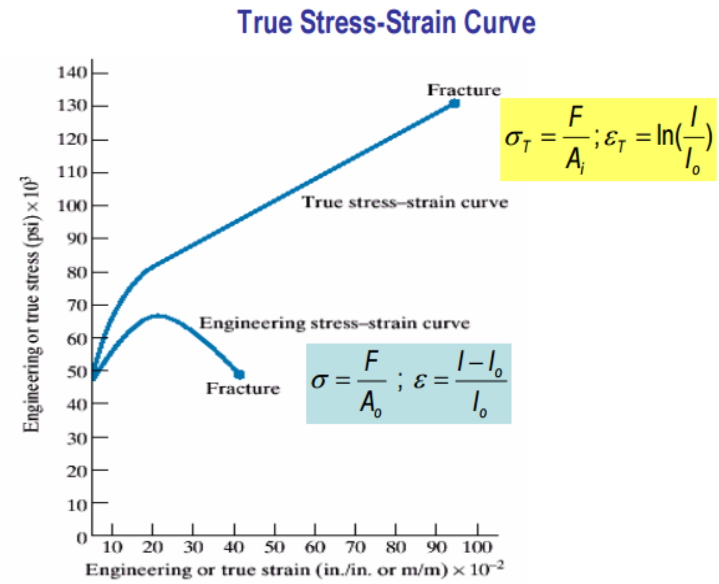


Figure 2.10.3. True Stress-strain curve

True stress-engineering stress relation:

$$\sigma_T = \sigma(\varepsilon + 1) \tag{2.10.5}$$

True strain-engineering strain relation:

$$\varepsilon_T = \ln (\varepsilon + 1) \tag{2.10.6}$$

Elastic region: The part of the stress-strain curve up to the yielding point. Elastic deformation is recoverable. In the elastic region stress and strain are related to each other linearly. *E* is Modulus of Elasticity or Young Modulus which is specific for each type of material.

$$Hooke's\ Law: \sigma = E\varepsilon$$

Plastic region: The part of the stress-strain diagram after the yielding point. At the yielding point, the plastic deformation starts. Plastic deformation is permanent. At the maximum point of the stress-strain diagram(σ_{UTS}), necking starts.

Ultimate Tensile Strength, σ_{UTS} is the maximum strength that material can withstand.

$$\sigma_{UTS} = \frac{Pmax}{A_0} \tag{2.10.7}$$

Yield Strength, σ_Y is the stress level at which plastic deformation initiates. The beginning of first plastic deformation is called yielding. 0,2% off-set method is a commonly used method to determine the yield stength. σ_Y (0.2%) is found by drawing a parallel line to the elastic region and the point at which this line intersects with the stress-strain curve is set as the yielding point (Fig 2.10.4).

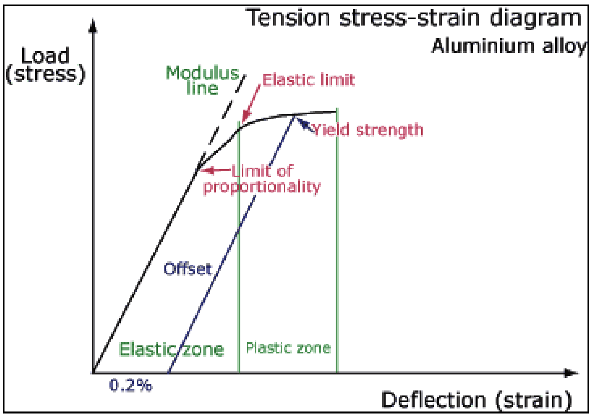


Figure 2.10.4. Stress-strain curve

Fracture Strength, σ_F: After necking, plastic deformation is not uniform and the stress decreases accordingly until fracture.

$$\sigma_F = \frac{Pf}{A_0} \tag{2.10.8}$$

Toughness: The ability of a metal to deform plastically and to absorb energy in the process before fracture is termed toughness. The emphasis of this definition should be placed on the ability to absorb energy before fracture. Toughness of the different materials is seen in the Fig. 2.10.5.

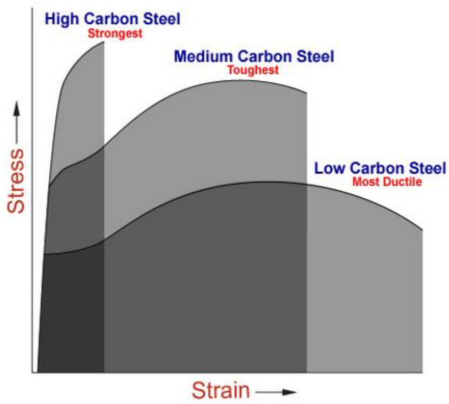


Figure 2.10.5. Toughness of the materials

Ductility is a measure of how much something deforms plastically before fracture, but just because a material is ductile does not make it tough. The key to toughness is a good combination of strength and ductility. A material with high strength and high ductility will have more toughness than a material with low strength and high ductility. Ductility can be described with the percent elongation or percent reduction in area.

$$\%\,Elongation = \frac{L_f - L_0}{L_0}100 \text{ (percent elongation)} \tag{2.10.9}$$

$$\%RA = \frac{A_0 - A_f}{A_0}100 \quad \text{(percent reduction in area)} \tag{2.10.10}$$

Resilience: By considering the area under the stress-strain curve in the elastic region, this area represents the stored elastic energy or resilience.

2.10.4 Experiments

The test unit will be introduced in the laboratory before the experiment by the relevant assistant.

Tensile Specimens: Consider the typical tensile specimen shown in Fig. 2.10.6. It has enlarged ends or shoulders for gripping. The important part of the specimen is the gage section. The cross-sectional area of the gage section is reduced relative to that of the remainder of the specimen so that deformation and failure will be localized in this region. The gage length is the region over which measurements are made and is centered within the reduced section. The distances between the ends of the gage section and the shoulders should be great enough so that the larger ends do not constrain deformation within the gage section, and the gage length should be great relative to its diameter. Otherwise, the stress state will be more complex than simple tension.

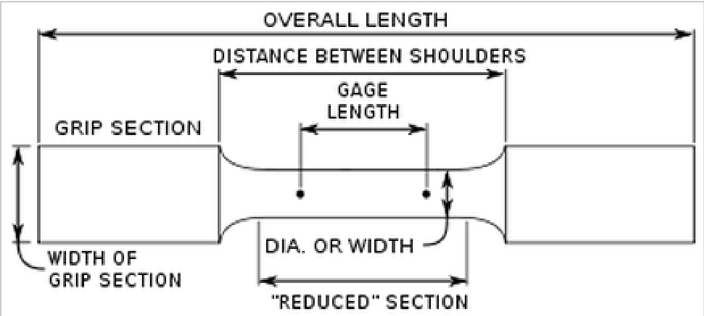


Figure 2.10.6. Test specimen

Test machine: The most common testing machines are universal testers, which test materials in tension, compression, or bending. Their primary function is to create the stress-strain curve. Testing machines are either electromechanical or hydraulic. The principal difference is the method by which the load is applied. Electromechanical machines are based on a variable-speed electric motor; a gear reduction system; and one, two, or four screws that move the crosshead up or down. This motion loads the specimen in tension or compression. Crosshead speeds can be changed by changing the speed of the motor (Fig.2.10.7)

Figure 2.10.7. Tension test equipment

Experimental steps: Specimen is machined in the desired orientation and according to the standards. Aluminum, steel or composite materials can be used as the specimen material mostly.

Magnitude of the load is chosen with respect to the tensile strength of the material. Specimen is fit to the test machine. Maximum load is recorded during testing. After fracture of the material, final gage length and diameter is measured. Diameter should be measured from the neck.

The necessary data for calculations will be recorded to the Table 2.10.1 given below.

Table 2.10.1. Data which is entered into the system

Measurement No:	Steel
Force, P [N]	
Specimen dimension, d_0 [mm]	
Length, l_0 [mm]	
Test speed, mm/dk	

2.10.4.1 Results

Calculate the values given in Table 2.10.2.

Table 2.10.2. Results obtained from test data

Details	Steel
*Maximum force, P_{max} [N]	
*Final length, l_f [mm]	
*Final Diameter, d_f [mm]	
Final Cross sectional area, A_f [mm^2]	
Young Modulus, E [GPa]	
*Yield Strength, $\sigma_{Y,}$ [MPa]	
*Ultimate tensile strength, σ_{UTS} [MPa]	
*Fracture stress, σ_F [MPa]	
% elongation	
% area of reduction	

(* it will be read during and after test)

Plot the engineering stress-strain and true stress-strain curve on the same graph on a milimetrical paper. Make scales for both x and y axis. Label the known values.

2.10.5 Report

In your laboratory reports must have the followings;

a) Cover
b) A short introduction
c) All the necessary calculations using measured data.
d) Discussion of your results and a conclusion.

APPENDICES

Appendix 1 Experiment Report Preparation Rules
Appendix 2 Exemplar Cover Page for the Experiment Reports

I. Laboratory Report Elements

A laboratory report (shortly *a lab report*) is created using the following characteristics.

1. Name, Title, Page Number, and Date: Lab report document requires Name, Title, Page Number, and Dates. These are essential elements of formatting. Place your name or title with the page number in the header.

2. Standard Formatting: This document follows standard academic formatting guidelines. These include Times New Roman 12 pt. font. The text of lab report is single-spaced.

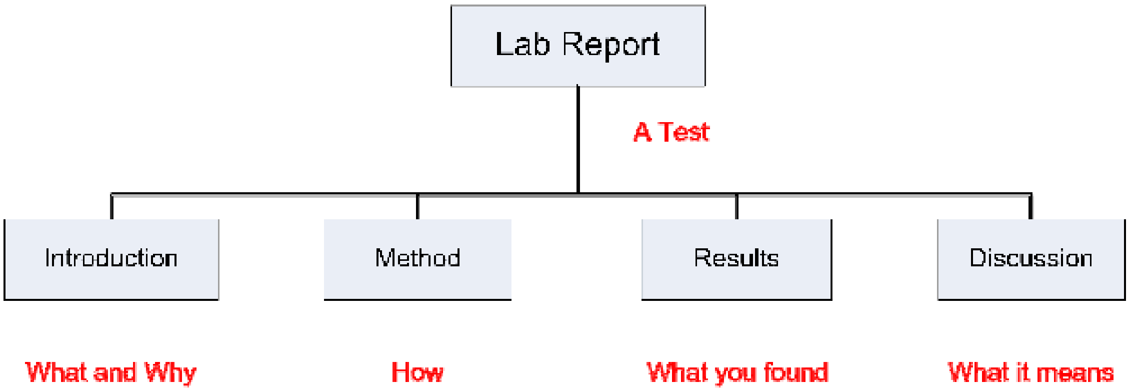
3. Graphic Numbering: This document uses visuals. Each graphic, such as: figures, tables, pictures, equations, etc. is labeled and numbered sequentially.

4. Format: The lab report follows the IMRD traditional report writing standard. It contains the following sections in this order: **I**ntroduction, **M**ethods, **R**esults, and **D**iscussion. Introduction provides background and the question addressed, methods describes how that question was answered, results show the resulting data from the experiment and discussion is the author's interpretation of those results. Often results and discussion are combined.

5. Tense: Technical writing varies its tense depending on what you are discussing. Tense should be consistent for each section you write.

➢ **Past Tense**
The lab report uses past tense. As a rule of thumb, past tense is used to describe work you did over the course of the report timeline.

➢ **Present Tense**
The lab report uses present tense. As a rule of thumb, present tense is used to describe knowledge and facts that were known before you started.



The lab report involves the solving of a specific question, described in the introduction and answered in the discussion.

II. How to Write a Lab Report

<table>
<tr><th colspan="2">Report Sections</th><th>Explanation</th></tr>
<tr><td colspan="2">Title Page</td><td></td></tr>
<tr><td colspan="2">Table of Contents</td><td></td></tr>
<tr><td>Introduction</td><td>• Background/Theory
• Purpose
• Governing Equations Discovery and Question</td><td>In this section, what you are trying to find and why are describe. Background and motivation are used to provide the reader with a reason to read the report.</td></tr>
<tr><td>Methods</td><td>• Experiment
• Overview Apparatus
• Equipment Table
• Procedures</td><td>In this section, how question addressed is answered, is explained. Clearly explain your work so it could be repeated.</td></tr>
<tr><td>Results</td><td>• Tables and Graphs
• Equations in Variable
• Form
• Uncertainties and Error Analysis
• Indicate Final Results</td><td>In this section, you present the results of your experiment. Tables, graphs, and equations are used to summarize the results. Link equations and visuals together.</td></tr>
<tr><td>Discussion</td><td>• Theoretical Comparison
• Explanation of Anomalies/Error
• Conclusion/Summary</td><td>In this section, you explain and interpret your results. Insert your opinion, backed by results. Discuss issues you had and how this could be corrected in the future. The conclusion is a summary of your results and discussion.</td></tr>
<tr><td colspan="3">References</td></tr>
<tr><td colspan="3">Appendices – Raw Data, Sample Calculations, Lab Notebook, etc.</td></tr>
</table>

T.C.
ANKARA YILDIRIM BEYAZIT UNIVERSITY
FACULTY OF ENGINEERING AND NATURAL SCIENCES
MECHANICAL ENGINEERING DEPARTMENT

MCE - 403 MACHINERY LABORATORY - I

……………………………….……. EXPERIMENT REPORT

Student No	**:**	
Name-Surname	**:**	
Experimental Group	**:**	
Experimental. Date	**:**	
Delivery Date	**:**	
Grade	**:**	

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[1] Genceli O. F., “Ölçme Tekniği (Boyut, Basınç, Akış ve Sıcaklık Ölçmeleri)”, *Birsen Yayınevi*, İstanbul, 2000.

[2] Holman J. P., “Experimental Methods for Engineers”, *McGraw-Hill Book Company*, 7nd Edition, New York, 2001.

[3] Bilen K., “Dar Kanallarda Yoğuşma”, *İTÜ Fen Bilimleri Enstitüsü,* Doktora Tezi, (*Danışman*: *Prof. Dr. A. F. Özgüç*), İstanbul, 2007.