UNIVERSITY OF JORDAN
FACULTY OF ENGINEERING & TECHNOLOGY

HEAT TRANSFER
LABORATORY MANUAL

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MECHANICAL
ENGINEERING
DEPARTMENT

A GUIDE FOR PREPARATION OF LABORATORY REPORT

A student often regards the writing up of his work into a report as the least necessary part of laboratory or project work. A student with a retentive memory and a set of notes may possibly be able to reproduce the work at a later date, but no experiment or research is complete until it is written up. Evaluating and grading of the experiment performed by a student in a laboratory is based primarily on the evaluation of the written report he submits to the instructor. The student must have a good command of English language if he is to produce an acceptable report. He should realize that apart from forming a personal record of his work, the writing of reports is an important and essential part of professional life.

An effective report should contain clear, precise, direct, restrained, logical and fluent statements. This should be achieved by using short words, sentences, and paragraphs in a well ordered arrangement with an objective and positive style. After reading through the notes a student should prepare a draft outline of the report, containing all the relevant data from the notes.

The report should be laid out to a coherent plan and could include the following headings :

- Title and other data such as
    - course number
    - student name
    - lab instructor name
    - date on which the experiment was performed.
- Objectives (purpose of the work).
- Theory (summary of relevant notes).
- Apparatus (brief of relevant notes).
- Procedure (including illustrations, diagrams... etc.).
- Results (observations made and entered in suitable tables).
- Calculations (sample calculation).
- Graphs (plotted on one side only of separate sheets).
- Conclusions (comments and recommendations).
- List of references consulted.
- Appendices (illustrations, tables, diagrams... etc.).

The report should be originated by the person preparing it. Copying or even paraphrasing of materials from other student's work is clearly unethical and must be positively avoided by all students.

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:

$$(q / A) \propto (dT / dx)$$

where;

q : The heat transfer rate
dT / dx : The temperature gradient in the direction of heat flow.

The above relation may be represented mathematically in the form;

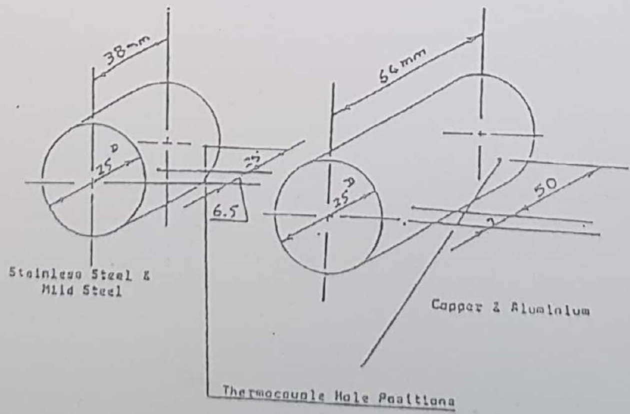
$$(q / A) = k\,(dT / dx)$$

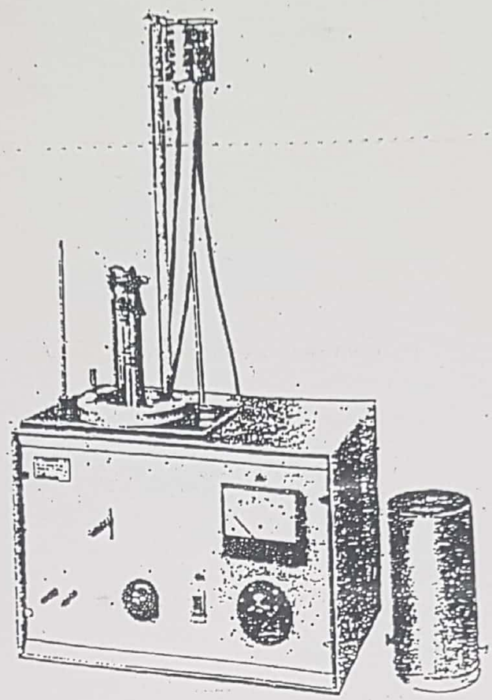
where k is the thermal conductivity of the material.

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.





PARATUS

Procedure:

1-The apparatus is assembled with one short specimen (mild steel or stainless steel, i.e. low conductivity material) in 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 at the ends of the specimens before assembly to ensure good thermal contact.

2- Operate the clamp by moving the protruding lever positioned on the front of the apparatus to a downward position and place specimens between heating 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 heating 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 top of calorimeter base.

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

(b) Turn 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 mains. Check that the supply voltage is correct.

8- 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 (T_4). 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:-

$$k = \frac{J * M * L(T_2 - T_1)}{A * t(T_4 - T_3)} \ldots\ldots\ldots W/mK$$

where

k = thermal conductivity
J = mechanical equivalent of heat (4186 Joules / kcal)
M = mass of water (kg)
T_1= water inlet temperature (°C)
T_2= water outlet temperature (°C)
A = area of specimen (m^2)
t = time for flow of M kg of water (seconds)
T_3= thermocouple temperature (cold end) (°C)
T_4= thermocouple temperature (hot end) (°C)
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 x_1 and x_2. Having found these values apply them to the formula;

$$q = \frac{(x_1 - x_2)}{(L_1 / Ak_1) + (L_2 / Ak_2)} \text{ ....} W/m^2$$

Where x_1 = Temp at element end. (°C)
x_2 = Temp at water end. (°C)
L_1 = length of short specimen. (m)
A = Area of specimen.(m)
k_1 = Thermal conductivity of short specimen. (W/mK)
L_2 = Length of long specimen. (m)
k_2 = Thermal conductivity of long specimen. (W/mK)

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

Aluminum	210 W/mK
Copper	385 W/mK
Mild steel	42 W/mK
Stainless steel	30 W/mK

Guide for Data Recording:-

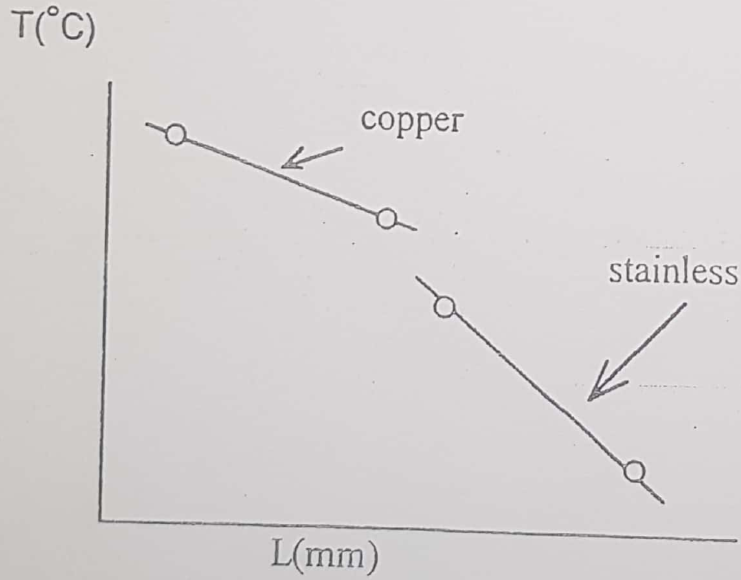
Test Material:
Current:
Water flow rate:

Time to reach steady state:
Total time for test:

Temperature readings obtained.

No	Time (sec)	T_1	T_2	T_3	T_4
1					
2					
3					
4					
5					
Total					
Average					

Typical Temperature Profile:



FORCED CONVECTION HEAT TRANSFER

Objectives:

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 by empirical formulae.

Introduction:

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.

Description of the apparatus

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 with in 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.

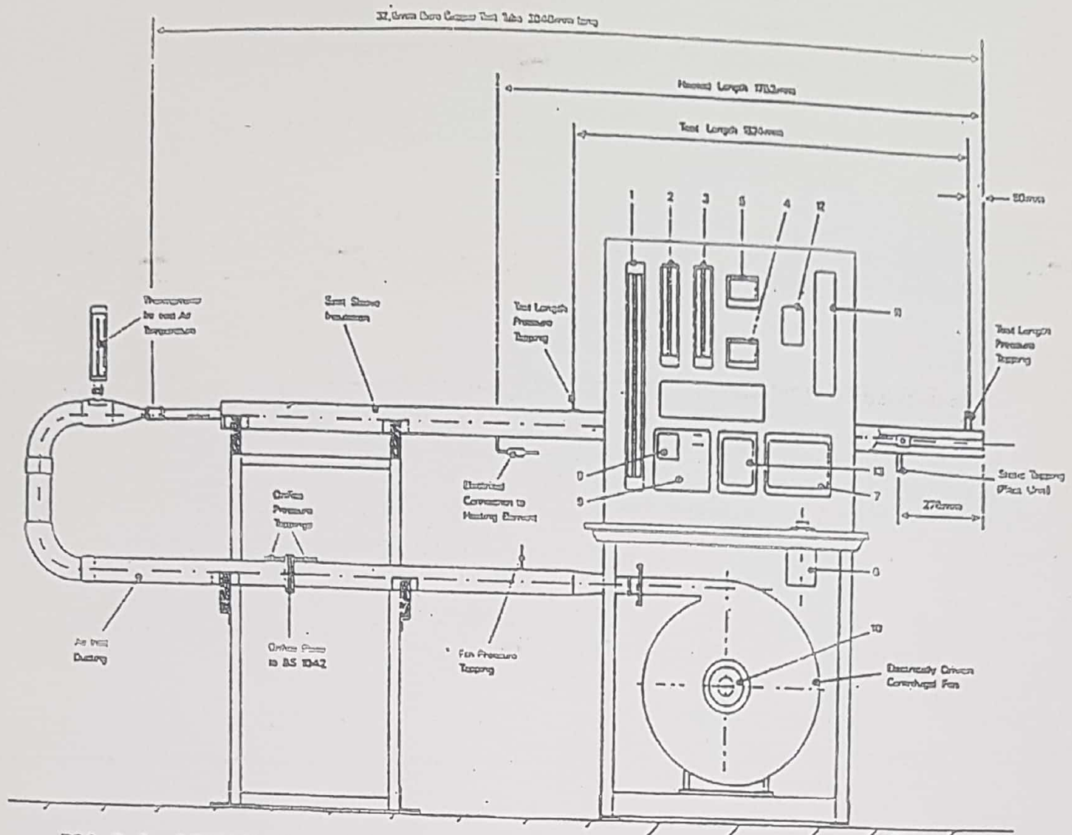


FIG 2.1 GENERAL ARRANGEMENT OF APPARATUS

OVERALL DIMENSIONS: LENGTH - 3,75 m; HEIGHT - 1,75 m; DEPTH - 0,91 m

Particulars of the apparatus:

Orifice-plate diameter	40 mm
Pipe internal diameter	32.6 mm
Pipe wall thickness	1.20 mm
k for pipe material (copper)	380. 6 J/ms °C
Thickness of lagging	25 mm
k for pipe lagging material	0.0415J/ms °C
Heated length of pipe	1753 mm
Thermocouple material	Copper Constantan to B.S. 1828

The pressure tapping on the pipe are at 51 mm and 1575 mm from the exit.
Electrical supply: 380/440 V, 3 phase neutral earth, 50 Hz, 15 amp, as standard.
Maximum allowable tube temperature; 150 °C(thermocouples 1 to 7)

Procedure:

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 steady temperature conditions. The maximum tube temperature (thermocouples 1 to 7) should not exceed 150°C. The following readings can then be taken.

1. Air pressure before the orifice plate (fan pressure)
2. Pressure drop across the orifice plate.
3. Air temperature at inlet to the test pipe.
4. Barometric pressure/Ambient temperature.

5. Pressure drop over the test 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.

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 allow the temperatures to stabilize. *On completion of the testing the fan should be allowed to run for at least five minutes after the heater is switched off in order to avoid overheating the thermocouples.*

Theory and Calculations:

The calculations fall into six parts as described in the following sections.

1. Mass flow rate

Air mass flow rate, W = ρ * orifice area * Cd $\sqrt{2\Delta p/\rho}$ kg/s (1)

Where, C_d = 0.613 the orifice discharge coefficient

ρ = air density at orifice (kg/m^3)

Δp = pressure drop across orifice (N/m^2)

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

2. Heat flux

Heat input by heating tape,

$$Q_1 = \frac{\text{Amps} \times \text{Volts}}{1000} \quad \text{kJ/s} \qquad (2)$$

Heat lost through lagging,

$$Q_2 = \frac{0.0415}{1000} \times \frac{2\pi \times 1.753}{\ln(r_o / r_i)} \times \left[\begin{matrix}\text{mean temp. drop} \\ \text{across lagging}\end{matrix}\right] \text{kJ / s} \qquad (3)$$

Where r_i and r_o are the inside and outside radii of the Lagging. Heat flux through tube wall,

$$\Phi = \frac{Q_1 - Q_2}{\text{internal pipe wall area}} \quad \text{kJ/m}^2\text{s} \qquad (4)$$

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 at the other.

3. Mean air temperature at chosen heat transfer section.

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 lost through the lagging.

Heat input by conduction,

$$Q_3 = \frac{380.6}{1000} 0.6 \times \frac{2\pi rt}{10^6} \times \frac{\text{temperature drop}}{L4(=1.0\text{m})} \quad \text{kW} \qquad (5)$$

Where:-

r = mean radius of copper tube (mm)
t = wall thickness (mm)
L_4 = Length of heated section (m).

Total heat input up to chosen section,

$$= (Q_1 - Q_2) \times \frac{(b)}{1753} + Q_3 \quad \text{kJ/s} \qquad (6)$$

where b is length of heated pipe up to chosen section (mm). The bulk mean air temperature,

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

Where:-

T_i = air inlet temperature
C_p = specific heat of air at inlet temperature

4. **Heat transfer coefficient.**

$$\text{Heat transfer coefficient, } h = \frac{\text{Heat Flux}}{(T_w - T_h)}$$

The wall temperature T_w 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.

5. **Experimental values of Nu, St, and f**

(i) Nusselt Number,

$$Nu = hd/k. \qquad (9)$$

(ii) Stanton Number,

$$St = h / (\rho \ V C_p) \qquad (10)$$

(iii) Calculation of friction factor, f using the simple equation,

$$p_1 - p_2 = (2f\,L/d)\,\rho\,v^2 \tag{11}$$

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 equation:-

$$p_1 - p_2 = \frac{1}{\bar{\rho}}\,\frac{W^2}{A^2}\left[\left[\frac{4fL}{2d} + \frac{T_2 - T_1}{\bar{T}} + \ln(p_1/p_2)\right]\right] \tag{12}$$

This is known as the Guggenheim Equation,

6. **Calculation of Nu, St and f using normally accepted expressions**

$$Nu = 0.023\,Re^{0.8}\,Pr^{0.4} \tag{13}$$

$$St = 0.023\,Re^{0.2}\,Pr^{0.6} \tag{14}$$

$$f = 0.079\,Re^{-1/4} \text{ (Turbulent region only)} \tag{15}$$

where,

$$Re = \rho v d/\mu$$

It may be noted that Prandtl number ($Pr = \mu Cp/k$) and has almost the same value for all gases and varies very little with temperature and pressure.

Reynolds analogy is based on the assumption that Pr = 1, and may be written as :-

$$Nu = (f/2)\;Re \tag{16}$$

Since $St = Nu/Re.Pr$ it follows that,

$$St = f/2 \tag{17}$$

By substituting in equation (14) and putting Pr = 1, we obtain an alternative formula from which f can be calculated:-

$$f = 0.046\,Re^{-0.2} \tag{18}$$

values obtained from these equations can then be compared with experimental values.

Test tube dimensions

Tube bore	31.75 mm
Wall thickness	1.63 mm
Lagging thickness	19.0 mm

Other particulars were as stated previously

Readings:

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

Reference Number	Actual T °C	ΔT across lagging °C
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.

Summary of Results:

Total heat input..kJ/s
Heat lost through lagging..kJ/s
Heat flux...kJ/m^2s
Heat input by conduction at 1270 mm......................................kJ/s
Net heat input up to 1270 mm...kJ/s
Bulk mean air temperature...^oC
Heat transfer coefficient...$kW/m^2\,^oC$
Experimental friction factor ignoring acceleration......................
Experimental friction factor considering acceleration..................
Calculated friction factor..
Prandtl number at 1270 mm...
Reynolds number at 1270 mm...
Experimental Nusselt number...
Calculated Nusselt number..
Experimental Stanton number...
Calculated Stanton number..
St by Reynolds analogy...

Conclusion:

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

MEASUREMENT OF VELOCITY AND TEMPERATURE PROFILES OF AIR USING A 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 varnier. 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 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, W;

Air pressure at orifice = (Barometric pressure + Fan pressure) kN/m2, Air density at orifice,

$$= \frac{\text{Air pressure at orifice } (kN^2)}{0.2871 \times \text{Air temperature at orifice (K)}} \qquad (1)$$

Air mass flow rate; $W = r * \text{orifice area} * C_d * \sqrt{2\Delta p / \rho}$ (2)

Where:-

C_d = 0.613 the orifice discharge coefficient
p = Pressure drop across the orifice (N/m^2)

For determining Δp it may be noted that 1mm 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; $v = \sqrt{2(p_s - p)/\bar{\rho}}$ (3)

where:-
P_s = stagnation pressure (N/m^2)
P = Static pressure (N/m^2)
$\bar{\rho}$ = mean air density in PITOT plane (kg/m^3)

3. Air density in PITOT plane

Mean air temperature rise,

$$= \frac{\text{Heat input rate (kJ / s)}}{\text{Mass flow rate(kg / s)}} \cdot \frac{\text{Heat loss factor}}{Cp} \cdot \frac{b}{1753} \qquad (4)$$

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.

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

The static pressure in the PITOT plane can be taken as

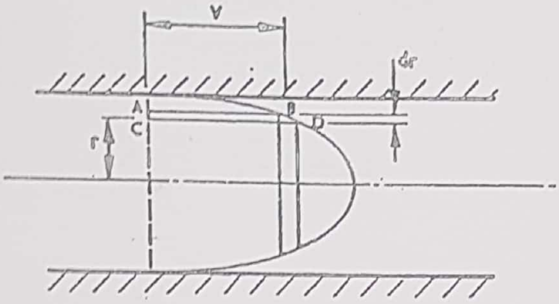
Barometric pressure + (276/1524) * test length pressure drop

4. Mean air velocity in PITOT plane

a) Mean velocity from mass flow $= \dfrac{\text{mass flow rate}}{\rho \times \text{area of pipe}}$

b) Mean velocity from velocity profile.

$$\bar{v} = \frac{2\pi * 10^{-6}}{\text{pipe area } (m^2)} \Sigma \text{Area of ABCD} \times r$$



VELOCITY PROFILE

Guide for data recording

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

PITOT Traverse Distance mm	Actual Distance Across Tube mm	$(p_s - p)$ mm of Water	v m / s	Air temperature (Above Inlet) °C

CROSS FLOW EXCHANGER

Objectives :

To determine the convection heat transfer coefficient and to investigate for the variation of Nusselt and Reynolds numbers with air flow past cylindrical tubes.

Apparatus :

The apparatus consists of a perspex working section through which air is drawn by a centrifugal fan. Perspex rods are inserted into the working section with their axes at right angles to the direction of flow, thus simulating a typical cross flow heat exchanger of the type used in many branches of engineering.

One of the spaces provided in the working section for the rods is occupied by an element consisting of a pure copper rod approximately 10cm in length carried between two extension rods of fabric-based plastic compound. Arrangements are made for heating this copper element in isolation from the working section, replacing it in the section and then recording its rate of cooling as indicated by a thermocouple embedded at its center. A semi-logarithmic plot of rate of cooling together with a knowledge of the thermal capacity and surface area of the copper then permits a direct calculation of the heat transfer coefficient between the copper element and the air flowing past it.

The element is heated by withdrawing it from the working section and placing it in a cylindrical electric heater. The heater is supplied with current at a low voltage from a rectifier and raises the temperature of the element to a maximum of about 80^{o}C. A potentiometer records the temperature difference between the hot junction embedded in the element and a cold junction in the air stream at the inlet to the working section. The initial temperature of the air is indicated by a mercury - in - glass thermometer at the air inlet.

The apparatus includes a centrifugal fan driven by a 1 hp electric motor and having its inlet connected to the working section. Air enters the apparatus by way of a bell mouth. After the working section a transition piece leads to the fan inlet and carries a honeycomb flow straightner intended to prevent the transmission of swirl from the fan back into the working section. The fan discharges to a graduated throttle valve by means of which the air velocity through the apparatus may be regulated.

To permit exploration of the flow pattern up stream of the tube bank a total head tube is provided, and this may be traversed in a direction perpendicular both to the air flow and the axes of the element. Five traversing stations are provided at 2.5cm centers, permitting a complete survey of the cross section. In addition, a traversing position is provided downstream of the tube bank, permitting investigation of the flow pattern in the wake.

Associated static tapping are provided so that the velocity head may be recorded by means of the manometer. The velocity distribution upstream of the tube bank is sensibly constant and may be established by a single measurement of the static wall pressure downstream of the bell mouth. When all the tube elements are in position, the static pressure drop across the four tube banks is about four times the velocity head, and once the relation between velocity head and pressure drop has been established it is preferable to observe the pressure drop rather than the velocity head as an indication of the air velocity past the tube bank.

The thermocouples in the element and at the air inlet are of copper and constantan according to British Standards. Within the range 0 - 50 °C temperature difference, the temperature characteristic of the thermocouples is approximately linear and:-

1 °C = 0.041 mV

The apparatus is mounted on a tubular steel bench carried on castors and an integral cabinet carries an isolator, starter, rectifier and control switch for the element heater.

Nominal dimensions

Width of working section	12.5 cm
Height of working section	12.5 cm
Diameter of elements	1.25 cm
Transverse pitch of elements	2.50 cm
Longitudinal pitch of elements	1.875 cm

Notation

	Units
Diameter of element, d	m
Length of element, L	m
Effective length of element, L_1	m
Surface area of element, A	m^2
Effective Surface area of element, A_1	m^2
Mass of element, m	kg
Specific heat of copper element, (C_p = 380)	J/ kg °C
Barometric pressure, P_A	N / m^2
Temperature of air, T_A	K
Velocity head, upstream, H_1	cm H_2O
Velocity head, downstream of element, H_2	cm H_2O
Static pressure drop across element, H_3	cm H_2O
Velocity upstream of working section, V_1	m/s
Mean velocity past element, V	m/s
Velocity downstream of element, V_2	m/s
Density of air, ρ	kg /m^3
Specific heat of air at constant pressure, C_p	J / kg °C
Viscosity of air, μ	kg / m s
Thermal conductivity of air, k	W/m°C
Temperature of element	K
Slope or cooling curve, M	-
Rate of heat transfer to air, q	W
Coefficient of heat transfer, h	W/m^2 °C
Nusselt Number, (Nu = h d / k	-
Prandtl Number, (Pr = C_pμ / k)	-

Reynolds Number, ($Re = \rho v d/\mu$)

Theory and Calculations :-

It is assumed that the whole of the heat lost from the cylindrical copper element is transferred to the air flowing past it. It is further assumed that temperature gradients within the element are negligible, so that the thermocouple embedded at the center gives a true indication of the effective surface temperature.

A certain amount of heat is conducted from the element into the plastic extension pieces. The extent of this effect has been determined by making comparative tests using copper elements of identical diameter but varying length. From these tests the equivalent additional surface area represented by the plastic extensions has been calculated and is allowed for by making an addition to the true length of the element to give an effective length that is used in the calculations. This correction amounts to 8.4mm. Whence :-

$$L_1 = L + 0.0084$$

From the definition of the heat transfer coefficient, the rate of transmission of heat from element to air is given by :-

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

In a period of time (dt) the fall in temperature (dT) is given by :-

$$-q\, d t = m c\, dT \qquad (2)$$

Combining equation (1) and (2) and eliminating q :-

$$- dT/ (T-T_A) = (h A_1 /m c)\ dt \qquad (3)$$

Integrating :-

$$\log_e (T - T_A) - \log_e (T_o - T_A) = -h A_1 t/m c \qquad (4)$$

Where T_o is the element temperature at $t = 0$.

This equation suggests that a plot of loge ($T - T_A$) against (t) should yield a straight line of slope ($-hA_1/mc$) and, since the other factors in this expression are known, the heat transfer coefficient (h) may be calculated.

In practice it is more convenient to plot $\log_{10} (T - T_A)$ against t. Then since $\log_e N = 2.3036 \log_{10} N$, the heat transfer coefficient is related to the slope M of this line by the expression :-

$$h = -2.3026\ (mc/ A_1)\ M \qquad (5)$$

In order to establish the effective velocity of the air passing the element it is necessary to calculate the velocity upstream from the velocity head upstream.

The velocity V_1 developed by a gas of density r expanding freely from rest under the influence P, when F is sufficiently small (as in the present case) for compressibility to be neglected is given by :-

$$\rho V_1^2 = 2P \tag{6}$$

The velocity head H_1 is measured in centimeters of water and since :-

$$1 \text{ cm } H_20 = 98.1 \text{ N/m}^2$$

equation (6) becomes :-

$$\rho V_1^2 /2 = 98.1 H_1 \tag{6a}$$

The density of air under pressure P_A and at temperature T_A is given by :-

$$\rho = P_A / R T_A \tag{7}$$

Where the gas constant R=287 m^2/s^2 K. Combining equations (6a) and (7) ;-

$$V_1 = 237.3 \sqrt{H_1 T_A / P_A} \tag{8}$$

It is usual when calculating the effective velocity through a bank of tubes to base this on the minimum flow area. When all the tubes are present this minimum area occurs in a transverse plane including a row of 5 tubes. Since the tubes have a diameter of 1.25 cm and the width of the working section is 12.5 cm, the effective area is one half that of the working section, and we may write for this case :-

$$V = 2V_1 \tag{9a}$$

When a single element is being studied in isolation, the minimum flow area is 9/10 of the full working section area, and we may write :-

$$V = (10.0/9.0)\, V_1 \tag{9b}$$

Equation (8) may also be used for calculating local velocities downstream of the element by substituting H_2 for H_1.

Procedure :-

The experimental technique has for its purpose the production of cooling curves for the element under various flow conditions. The apparatus should be set up with the heated element in any desired position. The manometer should be connected to the total head tube, which should be located in the center upstream position with the tube itself on the horizontal centerline of the working section and facing upstream. The other leg of the manometer should be connected to the static tapping at the upstream end of the working section. As the throttle valve closed start the fan and gradually open the throttle to give the desired flow rate.

It will be found that the velocity head upstream of the working section is in fact equal to the pressure drop between atmosphere and the upstream static pressure tapping. Once this has been established the depression at the static tapping may be employed as a measure of H_1.

Readings of air inlet temperature and total head tube should be recorded. The element heater switched on and the element is then removed from the working section and inserted in the heater. When the temperature of the element reaches 60° - 70°C, corresponding to a thermocouple voltage of about 2.4mV, replace the element in the working section. Now set the potentiometer to a reading rather lower than that corresponding to the temperature of the element, observe the galvanometer needle and start a stop watch when the needle passes through the zero position.

Reset the potentiometer to a lower value and observe the stop watch reading when the galvanometer needle again passes the zero mark. Repeat this operation for a series of diminishing potentiometer settings; the resulting information enables a cooling curve to be plotted.

It will be found instructive to plot cooling curves for a range of different air velocities and also with the element in each of the four banks of the heat exchanger and in isolation.

As a preliminary experiment when using the full tube bank it is useful to determine the relation between upstream velocity head and pressure drop across the tube bank. The latter pressure drop may then be used as a more accurate measure of flow velocity. As a further test, the velocity distribution upstream of the working section, and also at various positions in the wake, may be explored by means of the total head tube.

Readings and Results :-

The following dimensions are applied to the apparatus ;

$d = 0.01242m$

$L = 0.0951m$

$L_1 = L + 0.0084 = 0.1035m$

$A = \pi d L = 0.00371\ m^2$

$A_1 = \pi d L_1 = 0.00404\ m^2$
$m = 0.1093$ kg
$C_p = 380$ J/kg°C
$h = -2.3026\ (m\ C_p/A_1)\ M = -23600\ M$

Observations of the rate of cooling:

T_A =................K   t =.................

t (sec)	Thermocouple (mV)	$(T - T_A)$	$Log_{10}(T - T_A)$

Plot $Log_{10}(T - T_A)$ against (t) and find (M), or

$$M = \frac{\sum_{i=1}^{i=n} [\log_{10}(T - T_A)_{t=0} - \log_{10}(T - T_A)_{t=t_i}]}{\sum t_i}$$

where; t_i is the time step
n is the number of time steps

find

$h = -2.3026\ (mC/\ A_1)\ M\ =$

Whence :-

$Nu = h\ d/k =$ --------

to investigate for the relation between air flow rate and Nusselt Number, the previous test may be held at different throttle openings each at a time;

T_A =......K ρ =......kg/m^3
P_A =......N/m^2 C_P =......J/kg°C
P =...... N/m^2 k =......W/m °C

Throttle opening %	H_1 (cmH_2O)	V_1 (m/S)	V (m/S)	M x 10^2	(Nu)	(Re)
100						
90						
80						
70						
60						
50						
40						
30						
20						
10						

Note :- care should be taken to relate V to V_1 upon the case of the element being studied i.e. to use either equation (9a) or (9b).

Conclusion :-

1. Lay down your comments on the test
2. How would the Nusselt number vary with the Reynolds, number. (Plot a curve).
3. Replacing the heat transfer medium by another fluid would introduce a new controlling parameter. What would this parameter be ? and how its effect will be manifested ?

BOILING HEAT TRANSFER.

Objectives:

To measure the rate of heat transfer at different modes (Regimes) of boiling heat transfer.

Apparatus:

The apparatus shown in Figure 1 consists of a solid copper block 'C' of weight approximately 2.5 kg and diameter 100 mm. The block, the surface of which is chromium plated, is carried by a supporting arm ' b '. The block is positioned either between two electric heaters 'd ' or in a vessel of heat resisting material (polycarbonate) 'a', filled with water which is brought to boiling point by means of an immersion heater 'g'.

A micro switch is placed at the end of the arm 'b', so that the specimen heater can only be switched on when the copper block is in position between them.

Two copper-constantan thermocouples are located in the copper block, one at the surface in the center of one of the end faces 'f', and the second at a point 'h' chosen so as to have a temperature corresponding to the average of the whole block. The water temperature is measured by a third thermocouple 'k' immersed in the water at a suitable distance removed from the block when this is immersed. Both the surface and the body temperatures are measured relative to the water temperature which thus serves as a datum.

A temperature cut switch is set at approximately 250 ^{o}C and operates a relay which controls the electrical supply to the specimen heater. Since the temperature switch senses the temperature of the heater rather than of the specimen, it is important to ensure good thermal contact between the heaters and specimen. The cut out temperature can be adjusted, if necessary, by a small screw in the temperature cut out switch.

The following technical data may be added;

Specimen heater	230/240 volts 400 W, single phase
Immersion heater	220/240 volts, 3 kW, single phase
Nominal mass of the specimen :	2.5 kg
Nominal diameter of the specimen:	100 mm
Nominal length of the specimen:	36 mm

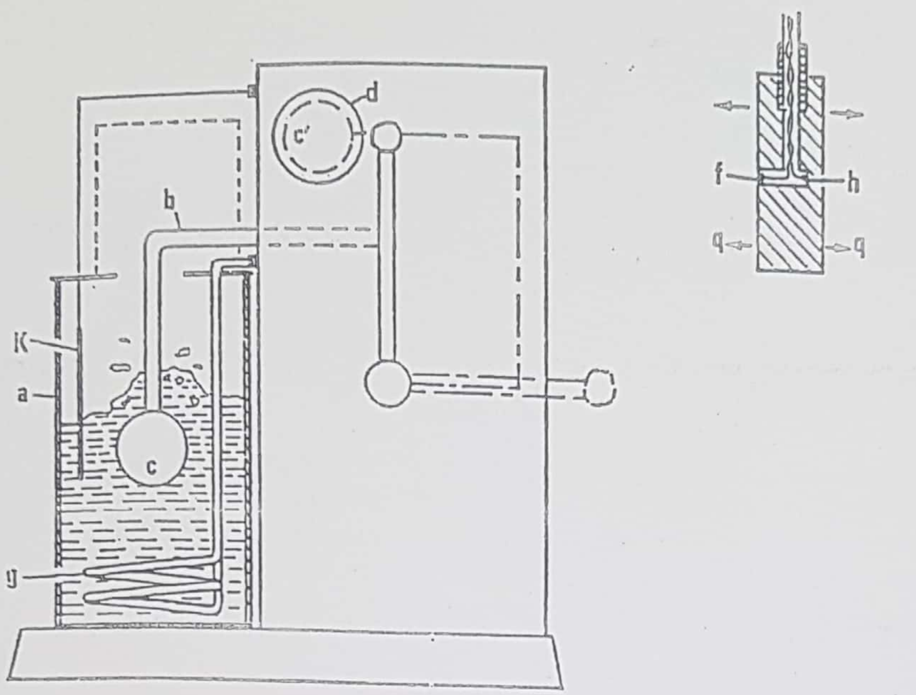


Figure 1 schematic Diagram

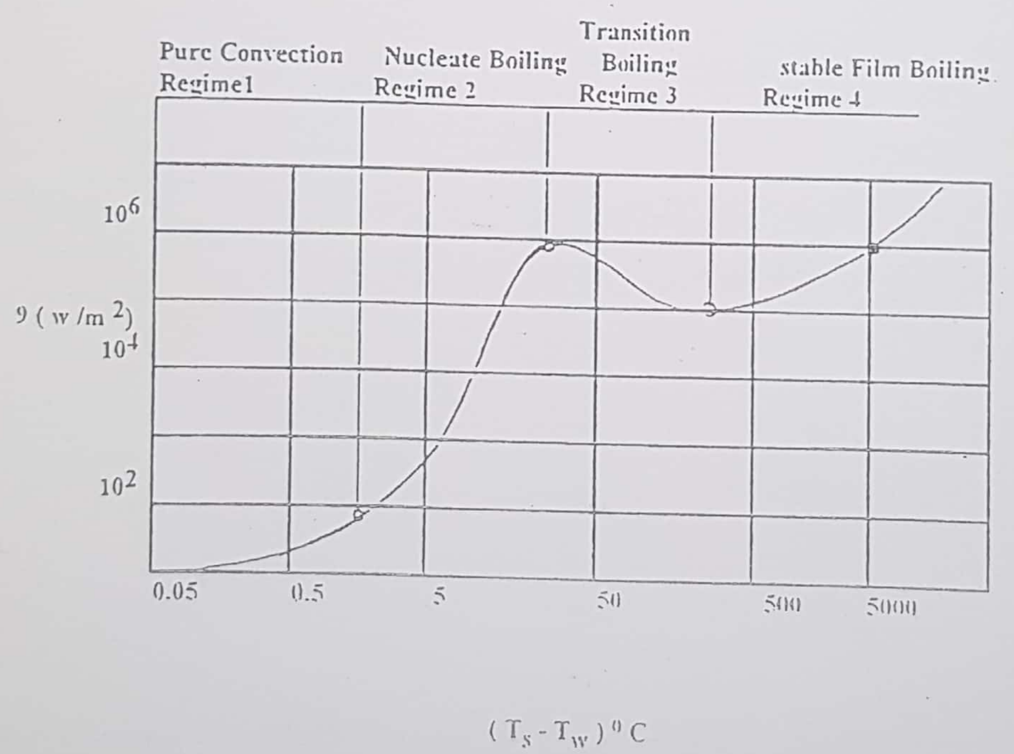


Figure 2 Different Regions of Boiling

Theory :

The different regimes of boiling are illustrated in figure 2. In this figure the heat flux per unit area is plotted as a function of the temperature difference between the surface and the saturation temperature. There are four basic regimes of boiling heat transfer.

Regime 1 : (AB)

If the temperature of the surface does not exceed the boiling point of the liquid by more than a few degrees, heat is transferred to liquid near the heating surface by free convection. The convection currents circulate in the form of slightly superheated liquid, and evaporation takes place at the free surface of the liquid. The heat transfer mechanism in this regime, although some evaporation occurs, is simple free convection, because only liquid is in contact with the heating surface.

Regime 2 : (BC)

As the temperature of the heating surface is increased a point is reached where, in certain places, the energy level of liquid adjacent to the surface becomes so high that some of the liquid molecules are transformed into vapor, forming first a vapor nucleus and finally form a vapor bubble. This process occurs simultaneously at a number of favored spots on the heating surface. The vapor bubbles are at first small and condense before reaching the liquid/air interface, but as the temperature is raised further, they become more numerous and larger until they finally penetrate the surface.

The process in this regime is called nucleate boiling, we observe that, in this regime the heat flux increases rapidly with increasing surface temperature until it reaches a maximum or critical heat flux, (point 'C') at the critical or 'burn out' temperature.

Regime 3 : (CD)

If the surface temperature exceeds the critical temperature, part of the surface is effectively insulated from the liquid by a vapor film. Large bubbles of steam detach themselves from the heating surface from time to time. In this regime the heat flux decreases as the surface temperature increases until the heat flux reaches a minimum at point 'd'. This regime is called the transition boiling regime.

Regime 4 : (DE)

In this regime the entire surface becomes surrounded by a film of steam this phenomenon is called film boiling. Heat is now transferred through the vapour film by conduction and radiation. The heat flux, as expected increases with increase of surface temperature.

Natural convection (Regime 1) and film boiling (Regime 4) are of little importance in boiler and reactor technology. Nucleate boiling (Regime 2) on the other hand is of major importance. Of particular interest to designers is the critical heat flux q_{max}. As a rule, It is desirable to operate as close to this heat flux as possible, whilst at the same time taking precautions to ensure that the burn-out point can in no circumstances be reached. If the critical point is exceeded the pipes in the steam boiler will burn out or the fuel rods in the nuclear reactor will melt.

The present apparatus demonstrates these four regimes in a reverse order, film boiling (if the starting temperature of the specimen temperature is high enough), transition boiling, nucleate boiling and natural convection.

Notation:

	Units
Internal energy of submerged body (specimen), U	kJ
Total rate of heat transfer, Q	kW
Mass of specimen, m	kg
Specific heat of specimen material (copper), C	kJ/kg K
Mean temperature of specimen, T_m	K
Surface temperature of specimen, T_s	K
Water temperature, T_w	K
Time, t	s
Rate of heat transfer per unit area, q	kW/m^2
Rate of change of internal energy, $\dot{U}$	kW
Total wetted area, A	m^2

Calculations:

The internal energy of the submerged body is:

$$U = m.C.\ T_m \qquad (1)$$

from a simple energy balance the rate of heat transfer is equal to the rate of change of the internal energy of the body, i.e.

$$Q_\theta = \Delta U_\theta = m\,C \quad (dT_m / dt)_\theta \qquad (2)$$

The rate of heat transfer per unit area:

$$q_\theta = (Q/A)_\theta = (m\,C/A) \quad (dT_m/dt)_\theta \qquad (3)$$

Where $A = 2 * d^2\ (\pi/4) + (5/6)\,\pi\, d * L$ (4)

$(dT_m /dt)_\theta$ at any time is obtained as follows:-

$$(dT_m /dt)_\theta = (1/t)\ [T_{m(\theta - \Delta t/2)} - T_{m(\theta + \Delta t/2)}] \qquad (5)$$

Procedure:

1- The thermocouples are connected to the chart recorder which is then set to 10 mv maximum scale, and a chart speed of 60 cm/min.

2- The water is brought to boiling, using the immersion heater and the copper element is heated to approximately 250 °C using the specimen heaters (note that the temperature cut out switch is set to turn the heater off at this temperature.)

3- The chart recorder is then started, the immersion heater switched off and the element is plunged into the water. The recorder produces two cooling curves, one showing the mean temperature of the element and the other showing the temperature of its surface.

Important note: ***For safety, the tank cover must be secured in place before plunging the block into the water.***

Readings and Results:- The following data is to be considered in the four equations given in the theory:

T = mv x21.4 °C   A = 0. 0251 m^2 (D =0.1m) from equation (4).

m = 2.45 kg

Table I. Experimental results for water

t s	Δt s	$(T_s - T_w)_t$ K	$T_{m(t-\Delta t/2)}$ K	$T_{m(t+\Delta t/2)}$ K	$(\Delta T_m)_t$ K	$(dT_m/dt)_t$	q kW / m^2

Conclusion:-

1. Plot the heat flux versus the temperature difference (T_S-T_W) for both water and the sodium chloride solution. Write down your comments.
2. write down your own conclusion on the test.
3. Can anyone have boiling process without using a solid surface? If yes explain.

BOILING AND CONDENSATION HEAT TRANSFER

Objectives:

1- Determination of heat flux and surface heat transfer coefficient up to and beyond the critical condition at a constant pressure of Boiling Heat Transfer.

2- Demonstration of filmwise condensation and measurement of overall heat tranfer coefficient.

3- Investigation of the effect of pressure on critical heat flux.

Apparatus:

The unit is built around a strong glass cylinder containing saturated liquid and vapor. (R11 is supplied as standard but other fluids with suitable properties and compatible with the materials of construction could be employed.) A copper thimble containing a "high watt density element " is inserted into the cylinder at the lower end and heat is transferred from this to the boiling liquid. The heater current is supplied from an infinitely variable transformer. A water cooled coil in the upper part of the cylinder condenses the vapour produced and returns it to the boiling liquid. The temperature and pressure of the boiling process is controlled by the condenser cooling water flow rate and temperature.

A thermocouple in the wall of the heater and a thermometer in the liquid enable the metal-liquid temperature difference to be continuously observed. Protection equipment has been introduced to prevent dangerously high surface temperatures occurring when the critical heat influx is exceeded and the boiling can be taken from the nucleate to film boiling mode rapidly and at will.

The apparatus consists of :

Boiling / condensing cylinder; Glass tube 305 mm long x 75 mm outer diameter x 66.6 mm inner diameter. Fitted with nickel plated brass end caps, P.T.F.E. seals and pressure relief valve set at 100 kPa (gauge).

Heater; Thick walled copper thimble containing element, fitted with thermocouple. Effective surface area 13 cm^2 approximately (see test sheet). Normal operating condition 300 W at 140 V.

Temperature measurement; Mercury - in - glass thermometers 0 - 50 ^oC to measure

a) Boiling liquid temperature
b) Vapor temperature
c) Condenser cooling water temperature at inlet
d) Condenser cooling water temperature at outlet

Comrak electronic thermometer with scales from - 60^{o}C to +10^{o}C;0 to 60^{o}C;0 to 170^{0}C and 0 to 400^{o}C, to measure thimble metal temperature.

Pressure gauge; Range - 1.0 to + 1.0 bar for vapor pressure.

High pressure cut out ; To interrupt power supply when vapor pressure exceeds 90 kPa (gauge) (0.9) Bar).

Variable transformer; Berco Controls Ltd., Rotary Regavolt 0-2 amps.

Condenser coil; Nickel plated copper tube - surface area 0.032m^2

High temperature cut out ; Pye Ether Mini controller - to limit thimble and element metal temperature to 225^oC approximately.

Water flow measurement; Rotameter - with valve - for control and measurement of condenser cooling water flow rate.

Voltmeter 0 to 150 V ; To measure voltage
Ammeter 0 to 2A ; To measure input to heater.

Range extension switch; To double the range of the voltmeter and ammeter.

Services Required ; 110 or 240 V single phase AC., cold water service and drain (1 liter / minute max.)

Theory:

Boiling heat transfer occurs when a liquid at saturation temperature is in contact with the surface of a solid (usually metal) at a higher temperature. Heat is transferred to the liquid and a phase change (evaporation) of some of the liquid occurs. The nature and rate of this heat transfer changes considerably as the temperature difference between the metal surface and the liquid is increased.

When the metal surface is a little hotter than the liquid convective current carry the warmed liquid to the surface and evaporation occurs largely at the surface with little ebullition. This process is called convective boiling.

As the metal surface temperature is increased small bubbles of vapor appear and rise to the surface where they burst and release the vapor. Surface tension in the liquid offers great resistance to the birth of a bubble and initially bubbles form at nucleating points on the surface where minute local imperfections or gas pockets exist and where surface tension effects are minimized. As the metal becomes hotter, bubbles form freely and boiling is vigorous with considerable turbulence and very high heat transfer rates. Boiling heat transfer in practical plants is normally of this type which is called nucleate boiling.

Above a critical surface - liquid temperature difference, it is found that the surface becomes "vapor locked " and the liquid is unable to wet the surface. When this happens there is a considerable reduction in heat transfer rate and if the heat input to the metal is not immediately reduced to match the lower ability of the surface to transfer heat, the metal temperature will rise until radiation from the surface plus the limited film boiling heat transfer is equal to the energy input.

If the energy input is in the form of work (including electrical energy) there is no limit to the temperature which could be reached by the metal and its temperature can rise until a failure or a burn-out occurs. If the source is radiant energy from, for example, a combustion process, a similar failure can occur, and many tube failures in the radiant section of advanced boilers are attributed to this cause. The consequences of a burn out in a nuclear power plant will be readily appreciated. Immersion heaters must obviously be designed with sufficient surface area so that the heat flux never exceeds the critical value.

Condensing Heat Transfer; Condensation of a vapor onto a cold surface may be filmwise or dropwise. When filmwise condensation occurs, the surface is completely wetted by the condensate and condensation is into the outer layer of the liquid film. The heat passing through the film and into the surface is largely by conduction.

By treating a surface with a suitable compound it may be possible to promote dropwise condensation. When this occurs the surface is not wetted by the liquid and the surface becomes covered with beads of liquid which coalesce to form drops which then fall away leaving the surface bare for a repetition of the action. Heat transfer coefficients with dropwise condensation are higher than with filmwise owing to the absence of the liquid film.

Boiling and condensation heat transfer are indispensable links in the production of power, all types of refining and chemical processes, refrigeration heating systems, etc. There is a constant pressure for more compact heat transfer units with high heat transfer rates and a clear understanding of the boiling and condensing processes is essential for every mechanical and chemical engineer.

Preparation for the test

1. Purging ; Switch on electrical supply and adjust the heater power to about 150 Watts. The liquid will start to boil vigorously and when the pressure reaches about 30 kPa gauge, or liquid exceeds 25°C, pull on the pressure release valve stem and release any air in the cylinder. It may be necessary to repeat this before all the air is expelled. Turn on water supply (to reduce the pressure) then switch off the electrical supply. The unit is now ready for use.

2. Before Starting any test ensure that :
   a) The cooling water is connected and ready for use.
   b) The pressure and temperature of the working fluid agree with those at saturation conditions - if not, it is probable that air is present and the purging operation should be carried out.
   c) The electrical supply is correctly connected and that the unit is properly earthed.
   d) If a battery operated electronic thermometer is fitted, check the battery condition.

3. During Use; Control the saturation pressure to the desired value by:
   a) Variation of the cooling water flow rate (or temperature).
   b) Variation of the power supplied to the heater.

   After Use;

a) Switch off the electrical supply and disconnect from the mains.
b) Circulate cooling water until pressure has fallen to atmospheric.
c) Switch off the electronic thermometer.

NOTE

Under normal conditions the voltmeter and ammeter will give direct readings. However, at high powers, (above about 300 W) it is necessary to switch to the (volts and ampsx2) position on the two pole switch. When this is done the observed meter reading must be multiplied by two.

Procedure and Results:-

1) Determination of heat flux and surface heat transfer coefficient at constant pressure.

Switch on the electric heater at about 30 watts and adjust the flow rate until the desired pressure is reached. Note the voltage, current, vapour pressure, liquid temperature and metal temperature. Increase the power to say 50 watts, adjust the cooling water flow rate to give the desired pressure and when steady, repeat the observation.

Repeat in similar increments until the transition from nucleate to film boiling is reached. By careful adjustment of voltage near this condition it is possible to make an accurate assessment of critical conditions. When film boiling is established the voltage should be reduced and the reading continued until the heater temperature reaches 200 ^oC.

Results at a pressure of..........kPa absolute are:-

Voltage	E	Volts									
Current	I	Amps									
Liquid Temperature	T_e	^oC									
Metal Temperature	T_m	^oC									

From Which :

Heat Transfer Rate	Q	W										
Heat Flux = Q/A = ϕ	ϕ	$\frac{kW}{m^2}$										
Temperature Difference $T_m - T_e$	ΔT	K										
Surface Heat Transfer Coefficient $\phi/\Delta T$ =	h	$\frac{kW}{m^2K}$										

Note : The effective area (A) of the heat transfer surface of the heater is 13 cm^2).
Plot the results on a log - log paper as :
- ΔT vs. ϕ - ΔT vs. h

a) Switch off the electrical supply and disconnect from the mains.
b) Circulate cooling water until pressure has fallen to atmospheric.
c) Switch off the electronic thermometer.

NOTE

Under normal conditions the voltmeter and ammeter will give direct readings. However, at high powers, (above about 300 W) it is necessary to switch to the (volts and ampsx2) position on the two pole switch. When this is done the observed meter reading must be multiplied by two.

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Results at a pressure of..........kPa absolute are:-

Voltage	E	Volts								
Current	I	Amps								
Liquid Temperature	T_e	^{o}C								
Metal Temperature	T_m	^{o}C								

From Which :

Heat Transfer Rate	Q	W									
Heat Flux = Q/A = ϕ	ϕ	$\frac{kW}{m^2}$									
Temperature Difference $T_m - T_e$	ΔT	K									
Surface Heat Transfer Coefficient $\phi/\Delta T$ =	h	$\frac{kW}{m^2K}$									

Note : The effective area (A) of the heat transfer surface of the heater is 13 cm^2).
Plot the results on a log - log paper as :
- ΔT vs. ϕ - ΔT vs. h

Compare the critical heat flux experimentally found to that calculated using the empirical relation proposed by Zuber and Tribus.

2) Filmwise condensation

The overall heat transfer coefficient between the condensing vapor and the water may be found as follows:-

Adjust the voltage and water flow rate until the desired pressure and condensing rate are established. When conditions are stable, note the water flow rate, water inlet and outlet temperatures and the saturation temperature of the R11.
Record the following:-

- Water flow rate $\dot{m}_w$=..............gram/s
- Water inlet temperature T_i =..............°C
- Water outlet temperature T_o =..............°C
- Saturation temperature of the working fluid T_s =..............°C
- Voltage V
- Current ....A

Calculate:-

* Heat transfer rate at cooling coil $Q_W = mCp\,(T_o - T_i)$ W
*Heat transfer rate from heater $Q_e = VA$ W
*Heat transfer to surroundings (by difference) $Q_e - Q_W =$ W

$\theta_1 = t_s - t_i$ K

$\theta_2 = t_s - t_o$ K

Log mean temperature difference

$\theta_m = (\theta_1 - \theta_2)/\ln(\theta_1/\theta_2)$ K

Overall Heat Transfer Coefficient

$U = (Q_w\ /\ A\theta_m)$ W/m^2K

3) Effect of Pressure on Critical Heat Flux

The method is similar to that given in the book "Introduction to Heat and Mass Transfer, By Eckert and Gross" but by careful adjustment of the power and water flow rate, the heat flux at transition from nucleate to film boiling at a variety of pressures may be established.

Pressure	P	kPa						
Voltage at Transition	E	V						
Current Transition	I	A						

From Which:-

Critical Heat Flux = E I/A	ϕ max.	kW/m^2						

Plot the saturation pressure vs. ϕ using:

- Experimental data obtained
- The empirical relation by Zuber & Tribus.

FILM AND DROPWISE CONDENSATION

Objectives:

To investigate :
a) Filmwise condensation
b) dropwise condensation
c) effect of air in condensers

Theory :

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, filmwise and dropwise. Filmwise condensation occurs on a cooled surface which grow by further condensation and coalescence and then roll over the surface new drops then form to take their place.

Apparatus :

Figure 1 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 filmwise 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 water jet vacuum pump to draw air and steam out of the steam chamber.

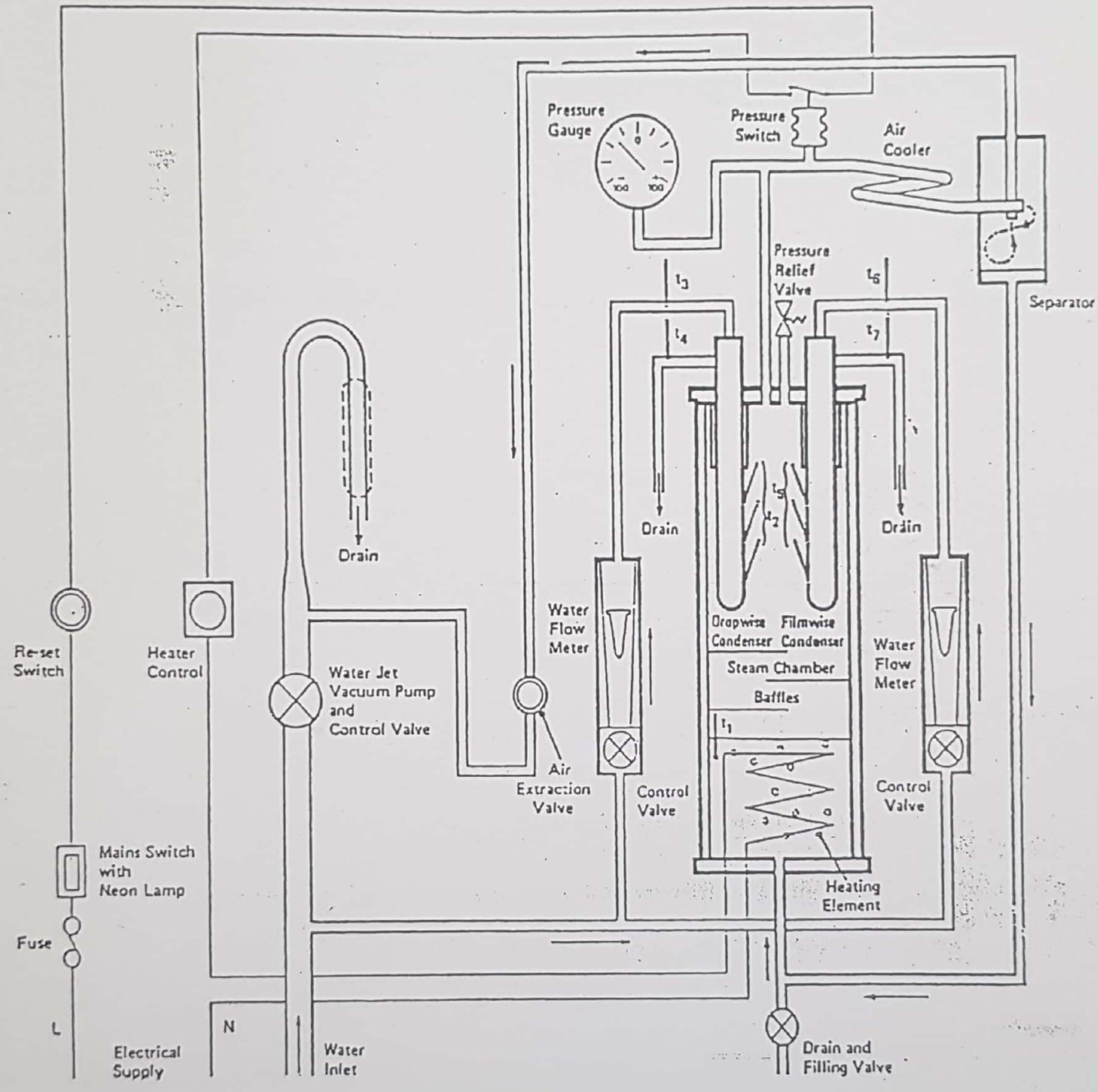
Controls are; heater control, condenser cooling water control valves pressure gauges, pressure relief valve, drain valves, separator, several thermocouples for temperature measurements, and flow meters.

Procedure:

A. Visual Demonstration of Filmwise and Dropwise Condensation, and of Nucleate Boiling.

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.

Adjust the condenser water flow rates until the surface temperatures of the dropwise (T_2) and the filmwise (T_5) are equal and about 8 to 10 K less than T_1.



Film and Dropwise Condensation Unit H910

1 - The condensation process may now be observed and compared.

i - 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 filmwise condenser. This indicates that for the same steam to surface temperature difference, dropwise condensation causes a much higher rate of heat transfer.

ii - 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.

iii - In filmwise 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).

2 -Nucleate Boiling

The very vigorous turbulence brought about by the vapour 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.

3 - Measurement of heat flux and surface heat transfer coefficient during filmwise and dropwise condensation.

- Ensure that the water level in the chamber is correct.
- Carry out the air extraction procedure.
- 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.
- Select the steam temperature (T_1) which is to be constant for the test. (This may be anywhere between 50 °C and 100 °C).
- 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.
- Note the steam temperature T_1, the surface temperature T_2, the cooling water inlet temperature T_3, the water outlet temperature T_4 and the water flow rate M_d.
- Increase the water flow rate (to say 10 gm/ s) and again adjust the heater input to bring the steam temperature (T_1) to the selected value.
- Again note T_1, T_2, T_3, T_4 and M_d.

- Repeat at other water flow rates up to the maximum.
- Repeat in similar manner but using the flimwisie condenser with appropriate water flow rates, observing T_1, T_5, T_6, T_7 and m_s.
- Repeat both tests at other constant values of T_1.

Notes :

a) 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 filmwise condenser.

b) 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.

c) 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 procedure.

d) Fresh distilled water must be available to make good the losses during air extraction.

Calculation Procedure:

- Use the observation sheet attached.
- Find heat transfer rate

$$Q = m_d \, C_p \, (T_4 - T_3)$$

- Heat Flux $\Phi = Q/A$

- Correction for temperature drop through condenser shell: $\Delta T_{cs} = 2 \times 10^{-6} \, \Phi$ w/m^2

- Corrected steam to surface temperature difference:
  ΔT = steam temperature - condenser surface temperature - ΔT_{cs}
- Surface heat transfer coefficient $h = \Phi / \Delta T$

The procedure applies for both filmwise and dropwise condensation. It is interesting to compare the performance of the filmwise condensing surface with that calculated from the theoretical considerations as follows :-

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

Useful Data:

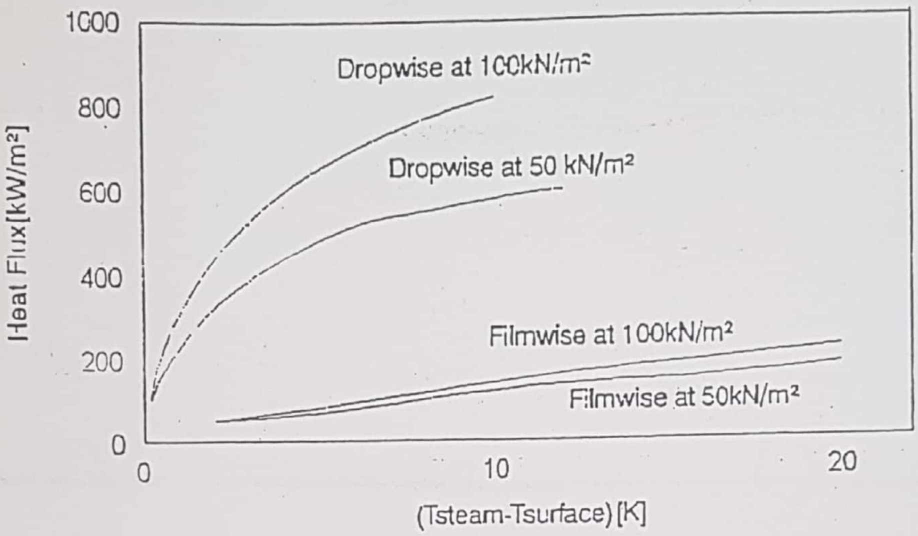
Dimensions of each Condenser :	Length	90 mm
	Diameter	12.7 mm
	Surface Area	37 cm^2

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 (where ϕ is in W/m^2)	$2x10^{-6}$ ϕk
Specific heat capacity of water (Cp):	4.18 kJ/ kg/K
Heat loss from steam chamber (by experiment):	2.5 W/K

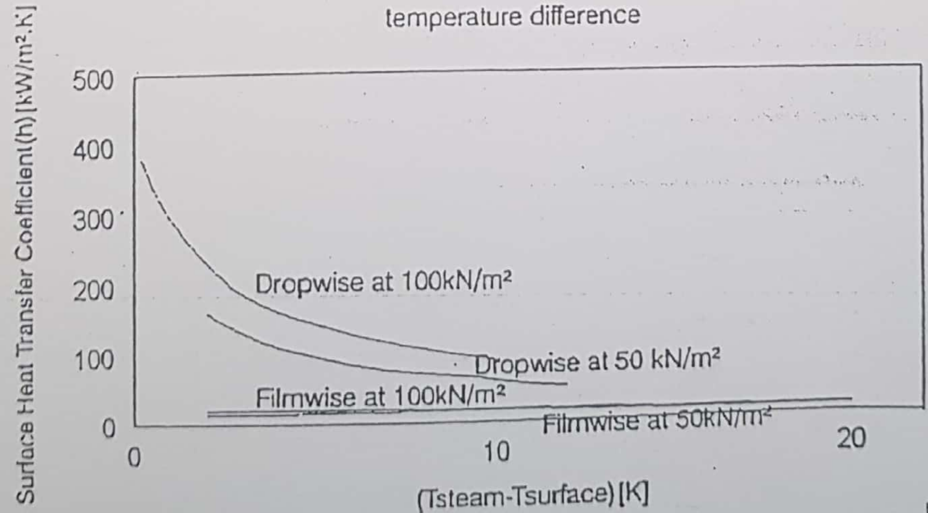
Absolute pressure = atmospheric pressure + gauge pressure

Standard atmospheric pressure = 1.013 bar = 101.3 kNm^{-2}

Filmwise and Dropwise Condensation
Relationship between heat flux and the steam to surface temperature difference

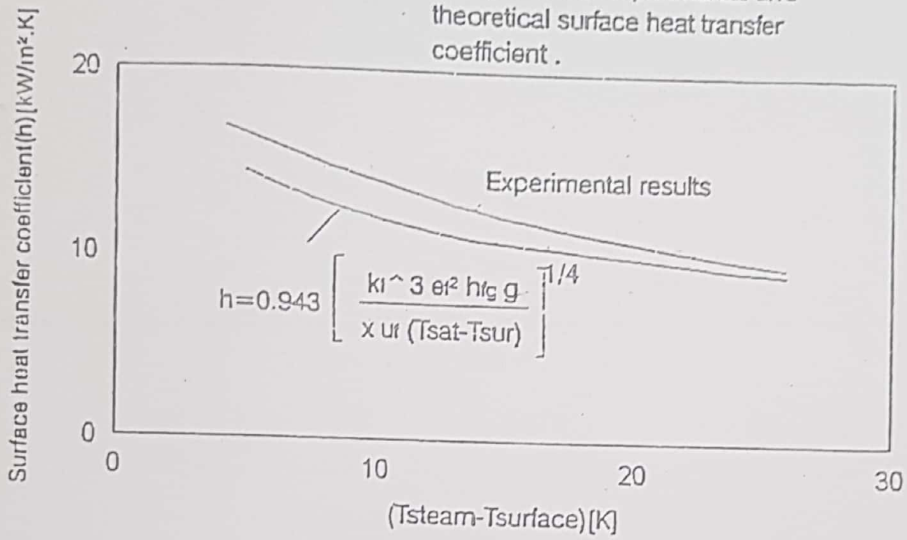


Filmwise and Dropwise Condensation
Relationship between Surface heat Transfer coefficient and the steam to surface temperature difference



Filmwise condensation at 100 kN/m²

Comparison of experimental and theoretical surface heat transfer coefficient.



Observation sheet no.   Date: Atmospheric Pressure:

Dropwise condenser

Test No.	1	2	3	4	5	6	7
Chamber Pressure Psat kNm^{-2}							
Saturation Temperature T_1 °C							
Indicated Surface Temperature T_2 °C							
Water Inlet Temperature T_3 °C							
Water Outlet Temperature T_4 °C							
Water Flow rate $\dot{m}_d$ 10^{-3} kg/s							

FILMWISE CONDENSER

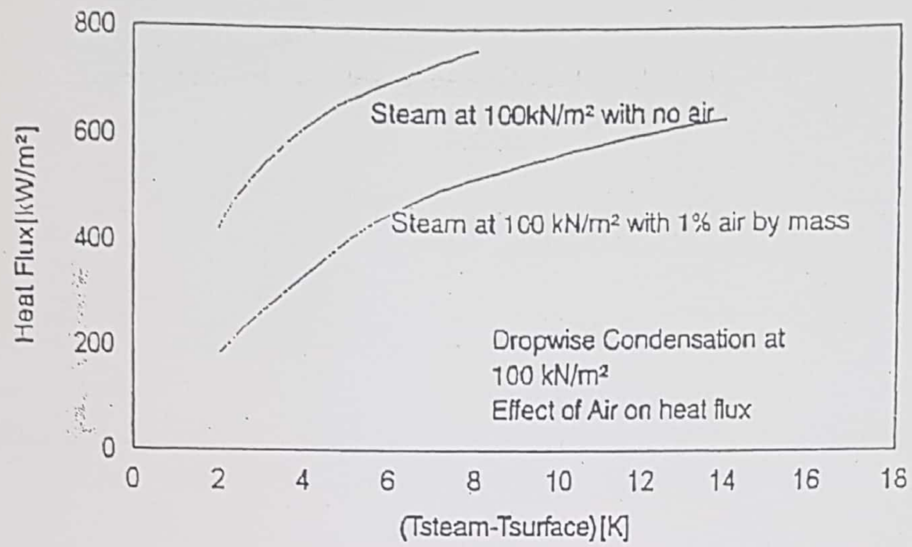
Test No.	1	2	3	4	5	6	7
Chamber Pressure Psat kNm^{-2}							
Saturation Temperature T_1 °C							
Indicated Surface Temperature T_5 °C							
Water Inlet Temperature T_6 °C							
Water Outlet Temperature T_7 °C							
Water Flow Rate $\dot{m}_e$ 10^{-3} kg/s							

DERIVED RESULTS

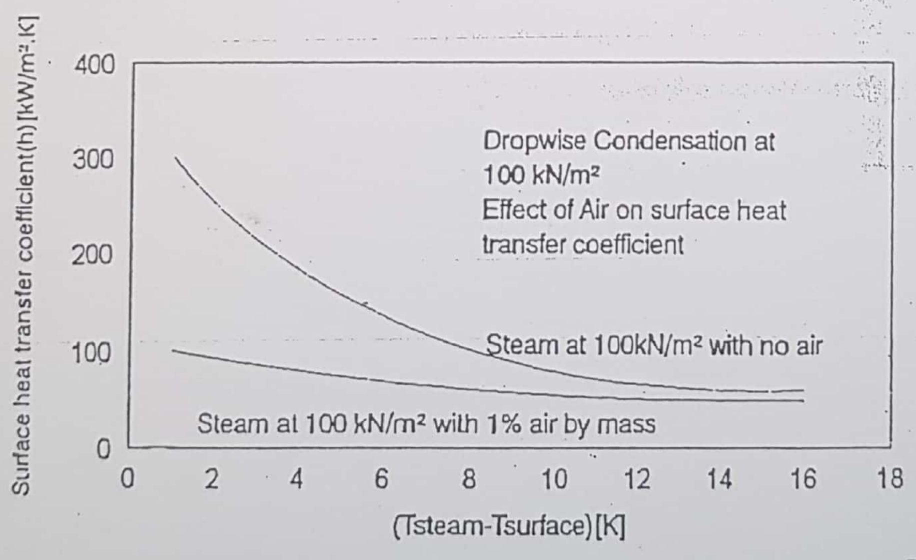
Date :

DROPWISE CONDENSER	1	2	3	4	5	6	7
Steam P_{sat} pressure (abs) kN/ m^2							
Steam temperature T_{sat} °C							
Heat transfer rate Q kW							
Heat flux Φ kW/m							
Temperature drop ΔT_{metal} through Shell K							
Corrected steam T_{sat}-T_{sur} to Surface Temperature difference K							
Surface Heat Transfer h Coefficient kW/m/ K							

FILMWISE CONDENSER	1	2	3	4	5	6	7
Steam P_{sat} Pressure (abs) kN/ m^2							
Steam Temperature T_{sat} °C							
Heat Transfer Q Rate kW							
Heat Flux Φ kWm^{-2}							
Temperature Drop ΔT_{metal} through Shell K							
Corrected Steam T_{sat}-T_{sur} to Surface Temperature difference K							
Surface Heat transfer h Coefficient kW/m^2 / K							

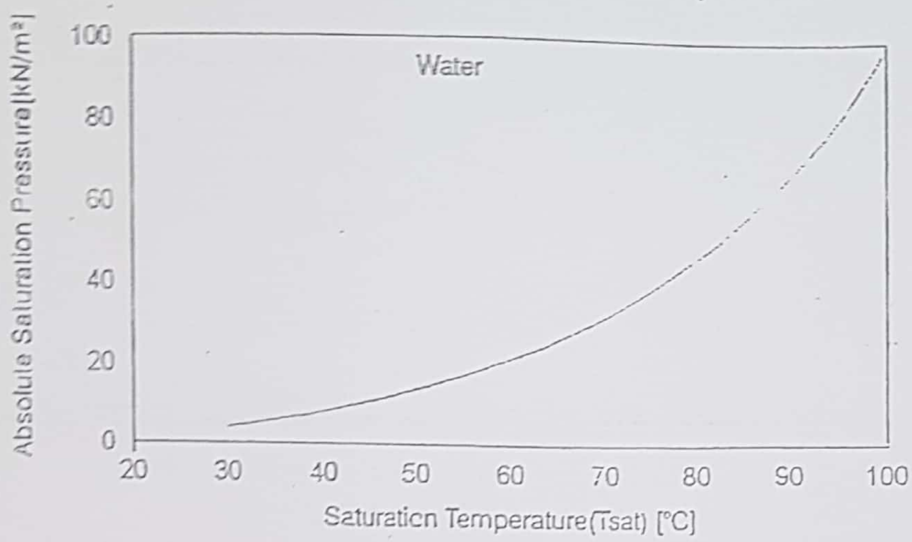


800
600
400
200
0
Heat Flux [kW/m²]
Steam at 100kN/m² with no air
Steam at 100 kN/m² with 1% air by mass
Dropwise Condensation at
100 kN/m²
Effect of Air on heat flux
0
2
4
6
8
10
12
14
16
18
(Tsteam-Tsurface) [K]

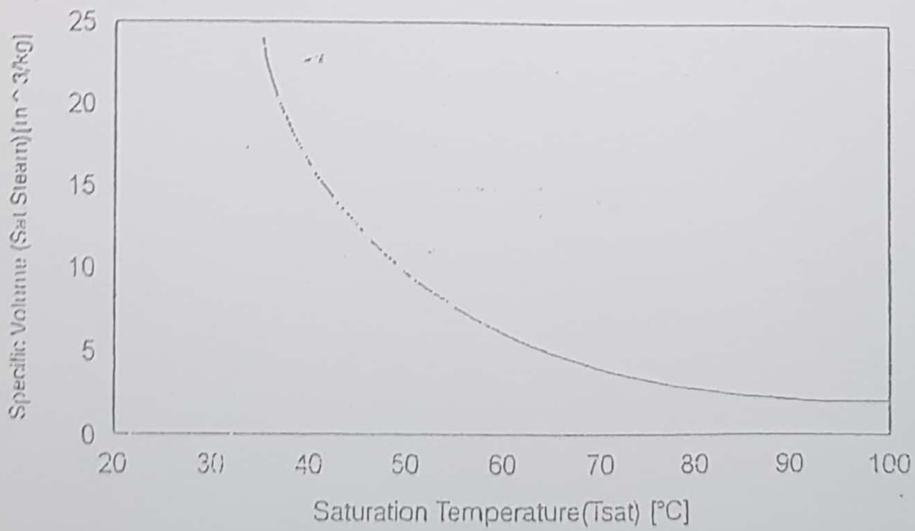


Surface heat transfer coefficient (h) [kW/m².K]
400
300
200
100
0
Dropwise Condensation at
100 kN/m²
Effect of Air on surface heat
transfer coefficient
Steam at 100kN/m² with no air
Steam at 100 kN/m² with 1% air by mass
0
2
4
6
8
10
12
14
16
18
(Tsteam-Tsurface) [K]

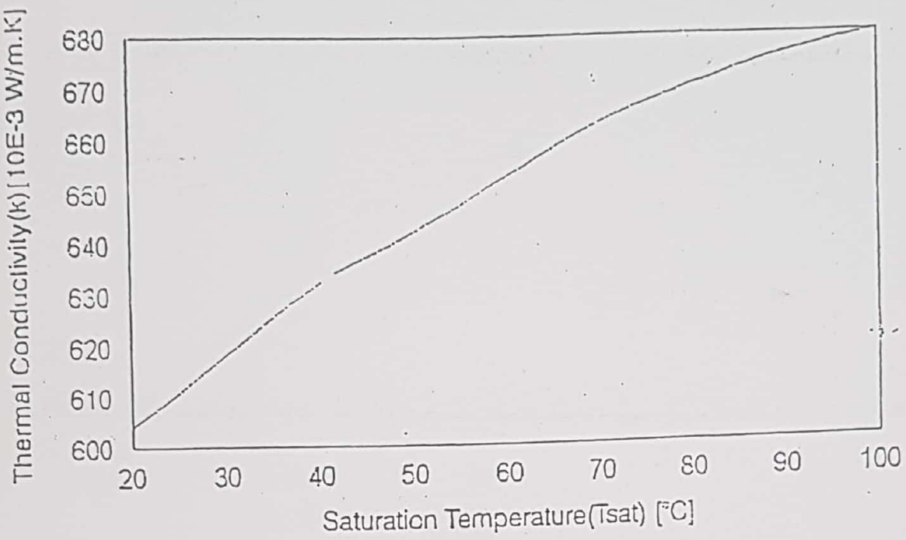
Saturation Pressure/Saturation Temperature



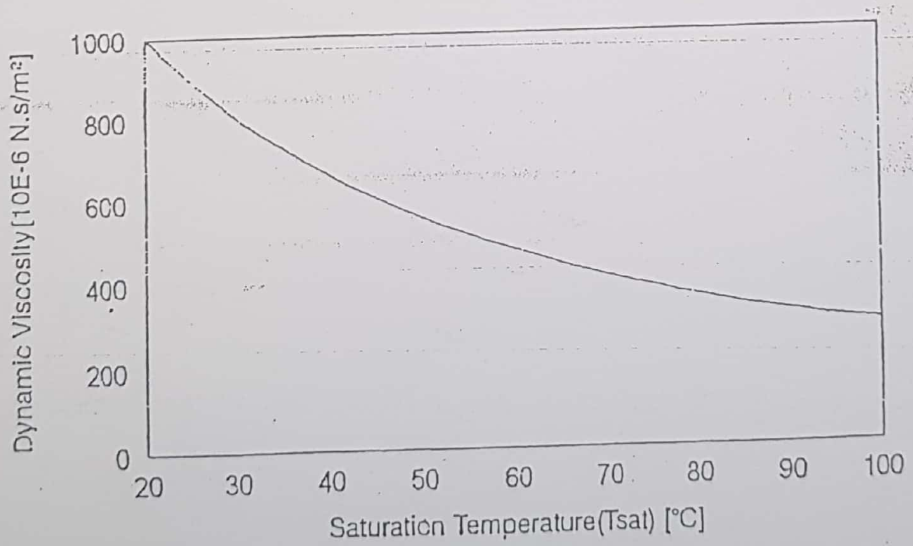
Specific Volume Of Saturated Steam

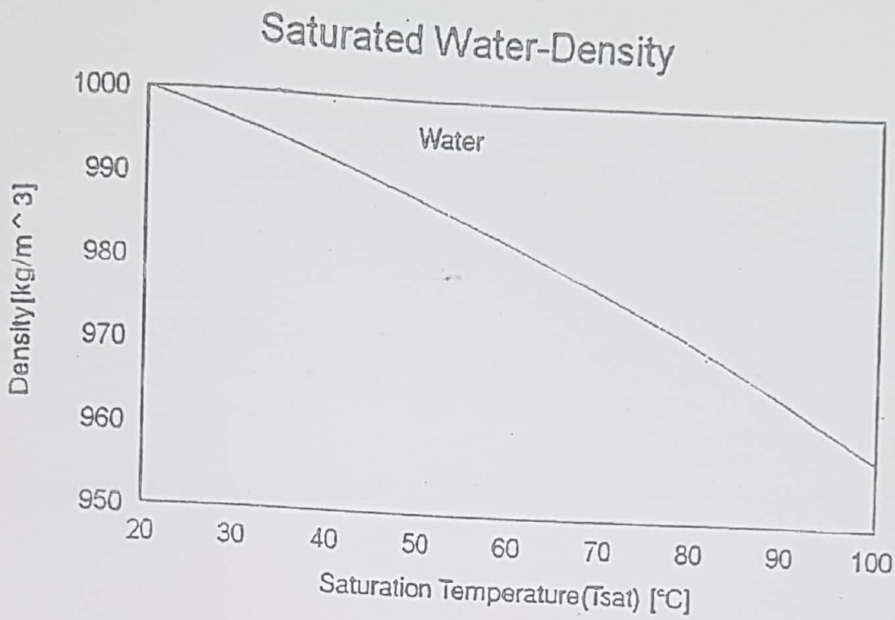


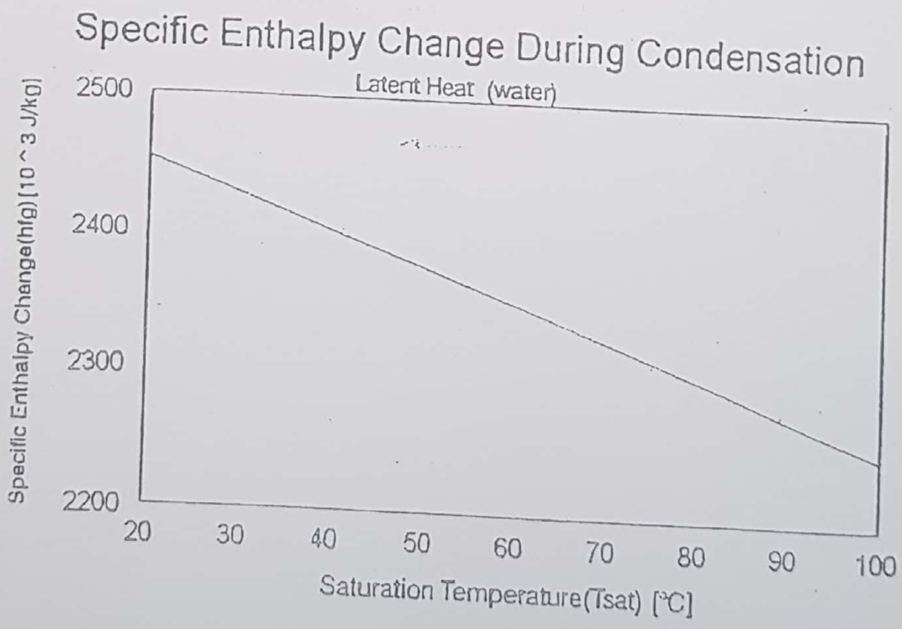
Saturated Water - Thermal Conductivity



Saturated Water - Dynamic Viscosity




Saturated Water-Density
Water
Density[kg/m ^ 3]
1000
990
980
970
960
950
20
30
40
50
60
70
80
90
100
Saturation Temperature(Tsat) [°C]


Specific Enthalpy Change During Condensation
Latent Heat (water)
Specific Enthalpy Change(hfg) [10 ^ 3 J/kg]
2500
2400
2300
2200
20
30
40
50
60
70
80
90
100
Saturation Temperature(Tsat) [°C]

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:

$$\dot{Q}_R = A\,\sigma\varepsilon\left[\left(\frac{T_E}{100}\right)^4 - \left(\frac{T_v}{100}\right)^4\right] \qquad \text{..............(1)}$$

Where $\sigma = 5.77\ W/(m^2K^4)$

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]:

$$(N_u) = 0.47\,[\,(G_r)\,(P_r)\,]^{0.25} \qquad (2)$$

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

$$\frac{2}{Nu} = \ln\left\{1+\frac{6.82}{Gr\,Pr^{1/3}}\right\} + K_n\,\frac{8\gamma}{0.96(\gamma+1)} - \ln(1+2K_n) \qquad (3)$$

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, $(Kn) > 0.001$, 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:-

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

$$A = 1.02\left(\frac{\pi d^2}{2} + \pi d L\right)$$

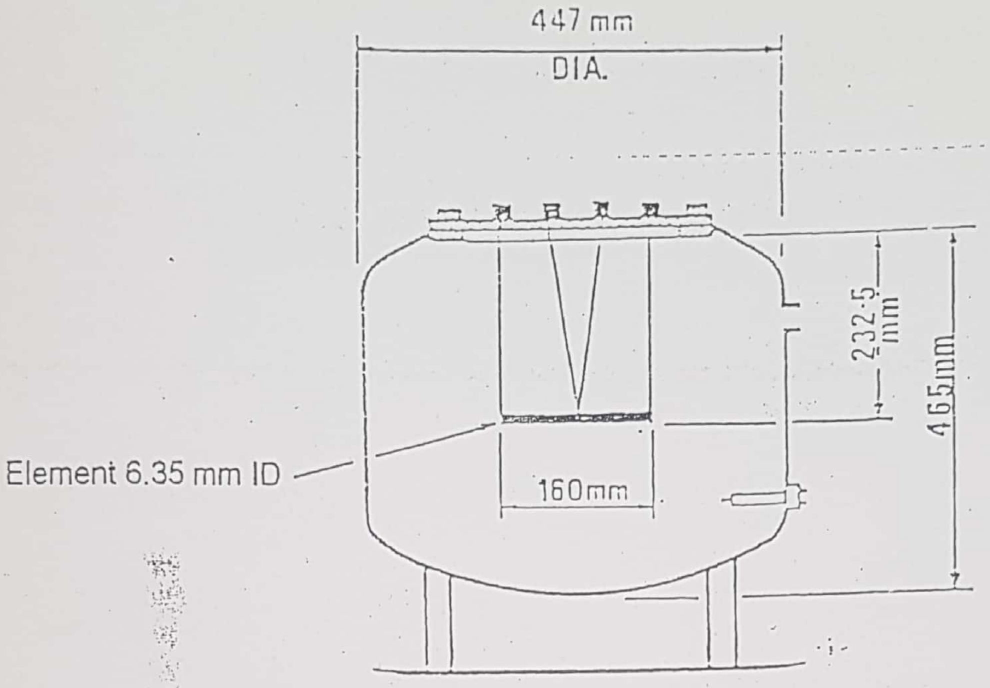


Figure 1 Schematic to show section through Pressure Vessel

Apparatus:

Element and Pressure Vessel; The apparatus consists essentially of a cylindrical element suspended horizontally in a steel pressure vessel, as show in 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 mid point. 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 200°C. 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.

At the right hand side of the control panel terminals are provided for external voltmeter and external ammeter connections. Furthermore, an external connection for compressed air supply is provided for use when pressures above atmospheric are being employed, this connection may also be used for charging the vessel with other gases when tests with these are to be made.

An isolator for the single phase AC. supply to the equipment is provided on the side of the control cabinet. The apparatus is mounted on a wheeled trolley, making it a fully portable unit.

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 turn 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 pressure 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 - Tv) against absolute pressure would be of little use as a means of determining by extrapolation the value of (T_E - Tv) corresponding to zero pressure. It is, however, observed that a plot of T_E - Tv against $h^{1/4}$ 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 - Tv)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 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 particular unit concerned :-

l = 160 mm

d = 6.27mm

A = 0.00328 m^2, from Equation (6).

Ten Sets of observations are sufficient. Figure 3 shows a expected plot of (T_E-Tv) against $h^{1/4}$ for 100 kPa pressure region. Extrapolate to zero pressure and find the value of (T_E - Tv).

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

Q_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 Q_R against (T_E - Tv) 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 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 of 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 = mm Hg

line	point	1	2	3	4	5	6	7	8	9	10
1	Volts, V										
2	Amps, I										
3	Utube, mmHg										
4	θ_E, °C										
5	θ_V, °C										
6	$\underline{Q}$, W										
7	T_E K										
8	T_V K										
9	T_m K										
10	h mm Hg										
11	$h^{1/4}$										
12	$\underline{Q}_R$										
13	$\underline{Q}_C$										
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) (Pr)										

TABLE 2

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 mm Hg							
10	$h^{1/4}$							
11	ρ							
12	k							
13	μ							
14	(Pr)							
15	(Gr)							
16	Q_c							
17	Q_R							
18	Q_R Eq. (1)							

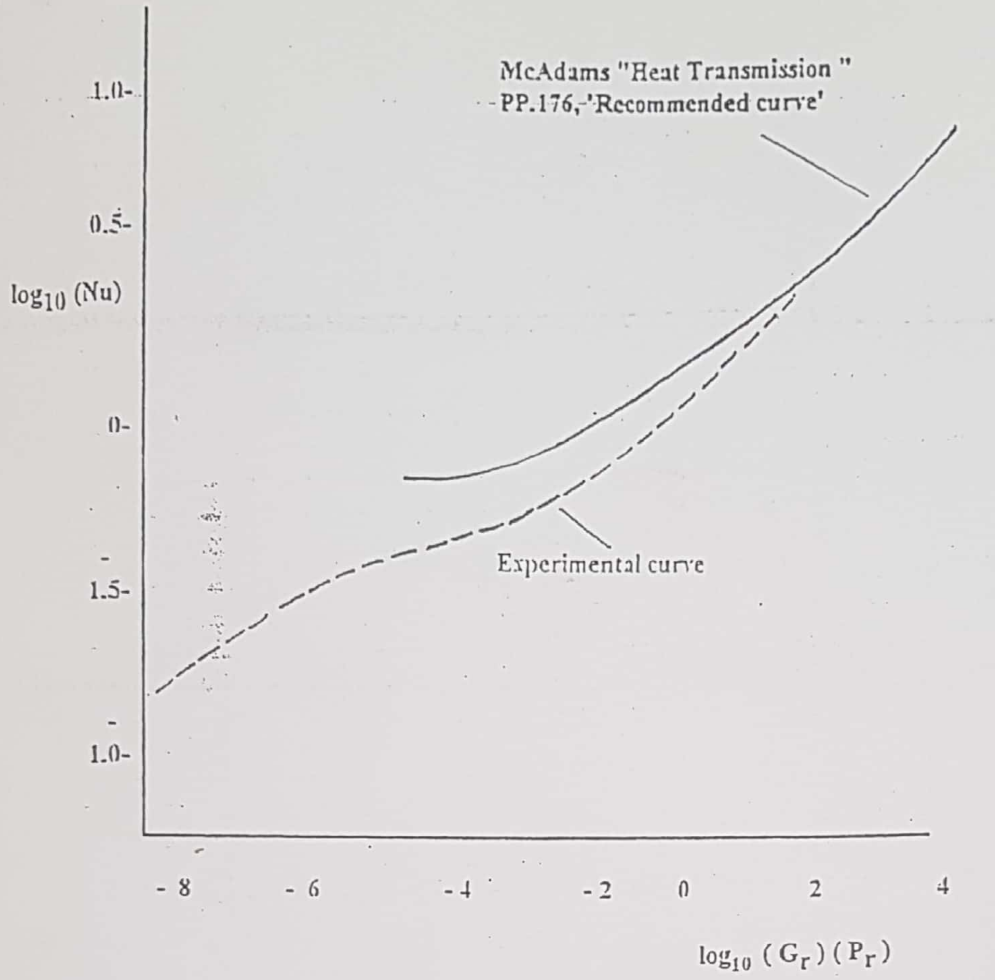


Figure 2 Relationship of $\log_{10}$ (Nu) against $\log_{10} (G_r)(P_r)$

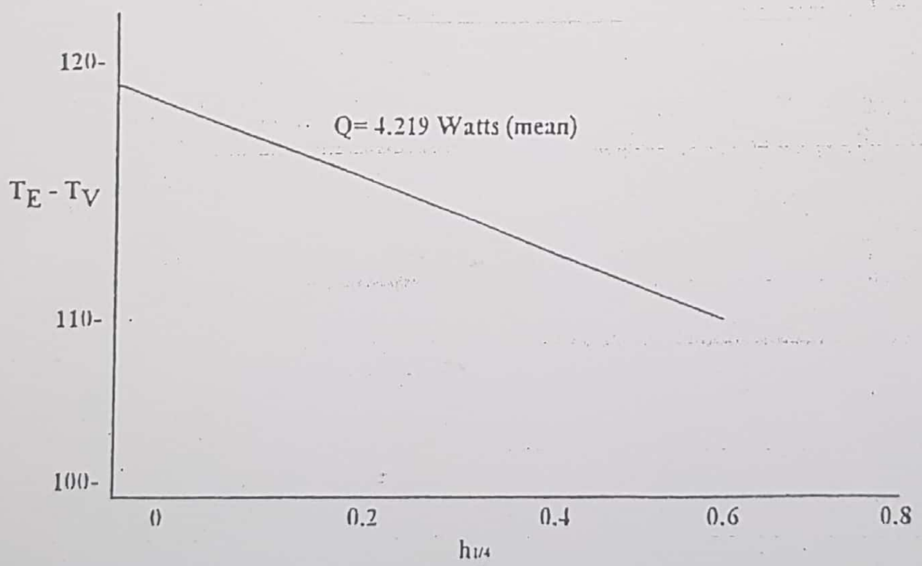


Figure 3 Plot of ($T_E - T_V$) against $h^{1/4}$

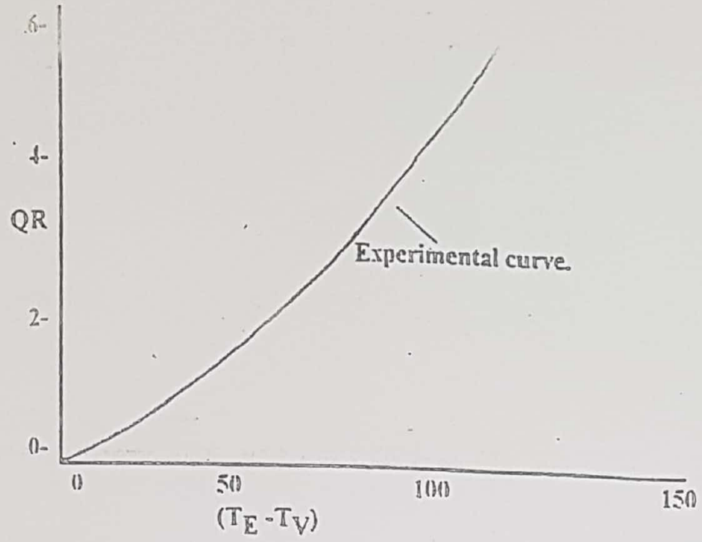


Figure 4 Plot of Q against (T_E-T_V)

Notation:

Diameter of element	d	m
Length of element	L	m
surface area of element	A	m^2
Power to element	V	volt
	I	amp
	W	Watt
Corrected power input	$\dot{Q}$	Watt
Temperature of element	θ_E	°C
	T_E	K
Temperature of vessel	θ_V	°C
	T_V	K
Mean temperature	θ_m	°C
	T_m	K
Barometer	h_a	mm Hg
Absolute Pressure	h	mm Hg
	P	kN / m^2
Heat transfer by radiation	$\dot{Q}_R$	W
Heat transfer by convection	$\dot{Q}_C$	W
Stefan - Boltzman Constant	σ	W/m^2K^4
Emissivity	ε	
Acceleration due to gravity	$g = 9.81 m/s^2$	
Heat transfer coefficient	α	W/m^2K
Properties of gas (at Tm)		
Density	ρ	kg/m^3
Specific heat at constant pressure	C_P	J/kg K
Ratio of specific heats	γ	
Coefficient of expansion 1/Tm)	β	
Thermal conductivity	k	W/mK

Dynamic viscosity	μ kg/ms
Gas constant	R kgm^2/s^2K
Mean free path	s

Dimensionless groups:

Nusselt Number $$Nu = \frac{d\alpha}{k}$$

Prandtl Number $$Pr = \frac{C_p\mu}{k}$$

Grashof Number $$Gr = \frac{g\beta(\theta_\varepsilon - \theta_v)d^3\rho^2}{\mu^2}$$

Knudsen Number $$Kn = s/d$$

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

References:-

(1) Rogers, G.F.C. and Mayhew Y.R. (1967)
Engineering Thermodynamics: Work and Heat Transfer Longman

(2) McAdam, W.H. (1954)
Heat Transmission , McGraw - Hill

(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

HEAT EXCHANGERS

Objectives :

To study the performance of different types of heat exchangers which include :-

a) Liquid to liquid, parallel - flow heat exchangers with
- single pass
- multi pass.

b) Liquid to liquid, counter - flow heat exchanger with
- Single pass'
- multi pass

Theory:

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

Ordinary heat exchangers may be divided into two general classes: cross flow and unidirectional heat exchangers. The unidirectional can be further classified into parallel flow and counter for heat exchangers. This experiment will treat the unidirectional heat exchangers only.

Apparatus: The bench;The hot water unit comprises a 156 liter, insulated tank fitted with three 3 kW electric immersion heaters. The hot water supply temperature is selected and controlled by a manually operated thermostat, while a fixed thermostatic safety control ensures that the temperature cannot exceed 80 ^{o}C.

Chilled water is produced in a 93 liters, insulated tank containing a cooling coil on which an "ice bank" can be formed. Refrigeration is obtained from a hermetically sealed condensing unit which a capacity of up to 5kW. the refrigerant employed being Freon 22.

Two motor driven pumps circulate up to 50 liters/minute of hot and chilled water respectively through Series 1000 Rotameters to the self - sealing sockets supplying the experiments. A direct tank return valve in the hot water circuit returns the surplus flow from the pump directly to the tank thus ensuring turbulence and promoting uniform water temperature.

The instrumentation includes a differential pressure gauge. There are six temperature measuring pockets incorporated in each of the exchangers detailed later. Plug-in hoses are provided to connect the experiment and the differential water pressure gauge.

Heat Exchangers; The heat exchangers consist of the following :

1. Shell and tube cross baffled exchanger for water to water experiments; In this exchanger, the tubes consist of five parallel fixed brass tubes, encased by a brass shell containing cross baffles, equally spaced along the length of the exchanger. The whole unit is contained in an outer casing, and the space between the shell and casing is filled with " Stillite " insulating material. Dimensions and other details are given on the exchangers and the accompanying drawings. Thermometer pockets and pressure tapping points are provided at the inlet and outlet ends of both the shell and tube circuits.

2. Concentric pipe exchanger for water to water experiments; This exchanger is similar in construction to the one above, except that the tube consists of a single brass pipe.

Preparation for Test:

It is recommended that the bench is prepared for the test about two hours before an experiment is due to begin.

1. Cold Side : Check that the tank contains sufficient liquid before switching on the refrigeration unit. It will take approximately two hours to form an ice-bank from room temperature, and when this is achieved, the fridge will automatically switch off. An observation hole in the lid of the tank enables an observer to see the ice bank. During this two hours the cold water pump should remain off, so that no water is circulated.

2. Hot Side : Check that the tank contains sufficient liquid. Using the thermostat, select the required hot water temperature, but do not exceed 70°C. Above this temperature, the fixed safety thermostat will over (ride the manual thermostat). Fully open the direct tank return valve and directly connect the supply and return sides of the hot water circuit with one of the rubber tubes supplied. Do not cross-connect the hot and cold water circuits. Switch on the hot water pump and use the flow control valve to the front of and beneath the bench top to regulate a nominal flow. Switch on the immersion heaters, allowing approximately 30 minutes to heat water from room temperature to a maximum of 70°C on the 9 kW setting. When the water has reached the selected temperature, the power will automatically switch off and then regulate about the chosen setting.

3. Heat Exchanger : Place the selected exchanger on the bench top and connect the 4 flexible hoses to the exchanger on 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.

Procedure:

When preparations are complete, the experiment may begin. First, switch off the hot water pump and connect the flexible hoses into the sockets on the bench, ensuring that the desired directions of flow through the exchangers are selected. Regulate the flow control valves until they are just partly open. Now start both the hot and cold water pumps simultaneously and note the time. Purge the system of all air. Use the flow control valves to regulate the flow through each circuit - if the hot water flow control valve is fully open and the desired flow has not been achieved, then partly close the direct tank return valve to attain the required flow.

At the start of the test, note the exchanger being tested, the flow rates through each circuit and the differential pressure drop across each fluid temperature at regular intervals, until sufficient results at steady conditions have been obtained.

When the test is complete, switch off the pumps, the immersion heaters and the refrigeration unit. Disconnect the flexible hoses at the bench and the pressure sensing tubes. Isolate the electrical supply to the bench.

Test Observations

The following comments and observations may be of value to an operator :-

a. Throughout each test, the immersion heaters were set at the 9 kW setting on the selector switch. This ensured that the hot water temperature cycled steadily about the chosen setting and remained nominally constant during the test.

b. Each test was begun with a full ice bank established in the cold tank. The refrigeration unit, which has switched itself off after making the ice bank, would re-start it self shortly after the commencement of a test, and then remain on throughout the remainder of the test period.

C. c. The exchangers were purged of all air by allowing full flow through both tubes and shell. This was checked 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 exchanger and into a tray or bucket. Any air remaining in the system can clearly be seen in the water running through the tubes. This operation should not be prolonged above 2 or 3 minutes at these high flow rates, to avoid adding unnecessary heat to the cold tank due to the high rates of heat transfer. Furthermore, it should be done with extreme care to avoid damaging the thermometers.

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 an 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:

In a shell and tube heat exchanger, the relative variation of the two fluid temperatures through the heat exchanger is influenced by whether $\dot{m}_c C_{pc}$ is greater or less than $\dot{m}_h C_{ph}$ This is shown in the figures below.

The heat flow rate (q) transferred between the two fluids is given by :

$$q = U A \Delta T_m$$

Where:

U: Overall heat transfer coefficient.

A : heat - transfer - surface area

ΔT_m: Log - mean temperature difference (LMTD).

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)}$$

The heat flow rate can also be measured by :-

$$q = \dot{m}_h C_{ph}(T_{h1} - T_{h2})$$

Or

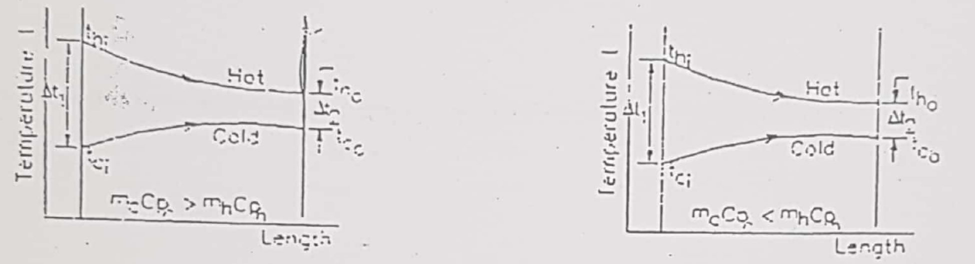
$$q = \dot{m}_c C_{pc}(T_{c2} - T_{c1})$$

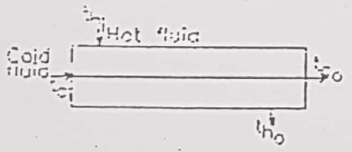
The heat transfer area of :-

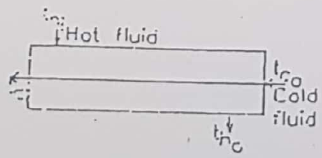
Multi - tube heat exchanger = $20.7\times10^{-2} m^2$

Single - tube heat exchanger = $7.9\times10^{-2} m^2$

Obtain the overall heat transfer coefficients and compare the different types of flow arrangements. Plot m vs. q for different arrangements and compare.







Guide for Data Recording

Heat Exchanger :- Multi - Tube
Flow Arrangement:- Counterflow
Immersion Heater Setting :- 9 kW
Hot Thermostat Setting:- 50^{o}C

Hot tube/ Cold shell
1. All air purged
2. Thermocal - 10%

		HOT	SIDE		
Test no.	Flow	T_1 (In)	T_2(Out)	Diff.	Velocity in tubes
	L/min.	^{o}C	^{o}C	^{o}C	m/s
1	5				
2	10				
3	15				
4	20				
5	30				
6	5				
7	10				

	COLD	SIDE	
Flow	T_3 (In)	T_4(Out)	Diff.
L/min.	^{o}C	^{o}C	^{o}C
5			
10			
15			
25			
30			
30			
30			

Heat Exchanger: Multi - Tube

Flow Arrangement:- Parallel Flow

HOT TUBES/COLD SHELL :HOT SIDE					
Test no.	Flow L/min.	T_1 (In) °C	T_2(Out) °C	Diff. °C	Velocity in tubes m/s
1	5				
2	10				
3	25				
4	40				
5	5				
6	10				
7	25				
8	25				
9	Check 25				
10	25				

	COLD SIDE		
Flow L/min.	T_3 (In) °C	T_4(Out) °C	Diff. °C
5			
10			
25			
40			
40			
40			
40			
40			
40			
40			

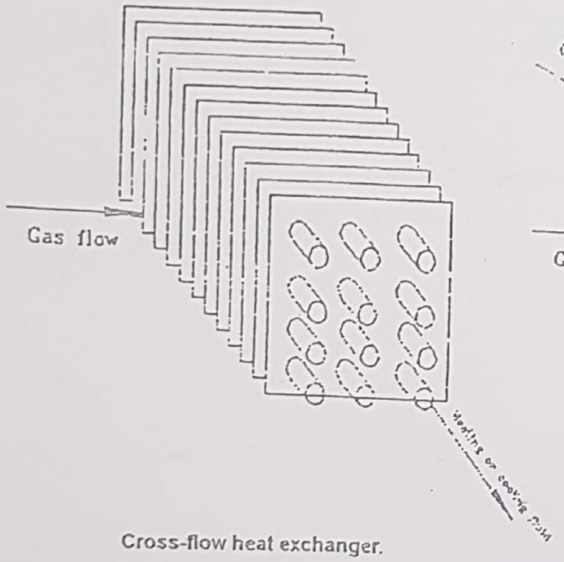
CROSS - FLOW HEAT EXCHANGER
With Refrigeration Unit

Objectives:

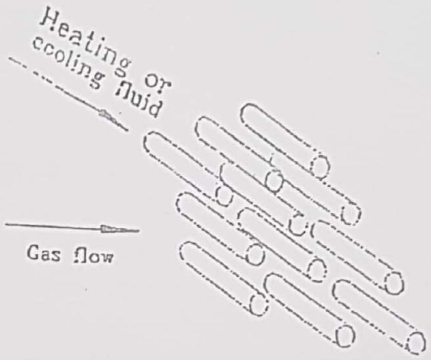
To study the performance of different types of cross - flow heat exchangers under different flow conditions. A comparative plot of total heat transfer with flow rate should be the final outcome of the experiment.

Theory:

Cross - flow heat exchangers are commonly used in air or gas heating or cooling applications. Two types are usually identified, mixed and unmixed. This is shown in the figure below.



Cross-flow heat exchanger.
both fluids unmixed



Cross - flow heat exchanger.
One fluid mixed and one unmixed.

The average velocity at the entry can be approximated as follows:

$$\overline{V} = K\sqrt{\frac{2\Delta P}{\rho_a}}$$

Where DP is the pressure drop in entry, K is the calibration constant (0.965), and r is the air density The air mass flow rate can then be calculated from

$$\dot{m}_a = \rho_a A_d \overline{V}$$

where

A_d is the duct area (=150x300 mm)

The heat transfer rate can be calculated using two approaches

1. $Q = \dot{m}_a (T_{ao} - T_{ai}) Cp_a$
2. $Q = \dot{m}_w (T_{wo} - T_{wi}) Cp_w$

Description of apparatus:

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 f'ow 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 copper tubes, in staggered configuration with aluminum block -fins. The tube side medium can be cool glycol solution or water for a and b, and cold R12 (freon) for c.

The tube side flow-rates 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.

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

- triple pass.

2- Finned tube heat transfer element
   - single pass
   - triple pass.

The flow of hot water is measured by the flow 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 tht theory section. The air-flow rate can be changed by varying the exit area of the suction fan. Heat transfer rate is then, calculated in the two methods described before.

Guide for Recording Data:

Plain tube

No.	Exit Area	P	V	T_{1a}	T_{2a}	$\dot{m}_w$	Tw_1	Tw_2
1	100%							
2	80%							
3	60%							
4	40%							
5	30%							
6	20%							

No.	$\dot{m}_a$	T_a	q_a	$\dot{m}_w$	T_w	q_w
1						
2						
3						
4						
5						
6						

Do the same for fined element.

On a single graph plot $\dot{m}_a$ vs. q_a for the four different arrangements and compare the result.

Thermocouple Characteristics

Objectives:

1. To know what is a **Thermocouple**.
2. To know how to convert the thermocouple voltage readings to temperature.
3. To understand the characteristics of the thermocouple.

Introduction:

Thermocouple (TC) is created whenever two dissimilar metals touch and the contact point produces a small open-circuit voltage as a function of temperature. This thermoelectric voltage is known as the Seebeck voltage, named after Thomas Seebeck, who discovered it in 1821.

The TC has been the popular choice over the years for a variety of reasons. Thermocouples are relatively inexpensive and can be produced in a variety of sizes and shapes. They can be of rugged construction, can cover a wide temperature range. However, TCs produce a very small microvolt output per degree change in temperature that is very sensitive to environmental influences.

As Mentioned above any two dissimilar metals may produce a TC, However, there are some standard thermocouples which have calibration tables and assigned letter-designations which are recognized worldwide, Such as, J-type (Iron / Constantan), K-type (Chromel / Alumel), E-type (Chromel / Constantan), N-type (Nicrosil / Nisil), B-type (Platinum / Rhodium), R-type (Platinum / Rhodium) and S-type (Platinum / Rhodium). In order to select the suitable TC for an application, sensitivity and temperature range should be taken into consideration, because each one of these thermocouples has different temperature range and sensitivity.

In the experiment two J type thermocouples are used. The first one is used for the experiments, and the other one is used with temperature controller to control the temperature of the hot plate.

Theory:

To measure a thermocouple Seebeck voltage, you cannot simply connect the thermocouple to a voltmeter or other measurement system, because connecting the thermocouple wires to the measurement system creates additional thermoelectric circuits.

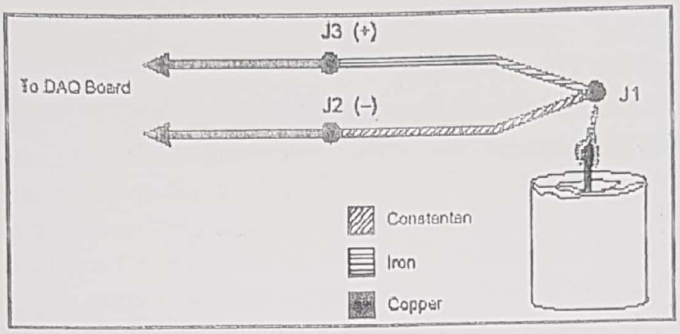


Figure (1): Thermocouple connection

Consider the circuit illustrated in Figure 1, in which a J-type thermocouple is in a candle flame that has a temperature you want to measure. The two thermocouple wires are connected to the copper leads of the measurement device. Notice that the circuit contains three dissimilar metal junctions J1, J2, and J3. J1, the thermocouple junction, generates a Seebeck voltage proportional to the temperature of the candle flame. J2 and J3 each have their own Seebeck coefficient and generate their own thermoelectric voltage proportional to the temperature at the measurement device terminals. To determine the voltage contribution from J1, you need to know the temperatures of junctions J2 and J3 as well as the voltage-to-temperature relationships for these junctions. You can then subtract the contributions of the parasitic junctions at J2 and J3 from the measured voltage at junction J1.

Thermocouples require some form of temperature reference to compensate for these unwanted parasitic "cold" junctions. The most common method is to measure the temperature at the reference junction with a direct-reading temperature sensor and subtract the parasitic junction voltage contributions. This process is called **cold-junction compensation**. You can simplify computing cold-junction compensation by taking advantage of some thermocouple characteristics.
By using the **Thermocouple Law of Intermediate Metals** and making some simple assumptions, you can see that the voltage a data acquisition system measures depends only on the thermocouple type, the thermocouple voltage, and the cold-junction temperature. The measured voltage is in fact independent of the composition of the measurement leads and the cold junctions, J2 and J3.

According to the Thermocouple Law of Intermediate Metals, illustrated in Figure 2, inserting any type of wire into a thermocouple circuit has no effect on the output as long as both ends of that wire are the same temperature, or isothermal.

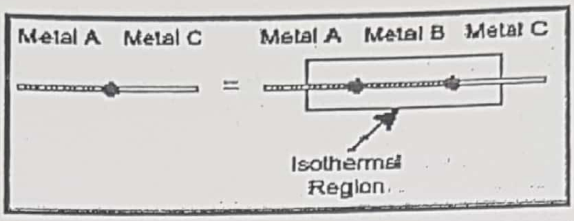


Figure (2): Thermocouple Law Intermediate Metals.

Consider the circuit in Figure 3. This circuit is similar to the previously described circuit in Figure 1, but a short length of constantan wire has been inserted just before junction J3 and the junctions are assumed to be held at identical temperatures. Assuming that junctions J3 and J4 are the same temperature, the Thermocouple Law of Intermediate Metals indicates that the circuit in Figure 3 is electrically equivalent to the circuit in Figure 1. Consequently, any result taken from the circuit in Figure 3 also applies to the circuit illustrated in Figure 1.

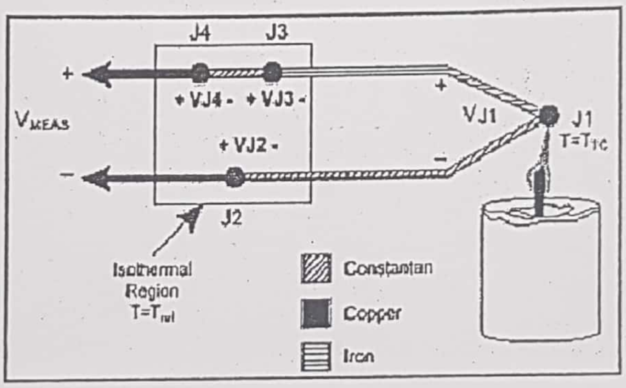


Figure (3): Intermediate Materials effect In Isothermal region.

In Figure 3, junctions J2 and J4 are the same type (copper-constantan); because both are in the isothermal region, J2 and J4 are also the same temperature. Because of the direction of the current through the circuit, J4 contributes a positive Seebeck voltage, and J2 contributes an equal but opposite negative voltage. Therefore, the effects of the junctions cancel each other, and the total contribution to the measured voltage is zero. Junctions J1 and J3 are both iron-constantan junctions, but may be at different temperatures because they do not share an isothermal region. Being at different temperatures, junctions J1, J3 both produce a Seebeck voltage, but with different magnitudes. To compensate for the cold junction J3, its temperature is measured and the contributed voltage is subtracted out of the thermocouple measurement.

Experiment Procedure:

1. Run the TMT001 Software.

2. A screen named "**Welcome to TMT001**" will appear, containing three buttons: **[Information]**, **[Run the Experiments]** and **[Quit]**.

3. The "**Welcome screen**" is shown in the figure below:

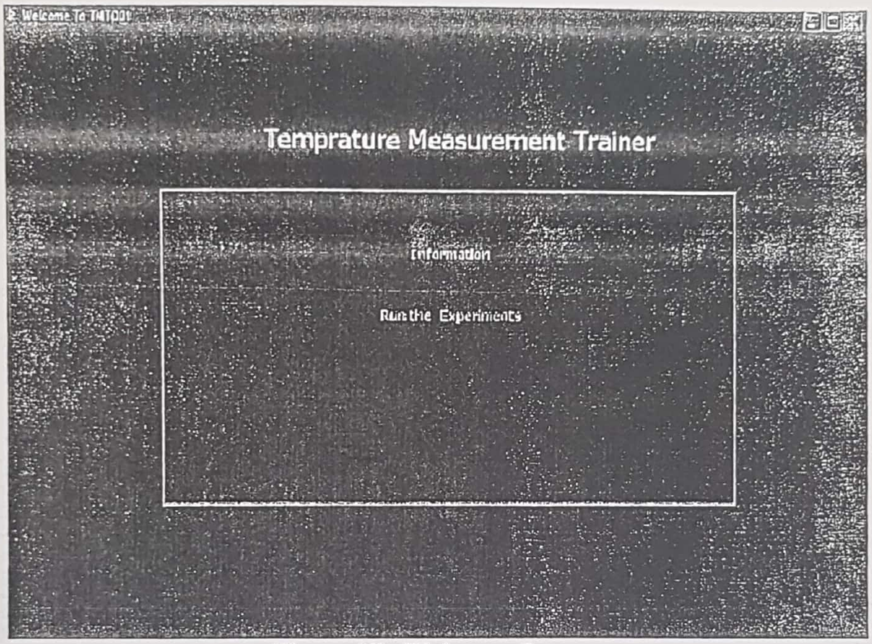


Figure (4): Welcome Screen.

4. Press the **[Information]** button to go to the Information screen.
5. The "**Information Screen**" is shown in the figure below:

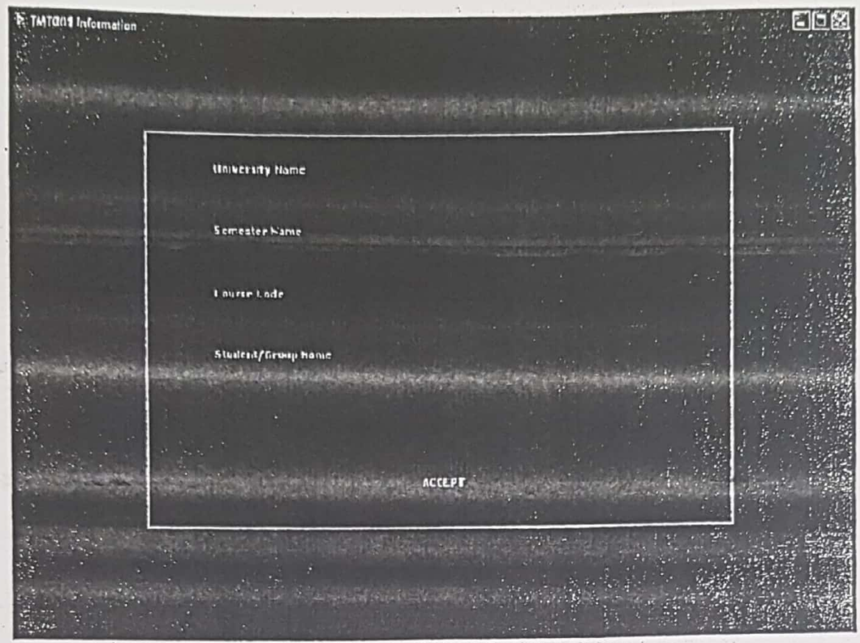


Figure (5): Information Screen.

6. Fill in the fields with your information, Press the **[Accept]** button and a confirmation message will appear asking you to press **[Accept]** the information you have entered, or **[Cancel]** if you need to go back to change anything. Pressing **[Accept]** will let you go back to the **"Welcome Screen"**.
7. Press **[Run the Experiments]** button to go to the **"Experiments screen"**.
8. The **"Experiments Screen"** is shown in the figure 6, containing four experiments; **Thermocouple Characteristics, RTD Characteristics, Thermistor Characteristics** and **Thermometers Comparison**.

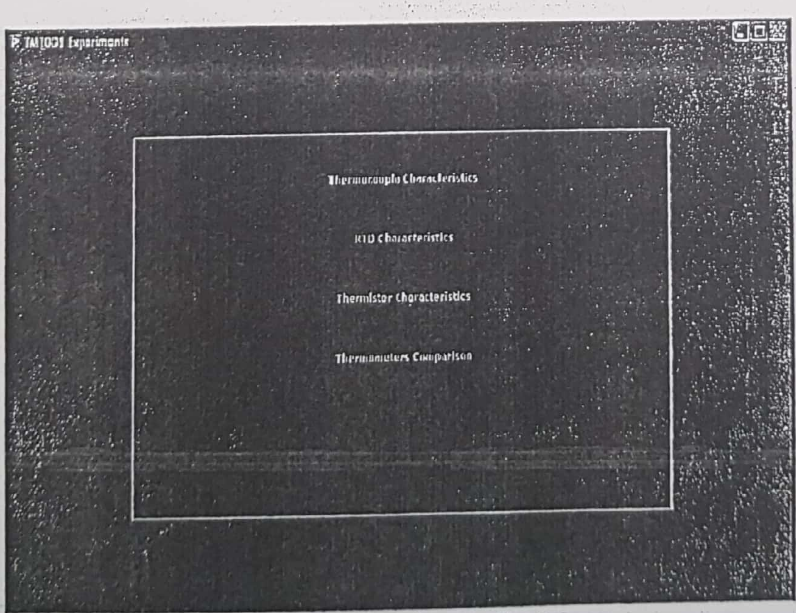


Figure (6): Experiments Screen.

9. Choose Experiment 1: **"Thermocouple Characteristics".**
10. Study the front panel carefully and observe the buttons on the screen.

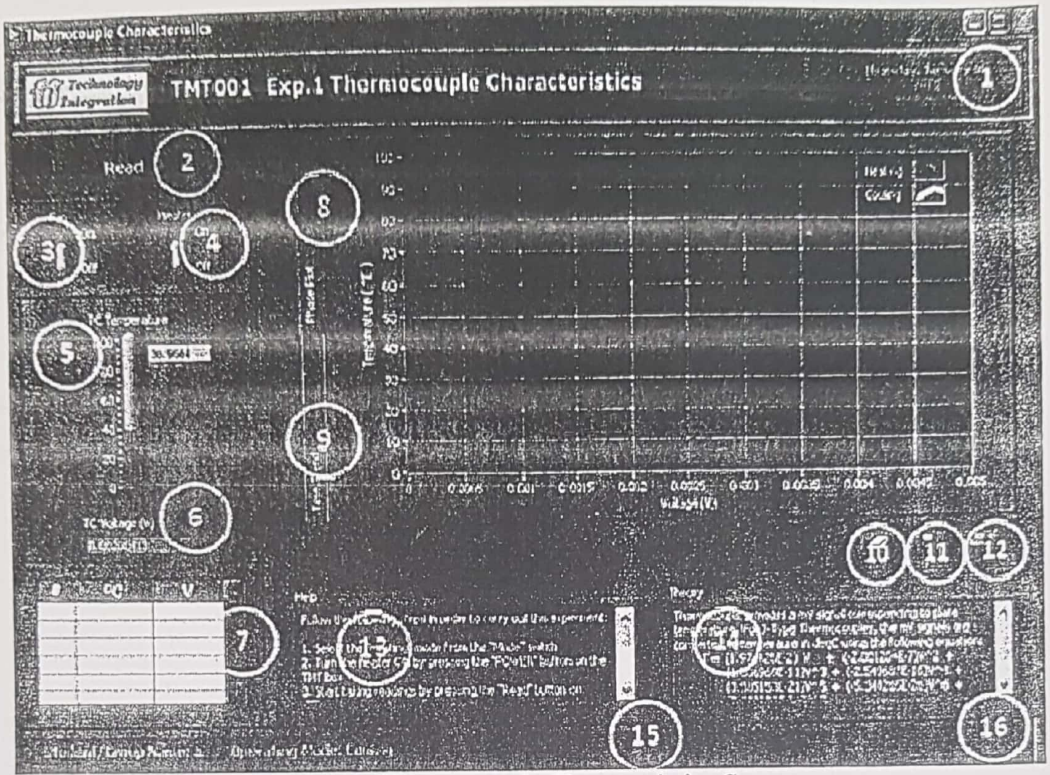


Figure (7): Thermocouple Characteristics Screen.

1) **Current Date and Time Indicator.**
2) **Read Button:** To read and plot the current temperature and voltage (resistance) of the current thermometer (here it is the **Thermocouple**).
3) **Fan Switch:** To turn the Fan ON or OFF.
4) **Heater Switch:** To turn the Heater ON or OFF.
5) **Thermometer Temperature (˚C):** Displays the current temperature of the current thermometer.
6) **Thermometer Voltage (Resistance):** Displays the current voltage (resistance) of the current thermometer.
7) **Readings Table:** Displays the current Temperature and Voltage (resistance) readings taken each time the **[Read]** button is pressed.
8) **Phase Plot:** Contains the Temperature vs. Voltage (Resistance) graph which displays the readings that have been taken by the user. Each point represents the Thermometer Temperature (˚C) with its corresponding Voltage (V) or Resistance (Ohm).

9) **Time Trend:** Contains the Temperature vs. Time graph which displays the temperature profile of the thermometer.
10) **Clear Chart Button:** To clear the Phase Plot graph.
11) **Save Report Button:** To save a report, the report will be saved in the "Temperature Trainer Files" folder on the desktop.
12) **Print Report Button:** To print a report, the report will be printed using your default printer.
13) **Help Window:** Displays the procedures needed to carry out the experiment
14) **Theory Window:** Displays the conversion theory of the thermometer of the current experiment (how to change from voltage (resistance) to temperature).
15) **Status Bar:** Displays the current Student/Group name as well as the current operating mode (Heating or Cooling).
16) **Quit Button:** To quit from this experiment and return to the **"Experiments"** window.

11. Turn the **Heater** ON by pressing ON the **Heater Switch** on the screen (Heating Mode).
12. Start taking readings by pressing **[Read]** button on different temperature values.
13. The acquired readings appear on the **Temperature-Voltage graph** as red points.
14. Compare the read temperature with the temperature of the **glass thermometer**. Is it the same temperature? Why?

....
....
....
....

15. Turn the **Heater** OFF by pressing OFF the **Heater Switch** on the screen.
16. Turn the **Fan** ON by pressing ON the **Fan Switch** on the screen (Cooling Mode).
17. Start taking readings by pressing **[Read]** button over different temperature values.
18. Notice that the acquired reading appears on the **Temperature-Voltage graph** as white points.
19. Is the cooling curve the same as the heating curve? Why?

....
....
....

20. In order to save the readings you have taken, press **[Save Report]** button, your report will be saved on your desktop in a folder named **Temperature Trainer Files**.
21. To print the report, press **[Print Report]** button.

22. Notice the **Temperature vs. Voltage** curve and answer the following questions:

    22.1 Is the curve linear?
    a) Yes
    b) No

    22.2 Does the thermocouple equation in the "Theory" window describe the curve on the **Temperature vs. Voltage graph**? If your answer is "No", what is the difference and why?

    ....

    ....

23. Choose one of the readings taken before from the Readings Table and write down its Voltage (V) and Temperature (°C) readings:

    23.1 Current Voltage (V) ....
    23.2 Current temperature (°C)........................
    23.3 Apply the current voltage in the thermocouple equation below

$$T = V(1.978425 * 10^{-2}) + V^2(-2.001204 * 10^{-7}) + V^3(1.036969 * 10^{-11}) + V^4(-2.549687 * 10^{-16}) + V^5(3.585153 * 10^{-21}) + V^6(-5.344285 * 10^{-26}) + V^7(5.099890 * 10^{-31})$$

Where: T : Calculated temperature in (°C)
V : Thermocouple voltage in microvolt ($V*10^6$)

    23.4 Write down the Calculated temperature (°C)....................
    23.5 Compare the calculated temperature with the current temperature.

24. Press **[Clear Chart]** button if you want to clear the chart.
25. Press **[Quit]** button to return to the "**Experiments**" window.

Conclusions

1. ....
....
2. ....
....
3. ....
....
4. ....
....

Thermocouple Characteristics

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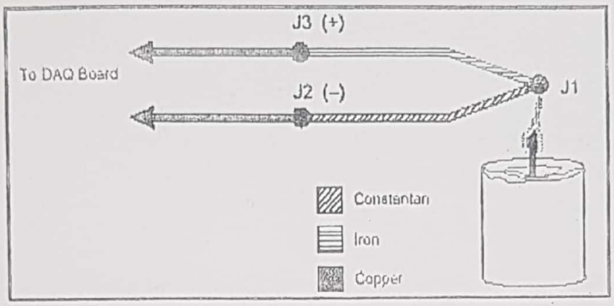

Figure (1): Thermocouple connection

Consider the circuit illustrated in Figure 1, in which a J-type thermocouple is in a candle flame that has a temperature you want to measure. The two thermocouple wires are connected to the copper leads of the measurement device. Notice that the circuit contains three dissimilar metal junctions J1, J2, and J3. J1, the thermocouple junction, generates a Seebeck voltage proportional to the temperature of the candle flame. J2 and J3 each have their own Seebeck coefficient and generate their own thermoelectric voltage proportional to the temperature at the measurement device terminals. To determine the voltage contribution from J1, you need to know the temperatures of junctions J2 and J3 as well as the voltage-to-temperature relationships for these junctions. You can then subtract the contributions of the parasitic junctions at J2 and J3 from the measured voltage at junction J1.

Thermocouples require some form of temperature reference to compensate for these unwanted parasitic "cold" junctions. The most common method is to measure the temperature at the reference junction with a direct-reading temperature sensor and subtract the parasitic junction voltage contributions. This process is called **cold-junction compensation**. You can simplify computing cold-junction compensation by taking advantage of some thermocouple characteristics.
By using the **Thermocouple Law of Intermediate Metals** and making some simple assumptions, you can see that the voltage a data acquisition system measures depends only on the thermocouple type, the thermocouple voltage, and the cold-junction temperature. The measured voltage is in fact independent of the composition of the measurement leads and the cold junctions, J2 and J3.

According to the Thermocouple Law of Intermediate Metals, illustrated in Figure 2, inserting any type of wire into a thermocouple circuit has no effect on the output as long as both ends of that wire are the same temperature, or isothermal.

Experiment Procedure:

1. Run the **TMT001** Software.

2. A screen named "**Welcome to TMT001**" will appear, containing three buttons: **[Information]**, **[Run the Experiments]** and **[Quit]**.

3. The "**Welcome screen**" is shown in the figure below:

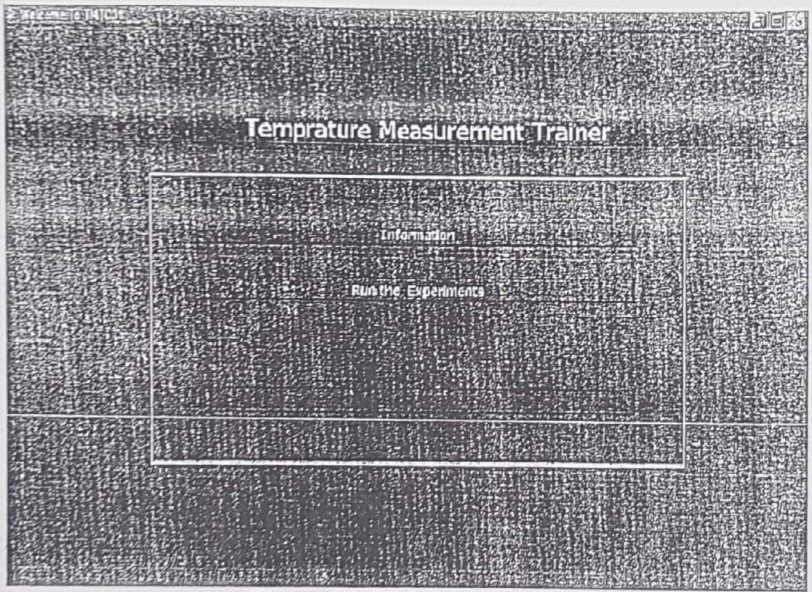

Figure (4): Welcome Screen.

4. Press the **[Information]** button to go to the Information screen.
5. The "**Information Screen**" is shown in the figure below:

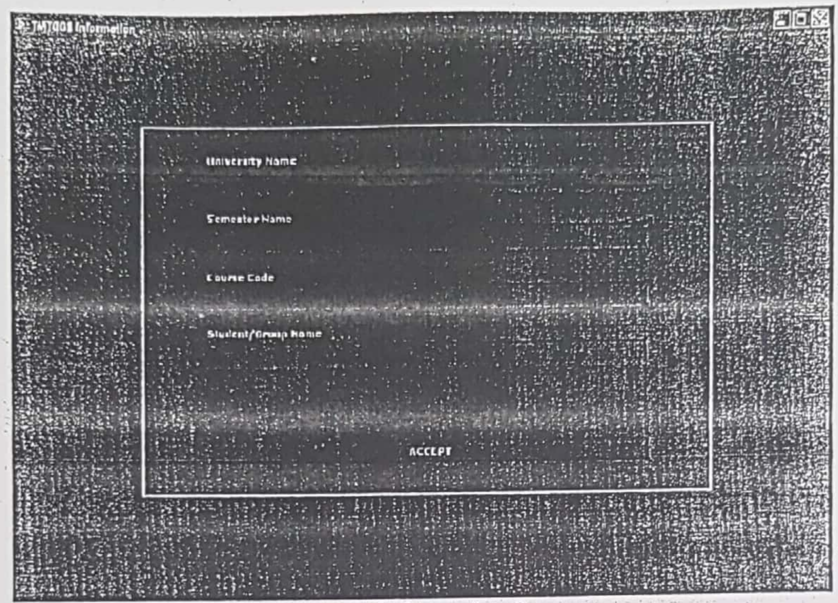

Figure (5): Information Screen.

6. Fill in the fields with your information, Press the **[Accept]** button and a confirmation message will appear asking you to press **[Accept]** the information you have entered, or **[Cancel]** if you need to go back to change anything. Pressing **[Accept]** will let you go back to the **"Welcome Screen"**.
7. Press **[Run the Experiments]** button to go to the **"Experiments screen"**.
8. The **"Experiments Screen"** is shown in the figure 6, containing four experiments; **Thermocouple Characteristics**, **RTD Characteristics**, **Thermistor Characteristics** and **Thermometers Comparison**.

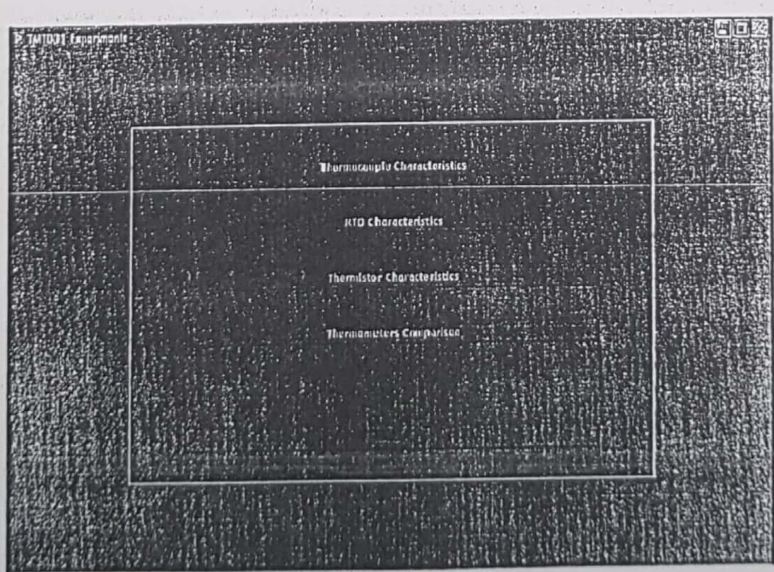

Figure (6): Experiments Screen.

9. Choose Experiment 1: "**Thermocouple Characteristics**".
10. Study the front panel carefully and observe the buttons on the screen.

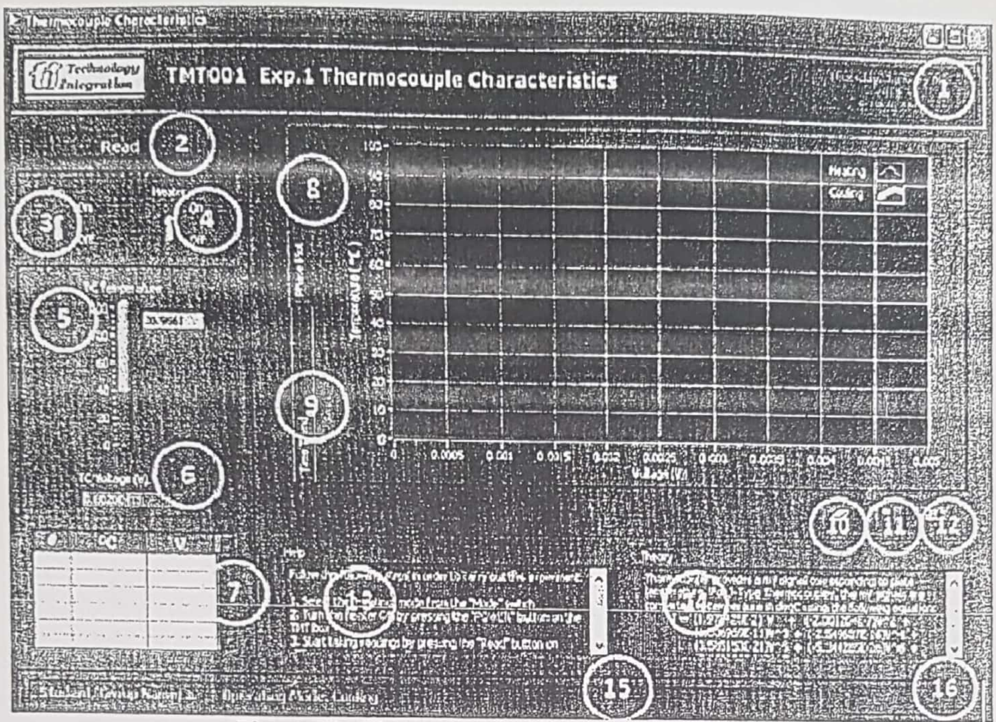

Figure (7): Thermocouple Characteristics Screen.

1) **Current Date and Time Indicator.**
2) **Read Button:** To read and plot the current temperature and voltage (resistance) of the current thermometer (here it is the **Thermocouple**).
3) **Fan Switch:** To turn the Fan ON or OFF.
4) **Heater Switch:** To turn the Heater ON or OFF.
5) **Thermometer Temperature (˚C):** Displays the current temperature of the current thermometer.
6) **Thermometer Voltage (Resistance):** Displays the current voltage (resistance) of the current thermometer.
7) **Readings Table:** Displays the current Temperature and Voltage (resistance) readings taken each time the **[Read]** button is pressed.
8) **Phase Plot:** Contains the Temperature vs. Voltage (Resistance) graph which displays the readings that have been taken by the user. Each point represents the Thermometer Temperature (˚C) with its corresponding Voltage (V) or Resistance (Ohm).

9) **Time Trend:** Contains the Temperature vs. Time graph which displays the temperature profile of the thermometer.
10) **Clear Chart Button:** To clear the Phase Plot graph.
11) **Save Report Button:** To save a report, the report will be saved in the **"Temperature Trainer Files"** folder on the desktop.
12) **Print Report Button:** To print a report, the report will be printed using your default printer.
13) **Help Window:** Displays the procedures needed to carry out the experiment
14) **Theory Window:** Displays the conversion theory of the thermometer of the current experiment (how to change from voltage (resistance) to temperature).
15) **Status Bar:** Displays the current Student/Group name as well as the current operating mode (Heating or Cooling).
16) **Quit Button:** To quit from this experiment and return to the **"Experiments"** window.

11. Turn the **Heater** ON by pressing ON the **Heater Switch** on the screen (Heating Mode).
12. Start taking readings by pressing **[Read]** button on different temperature values.
13. The acquired readings appear on the **Temperature-Voltage graph** as red points.
14. Compare the read temperature with the temperature of the **glass thermometer**. Is it the same temperature? Why?

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    ....
    ....
    ....

15. Turn the **Heater** OFF by pressing OFF the **Heater Switch** on the screen.
16. Turn the **Fan** ON by pressing ON the **Fan Switch** on the screen (Cooling Mode).
17. Start taking readings by pressing **[Read]** button over different temperature values.
18. Notice that the acquired reading appears on the **Temperature-Voltage graph** as white points.
19. Is the cooling curve the same as the heating curve? Why?

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20. In order to save the readings you have taken, press **[Save Report]** button, your report will be saved on your desktop in a folder named **Temperature Trainer Files.**
21. To print the report, press **[Print Report]** button.

22. Notice the **Temperature** vs. **Voltage** curve and answer the following questions:

    22.1 Is the curve linear?
    a) Yes
    b) No

    22.2 Does the thermocouple equation in the "Theory" window describe the curve on the **Temperature** vs. **Voltage graph**? If your answer is "No", what is the difference and why?
    ....
    ....

23. Choose one of the readings taken before from the **Readings Table** and write down its Voltage (V) and Temperature (°C) readings:

    23.1 Current Voltage (V) ....
    23.2 Current temperature (°C):........................
    23.3 Apply the current voltage in the thermocouple equation below

$$T = V(1.978425 * 10^{-2}) + V^2(-2.001204 * 10^{-7}) + V^3(1.036969 * 10^{-11}) + V^4(-2.549687 * 10^{-16}) + V^5(3.585153 * 10^{-21}) + V^6(-5.344285 * 10^{-26}) + V^7(5.099890 * 10^{-31})$$

Where: T : Calculated temperature in (°C)
V : Thermocouple voltage in microvolt ($V*10^6$)

    23.4 Write down the Calculated temperature (°C)......................
    23.5 Compare the calculated temperature with the current temperature.

24. Press **[Clear Chart]** button if you want to clear the chart.
25. Press **[Quit]** button to return to the "**Experiments**" window.

Conclusions

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2. ....
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3. ....
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4. ....
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