Bangladesh University of Engineering and Technology

Department of Mechanical Engineering

ME 306

Heat Transfer Sessional

Contact Hour: 1.5, Credit Hour: 0.75

Location: Heat Transfer Lab, Ground Floor, EME Building

Name of Experiments:

1.(a) Determination of Thermal Conductivity of Metals (Copper and Aluminum)
1.(b) Study of Thermal Contact Resistance
2. Study of Radiation Heat Transfer
3. Study of Boiling Heat Transfer
4. Study of Forced Convection Heat Transfer Over a Flat Plate

Instructions for Students

Necessary points of report writing:

- Objectives
- Apparatus (write specification like type, dimensions, range, material, etc.)
- Schematic Diagram of the Experimental Setup (label properly)
- Data and Calculation sheets
- Plotting graphs if any
- Sample Calculation for a particular observation
- Results and Discussions (Result and graph analysis, sources of error, means of improvement, question and answers if any)
- Conclusion

Important Instructions:

- ✓ Submit the reports in plastic spiral bound files of color specified for the group.
- ✓ You must come to the class before the starting time (for example 2.30 pm). No late attendance.
- ✓ You must submit all the reports of a group together before the end of a lab session.
- ✓ You must come to the class with prior preparation (study the lab sheet supplied, bring necessary graph papers, pages, calculator, reference books, etc.). **You must bring this lab instruction sheet during the sessional class**.
- ✓ Viva on the individual experiments will depend on the concerned teacher.
- ✓ **Copying another student's report will be severely dealt with.**

Experiment No. 1

a) Determination of Thermal Conductivity of Metals (Copper and Aluminum) and b) Study of Thermal Contact Resistance.

Introduction

When a temperature gradient exists in a body, heat transfer occurs from the high temperature region of the body to its low temperature region. According to Fourier's law of heat conduction, heat transfer through a homogeneous solid body is directly proportional to the area of the section at right angles to the direction of heat flow, and the temperature gradient in that direction. Mathematically, this can be written as,

$$Q \propto A\frac{dT}{dx}, \tag{1}$$

where,

Q = Heat flow rate by conduction through the material (W)

A = Surface area of the section at right angle to the direction of heat flow (m^2)

dx = Differential length of the specimen in the direction of heat flow (m)

dT = Temperature difference in the differential length of the specimen dx (°C or K)

dT/dx = Temperature gradient in the x-direction (K/m or °C/m)

The above equation can be written in the following form,

$$Q = -kA\frac{dT}{dx}, \tag{2}$$

where, the proportionality constant k is a transport property known as thermal conductivity (W/mK). It is a measure of the ability of a substance to conduct heat and provides the characteristics of the wall material through an indication of the rate at which energy is transferred by diffusion process. The value of thermal conductivity of a specimen depends on the physical structure of matter, atomic and molecular, its composition and temperature. The temperature gradient dT/dx in Eq. (2) is always negative along the direction of heat flow; because heat transfer occurs from the region of high temperature to that of low temperature of the body. Hence, a minus sign is inserted at the right hand side of Eq. (2) in order to make the heat flow rate Q to be positive.

Thermal conductivity is a thermo-physical property of the material, which is, in general, a function of both temperature (T) and location (s); i.e., $k = f(T, s)$. For isotropic materials, the value of k is the same in all directions, i.e., $k = f(T)$. However, for anisotropic materials such as wood, laminated materials, etc., the value of k will have a strong directional dependence.

For some materials over certain temperature range, the variation of thermal conductivity with temperature is almost negligible. The development of experimental approximations of boundary value problems is needed to measure the thermal conductivity. Direct measurement of thermal conductivity is based on the widely used ‘steady-state method’. It can provide high accuracy and simple data reduction, however, requires a relatively long time to reach steady state.

In thermal engineering, thermal contact resistance represents the resistance to the heat conduction between two solid bodies. When components are bolted or otherwise pressed together, a knowledge of the thermal performance of such joints are also needed. In these composite systems, the temperature drop across the interface between materials may be appreciable

Objectives

1. To plot the measured temperature versus distance curve, and hence, to determine the temperature gradient.
2. To determine thermal conductivity of the metal specimen.
3. To compare the calculated thermal conductivity of the metal specimen with its standard value.
4. To study the significance of thermal contact resistance.

Experimental Setup

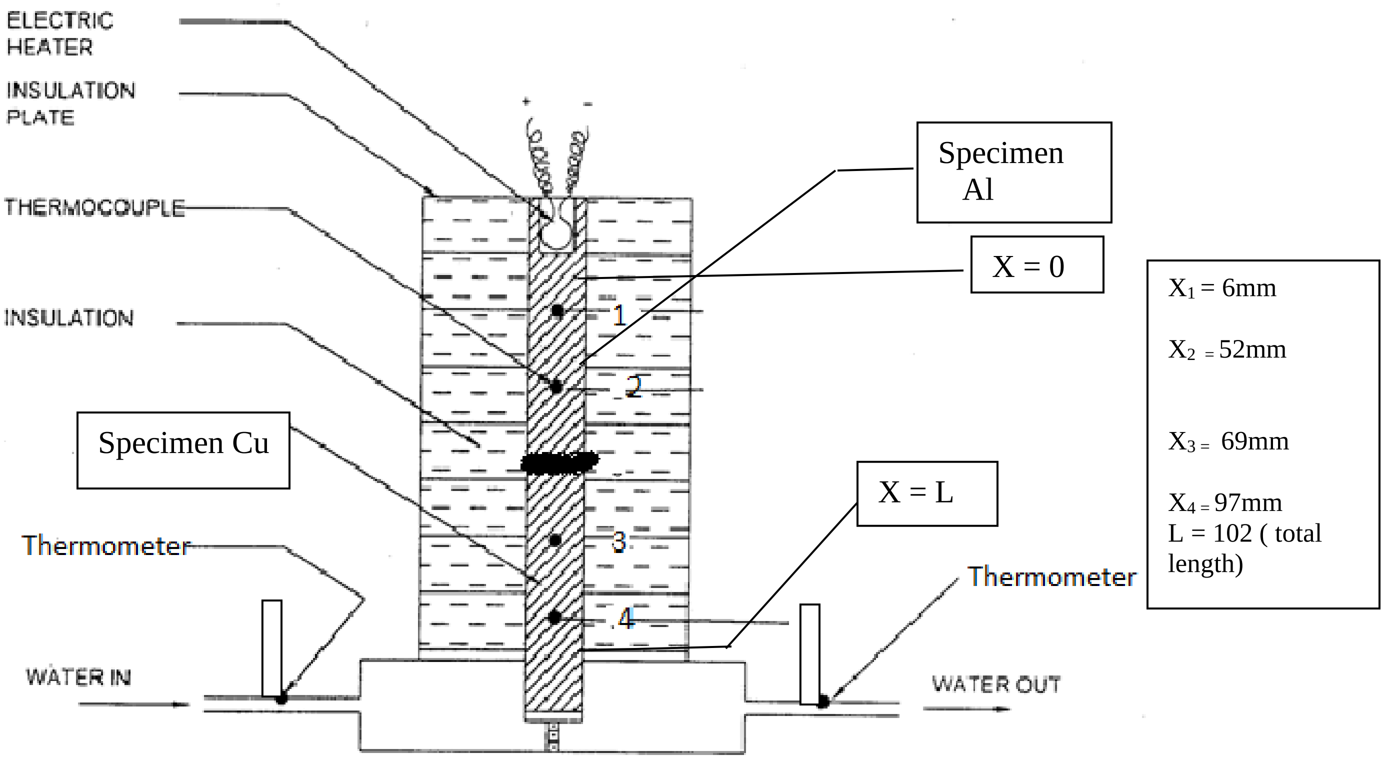

Fig 1. Schematic Diagram of the Experimental Setup.

A schematic diagram of the experimental setup is shown in Fig. 1. The apparatus consists of a vertical stack of specimens clamped between an electrically heated source at the top and a water cooled base, all contained within a Dewar vessel and furnished with a radiation shield and anticonvection baffle. The specimens are fitted with very small thermocouples at known distances apart and connected via a selector switch to a digital temperature readout. The heating current is supplied from a variable voltage power pack and displayed on a digital ammeter. The water cooled base is designed as a calorimeter to measure the heat flow and fitted with very accurate thermometers in the water circuit. Cooling water is supplied from the constant head water tank mounted above the Dewar vessel. A selection of cylindrical specimens of different materials is provided. A Copper specimen is given of 25mm diameter and 38mm long and a Aluminum specimen is given of 25mm diameter and 64 mm long both having cross sectional area of 4.9 x 10^{-4} m^2.

Experimental Procedures

1. The apparatus has been assembled with one short specimen (Cu) in the lower position and one long specimen (Al) in the upper position.

2. The clamping lever being held positioned on the front of the apparatus in the downward position the specimen is placed between the heater and calorimeter block, and clamped in the position by releasing the lever.
3. The thermocouple has been inserted in the sequence that they are wired to the support posts, into the holes provided in the sample. The potentiometer-measuring instrument has been connected to the terminals provided on front of the panel.
4. The Dewar vessel has been placed on position over the specimens.
5. The thermometers has been fitted into the special leak proof connections provided on the top of the calorimeter base (left hand water out, right hand water in), and the water pipes from the water supply to the header tank, the header tank to the inlet on the apparatus, the apparatus outlet connection to drain, via the spring valve provided and the header tank overflow to drain.
6. Turn on the water supply and adjust the flow at source to give a small regular overflow from the constant head tank to drain. Adjust the height of the header tank and the clip on the outlet hose to obtain a water flow through the apparatus of 0.5 to 1 cc/sec., whilst maintaining the overflow. During the experiment, if necessary, readjust the clip on the outlet hose to prevent the difference in temperature between the two mercury-in-glass thermometers from exceeding 10°C, whilst maintaining the small overflow to drain.
7. The supply voltage has been checked as indicated on the serial number label positioned on the back of the apparatus is correct. The apparatus has already been connected to a single phase AC supply point using the socket provided in the right hand side of the apparatus. The unit is then switched on.
8. The heat delivered to the sample is controlled by regulating the current supplied to the heater block using the control knob positioned on the front panel under the ammeter. Turn the knob fully clockwise so that the maximum current is supplied to the heater until temperature $T_{4,}$ as indicated by the thermocouple selection knob on the front panel approaches to 80°C and maintained at this temperature until the thermocouples indicate a stable output.

Governing Equations

The generalized three-dimensional heat conduction equation for a solid body with constant thermal conductivity in Cartesian coordinate can be expressed as:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{q'''}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t}, \qquad (3)$$

where,

T = Temperature distribution at any location in the body (°C or K)

x, y, z = Cartesian coordinates (m)

q''' = Internal heat generation rate per unit volume (W/m^3)

k = Thermal conductivity of the body (W/mK)

α = Thermal diffusivity [$= k/\rho C_p$] of the body (m^2/s)

t = Time (s)

ρ = Density of the body (kg/m^3)

C_p = Specific heat at constant pressure (J/kgK)

Assumptions

Following assumptions are made in order to simplify the generalized equation (3) applicable for performing the experiment:

1. The heat flow is one-dimensional, i.e., temperature varies along x-direction only. This is achieved by putting insulation around the circumferential surface area of the specimen.
2. Material is homogeneous and isotropic, and there is no internal heat generation.
3. Bounding surfaces of the experimental setup are isothermal in character.
4. The temperature gradient in the direction of heat flow is constant, i.e., the temperature profile is linear.
5. Heat conduction in steady state condition is achieved before final data is recorded.

Derivations of Temperature Distribution

Under the above assumptions, Eq. (3) can be reduced to the following form,

$$\frac{d^2T}{dx^2} = 0. \tag{4}$$

Integrating Eq. (4) twice with respect to x results,

$$T = c_1 x + c_2, \tag{5}$$

where, c_1 and c_2 are integration constants and can be determined from the appropriate boundary conditions. At steady state condition, the following boundary conditions are satisfied: at $x = 0$, $T = T_o$ and at $x = L$, $T = T_L$.

Applying these boundary conditions on Eq. (5), the following expression is obtained,

$$\frac{T - T_o}{T_L - T_o} = \frac{x}{L}, \tag{6}$$

where,

T = Temperature of the section at any distance x (°C)

T_o = Temperature of section at $x = 0$ (°C)

T_L = Temperature of section at $x = L$ (°C)
x = Any distance along the specimen (m)
L = Distance along the specimen between the sections at $x = 0$ and $x = L$ (m)

Equation (6) can be rearranged as follows for determination of the theoretical temperature distribution (T_t) along the specimen,

$$T_t = \frac{x}{L}\left(T_L - T_o\right) + T_o. \tag{7}$$

Determination of Heat Transfer Rate

Under steady state condition, the conduction heat transfer along the specimen is equal to the rate of heat carried away by the flowing water. Hence, the heat balance relation becomes,

$$Q_c = Q_w = m_w C_p \Delta T_w, \tag{8}$$

where,

Q_c = Conduction heat transfer along the specimen (W)
Q_w = Heat carried away by water (W)
m_w = Mass flow rate [= W_w/t] of water (kg/s)
W_w = Weight of collected water (kg)
t = time required for water collection (s)
C_p = Specific heat of water at constant pressure evaluated at T_w (J/kgK)
T_w = Mean/bulk temperature [= $(T_{wo} + T_{wi})/2$] of water (°C)
ΔT_w = Rise in temperature [= $T_{wo} - T_{wi}$] of flowing water (°C)
T_{wi} = Water temperature at inlet (°C)
T_{wo} = Water temperature at outlet (°C)

Determination of Thermal Conductivity

Using Eqs. (2) and (8), one can obtained the thermal conductivity of a metal as follows:

$$k = -m_w C_p \Delta T_w \Big/ A\frac{dT}{dx}, \tag{9}$$

where,

A = Cross-sectional area (= $\pi D^2/4$) of the cylindrical copper specimen (m^2)
D = Diameter of the cylindrical copper specimen (m)
dT/dx = Temperature gradient obtained from experimentally measured temperature (T_e) with varied distance (x) curve (W/m)

As per the manufacturing catalogue, the value of thermal conductivity for Aluminum (Al) is 172 W/mk, and for Copper (Cu) is 400 W/mk.

Discussion

1. Briefly explain the nature of experimental temperature distribution plot.
2. Is there any deviation in the values of thermal conductivity obtained in the two observations during the experiment? If yes, why?
3. Is there any discrepancy between the actual and the experimental values? If yes, why?
4. Discuss about thermal contact resistance from the measured temperature vs distance graph.
5. What happens to the thermal contact resistance if the spring pressure is increased? Also what will be the scenario if an absolute pressure is given

Conclusion

Write down the summary of key findings and observations as outlined in the objectives of this experiment.

Review Questions:

1. What do you mean by steady state condition and why is it necessary?
2. How can you maintain one-dimensional steady state heat conduction?
3. How does the value of thermal conductivity of copper vary with the change of its temperature?
4. How does the temperature gradient of a solid metal change with its thermal conductivity for a constant heat flux condition?
5. Does the conductivity of materials change with the change of water flow rate?

Data Sheet

Determination of Thermal Conductivity of Metals (Cu and Al)

Material of the cylinder is **copper and aluminum**

Diameter of the Cu cylinder, D_{Cu} = ………25................mm

Diameter of the Al cylinder, D_{Al} = ………25................mm

Thermocouple used:

Type:_______, Material: __________________________, Range: _______________________

Weight of the empty container, W_c = ……….. ....kg

Distance between consecutive thermocouple position, Δx = ……….......................mm

Length of the specimen considered for temperature measurement, L = ..102.............mm

Table 1: Collection of experimental data for different steady state conditions.

No. of Obs.	Distance, x (m)	Experimentally measured temperature (thermocouple reading), T_e (°C)	Water temperature		Weight of container with water, W_{wc} (kg)	Time of collection of water, t (s)
			Inlet T_{wi} (°C)	Outlet T_{wo} (°C)		
1	1					
	2					
	3					
	4					
2	1					
	2					
	3					
	4					

Obs 1 and 2 are for different flow rates of water.

Calculation Sheet

Table 2: Calculation of various parameters and thermal conductivity.

Calculated Parameters	Observation No.	
	1	2
dT/dx (°C/m or K/m) [slope of T_e versus x curve]		
Cross-sectional area of the specimen, A (m^2) [= $\pi D^2 / 4$]		
Weight of water collected, W_w (kg) [= $W_{wc} - W_c$]		
Mass flow rate of water, m_w (kg/s) [= W_w / t]		
Average water temperature, T_w (°C) [= $(T_{wo} + T_{wi}) / 2$]		
Specific heat of water at T_w, C_p (J/kgK) [use Appendix C]		
Temperature rise of water, ΔT_w (°C) [= $T_{wo} - T_{wi}$]		
Heat carried away by water, Q_w (W) [use Eq.(8)]		
Thermal conductivity of copper, k_{Cu} (W/mK) [use Eq.(9)]		
Thermal conductivity of aluminum, k_{Al} (W/mK) [use Eq.(9)]		
Error (%) [= $\left\| (k_s - k) / k_s \right\| \times 100$]		

Please bring 2 numbers of normal mm graph papers for this experiment.

Experiment No. 2
Study of Radiation Heat Transfer

Introduction

Heat transfer from a hot solid body to the surroundings takes place mainly by two processes: convection and radiation. Radiation is the heat transfer by the emission of electromagnetic waves, which carries energy away from the emitting object. For ordinary temperatures (less than red-hot), the radiation is in the infrared region of the electromagnetic spectrum. Heat loss by radiation does not depend on the nature of the surrounding fluid. Radiation may take place through perfect vacuum. However, heat transfer by convection depends on the conditions of the surrounding fluid.

If a hot object (electrically heated element) radiates energy at a temperature T_E to its cooler surroundings (inside a vessel) at a temperature of T_V, the net heat transfer by radiation can be calculated with the help of the Stefan-Boltzmann Law as given below:

$$Q_R = \varepsilon A \sigma \left(T_E^4 - T_V^4 \right), \tag{1}$$

where,

Q_R = Radiation heat transfer from the hot body (W)

T_E = Absolute temperature of the body (K)

T_V = Absolute temperature of the surrounding (K)

A = Exposed area of the body (m^2)

ε = Emissivity of the surface of the body

σ = Stefan-Boltzmann constant (= 5.669×10^{-8} W/m^{2}K^4)

Objectives

1. To determine temperature difference ($T_E - T_V$) at zero pressure by plotting ($T_E - T_V$) versus $H^{1/4}$ graph.
2. To determine the emissivity of the electrically heated element.
3. To calculate the radiation heat transfer.
4. To analyze the variation of radiation heat transfer with ($T_E - T_V$), and hence, to calculate radiation heat transfer coefficient.
5. To calculate the heat loss by convection.

Experimental Setup

A schematic of the experimental setup is shown in Fig. 1. The setup consists of a cylindrical pressure vessel (of diameter 450 mm and height 465 mm) containing a solid cylindrical element (6.35 mm in diameter and 160 mm in length) as a test specimen. The vessel may be charged with air or other gas at wide range of pressures. The element is suspended horizontally from the top cover-plate of the vessel and is finished with a matt black surface. The top cover plate, from which the element is suspended, is fixed with bolts. The solid element is heated internally by means of glass-insulated electric heater and its surface temperature is measured by a thermocouple at a certain point.

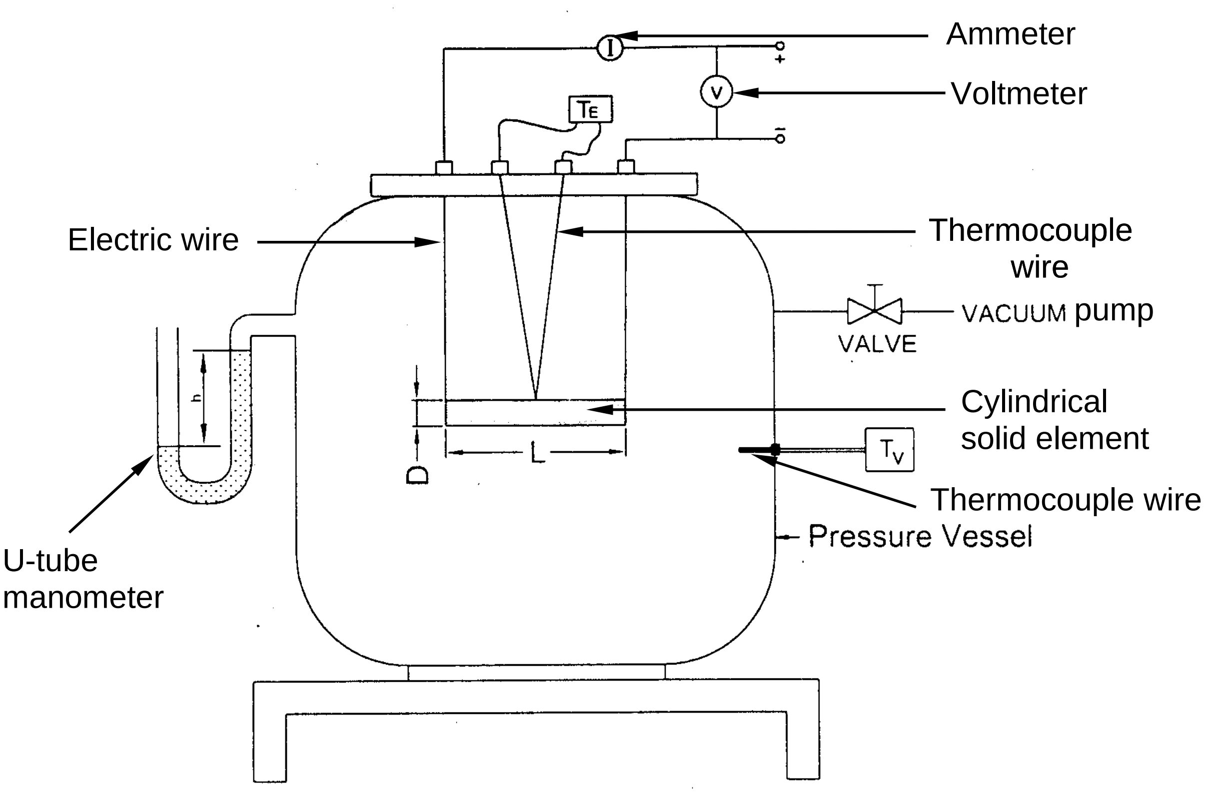

Fig 1. Schematic Diagram of the Experimental Setup.

The solid element is located at sufficiently remote from the walls of the vessel to get substantial free convection. The heat input to the element may range up to about 10W and the maximum working temperature is 200°C. With this small heat input, heating of the pressure vessel walls is considered to be negligible, and the temperature of the surrounding air/gas inside the vessel may be taken as equal to that of the inner wall of the vessel, which is measured by a thermocouple fitted to the vessel wall. The pressure vessel is connected by a copper tube and an isolating valve to an electrically driven vacuum pump (single stage, rotary type, capacity: 84 liters/min). The pressure in the vessel is determined by the mercury U-tube manometer. Other apparatus of the setup are barometer, voltmeter, ammeter, digital temperature indicator, rheostat, isolating control valve, selector switch, etc.

Experimental Procedures

1. The experiment will start with switching on the vacuum pump to evacuate the vessel until the pressure in the vessel is reduced to the minimum attainable absolute pressure.
2. Then the heater will be turned on adjusting the rheostat for a power input of about 5W.
3. Next, the isolating valve will be closed, and the vacuum pump will be shut off.
4. Now allow sufficient time in order to achieve the steady state condition, which will be indicated from the temperature readings of the thermocouples. When the temperature readings become almost constant with respect to time, the steady state is attained.
5. Note down the temperatures of the element and the vessel. Also, record the manometer deflection reading, voltmeter and ammeter readings.
6. Repeat the experiment at progressively higher pressures by letting the surrounding air to enter the vessel with the help of slowing opening the isolating control valve. The final reading will be taken at fully open condition of the control valve, when the pressure inside the vessel is equal to the atmospheric pressure.
7. In order to maintain constant heat input during each observation, check the voltmeter and the ammeter readings to ensure that they have remained approximately constant. This can be achieved by adjusting the rheostat if necessary.

Assumptions

Following assumptions are considered during the experiment:

1. Steady state condition is maintained before recording the final data.
2. Readings recorded by voltmeter and ammeter are kept constant throughout the experiment.
3. Power loss due to electrical resistance of the leads remains constant at 4 percent.

Governing Equations

Heat Supplied to the Element

Since a power loss of 4% of the product *VI* is considered as a consequence of the electrical resistance of the leads that supply power and support it, the expression of heat input to the solid element becomes,

$$Q_s = 0.96VI, \tag{2}$$

where,

Q_s = Supplied heat input to the element (W)
V = Voltmeter reading (V)
I = Ammeter reading (A)

Heat Loss by Conduction

A small part of the heat supplied to the element is lost through conduction along the leads and along the thermocouple wires. This loss is equivalent to the following approximation:

$$Q_K = 0.0017\left(T_E - T_V\right), \tag{3}$$

where,

Q_K = Conduction heat transfer along thermocouple wires and along the leads (W)
T_E = Temperature of the solid cylindrical element (°C or K)
T_V = Temperature of the vessel wall (°C or K)

Equivalent Surface Area

Due to the connection of the current carrying leads and the thermocouple leads to the solid cylindrical element, the surface area of the element including the end surfaces may be calculated using the following relation,

$$A = 1.02\left(\frac{\pi D^2}{2} + \pi DL\right), \tag{4}$$

where,

A = Total exposed surface area of the element (m^2)
D = Diameter of the cylindrical solid element (m)
L = Length of the cylindrical solid element (m)

Heat Loss by Convection

The surrounding fluid must take away the heat supplied to the element. Hence, heat balance relation is as follows:

$$Q_S = Q_C + Q_R + Q_K, \tag{5}$$

where, Q_C is convection heat loss by the surrounding fluid (W). Now, using (1), (2) and (3) in Eq.(5), one can get the expression of convection heat loss as follows:

$$Q_C = Q_S - Q_R - Q_K = 0.96VI - \varepsilon A\sigma\left(T_E^4 - T_V^4\right) - 0.0017\left(T_E - T_V\right). \tag{6}$$

Emissivity of the Element

If the pressure vessel can be maintained in perfect vacuum condition, there will be no heat loss by convection, and then Eq.(6) is reduced to as follows:

$$\begin{aligned} 0 &= 0.96VI - \varepsilon A\sigma\left(T_E^4 - T_V^4\right) - 0.0017\left(T_E - T_V\right) \\ \Rightarrow \varepsilon &= \frac{0.96VI - 0.0017\left(T_E - T_V\right)}{A\sigma\left(T_E^4 - T_V^4\right)}. \end{aligned} \tag{7}$$

In order to determine the emissivity of the element (ε) from Eq.(7), it is necessary to measure temperatures of the element and the vessel at zero pressure (perfect vacuum condition). However, due to limitation of experimental setup, it is not possible to attain perfect vacuum condition. Hence, an alternate procedure is followed for calculating the emissivity as mentioned in the following steps:

1. Plot temperature difference (T_E – T_V) versus $H^{1/4}$ graph (where, H is the absolute pressure in mmHg) and determine (T_E – T_V) at zero pressure from extrapolation.
2. Assume T_V at the lowest pressure reading as the value of T_V at zero pressure. Hence, calculate T_E at zero pressure from the extrapolation data of (T_E – T_V) at zero pressure as obtained in the previous step.
3. Finally, insert the values of T_E, T_V, V, I, σ, and A from Eq.(4) in Eq.(7) to calculate the emissivity of the element.

Radiation Heat Transfer Coefficient

Since Q_R versus ($T_E - T_V$) graph is almost linear, one can consider the following relationship analogous to Newton's law of cooling for convection heat transfer:

$$Q_R = h_R A\left(T_E - T_V\right), \tag{8}$$

where, h_R is the radiation heat transfer coefficient (W/m^{2}K) and can be obtained from the slope of the Q_R versus ($T_E - T_V$) curve as follows:

$$h_R = \frac{slope}{A}. \tag{9}$$

Discussions

1. Briefly explain the nature of ($T_E - T_V$) versus $H^{1/4}$ graph.
2. Discuss the effects of temperature difference on radiation heat transfer from Q_R versus ($T_E - T_V$) graph obtained from the experiment.
3. Discuss on the value of radiation heat transfer coefficient (h_R) obtained from the experiment.

4. Discuss the reasons for difference between the expected value and the calculated value of emissivity obtained from the experiment.

Conclusions

Write down the summary of key findings and observations as outlined in the objectives of this experiment.

Sample Quiz Questions:

1. What is emissivity and how does its value vary from black body to white body?
2. What are the limitations of calculating emissivity of the element observed during the experiment?
3. Mention the factors on which the rate of emission of radiation depends.

Data Sheet

Study of Radiation Heat Transfer

Diameter of the solid element, D = ……….................m

Length of the solid element, L = …..….....................m

Thermocouple used:

Type:_______, Material: _________________________, Range: ______________________

Barometric Pressure, P_{atm} = ………..................mm Hg

Table 1: Collection of experimental data for different observations.

No. of Observation	Supply Voltage, V (V)	Supply Current, I (A)	U-tube Manometer reading, h (mmHg)	Element temperature, T_E (°C)	Vessel temperature, T_V (°C)
1					
2					
3					
4					
5					
6					
7					
8					

Calculation Sheet

Table 2: Calculated various parameters and emissivity of the element.

Calculated Parameters	**Number of Observations**							
	1	2	3	4	5	6	7	8
T_E (K)								
T_V (K)								
$T_E - T_V$ (K)								
$H = P_{atm} - h$ (mm Hg)								
$H^{1/4}$ (mm Hg)$^{1/4}$								
A (m^2) [use Eq.(4)]								
ε [use Eq.(7)]								
Q_S (W) [use Eq.(2)]								
Q_K (W) [use Eq.(3)]								
Q_R (W) [use Eq.(1)]								
Q_C (W) [use Eq.(6)]								
h_R (W/m^{2}K) [use Eq.(9)]								

Please bring two mm graph papers for this experiment.

Experiment No. 3
Study of Boiling Heat Transfer

Introduction

Boiling is a phase change complex convection process with bubble formation that transfers heat, mass and momentum by utilizing buoyancy force acting on a fluid contained in a vessel. Unlike evaporation, boiling takes place in a solid–liquid interface when the solid surface temperature exceeds the saturation temperature of the liquid corresponding to a particular working pressure. Boiling is one of the most widely studied fields of heat transfer because of its application in mechanical, electrical appliances, in electronics cooling, power generation, extracting geothermal energy and so on.

Boiling can be classified as pool boiling and flow boiling depending on the presence of bulk fluid motion. In this experiment, pool boiling heat transfer method is observed. In pool boiling any motion of the fluid is only due to the motion of bulk fluid because of natural convection or continuous bubble formation and collapse. As a form of convection heat transfer, the boiling heat flux from a solid surface to the fluid is expressed from Newton's law of cooling as,

$$q_{boiling} = h(T_s - T_{sat}) = h\Delta T_{excess}, \tag{1}$$

where, *h* is the boiling heat transfer coefficient.

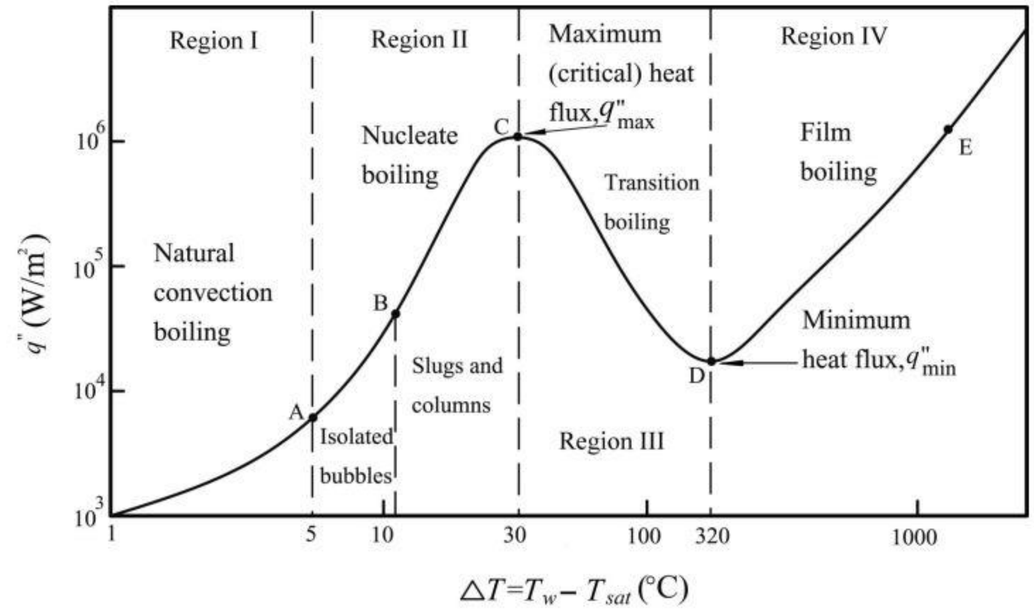

Figure 1. Boiling curve for water.

An important characteristic of a fluid-surface combination is the critical heat flux. This is the limiting value of heat flux when the rate of evaporation reaches such high values that it becomes difficult for liquid to rewet the heater surface. This is a key design parameter for heat transfer equipment that utilizes boiling.

To observe the critical heat flux, we need to construct a boiling curve which shows variation of boiling heat flux with excess temperature. As an example, boiling curve for water is given in Figure 1. In this experiment, we shall reconstruct such curve for nucleate boiling zone.

Objectives:

1. To plot the boiling curve of the heater-liquid combination at a constant pressure.
2. To find the critical heat flux.
3. To calculate boiling heat transfer coefficient, *h* and plot it against wall superheat.
4. To estimate the overall heat transfer coefficient, *U* associated with the water.
5. To estimate the heat loss to the surroundings.

Experimental Setup

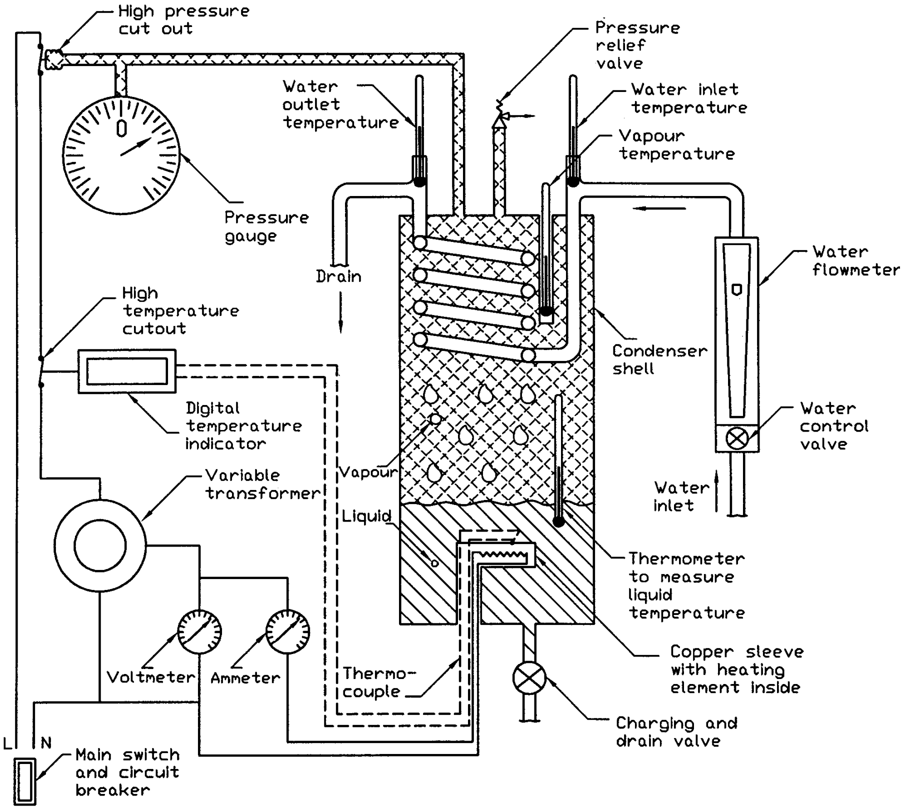

Figure 2**:** A Schematic of the Setup for Boiling Study

In this study, a cylindrical element to be heated electrically is placed in a vessel containing a boiling liquid. A schematic of the experimental setup is shown in Figure 2. The setup consists of a cylindrical pressure vessel containing the element and the boiling liquid. The element, protruded from the lower circumference, will be heated by electricity that will be controlled by a variable transformer. A thermocouple is attached to the element surface to measure the surface temperature.

The boiling liquid is Methylene chloride and its temperature will be measure by a thermometer submerged in the liquid pool. The vessel is equipped with a pressure gauge to monitor the pressure. A water cooling system is present to maintain a constant working pressure.

Experimental Procedures

1. The experiment will be started by switching on the setup to supply heat to the element and to enlighten the system as well.
2. A reasonable time will be allowed to raise the pressure of the vessel to a certain level.
3. To keep the pressure constant, the cooling water will be properly circulated through the condenser.
4. The pressure becomes constant when the rate of vapor formation equals to the rate of condensation.
5. At this stage, note down the electrical power supply to the element.
6. Record the temperature of the element surface and the temperature of the boiling liquid.
7. Write down also the water inlet temperature and water outlet temperature.
8. The experiment will have to be repeated at progressively higher heat inputs to the element and keeping the working pressure constant.

Governing Equations

Heat Supplied to the Element

The expression of heat input to the solid element while neglecting the power losses in lead wires is

$$Q_s = VI, \tag{2}$$

where,

Q_s = Supplied heat input to the element (W)

V = Voltmeter reading (V)

I = Ammeter reading (A)

Applied Heat Flux

Heat flux is calculated from Eq. (1) divided by A as given follows:

$$q = \frac{Q_s}{A}, \tag{3}$$

where,

q = Applied heat flux (W/m^2)

A = Effective heat transfer area of the element (= 1.3×10^{-3} m^2)

Wall Superheat or Excess Temperature

Wall superheat or excess temperature is defined as follows:

$$\Delta T_{sat} = T_w - T_s, \tag{4}$$

where,

ΔT_{sat} = Wall superheat (°C or K)

T_w = Surface temperature of the element (°C or K)

T_s = Saturation temperature of the liquid (°C or K)

Boiling Heat Transfer Coefficient

Boiling heat transfer coefficient can be calculated using Eqs. (3) and (4) as follows:

$$h = \frac{q}{\Delta T_{sat}}, \tag{5}$$

where,

h = Boiling heat transfer coefficient (W/mK)

Overall Heat Transfer Coefficient

Heat transfer during condensation can be calculated using the following relation:

$$Q_c = UA_c\Delta T_m, \tag{6}$$

where,

Q_c = Heat transfer during condensation (W)

A_c = condenser area exposed to cooling water (= 0.032 m^2)

ΔT_m = logarithmic mean temperature difference (LMTD) (°C or K)

U = Overall heat transfer coefficient (W/mK)

Q_c and ΔT_m can be calculated using the following relations:

$$Q_c = \dot{m}C_p\left(T_{wo} - T_{wi}\right), \tag{7}$$

$$\Delta T_m = \frac{(T_{wi} - T_s) - (T_{wo} - T_s)}{ln\left(\frac{T_{wi} - T_s}{T_{wo} - T_s}\right)}, \tag{8}$$

where,

$\dot{m}$ = mass flow rate of water (kg/s)

C_p = Specific heat of cooling water (= 4.18 kJ/kgK)

T_{wi} = Water inlet temperature (°C or K)

T_{wo} = Water outlet temperature (°C or K)

Discussions

1. Briefly explain the boiling curve obtained in the experiment and compare with one mentioned in any heat transfer books.
2. Comment on the critical heat flux (CHF).
3. Comment on the boiling heat transfer coefficient (h).

Conclusions

Write down the summary of key findings and observations as outlined in the objectives of this experiment.

Sample Quiz Questions:

1. How the boiling heat transfer coefficient is defined?
2. How does condensation occur during the experiment?
3. What is the role of film in the boiling heat transfer?

Data and Calculation Sheet

Study of Boiling Heat Transfer

Data at pressure *P* = __________ Pa		**Number of Observations**								
		1	2	3	4	5	6	7	8	9
To be Measured	Voltage, V (volt)									
	Current, I (amp)									
	Element Temperature, T_w (°C)									
	Liquid Temperature, T_s (°C)									
	Water Inlet Temperature, T_{wi} (°C)									
	Water Outlet Temperature, T_{wo} (°C)									
	Water Flow Rate, m/t (kg/s)									
To be Calculated	Supplied heat input, Q_s (W)									
	Heat flux, q (W/m^2)									
	Wall superheat, ΔT_{sat} (°C)									
	Boiling heat transfer coefficient, h (W/m^{2}K)									
	Condensation heat transfer, Q_c (W)									
	LMTD, ΔT_m (°C)									
	Overall heat transfer coefficient, U (W/m^{2}K)									

Please bring one log-log graph paper for this experiment.

Experiment No. 4
Study of Forced Convection Heat Transfer Over a Flat Plate

Introduction

When fluid flows over a solid body or inside a channel, while temperatures of the fluid and the solid surface are different, heat transfer between the fluid and the solid surface takes place as a consequence of the motion of the fluid relative to the surface; this mechanism of heat transfer is called convection. If the fluid motion is artificially induced, say with a pump or a fan that forces the fluid flow over the surface, the heat transfer is said to be by forced convection. If the fluid motion is set up by buoyancy effects resulting from density difference caused by temperature difference in the fluid, the heat transfer is said to be by free (or natural) convection.

There are numerous important engineering applications in which, heat transfer for flow over bodies such as a flat plate, a sphere, a circular tube or a tube bundle are needed.

Depending on the fluid flows over/through the geometry, forced convection can be divided into internal forced convection (flow is confined within a channel, example: flow inside a heated tube) or external forced convection (flow occurs over a surface, example: flow over a flat plate). Fluid flow can also be laminar, transition or turbulent in nature.

When a fluid flows along a surface, irrespective of whether the flow is laminar or turbulent, the particles near the surface are slowed down by virtue of viscous forces. The fluid particles adjacent to the surface stick to it and have zero velocity relative to the boundary (no-slip condition). Other fluid particles attempting to slide over them are retarded because of an interaction between faster and slower moving fluid, a phenomenon that gives rise to shearing forces. The effects of the viscous forces originating at the boundary extend into the body of the fluid, but a short distance from the surface until the velocity of the fluid particles approaches that of the undisturbed free stream. The layer, which separates the fluid contained within the region of the substantial velocity change, is called the hydrodynamic boundary layer. The thickness of this boundary layer has been defined as the distance from the surface at which the local velocity reaches 99% of the external velocity (i.e., free steam velocity). The thermal boundary layer also develops along with the hydrodynamic boundary layer due to temperature difference between the surface and the flowing fluid, and the thickness of this boundary layer is defined as the distance from the surface at which the temperature difference of the fluid from the surface reaches 99% of the temperature difference between the surface and the free steam value. The relative positions of the hydrodynamic and the thermal boundary layer depend on the value of the Prandtl number. These two boundary layers will coincide with each other, if the value of the Prandtl number is equal to unity. On the other hand, the thermal boundary layer becomes thicker than the hydrodynamic boundary layer when the Prandtl number reaches below unity. Many research have been conducted on forced convection over flat plates and many empirical correlations were proposed depending on the flow and the thermal conditions.

Objectives

1. To determine Reynolds number and the critical length of the plate, and to identify the type of flow over the plate.
2. To calculate the average convection heat transfer coefficient from thermal balance relation (experimental results) and compare those with the theoretical results (empirical correlations).
3. To plot surface temperature distribution along the plate for different heat inputs.
4. To plot the variation of average convection heat transfer coefficient (both theoretical and experimental) with the heat input.

Experimental Setup

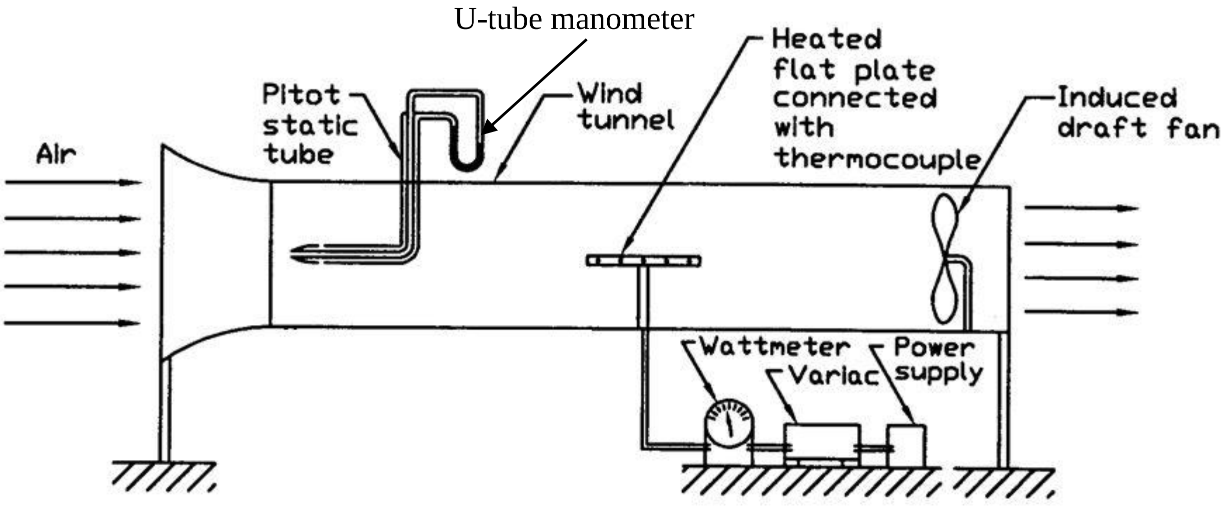

Fig 1. Schematic Diagram of the Experimental Setup.

A schematic diagram of the experimental setup is shown in Fig. 1. The main frame of the experimental setup consists of a wind tunnel fitted with an Induced Draft (ID) fan (type-aerofoil, rpm - 2800) to create forced flow through the tunnel, and a horizontal flat plate. The length and the width of the plate are 50.80 and 15.94 cm, respectively and it is placed at the middle of the cross-section of the wind tunnel using a support stand. The flat plate is constructed in such a way that there is a sandwich like heating coil placed inside the plate. As a result, the top and the bottom surfaces of the plate are heated uniformly by the heating coil. Insulation is applied on the surrounding sides of the plate in order to make the heat flow one-dimensional.

At the entry of the wind tunnel, a pitot-static tube is placed along the air-flow direction, which is connected to a U-tube manometer filled with water. Heat input is regulated by a variac and is measured by a wattmeter. Thermocouple wires are attached to the heated surface of the plate at five different locations along the plate. Temperature reading from the thermocouples can be controlled using a multipoint selector (rotary type) switch and can be recorded from a digital temperature indicator. Other apparatus of the setup is wall-mounted thermometer to measure surrounding air temperature of the room.

Experimental Procedures

1. Turn on the wind tunnel by switching on the ID fan, and ensure power supply to the heating coil of the flat plate.
2. Adjust the variac in order to set the desired power input to the electric heater.
3. Observe the temperature readings of the thermocouples and wait for steady state condition. When the steady state is reached, the temperature readings will not change significantly.
4. Once the steady state condition is attained, record the temperature reading of the thermocouples from the digital temperature indicator for all five locations of the plate surface.
5. Record manometer deflection from U-tube manometer, room temperature from wall-mounted thermometer and the supplied power input from wattmeter.
6. Repeat steps 2-4 for different power inputs.

Assumptions

Following assumptions are considered during the experiment:

1. Steady state is attained before recording the final data.

2. Loss of heat by conduction through thermocouple wires and the support stand for the flat plate is neglected.
3. Heat loss through the side ends of the plate has been ignored.
4. Flow is considered as incompressible and uniform over the flat plate.
5. Both hydrodynamic and thermal boundary layers are considered to be developed over the top and the bottom surfaces of the plate thoroughly without being distorted by the support stand.

Governing Equations

Air Velocity in the Wind Tunnel

We know, $P = \rho g h$

Hence, for a certain constant pressure, $\rho_{air} h_{air} = \rho_{water} h_{water}$

$$h_{air} = \frac{\rho_{water} h_{water}}{\rho_{air}}, \tag{1}$$

where,

h_{air} = Equivalent deflection of air in manometer (m)
h_{water} = Deflection of water in manometer (m)
ρ_{air} = Density of air at room temperature (kg/m^3)
ρ_{water} = Density of water at room temperature (kg/m^3)

Now, the velocity of air (V) in m/s flowing through the wind tunnel is,

$$V = \sqrt{2gh_{air}}. \tag{2}$$

Governing Parameters for External Forced Convection Heat Transfer

Table 1: List of governing parameters for external forced convection heat transfer.

Parameters	Definition	Expression	Limiting Value
Reynolds Number	$\frac{\text{Inertia Force}}{\text{Viscous Force}}$	$\mathrm{Re}_L = \frac{VL}{\nu}$	Re_{cr} = 5 × 10^5 for flow over a flat plate
Prandtl Number	$\frac{\text{Momentum Diffusivity}}{\text{Thermal Diffusivity}}$	$Pr = \frac{\nu}{\alpha}$	$Pr \approx 0.7$ for air and $Pr \approx 4.1 \sim 6.5$ for water (20° ~ 40°C)
Nusselt Number	$\frac{\text{Convection}}{\text{Conduction}}$	$Nu_L = \frac{hL}{k}$	$Nu = 1$ for pure conduction $Nu > 1$ for convection

Here, ν, α, k are kinematic viscosity (m^2/s), thermal diffusivity (m^2/s) and thermal conductivity (W/mK) of fluid, respectively, L is the length of the plate (m) and h is the convection heat transfer coefficient (W/m^{2}K), Re_{cr} is the critical Reynolds number.

Thermo-physical properties of the fluid should be taken at film temperature,

$$T_f = \frac{\left(T_s + T_\infty\right)}{2}, \qquad T_s = \frac{1}{n}\sum_{i=1,2\ldots n} T_{si} \tag{3}$$

where, T_s is the average surface temperature (°C or K) and T_∞ is the ambient temperature of flowing fluid (°C or K).

Critical Length of the Plate

It is the length up to which the flow is laminar. The ratio of the critical length (x_{cr}) to the length of the plate (L) can be calculated from the following relation:

$$\frac{x_{cr}}{L} = \frac{Re_{cr}}{Re_L} = \frac{5\times10^5}{Re_L}. \tag{4}$$

Using the ratio of x_{cr}/L and the value of Re_L, one can identify the type of flow over a flat plate as listed in Table 2.

Empirical Correlations of Average Nusselt Number

Table 2: List of empirical correlations for forced convection over a flat plate.

Type of flow	Restrictions	Thermal Boundary Conditions	
		Isothermal (T_w = constant)	Isoflux (q_w = constant)
Laminar	$\mathrm{Re_L} < 5 \times 10^5$ $0.6 < \Pr < 50$ $x_{cr}/L > 0.7$	$\mathrm{Nu}_L = 0.664\mathrm{Re}_L^{1/2}\Pr^{1/3}$	$\mathrm{Nu}_L = 0.680\mathrm{Re}_L^{1/2}\Pr^{1/3}$
Turbulent	$5 \times 10^5 \le \mathrm{Re_L} \le 10^7$ $0.6 \le \Pr \le 60$ $x_{cr}/L < 0.3$	$\mathrm{Nu}_L = 0.037\mathrm{Re}_L^{4/5}\Pr^{1/3}$	$\mathrm{Nu}_L = 0.037\mathrm{Re}_L^{4/5}\Pr^{1/3}$
Partly Laminar, Partly Turbulent	$5 \times 10^5 \le \mathrm{Re_L} \le 10^7$ $0.6 \le \Pr \le 60$ $0.3 \le x_{cr}/L \le 0.7$	$\mathrm{Nu}_L = \left(0.037\mathrm{Re}_L^{4/5} - 871\right)\Pr^{1/3}$	$\mathrm{Nu}_L = \frac{0.037\mathrm{Re}_L^{4/5}\Pr^{1/3}}{1+12.33\times10^6\,\mathrm{Re}_L^{-6/5}}$

Here, T_w is the wall temperature of the flat plate and q_w is the wall heat flux applied on the flat plate.

Once the average Nusselt number is calculated from the appropriate correlation listed in Table 2, the <u>theoretical</u> average convection heat transfer coefficient is obtained as follows:

$$h = \frac{Nu_L k}{L}. \tag{5}$$

Thermal Balance Relation

The fluid must take away the heat supplied to the plate under steady state condition. Hence, heat balance relation is as follows:

$$Q_s = Q_C + Q_R + Q_K, \tag{6}$$

where, Q_s – Heat Supplied to the plate (W)

Q_C – Convection Heat Transfer by the flowing fluid (W)

Q_R – Radiation Heat Transfer by the flowing fluid (W)

Q_K – Conduction Heat Transfer through thermocouple wires and support stand for the plate (neglected) (W)

Now, from Newton's law of cooling,

$$Q_C = hA\left(T_s - T_\infty\right) \tag{7}$$

where,

h = Average convection heat transfer coefficient (W/m^{2}K)

A = Total area (= 2 × L × W) of the top and the bottom surfaces of the plate (m^2)

W = Width of the plate (m)

T_s = Average surface temperature of the plate (°C or K)

T_∞ = Ambient temperature of the flowing fluid (°C or K)

Similarly, from Stefan-Boltzmann's law,

$$Q_R = \sigma\varepsilon A\left(T_s^4 - T_\infty^4\right), \tag{8}$$

where,

T_s = Average surface temperature of the plate (K)

T_∞ = Ambient temperature of the flowing fluid (K)

σ = Stefan-Boltzmann constant (= 5.669×10^{-8} W/m^{2}K^4)

ε = Emissivity of the heated plate

Then, using (7) and (8) in Eq.(6), one can get the expression of average convection heat transfer coefficient (experimental result) as follows:

$$\begin{aligned} h &= \frac{Q_s - \varepsilon\sigma A\left(T_s^4 - T_\infty^4\right)}{A\left(T_s - T_\infty\right)} \\ \Rightarrow h &= \frac{Q_s - 2LW\varepsilon\sigma\left(T_s^4 - T_\infty^4\right)}{2LW\left(T_s - T_\infty\right)}. \end{aligned} \tag{9}$$

Discussions

4. Discuss the benefits of calculating average convective heat transfer coefficient over local convective heat transfer coefficient.
5. Discuss the nature temperature profile of the flat plate along its length.
6. Discuss the effect of variation of power input on average convection heat transfer coefficient.
7. Discuss the reasons for difference between the experimental and the theoretical values of the convective heat transfer coefficient.
8. Show the development of typical hydrodynamic and thermal boundary layers over the flat plate that you expect from your experimental results.

Conclusions

Write down the summary of key findings and observations as outlined in the objectives of this experiment.

Sample Quiz Questions:

4. What is the function of pitot-static tube?
5. What are the advantages of using induced draft (ID) fan over forced draft (FD) fan?
6. What will happen when water is flowing over the heated flat plate instead of air? Explain with the concept of hydrodynamic and thermal boundary layers.
7. What are the physical significances of Reynolds number, Prandtl number and Nusselt number?
8. For forced convection heat transfer, $Nu = f(Re, Pr)$. With this correlation, explain the possible ways to enhance the convection heat transfer coefficient.

Data Sheet

Study of Forced Convection Heat Transfer Over a Flat Plate

Material of the plate is **copper**

Length of copper plate, L = ………..........................m

Width of the copper plate, W = ……...........................m

Thermocouple used:

Type:_______, Material: __________________________, Range: ______________________

Ambient (room) temperature of flowing fluid, T_∞ = ……….............°C

Density of air at T_∞, ρ_{air} = ………........... kg/m^3 [use Appendix B]

Density of water at T_∞, ρ_{water} = ……….............kg/m^3 [use Appendix C]

Emissivity of copper plate, ε = 0.78

Table 1: Collection of experimental data for different observations.

No. of Obs.	Power Input, Q_{in} (W)	Thermocouple reading (°C)					Inlet Air Temp, T_∞ (°C)	Manometer deflection of water, h_{water} (m)
		x_1 (m) ………	x_2 (m) ………	x_3 (m) ………	x_4 (m) ………	x_5 (m) ………		
		No.1 T_{s1}	No.2 T_{s2}	No.3 T_{s3}	No.4 T_{s4}	No.5 T_{s5}		
1								
2								
3								

Calculation Sheet

Table 2: Thermo-physical properties of air at different film temperatures.

Properties of air	Observation No. 1	Observation No. 2	Observation No. 3
	Film temperature, T_f = ……..........K	Film temperature, T_f = ……..........K	Film temperature, T_f = ……..........K
k (W/mK)			
α (m^2/s)			
v (m^2/s)			

Calculated Result

Table 3: Calculated governing parameters and convection heat transfer coefficient.

Observation No.	Power Input Q_s (W)	Air Velocity V (m/s)	Governing Parameters			Average Convection Heat Transfer Coefficient, h (W/m^2K)		
			Re_L	Pr	$\frac{x_{cr}}{L}$	Empirical Correlation		Thermal Balance
						Isothermal	Isoflux	Experimental
1								
2								
3								

Please bring two normal mm graph papers for this experiment.

Appendix A

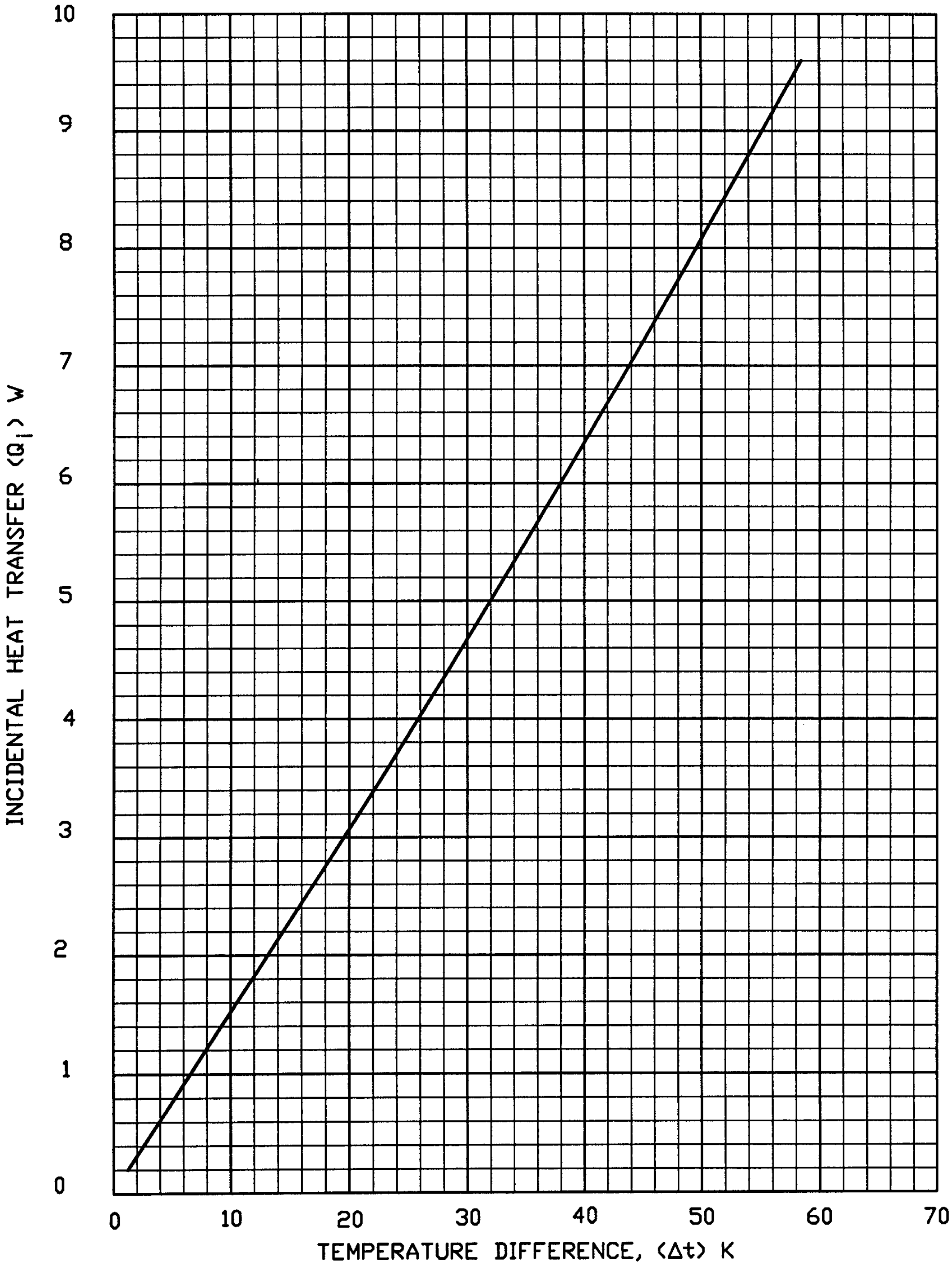

Figure: A. Calibration Curve for Incidental Heat Transfer with Temperature Difference.

Appendix B

Thermodynamic Properties of Dry Air at Atmospheric Pressure

Temperature T			Density ρ kg/m^3	Coefficient of thermal expansion $\beta \times 10^3$ 1/K	Specific heat c_p J/kg K	Thermal conductivity k W/m K	Thermal diffusivity $\alpha \times 10^6$ m^2/s	Absolute viscosity $\mu \times 10^6$ Ns/m^2	Kinematic viscosity $\nu \times 10^6$ m^2/s
°F	K	°C							
32	273	0	1.252	3.66	1011	0.0237	19.2	17.456	13.9
68	293	20	1.164	3.41	1012	0.0251	22.0	18.240	15.7
104	313	40	1.092	3.19	1014	0.0265	24.8	10.123	17.6
140	333	60	1.025	3.00	1017	0.0279	27.6	10.907	19.4
176	353	80	0.968	2.83	1019	0.0293	30.6	20.790	21.5
212	373	100	0.916	2.68	1022	0.0307	33.6	21.673	23.6
392	473	200	0.723	2.11	1035	0.0370	49.7	25.693	35.5

Appendix C

Thermodynamic Properties of Water at Saturation Pressure

Temperature T			Density ρ kg/m^3	Specific heat c_p J/kg K	Thermal conductivity k W/m K	Thermal diffusivity $\alpha \times 10^6$ m^2/s	Absolute viscosity $\mu \times 10^6$ Ns/m^2	Kinematic viscosity $\nu \times 10^6$ m^2/s
°F	K	°C						
32	273	0	999.9	4226	0.558	0.131	1794	1.789
41	278	5	1000	4206	0.568	0.135	1535	1.535
50	283	10	999.7	4195	0.577	0.137	1296	1.300
59	288	15	999.1	4187	0.585	0.141	1136	1.146
68	293	20	998.2	4182	0.597	0.143	993	1.006
77	298	25	997.1	4178	0.606	0.146	880.6	0.884
86	303	30	995.7	4176	0.615	0.149	792.4	0.805
95	308	35	994.1	4175	0.624	0.150	719.8	0.725
104	313	40	992.2	4175	0.633	0.151	658.0	0.658
113	318	45	990.2	4176	0.640	0.155	605.1	0.611
122	323	50	988.1	4178	0.646	0.157	555.1	0.556

Example : Here, if $\mu \times 10^6 = 1.781$, then $\mu = 1.781 \times 10^{-6}\ N\,s/m^2$

Again if $\nu \times 10 = 1.785$, then $\nu = 1.785 \times 10^{-1}\ m^2/s$