The University of Jordan
School of Engineering
Mechanical Engineering Department

Heat Transfer Lab. (0904446)

The University of Jordan
School of Engineering Department of Mechanical Engineering

Insert Your Course Name Here
(Course #)
Term Project/Home Work/Short or Full Lab Report …..

School of Engineering
The University of Jordan, Amman-Jordan

Project/Experiment/Report Title Goes here

by

FirstName Initial LastName (ID #)
FirstName Initial LastName (ID #)

Section #:

Month 9999

Abstract

An abstract consists of answering three basic questions:

1. What was done?
2. How it is was done? and
3. What were the basic findings and conclusions?

- ✓ Abstract should be written in passive voice.
- ✓ Abstract should not exceed 200 words.
- ✓ It should be written in three separate paragraphs.
- ✓ This section and all the coming sections should be written in Font 12, Times New Roman with regular style and single line spacing.
- ✓ This page should contain the abstract ONLY and numbered using the Roman Style (i.e. I, ii, iii …etc)
- ✓ It should be written in passive voice.

(i)

Nomenclature

The nomenclature defines the parameters, symbols and acronyms used in the report. Standardized symbols should be used whenever possible.

- The units should be added to the nomenclature.
- The parameters should be arranged alphabetically.
- This section should be written in separate page(s).

A	Area	[m2]
P	Pressure	[N/m2]
Re	Reynolds Number	[ND]

Subscript

f	Liquid
s	surface

Greek Symbols

μ	Dynamic viscosity	[N-s/m2]
α	Angle of attack	[deg]

(ii)

Objective

The objective(s) should be written based on the instructor's explanation of the experiment.
DO NOT copy from laboratory manual.

Experimental Setup and Procedure

This section should contain the working principle of the setup used in the experiment.
It should contain a clear image of the setup with the main parts identified in suitable manner.
The figure's caption (name) should be written below it.

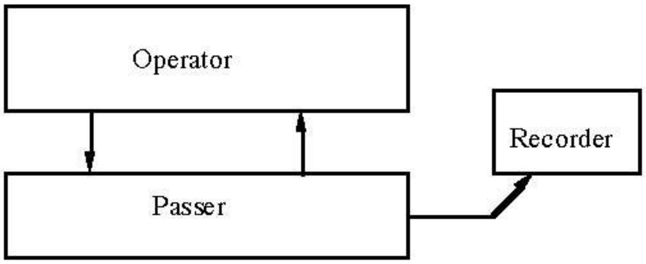


Figure (1): Some numbers from the result of the experiment on nothing

- ✓ Never start any paragraph with figure, table, graph …etc. You should allways write few introductry lines (e.g. This section discusses the setup used in conducting this experiment. The setup is shown below in Figure (1)).
- ✓ Define the major components of the setup.
- ✓ Explain briefly how it works.
- ✓ Finally, explain with your own words (DO NOT COPY FROM USER MANUAL) how you conducted the experiment.
- ✓ As of this page onwards, the page numbering should start using the 1-100 Arabic numbers.

Data Observation

The data observed are divide into two main items.

Given data

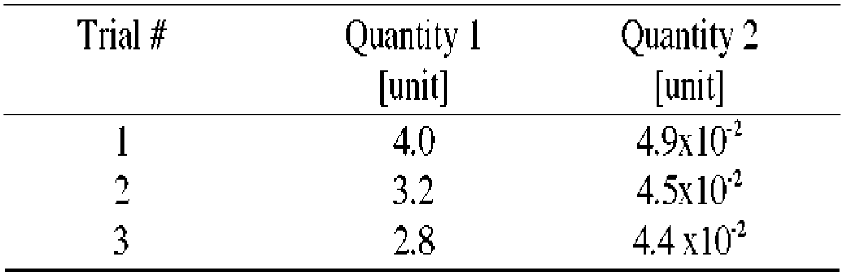
- o This includes the constants that were not changed in the experiment e.g atmspheric conditions, certain setup dimensions (if not changed) e,g diameter, length ….etc.
- o As for the material's properties e,g, density, viscosity, thermal conductivity …etc these should be mentioned with the reference wherefrom they were copied cited.

Observed data

- ✓ The data that were taken from the setup ONLY should be mentioned in the table.
- ✓ Table columns should be writen with units and without abbreviations.
- ✓ The table caption should be mentioned on top of the table.
- ✓ Do not add any calculated data in the table.

(1)

Table (1): The observed data



Trial #	Quantity 1 [unit]	Quantity 2 [unit]
1	4.0	$4.9 \mathrm{x} 10^{-2}$
2	3.2	$4.5 \mathrm{x} 10^{-2}$
3	2.8	$4.4 \mathrm{x} 10^{-2}$

If the experiment consists of several parts, put the tables with each case defined before that.

For example :

Case (I) : Partially submerged torous

Inset the data observed table for this case below.

Case (II) : Totally submerged torous

Inset the data observed table for this case below.

Sample calculations

In this section you are required to provide with proper explanation (NOT only use equations and substitute numbers) the steps for your calculations.

You should state which data you are taking for sample calculations.

If the calculations involve theoretical and experimental values for comparison, you should calculate the percentage error in the experimental value.

Uncertainty analysis

This is extremely important part that tells the accuracy of the test procedure (NOT ONLY in the final value).

This can be extremely helpful if one wishes to find the main factor responsible for the error.

There are many methods suggested for this section :

1) Uncertainty propagation (you can use suitable software for that as you have been taught)
2) Limiting and relative limiting errors using equations.
3) Limiting and relative limiting errors using maximum/minimum method.

Finally a summery of the calculations should be added in separate table(s) with errors and uncertainity calculations.

Results and discussion

Present your results in a logical sequence, highlighting what is important and how the data you obtained have been analyzed to provide the results you discuss.

- You should discuss what you infer from the data.
- You need to adopt a critical approach.
- For example, discuss the relative confidence you have in different aspects of the measurements.
- Make sure that all diagrams, graphs etc. are properly labeled and have a caption.

(2)

- A *neat hand drawn diagram is preferable to a poorly made computer diagram*, or a poor resolution image copied from the web.

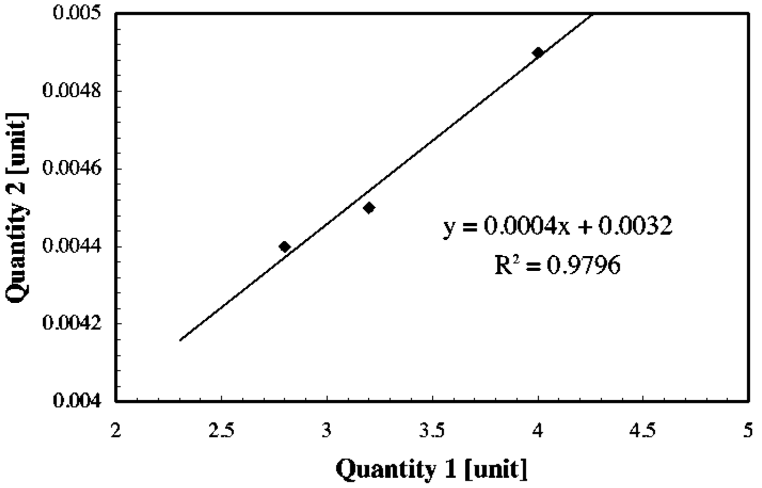


Figure 2 Quantity 1 versus Quantity 2 ✗

Figure (2) : Variation of Quantity (2) with Quantity (1)

- Graphs should be clear, informative, with proper legends and unit.
- If curve fiting is implemented, it should contain the fit model and its R2.
- Graph outline should be removed.

Conclusion

This is the section in which you need to put it all together. It differs from the abstract in that :

- It should be more informative, something that can easily be accomplished because you may devote more words to it. You should include a concise version of your discussion, highlighting what you found out, what problems you had, and what might be done in the future to remedy them.
- You should also indicate how the investigation could usefully be continued.

References

For this section, you should provide the source of information wherefrom you got the equations, fluid or materials properties.

Use this website : https://scholar.google.com/

- ✓ Textbooks, articles, company websites are trusted sources.
- ✓ Do not use the lab manual as a reference.
- ✓ List the references in same order as they appear in the text.
- ✓ For my students, I ask them to use the APA or Chicago style.

Book

Holman, J. P. (2012). Experimental methods for engineers. McGrawHill, New Yourk.

(3)

Journal article,

Sang, J., Yuan, Y., Yang, W., Zhu, J., Fu, L., Li, D., & Zhou, L. (2022). Exploring the underlying causes of optimizing thermal conductivity of copper/diamond composites by interface thickness. Journal of Alloys and Compounds, 891, 161777.

Web page,

http://www.gobbeldygook.co.uk. Viewed on 22/10/2020.

A word of caution on web based information. Journal articles and most books are peer reviewed. This means that other workers in the field have checked them for accuracy etc.. This is not true of web sites. Be careful in taking information from such sources and if at all possible verify the information by checking in books etc. You should also read the web information critically to see that it makes sense to you.

You are an engineer and should take pride in not being duped into making easy mistakes by faulty information.

Experiment [1]

Film and Dropwise Condensation

Objective

To investigate:

a) Film wise condensation

b) dropwise condensation

c) effect of air in condensers

Introduction and Theoretical Background

Condensation is defined as the removal of heat from a system in such a manner that vapor is converted into liquid. This may happen when vapor is cooled sufficiently below the saturation temperature to induce the nucleation of droplets. Such nucleation may occur homogeneously within the vapor or heterogeneously on entrained particulate matter. Heterogeneous nucleation may also occur on the walls of the system, particularly if these are two forms of heterogeneous condensation, film wise and dropwise. Film wise condensation occurs on a cooled surface which grows by further condensation and coalescence and then roll over the surface new drops then form to take their place.

Apparatus

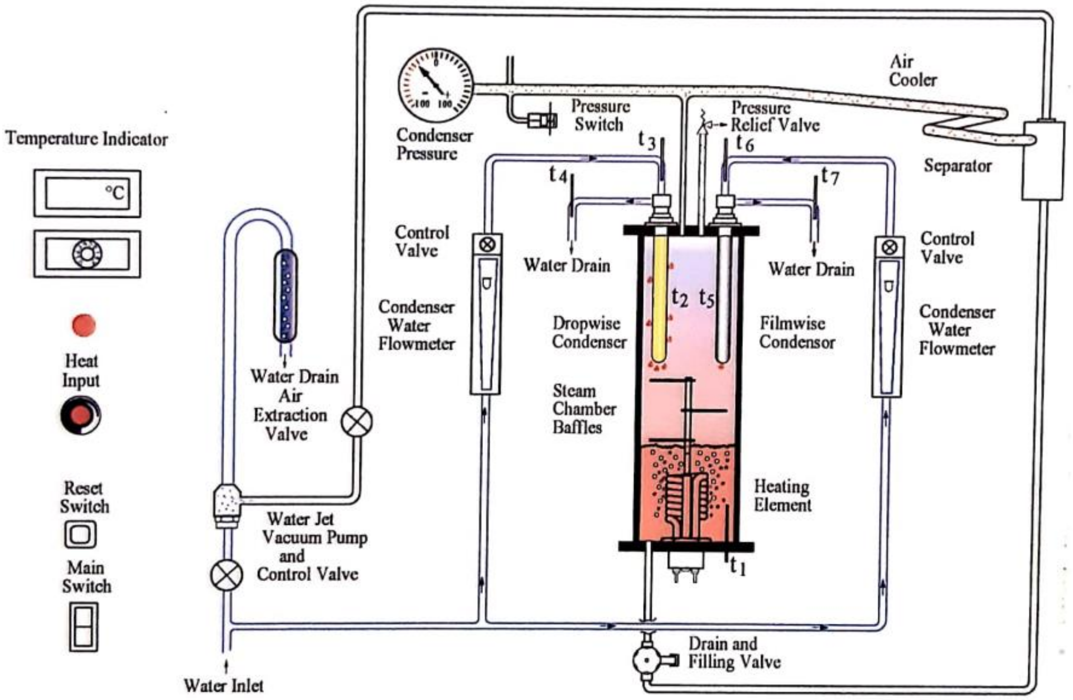


Figure (1): Film and Dropwise Condensation Unit H910

Figure (1) in the previous page shows a schematic diagram for the apparatus used. It consists of a steam chamber that contains saturated water and saturated steam. The water is boiled and evaporated by electric heating element and then condensed by two water cooled condensers returning back to liquid for re-evaporation. One of the two condensers use film wise condensation and the other use dropwise condensation.

Due to the tremendous effect that air can have on the condensation process, an air extraction system is fitted with the apparatus. It consists of a water jet vacuum pump to draw air and steam out of the steam chamber.

The controls used are heater control, condenser cooling water control valves pressure gauges, pressure relief valve, drain valves, separator, several thermocouples for temperature measurements, and flow meters.

Preparations for the test

Visual Demonstration of Film wise and Dropwise Condensation, and of Nucleate Boiling.

1. Having checked that there is sufficient water in the chamber to cover the element by about 30mm. Switch on the heater and increase the water temperature (T_1) to about 80°C. Carry out the air extraction procedure and then carry-on heating until T_1 reaches the desired value-say 100°C.
2. Adjust the condenser water flow rates until the surface temperatures of the dropwise (T_2) and the film wise (T_5) are equal and about 8 to 10 K less than T_1.

The condensation process may now be observed and compared.

1. It will be seen that the rate at which condensate falls from the dropwise condenser is several times greater than that at which it falls from the film wise condenser. This indicates that for the same steam to surface temperature difference, dropwise condensation causes a much higher rate of heat transfer.
2. In dropwise condensation, the steam condenses on the surface forming a large number of static beads which grow in size. When a bead reaches a certain size, it breaks away and rapidly runs down the surface, gathering all the static beads in its path. The surface in the trail of the bead is momentarily free from liquid but further beads of condensation quickly appear. It is interesting to observe the rapid small fluctuations in the value of T_2 as the beads of condensates from and break away giving local variations in heat flux.
3. In film wise condensation, the surface of the condenser is covered with an unbroken film of liquid which steadily increases in thickness as it flows downward. The smooth surface of the liquid film indicates that flow within it is probably laminar and that there will be little or no mixing of the hot outer layer with the cooler inner layer close to the condenser surface. In this case, heat transfer from the condensed steam (on outer layer of the film) to the metal surface is by conduction through the film of liquid. Although the film has a small thickness, its resistance is enough to account for the significant difference between the heat transfer rates observed in (i).

Nucleate Boiling.

The very vigorous turbulence brought about by the vapor bubble formation at the surface of the heating element is clearly seen and typical of nucleate boiling. This turbulence, which occurs automatically, accounts for the very high heat fluxes possible during boiling.

Caution

- It is possible to simultaneously run tests on both condensers. However, at the higher heat fluxes with the dropwise condenser, it will be necessary to turn off the water to the film wise condenser.
- Cooling water flow rates outside the range of the flow meters can be measured by timing the discharge of cooling water into a measuring cylinder.
- Air leakage into the chamber is unlikely at t_1 = 100°C, but at lower temperatures some air infiltration is possible and at intervals it will be necessary to carry out air extraction procedures.
- Fresh distilled water must be available to make good the losses during air extraction.

Procedure

Measurement of heat flux and surface heat transfer coefficient during film wise and dropwise condensation.

1. Ensure that the water level in the chamber is correct.
2. Carry out the air extraction procedure.
3. Run the unit for about five minutes with a saturation (steam) temperature T_1 of T_1 100°C and low condenser water flow rates. This is to warm all components and to reduce condensation on the glass.
4. Select the steam temperature (T_1) which is to be constant for the test. This may be
5. anywhere between 50 °C and 100 °C).
6. Circulate water through the dropwise condenser at a low rate (say 5 gm/s) and adjust the heater input to maintain the selected value of T_1.
7. Note the steam temperature T_1, the surface temperature T_2, the cooling water inlet
8. temperature T_3, the water outlet temperature T_4, and the water flow rate M_d.
9. Increase the water flow rate (to say 10 gm/ s) and again adjust the heater input to
10. bring the steam temperature (T_1) to the selected value.
11. Again, note T_1, T_2, T_3, T_4 and M_d.

Calculations

1- The heat transfer rate (Q):

$$Q= m_d*C_p*(T_4-T_3) \quad (1)$$

Where:

Symbol	Meaning	Unit
Q	Heat transfer rate	kW
$\dot{m}_d$	Mass flow rate	kg/sec
T_4	Water inlet temperature	°C
T_3	Water outlet temperature	°C

2- Heat Flux (Φ):

$\Phi = Q/A$ (2)

Where:

Symbol	Meaning	Unit
Φ	Heat flux	kW/m^2
Q	Heat transfer rate	kJ/sec
A	Surface Area	m^2

3- Correction for temperature drop through condenser shell:

$\Delta T_{cs} = 2 \times 10^{-5}\ \Phi$ (3)

Where:

Symbol	Meaning	Unit
ΔT_{cs}	Corrected temperature	K
Φ	Heat flux	kW/m^2

4- Corrected steam to surface temperature difference:

$\Delta T = T_1 - T_2 - \Delta T_{cs}$ (4)

Where:

Symbol	Meaning	Unit
ΔT	Corrected steam to surface temperature difference	K
ΔT_{cs}	Corrected temperature	K
T_1	Saturation temperature	K
T_2	Surface temperature	K

5- Surface heat transfer coefficient:

$h = \Phi/\Delta T$ (5)

Where:

Symbol	Meaning	Unit
h	Surface heat transfer coefficient	kW/m^2K
Φ	Heat flux	kW/m^2
ΔT	Corrected steam to surface temperature difference	K

6- Theoretical analysis:

$$h_{mean} = 0.943 \left[\frac{k_f^3\, \rho\, f^2\, h_{fg}\, g}{X \mu_f (t_{sat} - t_{sur})}\right]^{1/4} \qquad (6)$$

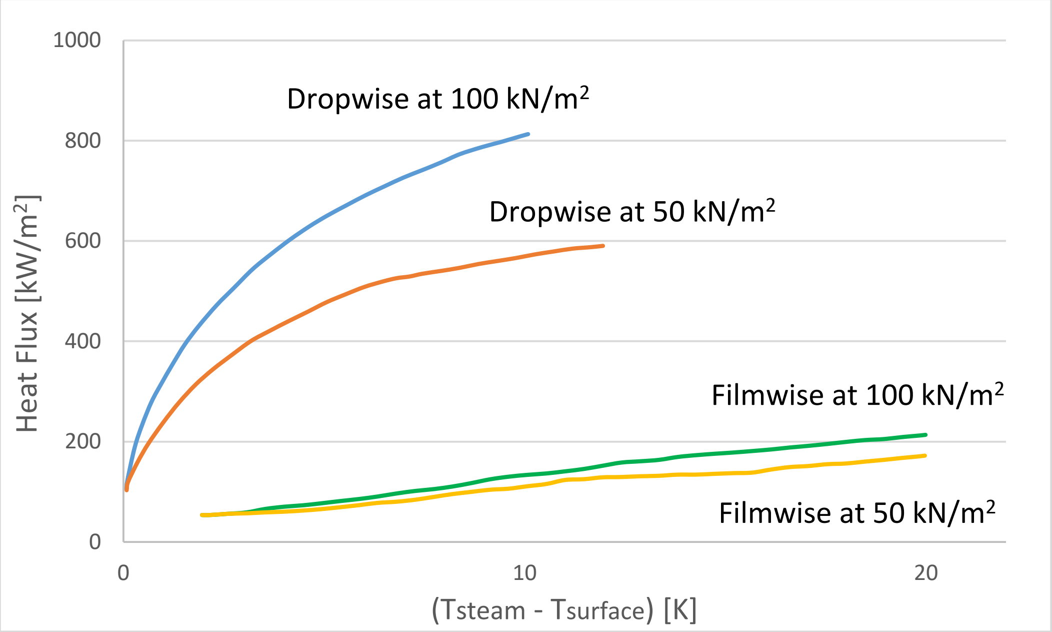


Figure (2): Relationship between heat flux and the steam to surface temperature difference

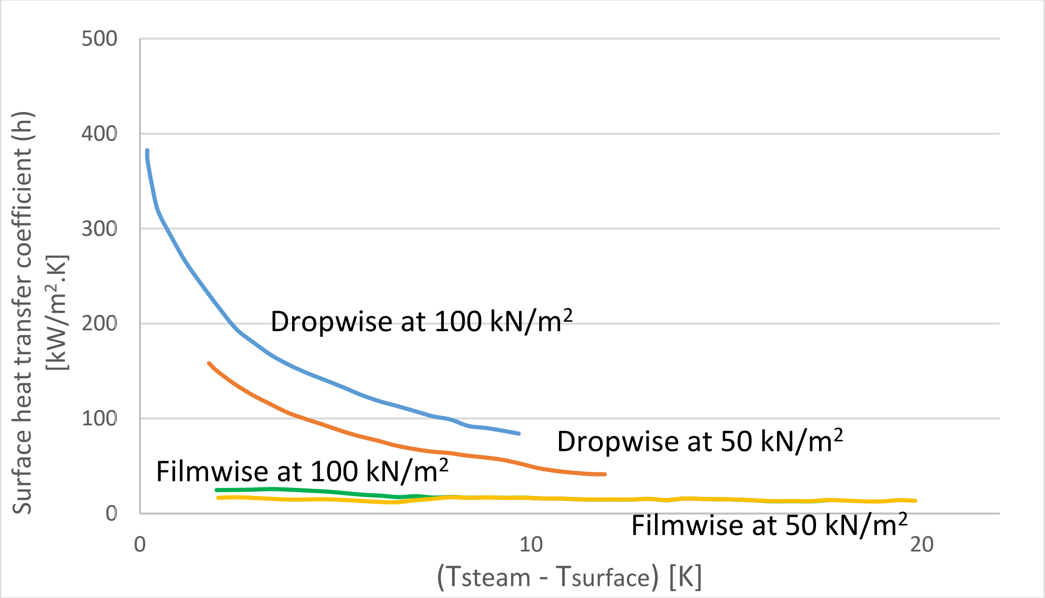


Figure (3): Filmwise and Dropwise Condensation Relationship between surface heat transfer coefficient and the steam to surface temperature difference

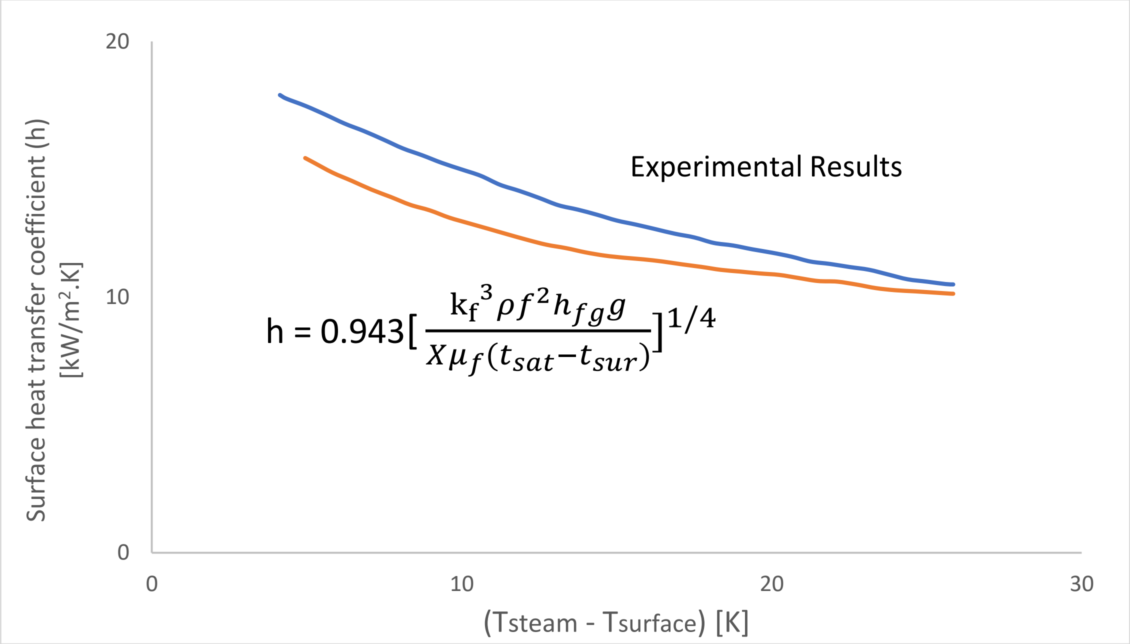


Figure (4): Comparison of experimental and theoretical surface heat transfer coefficient.

Given Data:

Parameter	Value	Unit
Dimensions of each Condenser:		
Length	90	mm
Diameter	12.7	mm
Surface Area	37	cm^2
Internal volume of Steam Chamber (When empty)	1840	cm^2
Internal diameter of chamber glass cylinder	76	mm
Normal water capacity	500	cm^3
Surface area of heating element	144	cm^2
Temperature drop across copper shell of condenser	$2x10^{-6}\ \Phi$	K
Specific heat capacity of water (Cp)	4.18	kJ/kg/K
Heat loss from steam chamber (by experiment)	2.5	W/K
Standard atmospheric pressure	101.3	kN/m^2

Observed Data

Dropwise Condensation:

Table (1): Collected data (Dropwise Condensation)

Test No.	**1**	**2**	**3**	**4**
Chamber Pressure Pgauge				
Saturation Temperature T_1 [ºC]				
Surface Temperature T_2 [ºC]				
Water Inlet Temperature T_3 [ºC]				
Water outlet Temperature T_4 [ºC]				
Mass Flow Rate [kg/s x 10^{-3}]				

Film Condensation:

Table (2): Collected Data (Film Condensation)

Test No.	**1**	**2**	**3**	**4**
Chamber Pressure Pgauge				
Saturation Temperature T_1 [ºC]				
Surface Temperature T_2 [ºC]				
Water Inlet Temperature T_3 [ºC]				
Water outlet Temperature T_4 [ºC]				
Mass Flow Rate [kg/s x 10^{-3}]				

Results Table

Dropwise Condensation:

Table (3): Calculated Data (dropwise Condensation)

Test No.	**1**	**2**	**3**	**4**
Saturation Temperature [^oC]				
Heat Transfer Rate Q [kW]				
Heat Flux [kW/m^2]				
Correction for Temperature Drop ΔT_{cs} [K]				
Corrected Steam to Surface Temperature ΔT [K]				
Heat Transfer Coefficient [kW/m^2. K]				

Film Condensation:

Table (4): Calculated Data (Film Condensation)

Test No.	**1**	**2**	**3**	**4**
Saturation Temperature [^oC]				
Heat Transfer Rate Q [kW]				
Heat Flux ϕ [kW/m^2]				
Correction for Temperature Drop ΔT_{cs} [K]				
Corrected Steam to Surface Temperature ΔT [K]				
Heat Transfer Coefficient [kW/m^2. K]				

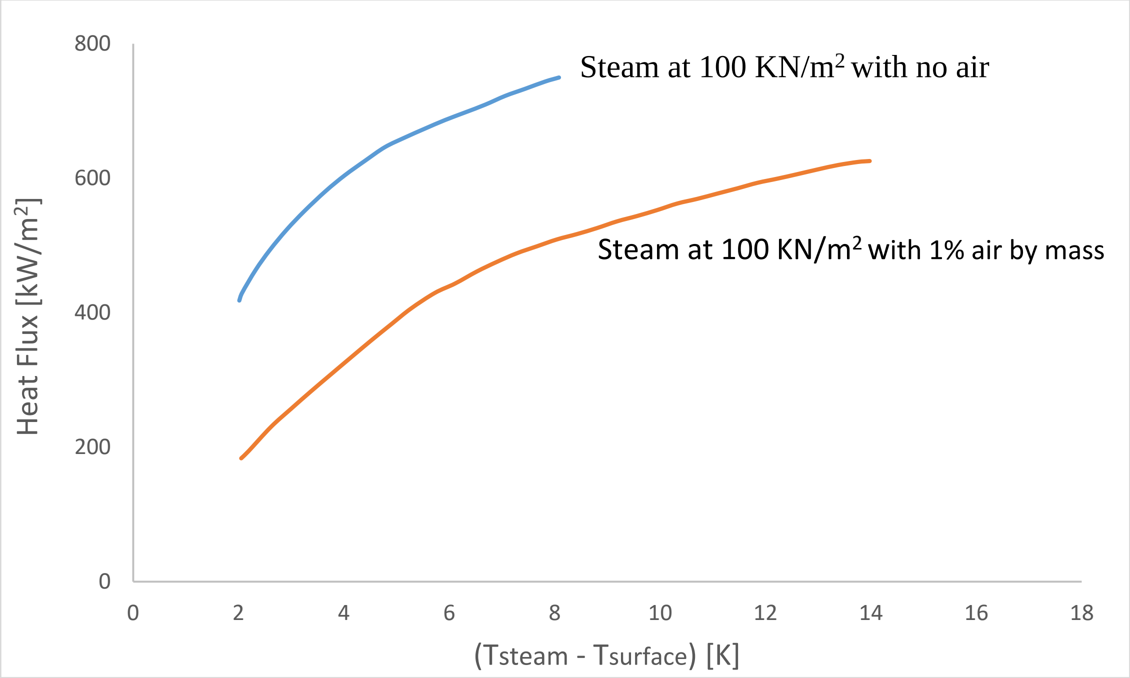


Figure (5): Dropwise condensation at 100 kN/m^2, Effect of Air on heat flux

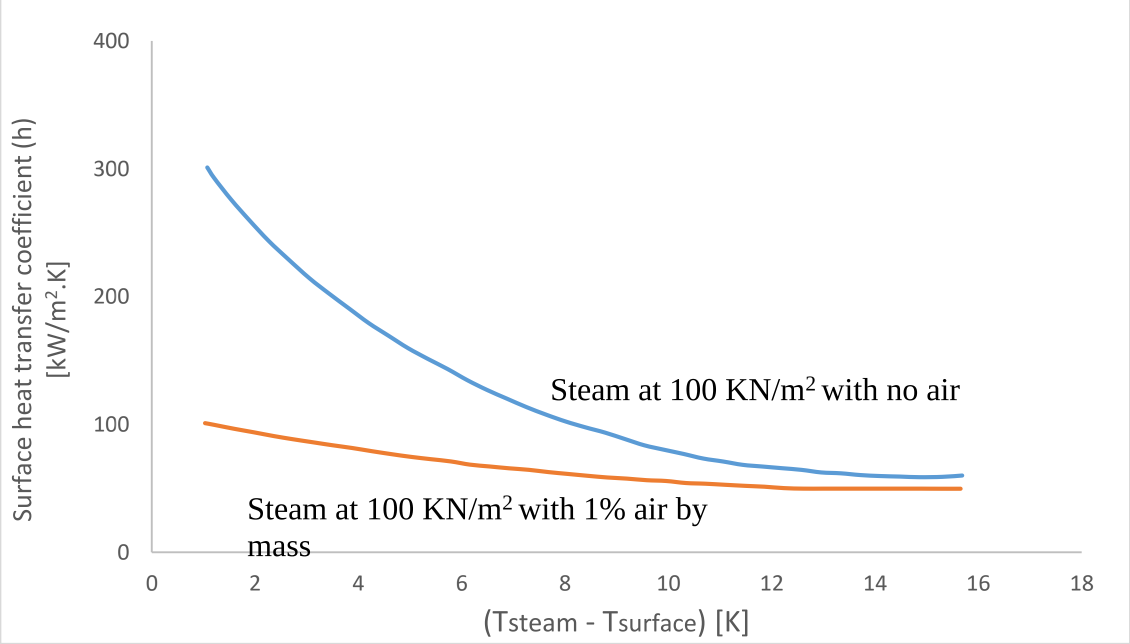


Figure (6): Dropwise condensation at 100 kN/m^2, Effect of Air on surface heat transfer coefficient

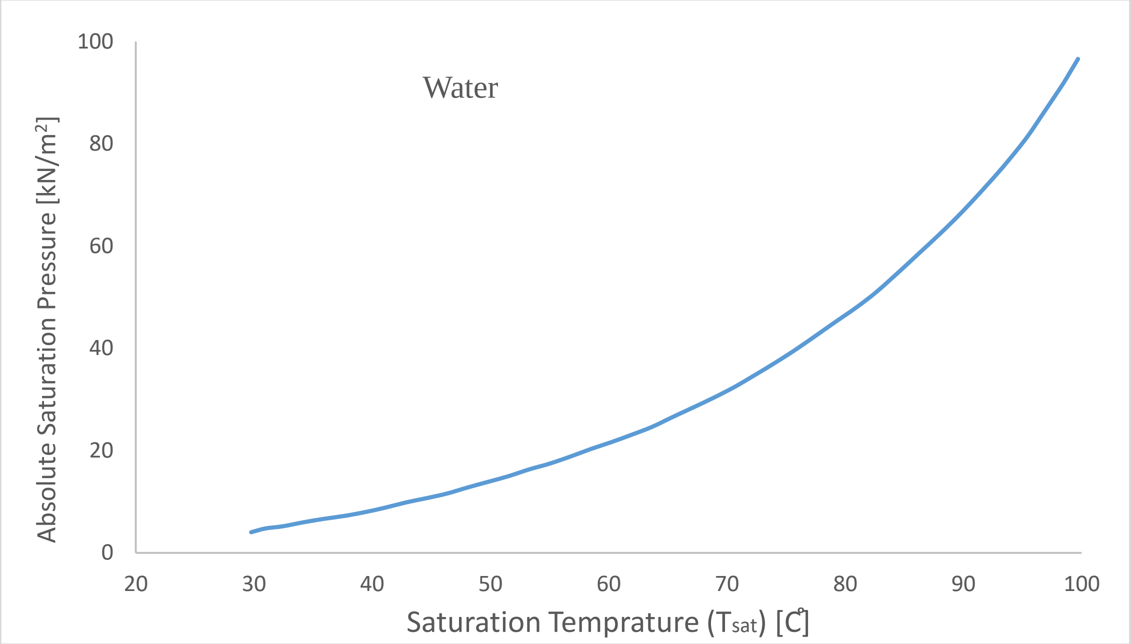


Figure (7): Saturation Pressure/Saturation Temperature

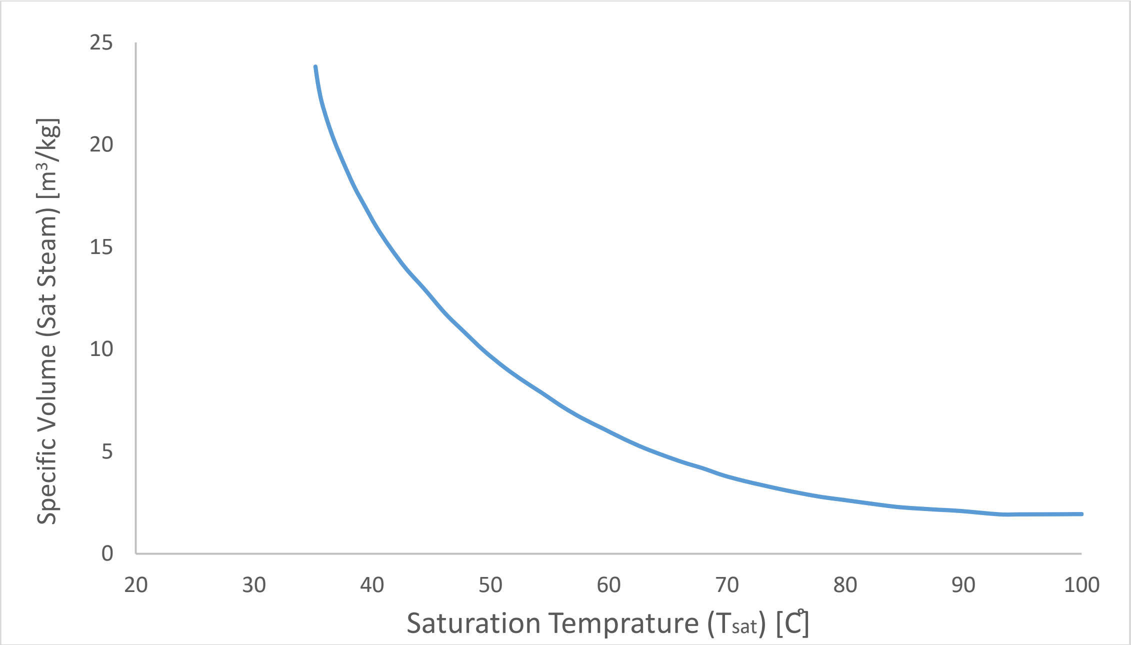


Figure (8): Specific Volume Of Saturated Steam

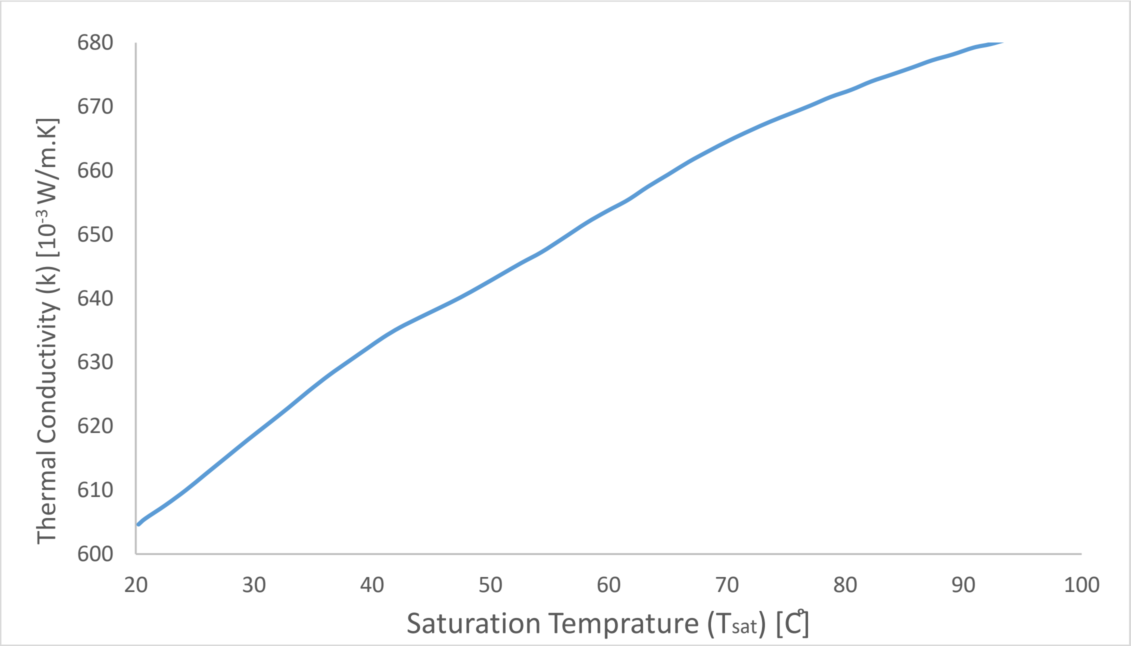


Figure (9): Saturated Water – Thermal conductivity

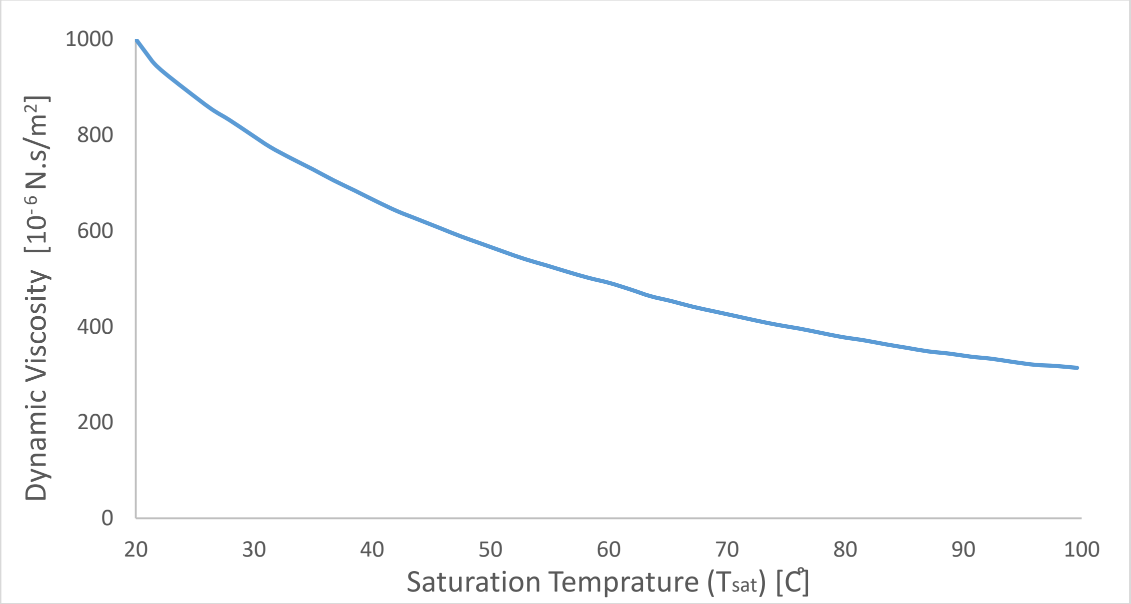


Figure (10): Saturated Water – Dynamic Viscosity

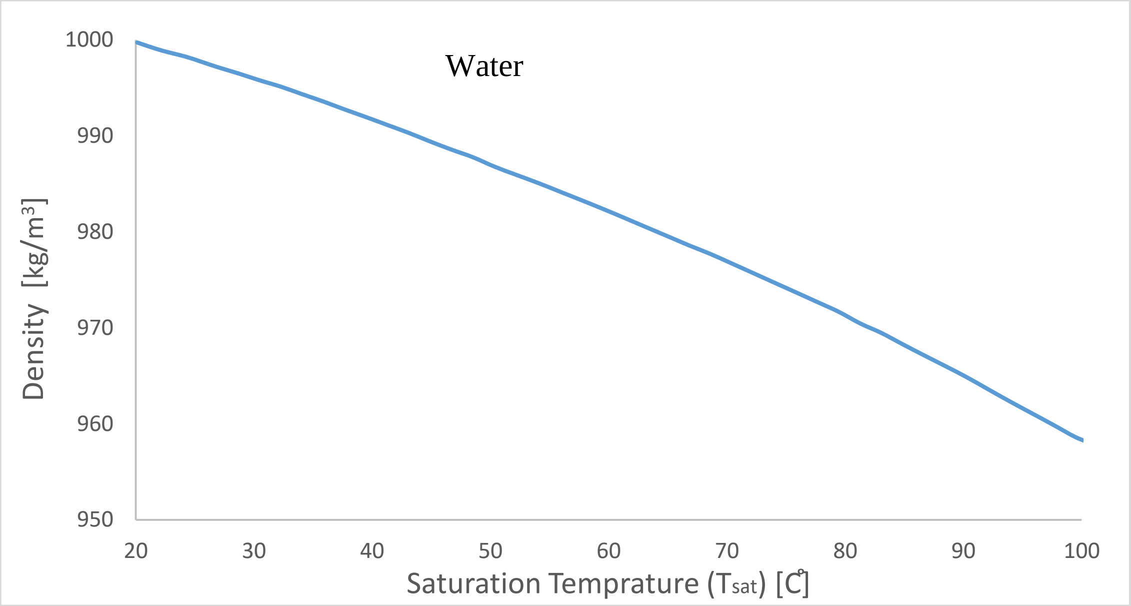


Figure (11): Saturated Water – Density

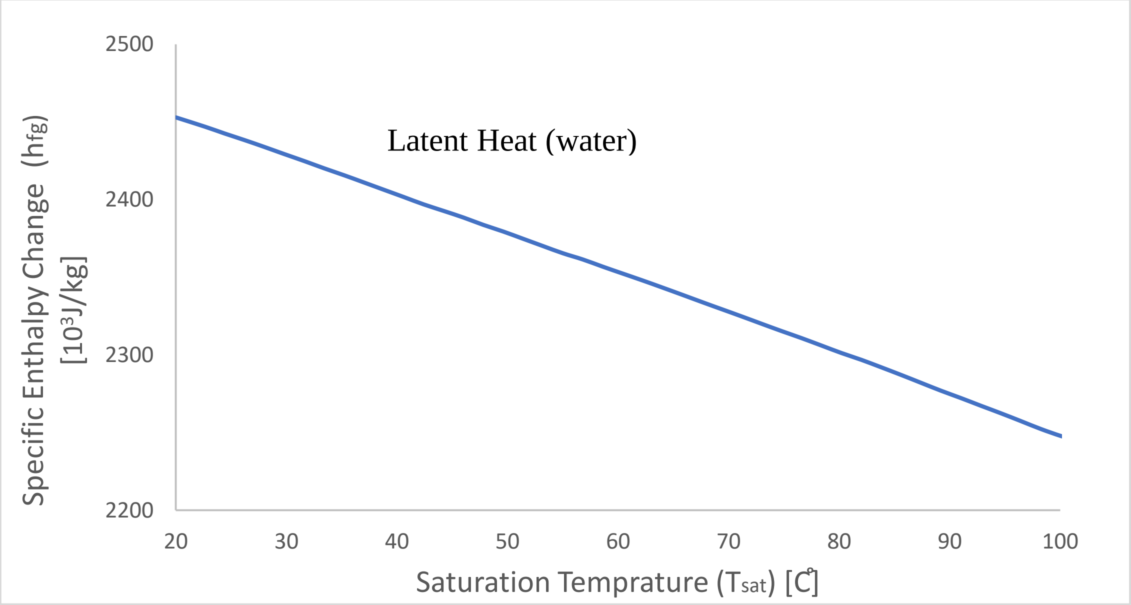


Figure (12): Specific Enthalpy Change During Condensation

Experiment [2]
Forced Convection Heat Transfer

Objective

To determine experimentally the validity of Reynolds Analogy (St = f/2) for air and also to compare the experimental values of Nu, St, and f with those given empirical formulae.

Introduction and Theoretical Background

This experiment enables the student to investigate the theory and associated formulae related to forced convection in pipes. Measured experimental data enables the student to calculate the heat transfer (film) coefficient (h), the pipe friction (f) and various non-dimensional groups including Reynolds Number (Re), Nusselt Number (Nu) and Stanton Number (St). The values obtained can be compared with those derived from accepted empirical formulae and the validity of Reynolds analogy may be explored.

Apparatus

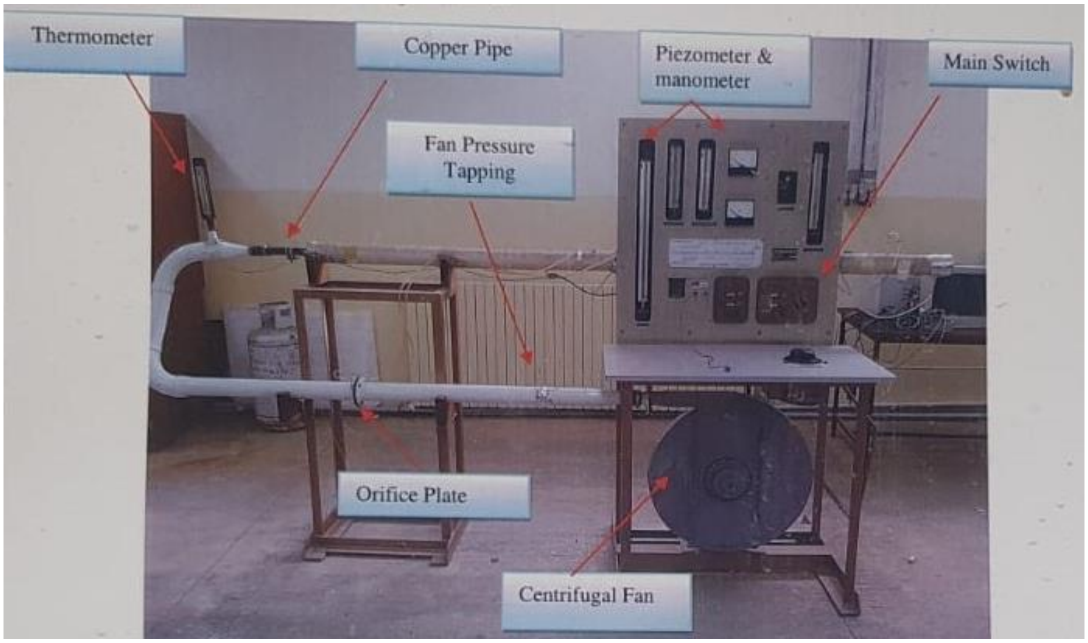


Figure (2): Experiment *S*etup

The apparatus consists of an electrically driven centrifugal fan which draws air through a control valve and discharges into a 76.2 mm diameter, U- shaped pipe. The fan speed remains constant throughout. A British standard orifice plate 40 mm diameter is fixed in this pipe to measure the air flow rate. This pipe is connected to a copper test pipe which is 3048 mm long, 32.6 mm internal diameter and has a wall thickness of 1.20 mm. The test pipe, which discharges to atmosphere, is electrically heated over the final 1753 mm by a heating tape wrapped around the outside of the pipe. The power input to the tape can be varied by means of a variable transformer fitted to the apparatus, the input being measured with the aid of a voltmeter and ammeter fixed to the instrument panel. The test pipe is insulated with 25 mm thick fiberglass lagging. All the pipe work rests on wooden blocks supported by the steel frame of the apparatus.

A 1524 mm test length, situated within the heated length of the test pipe, has pressure tapping at each end which are connected to a water manometer on the instrument panel. Other manometers fixed to the instrument panel measure fan discharge pressure and the orifice pressure drop.

Seven thermocouples (number 1 to 7) are fixed to the wall of the copper test pipe at various points along the heated length. A further six thermocouples (number 8 to 13) are situated at points within the lagging. The positions of all the thermocouples are shown on a diagram displayed on instrument panel. A mercury in glass thermometer measures the air temperature at the inlet to the test pipe. The output from any thermocouple may be chosen with a selector switch fitted to the instrument panel and measured with an electronic thermometer or potentiometer.

Preparations for the test

Switch on the fan with the inlet valve fully open. When this has been done the heater can be switched on with the variable transformer SET AT ZERO. Increase the voltage to give a maximum current of about 4.5 A. Leave the apparatus to warm up for at least thirty minutes to attain exceed 150℃ .

Procedure

1. Air pressure before the orifice plate (fan pressure)
2. Pressure drops across the orifice plate.
3. Air temperature at inlet to the test pipe.
4. Barometric pressure/Ambient temperature.
5. Pressure drops over the lest length.
6. Thermocouple readings on the pipe-thermocouples 1 to 7.
7. Thermocouple readings inside and outside the lagging – Thermocouples 8 to 13.
8. Ammeter reading.
9. Voltmeter reading.

Recommendations and Warnings:

After a change of flow rate and heat input, the apparatus must be allowed to settle down for a further 15 to 30 minutes to allowed to run for at least five minutes after the heater is switched off in order to avoid overheating the thermocouples.

Calculations

7- Mass Flow rate (W) of air:

$$W = \rho * \text{orifice area} * C_d * \sqrt{\frac{2\Delta P}{\rho}} \qquad (1)$$

Where:

Symbol	Meaning	Unit
W	Mass flow rate of air	kg/s
$C_d = 0.613$	The orifice discharge coefficient	-
ρ	Air density at orifice	kg/m^3
ΔP	pressure drop across orifice	N/m^2

Note: 1 $mmH_2O = 9.81\ N/m^2$

8- Heat input by heating tape (Q_1):

$$Q_1 = \frac{I \times V}{1000} \qquad (2)$$

Where:

Symbol	Meaning	Unit
Q_1	Heat input by heating tape	kJ/s
I	Current	A
V	Voltage	V

9- The Heat loss through lagging:

$$Q_2 = \frac{0.0415}{1000} \times \frac{2\pi \times 1.753}{\ln(\frac{r_o}{r_i})} \times [\Delta Tm] \qquad (3)$$

Where:

Symbol	Meaning	Unit
Q_2	Heat loss through lagging	kJ/s
r_o	Outside radius	mm
r_i	Inside radius	mm
ΔT_m	Mean temperature drop across lagging	°C

10-The Heat flux through the wall:

$$\emptyset = \frac{Q_1 - Q_2}{Ai} \tag{4}$$

Where:

Symbol	Meaning	Unit
$\emptyset$	Heat flux through the wall	kJ/m^2s
Q_1	Heat transfer rate	kJ/s
Q_2	Heat loss through lagging	kJ/s
A_i	Internal pipe wall area	m

Notes:

The heat flux is required in calculating the heat transfer coefficient, h. Heat conduction along the copper tube does not contribute to the heat flux since, for a given section of pipe, the heat flowing in at one end will be equal to the heat flowing out the other.

The thermocouple positions are shown on the diagram on the instrument panel. From the temperature readings it will be seen that the section between 2 and 5 is free of exit and entrance effects. It is suggested that the heat transfer calculations are made around section 4.

Calculate the total heat input up to this point per second and hence the bulk mean air temperature at this point. Total heat input includes heat input by the heating tape plus heat input by conduction in the pipe less the heat loss through the lagging.

11-Heat input by conduction:

$$Q_3 = \frac{380.6}{1000} \times 0.6 \times \frac{2\pi rt}{10^4} \times \frac{tempreature\ drop}{L_4} \tag{5}$$

Where:

Symbol	Meaning	Unit
Q_3	Heat input by conduction	kW
r	mean radius of copper tube	mm
t	wall thickness	mm
L_4=1m	length of heated section	m

12-Heat input up to chosen section:

$$Q4 = (Q_1 - Q_2) \times \frac{b}{1753} + Q_3 \qquad (6)$$

Where:

Symbol	Meaning	Unit
Q_4	Heat input up to chosen section	kJ/s
Q_1	Heat transfer rate	kJ/s
Q_2	Heat loss through lagging	kJ/s
Q_3	Heat input by conduction	kJ/s
b	length of heated pipe up to chosen section	mm

13-The bulk mean air temperature:

$$T_b = T_i + \frac{total\ heat\ input}{mass\ flow\ rate \times C_p} \qquad (7)$$

Where:

Symbol	Meaning	Unit
T_b	bulk mean air temperature	°C
T_i	air inlet temperature	°C
C_p	specific heat of air at inlet temperature	J/kg

14-Heat transfer coefficient (h):

$$h = \frac{\emptyset}{T_w - T_b} \qquad (8)$$

Where:

Symbol	Meaning	Unit
h	Heat transfer coefficient	W/m^2.K
$\emptyset$	Heat flux through the wall	kJ/m^{2}s
T_w	wall temperature	°C
T_b	bulk mean air temperature	°C

Note: The wall temperature Tw will be given by the thermocouple at the point at which the heat balance is taken or from the graph of wall temperature against pipe length.

15- Experimental values of Nusselt number (Nu), Stanton number (St), and friction factor (f):

$$Nu = \frac{hd}{k} \qquad (9)$$

$$St = \frac{h}{\rho V C_p} \qquad (10)$$

$$P_1 - P_2 = (\frac{2fL}{d})\rho v^2 \qquad (11)$$

Note: Equation (11) is based on the assumption that all of the pressure drop is due to friction. For flow in a heated pipe this assumption is not valid because part of the pressure drop is due to the acceleration head associated with the expansion of the air as it passes along the heated pipe. An allowance for the acceleration head can be made with reasonable accuracy using the Guggenheim equation:

$$P_1 - P_2 = \frac{1}{\bar{\rho}}\frac{W^2}{A^2}\left[\frac{4fL}{2d} + \frac{T_2 - T_1}{\bar{T}} + \ln\left(\frac{P_1}{P_2}\right)\right] \qquad (12)$$

16- Analytical Values of Nusselt number (Nu), Stanton number (St), and friction factor (f):

$$Nu = 0.023 Re^{0.8}\,\mathrm{Pr}^{0.4} \qquad (13)$$

$$St = 0.023\, Re^{0.2}\, Pr^{0.6} \qquad (14)$$

$$f = 0.079\, Re^{-\frac{1}{4}}\ (turbulent\ region\ only) \qquad (15)$$

$$Re = \frac{\boldsymbol{\rho v d}}{\boldsymbol{\mu}} \qquad (16)$$

$$\mathrm{Pr} = \mu\, C_p / k \qquad (17)$$

Note: Prandtl number (Pr) and has almost the same value for all gasses and varies very little with temperature and pressure, when Pr=1:

$$Nu = \left(\frac{f}{2}\right) Re \qquad (18)$$

$$St = \frac{f}{2} \qquad (19)$$

$$f = 0.046 Re^{-0.2} \qquad (20)$$

Given Data:

Parameter	Value	Unit
Tube Bore	31.75	mm
Wall thickness	1.63	mm
Lagging thickness	19	mm
Orifice-plate diameter	40	mm
Pipe intimal diameter	32.5	mm
Pipe wall thickness	1.20	mm
K for pipe material (copper)	380.6	J/ms℃
Thickness of lagging	25	mm
Heated length of pipe	0.0415	J/ ms ℃
Thermocouple material length	1753	mm
Thermocouple material	copper constantan to B.S. 1828	
Pressure tapping on the pipe inlet	51	mm
	1575	mm
Electrical supply (3 phase neutral earth)		
Voltage	380/440	V
Frequency	50	Hz
Current	15	Amp
Maximum allowable tube temperature (thermocouples 1 to 7)	150	℃

Observed Data

Table (1): Collected Data of the environment and apparatus

Room temperature	
Barometric pressure	
Air inlet temperature	
Fan pressure	
Orifice pressure drop	
Test length pressure drop	
Heater current	
Heater voltage	

Table (2): Temperature collected and calculated

Reference Number	**Actual T [^oC]**	**ΔT across lagging [^oC]**
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		

Plot the following:

- Temperature profile along the tube.
- Temperature difference across the lagging.

Conclusion:

Compare the experimental values with those obtained from normally accepted expressions and comment on the deviation if any.

Experiment [3+4]

Heat Exchangers

Objective

To determine the heat transfer rate and the overall heat transfer coefficient of both the parallel and counter flow heat exchanger.

Introduction and Theoretical Background

The process of exchanging heat between two different fluids is one of the most important and frequently encountered processes found in engineering practice. The devices used to exchange heat between two fluids are generally termed, Heat Exchangers.

Ordinary heat exchangers may be divided **into two general classes:**

1) Crossflow heat exchangers
2) Unidirectional heat exchangers.

This experiment will treat the unidirectional heat exchangers.

The heat exchanger is a device in which heat is transferred from a hot to a cold fluid across a separating wall. This is an important component of any thermal system; such as a condenser in a thermal power plant, evaporate and condensers in a refrigerator, radiator of a motorcar, etc. One of the important classifications of heat exchangers is based on the direction of the flow of hot and cold fluids. In the parallel flow heat exchangers, both hot and cold fluids flow in the same direction, whereas in the counter flow type, fluids flow in opposite directions.

Apparatus

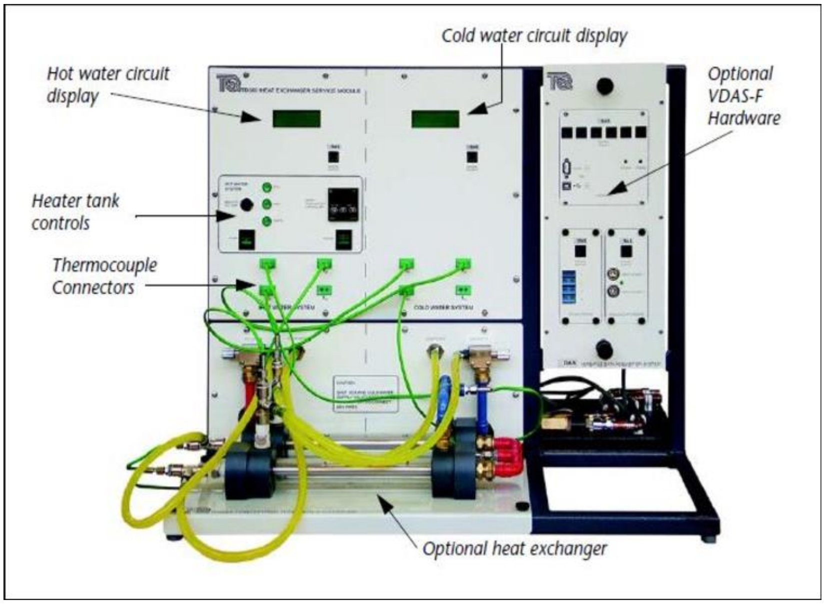


Figure (3): Experiment Setup

This equipment has been designed to determine the overall heat transfer coefficient in parallel and counter-flow heat exchangers.

It is a compact frame that is set on a benchtop and features two water circuits (hot and cold), the heat exchanger is fitted separately onto the front of the device and then is connected to the water circuit. The cold water comes in via a flow regulator through a needle valve to the heat exchanger and out to a suitable drain. Same as the hot water which has an electric heater with an adjustable controller to set the tank temperature. The water is circulated through a closed tank back to it through a pump found behind the device.

Preparations for the test

Cold water: check that the cold-water tank contains sufficient liquid before switching on the refrigeration unit, it will take two hours to form the ice bank from room temperature and then the fridge will automatically switch off. During that the Coldwater pump should be switched off; so, no water is circulated

Hot water: check that the hot-water tank contains sufficient liquid before swathing on the heater, select the hot water temperature using the thermostat but don't exceed 70 (above this temperature the fixed safety thermostat will be over). switch on the hot water pump and a set control valve to regulate the flow. Switch on the immersion heaters (it takes 30 minutes to reach the maximum temperature of 70 on the 9 kW settings) when the maximum temperature is reached the pump will switch off automatically and then regulate the water to the chosen setting).

Heat Exchanger: Place the selected exchanger on the bench top and connect the 4 flexible hoses to the exchanger. Do not plug the couplings into the sockets on the bench. If required, connect the differential pressure gauge to any pair of tapping on the exchanger, using the plastic hoses with plug-in connectors.

Caution

- Do not cross the circuits and interconnect the hot and cold-water tanks; this could result in flooding and will delay the experiment while the starting conditions are re-established.
- Data should be collected at a steady state; flow rates across each circuit and pressure drops across each temperature should be noted until sufficient steady state conditions are reached.

Procedure

1- Switch off the water pumps.
2- Connect the flexible hoses to the socket on the bench ensuring that the desired direction of flow through the exchanger is selected. If required, connect the deferential pressure gauge to any pair of tapping on the exchanger using the plastic hoses with plug-in connectors.
3- Regulate the flow control valves until they are partially open.
4- Purge the system of air by turning the exchangers over on their sides and using the manometer tapping valves as air purge points allow the free end of the clear plastic tubes to loop over the exchangers and into a tray or bucket any remaining air can be seen as water run through the tube. This process should not take more than 3 minutes to avoid adding unscary heat to the cold tank also it should be done with high care to avoid damaging the thermometers.
5- Start the hot and cold-water pumps simultaneously.
6- Use the flow control valves to regulate the flow rate of each circuit (if the hot water valve is fully open but the desired flow rate is not reached then close partially the direct tank return valve to attain the required flow).

When the test is completed:

1- Switch off the pumps, immersed heaters, and refrigeration unit.
2- Disconnect the flexible holes and the pressure-sensing tubes.
3- Isolate the electrical supply of the bench.

Recommendations and Warnings:

1- Ensure that the flexible hoses from the exchanger are plugged into the correct sockets on the bench. Do not cross the circuits and interconnect the hot and cold-water tanks - this could result in flooding and will delay an experiment while starting conditions are re-established in the bench.
2- It is most important to purge the system of air before taking readings, and the utmost care should be taken to ensure this is done.
3- Do not remove the pressure tapping hoses from the differential gauge with the pumps in operation a dangerous jet of hot water will issue forth, always disconnect the hoses from the self-sealing couplings on the exchanger.

Calculations

17-The heat flow rate (Q_h) transferred between the two fluids by the hot side:

$$Q_h = m_h \text{ x } Cp_h \text{ x } (T_{hi} - T_{ho}) \qquad (1)$$

Where:

Symbol	Meaning	Unit
Q_h	Heat transfer rate from hot water	kJ/sec
$\dot{m}_h$	Mass flow rate of hot water	Kg/sec
T_{hi}	Inlet temperature of hot water	°C
T_{ho}	Outlet temperature of hot water	°C

18-The heat flow rate (Q_c) transferred between the two fluids by the cold side:

$$Q_c = m_c \text{ x } Cp_c \text{ x } (T_{co} - T_{ci}) \qquad (2)$$

Where:

Symbol	Meaning	Unit
Q_c	Heat transfer rate from cold water	kJ/sec
$\dot{m}_h$	Mass flow rate of cold water	Kg/sec
T_{ci}	Inlet temperature of cold water	°C
T_{co}	Outlet temperature of cold water	°C

19-The heat flow rate can also be measured by:

$$Q = U * A * \Delta T_m \qquad (3)$$

Where:

Symbol	Meaning	Unit
Q	Heat transfer rate	kJ/sec
U	Overall heat transfer coefficient	Kg/sec
A	Surface area of heat transfer	m^2
ΔT_m	Logarithmic mean temperature	°C

20-The logarithmic mean temperature can be calculated using:

$$\Delta Tm = (\Delta T1 - \Delta T2)/(\ln(\Delta T1/\Delta T2)) \quad (4)$$

Where:

For counter flow

$$\Delta T_1 = (T_{hi} - T_{co}) \quad (5)$$

$$\Delta T_2 = (T_{ho} - T_{ci}) \quad (6)$$

For parallel flow

$$\Delta T_1 : (T_{hi} - T_{ci}) \quad (7)$$

$$\Delta T_2 = (T_{ho} - T_{co}) \quad (8)$$

Obtain the overall heat transfer coefficient, plot mass flow rate versus heat transfer rate

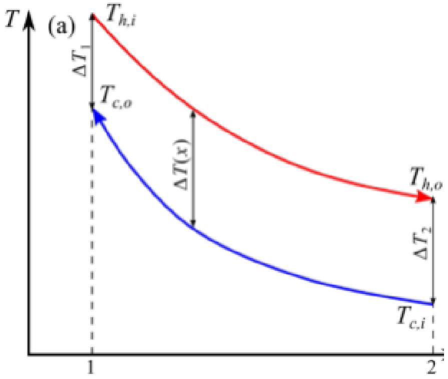


Figure (2): Temperature versus length diagram of the counter flow heat exchanger

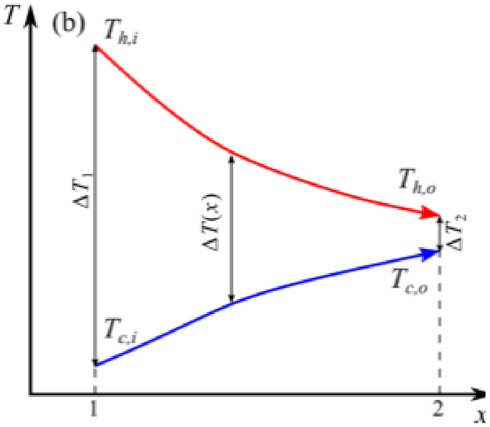


Figure (3): Temperature versus length diagram of parallel flow heat exchanger

Given Data:

Symbol	Value	Unit
A	0.2	m^2
Cp	4180	J/kg
ρ	1000	kg/m^3
$\dot{V}_c$	2	L/m

Observed Data

Counter Flow:

Table (1): Data observed for hot water.

No.	Flow rate [L/min]	Flow rate [kg/s]	$T_{h,in}$ [°C]	$T_{h,out}$ [°C]	Difference [°C]
1	0.5				
2	1				
3	1.5				
4	2				

Table (2): Data Observed for Cold Water

No.	Flow rate [L/min]	Flow rate [kg/s]	$T_{c,in}$ [°C]	$T_{c,out}$ [°C]	Difference [°C]
1	2				
2	2				
3	2				
4	2				

Parallel Flow:

Table (3): Data observed for hot water.

No.	Flow rate [L/min]	Flow rate [kg/s]	$T_{h,in}$ [^oC]	$T_{h,out}$ [^oC]	Difference [^oC]
1	0.5				
2	1				
3	1.5				
4	2				

Table (4): Data observed for cold water.

No.	Flow rate [L/min]	Flow rate [kg/s]	$T_{c,in}$ [^oC]	$T_{c,out}$ [^oC]	Difference [^oC]
1	2				
2	2				
3	2				
4	2				

Results Table

Table (5): Summary of Results for Counter Flow

Trail	Hot Side		Cold Side		Overall	ΔTm $[^oC]$
	Q_h [W]	U_h $[W/m^2.^oC]$	Q_c [W]	U_c $[W/m^2.^oC]$	U_{avg} $[W/m^2.^oC]$	
1						
2						
3						
4						

Table (6): Summary of Results for Parallel Flow

Trail	Hot Side		Cold Side		Overall	ΔTm $[^oC]$
	Q_h [W]	U_h $[W/m^2.^oC]$	Q_c [W]	U_c $[W/m^2.^oC]$	U_{avg} $[W/m^2.^oC]$	
1						
2						
3						
4						

Experiment [5]

NATURAL CONVECTION AND RADIATION

Objectives

To investigate:

a) The natural convection from a hot element enclosed in a calm space at different pressures.
b) The radiation heat transfer and the surface emissivity of the hot elements.

Theory

Heat transfer from a hot element placed in clam space to its surroundings takes place by two processes: free or natural convection and radiation. While the process of convection is a function of the gas pressure, the heat loss by radiation is effectively independent of this pressure.

It is characteristic of the process convective heat transfer in gases, and an implication of the molecular theory, that convection remains appreciable even at very low gas pressures. It is thus not possible to measure the radiation from the element by reducing the gas pressure to the lowest attainable and assuming that convective heat transfer will then be negligible. A technique of extrapolation is employed and will be described later.

The heat loss due to radiation from a body at temperature T_E located in a space of dimensions substantially larger than that of the body and at temperature T_V is given by the Stefan-Boltzmann equation:

$$Q_R = A\,\sigma\varepsilon\,[(T_E/100)^4 - (T_v/100)^4] \qquad (1)$$

Where:

Symbol	Meaning	Unit	Value
σ	Stefan Boltzmann constant	$W/m^2.K^4$	$5.67*10^{-8}$
T_E	Element temperature	K	-
T_V	Vessel temperature	K	-
ε	Emissivity	W/m	-

Heat transfer theory suggests that data on free convection heat transfer in gases may be correlated by treating the Nusselt number as a function of the product of the Grashof and Prandtl numbers. Various empirical equations are given in the literature, for example [1]:

$$N_u = 0.47[G_rP_r]^{0.25} \qquad (2)$$

Where:

Symbol	Meaning
G_r	Grashof number
P_r	Prandtl number

Macadam [2] also gives a set of coordinates for a "recommended curve" and these are reproduced in figure 2.

At low pressures the mechanism of convective heat transfer changes as a consequence of the increase in mean free path of the gaseous molecules with falling pressure. Once the length of the mean free path becomes comparable with the dimensions of the body and the thickness of the boundary layer empirical equations such as Equation (2) are no longer applicable and more elaborate expressions such as the following, taken from [4] must be use

$$2/Nu = \ln(1+6.82/(G_rP_r^{1.3}) + K_n \times 8y/0.96(y+1) - \ln(1+2K_n) \qquad (3)$$

The Nusselt number, which is a measure of the rate of heat transfer, becomes a function of the Knudsen number, the ratio between the mean free path and a characteristic dimension of the body.

With the present apparatus the influence of the Knudsen number begins to be significant, $(K_n)>0.001$, at absolute pressures of less than about 9 mmHg.

Correction Factors

As a consequence of the electrical resistance of the leads that supply power to the element and support it, a correction factor must be applied to be voltmeter and ammeter readings:

$$Q_{corrected} = 0.96\ VI \qquad (4)$$

In addition, an allowance must be made for heat losses by conduction along the current carrying the thermocouple leads. The effect of these is complex heat is lead down the conductors and then carried radially to the surface of the insulating sleeve covering the conductor where it is dissipated by radiation and convection.

It is found that a good approximation to the effect of the supporting leads may be by considering them as equivalent to the combination of a conductor and an increase in surface area of the cylinder.

The conductivity factor is equivalent to a loss of:

$0.0017\ (T_E - T_V)$ W

While the additional surface is equivalent to: 0.02A

Combining all these corrections we may write: -

$$Q = 0.96VI - 0.0017(T_E - T_V) \qquad (5)$$

$$A = 1.02(\pi d^2/2 + \pi dL) \qquad (6)$$

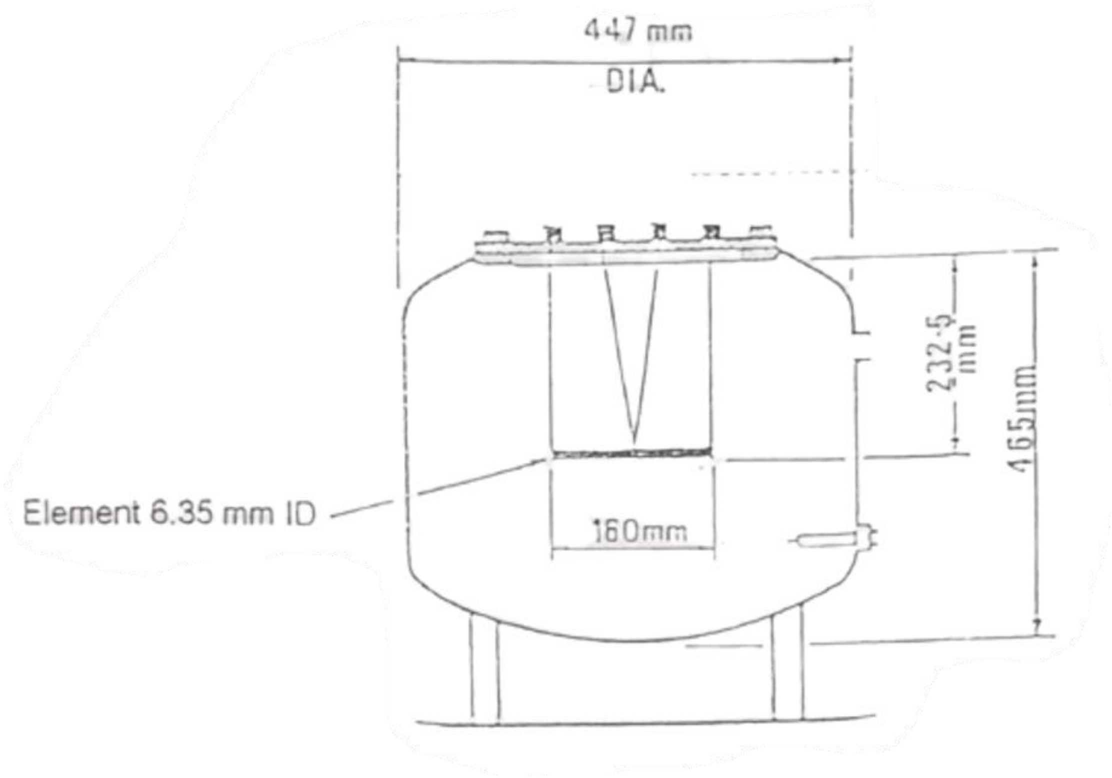


Figure (1): Schematic to show section through pressure vessel

Apparatus

Element and Pressure Vessel; The apparatus consists essentially of a cylindrical element suspended horizontally in a steel pressure vessel, as shown Figure 1. The vessel may be charged with air or other gas at a wide range of pressures. The element, of nominal dimensions 6.35 mm. diameter x 160 mm. long is of copper and is finished with a matte black surface. It is heated internally by means of a glass-insulated electrical heater, and its surface temperature is measured by a thermocouple at the midpoint. The top cover plate, from which the element is suspended, is bolted on. The element is sufficiently remote from the walls of the vessel to give substantially free convection.

The heat input to the element may range up to about 10 watts, and the maximum working temperature is 200C.With this very small heat input, heating of the pressure vessel is negligible and the temperature of the "atmosphere" in which the element is suspended may be taken as equal to that of the vessel and is measured by a thermocouple in the vessel wall.

The pressure vessel is connected by way of a copper pipe of large bore and an isolating valve to an electrically driven vacuum pump.

Instruments and Controls; The control panel at the front of the apparatus carries the following: -

a) Voltmeter and ammeter for indicating power supply to element.

b) On/Off switch for element power supply.

c) Rheostat for regulating element power supply.

d)Mercury 'U' tube for measuring pressure in vessel.

e) Mcleod vacuum gauge for measuring low pressures in vessel.

f) Thermocouple indicator for temperatures of element and vessel.

g) Screw down valves to put vessel in communication either with atmosphere or with compressed gas supply.

h) Pressure regulator for controlling compressed gas supply.

i) Change-over switch to permit measurement of element power input either by panel instruments or by external instruments.

j) Change-over switch: element thermocouple or vessel thermocouple to indicator.

k) Change-over switch: temperature measurement either by panel instrument or by external instrument.

l) On-Off switch for vacuum pump.

procedure:

A single set of observations, which will occupy a laboratory period of perhaps three hours, is sufficient to illustrate most features of the phenomenon. The element should be switched on and the rheostat adjusted to give a power input of about 5W. Close the valves leading to atmosphere and to the vacuum pump, turn the pressure regulator anti - clockwise to minimize the air supply pressure, carefully open the isolating valve between the air supply and the vessel and tum the pressure regulator clock- wise, observing the pressure in the vessel on the mercury 'U' tube.

When the pressure in the vessel reaches about 1600 mmHg as shown on the 'U' tube, close the isolating valve on the compressed air supply and observe the temperature of the element on the thermocouple indicator.

This temperature takes some minutes to stabilize, and it should be recorded when no further change is taking place. Record the temperatures of the element and the vessel, the voltage, current and the 'U' tube reading. The absolute pressure is determined by adding the barometric pressure to the 'U' tube reading.

Reduce the pressure in the vessel by about 500 mmHg by opening the atmospheric isolating valve and again observe the element temperature. This will increase and eventually stabilize. Repeat this operation for perhaps four different pressures including a reading at atmospheric pressure with the isolating valve open.

Now close the isolating valve, switch on the vacuum pump, and open the vacuum pump isolator, running the pump until the pressure in the vessel has been reduced to perhaps 150 mmHg below atmospheric. Close the vacuum pump isolator, shut off the vacuum pump, and take a set of readings once the temperature has stabilized.

Repeat the operation at progressively lower pressures. Once the absolute pressure has fallen below about 150 mmHg it is observed with the Mcleod gauge rather than the 'U' tube.

At each observation check the voltage and current reading to ensure that they have remained approximately constant, adjusting the rheostat if necessary. (Small variations from point to point do not affect the accuracy of the subsequent analysis.)

It will be found that as low absolute pressures are approached, the successive increases in element temperature become greater and a direct plot of the temperature difference (T_E-T_V) against absolute pressure would be of little use as a means of determining by extrapolation the value of (T_E-T_V) corresponding to zero pressure. It is, however, observed that a plot of T_E-T_V against 1/4 gives an approximately straight line, see Figure 3, and this provides a satisfactory basis for estimating conditions at zero pressure.

The procedure is to take a series of readings at progressively lower pressures, finally leaving the vacuum pump running for as long a time as is available to reach the ultimate vacuum of which the apparatus is capable, (this is nominally 0.03 mmHg, but under favorable conditions even lower pressures may be obtained).

It is possible that in transit a thread of mercury may become trapped in one or other of the Mcleod gauge tubes. This may be rectified by applying vacuum and gently tapping the tube. It should not be necessary to dismantle the gauge.

Two further experimental sequences may be found to be of interest. With the vacuum pump running and the pressure in the vessel at the lowest attainable value, the Stefan-Boltzmann equation may be verified by observing the relation between power input and element temperature, pressure remaining constant.

It is also interesting to determine the relation between power input and (T_E-T_V) at a range of different set pressures. Where a number of groups of students are to conduct laboratory work on the apparatus it may be appropriate to set each group to investigate a particular range of conditions, subsequently bringing all the results together.

Experimental results

Table (1) shows a set of observations made in accordance with the previous Section, with the vessel charged with air. The electrical input to the element should be maintained constant and the gas pressure varies over the full range.

For the unit concerned:

Given Data

Symbol	Value	Unit
L	160	mm
D	6.27	mm
A	0.00328	m^2

Ten sets of observations are sufficient. Figure 3 shows an expected plot of $(T_E - T_V)$ against $h^{\frac{1}{4}}$ for 100 [kPa] pressure region. Extrapolate to zero pressure and find the value of $(T_E - T_V)$

Take mean values for T_V, Q & T_e and insert these values in Equation (1) to get in emissivity ε.

O_R may now be calculated for each observed point by inserting this value in Equation (1). A typical logarithmic plot of (Nu) against (Gr) (Pr) is shown in Figure (2), which also shows the curve of "recommended values" from [2].

Table 2 shows a guide for a set of readings to be taken at minimum pressure with variable electrical input, to confirm the predictions of the Stefan - Boltzmann equation.

Figure 4 shows a typical plot of O_R against $(T_E - T_V)$ for the conditions listed in Table 2. Note that there is no specific theoretical justification for the method of extrapolation to zero pressure. It is merely a matter of experience that the observations at low pressure fall approximately on a straight line when plotted as in Figure 3.

A word of warning is necessary regarding the value of emissivity arrived at by the method outlined above. The true value of the emissivity of the cylinder surface is approximately 0.98. However, the various tolerances involved in the measurements are such that there is a possible scatter of approximately + 5% in the apparent value implying that in some cases values greater than unity may be thrown up. The reason for such results should be investigated by the student since they form a useful basis for a discussion on experimental accuracy. If instruments of secondary standard quality are available for measuring the power input to the element and the thermocouple potential they may be employed, with a resulting increase in accuracy of the determination of emissivity.

It is worth pointing out that even at the very low pressure of 0.004mmHg Table 2 shows that convective heat transfer accounts for nearly 10% of the total heat loss from the cylinder.

The student is urged to note the percentage of the convective heat transfer from the total heat loss from the cylinder for very low-pressure cases.

Table (1): Experimental results.

Barometer h_{a} = mmHg

Line	Point	1	2	3	4	5	6	7	8	9	10
1	Volts, V										
2	Amps, I										
3	U_{tube} mmHg										
4	θ_E , C										
5	θ_V , C										
6	Q, W										
7	T_E , K										
8	T_V , K										
9	T_m , K										
10	h, mmHg										
11	$h^{\frac{1}{4}}$										
12	Q_R										
13	Q_c										
14	α										
15	ρ										
16	k										
17	μ										
18	(Pr)										
19	(Nu)										
20	(Gr)										
21	(Gr)(Pr)										
22	$\log_{10}(Nu)$										
23	$\log_{10}(Gr)(\mathrm{Pr})$										

Table (2): Experiment results.

Line	Point	1	2	3	4	5	6	7
1	Volts, V							
2	Amps, I							
3	θ_E , C							
4	θ_V , C							
5	Q, W							
6	T_E , K							
7	T_V , K							
8	T_m , K							
9	h, mmHg							
10	$h^{\frac{1}{4}}$							
11	ρ							
12	k							
13	μ							
14	(Pr)							
15	(Gr)							
16	Q_c							
17	Q_R							
18	Q_R, Eq. (1)							

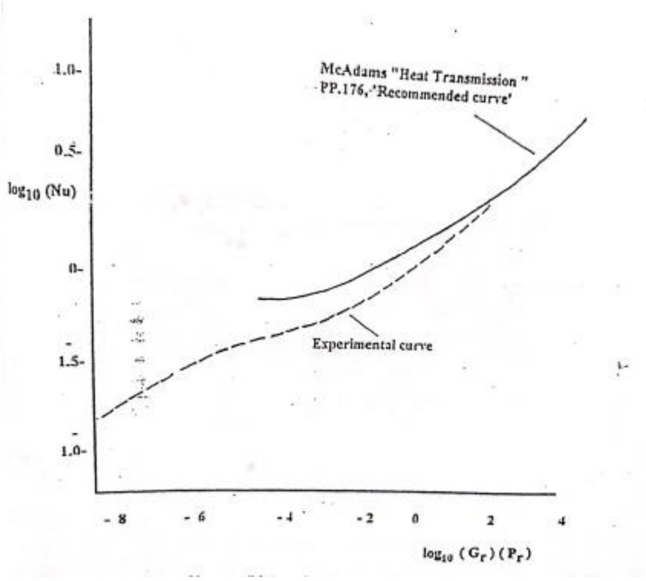


Figure (2): Relationship between 10Log(Nu) against 10Log(Gr)(Pr)

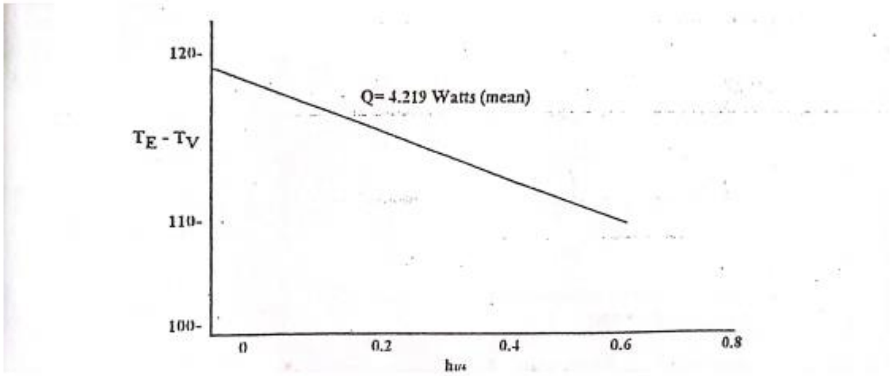


Figure (3): plot of ($T_E - T_V$) against $h^{\frac{-}{4}}$

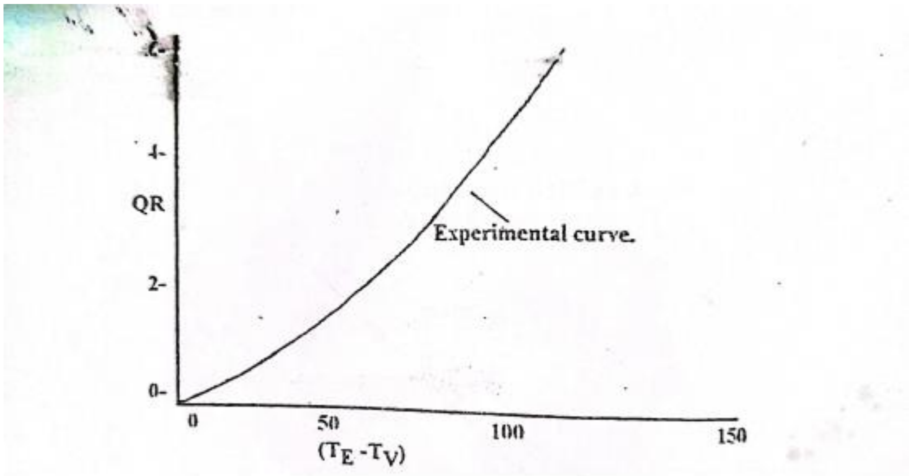


Figure (4): Plot of Q against ($T_E - T_V$)

Table (3): List of symbols.

Symbol	Meaning	Unit
d	Diameter of element	m
L	Length of element	m
A	surface area of element	m^2
V	Voltage	volt
I	Current	A
Q.	Corrected power input	W
Tm	Mean temperature	K
ha	Barometer	mmHg
h	Absolute pressure	mmHg
$\dot{Q}_R$	Heat transfer by radiation	W
$\dot{Q}_C$	Heat transfer by convection	W
g	Acceleration due to gravity	m/s^2
α	Heat transfer coefficient	$W/m^2.K$
ρ	Density	Kg/m^3
C_P	Specific heat at constant pressure	j/Kg.K
γ	Ratio of specific heats	-
β	Coefficient of expansion	-
K	Thermal conductivity	W/m.K
μ	Dynamic ciscosity	Kg/m.s
R	Gas constant	$Kg.m^2/s^2.K$
s	Mean free path	-

Table(4): Dimensionless numbers.

Dimensionless number	Formula
Nusselt number	$Nu = d\alpha/K$
Prandtl number	$Pr = Cp\mu/K$
Grashof number	$g\beta(\Theta_E-\Theta_V)d^3\rho^2/\mu^2$
Kundsen number	s/d

Theoretical Background

No attempt was given to give a complete theory. This is given in many standard texts, see for example

References

(1967). Rogers, G.F.C. and Mayhew Y.R(1)

(2) Engineering Thermodynamics: Work and Heat Transfer Longman McAdam Heat Transmission, McGraw-Hill (1954).

(3) Plint, M.A. and Boswirth, L. Engineering Thermodynamics; A Laboratory Course in Preparation.

(4) Boswirth, L. and Plint, M.A.(1975),Technische Stromungslehre. Schroedel.

Experiment [6]

Measurement of velocity and temperature profiles of air using pitot tube assembly

Objectives:

To examine the velocity and temperature profiles of air flowing in a section of heated pipe. Also, to determine the mean temperature rise in the air and to compare the mean velocity of the air by (a) the mass flow /mean density and (b) velocity profile methods.

Introduction:

The PITOT tube traverse unit and a manometer may be fitted to the forced convection heat transfer apparatus to enable studying the velocity and temperature profiles of the flow across a diameter of the pipe.

Apparatus:

The velocity and temperature traverse assembly, (a PITOT tube) may be traversed across a diameter of the heated pipe. Its position at any point is read directly from a combined linear scale and vernier. The PITOT tube measures the stagnation pressure only, the associated static pressure being sensed at a tapping point in the wall of the heated pipe. The difference between the two pressures is measured by a differential water manometer mounted on the panel and is used to calculate the velocity at points across the plane of the traverse.

The temperature of the air is measured by a thermocouple situated in the PITOT tube just behind the piezometer opening. The output from this thermocouple appears at selector switch position 14.

The whole assembly is mounted on a small flange secured to the heated pipe in such a position that the plane of the piezometer opening is at a distance of 276mm from the discharge end of the Pipe.

Procedure:

Switch on the fan with inlet valve fully open. When this has been done, the heater current can be switched on with the variable transformer SET AT ZERO. Increase the voltage to give a maximum current of about 4.5A. Leave the apparatus to warm up for at least thirty minutes to attain steady temperature conditions. The following observations can then be taken.

a. Air pressure before the orifice plate (fan pressure).
b. Pressure drop across the orifice plate.
c. Air temperature at inlet to the test pipe.
d. Barometric pressure / Ambient temperature.
e. PITOT pressure at 2mm intervals across the section of the pipe.
f. PITOT thermocouple reading at 2mm intervals.
g. Ammeter reading.
h. Voltmeter reading.

On completion of the experiment allow the fan to run for at least five minutes after the heater has been switched off to avoid overheating of the thermocouples. It should also be noted that when the PITOT tube is in a position near to the walls of tube a "whistling" sound may be heard. This is in no way injurious to the apparatus and will not affect the results. The velocity and temperature measured by the PITOT tube cannot be made at points less than half the diameter of the PITOT tube from the walls of the pipe. The diameter of the PITOT tube is 2mm.

Theory and Calculations:

1. **Mass flow rate** (**$\dot{m}$**):

Air pressure at orifice = (Barometric pressure + Fan pressure) kPa (1)

$$\text{Air density at orifice } (\rho_{\text{air}}) = \frac{\text{Air pressure at orifice (kPa)}}{0.2871 \times \text{Air temperature at orifice (K)}} \tag{2}$$

$$\text{Air mass flow rate } (\dot{m}) = \rho_{\text{air}} \times \text{orifice area} \times c_d \times \sqrt{2\Delta p/\rho_{\text{air}}} \tag{3}$$

Where:

Symbol	Meaning	Value
C_d	The orifice discharge coefficient	0.613
P	Pressure drop across the orifice	[ ] N/m^2

For determining Δp it may be noted that 1 mm of water = 9.81 N/m^2

2. **Air velocity at a point in the PITOT plane; Apply Bernoulli s equation.**

Air velocity at any point: $v = \sqrt{2 \times \frac{(P_s - P)}{\bar{\rho}_{air}}}$ (4)

Where:

Symbol	Meaning	Unit
Ps	Stagnation pressure	N/m^2
Ps	Static pressure	N/m^2
$\bar{\rho}_{air}$	Mean air density in PITOT plane	kg/m^3

3. **Air density in PITOT plane:**

- Mean air temperature rise (Kelvin) = $\frac{\text{Heat input rate (kJ/s)}}{\text{Mass flow rate (kg/s)}} \times \frac{\text{Heat loss factor}}{C_p} \times \frac{b}{1753}$

Mean air temperature rise (Kelvin) = $\frac{\text{Heat input rate (kJ/s)}}{\text{Mass flow rate (kg/s)}} \times \frac{\text{Heat loss factor}}{C_p} \times \frac{b}{1753}$ (5)

where b is the length of heater tape up to the PITOT plane (1477 mm) and the heat loss factor may be taken as 0.94 or as determined from prior experiment. C_p for air may be taken as 1.0 kJ/kg °C.

Mean air temperature = Inlet air temperature + temperature rise. (6)

Mean density in PITOT plane ($\bar{\rho}$) = $\frac{\text{Static pressure in PITOT plane}}{0.2871 \times \text{Mean air temperature}}$ (7)

The static pressure in the PITOT =Barometric pressure + (276/1524) * test length pressure drop (8)

4. **Mean air velocity in PITOT plane:**

a) Mean velocity from mass flow = $\frac{\text{mass flow rate (kg/s)}}{\bar{\rho} \times \text{pipe area}}$ (9)

b) Mean velocity [from velocity profile]: $\bar{V}(\mathrm{m/s})\ \frac{2\,\pi \times 10^{-6}}{\text{pipe area }(\mathrm{m}^2)} \sum \text{Area of (ABCD} * \text{r)}$ (10)

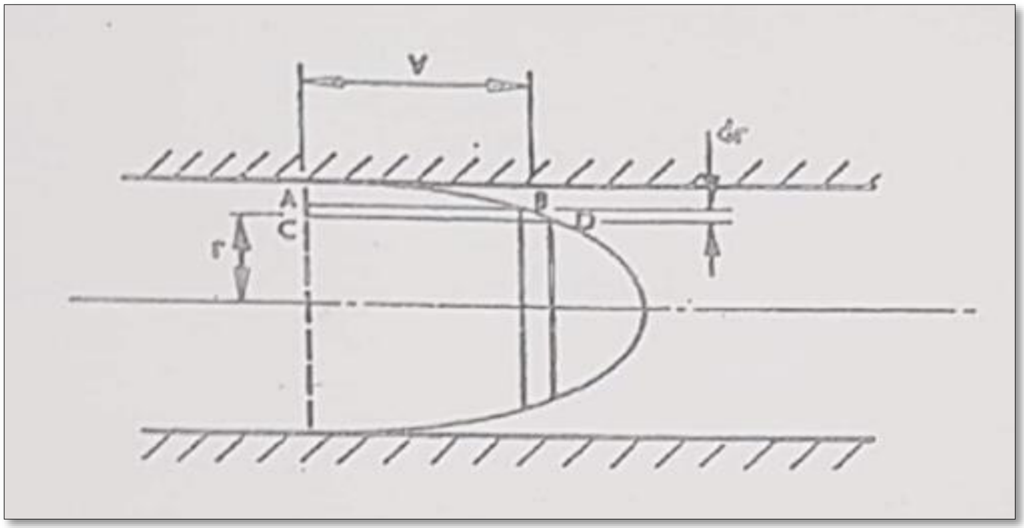


Figure (1): Velocity profile.

Guide for data recording:

Table (1): Collected data.

Room temperature	
Barometric pressure	
Air inlet temperature	
Fan pressure	
Orifice pressure drop	
Test length measure drop	
Heat current	
Heater voltage	

Table (2): Data observed

	PITOT Traverse Distance mm	Actual Distance Across Tube mm	(Ps - P) mm of Water	v m/s	Air temperature (Above Inlet) °C
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Experiment (7)
Cross Flow Heat Exchanger

Objective

- To learn the meaning of cross flow heat exchanger, convection heat transfer coefficient, the variation of Nusselt and Reynolds numbers with air flow past cylindrical tubes.
- To study the performance of cross flow heat exchanger and calculate heat transfer coefficient and also heat transfer rate

Introduction

Cross flow heat exchanger is a device that exchanges heat between hot and cold streams flowing at right angle to one another.in addition to Flow of a fluid normal to objects or groups of objects such as cylinders is referred to as crossflow. It is to be differentiated from longitudinal flow along the axis of symmetry, the term inclined crossflow being used to describe the intermediate condition.

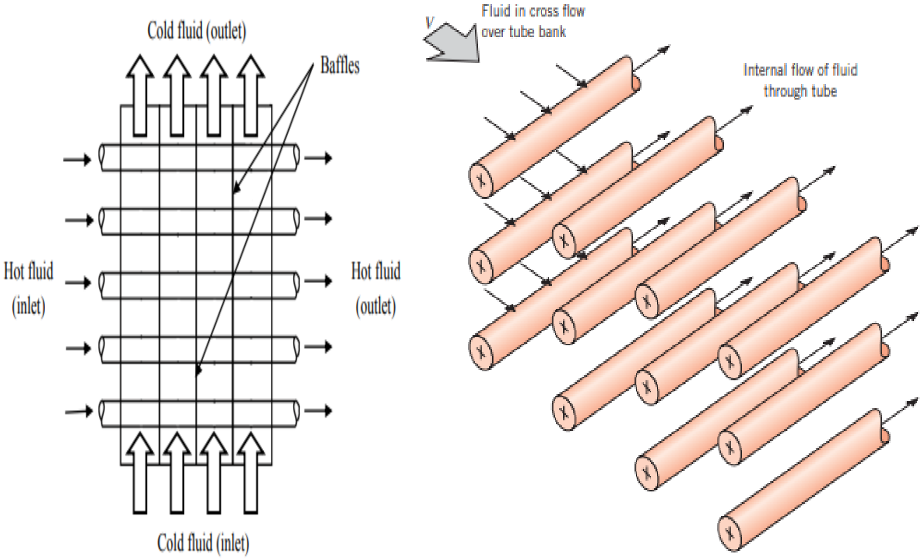


Figure (1): Diagram showing cross flow heat exchanger

The tube rows of a bank can be either aligned or staggered in the direction of the fluid velocity V (Figure 2). The configuration is characterized by the tube diameter D and by the transverse pitch ST and longitudinal pitch SL measured between tube centers.

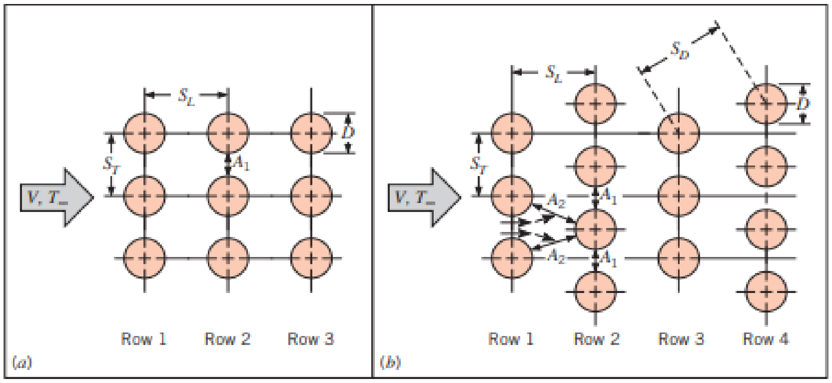


Figure (2): (a) Aligned, (b) Staggered

Apparatus

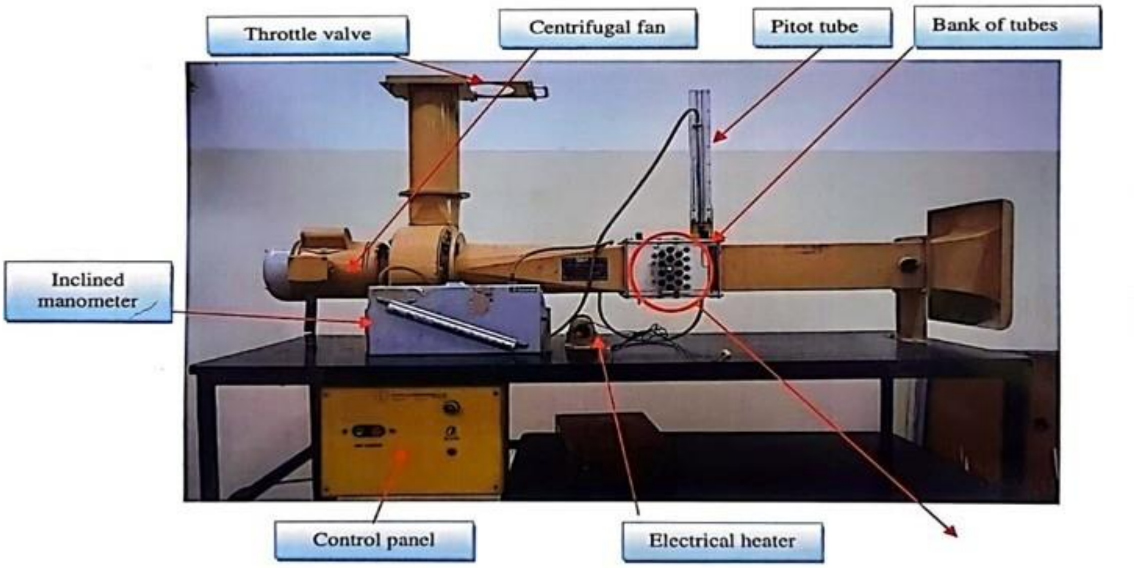


Figure (3): Experiment Setup

Consists of Perspex working section through which air is draw by a centrifugal fan, cylindrical electric heater and copper element, inclined manometer, Pitot tube to measure the velocity of flow, thermocouple wires and control unit.

The apparatus consists of a rectangular duct which is designed and constructed in sections, clipped tightly together with snap – action fasteners and supported at four points along its length. Entry and exit duct – sections are separated by a plain center – section which is easily removed for insertion of the optional heat – exchangers and an electrical re-heat element. A flow straightener is fitted upstream of the heat-exchangers

Inspection windows, made from double-glazed glass, are provided upstream, downstream, and on both sides of the inter – changeable center sections; these windows are for observation of the heat exchangers during tests. A window above the Refrigerant 12 cooling coil permits close observation of the air-cooling process and of conditions upon the coil surface.

The centrifugal fan is arranged to draw air along the duct and is provided with means for varying the flow rate i.e., a throttle slide-plate at the fan delivery. An alternative axial –flow air screw fan is supplied with a transformation duct, as rapid replacement for the Centrifugal fan.

Determination of the air-flow rate; The air velocity profiles can b made by PITOT Static tubes mounted in a traversing mechanism at two measuring stations. The air flow rate so obtained may be used to calibrate the conical duct entry which is equipped with a piezometer ring comprising four pressure tapping one at the center of each side. The ring – tube links all four tapping an average pressure reading.

Three forms of tube-banks are currently available; these are:

a. Plain copper tubes for a liquid – to – air heat transfer element; The plain tubes are arranged normal to the direction of airflow, in a staggered configuration.
b. Gilled tubes for a liquid-to-air heat-transfer element; The gilled tubes are arranged normal to the direction of airflow, in a staggered configuration.
c. A refrigeration coil for air-cooling by direct-expansion of R12 refrigerant in a bank of a Copper tubes, in staggered configuration with aluminum block -fins. The tube side medium car Be cool glycol solution or water for a and b, and cold R12 (Freon) for c.

The tube side flowrates can in all cases be measured and adjusted to give single (serial) or triple (parallel) pass by adjustment of the fitted control valves Air pressure changes are measured by PITOT static tubes linked to a precision multi range Manometer.

The temperature measurement facility consists of two electrical resistance grids Linked to a calibrated temperature meter. These grids can be slotted into the duct, upstream and down – stream of the heat transfer element, and provide accurate measurement across the Full duct cross sections of the temperature change of the air passing over any of the coils

This feature, instantly and accurately, measures the average temperature change in the stream of air entering and leaving the heat – exchange elements.

Advantage of Cross Flow

1- The fluids in the cross-flow heat exchanger is passing vertically to each other, unlike parallel heat exchangers. So, it is considered an efficient design than a parallel heat exchanger.
2- Compared to parallel and counter flow heat exchangers, the cross-flow heat exchanger is thermodynamically effective
3- Logarithmic mean temperature difference (LMTD) is greater than parallel-flow heat exchanger.
4- Cross-flow heat exchangers require less surface area to attain the same heat transfer rate than other exchangers.
5- The multi-pass cross-flow heat exchanger can be easily manufactured than parallel and counter flow heat exchangers.

Disadvantage of Cross Flow

1- Multiple passes have a disadvantage of load loss, i.e., the pressure difference between inlet and outlet.
2- Relative smaller operating pressures when compared to shell and tube HE.
3- Typically, medium to high pressure drop
4- Relatively small tolerance to fouling and chemical aggressive fluids.
5- Limitations in terms of phase change applications.

Applications

Air cross-flow heat exchangers are used extensively in the refrigeration and cooling industry. Another primary application of cross-flow heat exchangers is automobile radiators. These exchangers are also used in air conditioning circuits.

Procedure

The air – duct is linked to the heat transfer bench for the production of hot water the linkage is through the entry duct system which can be one of two:

1- Plain tube heat transfer element
   - Single pass
2- Finned tube heat transfer element
   - Single pass
   - Triple pass

The flow of hot water is measured by the floe meter fitted in the heat transfer bench. The flow of air along the air-duct is calculated from the measured pressure drop in the entry section using equations described in the theory section. The air-flow rate can be changed by varying the exit area of the suction fan. The heat transfer rate is then, calculated in the two methods described before.

Calculations

21-The heat flow rate (q) transferred between the two fluids by the hot side:

$$q = h \times A_1 \times (T_e - T_A) \qquad (1)$$

Where:

Symbol	Meaning	Unit
q	Heat transfer rate	kJ/sec
h	heat transfer coefficient	$W/m^2.K$
A	surface Area	m^2
T_e	temperature of flow	°C
T_A	Temperature of surface	°C

22-The heat transferred coefficient:

$$h = -2.3026\left(\frac{m\ c}{A_1}\right) \times M \qquad (2)$$

Where:

Symbol	Meaning	Unit
h	Heat transfer coefficient	$W/m^2.K$
c	Specific heat	J/K.kg
M	$slope = \frac{\Delta T_{log}}{\Delta time}$	°C /s

23-Nusselt number:

$$\mathrm{N_u} = \frac{\mathrm{h\ d}}{\mathrm{K_{air}}} \tag{3}$$

Where:

Symbol	Meaning	Unit
h	Heat transfer coefficient	$W/m^2.K$
d	Tube diameter	m
k	Thermal conductivity	W/m.K

24-Reynolds number:

$$R_e = \frac{\rho\ d\ V}{\mu} \tag{4}$$

Where:

Symbol	Meaning	Unit
ρ	Density of flow	Kg/m^3
d	Tube diameter	m
V	Velocity of flow	m/s
μ	Dynamic viscosity	$N.s/m^2$

25-Velocity of flow:

$$V_1 = 237.3 \times \sqrt{\frac{H_1\ T_A}{P_A}} \tag{5}$$

Where:

Symbol	Meaning	Unit
H_1	Pressure difference	mm
P_A	Pressure	Pa
V_1	Velocity of flow	m/s
T	Temperature	K

The relation between Log(T-Ta) with Time at different percentage of throttle opening as shown below in figure (4).

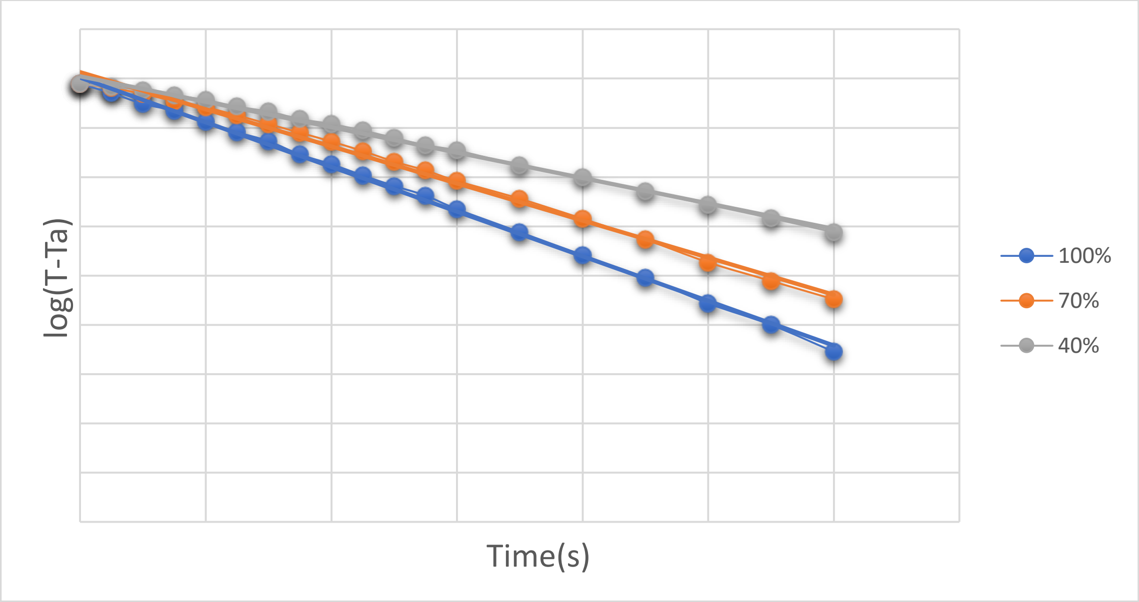


Figure (4) variation of Log(T-Ta) with Time (s)

Observed Data

T_{air} =

P_{atm} =

Table (1): Data Observed

	ΔP=	**ΔP=**	**ΔP=**
	100%	**70%**	**40%**
Time(s)	**Te [^{o}C]**	**Te [^{o}C]**	**Te [^{o}C]**
0			
5			
10			
15			
20			
25			
30			
35			
40			
45			
50			
55			
60			
70			
80			
90			
100			
110			
120			

Results Table

Table (2): Data Calculated

	$\Delta P=$ [mmH$_2$O]	**$\Delta P=$ [mmH$_2$O]**	**$\Delta P=$ [mmH$_2$O]**			
	100%	**70%**	**40%**	**100%**	**70%**	**40%**
Time(s)	**Te [^{o}C]**	**Te [^{o}C]**	**Te [^{o}C]**	**log(T-Ta)**	**log(T-Ta)**	**log(T-Ta)**
0						
5						
10						
15						
20						
25						
30						
35						
40						
45						
50						
55						
60						
70						
80						
90						
100						
110						
120						

Table (3): Data Calculated

Throttle opens	**H [mm.H_2O]**	**V1 [m/s]**	**V [m/s]**	**h [$W/m^2.°C$]**	**Re**	**Nu**
100%						
70%						
40%						

Result and Discussion

- Calculate the value of heat transfer rate and Reynolds number and Nusselt number when throttle opening by different percentage and fill table (2) and table (3) and show sample of calculation.
- Plot log(T-Ta) variation with time.
- Mention the impossible source of error during the experiment.

Experiment [8]
THERMAL CONDUCTIVITY

Objectives

To determine;

a) The coefficient of thermal conductivity for a good conductor.

b) Rate of heat transfer.

Theory

When a temperature gradient exists in a body, an energy transfer from high-temperature region to low-temperature region takes place. It is said that the energy is transferred by conduction, and that the heat transfer rate per unit area is proportional to the temperature gradient:

$$\frac{q}{A} \& (\frac{dT}{dx}) \qquad (1)$$

The above relation may be represented mathematically in the form:

(q / A) = k (dT / dx)

$$\frac{q}{A} = K \times (\frac{dT}{dx}) \qquad (2)$$

Where:

Symbol	Meaning	Unit
q	heat transfer rate	Watt
dT/dx	The temperature gradient in the direction of heat flow.	^{o}K/m
K	Thermal conductivity of the material	W/m.^{o}K
A	Cross sectional area of the material	m^{2}

The Apparatus

The apparatus consists of a self-clamping specimen stack assembly with electrically heated source, calorimeter base, Dewar vessel enclosure to ensure negligible loss of heat and constant head cooling water supply tank. A multipoint thermocouple switch is mounted on the steel cabinet base and two mercury and glass thermometers are provided for water inlet and outlet temperature readings.

Four NiCr/NiAl thermocouples are fitted and connections are provided for a suitable potentiometer instrument to give accurate metal temperature readings.

Four metal specimens are provided. Two holes are provided in each specimen for insertion of the thermocouples. A sketch of the specimens is shown below:

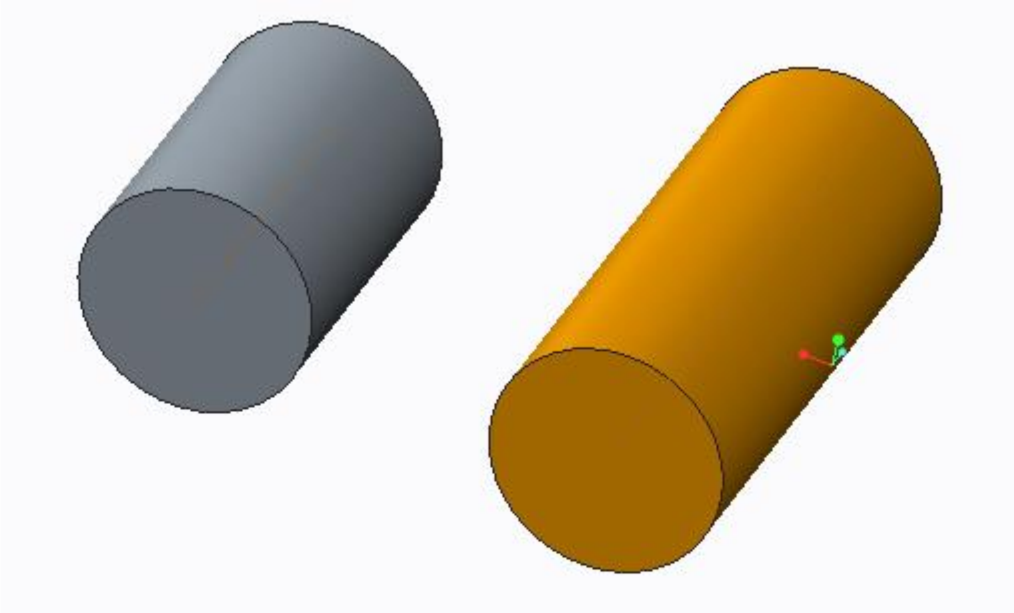


Figure (5): Geometry of specimens.

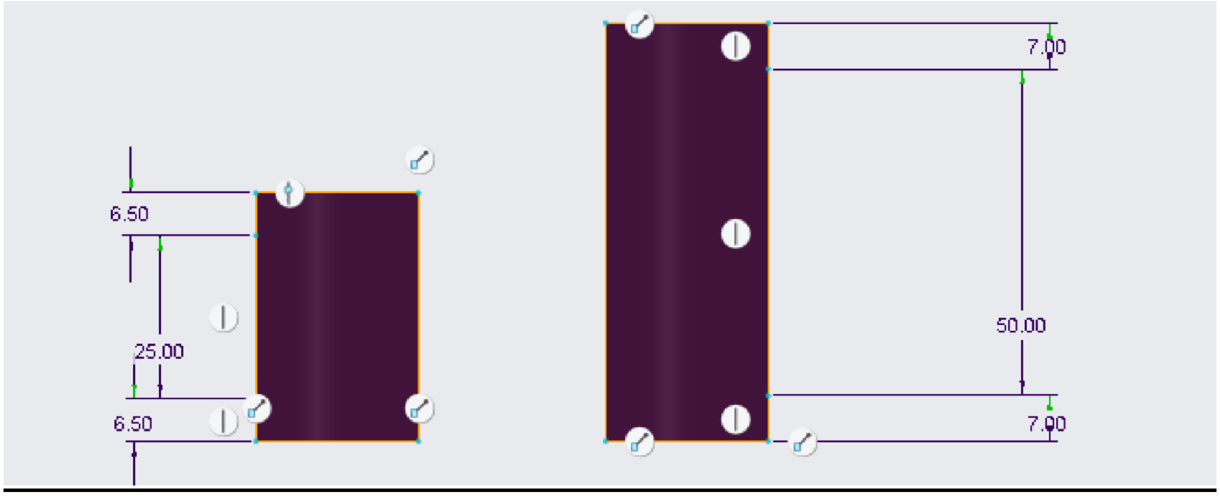
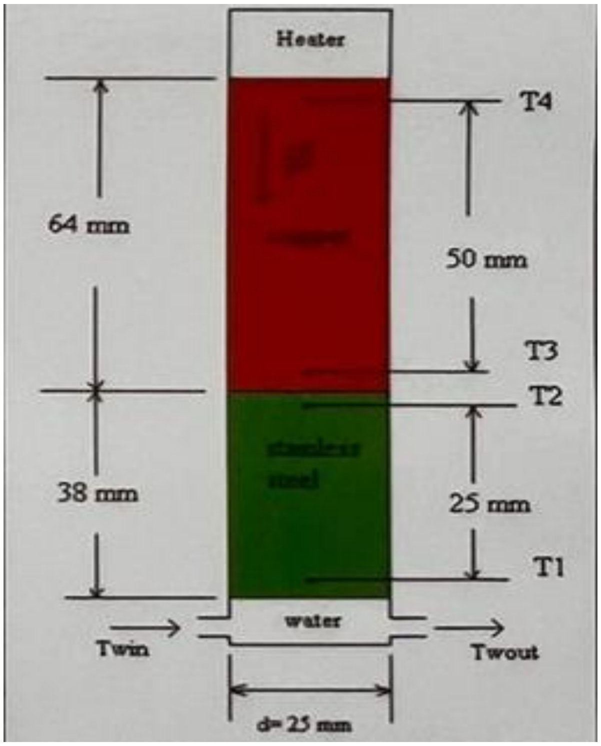


Figure (6): Dimensions of specimens.



Figure(7): All dimensions.

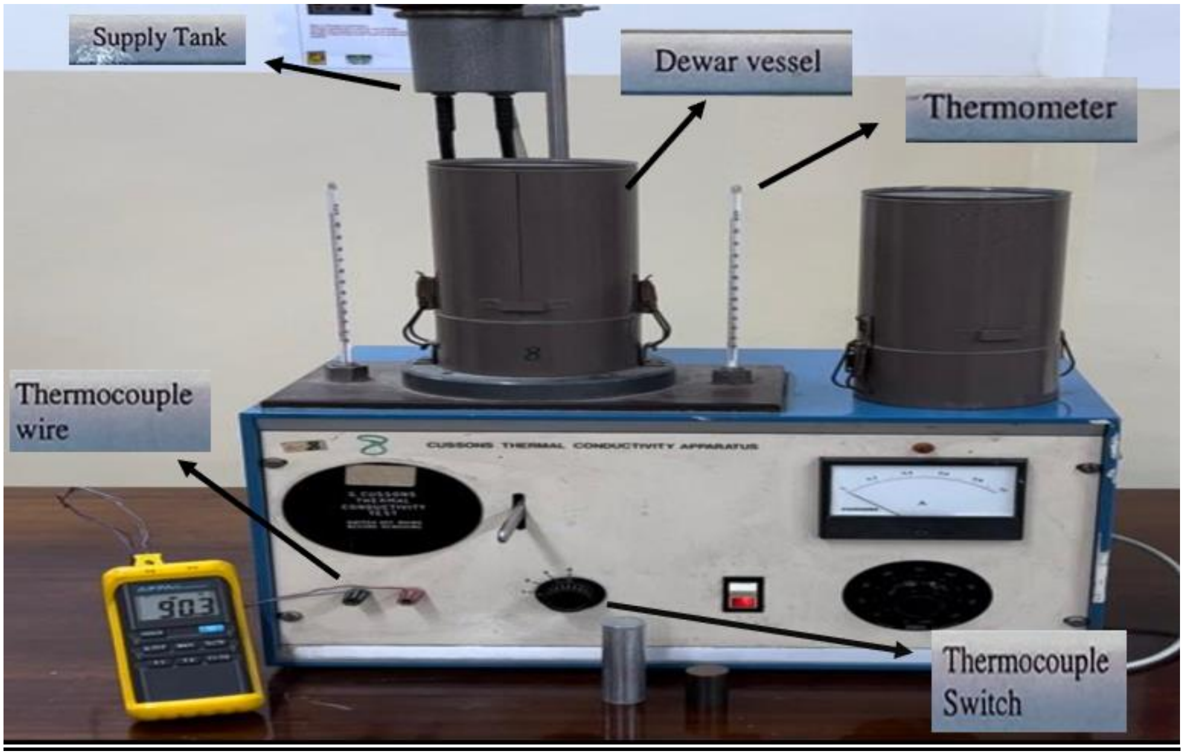


Figure (8): Apparatus of the experiment.

Procedure

The apparatus is assembled with one short specimen (mild steel or stainless steel, i.e. low conductivity material) in the lower position, and one long specimen (copper or aluminum, i.e. high conductivity material) in upper position.

After selecting specimens to be used in the experiment, ensure that they are completely. free from dirt especially at the ends where contact is to be made. Apply a light smear of Silicone Grease al the ends of the specimens before assembly to ensure good thermal contact.

Operate the clamp by moving the protruding lever positioned on the front of the apparatus to a downward position and place specimens between healing element and clamp. Ensure that the holes for the thermocouples are accessible. Release the lever, thereby clamping specimens in position. Insert thermocouples into holes provided.

3- Ensure that the thermostat adjustment control which is situated on the front of healing element is turned fully clockwise. This sets the cut-out temperature to approximately 210 °C. The normal maximum working temperature is 200 * C.

4- Place the Dewar vessel in position over specimens.

5- Fit the thermometers into the special leak proof connections provided on lop of calorimeter base.

(a) Connect water pipes from water supply to header lank, header tank to inlet on apparatus, and header tank overflow to drain.

(b) Tum on water supply. Adjust flow rate through the apparatus by means of the inlet flow valve positioned at inlet pipe. Note that the actual flow rate is not critical, however, a temperature difference of about 8 °C should be sought.

6- Connect the potentiometer instrument to the two terminals provided on the front of the apparatus.

7- Connect the control box to the socket on the right-hand side of the conductivity apparatus and connect the control box to a single-phase AC main. Check that the supply voltage is correct.

&- Switch on the electrical supply and check that indicating lights on both control box and calorimeter base are operative.

9-Before readings can be obtained from the apparatus, the heat flow must reach a steady state condition. This can be done in either of two ways as follows: -

(a) Set current input to a maximum, this being about 0.55 amps.

Maintain this until a temperature of 200 °C is obtained from the thermocouple nearest the element (T4). This will take 15-20 minutes. Reduce the current to 0.3 amps until the temperatures have become steady. This will take 20-25 minutes.

(b)

Set current to 0.3 amps. Leave for a period of approximately 2 hours.

NOTE: - In both of the above methods the water must be flowing continuously.

Calculations

(a) To determine the thermal conductivity of each specimen use: -

$$K = \frac{J \times M \times L \times (T_2 - T_1)}{A \times t \times (T_4 - T_3)} \tag{3}$$

Where:

Symbol	Meaning	Unit
K	Thermal conductivity	W/m.ºK
J	mechanical equivalent of heat	Joule/kCal
M	Mass of water	kg
T1	Water inlet temperature	ºC
T2	Water outlet temperature	ºC
A	Area of specimen	m^2
t	Time for flow of M kg of water	seconds
T3	Thermocouple temperature (cold end)	ºC
T4	Thermocouple temperature (hot end)	ºC
L	Distance between thermocouples	m

b- To determine the heat flow per second over the whole length of the two specimens. Construct the temperature gradient graphs and extrapolate to determine the temperatures at the extreme faces x1 and x2. Having found these values apply them to the formula;

q= （x1 – x2) / (L1/AK1) + (L2/AK2) ....W /m^2

$$q = \frac{\mathrm{x}_1 - \mathrm{x}_2}{\frac{\mathrm{L}_1}{\mathrm{AK}_1} + \frac{\mathrm{L}_2}{\mathrm{AK}_2}} \qquad (4)$$

Where:

Symbol	Meaning	Unit
X1	Temperature at element end	ºC
X2	Temperature at water end	ºC
L1	Length of short specimen	m
K1	Thermal conductivity of the short specimen	W/m.ºK
L2	Length of long specimen	m
K2	Thermal conductivity of the long specimen	W/m.ºK
A	Cross sectional area of the specimens	m^2

The text book values for thermal conductivity for the specimens provided are:

Table (1): Thermal conductivity of some materials.

Material	Value	Unit
Aluminum	210	W/m.K
Copper	385	W/m.K
Mild steel	42	W/m.K
Stainless steel	30	W/m.K

Guide for Data Recording

Test Material: **Time to reach steady state :**

Current: **Total time for test:**

Water Flow Rate:

Table (2): Temperature readings obtained.

No	Time(sec)	T1	T2	T3	T4
1					
2					
3					
4					
5					
Total					
Average					

Typical Temperature Profile:

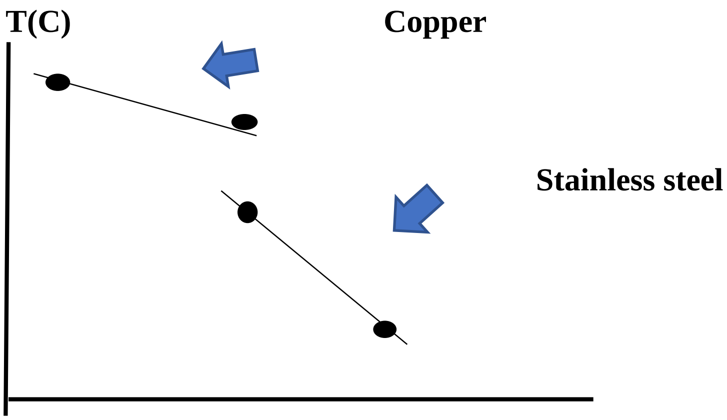


Figure (5): Temperature reading profiles for both materials.