HEAT AND MASS TRANSFER

LABORATORY MANUAL

UET

DEPARTMENT OF MECHANICAL ENGINEERING (KSK CAMPUS)

UNIVERSITY OF ENGINEERING & SCIENCE TECHNOLOGY
LAHORE

ENGR. MUHAMMAD ADEEL MUNIR
(BSc. Mechanical Engineering UET, Lahore)
(MSc. Engineering Management UET, Lahore)

Submitted by:

Name =

Registration No =

Submitted to:

Preface

In most of the engineering institutions, the laboratory course forms an integral form of the basic course in Heat and mass transfer at undergraduate level. The experiments to be performed in a laboratory should ideally be designed in such a way as to reinforce the understanding of the basic principles as well as help the students to visualize the various phenomenon encountered in different applications.

The objective of this manual is to familiarize the students with practical skills, measurement techniques and interpretation of results. It is intended to make this manual self-contained in all respects, so that it can be used as a laboratory manual. In all the experiments, the relevant theory and general guidelines for the procedure to be followed have been given. Tabular sheets for entering the observations have also been provided in each experiment while graph sheets have been included wherever necessary.

The students are advised to refer to the relevant text before interpreting the results and writing a permanent discussion. The questions provided at the end of each experiment will reinforce the students understanding of the subject and also help them to prepare for viva-voce exams.

General Instructions To Students

- The purpose of this laboratory is to reinforce and enhance your understanding of the fundamentals of Heat and mass transfer. The experiments here are designed to demonstrate the applications of the basic heat transfer principles and to provide a more intuitive and physical understanding of the theory. The main objective is to introduce a variety of classical experimental and diagnostic techniques, and the principles behind these techniques. This laboratory exercise also provides practice in making engineering judgments, estimates and assessing the reliability of your measurements, skills which are very important in all engineering disciplines.
- Read the lab manual and any background material needed before you come to the lab. You must be prepared for your experiments before coming to the lab.
- Actively participate in class and don't hesitate to ask questions. Utilize the teaching assistants. You should be well prepared before coming to the laboratory, unannounced questions may be asked at any time during the lab.
- Carelessness in personal conduct or in handling equipment may result in serious injury to the individual or the equipment. Do not run near moving machinery. Always be on the alert for strange sounds. Guard against entangling clothes in moving parts of machinery.
- Students must follow the proper dress code inside the laboratory. To protect clothing from dirt, wear a lab apron. Long hair should be tied back.
- Calculator, graph sheets and drawing accessories are mandatory.
- In performing the experiments, proceed carefully to minimize any water spills, especially on the electric circuits and wire.
- Make your workplace clean before leaving the laboratory. Maintain silence, order and discipline inside the lab.
- Cell phones are not allowed inside the laboratory.
- Any injury no matter how small must be reported to the instructor immediately.
- Wish you a nice experience in this lab

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1. LAB SESSION 1

To understand the use of Fourier Rate Equation for steady flow of heat through plane solid materials.

1.1 Learning Objective

[i] To identify a given sample by determining its thermal conductivity.

[ii] To measure temperature distribution through a uniform plane wall and demonstrate the effect of a change in heat flow.

[iii] To measure the temperature distribution through a composite plane wall and determine the overall Heat Transfer Coefficient.

1.2 Apparatus

Linear Heat Transfer unit H111A (Serial no H111A/04417)

1.3 Main Parts of Linear Heat Transfer Unit

1) Hydraulic Bench
2) Specimen of different materials (Brass, Aluminium, Stainless Steel)
3) Main digital Control panel (H111)
4) Temperature Sensors

1.4 Useful Data

Heated Section:

Material: Brass 25 mm diameters, Thermocouples T1, T2, T3 at 15mm spacing. Thermal Conductivity: Approximately 121 W/mK

Cooled Section:

Material: Brass 25 mm diameters, Thermocouples T6, T7, T8 at 15mm spacing. Thermal Conductivity: Approximately 121 W/mK

Brass Intermediate Specimen:

Material: Brass 25 mm diameters * 30mm long. Thermocouples T4, T5 at 15mm spacing centrally spaced along the length. Thermal Conductivity: Approximately 121 W/mK

Stainless Steel Intermediate Specimen:

Material: Stainless Steel, 25 mm diameters * 30mm long. No Thermocouples fitted.

Thermal Conductivity: Approximately 25 W/mK

Aluminum Intermediate Specimen:

Material: Aluminum Alloy, 25 mm diameters * 30mm long. No Thermocouples fitted.

Thermal Conductivity: Approximately 180 W/mK

Reduced Diameter Brass Intermediate Specimen:

Material: Brass, 13 mm diameters * 30mm long. No Thermocouples fitted.

Thermal Conductivity: Approximately 121 W/mK

Hot and Cold Face Temperature:

Due to the need to keep the spacing of the thermocouples constant at 15mm with, or without the intermediate specimens in position the thermocouples are displaced 7.5 mm back from the ends faces of the heated and cooled specimens and similarly located for the Brass Intermediate Specimen.

$T_{\text{hot face}} = T_3 - (T_2 - T_3)/2$ $\quad$ $T_{\text{cold face}} = T_6 + (T_6 - T_7)/2$

So that the equations are of the above form as the distance between T3 and the hot face and T6 and the cold face are equal to half the distance between the adjacent pairs of thermocouples.

1.5 Theory

1.5.1 Conduction Heat Transfer

When a temperature gradient exists in a body, there is an energy transfer from the high-temperature region to the low-temperature region. The energy is transferred by conduction and that the heat-transfer rate per unit area is proportional to the normal temperature gradient

1.5.2 Fourier’s law of heat conduction

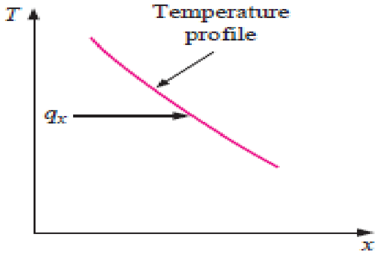


Figure 1.1: Temperature Profile in Fourier heat conduction

$q_x = -KA\frac{\partial T}{\partial x}$ Equation I.1: Fourier law heat conduction equation

Where q_x is the heat-transfer rate and $\partial T/\partial x$ is the temperature gradient in the direction of the heat flow. The positive constant k is called the thermal conductivity of the material, and the minus sign is inserted so that the second principle of thermodynamics will be satisfied; i.e., heat must flow downhill on the temperature scale as shown in figure 1.1. Equation 1.1 is called Fourier’s law of heat conduction after the French mathematical physicist Joseph Fourier, who made very significant contributions to the analytical treatment of conduction heat transfer. (Equation 1.1) is the defining equation for the thermal conductivity and that k has the units of watts per meter per Cels1ius degree in a typical system of units in which the heat flow is expressed in watts

1.5.3 The Plane wall

First consider the plane wall where a direct application of Fourier's law. Integration yields

$$q=-\frac{KA}{\Delta x}(T_2-T_1)$$

Equation 1.2: Integration of Fourier law

When the thermal conductivity is considered constant. The wall thickness is x, and T_1 and T_2 are the wall-face temperatures.

1.5.4 The Composite wall

If more than one material is present, as in the multilayer wall shown in Figure 2, the analysis would proceed as follows: The temperature gradients in the three materials are shown, and the heat flow may be written

$$q=-k_A A\frac{T_2-T_1}{\Delta x_A}=-k_B A\frac{T_3-T_2}{\Delta x_B}=-k_C A\frac{T_4-T_3}{\Delta x_C}$$

Equation 1.3: Heat through composite wall

Note that the heat flow must be the same through all sections

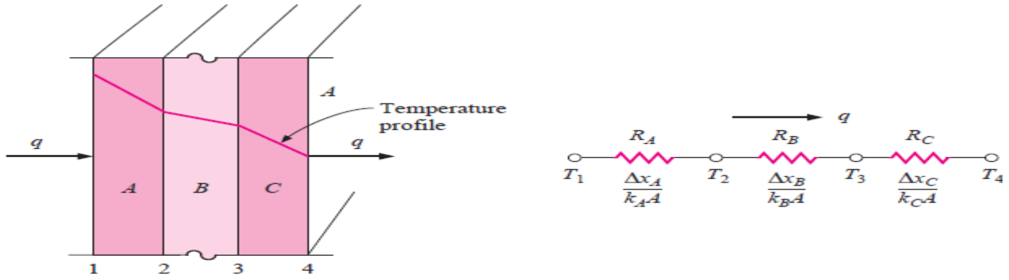


Figure 1.2: Heat through composite wall

Solving these three equations simultaneously, the heat flow is written

$$q=\frac{T_1-T_4}{\frac{\Delta x_A}{k_A A}+\frac{\Delta x_B}{k_{BA} A}+\frac{\Delta x_C}{k_C A}}$$

Equation 1.4: Heat flow equation through composite wall

With composite systems, it is often convenient to work with an overall heat transfer coefficient U, which is defined by an expression analogous to Newton's law of cooling. Accordingly

$$Q=UA\Delta T$$

Equation 1.5: Overall heat transfer coefficient

Where ΔT is the overall temperature difference. Readers can read Further detail from book "heat transfer by J.P Holman" in "chapter 2"

1.6 Experimental Procedure

1. Ensure that the main switch is in the off position (the digital displays should not be illuminated). Ensure that the residual current circuit breaker on the rear panel is in the ON position.

2. Turn the voltage controller anti-clockwise to set the AC voltage to minimum.

3. Ensure the cold water supply and electrical supply is turned on at the source. Open the water tap until the flow through the drain hose is approximately 1.5 liters/minute. The actual flow can be checked using a measuring vessel and stopwatch if required but this is not a critical parameter. The flow has to dissipate up to 65W only.

4. Release the toggle clamp tensioning screw and clamps. Ensure that the faces of the exposed ends of the heated and cooled sections are clean. Similarly, check the faces of the Intermediate specimen to be placed between the faces of the heated and cooled section. Coat the mating faces of the heated and cooled sections and the intermediate section with thermal conduction paste. Ensure the intermediate section to be used is in the correct orientation then clamp the assembly together using the toggle clamps and tensioning screw.

5. Turn on the main switch and the digital displays should illuminate. Set the temperature selector switch to T1 to indicate the temperature of the heated end of the bar.

6. Following the above procedure ensure cooling water is flowing and then set the heater voltage V to approximately 150 volts. This will provide a reasonable temperature gradient along the length of the bar. If however the local cooling water supply is at a high temperature (25-35℃ or more) then it may be necessary to increase the voltage supplied to the heater. This will increase the temperature difference between the hot and cold ends of the bar.

7. Monitor temperatures T1, T2, T3, T4, T5, T6, T7, T8 until stable. When the temperatures are stabilized record T1, T2, T3, T4, T5, T6, T7, T8, V, I

8. Increase the heater voltage by approximately 50 volts and repeat the above procedure again recording the parameters T1, T2, T3, T4, T5, T6, T7, T8, V, I when temperature have stabilized.

9. When the experimental procedure is completed, it is good practice to turn off the power to the heater by reducing the voltage to zero and allow the system a short time to cool before turning off the cooling water supply.

10. Ensure that the locally supplied water supply isolation valve to the unit is closed. Turn off the main switch and isolate the electrical supply.

11. Note that if the thermal conducting paste is left on the mating faces of the heating and cooled sections for a long period it can be more difficult to remove than if removed

immediately after completing an experiment. If left on the intermediate sections it can attract dust and in particular grit which acts as a barrier to good thermal conduct.

12. Thermal Conductivity of intermediate sample can be calculated by using the formula $k_{int}=\frac{\dot{Q}\Delta x_{int}}{A_{int}\Delta T_{int}}$
13. By using different samples, thermal conductivities can be calculated by using above formula.
14. The value of thermal conductivities can be compared and material of sample can be identified.

1.7 Observations

Sample No.	**T_1**	**T_2**	**T_3**	**T_4**	**T_5**	**T_6**	**T_7**	**T_8**	**V**	**I**
	°C	**°C**	**°C**	**°C**	**°C**	**°C**	**°C**	**°C**	**Volts**	**Amps**
1										
2										
3										
4										
Distance from T1	**0.000**	**0.015**	**0.030**	**0.045**	**0.060**	**0.075**	**0.090**	**0.105**		

Table 1.1: Temperatures observation at different points of specimen

1.8 Calculated Data

1.8.1 Objective:1

To identify a given sample by determining its thermal conductivity.

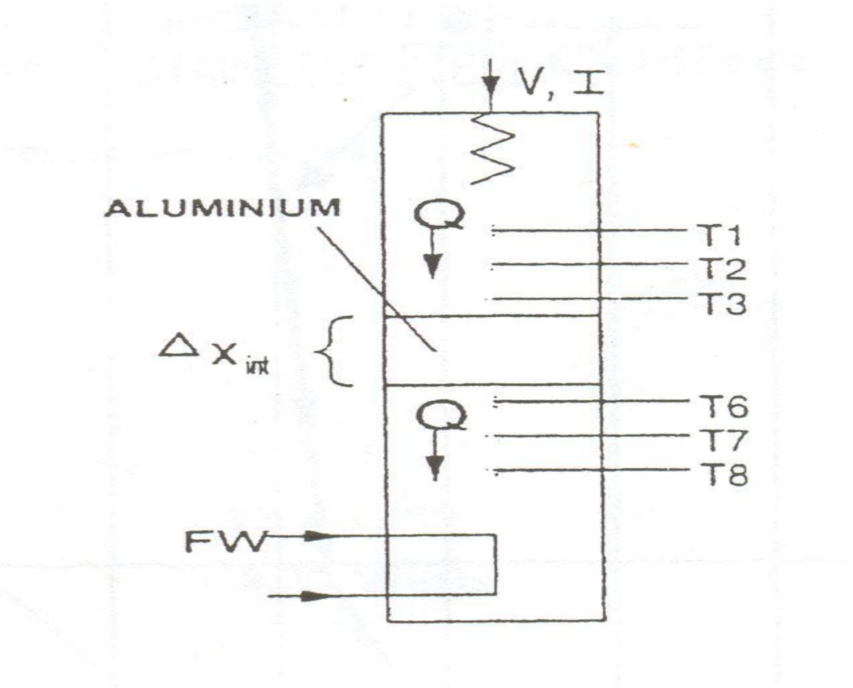


Figure.1.3: Schematic diagram of experiment

Specimen cross sectional Area A=0.00049m^2

Specimen Length =0.030m

Sample No.	$\dot{Q}$	$T_{hotface}$	$T_{coldface}$	ΔT_{int}	k_{int}	**Material Name**
	$Watts$	℃	℃	K	W/mK	
1						
2						
3						
4						

Table 1.2: Calculation of thermal conductivity

1.8.1.1 Specimen Calculations

Intermediate Specimen and hot and cold section cross sectional Area;

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

Heat transfer rate from the heater;

$$\dot{Q} = V * I$$

Note that the thermocouples T3 and T6 do not record the hot face and cold face temperatures, as are both displaced by 0.0075m from T3 and T6 as shown.

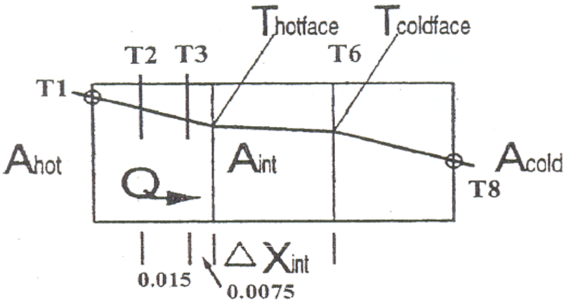


Figure.1.4: Schematic diagram of experiment

If it is assumed that the temperature distribution is linear, then the actual temperature at the hot face and cold face may be determined from the following equations.

$$T_{\text{hot face}} = T_3 - (T_2 - T_3)/2$$

And

$$T_{\text{cold face}} = T_6 + (T_6 - T_7)/2$$

$$\Delta T_{int} = T_{hotface\_}T_{coldface}$$

From the above parameters, the thermal conductivity of the aluminum intermediate section may be calculated.

$$k_{int} = \frac{\dot{Q}\Delta x_{int}}{A_{int}(T_{hotface} - T_{coldface})} = \frac{\dot{Q}\Delta x_{int}}{A_{int}\Delta T_{int}}$$

1.8.1.2 Graph:

Plot a graph b/w Temperature and Distance from T1 thermocouple. The thermal conductivity of the intermediate sample may also be calculated from the data it is plotted on a graph. From the graph the slope of the line is.

$$\frac{\Delta T_{int}}{\Delta x_{int}} = X$$

Hence

$$k_{int} = \frac{\dot{Q}}{A} * \frac{\Delta T_{int}}{\Delta x_{int}}$$

1.8.1.3 Statistical Analysis

For Thermal conductivity

% Error= $\frac{K_{th}-K_{exp}}{K_{th}}$

$x_{avg}= \frac{x_1+x_2+x_3}{n}$

$S_x=\sqrt{\frac{1}{n-1}((x_1-x_{avg})^2+(x_2-x_{avg})^2+(x_3-x_{avg})^2)}$

1.8.1.4 Conclusion

1.8.2 Objective:2

To measure the temperature distribution through a uniform plane wall and demonstrate the effect of a change in heat flow.

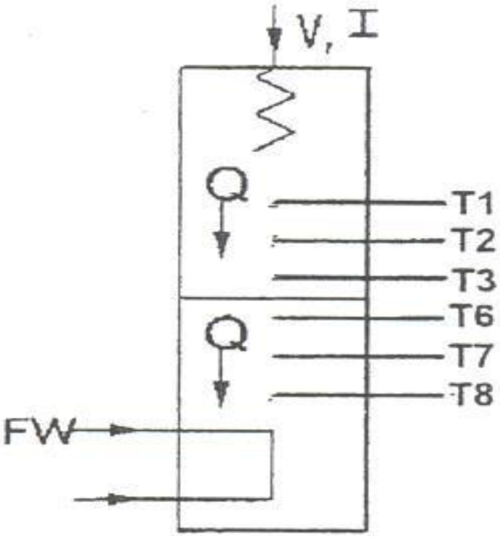


Figure 1.5: Schematic diagram of experiment

Sample No.	$\dot{Q}$	ΔT 1-3	ΔT 6-8	Δx 1-3	Δx 6-8	$\frac{\Delta T_{1-3}}{\Delta x_{1-3}}$	$\frac{\Delta T_{6-8}}{\Delta x_{6-8}}$	$\dot{Q}/(\frac{\Delta T_{1-3}}{\Delta x_{1-3}})$	$\dot{Q}/(\frac{\Delta T_{6-8}}{\Delta x_{6-8}})$
	W	℃	℃	m	M	℃/m	℃/m	W/mK	W/mK
1									
2									
3									
4									

Table 1.3: Distribution of temperature through uniform plane wall

1.8.2.1 Specimen Calculations

Heat transfer rate from the heater;

$$\dot{Q} = V * I$$

Temperature difference in the heated section between T1 and T3;

$$\Delta T_{hot} = \Delta T_{1-3} = T_1 - T_3$$

Similarly the temperature difference in the cooled section between T6 and T8;

$$\Delta T_{cold} = \Delta T_{6-8} = T_6 - T_8$$

The distance between the temperatures measuring points, T1 and T3and T6 and T8, are similar;

$$\Delta x_{1-3} =$$

$$\Delta x_{6-8} =$$

Hence the temperature gradient along the heated and cooled sections may be calculated from

$$\text{HeatedSection} = \frac{\Delta T_{1-3}}{\Delta x_{1-3}} =$$

$$\text{CooledSection} = \frac{\Delta T_{6-8}}{\Delta x_{6-8}} =$$

If the constant rate of heat transfer is divided by the temperature gradients, the value obtained will be similar if the equation is valid.

$$\dot{Q} = C\frac{\Delta T}{\Delta x}$$

$$\frac{\dot{Q}}{\left(\frac{\Delta T}{\Delta x}\right)} = C$$

Hence, substituting the values obtained gives for the heated section and cooled sections respectively for following values.

$$\dot{Q} \Big/ \left(\frac{\Delta T_{1-3}}{\Delta x_{1-3}}\right) =$$

$$\dot{Q} \Big/ \left(\frac{\Delta T_{6-8}}{\Delta x_{6-8}}\right) =$$

As may be seen from the above example and the tabulated data the function does result in a constant value within the limits of the experimental data.

$$\frac{\dot{Q}}{\left(\frac{\Delta T}{\Delta x}\right)} = C$$

1.8.2.2 Statistical Analysis

For Constant “C”

% Error= $\frac{K_{th}-K_{exp}}{K_{th}}$

x_{avg}= $\frac{x_1+x_2+x_3}{n}$

S_x=$\sqrt{\frac{1}{n-1}((x_1-x_{avg})^2+(x_2-x_{avg})^2+(x_3-x_{avg})^2)}$

1.8.2.3 Conclusion

1.8.3 Objective: 3

To measure the temperature distribution through a composite plane wall and determine the overall Heat Transfer Coefficient for the flow of heat through a combination of different materials in use.

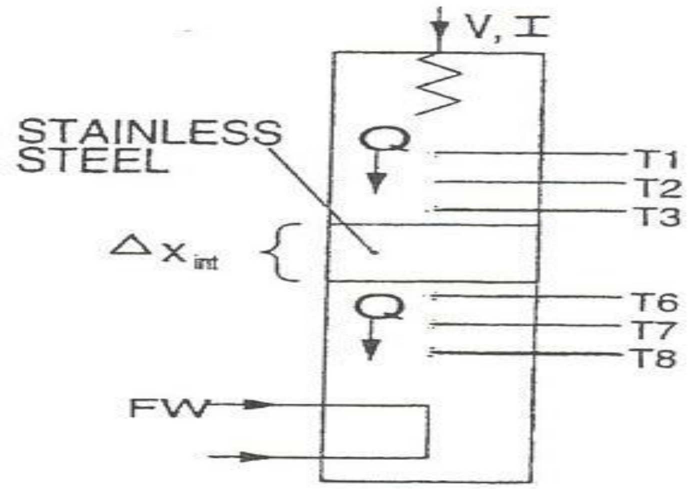


Figure 1.6: Schematic diagram of experiment

Specimen cross sectional Area A = 0.00049m^2

Conductivity of Brass heated and cooled section =121$W/_{m}K$

Conductivity of Stainless steel intermediate section =25$W/_{m}K$

Sample No.	Q	ΔT_{1-8}	Δx_{hot}	Δx_{int}	Δx_{cold}	k_{hot}	k_{int}	k_{cold}
--	W	K	m	M	m	$W/_{mK}$	$W/_{mK}$	$W/_{mK}$
1								
2								
3								
4								

Sample No.	$U = \frac{1}{(\frac{x_{hot}}{k_{hot}} + \frac{x_{int}}{k_{int}} + \frac{x_{cold}}{k_{cold}})}$	$\frac{Q}{A(T_1 - T_8)} = U$
--	$\frac{W}{m^2K}$	$\frac{W}{m^2K}$
1		
2		
3		
4		

Table 1.4: Calculation of overall heat transfer coefficient

1.8.3.1 Specimen Calculations

Brass Intermediate Specimen and hot and cold section cross sectional Area;

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

The temperature difference across the bar from T1 to T8;

$$T_1 - T_8 = X$$

Note that Δx_{hot} and $\Delta x_{cold}$are the distances between the thermocouple T1 and the hot face and the cold face and the thermocouple T8 respectively. Similarly Δx_{int} is the distance between the hot face and cold face of the intermediate stainless steel section.

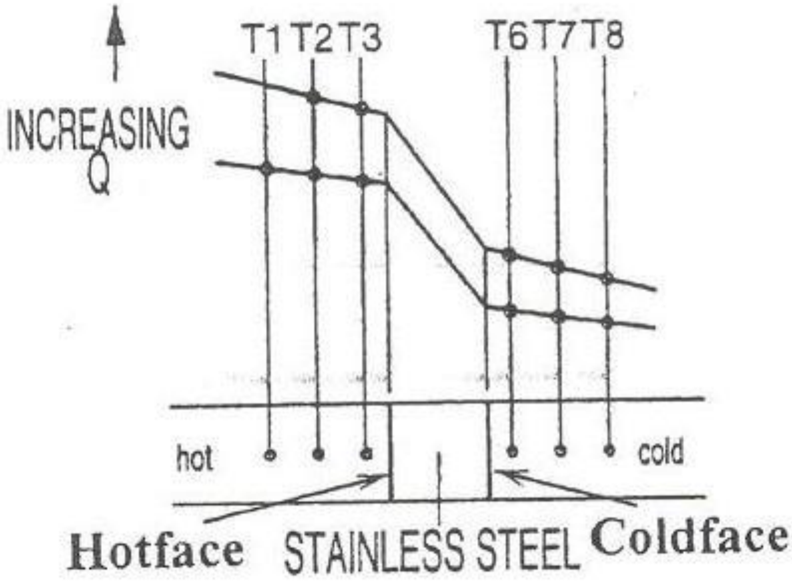


Figure 1.7: Schematic diagram of experiment

The distances between surfaces are therefore as follows.

$\Delta x_{hot} =$ 0.0375m

$\Delta x_{int} =$ 0.030m

$\Delta x_{cold} =$ 0.0375m

Heat transfer rate from the heater;

$$Q = VI$$

Hence

$$U = \frac{Q}{A(T_1 - T_8)}$$

Similarly,

$$U = \frac{1}{(\frac{x_{hot}}{k_{hot}} + \frac{x_{int}}{k_{int}} + \frac{x_{cold}}{k_{cold}})}$$

Note that the U value resulting from the test data differs from that resulting from assumed thermal conductivity and material thickness. This is most likely due to un-accounted for heat losses and thermal resistances between the hot face interface and cold face inter face with the stainless steel intermediate section.

1.8.3.2 Graph

Plot a graph b/w Temperature and Distance from T_1 thermocouple. The temperature data may be plotted against position along the bar and straight lines drawn through the temperature points for the heated and cooled sections. Then a straight line may be drawn through the hot face and cold face temperature to extrapolate the temperature distribution in the stainless steel intermediate section.

1.8.3.3 Statistical Analysis

For Constant "U"

% Error= $\frac{K_{th}-K_{exp}}{K_{th}}$

$x_{avg}=\frac{x_1+x_2+x_3}{n}$

$S_x=\sqrt{\frac{1}{n-1}((x_1-x_{avg})^2+(x_2-x_{avg})^2+(x_3-x_{avg})^2)}$

1.8.3.4 Conclusion

1.9 Questions

1) What is conduction heat transfer
2) What is Fourier law of heat conduction
3) What is meant by thermal resistance
4) Define Overall heat transfer coefficient
5) Define thermal conductivity and explain its significance in heat transfer.

1.10 Comments

2. LAB SESSION NO: 02

To understand the use of the Fourier Rate Equation for steady flow of heat through cylindrical solid materials

2.1 Learning Objective:

[i] To identify a given sample (disc material) by determining its thermal conductivity.

[ii] To measure the temperature distribution through the wall of a thick cylinder (Radial energy flow) and demonstrate the effect of a change in heat flow.

2.2 Apparatus

Radial Heat Transfer unit H111B

2.3 Main Parts of Radial Heat transfer unit

1) Hydraulic Bench
2) Specimen of different materials
3) Main digital Control panel (H111)
4) Temperature Sensors

2.4 Useful Data

2.4.1 Radial Heat Conduction

2.4.2 Heated disc:

Material: Outside Diameter: 0.110m

Diameter of Heated Sample Core: 0.014m

Thickness of Disc (x): 0.0032m

Radial Position of Thermocouples:

T1=0.007m

T2=0.010m

T3=0.020m

T4=0.030m

2.5 Theory

2.5.1 Conduction Heat Transfer

When a temperature gradient exists in a body, there is an energy transfer from the high-temperature region to the low-temperature region. The energy is transferred by conduction and that the heat-transfer rate per unit area is proportional to the normal temperature gradient.

2.5.2 Radial Systems

2.5.2.1 Cylinders

Consider a long cylinder of inside radius r_i, outside radius r_o, and length L, such as the one shown in Figure 2.1.We expose this cylinder to a temperature differential $T_i - T_o$. For a cylinder with length very large compared to diameter, it may be assumed that the heat flows only in a radial direction, so that the only space coordinate needed to specify the system is r. Again, Fourier's law is used by inserting the proper area relation. The area for heat flow in the cylindrical system is

$$A_r = 2\pi rL$$

So that Fourier's law is written

$$q_r = -kA_r \frac{dT}{dr}$$

$$q_r = -2\pi krL \frac{dT}{dr}$$ Equation 2.1: Fourier Law equation for cylinders

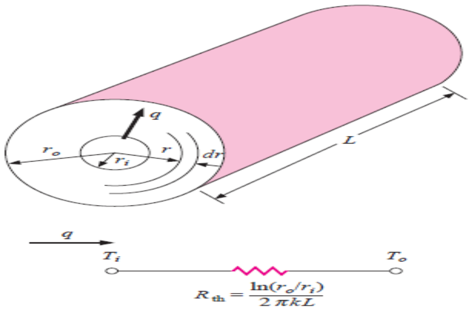


Figure 2.1: Heat transfer through cylinder

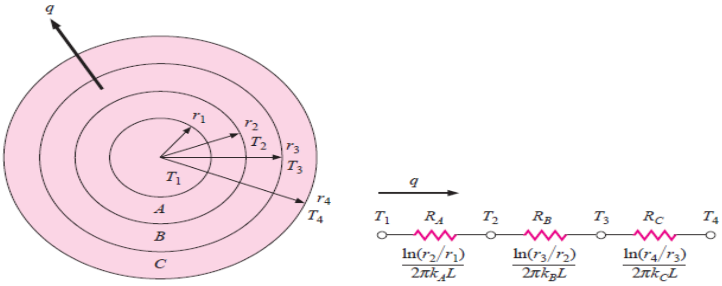


Figure 2.2: Temperature distribution in cylinder

With the boundary conditions

$$T = T_i \text{ at } r = r_i$$

$$T = T_0 \text{ at } r = r_0$$

The solution to Equation 2.1 is

$$q = \frac{2\pi kL(T_i - T_\circ)}{\ln(\frac{r_\circ}{r_i})}$$ Equation 2.2: Fourier Law equation for cylinders

2.6 Procedure

1. Ensure that the main switch is in the off position (the digital displays should not be illuminated).
2. Ensure the cold water supply and electrical supply is turned on at the source. Open the water tap until the flow through the drain hose is approximately 1.5 liters/minute. The actual flow can be checked using a measuring vessel and stopwatch if required but this is not a critical parameter. The flow has to dissipate up to 100W only.
3. Turn on the main switch and the digital displays should illuminate. Set the temperature selector switch to T1 to indicate the temperature of the heated centre of the disc.
4. Following the above procedure ensure cooling water is flowing and then set the heater voltage V to approximately 50 volts.
5. Monitor temperatures T1, T2, T3, T4, T5, and T6 until stable. When the temperatures are stabilized record: T1, T2, T3, T4, T5, T6, V, I
6. Reset heater voltage to 100 volts and repeat the above procedure again and Monitor temperatures T1, T2, T3, T4, T5, and T6 until stable. When the temperatures are stabilized record: T1, T2, T3, T4, T5, T6 V, I
7. Reset heater voltage to 150 volts and repeat the above procedure again and Monitor temperatures T1, T2, T3, T4, T5, and T6 until stable. When the temperatures are stabilized record: T1, T2, T3, T4, T5, T6 V, I
8. Reset heater voltage to 200 volts and repeat the above procedure again and Monitor temperatures T1, T2, T3, T4, T5, and T6 until stable. When the temperatures are stabilized record: T1, T2, T3, T4, T5, T6 V, I
9. When the experimental procedure is completed, it is good practice to turn off the power to the heater by reducing the voltage to zero and allow the system a short time to cool before turning off the cooling water supply.
10. Ensure that the locally supplied water supply isolation valve to the unit is closed. Turn off the main switch and isolate the electrical supply.

2.7 Observations

Sample No.	**T_1**	**T_2**	**T_3**	**T_4**	**T_5**	**T_6**	**V**	**I**
	^{0} C	**^{0} C**	**^{0} C**	**^{0} C**	**^{0} C**	**^{0} C**	**Volts**	**Amps**
1								
2								
3								
4								
Radius	**0.007**	**0.010**	**0.020**	**0.030**	**0.040**	**0.050**	**---**	**---**

Table 2.1: Distribution of temperature for different voltages

2.8 Calculated Data

2.8.1 Objective:1

To identify a given sample (disc material) by determining its thermal conductivity.

Sample No.	$\dot{Q}$	$\dot{Q} \times \frac{\ln(\frac{R_6}{R_1})}{2\pi x(T_1 - T_6)}$	$\dot{Q} \times \frac{\ln(\frac{R_3}{R_1})}{2\pi x(T_1 - T_3)}$	$\dot{Q} \times \frac{\ln\left(\frac{R_6}{R_4}\right)}{2\pi x(T_4 - T_6)}$
	Watts	W/mK	W/mK	W/mK
1				
2				
3				
4				

Table 2.2: Thermal conductivity of given sample

2.8.1.1 Specimen Calculations

X=0.0032 (Thickness or length of disc)

Heat transfer rate from the heater;

$$\dot{Q} = V * I$$

From Fourier's equation (ignoring the negative sign)

$$k = \frac{\dot{Q}\ln\left(\frac{R_{\circ}}{R_i}\right)}{2\pi x(T_{\circ} - T_i)}$$

Examining the points T1 and T6 and substituting values gives

$$k = \dot{Q} \times \frac{\ln(\frac{R_6}{R_1})}{2\pi x(T_1 - T_6)}$$

Similarly the other pair of points on Radius;

$$k = \frac{\dot{Q}\ln\left(\frac{R_3}{R_1}\right)}{2\pi x(T_1 - T_3)}$$

$$k = \frac{\dot{Q}\ln\left(\frac{R_6}{R_4}\right)}{2\pi x(T_4 - T_6)}$$

2.8.1.2 Conclusion

2.8.2 Objective:02

To measure the temperature distribution through the wall of a thick cylinder (Radial energy flow) and demonstrate the effect of a change in heat flow

Sample No.	$\dot{Q}$
--	W
1	
2	
3	
4	

Table 2.3: Thermal conductivity of given sample

2.8.2.1 Specimen Calculation

Heat transfer rate from the heater;

$$\dot{Q} = VI$$

If lines are drawn between each temperature measurement point and a second line is drawn between T5 and T6, the change in temperature gradient as the radius increases seen.

In addition as the input Q is increases the overall slope of the temperature gradients also increases.

2.8.2.2 Graph

Plot a graph b/w Radius from heated disc centre (x-axis) and Temperature (y-axis).

2.8.2.3 Conclusion

2.9 Statistical Analysis

For Thermal conductivity

% Error= $\frac{K_{th}-K_{exp}}{\mathrm{K_{th}}}$

$x_{avg}= \frac{x_1+x_2+x_3}{n}$

$S_x=\sqrt{\frac{1}{n-1}((x_1-x_{avg})^2+(x_2-x_{avg})^2+(x_3-x_{avg})^2)}$

2.10 Questions

1) How temperature distribution through the wall of a thick cylinder

2) What is steady-state heat transfer?

3) What is effect of changing the thickness of cylinder on thermal conductivity?

4) Why by increasing input heat Q, overall slope of the temperature gradients increases.

2.11 Comments

3. LAB SESSION 3

To understand basics about radiation heat transfer mechanism

3.1 Learning Objective

To demonstrate the inverse square law for thermal radiation

To demonstrate the Stefan Boltzmann Law

To demonstrate the role of shape factor involved in radiation heat transfer

3.2 Apparatus

Radiation Heat Transfer unit H111C (Serial no H111C/01310)

3.3 Main Parts

1) Heat Source
2) Radiation detector
3) Temperature Sensors
4) Radiometer output unit
5) Main digital Control panel (H111)

3.4 Useful Data

Laws of radiant heat transfer and radiant heat exchange (H111C)

Stefen-Boltzman Constant σ =$5.67x10^{-8}\ \frac{\mathrm{w}}{\mathrm{m}^2\mathrm{k}^4}$

3.5 Theory

3.5.1 Radiation

Radiation is the emission or transmission of energy in the form of waves or particles through space or through a material medium.

3.5.2 Radiation Heat Transfer

Thermal radiation is electromagnetic radiation generated by the thermal motion of charged particles in matter. All matter with a temperature greater than absolute zero emits thermal radiation. When the temperature of the body is greater than absolute zero, interatomic collisions cause the kinetic energy of the atoms or molecules to change. All bodies radiate energy in the form of photons moving in a random direction, with random phase and frequency. When radiated photons reach another surface, they may be absorbed, reflected or transmitted. The behavior of a surface with radiation incident upon it can be described by the following quantities:

α= absorptance =fraction of incident radiation absorbed

P= reflectance = fraction of incident radiation reflected

τ = transmittance = fraction of incident radiation transmitted.

3.5.3 Inverse square law

Intensity is inversely proportional to the square of the distance from the source of that physical quantity. Mathematically formulated:

$$\text{Intensity} \propto \frac{1}{\text{distance}^2}$$

3.5.4 Stefan–Boltzmann law

To show that the intensity of radiation varies as the fourth power of the source temperature. The Stefan-Boltzmann law states that for a black body

$$q_b = \sigma\,(Ts^4 - Ta^4)$$

Equation 3.1: Stefan-Boltzmann law

Where

q_b = The energy emitted per unit area of a black body radiator $\frac{W}{m^2}$

T_s = The absolute temperature of the black body K

T_a = The absolute temperature of the surroundings K

σ = Stefen-Boltzman Constant $\sigma = 5.67\text{x}10^{-8}\ \frac{w}{m^2k^4}$

This is the energy emitted from the surface.

At a distance x from the surface the energy received (and indicated) by a detector R will be related to the Stefan-Boltzmann constant by a factor F such that.

$$R = F \text{ x } \sigma(Ts^4 - Ta^4)$$

3.5.5 Shape Factor

Hence

$$F = \frac{R}{\sigma\,((Ts^4 - Ta^4)}$$

$$F = \frac{R}{q_b}$$

It can be shown that the view factor F is related to the view angle θ such that

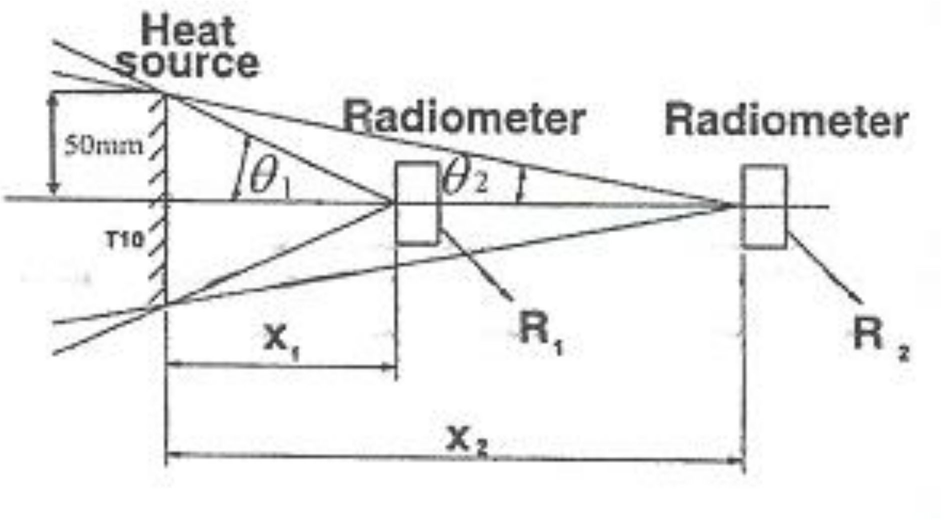


Figure.3.1: Schematic diagram for shape factor

$$F = \sin^2\theta$$

Hence

$$R = \sin^2\theta \times \sigma \times (Ts^4 - Ta^4) = \sin^2\theta \times q_b$$ Equation 3.2: Energy received by detector

Test data is shown overleaf to illustrate the relationship.

3.6 Procedure

1. Ensure that the H111 main switch is in the off position (the three digital displays should not be illuminated). Ensure that the residual current circuit breaker on the rear panel is in the ON position.
2. Turn the voltage controller anti-clock wise to set the AC voltage to minimum.
3. Connect the 8-way plug for heat source.
4. Install the heated plate C1 (10) at the left hand side of the track and install the radiometer C1 (12) on the right hand carriage C1 (2). No items are installed in the left hand carriage for the experiment but one of the black plates should be placed on the bench and connected to the thermocouple socket T9.
5. Schematically this produces a system as shown below.
6. Fit the light radiometer to the sensor carriage C1 (13).
7. Ensure that the radiation shield is in position in the radiometer aperture and station the radiometer in the 900mm position as shown above.
8. The radiometer should be left for several minutes after handling with the radiation shield in position to ensure that residual heating has dissipated.

9. For radiometer experiments, position the $\frac{W}{m^2}$ displays console on top of the H111 console. Connect the power cable between both consoles and plug the radiometer signal cable into the front panel.
10. Turn on the H111 main switch and three digital displays should illuminate. The radiometer should also illuminate. The required temperature is displayed on the LED digital display by turning the rotary sector switch.
11. 'Auto-Zero' the radiometer by pressing the right hand * button twice.

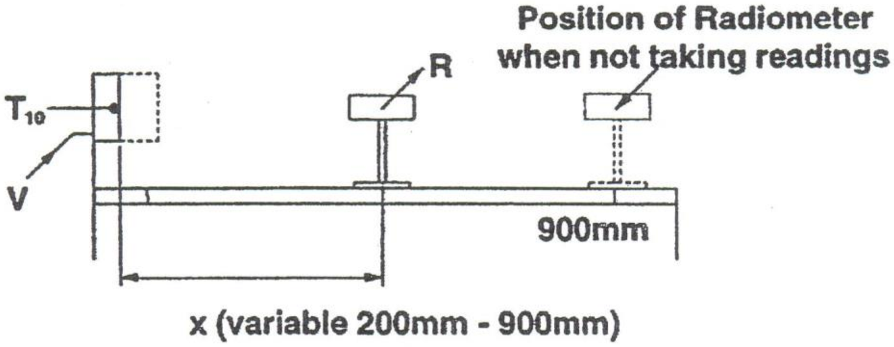


Figure 3.2: Schematic diagram of experiment

12. Rotate the voltage controller clockwise to increase the voltage.
13. Monitor the $\frac{W}{m^2}$ digital displays and after several minutes, the display should reach a minimum.
14. Finally, "Auto-Zero" the radiometer by pressing the right hand * button twice.
15. Leave the radiation shield in position and rotate the voltage controller clockwise to increase the voltage to maximum volts. Select the T_{10} position on the temperature selector switch and monitor the T_{10} temperature.
16. When the T_{10} temperature has reached a maximum condition, remove the radiation shield (without touching the radiometer). Immediately the indicated value should start to rise. Monitor the digital display until the displayed value reaches a maximum and then record the following.

    T_7, T_{10}, X (900mm in this case), R.

17. Again without touching the radiometer, move the carriage holding the radiometer to a position 800mm from the heated plate. Again, the radiometer reading will start to rise. Allow this to reach a maximum and repeat the observations

T_7, T10, X (800mm in this case), R.

18. Repeat the above procedure in reducing steps of 100mm until the radiometer is 200mm from the heated plate.
19. Note that at a distance of less than 200mm, the heated plate completely fills the field of view of the radiometer and accuracy of measurement reduces.
20. When the experimental procedure is completed, it is good practice to turn off the power to the heater by reducing the AC voltage to zero and then turn off H111 main switch. Allow the components to cool before storing them away safely.

3.7 Observations:

Sample test results

For the unit tested C = 0.786

V	**I**	**T_7**	**T_{10}**	**x**	**R**	**R_c**
				900		
				800		
				700		
				600		
				500		
				400		
				300		
				200		

Table 3.1: Measurement of temperatures from radiometer

While

T_7= Temperature of black body

T_{10}= Temperature of heater

X=Distance of radiometer from heater

V= Voltage

I= Current

R= Reading of radiometer in $\frac{W}{m^2}$

$R_{c=}$ Corrected radiometer reading=Rc $= \mathrm{R} \times \mathrm{C}$

3.8 Calculated Data

3.8.1 Objective:01

To demonstrate the inverse square law for thermal radiation

R_c	x	Log_{10} x	$Log_{10} R_c$
	900		
	800		
	700		
	600		
	500		
	400		
	300		
	200		

Table 3.3: Calculation of intensity of radian

The data may either be converted to Log_{10} format as shown above and then plotted on a linear graph or alternatively if log-log graph paper is available, the data may be plotted directly without taking log values.

3.8.1.1 Specimen Calculation

3.8.1.2 Graph

Plot a graph b/w $\log_{10}x$ and $\log_{10}Rc$

3.8.1.3 Conclusion

3.8.2 Objective:02

To demonstrate the Stefan Boltzmann Law

T_s	T_a	q_b	R_c	$F = \frac{R_c}{q_b}$

Table 3.3: Calculation of shape factor

3.8.2.1 Specimen Calculation

For the first sample the calculations are as follows:

$T_a = T_9 + 273.15$ $T_s = T_{10}+273.15$ While T_9= ambient temperature

Hence $q_b = \sigma (Ts^4 - Ta^4)$

From the radiometer reading:

$$R_{c=} \text{ C x R } \quad (\frac{W}{m^2})$$

Hence $F = \frac{R_c}{q_b}$

It may be seen from the test results that the factor F remains essentially constant thereby demonstrating that the Steffen-Boltzman relationship applies.

3.8.3 Objective:03

To demonstrate the role of shape factor involved in radiation heat transfer

From figure 3.1 in theory section

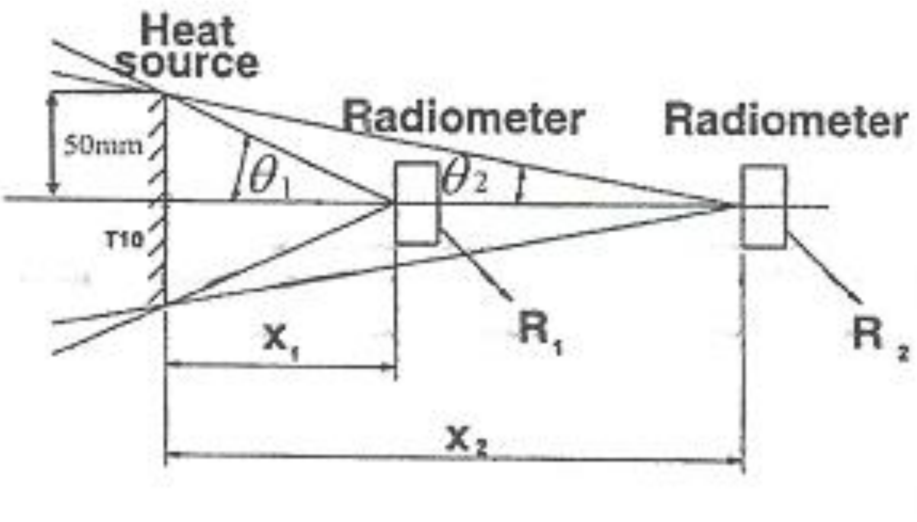


Figure.3.3: Schematic diagram for shape factor

Ts	Ta	q_b	θ	$\sin^2\theta$	$q_{b \times \sin^2\theta}$	R_c
K	K	$\frac{W}{m^2}$	Radians		$\frac{W}{m^2}$	$\frac{W}{m^2}$

Table 3.4: Radiation incident on the detector

3.8.3.1 Specimen Calculation

For the first data point at x = 900mm

$$Ts = T_{10}+273.15 \qquad Ta = T_9+273.15$$

Hence

$$q_b = \sigma\,(T_s^4 - T_a^4)$$

From the geometry

$$\theta = \tan^{-1}(\frac{50}{900})$$

Hence

$$\sin^2\theta =$$

From this data

$$q_b.\ \sin^2\theta$$

The corrected radiation R_c recorded by the radiometer under these conditions was

$$R_c = \ (\ )\ \frac{W}{m^2}$$

Comparing the calculated radiation incident on the detector $qb\ x\ sin^2\theta$ and the corrected radiation measured by the detector R_c it may be seen that the value are similar.

Note that small errors in temperature measurement affect the data to the fourth power i.e. T^4

3.8.3.2 Conclusion

3.9 Statistical Analysis

For Shape Factor F

$x_{avg}= \frac{x_1+x_2+x_3}{n}$

$S_x=\sqrt{\frac{1}{n-1}((x_1-x_{avg})^2+(x_2-x_{avg})^2+(x_3-x_{avg})^2}$

3.10 Questions

1) What is value of Log_{10} x corresponding to the value of 550 mm, Calculate from graph
2) How does thermal radiation differ from other types of electromagnetic radiation?
3) What is inverse square law for thermal radiation
4) Define absorptivity, reflectivity and transmissivity
5) What is the Stefan-Boltzmann law?
6) What is a gray body
7) What is meant by the radiation shape factor?
8) What is radiation shields and its effect

3.11 Comments

4. LAB SESSION 4

To understand basics about combined Convection and Radiation heat transfer mechanism

4.1 Learning Objective

[i] Determination of the combined (radiation and convection) heat transfer ($Q_r + Q_c$) from a horizontal cylinder.

[ii] Determination of the effect of forced convection on the heat transfer from a cylinder at varying air velocities.

4.2 Apparatus

Combined Convection and Radiation Heat Transfer unit H111D (Serial No= H111D/01641)

4.3 Main Parts

1) Heater Power
2) T10 Heater surface temperature
3) Air velocity sensor (Hot wire anemometer)
4) T9 Air temperature
5) Throttle butterfly
6) Fan
7) Main Switch

8) Main digital Control panel (H111)

4.4 Useful Data

Combined Convection and Radiation H111D

T	ν	k	Pr
K	m^2/s	w/mK	_
300	1.568E-05	0.02624	0.708
350	2.076 E-05	0.03003	0.697
400	2.590 E-05	0.03365	0.689
450	2.886 E-05	0.03707	0.683
500	3.790 E-05	0.04038	0.680
550	4.434 E-05	0.04360	0.680
600	5.134 E-05	0.05659	0.680

Table 4.1: Table of Physical properties of Air at Atmospheric Pressure

The above data is presented graphically on Graphs D1, D2, and D3.

If spreadsheet is to be utilized for data evaluation then the values may be determined with reasonable accuracy from the following equations.

Where T is the air temperature in K

Cylinder diameter D = 0.01m

Cylinder heated length L = 0.07m

Cylinder effective heated area $A_s = 0.0022m^2$

Effective air velocity local to cylinder due to blockage effect $U_e = U_a$ X 1.22

4.5 Theory

When a horizontal cylinder, with its surface at a temperature above that of its surroundings, is located in stationary air, the heat loss from the cylinder will be a combination of natural convection to the air (air surrounding the cylinder becomes less dense and rises when it is heated) and radiation to the surroundings.

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

The following theoretical analysis uses an empirical relationship for the heat transfer due to natural convection proposed by WH McAdams in the publication "Heat Transmission", third edition, McGraw-Hill, New York, 1959.

Total heat loss from the cylinder: $Q_{total} = Q_c + Q_r$

Equation 4.1

Heat loss due to natural convection: $Q_c = h_c A_s (T_s - T_a)$

Equation 4.2

Heat loss due to radiation: $Qr = h_r A_s (T_s - T_a)$

Equation 4.3

Heat transfer area (surface area): $A_s = (\pi D L)$

Equation 4.4

The heat transfer coefficients h_c and h_r can be calculated using the following relationships

$$h_c=1.32 \left[\frac{T_s-T_a}{D}\right]^{0.25}$$ Equation 4.5

$$h_r=\epsilon\sigma \frac{(T_s^4-T_a^4)}{(T_s-T_a)}$$ Equation 4.6

σ= Stefan Boltzmann constant

Є = Emissivity of surface (dimensionless)

Ts = Surface temperature of cylinder (K)

Ta = Ambient temperature (K)

4.5.1 Forced convection

Forced convection is a mechanism, or type of transport in which fluid motion is generated by an external source (like a pump, fan, suction device, etc.). It should be considered as one of the main methods of useful heat transfer as significant amounts of heat energy can be transported very efficiently.

Actual power supplied to the heated cylinder Qin = V I (Watts) Equation 4.7

This results in a radiant heat transfer of from equation 4.3

$$Qr = h_r A_s (T_s - T_a)$$

So Nusselt number is

$$\mathrm{Nu} = 0.3 + (0.62\mathrm{Re}^{0.5}\mathrm{Pr}^{0.33})/\left(1 + \left(\frac{0.4}{\mathrm{Pr}}\right)^{0.66}\right)^{0.25} * \left(1 + \left(\frac{\mathrm{Re}}{282000}\right)^{0.5}\right)$$

Equation 4.8

And Reynolds number is

$$\mathrm{Re} = \mathrm{UeD}/\mathrm{v}$$ Equation 4.9

So

$$h_f = \frac{k}{D}\mathrm{Nu}$$ Equation 4.10

This results in a convective heat transfer of

$$Q_f = h_f A_s (\mathrm{Ts} - \mathrm{Ta})$$ Equation 4.11

Hence the total heat transfer from the cylinder

$$Q_{\mathrm{total}} = (Q_r + Q_f)$$ Equation 4.12

4.6 Procedure

1. Ensure that the H111 main switch is in the off position (the three digital displays should not be illuminated). Ensure that the residual current circuit breaker on the rear panel is in the ON position.
2. Turn the voltage controller anti-clock wise to set the AC voltage to minimum. Ensure the Combined Convection and Radiation H111D accessory has been connected to the Heat Transfer Service Unit H111.
3. Ensure that the heated cylinder is located in its holder at the top of the duct and that the cylinder is rotated so that the thermocouple location is on the side of the cylinder. This is shown schematically below.
4. Turn on the main switch and the digital displays should illuminate. Turn the rotary selector switch to display T10. Rotate the voltage control clockwise to increase the voltage. Note that for natural convection experiments are to be undertaken it is

recommended that the cylinder surface temperature T_{10} is NOT allowed to exceed 500℃.

5. Rotate the voltage controller to give a 50-volt reading.
6. Select the temperature position T10 using the rotary selector switch and monitor the temperature.
7. Open the throttle butterfly on the fan intake but do not turn on the fan switch, as the fan will not be used for this experiment.
8. When T10 has reached a steady state temperature record the following T9, T10, V, I.
9. Increase the voltage controller to give an 80-volt reading, monitor T10 for stability and repeat the readings.
10. Increase the voltage controller to give a 120-volt reading, monitor T10 for stability and repeat the readings.
11. Increase the voltage controller to give a 150-volt reading, monitor T10 for stability and repeat the readings.
12. Finally increase the voltage controller to give approximately a 185-volt reading, monitor T10 for stability and repeat the readings. However the temperature of the cylinder should not be allowed to exceed 500℃ and if local conditions result in a higher temperature the voltage should be reduced accordingly.
13. Once reading has been completed the fan switch may be turned on and the voltage control reduced to zero in order to allow the cylinder to cool. Before turning off the main switch as detailed in the procedure on page D6.
14. When the experimental procedure is completed, it is good practice to turn off the power to the heater by reducing the AC voltage to zero and leaving the fan running for a short period until the heated cylinder has cooled. Then turn off the main switch.

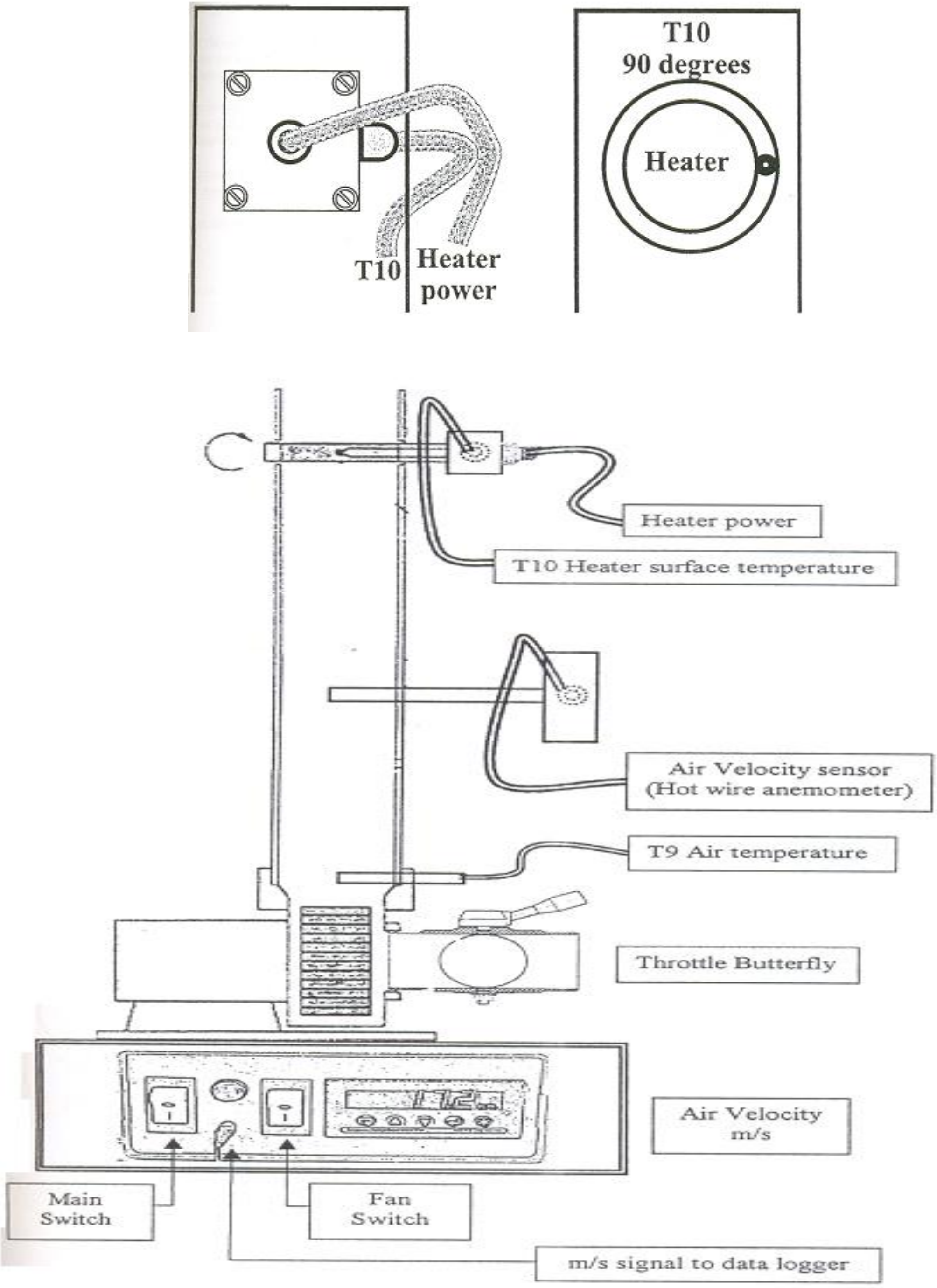


Figure 4.1: Schematic Diagram of Experiment

4.7 Calculated Data

4.7.1 Objective:01

Determination of the combined (radiation and convection) heat transfer ($\mathbf{Q_r}$ + $\mathbf{Q_c}$) from a horizontal cylinder.

4.7.1.1 Observations

Sample test results

Sample	V	I	T_9	T_{10}
-	Volts	Amps	℃	℃
1				
2				
3				
4				
5				

Table 4.2: Measurement of temperature for free convection

T_9= Ambient Temperature
T_{10}= Heater temperature
V= Input voltage
I= Input current

Sample	Q_{input}	h_r	h_c	Q_r	Q_c	Q_{tot}
-	W	$\frac{W}{m^2k}$	$\frac{W}{m^2k}$	W	W	W
1						
2						
3						
4						
5						

Table 4.3: Heat transfer due to free convection and radiation

4.7.1.2 Specimen Calculations

For the first sample the calculation are as follows:

$$Q_{input} = V\,I$$

For the radiant component;

$$h_r = \frac{\varepsilon F\,\sigma(T_s^4 - T_a^4)}{(T_s - T_a)}$$

$$T_s = T_{10} + 273.15\ (K)$$

$$T_a = T_9 + 273.15\ (K)$$

$$h_r = \frac{0.95 \text{ X } 1 \text{ X } 5.67 \text{ X } 10^{-8} \left(T_s^4 - \ T_a^4\right)}{(T_s - T_a)}$$

$$= \qquad \frac{W}{m^2 k}$$

Hence the heat lost to radiation Q_r

(A_s is obtained from USEFUL DATA on)

$$Q_r \ = \ h_r A_s \left(T_s - T_a\right)$$

For the convective component using the simple formula

$$h_c = 1.32 \ \left[\frac{T_s - T_a}{D}\right]^{0.25}$$

$$= \quad \frac{W}{m^2 k}$$

Hence the heat lost to convection;

(A_s Is obtained from USEFUL DATA)

$$Q_c = h_c A_s \left(T_s - T_a\right)$$

Hence the total heat lost by calculation

$$Q_{tot} = \ Q_r + Q_c \ = \qquad (W)$$

In addition it may be seen that at low temperatures the convective component of heat transfer is predominant while at higher temperatures the radiant component becomes predominant.

The temperature, at which the conditions reverse, is also influenced by the emissivity of the surface, and that of the surroundings.

4.7.1.3 Graph

Draw the Graph of h_c, h_r (y-Axis) and surface Temperature T_{10}(X- Axis)

4.7.1.4 Conclusion

4.7.2 Objective:02

Determination of the effect of forced convection on the heat transfer from a cylinder at varying air velocities.

4.7.2.1 Observations:

Sample test results

Sample	V	I	Ua	T9	T10
-	Volts	Amps			
1					
2					
3					
4					
5					

Table 4.4: Measurement of temperature due to forced convection

T_9= Ambient Temperature
T_{10}= Heater temperature
V= Input voltage
I= Input current

4.7.2.2 Calculated Data

Calculation results in the following parameters

Sample	Q_{input}	Ue	Pr	v	k	R_e	N_u
-	W	m/s		m^2/s	W/mK	-	-
1							
2							
3							
4							
5							

Sample	h_r	Q_r	h_f	Q_f	Q_{total}
-	W/m^2K	W	W/m^2K	W	W
1					
2					
3					
4					
5					

Table 4.5: Heat transfer due to forced convection

4.7.2.3 Specimen Calculations

For the first sample the calculations are as follows

$$Q_{input} = V * I \quad (W)$$

For the radiant component

$$h_r = \frac{\varepsilon F\, \sigma(T_s^4 - T_a^4)}{(T_s - T_a)}$$

$$T_s = T_{10} + 273.15\ (K)$$

$$T_a = T_9 + 273.15\ (K)$$

$$h_r = \frac{0.95 \times 1\, X\, 5.67 \times 10^{-8}\, (T_s^4 - T_a^4)}{(T_s - T_a)}$$

$$= \qquad \frac{W}{m^2 k}$$

This results in a radiant heat transfer of

$$Q_r = h_r A_s\, (T_s - T_a)$$

For the above convective component using the formula

$$Nu = 0.3 + [(0.62 Re^{0.5} Pr^{0.33})/(1 + (\frac{0.4}{Pr})^{0.66})^{0.25}] \times (1 + (\frac{Re}{282000})^{0.5})$$

First the physical parameters must be determined at the air stream temperature T9

From the graphs D1, D2, D3 for example at T_9=296K

$$v = 1.4 * 10^{-5}\ m^2/s$$

$$K = 0.026\ W/mK$$

$$P_r = 0.716$$

The measured duct velocity Ua *i*s locally increased around the cylinder to Ue (effective air velocity) due to the blockage effect of the cylinder itself. This relates to the area ratio between the duct cross sectional area and the plan area of the cylinder in the duct.

$$Ue = Ua * 1.22 \quad (m/s)$$

Hence

$$Re = U_e D/v$$

Hence substituting the values in the equation;

$$Nu = 0.3 + (0.62 Re^{0.5} Pr^{0.33})/(1 + (\frac{0.4}{Pr})^{0.66})^{0.25} * (1 + (\frac{Re}{282000})^{0.5})$$

From the Nusselt number Nu ;

$$h_f = \frac{k}{D} Nu \qquad (\frac{W}{m^2 k})$$

This results in a convective heat transfer of

$$Q_f = h_f A_s (Ts - Ta)$$

Hence the total heat transfer from the cylinder

$$Q_{total} = (Q_r + Q_f)$$

4.7.2.4 Graph:

If the surface temperature T10 is plotted against the effective air velocity Ue it may be seen that for a constant heat input the surface temperature falls as the velocity increases.

4.7.2.5 Conclusion

4.8 Statistical Analysis

For total heat transfer in free and forced convection

$x_{avg} = \frac{x_1+x_2+x_3}{n}$

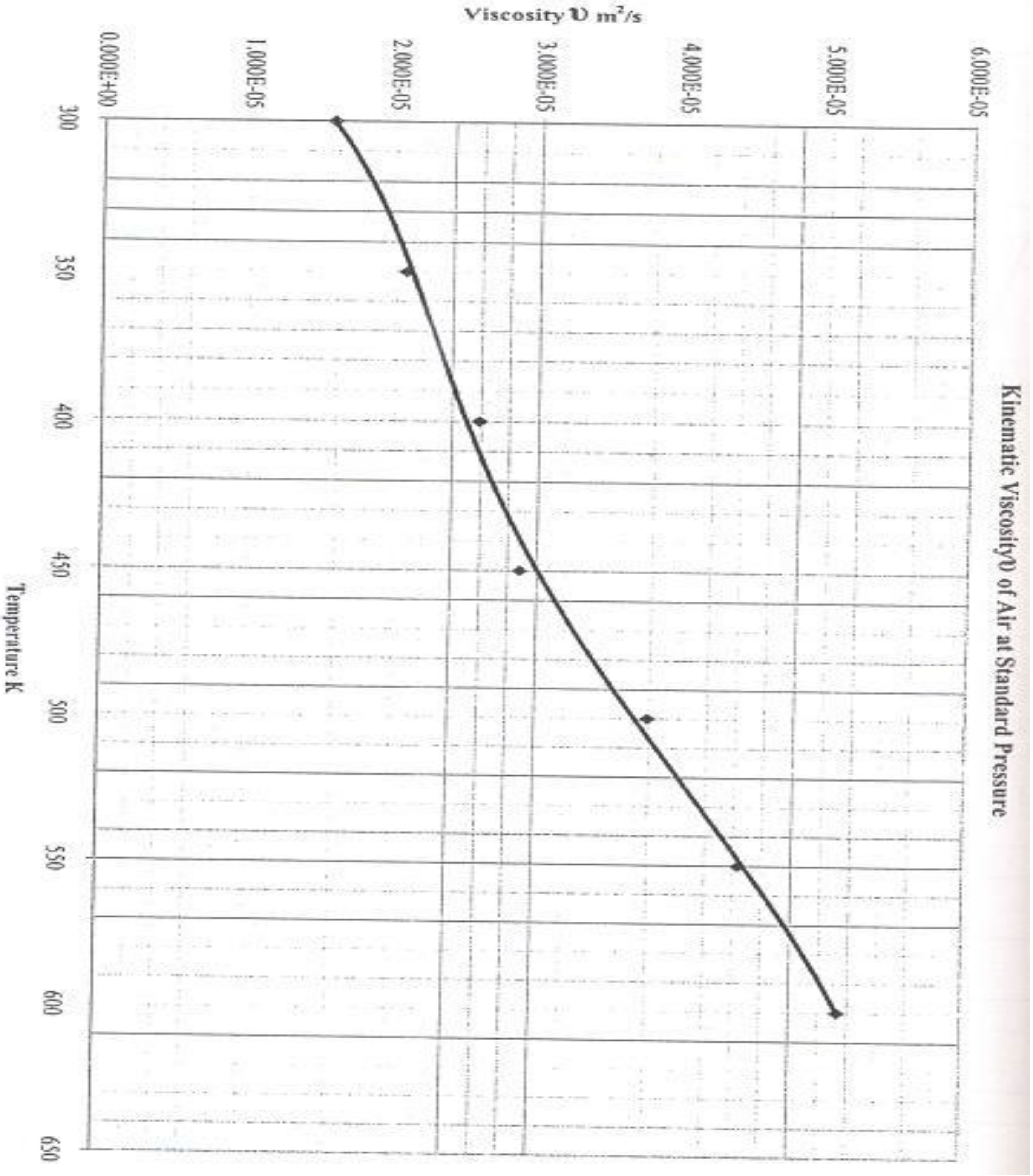
$S_x = \sqrt{\frac{1}{n-1}((x_1 - x_{avg})^2 + (x_2 - x_{avg})^2 + (x_3 - x_{avg})^2)}$

4.9 Questions

1) Write about the trend of convective heat transfer coefficient with heater temperature
2) What is value of heater temperature at air velocity of 2.3 m/s, compute it from graph.
3) Write about the trend of Radiant heat transfer coefficient with heater temperature
4) What is free and forced convection
5) What is drag coefficient

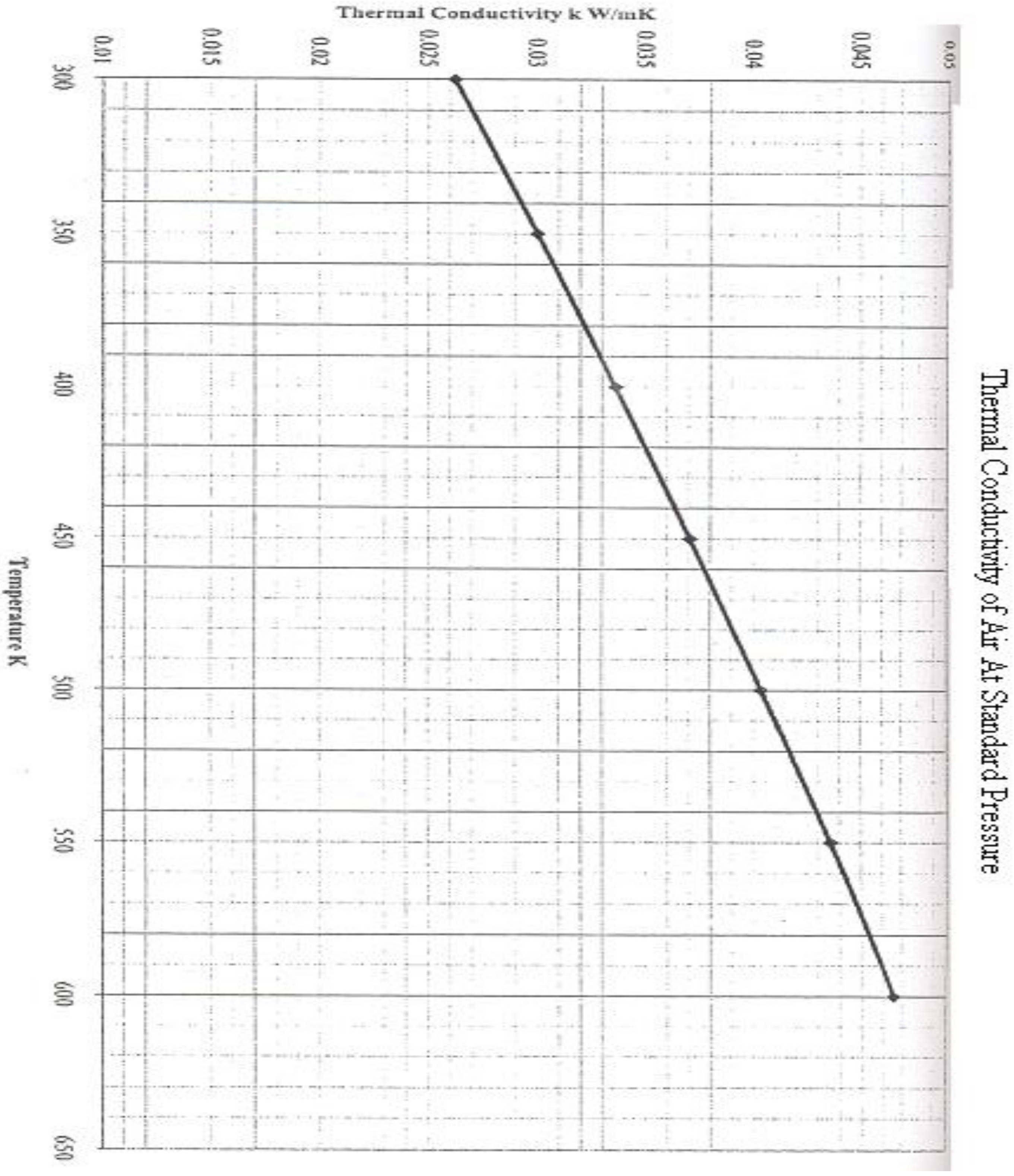
4.10 Comments

Graph 1



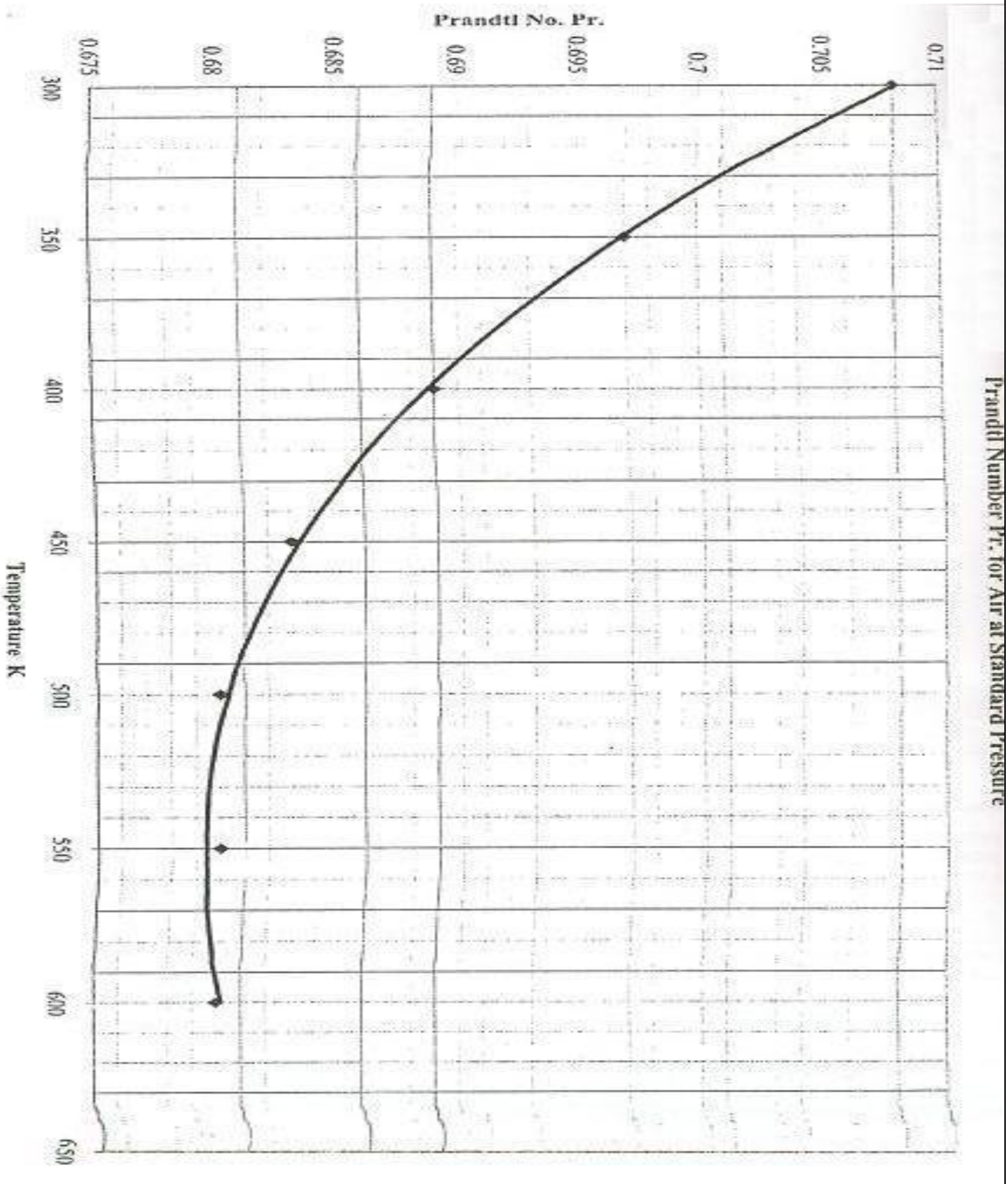
Graph 4.1: Kinematic velocity of air at standard Pressure

GRAPH# D2



Graph 4.2: Thermal conductivity of air at standard pressure

GRAPH# D3



Graph 4.3: Prandtl number of air at standard pressure

5. LAB SESSION 5

To calculate the heat transfer from an extended surface resulting from the combined modes of free conduction, free convection and radiation heat transfer and comparing the result with the theoretical analysis

5.1 Learning Objective

To analyse the increase in heat transfer by using extended surface body

5.2 Apparatus

Extended Surface Heat Transfer unit H111E (Serial no H111E/00832)

5.3 Main Parts

1) Heated cylinder
2) Eight temperature sensors (Thermocouples)
3) Heater
4) Heat transfer service unit (H111)

5.4 Useful Data

1) HEATED ROD Diameter $D = 0.01\text{m}$
2) Heated rod length $L = 0.35\text{m}$
3) Heated rod effective cross sectional area $\text{As} = 7.854\times10^{-5}\text{m}^2$
4) Heated rod surface area $\text{A} = 0.01099\text{m}^2$
5) Thermal conductivity of heated rod material $\text{k} = 121 \ {}^{\text{W}}/_{\text{m}^2}$
6) Stefan Boltzmann constant $\sigma = 5.67\times10^{-8}\text{W/m}^2$

5.5 Theory:

5.5.1 Fin (extended surface)

In the study of heat transfer, fins are surfaces that extend from an object to increase the rate of heat transfer to or from the environment by increasing convection. The amount of conduction, convection, or radiation of an object determines the amount of heat it transfers. Increasing the temperature gradient between the object and the environment, increasing the convection heat transfer coefficient, or increasing the surface area of the object increases the heat transfer. Sometimes it is not feasible or economical to change the first two options. Thus, adding a fin to an object, increases the surface area and can sometimes be an economical solution to heat transfer problems.

The heat Transferred can be calculated at a given point x

$\boldsymbol{Q_x = kAm(T_x - T_a)\,tanh(mL)}$ *Equation 5.1: Heat transferred through extended surface*

While

Q_x=Heat transferred at a given point x

T_x=Temperature at a given point x

$T_{a=}$ Ambient temperature

L= Length of rod

$$m = \sqrt{\frac{hP}{kA}}$$

h=Overall heat transfer coefficient

P= Perimeter

K= Thermal conductivity

A= Heated rod surface area

5.6 Procedure:

15. Ensure that the H111 main switch is in the off position (the three digital displays should not be illuminated). Ensure that the residual current circuit breaker on the rear panel is in the ON position.
16. Turn the voltage controller anti-clock wise to set the AC voltage to minimum. Ensure the Extended Surface Heat Transfer Unit H111E accessory has been connected to the Heat Transfer Service Unit H111.
17. Ensure that the heated cylinder is located inside its hosing before turning on the power to the unit. This is shown schematically below.
18. Turn on the main switch and the digital displays should illuminate. Select the temperature position T1 using the rotator switch and monitor the temperatures regularly until the T1 reaches approximately to the 80˚C then reduce the heater voltages to approximately 70 volts. This procedure will reduce the time taken for the system to reach a stable operating condition.
19. After adjusting the heater voltage ensure that T1 (the thermocouple closest to the heater) varies in accordance with the sense of adjustment. i.e. if the voltage is increased the temperature T1 should also increase, if the voltage is reduced the temperature T1 should be reduce. Note that the if T1 is close to 100˚C and the current (Amps) displays Zero, it may be that the safety thermostat E1 (2) has activated. Reduce the voltage and wait for the thermostat to set.
20. It is now necessary that to monitor the temperature T1 to T8 until all the temperatures are stable.

21. Allow the system to reach satiability, and make readings adjustment. Note that due to the conduction and the small differential temperatures involved for reason s of safety the time taken to achieve stability can be long.
22. When T1 through T8 have reached a steady state temperatures record the following. T1 to T9, V and I.
23. If time permits increase the voltage to a 120volts reading, repeat the monitoring of all temperatures and when stable repeat the above readings.
24. When the experimental procedure is completed, it is good practice to turn off the power to the heater by reducing the AC voltage to zero and leaving the fan running for a short period until the heated cylinder has cooled. Then turn off the main switch.

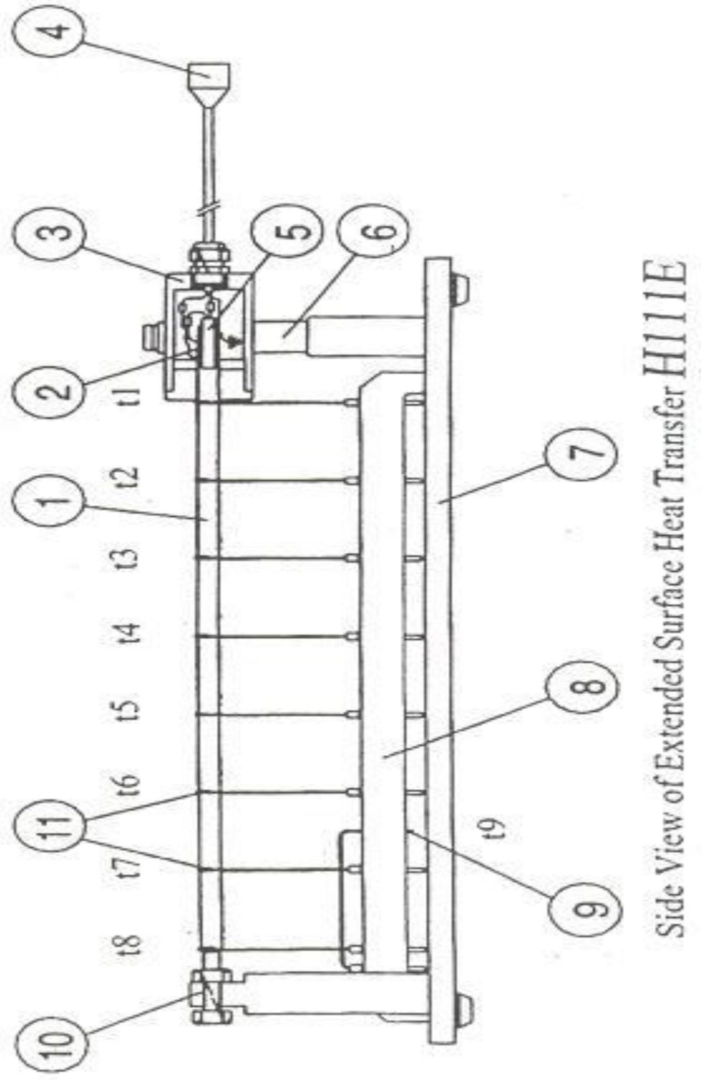


Figure 5.1: Schematic Diagram of Experiment

5.7 Observations

Sample No		1	Distance From T1(m)
V	volts	-	-
I	Amps	-	-
t_1	℃		0
t_2	℃		0.05
t_3	℃		0.1
t_4	℃		0.15
t_5	℃		0.2
t_6	℃		0.25
t_7	℃		0.3
t_8	℃		0.35
t_9	℃		-

Table 5.1: Temperatures measured at different distances from T1

5.8 Calculated Data

Heat input Q_{in} W	Distance x form T1 (m)	$\frac{T_x - T_a}{T_1 - T_a}$	$\frac{\cos h[m(L-x)]}{\cos h\ [m\ L]}$	Calculated heat transferred
	0			
	0.05			
	0.1			
	0.15			
	0.2			
	0.25			
	0.3			
	0.35			

Table 5.2: Heat transfer from extended surface

5.8.1 Specimen Calculation

For the first sample the calculations are as follows

$$Q_{input} = V * I \qquad (W)$$

The value of h will be that due to both convective and radiation heat transfer

$$h = h_r + h_c$$

For the radiant component;

$$hr = \varepsilon F \sigma \frac{Tmean^4 - Ta^4}{Tmean - Ta} = \frac{W}{m^2 k}$$

$$T_{mean} = \frac{(t1+t2+t3+t4+t5+t6+t7+t8)}{8} + 273.15$$

$$T_a = T_9 + 273.15\ (K)$$

Where σ = Stefan Boltzmann Constant σ = $5.67 \times 10^{-8} \frac{W}{m^2\ K}$

F = Shape factor or view factor (relating to the element geometry and the surroundings)

ε = Emissivity of the rod surface = 0.95

T_a = Absolute ambient temperature t_9 + 273.15K

T_{mean} = Absolute mean of the measured surface temperature of the rod.

$T_{mean} = \frac{(t1+t2+t3+t4+t5+t6+t7+t8)}{8} + 273.15$

For the convective component;

$$h_c = 1.32\ \left[\frac{T_{mean} - T_a}{D}\right]^{0.25} = (\frac{W}{m^2 k})$$

This is a simplified empirical equation for natural convection from a horizontal cylinder. Where

T_a = Absolute ambient temperature t_9 + 273.15K

T_{mean}= Absolute mean of the measured surface temperature of the rod.

D = Diameter of the rod

Hence the overall estimated heat transfer coefficient

$$h = h_r + h_c = (\frac{W}{m^2\ K})$$

Now m can be determined to a reasonable degree of accuracy such that

$$m = \sqrt{\frac{hP}{kA}}$$

Where P is the perimeter of the rod = π D

Now the heat Transferred can be calculated at a given point x;

$$Q_x = kAm(T_x - T_a)\tanh(mL)$$

While Tan h (mL) $=\frac{e^{mL} - e^{-mL}}{e^{mL} + e^{-mL}}$

And Cos h (mL)= $\frac{e^{mL} + e^{-mL}}{2}$

<u>Note:</u> For insulated fin tip and negligible heat loss from fin tip

$$\frac{\cosh [\ m(L-x)]}{\cosh\ \ [m\ L]} \text{ Should be equal to } \frac{T_x - T_a}{T_1 - T_a}$$

5.8.2 Graph

Draw the graph b/w the distance from T1 thermocouple (X-Axis) and Temperature (Y-Axis).

5.8.3 Conclusion

5.9 Statistical Analysis

NIL

5.10 Questions

1) How heat transfer is varied by varying heat transfer area
2) What is effect of perimeter on heat transfer
3) At which position, the temperature reaches the maximum value, give reason.

5.11 Comments

6. LAB SESSION 6

Study of radiation errors in measurement of temperature

6.1 Learning Objective

1) To demonstrate how temperature measurements can be affected by radiant heat transfer to a sensor from its surroundings
2) To reduce the errors in temperature measurement due to radiation from a source by using radiation shield between the sensor and the source of radiation.

6.2 Apparatus

Radiation Errors in temperature Measurements H111F (Serial no H111F/00315)

6.3 Main Parts

1) Radiant Source
2) Temperature Sensors
3) Shields of different grades
4) Main digital Control panel (H111)

6.4 Theory

The objective for the temperature sensors is to accurately measure the temperature of the air stream. In order to do this the sensors must stabilize at the same temperatures as the air stream. Under ideal conditions the sensors will gain or lose heat until stabilization occurs and the sensors are at the same temperature as the air. However, if a source of thermal radiation is visible to the sensor then depending upon the emissivity of the sensor and the source more or less energy may be absorbed by the sensor. Hence the sensor may stabilize at a temperature above or below the temperature of the air depending upon the temperature of the radiant source.

The magnitude of the difference in sensor temperature relative to the air stream will depended upon several factors.

- The difference in temperature between the sensor and the radiating surface.
- The velocity of the air passing the sensor.
- The size of the sensor.
- The emissivity of the sensor, the surroundings and the radiant source.
- The thermal conductivity of the sensor material and its connecting lead.
- Other material that may be in the air stream such as dust or water vapor.

If a suitable shield can be placed between the radiant source and the thermocouple the errors in measurement can be reduced. Though the shield will be heated or cooled by the radiant source the temperature reached by the shield will have less influence on the thermocouple then that of the radiant source. In the apparatus, the shield is a polished stainless steel plate that can be lowered between the ceramic heater and the three test thermocouples. The shield allows air to pass through but prevents direct line of sight influence from the radiant source

6.5 Procedure:

1. Ensure that the H111 main switch is in the off position (the three digital displays should not be illuminated). Ensure that the residual current circuit breaker on the rear panel is in the ON position.
2. Turn the voltage controller anti-clock wise to set the AC voltage to minimum. Ensure the Radiation Errors H111F accessory has been connected to the Heat Transfer Service Unit H111.
3. Ensure that the radiation shield is not fitted.
4. Turn on the main switch and the digital displays should illuminate. Select the temperature position T10 using the rotator switch and monitor the temperatures regularly.
5. Set the temperature selector switch to display temperatures T6, T7, T8, T9 and T10 and record the values.
6. Open the throttle butterfly but do not turn on the centrifugal fan at this point.
7. Rotate the voltage controller clockwise to increase the heater voltage to 80 Volts. Select the T10 position on the temperature selector switch and monitor the T10 temperature. Also monitor temperatures T7 to T9 until these reach a stable temperature (Note that the temperatures may not be equal).
8. When the temperatures are stable record T6, T7, T8, T9, T10, V, and I.
9. Rotate the voltage controller clockwise to increase the heater voltage to 120 Volts. Again allow the temperatures to stabilize and then record T6, T7, T8, T9, T10, V, and I.
10. Repeat the above procedure at heater voltages of 180 and 230 volts (Note that the heater temperature T10 should not be allowed to exceed 400℃).
11. Completely close the throttle butterfly on the fan intake and then turn on the centrifugal fan.
12. Adjust the throttle until a velocity of approximately 0.5m/s is indicated.
13. Observe the temperature T6 to T10 and when stable record T6, T7, T8, T9, T10, V, and I.

14. Increase the air velocity to 1m/s, allow the temperatures to stabilize and repeat the observations. Further increase the velocity to 2m/s and 4m/s and again repeat the observations.
15. When the experimental procedure is completed, it is good habit to turn off the power to the heater by reducing the AC voltage to zero. And fan leaving the fan running for a short period until the heater has cooled. Then turn off the main switch.
16. Repeat all the procedure for objective 2 by using the radiation shield.

6.6 Observations

6.6.1 Objective:01

To demonstrate how temperature measurements can be affected by radiant heat transfer to a sensor from its surroundings

WITHOUT FAN ASSISTED AIR FLOW							
V	I	U_a	T6	T7	T8	T9	T10
0		0					
100		0					
125		0					
150		0					
200		0					
WITH FAN ASSISTED AIR FLOW							
200	0.77	0.0					
200	0.77	1.0					
200	0.77	1.5					
200	0.77	2.0					
200	0.77	2.5					
200	0.77	3.0					

Table 6.1: Temperatures at different points from radiant source

While

V= Voltage

I= Current, T6= Temperature of air and T7, T8, T9= Temperature at different points

T10= Temperature of heater

U_a= Air velocity

6.6.1.1 Specimen Calculation

NIL

6.6.1.2 Graph

i) Draw the graph b/w heater volts (V) along x-Axis and Temperature T6, T7, T8, T9 along Y-Axis. (i.e V vs T6, V vs T7, V vs T8, Vvs T9, V vs T10)

ii) Draw the graph b/w Air Velocity (m/s) along x-Axis and Temperature T6, T7, T8, T9 along Y-Axis. (i.e Ua vs T6, Ua vs T7, Ua vs T8, Ua vs T9, Ua vs T10)

6.6.1.3 Conclusion

6.6.2 Objective:02

To reduce the errors in temperature measurement due to radiation from a source by using radiation shield between the sensor and the source of radiation.

TEST NUMBER	V	I	Ua	T6	T7	T8	T9	T10
1	0							
2	150 No Shield							
3	150 Shield							
4	175 No Shield							
5	175 Shield							
6	200 No Shield							
7	200 Shield							

Table 6.2: Temperatures at different points with different shields

6.6.2.1 Graph

Draw the graph b/w Test Number along x-Axis and Temperature T6, T7, T8, T9 along Y-Axis.

6.6.2.2 Specimen Calculation

NIL

6.6.2.3 Conclusion

6.7 Statistical Analysis

NIL

7. LAB SESSION 7

Using analytical transient temperature/heat flow charts to determine the thermal conductivity of a solid cylinder from measurements takes on a similar cylinder but having a different thermal conductivity

7.1 Learning Objective

1) Learn how to use transient charts
2) Determine the thermal conductivity of unknown materials
3) Using the properties like biot number and fourier number

7.2 Apparatus

Heat Transfer service unit with Unsteady State Heat Transfer Unit H111G

7.3 Main Parts

1) Drain Valve
2) Water supply
3) Pump
4) 20mm diameter Brass cylinder
5) Temperature sensors prob
6) water bath
7) 20 mm diameter stainless steel cylinder

7.4 Theory

7.4.1 Transient Heat-Transfer

If a solid body is suddenly subjected to a change in environment, some time must elapse before an equilibrium temperature condition will prevail in the body. In the transient heating or cooling process that takes place in the interim period before equilibrium is established, the analysis must be modified to take into account the change in internal energy of the body with time, and the boundary conditions must be adjusted to match the physical situation that is apparent in the unsteady-state heat-transfer problem. Unsteady-state heat-transfer analysis is obviously of significant practical interest because of the large number of heating and cooling processes that must be calculated in industrial applications

7.4.2 Lumped-Heat-Capacity System

Transient heat conduction can be analyzed in systems that may be considered uniform in temperature. This type of analysis is called the lumped-heat-capacity method. Such systems are obviously idealized because a temperature gradient must exist in a material if heat is to be conducted into or out of the material. In general, the smaller the physical size of the body, the more realistic the assumption of a uniform temperature throughout; in the limit a differential volume could be employed as in the derivation of the general heat-conduction equation

7.4.3 Biot number (Bi)

The **Biot number** (**Bi**) is a dimensionless quantity used in heat transfer calculations. It is named after the French physicist Jean-Baptiste Biot (1774–1862), and gives a simple index of the ratio of the heat transfer resistances inside of and at the surface of a body. This ratio determines whether or not the temperatures inside a body will vary significantly in space, while the body heats or cools over time, from a thermal gradient applied to its surface. In general, problems involving small Biot numbers (much smaller than 1) are thermally simple, due to uniform temperature fields inside the body. Biot numbers much larger than 1 signal more difficult problems due to non-uniformity of temperature fields within the object. It should not be confused with Nusselt number, which employs the thermal conductivity of the fluid and hence is a comparative measure of conduction and convection, both in the fluid.The Biot number has a variety of applications, including transient heat transfer and use in extended surface heat transfer calculations.

The Biot number is defined as

$$B_i=\frac{\boldsymbol{hL}}{\boldsymbol{k}}$$ *Equation 7.1: Biot number*

h = film coefficient or heat transfer coefficient or convective heat transfer coefficient

L = characteristic length, which is commonly defined as the volume of the body divided by the surface area of the body, such that $L=\frac{\text{Volume}}{\text{Area}}$

k = Thermal conductivity of the body

The physical significance of Biot number can be understood by imagining the heat flow from a small hot metal sphere suddenly immersed in a pool, to the surrounding fluid. The heat flow experiences two resistances: the first within the solid metal (which is influenced by both the size and composition of the sphere), and the second at the surface of the sphere. If the thermal resistance of the fluid/sphere interface exceeds that thermal resistance offered by the interior of the metal sphere, the Biot number will be less than one. For systems where it is much less than one, the interior of the sphere may be presumed always to have the same temperature, although this temperature may be changing, as heat passes into the sphere from the surface. The equation to describe this change in (relatively uniform) temperature inside the object is simple exponential one described in Newton's law of cooling.

In contrast, the metal sphere may be large, causing the characteristic length to increase to the point that the Biot number is larger than one. Now, thermal gradients within the sphere become important, even though the sphere material is a good conductor. Equivalently, if the sphere is made of a thermally insulating (poorly conductive) material, such as wood, the interior resistance to heat flow will exceed that of the fluid/sphere boundary, even with a much smaller sphere. In this case, again, the Biot number will be greater than one.

7.4.4 Fourier number (Fo)

Fourier number (Fo) or Fourier modulus, named after Joseph Fourier, is a dimensionless number that characterizes transient heat conduction. Conceptually, it is the ratio of diffusive or conductive transport rate to the quantity storage rate, where the quantity may be either heat (thermal energy) or matter (particles). The number derives from non-dimensionalization of the heat equation (also known as Fourier's Law) or Fick's second law and is used along with the Biot number to analyze time dependent transport phenomena.

The general Fourier number is defined as

$$F_o = \frac{\text{Diffusive transport rate}}{\text{Storage rate}}$$

$$Fo = \frac{\alpha \text{ X t}}{(\text{Length})^2}$$ Equation 7.2: Fourier number

$$\alpha = \frac{k}{\rho c}$$ Equation 7.3: Thermal diffusivity

α is the thermal diffusivity (SI units: m^2/s)

t is the characteristic time (s)

L is the length through which conduction occurs (m)

K is thermal conductivity (W/(m·K))

ρ is density (kg/m^3)

c is specific heat capacity (J/(kg·K))

7.4.5 Heisler charts

Heisler charts are a graphical analysis tool for the evaluation of heat transfer in thermal engineering. They are a set of two charts per included geometry introduced in 1947 by M. P. Heisler which were supplemented by a third chart per geometry in 1961 by H. Gröber. Heisler charts permit evaluation of the central temperature for transient heat conduction through an infinitely long plane wall of thickness 2*L*, an infinitely long cylinder of radius r_o, and a sphere of radius r_o.

Although Heisler-Gröber charts are a faster and simpler alternative to the exact solutions of these problems, there are some limitations. First, the body must be at uniform temperature initially. Additionally, the temperature of the surroundings and the convective heat transfer coefficient must remain constant and uniform. Also, there must be no heat generation from the body itself.

7.5 Procedure

1. Ensure that the residual current circuit breaker (RCCB) is open-circuit. Ensure that the drain valve adjacent to the circulating pump is in the closed position and half-fill the water bath with clean water.
2. Pump bleeding- Switch on the RCCB/MCB to cause the pump to run. Incline the pump by lifting the baseboard from the front to allow the air to escape. Noise from the pump is the sign of trapped air. A bleed screw is fitted to the head of the pump.

3. Continue the filling of bath until the water level is at mid height of the holes in the flow duct. If the local water contains of a large amount of dissolved solids that normally result in scale build up then it is recommended that the bath id fitted with de-ionized or mineralized water. Ensue that the thermostat has been turned fully anti-clockwise and is in the off position.
4. Ensure that the H111 unit main switch is in the off position (None of three digital displays should be illustrated). Ensure that the residual current circuit breaker on the H111 rear panel is in the ON position. Ensure that the residual current circuit breaker on the H111G baseboard is in the on position. Not that the residual current circuit breaker on the both units (H111 and H111G) should be tested for normal operation at intervals specified by local regulations.
5. Turn on the power supply to the Unsteady State Heat Transfer unit and turn on the 16A Heater miniature circuit breaker (MCB). Ensure that the red power indicator adjacent to the thermostat is illustrated. Turn the thermostat to position 6 for faster heating. The water will take approximately 30 minutes to heat from cold. At this setting the water will boil, if left unattended. While the water bath is heating the following may be auctioned.
6. Install the 20mm diameter brass cylinder in the shape carrier.
7. Insert the T3 probe to engage fully into the center of the shape.
8. Insert the T2 probe to sense water temperature adjacent to the shape.
9. Avoid touching the shape by hand to reduce thermal effects and place the shape on the bench to reach ambient temperature.
10. The water bath temperature T1 should be stabilized at approximately 80 to 90˚C
11. Set the circulating pump to 3 and therefore the water flow velocity in the flow duct.
12. Turn on the power supply to the Heat Transfer Service Unit H111 and main switch and three digital displays illustrate. Set the temperature selector switch to the T1to indicate the temperature of the bath. Observe the T1 to confirm that it is slowly increasing as the bath is heated.
13. Record the start conditions temperatures and then plunge the shapes in the flow duct. Then record temperatures and time.
14. Observe the T1. If the bath temperature exceeds that is required, reduce the thermostat setting to OFF and wait for the water to cool. The water bath temperature T1 should not be allowed to exceed 85-90 as the pump will cavitate.
15. Once the 20mm diameter brass has reached the water bath temperature, remove it from the tank install the 20mm stainless steel cylinder in the shape carrier.
16. Record the starting condition temperatures and then plunge the shape in the flow duct. Then record temperatures and time.
17. Having achieved the desired temperature, say85, reduces the thermometer setting to position 2. It will cycle ON/OFF to maintain the existing temperature.
18. If time permits the procedures may be repeated for the brass and stainless steel sphere and/or the Brass and Stainless Slab.
19. In addition, by varying the circulating pump speed, the effect of variation of water velocity on local heat transfer coefficient may be investigated.

20. When the experimental procedure is completed, it is good habit to turn off the power to the heater by reducing the AC voltage to zero. And fan leaving the fan running for a short period until the heater has cooled. Then turn off the main switch.

7.6 Observations

Recorded Time	T1 Bath Temp.	T2 Air/ Water Temp.	T3 Geometric Centre Temp.
Seconds	ºC	ºC	ºC
0			
5			
10			
15			
20			
25			
30			
35			
40			

Table 7.1: Specimen: 20mm diameter Brass Cylinder.

Recorded Time	T1 Bath Temp.	T2 Air/ Water Temp.	T3 Geometric Centre Temp.
Seconds	ºC	ºC	ºC
0			
5			
10			
15			
20			
25			
30			
35			
40			

Table 7.2: Specimen: 20mm Stainless steel Cylinder

7.7 Calculated Data

Recorded Time	T1 Bath Temperature	T3 Geometric Centre Temperature	θ Non-dimensional Temperature	F_o Fourier Number	1/Bi Inverse Biot Number
Seconds					
0					
5					
10					
15					
20					
25					
30					
35					
40					

Table 7.3: Properties of Specimen: 20mm diameter Brass Cylinder

Recorded Time	T1 Bath Temperature	T3 Geometric Centre Temperature	θ Non-dimensional Temperature	F_o Fourier Number	1/Bi Inverse Biot Number
Seconds					
0					
5					
10					
15					
20					
25					
30					
35					
40					

Table 7.4: Properties of Specimen: 20mm diameter stainless steel Cylinder

7.7.1 Sample Calculations

The calculation procedure for system with finite internal and surface heat transfer resistance is as follows.

For each sample after intermission the non-dimensional temperature θ is calculated.

$$\mathrm{T_c = T3}$$

$$\mathrm{T\infty = T1}$$

$$\mathrm{T_i = T3 \text{ at time } 0}$$

$$\theta = \frac{T_c - T\infty}{T_i - T\infty} =$$

Similarly, the Fourier Number For non-dimensional time

$$Fo = \frac{\alpha \times t}{(\text{Length})^2}$$

Thermal diffusivity $=\alpha$

$$\alpha = \frac{k}{\rho c}$$

For brass from USEFUL DATA

$$K = 121\ Wm^{-1}K^{-1}$$

$$\rho = 8500\ kgm^{-3}$$

$$C = 385\ Jkg^{-1}$$

Hence

$$\alpha = k/\rho c = \frac{121}{8500 \times 385} = 3.7\ X10^{-5}$$

T =5 second

For cylinder the characteristics length=Length $=$ R $= 10\ X\ 10^{-3}$ m

Hence

$$Fo = \frac{\alpha t}{(\text{Length})^2} = \frac{3.7\ X10^{-5}\ \ X\ 5}{(10\ X\ 10^{-3})^2} = 1.85$$

From the Heisler chart for a semi-infinite cylinder.

The co-ordinates for $F_o =$ and $\theta =$ give

$$\frac{1}{Bi} =$$

Where $Bi = \frac{h \text{ x Length}}{k}$

Note that both the 20mm diameter brass and stainless steel cylinders after immersion $\frac{1}{Bi}$ becomes near constant.

Length = R the radius = 10×10^{-3}m

Hence for the brass cylinder where $k = 121Wm^{-1}k^{-1}$

$$h = \frac{(Bi \text{ x } k)}{R}$$

This is the heat transfer coefficient around the cylinder due to the velocity of the hot water in the flow duct. This velocity depends only upon the pump speed.

As the pump speed and hence velocity was constant for both the brass and stainless steel cylinder then the local heat transfer coefficient h will be the same value for the stainless-steel cylinder

Therefore, for the stainless steel cylinder

$$h_{\text{stainles steel}} = h_{\text{brass=}} \dots \dots .. \text{Wm}^{-2}\ \text{K}^{-2}$$

$$\frac{1}{\text{Bi}} = 5.5$$

$$\text{R} = 10\text{x}10^{-3}$$

$$\text{k} = \frac{\text{hxR}}{\text{B}_\text{i}}$$

7.7.2 Graph

Draw graph between time (x-axis) and temperatures (y-axis)

7.7.3 Conclusion

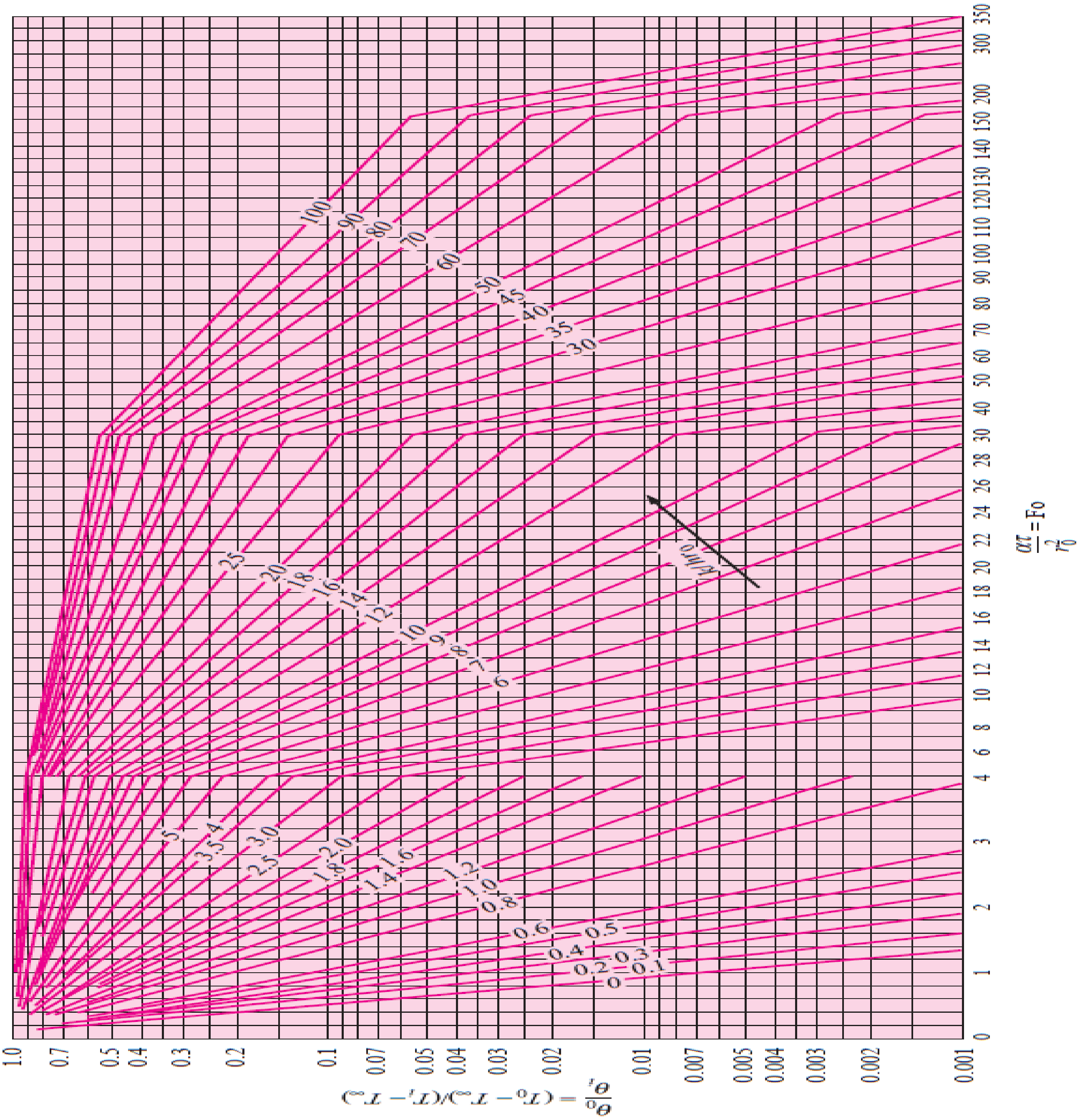
7.8 Statistical Analysis

NIL

7.9 Questions

1) How the temperature is distributed at different interval of time
2) What is Fourier Number
3) What is Biot number
4) What is Transient Heat-Transfer
5) What is Lumped-Heat-Capacity System
6) How Geometric Centre Temp is distributed at different intervals of time
7) How Fourier number and Biot number vary with time. Give reason

7.10 Comments



Graph 7.1: Heisler charts

8. LAB SESSION 8

To understand basics about Convection heat transfer mechanism

8.1 Learning Objective

1) Free convection in flat surfaces
2) Forced convection in flat surfaces
3) Dependence of the heat transmission with the exchanger geometry.

8.2 Apparatus

Free and forced convection heat transfer unit TCLFC (Serial No= TCLFC 0009/07)

8.3 Main Parts

1) Stainless steel tunnel of rectangular section
2) Flat exchanger, tenon exchanger and fins exchanger
3) Thermocouple
4) fan supply
5) A branded computer attached to unit
6) Interface

8.4 Useful Data

- Structure of anodized aluminium that guarantees a good stability and resistance to the environment.
- Stainless steel tunnel 700 mm long, painted and resistant to corrosion.
- Methacrylate viewer that allows a good visualization of the exchanger that is in use.
- Grey PVC stabilizers to guarantee a uniform air flux.
- Thermocouples type J.
- Maximum working temperature: 100ºC.
- Flow sensor with digital output.
- Aluminium exchangers of flat, spiked and bladed surfaces.
- Heating resistances of 150W.

Dimensions and weights

- Approximate dimensions of the equipment: 37x61x92
- Approx. shipment volume: 0.2m^3
- Approx. weight: 10 Kg

8.5 Theory

Convection is the term used for the process of energy transmission, which takes place in the fluid mainly due to the energy transported by the movement of the fluid. The conduction energy process by molecular exchange is, as logical, always present. However, big quantities of energy (or heat) of the fluids are in contact with regions of inferior energy (colder regions) due to the existence of big displacements of the fluid particles. If external forces in form of difference of pressures produce the movement of the fluid, this mechanism is called forced convection. An example of forced convection is the pumping of a fluid, in contact with solid surfaces at different temperatures to that of the fluid. If no external forces are applied to a fluid, it can move due to density differences that could be produced by a solid body submerged in a fluid whose temperature is different to that of the fluid. This type of heat exchange is called free

Convection and it can be observed in a recipient with boiling water, in the air that surrounds radiators in rooms, etc. The following theoretical analysis uses an empirical relationship for the heat transfer due to natural convection proposed by WH McAdams in the publication "Heat Transmission", third edition, McGraw-Hill, New York, 1959

Heat loss due to natural convection: $Q_c = h_c A_s (T_s - T_a)$
Equation 8.1
Heat transfer area (surface area): $A_s = (\pi D L)$
Equation 8.2

The heat transfer coefficient h_c can be calculated using the following relationships

$$h_c = 1.32 \left[\frac{T_s - T_a}{D}\right]^{0.25} \qquad \text{Equation 8.3}$$

Ts = Surface temperature of cylinder (K)
Ta = Ambient temperature (K)

8.5.1 Introduction of The Equipment

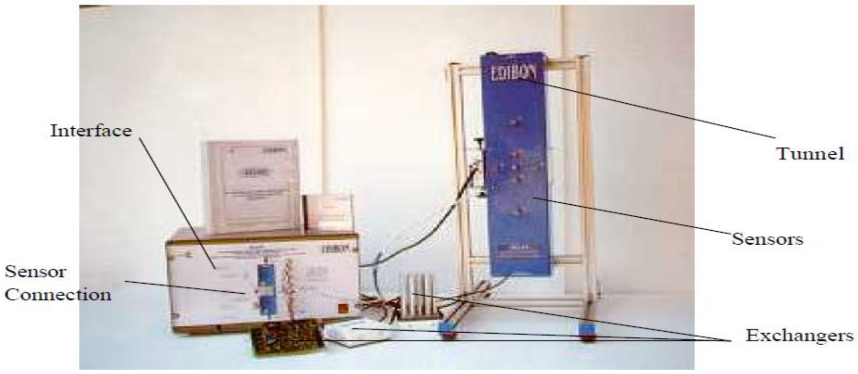


Figure 8.1: Schematic Diagram of Experiment

Simultaneous heat transference by conduction and convection (free or forced) is the base of several industrial heat exchangers, as well as the several devices related to them. This

equipment of EDIBON allows studying the efficiency of different exchangers, analyzing the heat transmission coefficients of each of the exchangers exposed to different airflows. A fan placed in the upper part of the tunnel allows
controlling the airflow that goes through the tunnel. An interface connectable to a PC contains the control circuits to measure temperatures, electrical control, electrical supply and speed control of the fan.
The interface provides an output to a PC where the values and graphics of all the variables involved in the practices are shown. The airflow is measured with a flowmeter set on the inferior part of the tunnel. This EDIBON equipment allows making a study of the heat transmission in three different types of exchangers

1. Flat exchanger
2. Tenon exchanger
3. Fins exchanger

8.5.2 Description Of The Equipment

The equipment consists of a stainless steel tunnel of rectangular section supported by a structure in anodized aluminum that allows to be set on the worktable. In the tunnel, three types of different heat exchangers can be set: flat exchanger, tenon exchanger and fins exchanger. Each exchanger has an electric
resistance for its heating. In the three bases of the exchangers we set a thermocouple that serves to control the temperature that the exchangers reach. The heat exchanger that is used in each moment can be observed by a methacrylate window placed in the opposite side of the tunnel The rising air flux through the tunnel can be generated by a variable speed fan set on the superior part. The airflow generated in the tunnel is measured by a flow meter placed in the inferior part of the tunnel. By some air flux concentrators a correct distribution of the airflow is guaranteed by the area of heat exchange. Two thermocouples measure the air temperature at the inlet and outlet of the area of heat exchange. Temperature measurements, at different distances of the base of the tenon and fins exchangers, are made by other five thermocouples that are introduced by one side of the tunnel. These measurements allow observing the gradients of temperature
in the longitudinal direction of the exchangers and in the direction of the air flux. An interface receives the signal of all the thermocouples and the flow meter, providing a computerized outlet of all the measurements. By the interface we make a control of temperature at the bases of the exchangers. Besides, the fan supply and the electrical resistance are provided by the interface. The electric supply of all the equipment is made by the connection of the interface to the net.

8.6 Objective: 01

To demonstrate the relationship between power input and surface temperature in free convection

8.6.1 Procedure

1. We will start taking the measure of the surface that exchanges heat.
2. Next, we place the flat exchanger in the tower
3. We insert the thermocouples. A thermocouple will be placed in the exchanger, and the other three in the three orifices placed in the middle of the tunnel.

4. The equipment is connected. The power of the resistance is regulated in fixed values.
5. When the temperatures are established we will proceed to its measurement, as well as that of the air speed.
6. Once all the measures are taken the equipment is unplugged. When some time has gone by, the thermocouples and the exchanger are removed

8.6.2 Observations

No	AR-1 (Ohm)	SC-1 (l/s)	ST-1 (°C)	ST-2 (°C)	ST-3 (°C)	ST-4 (°C)	ST-5 (°C)	ST-6 (°C)	ST-7 (°C)

Table 8.1: Temperatures in free convection

8.6.3 Graph

Draw the Graph of temperatures (y-Axis) and AR-1 (X- Axis)

8.7 Objective:02

To demonstrate the relationship between power input and surface temperature in forced convection

8.7.1 Procedure

1. We will start taking the measure of the surface that exchanges heat.
2. Next, we place the flat exchanger in the tower
3. We insert the thermocouples. A thermocouple will be placed in the exchanger, and the other three in the three orifices placed in the middle of the tunnel.
4. The equipment is connected. We regulate the fan speed and the power of the resistance in fixed values.
5. When the temperatures are stabilized you will proceed to their measurement, as well as that of the speed of the air.
6. Once all the measures are taken, the equipment is disconnected. When some time has gone by the thermocouples and the exchanger are removed.

7. The equipment is connected. The speed of the fan is regulated and the power of the resistance is fixed at some values.

8.7.2 Observations

No	AR-1 (Ohm)	SC-1 (l/s)	ST-1 (°C)	ST-2 (°C)	ST-3 (°C)	ST-4 (°C)	ST-5 (°C)	ST-6 (°C)	ST-7 (°C)

Table 8.2: Temperatures in forced convection

8.7.3 Graph

Draw the Graph of temperatures (y-Axis) and AR-1 (X- Axis)

8.7.4 Conclusion

8.8 Objective:03

Dependence of the heat transmission with the exchanger geometry

8.8.1 Procedure

1. You will begin placing the blade exchanger in the tower. Next, the thermocouples are introduced to measure the temperature in the base of the exchanger, that of the inlet air and that of outlet.
2. Fix the electric power of the resistance and the speed of the fan at fixed values
3. Once the measures are taken, repeat the experiment with the spike exchanger.

8.8.2 Observations:

	No	AR-1 (Ohm)	SC-1 (l/s)	ST-1 (°C)	ST-2 (°C)	ST-3 (°C)	ST-4 (°C)	ST-5 (°C)	ST-6 (°C)	ST-7 (°C)
Blade Heat exchanger										
spike exchanger										

Table 8.3: Temperatures for different geometry of exchangers

8.8.3 Graph

Draw the Graph of temperatures (y-Axis) and AR-1 (X- Axis)

8.8.4 Conclusion

8.9 Specimen Calculation

NIL

8.10 Statistical Analysis

NIL

8.11 Questions

1) Write is difference on temperatures in free and forced convection. Explain
2) What is free and forced convection
3) What is effect on heat transfer by changing the geometry of exchanger

8.12 Comments

9. LAB SESSION 9

To measure the Thermal Conductivity of Liquids and Gases

9.1 Learning Objective:

1) To determine the thermal conductivity of the air.
2) Determination of the water thermal conductivity

9.2 Apparatus

TCLGC equipment, SACED System for the data acquisition, Flexible tubes, Load syringe, Tank

9.3 Main Parts

1) Aluminium Cylinder
2) Temperature Sensors
3) Resistance
4) Brass Jacket
5) Syringe
6) Main computer attached to unit

9.4 Useful Data

1) Power of the resistance P = 150W
2) Length of contact surface L = 94 mm
3) Brass thickness e = 0.5 mm
4) Aluminium body radius r_5 =19.7 mm
5) Distance from the center to the sensor ST-4 r_4 = 7 mm
6) Distance from the center to the sensor ST-3 r_3 = 10 mm
7) Distances from the center to the sensor ST-2 r_2 = 7 mm
8) Radial space R1 = 0.3 mm
9) Thermal conductivity of the aluminum k = 198 W/mK
10) Conductivity thermal brass k = 62 W/mK
11) Contact Surface of the aluminum element with
12) the sample, surface body Aa = 11635,20 mm^2 = 0.116 m^2
13) Contact Surface of the element of the radial space
14) with the cover Ac = 11.812,39 mm^2 = 0.118 m^2

9.5 Related theory

9.5.1 Temperature

We suppose two systems separated by a mobile wall which are in mechanical balance; that means that all forces are balanced and each system exercises the same but opposed force on the separation wall; each system exercises pressure on this wall. Systems in mechanical balance have the same pressure. What does it happen in the thermal balance?
In the same way those systems in mechanical balance have a common pressure, it seems reasonable to suppose that there is some thermodynamic property in common with systems in thermal balance; this property is defined as temperature. By definition, two systems in

thermal balance have the same temperature, but this will be different if that balance doesn't exist. It is an experimental fact that:
Two systems in thermal balance with a third one is in balance to each other**.**
This generalization of the experience is the zero law of the thermodynamic

9.5.2 Heat

When two bodies with different temperatures are in contact through a wall that conducts thermally, they reach the thermal balance at an intermediate temperature, and we say that the heat has passed from the hottest to the coldest body. The heat is an energy form, while the temperature is the level this energy has. The heat is transferred by means of convection, radiation or conduction. Although these three processes can take place simultaneously, it can happen that one of the mechanisms prevails over the other two. For example, the heat is fundamentally transmitted through the wall of a house by conduction, the water of a saucepan located on a gas burner warms in great measure by convection, and the earth receives heat from the sun almost exclusively by radiation.

Transmission in stationary regime

When a system is in thermodynamic balance, the heat flow and the temperature in each point of it are constant.

Transmission in transitory regime

When the previous balance doesn't exist, either because the system has not had time to be stabilized or because the environment conditions vary with the time, the temperature in each point of the system varies with the time.

Heat accumulation

It is the consequence of the temperature variation inside the system, due to the property of the materials to absorb or to dissipate energy when their temperature varies (specific heat).

9.5.3 Heat transfer in solids

In solids, the only heat transfer form is conduction. If we warm an end of a metallic bar, so that its temperature increases, the heat is transmitted to the coldest end by conduction.
The exact mechanism of heat conduction in solids is not completely understood, but it is believed that it is partly caused by the movement of the free electrons that transports energy when there is a difference of temperature. In solids, thermal conductivity varies in an extraordinary way, from low values, as in the case of the amianthus fibbers, to very high values in the case of the metals. Fibrous materials, as amianthus, are very bad conductors (good insulating) when they are dry; if they get quite wet, they conduct the heat quite well. One of the difficulties for these materials uses as insulators is maintaining them dry. Thermal energy in solids can be transferred by conduction by means of two mechanisms: vibration of the net and transport of free electrons.
In good electric conductors, a quite big number of free electrons move in the reticular structure. As well as those electrons can transport electric load, they can also transport thermal energy from a region of high temperature to another of low temperature as in the case of the gases. In fact, reference is made to these electrons as *gas of electrons*. The energy can also be transmitted as vibration energy in the reticular structure of the material. However, this way of transferring energy is not, in general, as effective as the transport of electrons, and for this reason, good electric conductors are almost always good conductors of the heat, as copper, aluminium and silver, and the electric insulators are, normally, good thermal insulators. An exception is the diamond that is an electric insulator but has a thermal conductivity around five times higher than the silver or the copper. This fact allows the jewellers to distinguish between authentic diamonds and false stones. There exist mall

instruments that measure the response from the stones to a thermal pulse. An authentic diamond samples a much quicker response that a false stone.

At high temperatures, the energy movement through insulating materials involves several ways: conduction through the fibrous or porous solid; conduction through the air caught in the interstices of the material; and at high enough temperatures, radiation.

9.5.4 Heat transfer in gases

The mechanism of thermal conduction in gases is very simple. The kinetic energy of a molecule is identified with its temperature. In a high temperature region, the molecules have higher velocities than in a region of low temperature. The molecules are in continuous random movement, crashing one to the other and exchanging energy and quantity of movement The molecules have that random movement, with or without a gradient of temperature in the gas. If a molecule moves from a region of high temperature to another with smaller temperature, it transports kinetic energy toward the area of the system of low temperature and it gives this energy by means of the crashes with the molecules of smaller energy.

In general, thermal conductivity depends strongly on the temperature. The quicker the molecules move, the quicker the energy will be transported. A simplified analytic treatment samples that the thermal conductivity of a gas varies with the square root of the absolute temperature. The water steam is revealed as a gas of irregular behaviour that shows a strong dependence on pressure and temperature over the thermal conductivity.

9.5.5 Heat transfer in liquids

The physical mechanism of the conduction of the thermal energy in liquids is qualitatively the same one as in gases; nevertheless, the situation is considerably more complex, since the molecules are next and the field of molecular forces exercises a great influence in the energy exchange in the crash process. It can be observed that thermal conductivities of the liquid metals are much higher than those of other liquid substances.

9.5.6 Conduction of heat in concentric cylinders

Since the configuration that is adopted for this equipment of EDIBON is the cylindrical one, it is convenient to study this geometric configuration in detail

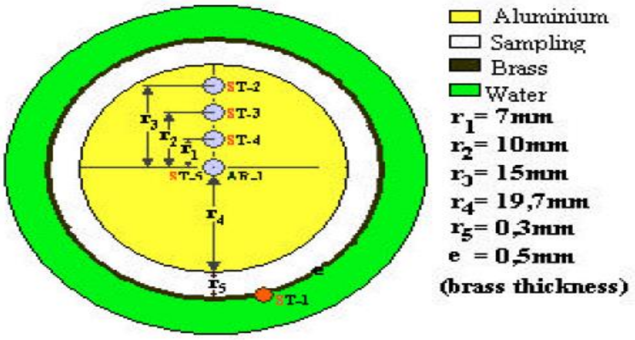


Figure 9.1: TCLGC traverse section.

The cylindrical surfaces that separate fluids of different temperatures have an enormous practical importance because the fluids are transported, they get hot, they get cold, they evaporate and they condense in pipes, tubes and cylindrical recipients. These processes constantly appear in the industry when fluids are

Managed or there is heat transmission. It is a geometric configuration, very simple from the mathematical point of view. We will take as an example the hollow cylinder represented in figure 10.2

To facilitate the resolution of this case it is convenient to use the cylindrical coordinate system.

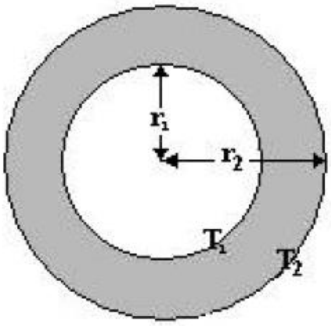


Figure 9.2: Hollow cylinder of radius r_1 and wall thickness (r_2-r_1), with different temperatures in the internal (T_1) and external (T_2) surface

If the internal surface, of radius r_1, and the external one, of radius r_2, are at uniform temperatures, T1 and T_2 respectively, then in a cylinder long enough, the border effects can be rejected. so the heat transferred is

$$\frac{q}{L}=\frac{2\pi k(T_1-T_2)}{\ln\frac{r_2}{r_1}}$$ Equation 9.1: Heat transfer from cylinder

9.6 Objective No: 01

Determine the thermal conductivity of the air

9.6.1 Procedure

1. Check that the unit is perfectly clean.
2. Open the filling valve.
3. Aspire with the syringe.
4. Locate the non-returnable valve in the sample outlet.
5. Lose the air toward the unit. When it is about to finish the possible pressure with the syringe, close the filling valve.
6. Open the refrigeration water inlet, so that it finds a constant flow of water circulating.
7. The heat exchange unit is prepared.
8. Connect the computer, execute the SACED-TCLGC program and switch on the INTERFACE.
9. Mark a small electrical power in the resistance. Wait until the system is stabilized and write down the data obtained.
10. Increase gradually the power of the resistance, until the maximum allowed, scoring in each increase the values indicated by all the temperature sensors when the system has been stabilized.
11. Try to use different power values to those used in the previous practice.

12. The temperature ST-COM is the control of the resistance.
13. Try to use different electric potential values for the resistance to those used in the previous practice

9.6.2 Observations

Experience	Electric power (W)	ST-1 (ºC)	ST-2 (ºC)	ST-3 (ºC)	ST-4 (ºC)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					

Table 9.1: Temperatures at different points for air

9.6.3 Specimen Calculations

The equipment configuration shown in the following figure, makes that the heat transfer by the resistance warms firstly the aluminum carcase. Later on it warms the radial space among both pieces and then it passes to the water jacket.

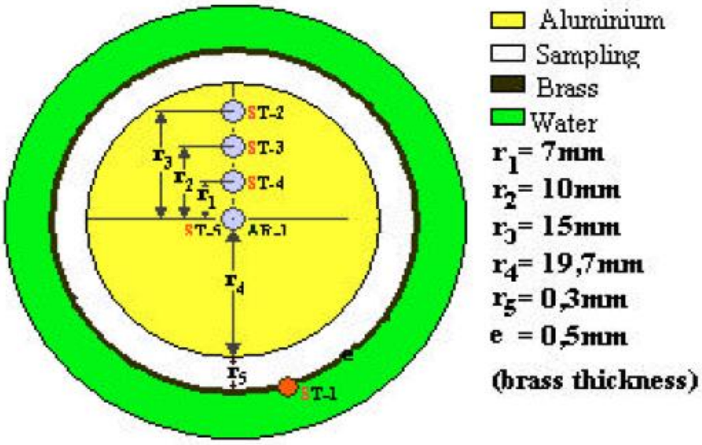


Figure 9.3: TCLGC traverse section Calculations for air

To find the temperatures just at the beginning and at the end of the radial space that contains the sample (internal temperature, Ti, and external temperature) Te, we must calculate the temperature gradient that there is among the diverse points where the temperature is taken and extrapolate it to the position where we want to know it.

T_i=Temperature at r_4=Temperature at r_2+ (Temperature at r_3- Temperature at r_2) $(\frac{r_4-r_2}{r_3-r_2})$

$$T_i=ST_3+ST_2 - ST_3) (\frac{19.7-10}{15-10})$$

With the measurements obtained for the aluminium, we find the temperature in the body surface. We suppose that aluminium thermal conductivity is practically constant (it is good approach, since the variation of conductivity that the alloy used suffers is of hardly 10W/mºC each 100ºC). Evidently, the temperature in the surface of the aluminium piece will vary with the voltage applied to the resistance. This voltage is controlled from software controller ASCR-1 which vary from 0V (ASCR-1: 0) to 220V (ASCR-1: 10). If you want know the power consumed by resistance, you must measure the resistance value

between resistance's contacts in connector. When you know resistance and voltage values (220V if ASCR-1 is 10), you can obtain the power consumed through this relation

$$\text{Power} = V^2 / R$$

	Electric power (W)= V^2 / R	Temperature in r_5= ST-1 (ºC)=T_e	T_i	$\Delta T=T_e-T_i$	Average value (ºC)	Thermal Conductivity (Actual)	Thermal Conductivity (Theoretical)
1							
2							
3							
4							
5							
6							
7							

Table 9.2: Thermal conductivity of air

External Temperature= T_e

Internal Temperature=$T_i=ST_3+ST_2 - ST_3) (\frac{9.7}{5})$

Thermal Conductivity= $\frac{\text{Electric Power}}{2\pi L(T_e-T_i)}(\ln\frac{20}{19.7})$

9.6.4 Graph

Draw the graph between Electric power and radius of cylinder. Take the five values of cylinder on X-axis and electric power on Y-axis

9.6.5 Conclusion

9.7 Objective No: 02

Determination of the water thermal conductivity

9.7.1 Procedure:

1. Check that the unit is totally clean and correctly assembled.
2. Open the filling valve.
3. Disconnect the flexible tube, pressing the blue part and pulling on the tube. It is a quick closing and it should be easily made.
4. Aspire with the syringe, through the tube, the liquid to study (water, oil or any other substance compatible with the materials of the equipment)
5. Connect the flexible tube of the filling valve, by pressing slightly. It is properly connected if it doesn't come off when pulling on it.
6. Place the non-returnable valve in the tube of sample outlet.
7. Inject sample to the radial space. To avoid the formation of bubbles and to get a uniform layer, maintain the sample injection during a time (until lasts all the capacity of the syringe).
8. Close the sample valve.
9. Connect at constant flow the water thermostatization.
10. Switch on the computer, execute the SACED-TCLGC program and switch on the INTERFACE.
11. Follow the experimental procedure described in section 3.1.4 for the work with liquids.
12. Mark a small electrical power in the resistance. Wait until the system is stabilized and write down the data obtained.
13. Increase gradually the power of the resistance, until the maximum allowed, scoring in each increase the values indicated by all the temperature sensors when the system has been stabilized
14. The temperature ST-COM is the control of the resistance

9.7.2 Observations:

Experience	Electric power (W)	ST-1 (ºC)	ST-2 (ºC)	ST-3 (ºC)	ST-4 (ºC)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Table 9.3: Temperatures at different points for water

9.7.3 Specimen Calculations:

The equipment configuration shown in the following figure, makes that the heat transfer by the resistance warms firstly the aluminium carcase. Later on, it warms the radial space among both pieces and then it passes to the water jacket.

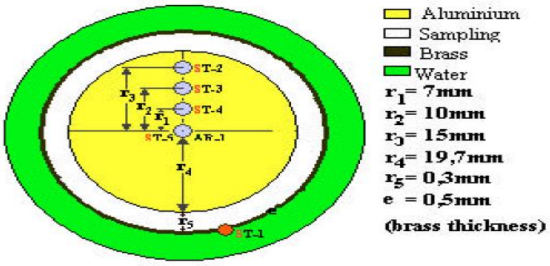


Figure 9.4: TCLGC traverse section Calculations for water

To find the temperatures just at the beginning and at the end of the radial space that contains the sample (internal temperature, Ti, and external temperature) Te, we must calculate the temperature gradient that there is among the diverse points where the temperature is taken and extrapolate it to the position where we want to know it.

T_i=Temperature at r_4=Temperature at r_2+ (Temperature at r_3- Temperature at r_2) $\left(\frac{r_4 - r_2}{r_3 - r_2}\right)$

$$T_i = ST_3 + ST_2 - ST_3)\ (\frac{19.7-10}{15-10})$$

With the measurements obtained for the aluminium, we find the temperature in the body surface. We suppose that aluminium thermal conductivity is practically constant (it is good approach, since the variation of conductivity that the alloy used suffers is of hardly 10W/mºC each 100ºC). Evidently, the temperature in the surface of the aluminium piece will vary with the voltage applied to the resistance. This voltage is controlled from software controller ASCR-1 which vary from 0V (ASCR-1: 0) to 220V (ASCR-1: 10). If you want know the power consumed by resistance, you must measure the resistance value

between resistance's contacts in connector. When you know resistance and voltage values (220V if ASCR-1 is 10), you can obtain the power consumed through this relation

$$\text{Power} = V^2 / R$$

	Electric power (W)= V^2 / R	Temperature in r_5= ST-1 (ºC)=T_e	T_i	$\Delta T = Te - T_i$	Average value (ºC)	Thermal Conductivity (Actual)	Thermal Conductivity (Theoretical)
1							
2							
3							
4							
5							
6							
7							

Table 9.4: Thermal conductivity for water

External Temperature= T_e

Internal Temperature=$T_i = ST_3 + ST_2 - ST_3)\ (\frac{9.7}{5})$

Thermal Conductivity = $\frac{\text{Electric Power}}{2\pi L(T_e - T_i)}(\ln\frac{20}{19.7})$

9.7.4 Graph:

Draw the graph between Electric power and radius of cylinder. Take the five values of cylinder on X-axis and electric power on Y-axis.

9.7.5 Conclusion

9.8 Statistical Analysis

For Thermal conductivity

% Error= $\frac{K_{th}-K_{exp}}{\mathrm{K_{th}}}$

x_{avg}= $\frac{\mathrm{x_1+x_2+x_3}}{\mathrm{n}}$

S_x=$\sqrt{\frac{1}{n-1}((x_1-x_{avg})^2+(x_2-x_{avg})^2+(x_3-x_{avg})^2)}$

9.9 Questions

1) What is conduction heat transfer?
2) Define thermal conductivity and explain its significance in heat transfer.

9.10 Comments:

10. LAB SESSION 10

To demonstrate the working principle of turbulent flow heat exchanger operating under parallel & counter flow condition.

10.1 Learning Objective

1) To study the Global energy balance in the Turbulent Flow exchanger and heat losses.
2) Determination of the heat exchanger effectiveness by NTU method.
3) To calculate the Reynolds number and study the Influence of the flow in heat transfer.

10.2 Apparatus

Turbulent Flow Heat Exchanger (TIFTC) (Serial no TIFT 0003/06)

10.3 Main Parts

IDENTIFICATION	DESCRIPTION
ST-16	Temperature sensor in the water tank.
ST-1	Cold water temperature sensor at the exchanger inlet or outlet
ST-2	Hot water sensor at the exchanger inlet
ST-3	Cold water sensor between the first and second stretch of the exchanger
ST-4	Hot water sensor between the first and second stretch of the exchanger
ST-5	Cold water sensor between the second and third stretch of the exchanger
ST-6	Hot water sensor between the second and third stretch of the exchanger
ST-7	Cold water sensor between the third stretch and end of the exchanger
ST-8	Hot water sensor between the third stretch and end of the exchanger
ST-9	Cold water temperature sensor at the exchanger inlet or outlet
ST-10	Hot water sensor at the exchanger outlet
ST-11	Temperature sensor of the exterior surface of the interior tube at the exchanger Inlet.
ST-12	Temperature sensor of the exterior surface of the interior tube at the exchanger Outlet
SC-1	Hot water flow sensor
SC-2	Cold water flow sensor
AVR-1	Hot water flow regulation valve.
AVR-2	Cold water flow regulation valve
AN-1	Water level switch of the tank
AR-1	Electric resistance
AB-1	Centrifugal pump for hot water circulation
AP-1	Cold water circuit purge
AP-2	Hot water circuit purge
AV-2,AV-3, AV-4	Ball valves of the cold water circuit to fix parallel or crosscurrent

and AV-5	flow
AV-1,AV-6, AV-7 and AV-8	Ball valves to drain the pipes

10.4 Useful Data

Exchange Length: L = 3 × 0.5 = 1.5 m.

10.4.1 Interior Tube

Internal Diameter: $D_{int} = 8\times10^{-3}$ m
External Diameter: $D_{ext} = 10\times10^{-3}$ m
Thickness = 10^{-3} m
Internal heat transference area: $A_h = 0.0377\ m^2$
External heat transference area: $A_c = 0.0471\ m^2$

10.4.2 Exterior Tube

Internal Diameter: $D_{int,c} = 13\times10^{-3}$ m
External Diameter: $D_{ext,c} = 15\times10^{-3}$ m
Thickness = 10- 3 m

10.4.3 Base Unit

Net weight: 30 kg.
Height: 400 mm
Width: 1000 mm
Depth: 500 mm

10.4.4 Heat Exchanger

Net weight: 20 kg.
Height: 200 mm
Width: 1000 mm
Depth: 500 mm

10.4.5 Physical Properties of The Hot And Cold Water

To determine their physical properties, the average temperature of each fluid has to be calculated.

$$\text{Hot water average temperature: } Tm_h = \frac{ST3+ST9}{2}$$

$$\text{Cold Water Average Temperature: } Tm_c = \frac{ST2+ST8}{2}$$

From the table of the appendix A, the physical properties based on the average temperature can be obtained

	ρ	Cp=Specific heat(J/kgK)	μ= Dynamic viscosity (kg/ms)
Hot water at Tm_h °C	ρ_h=	Cp_h	μ_h
Cold water at Tm_c °C	ρ_c=	Cp_h	μ_c

10.4.6 Mass Flow Rates

The mass flows of both fluids, are going to be obtained from the measurements taken in the flow sensors (SC1 for hot water and SC2 for cold water)

$$\text{m (kg/s)} = \rho.SC = \frac{\rho\left(\frac{\text{kg}}{\text{m}^3}\right).\text{SC}\left(\frac{\text{l}}{\text{min}}\right)}{60\times1000}$$

$$\text{Mass flow for hot water} = \text{m}_\text{h}\ \text{(kg/s)} = \rho.SC = \frac{\rho_\text{h}\left(\frac{\text{kg}}{\text{m}^3}\right).\text{SC}\left(\frac{\text{litre}}{\text{min}}\right)}{60\times1000} = \text{........kg/s}$$

$$\text{Mass flow for cold water} = \text{m}_\text{c}\ \text{(kg/s)} = \rho.SC = \frac{\rho_\text{c}\left(\frac{\text{kg}}{\text{m}^3}\right).\text{SC}\left(\frac{\text{litre}}{\text{min}}\right)}{60\times1000} = \text{........kg/s}$$

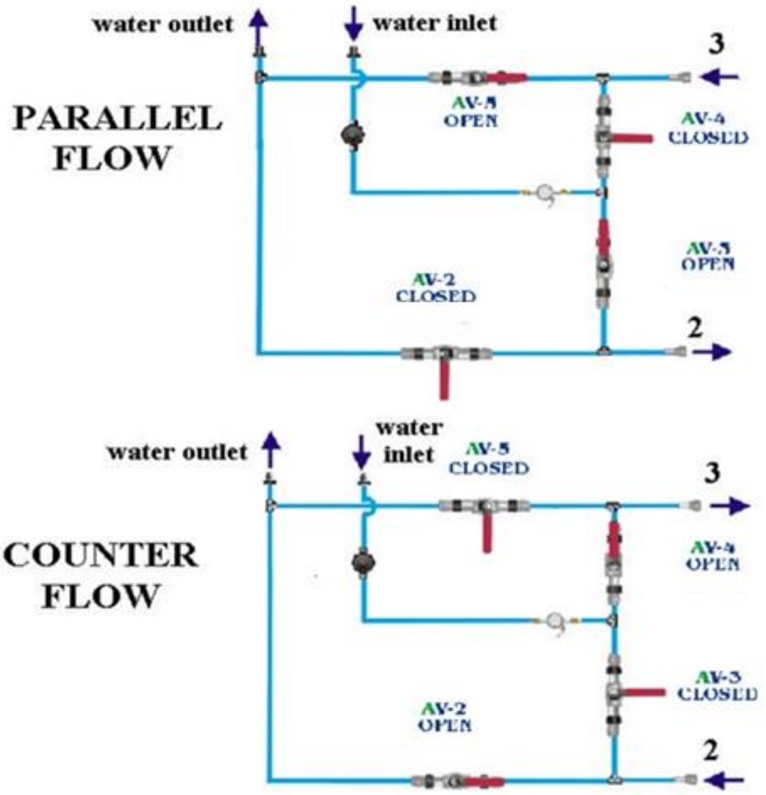
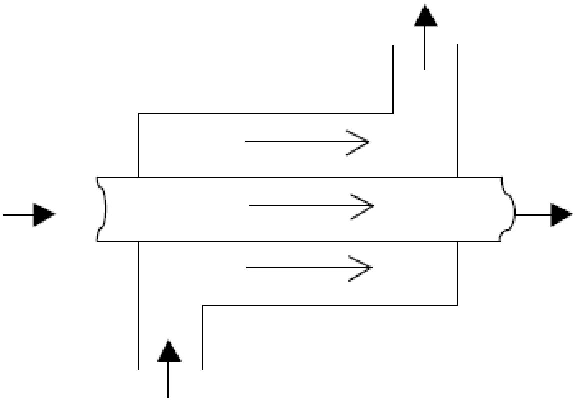


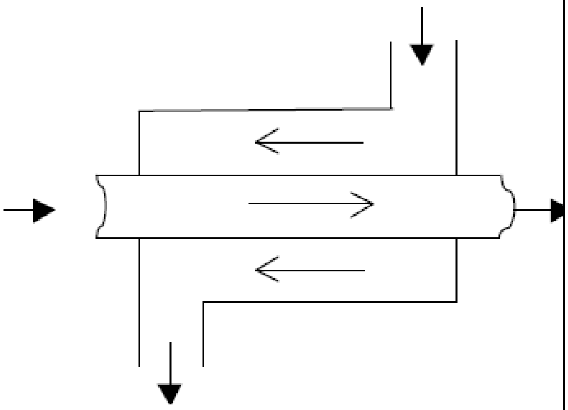
Figure 10.1: Schematic Diagram of Experiment

10.5 Theory

10.5.1 Heat transference in heat exchangers

A heat exchanger is a device developed by humans for the heat transference between two fluids at different temperatures separated by a solid wall. They have many engineering applications and, as a consequence, there are many models adapted to each application. The simplest one is the one built with two concentric tubes, where fluids can move in the same sense or in the opposite one. In parallel flow, the hot and the cold water go in and out through the same end. In crosscurrent flow, the fluids go in and out through opposite ends and they circulate in opposite senses.





10.5.2 Overall Heat-Transfer Coefficient

The overall heat-transfer coefficient U is defined by the relation

$$q = UA\Delta T_{overall} \qquad \textit{Overall heat transfer coefficient}$$

Although final heat-exchanger designs will be made on the basis of careful calculations of U, it is helpful to have a tabulation of values of the overall heat-transfer coefficient for various situations that may be encountered in practice

10.5.3 The Log Mean Temperature Difference (LMTD)

Being $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ in parallel flow

$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ in countercurrent flow.

$$T_{lm}=\frac{(\Delta T1)-(\Delta T2)}{\ln[\frac{\Delta T1}{\Delta T2}]}$$

Equation 9(a).2: The Log Mean Temperature Difference

10.5.4 Effectiveness-Ntu Method

$$\text{Effectiveness}=\frac{\text{Actual heat transfer}}{\text{Maximum possible heat transfer}}$$

Equation 9(a).3

10.5.5 Capacity coefficient

Capacity coefficient will be defined as (CR)

$$C_r=\frac{C_{min}}{C_{max}}=\ldots\ldots\ldots\ \frac{w/k}{w/k}$$

Equation 9(a).4

Mass flow rate multiplied by specific heat) C_h and C_c for the hot and cold fluids respectively, and denoting the smaller one as C_{min}

10.5.6 Reynolds number

Reynolds number (Re) is a dimensionless quantity that is used to help predict similar flow patterns in different fluid flow situations. The Reynolds number is defined as the ratio of momentum forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. They are also used to characterize different flow regimes within a similar fluid, such as laminar or turbulent flow

1) Laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion;
2) Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic eddies, vortices and other flow instabilities.

Readers can read further detail from book “heat transfer by J.P Holman” in “chapter 10”

10.6 Objective 01

To study the Global energy balance in the Turbulent Flow exchanger and heat losses.

10.6.1 Procedure:

1. Check that the valves are opened and that we have crosscurrent flow configuration.
2. Check that the heating tank is full of water, above the level switch
3. Switch on the pump and the resistor (Equipment supply)
4. Fix the tank temperature at 50 °C (STI)
5. Fix the hot water flow in 3 l/min (SCI) and adjust the cold water flow until reaching stationary operation conditions maintaining constant the temperature fixed in the tank.
6. Note down the temperature and flow measures in the experimental sheet
7. Repeat steps 5 and 6 for different water temperatures in the deposit 55 °C, 60°C and 65 °C.
8. Once the measures are made, Calculate the heat transferred by the hot water, the heat absorbed by the cool water, the heat looses, the logarithmic mean temperature and global heat transference coefficient

10.6.2 Observations

	TEST 1	TEST 2	TEST 3	TEST 4
ST1 (°C)	50	55	60	65
ST2 (°C)				
ST3 (°C)				
ST4 (°C)				
ST5 (°C)				
ST6 (°C)				
ST7 (°C)				
ST8 (°C)				
ST9 (°C)				
ST10 (°C)				
ST11 (°C)				
SC1 (l/min)	3	3	3	3
SC2 (l/min)				

Table 10.1: Temperature at different points of turbulent flow heat exchanger

10.6.3 Calculated Data

	TEST 1	TEST 2	TEST 3	TEST 4
q_h (w)				
q_c (w)				
q_l (w)				
ΔT_{lm} (K)				
U (w/m^2k)				

Table 10.2: Heat transfer calculation in lent flow heat exchanger

10.6.4 Specimen Calculations

10.6.4.1 Heat transferred by the hot water

$$q_h=m_hCp_h(ST3-ST9)=\ldots\ldots\ldots\ldots\ldots\ldots..\text{watt}$$

10.6.4.2 Heat absorbed by the cold water

$$q_c=m_cCp_c(ST8-ST2)=\ldots\ldots\ldots\ldots\ldots\ldots..\text{watt}$$

10.6.4.3 Heat Losses

$$q_{l=}\ q_{h-}\ q_c=\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{watt}$$

10.6.4.4 Logarithmic temperatures mean difference between hot water and cold water

$$\Delta T_{lm}=\frac{(ST3-ST2)-(ST9-ST8)}{\ln[\frac{ST3-ST2}{ST9-ST8}]}=\ldots\ldots\ldots\ldots\ldots\ldots\text{Watt}$$

The logarithmic temperatures mean difference between the hot fluid and the external surface of the interior tube is $(\Delta T_{lm})_{hot}=\frac{(ST3-ST10)-(ST9-ST11)}{\ln[\frac{ST3-ST10}{ST9-ST11}]}=\ldots\ldots\ldots\ldots\ldots\ldots\text{Watt}$

The logarithmic temperatures mean difference between the cold fluid and the external surface of the interior tube is $(\Delta T_{lm})_{cold}=\frac{(ST10-ST2)-(ST11-ST8)}{\ln[\frac{ST10-ST2}{ST11-ST8}]}=\ldots\ldots\ldots\ldots\ldots\ldots\text{Watt}$

10.6.4.5 Global heat transference coefficient= (U)

From the heat transfer rate $Q=UA\Delta T_{lm}$

$$U.A=q/\Delta T_{lm}=q_h/\Delta T_{lm}=\ldots\ldots\ldots\ldots\ldots..\text{w/k}$$

If we take an average heat transfererence area

$$A_m=\pi.L=\frac{\text{Dint+Dext}}{2}=\pi.1.5.\frac{8+10}{2000}=0.04241\text{m}^2$$

Where

$D_{int}=8.10^{-3}$m and $D_{ext}=10.10^{-3}$m are interior and exterior diameters of the interior tube and L=1.5 m is the exchanger length.Finally global heat transference coefficient will be

$$U=\frac{\ldots\ldots.W/K}{A_m}=\frac{\ldots..w/k}{0.04241}=\cdots w/m^2k$$

10.7 Objective:02

Determination of the heat exchanger effectiveness by NTU method

10.7.1 Procedure

1. Check that the valves are opened and that we have crosscurrent flow configuration.
2. Check that the heating tank is full of water, above the level switch
3. Switch on the pump and the resistor (feeding of the equipment)
4. Fix the tank temperature at 65 °C (STI)
5. Fix the hot water flow in 2.5 l/min (SCI) and adjust the cold water flow until reaching stationary operation conditions maintaining constant the temperature fixed in the tank.
6. Note down the temperature and flow measures in the experimental sheet
7. Place conveniently the valves to invert the cold water flow sense obtaining a parallel flow disposition
8. Make sure that the 65 °C are maintained in the tank and that the same hot and cold water flows fixed in step 5 are also maintained.
9. Once the system is stabilized, note down the measures and flows in the experimental sheet.
10. Once the measures are taken, calculate the experimental effectiveness, the theoretical effectiveness with the NTU method and theoretical temperatures at the exchanger outlet.

10.7.2 Observations

	TEST 1 Crosscurrent Flow	TEST 2 Parallel Flow
ST1 (°C)	65	65
ST2 (°C)		
ST3 (°C)		
ST4 (°C)		
ST5 (°C)		
ST6 (°C)		
ST7 (°C)		
ST8 (°C)		
ST9 (°C)		
ST10 (°C)		
ST11 (°C)		
SC1 (l/min)	3	3
SC2 (l/min)		

Table 10.3: Temperature for parallel and cross flow

10.7.3 Calculations

From these measures, calculate the following thermodynamic variables

Experimental effectiveness (ϵ)

Heat transferred by the hot water (q_h)

Logarithmic temperatures mean difference between hot and cold water (ΔT_{lm})

Parameters: U.A, NTU and C_R

Effectiveness obtained by NTU method (ϵ_{NTU})

Hot and cold water temperatures at the exchanger outlet obtained from the experimental effectiveness ($T_{h,\circ}y,T_{c,o}$)

	TEST 1 Crosscurrent Flow	TEST 2 Parallel flow
ϵ		
$q_{h\ (w)}$		
ΔT_{lm} (K)		
U.A (w/k)		
NTU		
C_R		
ϵ_{NTU}		
$T_{h,\circ}$ (°C)		
$T_{c,o\ (°C)}$		

Table10.4: Effectiveness of turbulent flow exchanger

10.7.4 Specimen Calculations

The effectiveness is the quotient between the heat really exchanged and the maximum heat that could be transferred in an infinite area exchanger in a crosscurrent flow.

If $m_hCp_h<m_cCp_c$ $\qquad \epsilon=\frac{(Th,i)-(Th,o)}{Th,i-Tc,o}$

$m_hCp_h>m_cCp_c$ $\qquad \epsilon=\frac{(Tc,o)-(Tc,i)}{Th,i-Tc,i}$

10.7.4.1 Heat transferred by the hot water

$q_h=m_hCp_h(ST3-ST9)=$………………..watt

10.7.4.2 Logarithmic temperatures mean difference between hot water and cold water

$\Delta T_{lm}=\frac{(ST3-ST2)-(ST9-ST8)}{\ln[\frac{ST3-ST2}{ST9-ST8}]}=$………………Watt

From the heat transfer rate $\qquad Q=UA\Delta T_{lm}$

$U.A=q/\Delta T_{lm}=q_h/\Delta T_{lm}=$……………..w/k

10.7.4.3 Number of transmission units

Calculating NTU

$NTU=\epsilon=\frac{U.A}{(m.Cp)min}$

10.7.4.4 Capacity coefficient

Capacity coefficient is determined by

$$C_r = \frac{mCp_{min}}{mCp_{max}} = \ldots\ldots\ldots \frac{w/k}{w/k}$$

Once the NTU and C_r are obtained, we can calculate the effectiveness, but depending if the flow is in crosscurrent or in parallel flow, we will have to use different expressions

$$\epsilon_{NTU} = \frac{1 - e^{-NTU.(1+C_R)}}{1+C_R} \qquad \text{For Parallel flow}$$

$$\epsilon_{NTU} = \frac{1 - e^{-NTU.(1-C_R)}}{1 - C_R \times\ e^{-NTU.(1-C_R)}} \qquad \text{For Crosscurrent flow}$$

Comparing the value of ϵ with ϵ_{NTU} we will have to observe if both values are similar or, if on the other hand, they are very different one from each other

10.7.4.5 Temperatures at the exchanger outlet

From the experimental effectiveness (ε), previously calculated, the hot and the cold fluid temperatures at the exchanger outlet can be estimated

$$\left.\begin{aligned} T_{h,o} &= T_{h,i} - \varepsilon\,(T_{h,i} - T_{c,i}) \\ T_{c,o} &= T_{c,i} + C_R\,(T_{h,i} - T_{h,o}) \end{aligned}\right\} \text{ if } \quad m_h \cdot Cp_h < m_c \cdot Cp_c$$

$$\left.\begin{aligned} T_{c,o} &= T_{c,i} + \varepsilon\,(T_{h,i} - T_{c,i}) \\ T_{h,o} &= T_{h,i} - C_R\,(T_{c,o} - T_{c,i}) \end{aligned}\right\} \text{ if } \quad m_c \cdot Cp_c < m_h \cdot Cp_h$$

10.8 Objective:03

To calculate the Reynolds number and study the Influence of the flow in heat transfer.

10.8.1 Procedure:

1. Check that the valves are opened and that we have crosscurrent flow configuration.
2. Check that the heating tank is full of water, above the level switch
3. Switch on the pump and the resistor (feeding of the group)
4. Fix the tank temperature at 65 °C (STI)
5. Fix the hot water flow in 3 l/min (SCI) and adjust the cold water flow until reaching stationary operation conditions maintaining constant the temperature fixed in the tank.
6. Note down the temperature and flow measures in the experimental sheet.
7. Reduce the hot water flow at around 2.5 l/min maintaining constant the cold water flow. At the same time, the same average temperature for the hot water has to be

reached (this way, hot water physical properties do not change during the experiment). For it, the tank resistor has to be lowered and make the average between the temperatures ST2 and ST10 (Tmh=$\frac{ST2+ST10}{2}$) until reaching a value closer, as much as possible, to the previous experiment.

8. When the system is stabilized, note down the temperatures and flows in the experimental sheet.
9. Repeat steps 7 and 8 for hot water flows of 2 l/min and 1.5 l/min.
10. Calculate the heat transferred by the hot fluid, the heat gained by the cold fluid and the losses. Determine the logarithmic temperature mean difference, global heat transfer coefficient and Reynolds number

10.8.2 Observations

	TEST 1	TEST 2	TEST 3	TEST 4
ST1 (°C)				
ST2 (°C)				
ST3 (°C)				
ST4 (°C)				
ST5 (°C)				
ST6 (°C)				
ST7 (°C)				
ST8 (°C)				
ST9 (°C)				
ST10 (°C)				
ST11 (°C)				
SC1 (l/min)	3	2.5	2	1.5
SC2 (l/min)				

Table10.5: Temperatures for turbulent flow exchanger

10.8.3 Calculated Data

	TEST 1	TEST 2	TEST 3	TEST 4
q_{h} (w)				
q_{c} (w)				
q_{l} (w)				
ΔT_{lm} (K)				
U (w/m^{2}k)				
u_h (m/s)				
u_c (m/s)				
Re_{Dh}				
Re_{Dc}				

Table 10.6: Rynold number for turbulent flow heat exchanger

10.8.4 Specimen Calcularions

While

10.8.4.1 Heat transferred by the hot water

$q_h=m_hCp_h(ST3-ST9)=$………………..watt

10.8.4.2 Heat absorbed by the cold water

$q_c=m_cCp_c(ST8-ST2)=$………………..watt

Heat Losses $q_l= q_h- q_c=$……………………watt

10.8.4.3 Logarithmic temperatures mean difference between hot water and cold water

$$\Delta T_{lm}=\frac{(ST3-ST2)-(ST9-ST8)}{\ln[\frac{ST3-ST2}{ST9-ST8}]}=\ldots\ldots\ldots\ldots\ldots\ldots \text{Watt}$$

10.8.4.4 Global heat transference coefficient= (U)

From the heat transfer rate $Q=UA\Delta T_{lm}$

$$U.A=q/\Delta T_{lm}= q_h/\Delta T_{lm}=\ldots\ldots\ldots\ldots\ldots\ldots \text{w/k}$$

If we take an average heat transfererence area

$$A_m=\pi.L= \frac{Dint+Dext}{2}= \pi.1.5.\frac{8+10}{2000}=0.04241m^2$$

D_{int}=8.10^{-3}m and D_{ext}=10.10^{-3}m are interior and exterior diameters of the interior tube and L=1.5 m is the exchanger length.Finally global heat transference coefficient will be

$$\mathrm{U} = \frac{\ldots\ldots.\mathrm{W/K}}{\mathrm{A_m}} = \frac{\ldots..\mathrm{w/k}}{0.04241} = \cdots \mathrm{w/m^2k}$$

10.8.4.5 Hot and cold water velocity in the exchanger

From the average flow measured during the experiment, we can calculate easily the velocity

$$u_{(m/s)} = \frac{Q_{(l/min)}}{A_t(m^2).60.10^3}$$

Being At the cross area in a longitudinal section, which will be change depending on The fluid we are referring to, for example, for the hot water that flow through the Interior tube

$$A_{t,\,hot} = \frac{\pi D_{int}^2}{4} = \frac{\pi.(0.008)^2}{4} = 50.26.10^{-6}\mathrm{m}^2$$

While for the cold water that circulates through the annular zone of both tubes.

$$A_{t,\,cold} = \frac{\pi D_{int,c}^2}{4} - \frac{\pi D_{ext}^2}{4} = \frac{\pi.(0.013)^2}{4} - \frac{\pi.(0.010)^2}{4} = 54.19.10^{-6}\mathrm{m}^2$$

Where D_{int},c is the internal diameter of the exterior tube and D_{ext} is the exterior diameter of the interior tube. This way, the velocities are, for the hot water

$$u_h\,(m/s) = \frac{Q_{(l/min)}}{A_{t,hot}(m^2).60.10^3} = \frac{Q_{(l/min)}}{50.26.10^{-6}.60.10^3} = \ldots\ldots \mathrm{m/s}$$

For the cold water

$$u_C\,(m/s) = \frac{Q_{(l/min)}}{A_{t,cold}(m^2).60.10^3} = \frac{Q_{(l/min)}}{54.19.10^{-6}.60.10^3} = \ldots\ldots \mathrm{m/s}$$

10.8.4.6 Reynolds number

Reynolds number is an adimensional parameter that relates the inertial forces with the viscosity forces in a fluid. For internal flows, its expression is

$$Re_D = \frac{\rho,u.D}{\mu}$$

ρ= fluid density (kg/m3)

u =average velocity of the fluid at the transversal section of the tube (m/s)

D = internal diameter of the fluid (m)

μ= dynamic viscosity of the fluid (kg/m·s)

For the hot fluid

$$Re_D = \frac{\rho_h,u_h.D_{int}}{\mu_h} = \frac{\rho_h,u_h.8\times10^{-3}}{\mu_h} =$$

For the cold fluid, it has to be taken into account that the longitudinal section in which it flows is not circular, but annular. For it, an hydraulic diameter will have to be calculated, which comes given by the expression

$$D_H = \frac{4.A}{P}$$

Where A is the area of the longitudinal section and P is its perimeter. As we have previously seen, they are in which the flow circulates was

$$A_{t,cold}=\frac{\pi.D_{int,c}^2}{4}-\frac{\pi.D_{ext}^2}{4}=\frac{\pi}{4}.(D_{int,c}^2-D_{ext}^2)$$

While the perimeter was

$$P=\pi.D_{int,c}+\pi.D_{ext}=\pi\,(D_{int,c}+D_{ext})$$

So the hydraulic diameter is

$$D_H=\frac{4.A}{P}=\frac{\frac{4\,\pi}{4}.(D_{int,c}^2-D_{ext}^2)}{\pi\,(D_{int,c}+D_{ext})}=(D_{int,c}-D_{ext})=3.10^{-3}$$

Reynolds number for the cold fluid will be

$$Re_D=\frac{\rho_c,u_c.D_H}{\mu_c}=\frac{\rho_c,u_c.3.10^{-3}}{\mu_c}$$

10.9 Graph

Draw the graph between the temperature distribution for parallel and crosscurrent flow. To do this, place temperature values on the vertical (y-) axis for the hot water, cold water and of the interior tube surface in ºC (T); and in the x-axis place the position along the exchanger in meters (x). Take into account that the exchange length is 1.5m and that there are four points to measure the temperature

10.10 Statistical Analysis

1) $x_{avg}=\frac{x_1+x_2+x_3}{n}$

2) $S_x=\sqrt{\frac{1}{n-1}((x_1-x_{avg})^2+(x_2-x_{avg})^2+(x_3-x_{avg})^2)}$

10.11 Conclusion

10.12 Questions

1) What is the difference between the temperature distribution for parallel and crosscurrent flow?
2) What is Global heat transference coefficient
3) What is Logarithmic temperatures mean difference

10.13 Comments

11. LAB SESSION 11

To demonstrate the working principle of Shell and tube heat exchanger operating under parallel & counter flow condition

11.1 Learning Objective

[i] To study the Global energy balance in the Shell and Tube exchanger and heat losses.
[ii] Determination of the heat exchanger effectiveness by NTU method.
[iii] To calculate the Reynolds number and study the Influence of the flow in heat transfer.

11.2 Apparatus

EDIBON TICT's Shell and Tube exchanger (Serial No= TICT ϕϕ 67/11)

11.3 Main Parts

IDENTIFICATION	DESCRIPTION
ST-16	Water Tank Temperature Sensor
ST-1	Hot Water Temperature sensor at the inlet/outlet of the exchanger
ST-2	Hot Water temperature Sensor at the outlet of the exchanger
ST-3	Cold Water Temperature Sensor at the inlet/outlet of the exchanger
ST-4	Cold Water Temperature Sensor in the first section of the exchanger
ST-5	Cold Water Temperature Sensor in the second section of the exchanger
ST-6	Cold Water Temperature Sensor in the third section of the exchanger
ST-7	Cold Water Temperature Sensor at the inlet/outlet of the exchanger
SC-1	Hot water flow sensor
SC-2	Cold water flow sensor
AVR-1	Hot water flow regulation valve.
AVR-2	Cold water flow regulation valve
AN-1	Water level switch of the tank
AR-1	Electric resistance
AB-1	Hot Water Flow Centrifugal Pump
AP-1	Cold Water Circuit Purge Valve
AP-2	Hot Water Circuit Purge Valve
AV-2,AV-3, AV-4 Y AV-5	Ball valves of the cold water circuit to fix parallel or crosscurrent flow

AV-1, AV-6, AV-7 Y AV-8	Ball valves to drain the pipes
AVS-1	Safety Valve
AVS-2	Safety Valve

11.4 Useful Data

Exchange Length: L = 0.5 m.

11.4.1 Interior Tube

Internal Diameter: $D_{int} = 8\times10^{-3}$ m
External Diameter: $D_{ext} = 10\times10^{-3}$ m
Thickness = 10^{-3} m
Internal heat transference area: $A_h = 0.0126\ m^2$
External heat transference area: $A_c = 0.0157\ m^2$

11.4.2 Exterior Tube

Internal Diameter: $D_{int,c}$ =0.148 m
External Diameter: $D_{ext,c}$ =0.160 m
Thickness =6×10^{-3} m

11.4.3 Base Unit

Net weight: 30 kg.
Height: 400 mm
Width: 1000 mm
Depth: 500 mm

11.4.4 Heat Exchanger

Net weight: 20 kg.
Height: 300 mm
Width: 1000 mm
Depth: 500 mm

11.4.5 Physical Properties Of The Hot And Cold Water

To determine their physical properties, the average temperature of each fluid has to be calculated.

$$\text{Hot water average temperature: } Tm_h = \frac{T_{hi}+T_{ho}}{2}$$

$$\text{Cold Water Average Temperature: } Tm_c = \frac{T_{ci}+T_{co}}{2}$$

From the table of the appendix A, the physical properties based on the average temperature can be obtained

	ρ	Cp=Specific heat(J/kgK)	μ= Dynamic viscosity (kg/ms)
Hot water at Tm_h °C	ρ_h=	Cp_h	μ_h
Cold water at Tm_c °C	ρ_c=	Cp_h	μ_c

11.4.6 Mass Flow Rates

The mass flows of both fluids, are going to be obtained from the measurements taken in the flow sensors (SC1 for hot water and SC2 for cold water)

$$\text{m (kg/s)} = \rho.SC= \frac{\rho\left(\frac{\text{kg}}{\text{m}^3}\right).\text{SC}(\frac{\text{l}}{\text{min}})}{60\times1000}$$

$$\text{Mass flow for hot water= m}_\text{h}\text{ (kg/s)} = \rho.SC= \frac{\rho_\text{h}\left(\frac{\text{kg}}{\text{m}^3}\right).\text{SC}(\frac{\text{litre}}{\text{min}})}{60\times1000}=\text{........kg/s}$$

$$\text{Mass flow for cold water= m}_\text{c}\text{ (kg/s)} = \rho.SC= \frac{\rho_\text{c}\left(\frac{\text{kg}}{\text{m}^3}\right).\text{SC}(\frac{\text{litre}}{\text{min}})}{60\times1000}=\text{........kg/s}$$

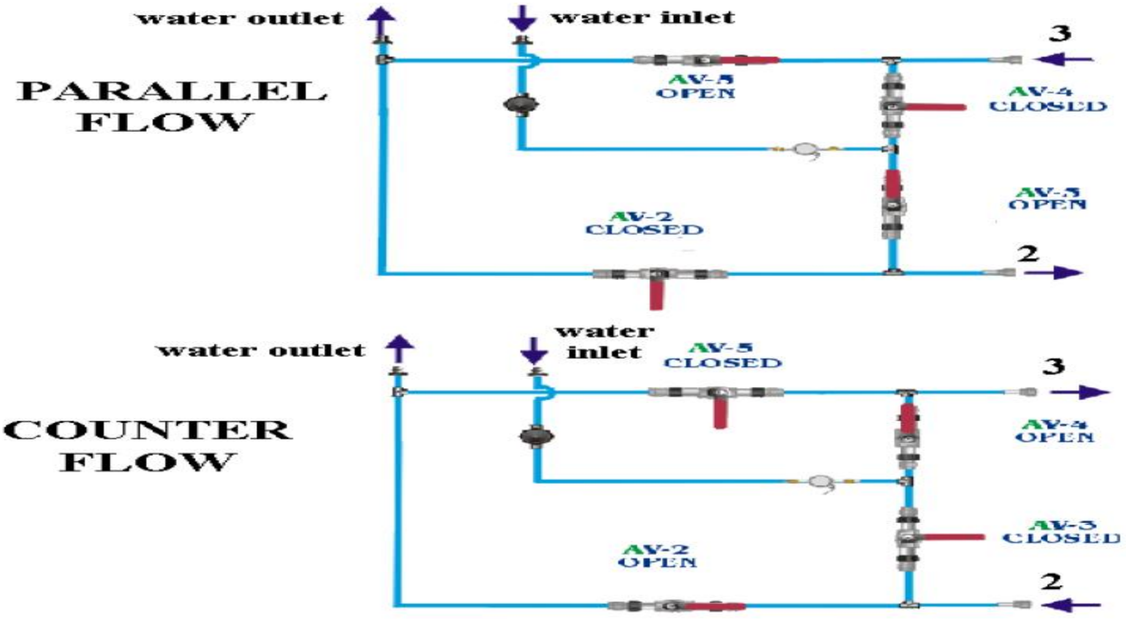


Figure 11.1: Schematic Diagram of Experiment

COUNTERCURRENT FLOW	
AV-2 Valve	CLOSED
AV-3 Valve	OPEN
AV-4 Valve	OPEN
AV-5 Valve	CLOSED
PARRALLEL FLOW	
AV-2 Valve	OPEN
AV-3 Valve	CLOSED
AV-4 Valve	CLOSED
AV-5 Valve	OPEN

Table 11.1: Valve positions of shell and tube heat exchanger

11.5 Theory

11.5.1 Heat transference in heat exchangers

A heat exchanger is a device developed by humans for the heat transference between two fluids at different temperatures separated by a solid wall. They have many engineering applications and, as a consequence, there are many models adapted to each application. The simplest one is the one built with two concentric tubes, where fluids can move in the same sense or in the opposite one. In parallel flow, the hot and the cold water go in and out through the same end. In crosscurrent flow, the fluids go in and out through opposite ends and they circulate in opposite senses.

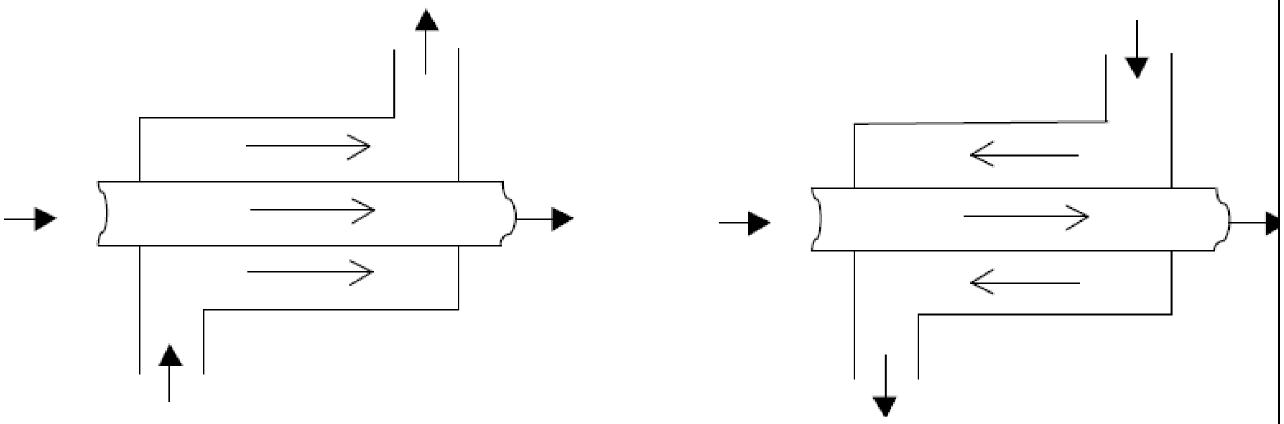


Figure 11.2: Parallel and counter parallel flow

11.5.2 Shell and tube heat exchanger

A shell and tube heat exchanger is a class of heat exchanger designs. It is the most common type of heat exchanger in oil refineries and other large chemical processes, and is suited for higher-pressure applications. As its name implies, this type of heat exchanger consists of a shell (a large pressure vessel) with a bundle of tubes inside it. One fluid runs through the tubes, and another fluid flows over the tubes (through the shell) to transfer heat between the two fluids. The set of tubes is called a tube bundle, and may be composed of several types of tubes: plain, longitudinally finned, etc.

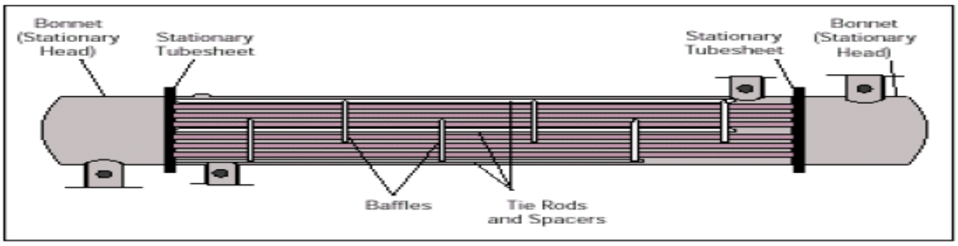


Figure 11.3: Shell and tube heat exchanger

11.5.3 Overall Heat-Transfer Coefficient

The overall heat-transfer coefficient U is defined by the relation

$q=UA\Delta T_{overall}$ Overall heat transfer coefficient

Although final heat-exchanger designs will be made on the basis of careful calculations of U, it is helpful to have a tabulation of values of the overall heat-transfer coefficient for various situations that may be encountered in practice

11.5.4 The Log Mean Temperature Difference (LMTD)

Being $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ in parallel flow

$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ in countercurrent flow.

$$T_{lm}=\frac{(\Delta T1)-(\Delta T2)}{\ln[\frac{\Delta T1}{\Delta T2}]}$$

11.5.5 Effectiveness-Ntu Method

$$\text{Effectiveness}= \frac{\text{Actual heat transfer}}{\text{Maximum possible heat transfer}}$$

11.5.6 Capacity coefficient

Capacity coefficient will be defined as (CR)

$$C_r=\frac{C_{min}}{C_{max}}=\ldots\ldots\ldots \frac{\text{w/k}}{\text{w/k}}$$

Mass flow rate multiplied by specific heat) C_h and C_c for the hot and cold fluids respectively, and denoting the smaller one as C_{min}

11.5.7 Reynolds number

In fluid mechanics, the Reynolds number (Re) is a dimensionless quantity that is used to help predict similar flow patterns in different fluid flow situations. The Reynolds number is defined as the ratio of momentum forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. They are also used to characterize different flow regimes within a similar fluid, such as laminar or turbulent flow

3) Laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion;
4) Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic eddies, vortices and other flow instabilities.

11.6 Objective 01

To study the Global energy balance in the Shell and tube exchanger and heat losses.

11.6.1 Procedure:

1. Check that the valves are opened and that we have parallel flow configuration.
2. Check that the heating tank is full of water, above the level switch.
5) Switch on the pump and the resistor (equipment supply).
6) Set the tank temperature at 45 ºC (ST16).
7) .Fix the hot water flow in about 3 l/min (SC1) and adjust cold water flow until reaching stationary operating conditions keeping the temperature set in the tank constant.
8) Write down temperature and flow measurements on the experimental sheet.
9) Repeat steps 5 and 6 for different water temperatures in the tank: 50ºC, 55ºC and 60 ºC.
10) Once the measurements may have been taken, you may calculate the heat transferred by the hot water, the heat absorbed by the cool water, heat losses, the logarithmic mean temperature and the global heat transfer coefficient

11.6.2 Observations

	TEST 1	TEST 2	TEST 3	TEST 4
ST_{16}	45	50	55	60
ST_1 (°C)				
ST_2 (°C)				
ST_3 (°C)				
ST_4 (°C)				
ST_5 (°C)				
ST_6 (°C)				
ST_7 (°C)				
SC1 (l/min)	3	3	3	3
SC2 (l/min)				

Table 11.2: Temperatures at shell and tube heat exchanger

11.6.3 Calculated Data

	TEST 1	TEST 2	TEST 3	TEST 4
q_h (w)				
q_c (w)				
q_l (w)				
ΔT_{lm} (K)				
U (w/m^2k)				

Table11.3: Heat transfer coefficient of shell and tube heat exchanger

11.6.4 Specimen Calculations

11.6.4.1 Heat transferred by hot water (q_h)

$$q_h = m_h Cp_h (T_{h,i} - T_{h,o})$$

11.6.4.2 Heat absorbed by the cold water (q_c)

$$q_c = m_c Cp_c (T_{c,o} - T_{c,i})$$

Where m_h and m_c are the mass expenses, and Cp_h and Cp_c are the specific heats of the hot and cold fluids

<u>Note:</u> Theoretically q_h should equal q_c but due to environmental energy losses and to instrumental and observation measurement errors, they are not always equal

11.6.4.3 Heat losses (q_l)

$$q_l = q_h - q_c$$

11.6.4.4 Logarithmic average temperatures difference between hot and cold water (ΔT_{lm})

Being $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ in parallel flo

$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ in countercurrent flow.

$$T_{lm} = \frac{(\Delta T1) - (\Delta T2)}{\ln[\frac{\Delta T1}{\Delta T2}]}$$

11.6.4.5 Global heat transfer coefficient (U)

$$q = U A \Delta T_{lm}$$

Global Heat Transfer Coefficient multiplied by the Transfer Area will be

$$U.A = \frac{Q_h}{\Delta T_{lm}}$$

<u>Note:</u> U can be calculated obtaining an average value of the heat transfer area: A_m= 0.00192

11.7 Objective:02

Determination of the heat exchanger effectiveness by NTU method.

11.7.1 Procedure

1. Check that the valves are opened and that we have countercurrent flow configuration.
2. Check that the heating tank is filled with water above the level switch.
3. Switch on the pump and the resistor (equipment supply).
4. Set the tank temperature in 60 ºC (ST16).
5. Fix the hot water flow in 3 l/min approx. (SC1) and adjust cold water flow to reach stationary operating conditions, keeping constant temperatures set for the tank.
6. Write down the temperature and flow measurements on the experimental sheet.
7. Set the valves appropriately in order to invert cold water flow direction to produce a parallel flow configuration.
8. Make sure that 60ºC temperatures are kept in the tank and that the same hot and cold water flows set in step 5 are also maintained.
9. Once the system is stabilized, write down the temperature measurements and flow values on the experimental sheet.
10. Once the measurements have been taken, calculate the experimental effectiveness, the theoretical effectiveness by the NTU method and the theoretical temperatures at the exchanger outlet.

11.7.2 Observations

	TEST 1	TEST 2
ST16	45	50
ST1 (°C)		
ST2 (°C)		
ST3 (°C)		
ST4 (°C)		
ST5 (°C)		
ST6 (°C)		
ST7 (°C)		
SC1 (l/min)	3	3
SC2 (l/min)		

Table 11.4: Temperatures for shell and tube heat exchanger

11.7.3 Calculated Data

	TEST 1 Crosscurrent Flow	TEST 2 Parallel flow
ϵ		
q_h (W)		
ΔT_{lm} (K)		
U.A (w/k)		
NTU		
C_R		
ϵ_{NTU}		
$T_{h,o}$ (°C)		
$T_{c,o}$ (°C)		

Table 11.5: Effectiveness of shell and tube heat exchanger

11.7.4 Specimen Calculations

11.7.4.1 Experimental effectiveness (ϵ)

The effectiveness is the quotient between the heat really exchanged and the maximum heat that could be transferred in an infinite area exchanger in a crosscurrent flow.

If $m_h Cp_h < m_c Cp_c \qquad \epsilon = \frac{(Th,i)-(Th,o)}{Th,i - Tc,o}$

$m_h Cp_h > m_c Cp_c \qquad \epsilon = \frac{(Tc,o)-(Tc,i)}{Th,i - Tc,i}$

11.7.4.2 Logarithmic average temperatures difference between hot and cold water (ΔT_{lm})

Being $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ in parallel flow

$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ in countercurrent flow.

$$T_{lm} = \frac{(\Delta T_1)-(\Delta T_2)}{\ln[\frac{\Delta T_1}{\Delta T_2}]}$$

11.7.4.3 Global heat transfer coefficient (U)

$$q = U\ A\ \Delta T_{lm}$$

Global Heat Transfer Coefficient multiplied by the Transfer Area will be

$$U.\ A = \frac{Q_h}{\Delta T_{lm}}$$

11.7.4.4 Number of transmission units

$$NTU = \frac{U.A}{(m.Cp)min}$$

11.7.4.5 Capacity coefficient

Capacity coefficient is determined by

$$C_r=\frac{\mathrm{mCp_{min}}}{\mathrm{mCp_{max}}}=\ldots\ldots\ldots\frac{\mathrm{w/k}}{\mathrm{w/k}}$$

Once the NTU and C_r are obtained, we can calculate the effectiveness, but depending if the flow is in crosscurrent or in parallel flow, we will have to use different expressions

11.7.4.6 Temperatures at the exchanger outlet

$$\epsilon_{NTU}=\frac{1-e^{-NTU.(1+C_R)}}{1+C_R} \qquad \text{For Parallel flow}$$

$$\epsilon_{NTU}=\frac{1-e^{-NTU.(1-C_R)}}{1-C_R\times\ e^{-NTU.(1-C_R)}} \qquad \text{For Crosscurrent flow}$$

From the experimental effectiveness (ε), previously calculated, the hot and the cold fluid temperatures at the exchanger outlet can be estimated

$$\left.\begin{aligned} T_{h,o} &= T_{h,i} - \varepsilon\,(T_{h,i} - T_{c,i}) \\ T_{c,o} &= T_{c,i} + CR\,(T_{h,i} - T_{h,o}) \end{aligned}\right\} \text{ if } \quad m_h \cdot Cp_h < m_c \cdot Cp_c$$

$$\left.\begin{aligned} T_{c,o} &= T_{c,i} + \varepsilon\,(T_{h,i} - T_{c,i}) \\ T_{h,o} &= T_{h,i} - CR\,(T_{c,o} - T_{c,i}) \end{aligned}\right\} \text{ if } \quad m_c \cdot Cp_c < m_h \cdot Cp_h$$

11.8 Objective:03

To calculate the Reynolds number and study the Influence of the flow in heat transfer**.**

11.8.1 Procedure:

1. Verify that valves may be opened and counter flow configuration has been set.
2. Verify that the heating tank is filled with water over the level switch.
3. Switch on the pump and the resistor (equipment supply).
4. Set the tank temperature at 60 ºC (ST16).
5. Fix the hot water flow in 3 l/min approx. (SC1) and adjust the cold water flow until reaching stationary operation conditions are met maintaining the temperature set for the tank constant
6. Write down temperature and flow measurement on the experimental sheet.
7. Reduce the hot water flow to 2.5 l/min approx. keeping the cold water flow constant.
8. Once the system is stable, write down temperature and flow measures on the experiment sheet.
9. Repeat steps 7 and 8 for 2 l/min and 1.5 l/min hot water flow rate.
10. Calculate the heat transferred by the fluid, the heat gained by the cold fluid and determine the losses. Determine the logarithmic temperature mean difference, the global heat transfer coefficient and the Reynolds number

11.8.2 Observations

	TEST 1	TEST 2
ST16	45	50
ST1 (°C)		
ST2 (°C)		
ST3 (°C)		
ST4 (°C)		
ST5 (°C)		
ST6 (°C)		
ST7 (°C)		
SC1 (l/min)	3	3
SC2 (l/min)		

Table 11.6: Temperature for measuring different parameter

11.8.3 Calculations

Considering the measurements above, you should calculate the following thermodynamic variables:

	TEST 1	TEST 2	TEST 3	TEST 4
q_{h} (w)				
q_{c} (w)				
q_{l} (w)				
ΔT_{lm} (K)				
U (w/m^{2}k)				
u_h (m/s)				
u_c (m/s)				
Re_{Dh}				
Re_{Dc}				

Table 11.7: Rynold number in shell and tube heat exchanger

11.8.4 Specimen Calculations

11.8.4.1 Hot and cold water velocity in the exchanger

The procedure is same for the calculation of LMDT and heat transfer coefficient as given in objective one and two, further calculations are given below.

From the average flow measured during the experiment, we can calculate easily the velocity

$$u\ (\mathrm{m/s}) = \frac{Q\ (\mathrm{l/min})}{A(\mathrm{m}^2).60.10^3}$$

For a Shell and Tube exchanger of length L, in which the hot fluid flows through the internal tube and the cold fluid flows through the space between the internal and external tubes the exchange surfaces will be

$$A_h = \pi\, D_{int}\, L \text{ and}$$
$$A_c = \pi\, D_{ext}\, L$$

Where D_{int} is the internal diameter and D_{ext} is the external diameter. This way, the velocities are, for the hot water

$$u_h\ (\mathrm{m/s}) = \frac{Q_{(\mathrm{l/min})}}{A_{hot}(\mathrm{m}^2).60.10^3} = \ldots\ldots \mathrm{m/s}$$

For the cold water

$$u_c\ (\mathrm{m/s}) = \frac{Q_{(\mathrm{l/min})}}{A_{cold}(\mathrm{m}^2).60.10^3} = \ldots\ldots \mathrm{m/s}$$

11.8.4.2 Reynolds number

Reynolds number is an a dimensional parameter that relates the inertial forces with the viscosity forces in a fluid. For internal flows, its expression is

$$Re_D = \frac{\rho, u.D}{\mu}$$

Being

ρ= fluid density (kg/m3)

u =average velocity of the fluid at the transversal section of the tube (m/s)

D = internal diameter of the fluid (m)

μ= dynamic viscosity of the fluid (kg/m·s)

11.9 STATISTICAL ANALYSIS

For overall heat transfer coefficient "U"

1) $x_{avg} = \frac{x_1+x_2+x_3}{n}$
2) $S_x = \sqrt{\frac{1}{n-1}((x_1 - x_{avg})^2 + (x_2 - x_{avg})^2 + (x_3 - x_{avg})^2)}$

11.10 Conclusion

11.11 Questions

1) What is the difference between the temperature distribution for parallel and crosscurrent flow in shell and tube heat exchanger
2) What is Global heat transference coefficient
3) What is Logarithmic temperatures mean difference
4) What is difference of shell and tube heat exchanger from other heat exchangers

11.12 Comments

12. LAB SESSION 12

To demonstrate the working principle of Plate heat exchanger operating under parallel & counter flow condition

12.1 Learning Objective

1) To study the Global energy balance in the Plate heat exchanger and heat losses
2) Determination of the heat exchanger effectiveness by NTU method
3) To calculate the Reynolds number and study the Influence of the flow in heat transfer.

12.2 Apparatus

EDIBON’s TIPL Plate Heat Exchanger **(**Serial No= TIPL 0047/11)

12.3 Main Parts

IDENTIFICATION	DESCRIPTION
ST-16	Water Tank Temperature Sensor
ST-1	Hot Water Temperature Sensor at the inlet of the exchanger
ST-2	Hot Water Temperature sensor at the inlet of the exchanger
ST-3	Cold Water Temperature sensor at the inlet/outlet of the exchanger
ST-4	Hot Water Temperature sensor at the outlet of the exchanger
SC-1	Hot water flow sensor
SC-2	Cold water flow sensor
AVR-1	Hot water flow regulation valve.
AVR-2	Cold water flow regulation valve
AN-1	Water level switch of the tank
AR-1	Electric resistance
AB-1	Hot Water Flow Centrifugal Pump
AV-2,AV-3, AV-4 Y AV-5	Ball valves of the cold water circuit for setting parallel or counter current flow
AV-1,AV-6, AV-7 and AV-8	Ball valves for draining the pipes

12.4 Useful Data

12.4.1 BASE UNIT

Net weight: 30 kg.
Height: 400 mm
Width: 1000 mm
Depth: 500 mm

12.4.2 Heat Exchanger

Net weight: 20 kg.
Height: 300 mm
Width: 1000 mm
Depth: 500 mm
Maximum Flow 12m^3/h
Max. Work Pressure 10bar
Max. Work Temperature 100ºC

Minimum. Work Temperature 0ºC
Maximum number of plates 10
Internal Circuit Capacity 0.176 liters
External Circuit Capacity 0.22 liters
Surface 0.32m^2

Pressures drop 1.4 m.c.a.

12.4.3 Physical Properties of The Hot And Cold Water

To determine their physical properties, the average temperature of each fluid has to be calculated.

$$\text{Hot water average temperature: } Tm_h = \frac{T_{hi}+T_{ho}}{2}$$

$$\text{Cold Water Average Temperature: } Tm_C = \frac{T_{ci}+T_{co}}{2}$$

From the table of the appendix A, the physical properties based on the average temperature can be obtained

	ρ	Cp=Specific heat(J/kgK)	μ= Dynamic viscosity (kg/ms)
Hot water at Tm_h °C	ρ_h=	Cp_h	μ_h
Cold water at Tm_c °C	ρ_c=	Cp_h	μ_c

12.4.4 Mass Flow Rates

The mass flows of both fluids, are going to be obtained from the measurements taken in the flow sensors (SC1 for hot water and SC2 for cold water)

$$m\ (\text{kg/s}) = \rho.SC = \frac{\rho\left(\frac{\text{kg}}{\text{m}^3}\right).SC(\frac{\text{l}}{\text{min}})}{60\times1000}$$

$$\text{Mass flow for hot water} = m_h\ (\text{kg/s}) = \rho.SC = \frac{\rho_h\left(\frac{\text{kg}}{\text{m}^3}\right).SC(\frac{\text{litre}}{\text{min}})}{60\times1000} = \text{........kg/s}$$

$$\text{Mass flow for cold water} = m_c\ (\text{kg/s}) = \rho.SC = \frac{\rho_c\left(\frac{\text{kg}}{\text{m}^3}\right).SC(\frac{\text{litre}}{\text{min}})}{60\times1000} = \text{........kg/s}$$

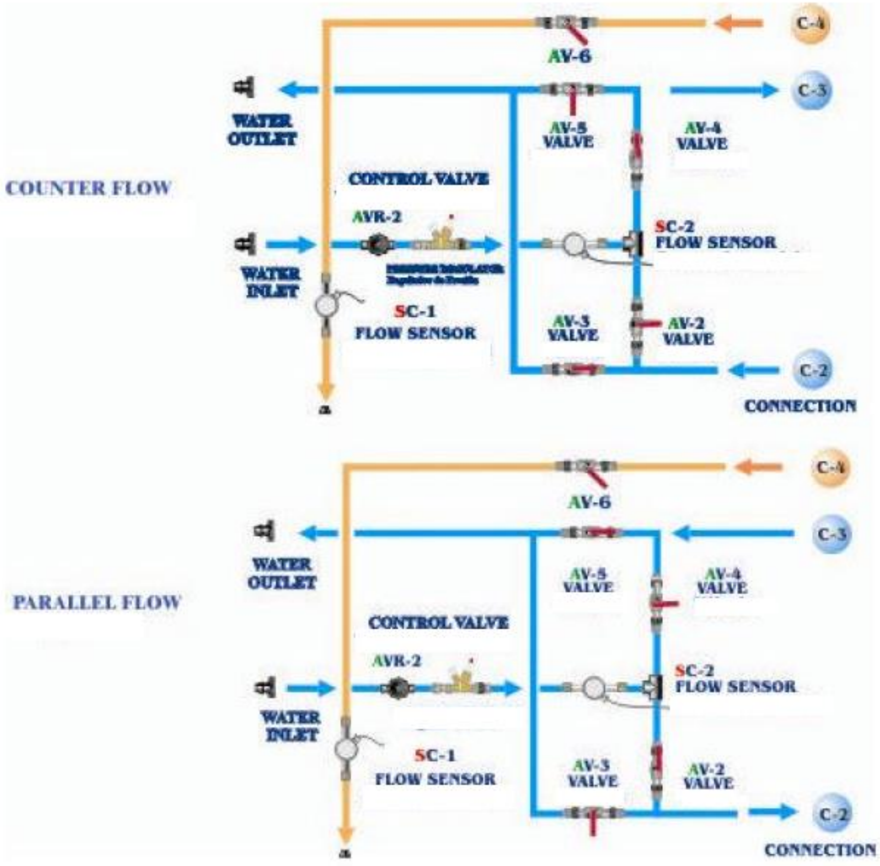


Figure 12.1: Schematic Diagram of Experiment

COUNTERCURRENT FLOW	
AV-2 Valve	CLOSED
AV-3 Valve	OPEN
AV-4 Valve	OPEN
AV-5 Valve	CLOSED
PARRALLEL FLOW	
AV-2 Valve	OPEN
AV-3 Valve	CLOSED
AV-4 Valve	CLOSED
AV-5 Valve	OPEN

Table 12.1: Position of valves in plate heat exchanger

12.5 Theory

12.5.1 Heat transference in heat exchangers

A heat exchanger is a device developed by humans for the heat transference between two fluids at different temperatures separated by a solid wall. They have many engineering applications and, as a consequence, there are many models adapted to each application. The simplest one is the one built with two concentric tubes, where fluids can move in the same sense or in the opposite one. In parallel flow, the hot and the cold water go in and out through the same end. In crosscurrent flow, the fluids go in and out through opposite ends and they circulate in opposite senses.

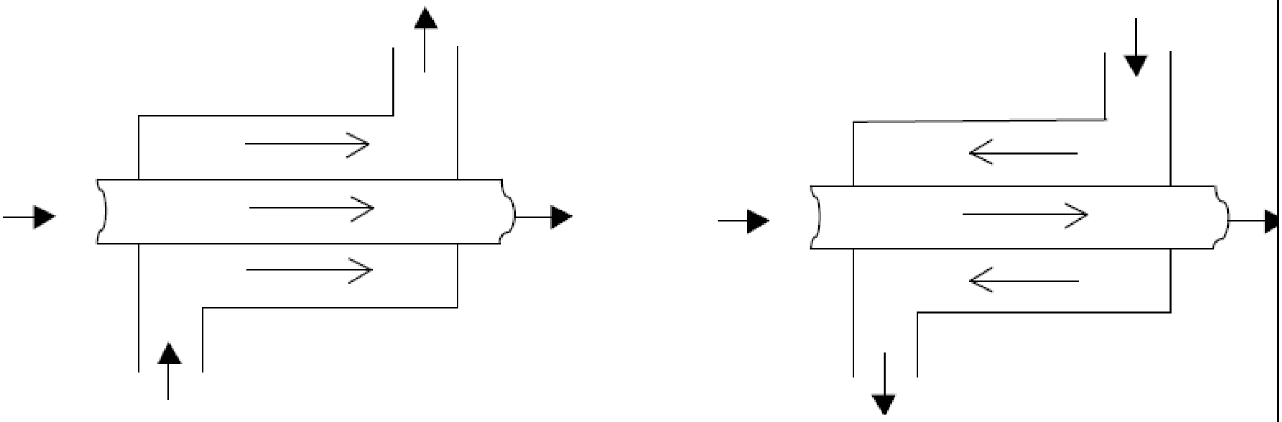


Figure 12.2: Parallel and counter parallel flow

12.5.2 Plate heat exchanger

Plate heat exchanger is a type of heat exchanger that uses metal plates to transfer heat between two fluids. This has a major advantage over a conventional heat exchanger in that the fluids are exposed to a much larger surface area because the fluids spread out over the plates. This facilitates the transfer of heat, and greatly increases the speed of the temperature change. Plate heat exchangers are now common and very small brazed versions are used in the hot-water sections of millions of combination boilers. The high heat transfer efficiency for such a small physical size has increased the domestic hot water (DHW) flow rate of combination boilers. The small plate heat exchanger has made a great impact in domestic heating and hot-water. Larger commercial versions use gaskets between the plates, whereas smaller versions tend to be brazed.

12.5.3 Overall Heat-Transfer Coefficient

The overall heat-transfer coefficient U is defined by the relation

$$q=UA\Delta T_{overall} \qquad \text{Overall heat transfer coefficient}$$

Although final heat-exchanger designs will be made on the basis of careful calculations of U, it is helpful to have a tabulation of values of the overall heat-transfer coefficient for various situations that may be encountered in practice

12.5.4 The Log Mean Temperature Difference (LMTD)

Being $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ in parallel flow

$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ in countercurrent flow.

$$T_{lm}=\frac{(\Delta T1)-(\Delta T2)}{\ln[\frac{\Delta T1}{\Delta T2}]}$$ The Log Mean Temperature Difference

12.5.5 Effectiveness-Ntu Method

$$\text{Effectiveness}=\frac{\text{Actual heat transfer}}{\text{Maximum possible heat transfer}}$$

12.5.6 Capacity coefficient

Capacity coefficient will be defined as (C_r)

$$C_r=\frac{C_{min}}{C_{max}}=\ldots\ldots\ldots\frac{\text{w/k}}{\text{w/k}}$$

Mass flow rate multiplied by (specific heat) C_h and C_c for the hot and cold fluids respectively, and denoting the smaller one as C_{min}

12.5.7 Reynolds number

In fluid mechanics, the Reynolds number (Re) is a dimensionless quantity that is used to help predict similar flow patterns in different fluid flow situations. The Reynolds number is defined as the ratio of momentum forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. They are also used to characterize different flow regimes within a similar fluid, such as laminar or turbulent flow

1) Laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion;
2) Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic eddies, vortices and other flow instabilities.

12.6 Objective 01

To study the Global energy balance in the Plate heat exchanger and heat losses

12.6.1 Procedure

1. Verify that valves are opened and that parallel flow configuration has been set.
2. Verify that the heating tank is filled with water over the level switch.
3. Turn on the pump and the resistance (the equipment power supply).
4. Set the tank temperature in 50ºC (ST16).
5. Set the hot water flow in 3 l/min approx. (SC1) and adjust the cold water flow so stationary operating conditions may be reached keeping the temperature in the tank constant
6. Write down temperature and flow measurements on the experimental sheet.
7. Repeat steps 5 and 6 for different temperatures of the water tank: 55ºC, 60ºC and 65ºC.
8. Once the measurements have been taken you may calculate the heat transferred by the hot water, the heat absorbed by the cold water, heat losses, the logarithmic average temperatures difference and the heat transfer global coefficient

12.6.2 Observations

	TEST 1	TEST 2	TEST 3	TEST 4
ST16	50	55	60	65
ST1 (°C)				
ST2 (°C)				
ST3 (°C)				
ST4 (°C)				
SC1 (l/min)	3	3	3	3
SC2 (l/min)				

TABLE 12.2: Temperatures of Plate Heat Exchangers

12.6.3 Calculated Data

	TEST 1	TEST 2	TEST 3	TEST 4
q_h (w)				
q_c (w)				
q_l (w)				
ΔT_{lm} (K)				
U (w/m^{2}k)				

Table12.3: Heat transfer in Plate heat exchanger

12.6.4 Specimen Calculations

12.6.4.1 Heat transferred by hot water (q_h)

$$q_h = m_h \, Cp_h \, (T_{h,i} - T_{h,o})$$

12.6.4.2 Heat absorbed by the cold water (q_c)

$$q_c = m_c \, Cp_c \, (T_{c,o} - T_{c,i})$$

Where m_h and m_c are the mass expenses, and Cp_h and Cp_c are the specific heats of the hot and cold fluids

Note: Theoretically q_h should equal q_c but due to environmental energy losses and to instrumental and observation measurement errors, they are not always equal

12.6.4.3 Heat losses (q_l)

$$q_l = q_h - q_c$$

12.6.4.4 Logarithmic average temperatures difference between hot and cold water (ΔT_{lm})

Being $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ in parallel flow
$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ in countercurrent flow.

$$T_{lm} = \frac{(\Delta T1) - (\Delta T2)}{\ln[\frac{\Delta T1}{\Delta T2}]}$$

12.6.4.5 Global heat transfer coefficient (U)

$$q = U \, A \, DT_{lm}$$

Global Heat Transfer Coefficient multiplied by the Transfer Area will be

$$U.\,A = \frac{Q_h}{\Delta T_{lm}}$$

Note: U can be calculated obtaining an average value of the heat transfer area: $A_m = 0.192$

12.7 Objective:02

Determination of the heat exchanger effectiveness by NTU method

12.7.1 Procedure

1. Verify that valves are opened and that parallel flow configuration has been set.
2. Verify that the heating tank is filled with water over the level switch.
3. Turn on the pump and the resistance (the equipment power supply).
4. Set the tank temperature in 65ºC (ST16).
5. Set the hot water flow in 3 l/min approx. (SC1) and adjust the cold water flow so stationary operating conditions may be reached keeping the temperature in the tank constant
6. Write down temperature and flow measurements on the experimental sheet.
7. Set the valves in order to change the direction of cold water flow to get a counter-current flow configuration
8. Verify that a temperature of 65ºC is maintained in the tank and that the same hot and cold water flows set previously in step 5 are circulating.
9. Once the system is stabilized write down the temperature and flow measurements on the experimental sheet.
10. Once the measurements have been taken you may calculate the experimental effectiveness, the theoretical effectiveness by the NTU method and the theoretical temperatures at the exchanger outlet.

12.7.2 Observations

	TEST 1	TEST 2
ST16	65	65
ST1 (°C)		
ST2 (°C)		
ST3 (°C)		
ST4 (°C)		
SC1 (l/min)	3	3
SC2 (l/min)		

Table 12.4: Temperatures for measuring parameters

12.7.3 Calculated Data

	TEST 1 Crosscurrent Flow	TEST 2 Parallel flow
ϵ		
q_h (W)		
ΔT_{lm} (K)		
U.A (w/k)		
NTU		
C_R		
ϵ_{NTU}		
$T_{h,o}$ (°C)		
$T_{c,o}$ (°C)		

Table 12.5: Effectiveness of plate heat exchanger

12.7.4 Specimen Calculations

12.7.4.1 Experimental effectiveness (ϵ)

The effectiveness is the quotient between the heat really exchanged and the maximum heat that could be transferred in an infinite area exchanger in a crosscurrent flow.

If $m_hCp_h<m_cCp_c$ $\quad \epsilon=\frac{(Th,i)-(Th,o)}{Th,i-Tc,o}$

$m_hCp_h >m_cCp_c$ $\quad \epsilon=\frac{(Tc,o)-(Tc,i)}{Th,i-Tc,i}$

12.7.4.2 Logarithmic average temperatures difference between hot and cold water (ΔT_{lm})

Being $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ in parallel flow
$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ in countercurrent flow.

$$T_{lm}=\frac{(\Delta T1)-(\Delta T2)}{\ln[\frac{\Delta T1}{\Delta T2}]}$$

12.7.4.3 Global heat transfer coefficient (U)

$$q = U\ A\ \Delta T_{lm}$$

Global Heat Transfer Coefficient multiplied by the Transfer Area will be

$$U.\ A=\frac{Q_h}{\Delta T_{lm}}$$

12.7.4.4 Number of transmission units

$$NTU=\frac{U.A}{(m.Cp)min}$$

Capacity coefficient is determined by

12.7.4.5 Capacity coefficient

$$Cr=\frac{(mCp)min}{(mCp)max}=\ldots\ldots\ldots\frac{w/k}{w/k}$$

Once the NTU and C_r are obtained, we can calculate the effectiveness, but depending if the flow is in crosscurrent or in parallel flow, we will have to use different expressions

12.7.4.6 Temperatures at the exchanger outlet

$$\epsilon_{NTU}=\frac{1-e^{-NTU.(1+C_R)}}{1+C_R} \qquad \text{For Parallel flow}$$

$$\epsilon_{NTU}=\frac{1-e^{-NTU.(1-C_R)}}{1-C_R\times\ e^{-NTU.(1-C_R)}} \qquad \text{For Crosscurrent flow}$$

From the experimental effectiveness (ε), previously calculated, the hot and the cold fluid temperatures at the exchanger outlet can be estimated

$$\left.\begin{array}{l} Th,o = Th,i - \varepsilon\ (\ Th,i - Tc,i\ ) \\ Tc,o = Tc,i + CR\ (\ Th,i - Th,o\ ) \end{array}\right\} \text{if} \qquad m_h\cdot C_{ph} < m_c\cdot C_{pc}$$

$$\left.\begin{array}{l} Tc,o = Tc,i + \varepsilon\ (\ Th,i - Tc,i\ ) \\ Th,o = Th,i - CR\ (\ Tc,o - Tc,i\ ) \end{array}\right\} \text{if} \qquad m_c\cdot C_{pc} < mh\cdot C_{ph}$$

12.8 Objective:03

To calculate the Reynolds number and study the Influence of the flow in heat transfer.

12.8.1 Procedure

1. Verify that valves are opened and a parallel fluid configuration has been set.
2. Verify that the heating tank is filled with water over the level switch.
3. Turn on the pump and the resistance (equipment power supply).
4. Fix the tank temperature in 65ºC (ST16).
5. Fix the hot water flow in about 3 l/min (SC1) and adjust the cold water flow until getting stationary operating conditions keeping the tank temperature constant.
6. Write down the temperature and flow measurements on the experimental sheet, keeping in mind that we may calculate the hot water average temperature.
7. Decrease the hot water flow to 2.5 l/min (approx.) keeping cold water flow constant. The same average temperature must be reached for hot water as well (so hot water physical properties may not vary through the practical exercise). In order to do so, the power of the tank resistance should be decreased and the average between temperatures T2 and T4 should be calculated $Tm_h=\frac{T_2+T_4}{2}$ until you reach a value as close to the former test value as possible.
8. Once the system is stabilized write down the flow and temperature measures on the experimental sheet.

9. Repeat steps 7 and 8 for 2 l/min and 1.5 l/min hot water flows.
10. You may calculate the heat transferred by the hot fluid, the heat gained by the cold fluid, and heat losses. Determine the logarithmic average temperatures difference and global heat transfer coefficient. Obtain the hot and cold flow rates and the Reynolds number.

12.8.2 Observations

	TEST 1	TEST 2	TEST 3	TEST 4
ST16	65			
ST1 (°C)				
ST2 (°C)				
ST3 (°C)				
ST4 (°C)				
$Tm_h=\frac{ST_2+ST_4}{2}$				
SC1 (l/min)	3	2.5	2	1.5
SC2 (l/min)				

Table12.6: Temperatures measurement for rynold number

12.8.3 Calculated Data

	TEST 1	TEST 2	TEST 3	TEST 4
$q_{h\ (w)}$				
$q_{c\ (w)}$				
$q_{l\ (w)}$				
ΔT_{lm} (K)				
U (w/m^{2}k)				
u_h (m/s)				
u_c (m/s)				
Re_{Dh}				
Re_{Dc}				

Table12.7: Rynold number in plate heat exchanger

12.8.4 Specimen Calculations

12.8.4.1 Heat transferred by hot water (q_h)

$$q_h = m_h Cp_h (T_{h,i} - T_{h,o})$$

12.8.4.2 Heat absorbed by the cold water (q_c)

$$q_c = m_c Cp_c (T_{c,o} - T_{c,i})$$

Where m_h and m_c are the mass expenses, and Cp_h and Cp_c are the specific heats of the hot and cold fluids

Note: Theoretically q_h should equal q_c but due to environmental energy losses and to instrumental and observation measurement errors, they are not always equal

12.8.4.3 Heat losses (q_l)

$$q_l = q_h - q_c$$

12.8.4.4 Logarithmic average temperatures difference between hot and cold water (ΔT_{lm})

Being $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ in parallel flow

$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ in countercurrent flow.

$$T_{lm} = \frac{(\Delta T1) - (\Delta T2)}{\ln[\frac{\Delta T1}{\Delta T2}]}$$

12.8.4.5 Global heat transfer coefficient (U)

$$q = U\ A\ \Delta T_{lm}$$

Global Heat Transfer Coefficient multiplied by the Transfer Area will be

$$U.\ A = \frac{Q_h}{\Delta T_{lm}}$$

Note: U can be calculated obtaining an average value of the heat transfer area: $A_m = 0.192$

12.8.4.6 Hot and cold water velocity in the exchanger

Heat transfer area in this type of exchangers is:

$$A = N \times a = N \times L \times W$$

N = Number of Thermal Plates (Total Number of Plates excluding the 2 at both ends)
a = Plate Area
L = Plate Length (in the direction of the flow)
W = Plate Width

From the average flow measured during the experiment, we can calculate easily the velocity

$$u_h\ (_{m/s}) = \frac{Q_{(l/min)}}{A_{\text{hot}}(m^2).60.10^3}$$

For the cold water

$$u_c\,(\mathrm{m/s}) = \frac{Q_{(l/min)}}{A_{\mathrm{cold}}(m^2).60.10^3}$$

12.8.4.7 Reynolds number

We may start by defining the diameter equivalent for a Plate Heat Exchanger,

$$\mathrm{De} = \frac{4\ \mathrm{Volume}}{\mathrm{Perimeter}} = \frac{4\,.W.L.b}{2.W.L} = 2.\mathrm{b}$$

Where b is the separation between adjacent plates

Reynolds Number for the hot fluid (similarly for the cold fluid) may be defined as follows

$$\mathrm{Re_D} = \frac{\rho_h, u_h.D_e}{\mu_h} = \frac{m_h.D_e}{s.\mu_h} = \frac{m_h.2.b}{b.W.\mu_h} = \frac{2m_h}{W.\mu_h}$$

Where, S = b × W being is the transversal passage area of the fluid and mh is the dynamic viscosity based on the hot fluid average temperature.

12.9 Graph

Represent the temperature distribution in counter-current and parallel flow configurations. For that purpose represent hot and cold water temperature values in ºC (T) on the vertical axis; and the position along the exchanger in meters on the horizontal axis. You should consider the length of the exchanger to be 0.5m and that we have three measure points.

12.10 Statistical Analysis

For overall heat transfer coefficient “U”

1) $x_{avg} = \frac{x_1+x_2+x_3}{n}$
2) $S_x = \sqrt{\frac{1}{n-1}\left((x_1 - x_{avg})^2 + (x_2 - x_{avg})^2 + (x_3 - x_{avg})^2\right)}$

12.11 Conclusion

12.12 Questions

1) What is the difference between the temperature distribution for parallel and crosscurrent flow in Plate heat exchanger
2) What is Global heat transference coefficient
3) What is Logarithmic temperatures mean difference
4) What is difference of Plate heat exchanger from other heat exchangers

12.13 Comments

13. LAB SESSION 13

To demonstrate the working principle of jacketed and vessel heat exchanger operating under parallel & counter flow condition

13.1 Learning Objective

[i] To study the Global energy balance in the Jacketed and Vessel heat exchanger and heat losses.
[ii] Determination of the heat exchanger effectiveness by NTU method.

13.2 Apparatus

IDENTIFICATION	DESCRIPTION
ST-16	Temperature sensor of the water in the tank
ST-1	Temperature sensor of the hot water at the inlet of the exchanger
ST-2	Temperature sensor of the hot water at the outlet of the exchanger
ST-3	Temperature sensor of the cold water at the inlet of the exchanger
ST-4	Temperature sensor of the cold water at the interior of the vessel
ST-5	Temperature sensor of the cold water at the outlet of the exchanger
SC-1	Hot water flow sensor
SC-2	Cold water flow sensor
AVR-1	Hot water flow regulation valve.
AVR-2	Cold water flow regulation valve
AN-1	Water level switch of the tank
AR-1	Electric resistance
AB-1	Hot Water Flow Centrifugal Pump
AV-2,AV-3, AV-4 ,AV-5	Ball valves of the cold water circuit for setting parallel or counter current flow
AV-1, AV-6, AV-7 Y AV-8	Ball valves to drain the pipes
AV-9	Ball valve of the overflowing
AV-10	Ball valve for draining the vessel

13.3 Useful Data

13.3.1 Base Unit

Net weight: 30 kg.
Height: 400 mm
Width: 1000 mm
Depth: 500 mm

13.3.2 Heat Exchanger

Net weight: 20 kg.
Height: 500 mm

Width: 1000 mm
Depth: 500 mm

13.3.3 Physical Properties Of The Hot And Cold Water

To determine their physical properties, the average temperature of each fluid has to be calculated.

$$\text{Hot water average temperature: } Tm_h = \frac{T_{hi}+T_{ho}}{2}$$

$$\text{Cold Water Average Temperature: } Tm_c = \frac{T_{ci}+T_{co}}{2}$$

From the table of the appendix A, the physical properties based on the average temperature can be obtained

	ρ	Cp=Specific heat(J/kgK)	μ= Dynamic viscosity (kg/ms)
Hot water at Tm_h °C	ρ_h=	Cp_h	μ_h
Cold water at Tm_c °C	ρ_c=	Cp_h	μ_c

13.3.4 Mass Flow Rates

The mass flows of both fluids, are going to be obtained from the measurements taken in the flow sensors (SC1 for hot water and SC2 for cold water)

$$m\ (\text{kg/s}) = \rho.SC = \frac{\rho\left(\frac{\text{kg}}{\text{m}^3}\right).SC\left(\frac{\text{l}}{\text{min}}\right)}{60\times1000}$$

$$\text{Mass flow for hot water} = m_h\ (\text{kg/s}) = \rho.SC = \frac{\rho_h\left(\frac{\text{kg}}{\text{m}^3}\right).SC\left(\frac{\text{litre}}{\text{min}}\right)}{60\times1000} = \text{........kg/s}$$

$$\text{Mass flow for cold water} = m_c\ (\text{kg/s}) = \rho.SC = \frac{\rho_c\left(\frac{\text{kg}}{\text{m}^3}\right).SC\left(\frac{\text{litre}}{\text{min}}\right)}{60\times1000} = \text{........kg/s}$$

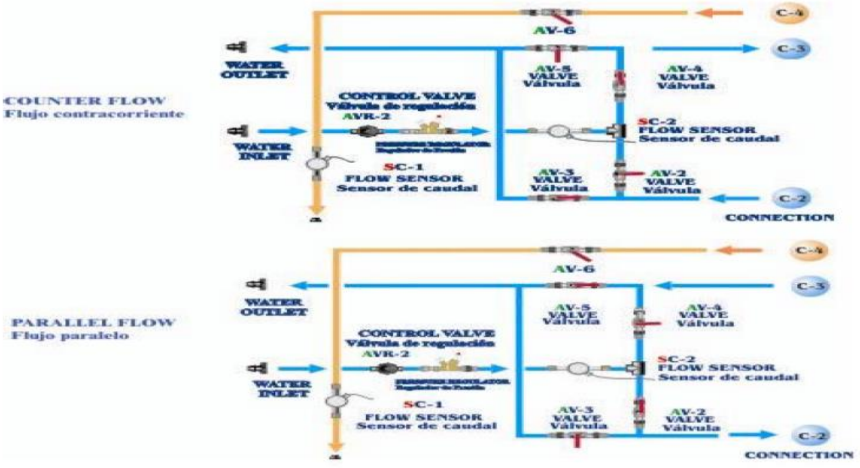


Figure 13.1: Schematic Diagram of Experiment

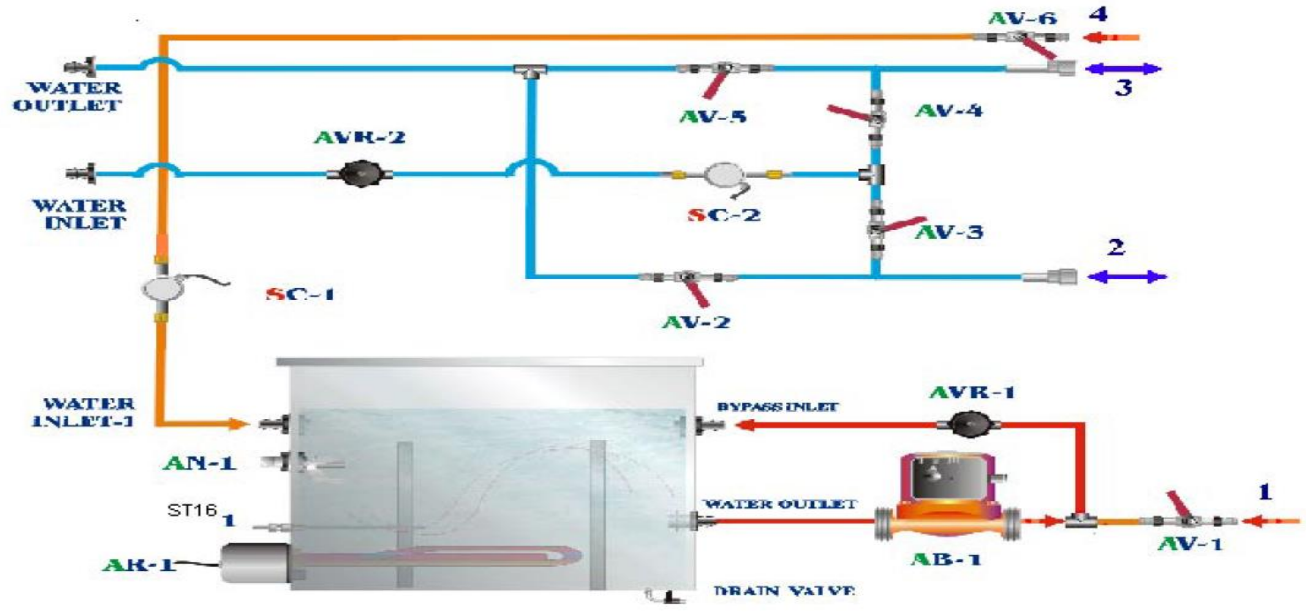


Figure 13.2: Diagram of the equipment base unit

Points numbered 1, 2, 3 and 4 represent the connections of the flexible tubes joining the exchanger to the base unit.

COUNTERCURRENT FLOW	
AV-2 Valve	CLOSED
AV-3 Valve	OPEN
AV-4 Valve	OPEN
AV-5 Valve	CLOSED
PARRALLEL FLOW	
AV-2 Valve	OPEN
AV-3 Valve	CLOSED
AV-4 Valve	CLOSED
AV-5 Valve	OPEN

Table 13.1: Position of valves in jacketed and vessel heat exchanger

13.4 Theory

13.4.1 Heat transference in heat exchangers

A heat exchanger is a device developed by humans for the heat transference between two fluids at different temperatures separated by a solid wall. They have many engineering applications and, as a consequence, there are many models adapted to each application. The simplest one is the one built with two concentric tubes, where fluids can move in the same sense or in the opposite one. In parallel flow, the hot and the cold water go in and out through the same end. In crosscurrent flow, the fluids go in and out through opposite ends and they circulate in opposite senses.

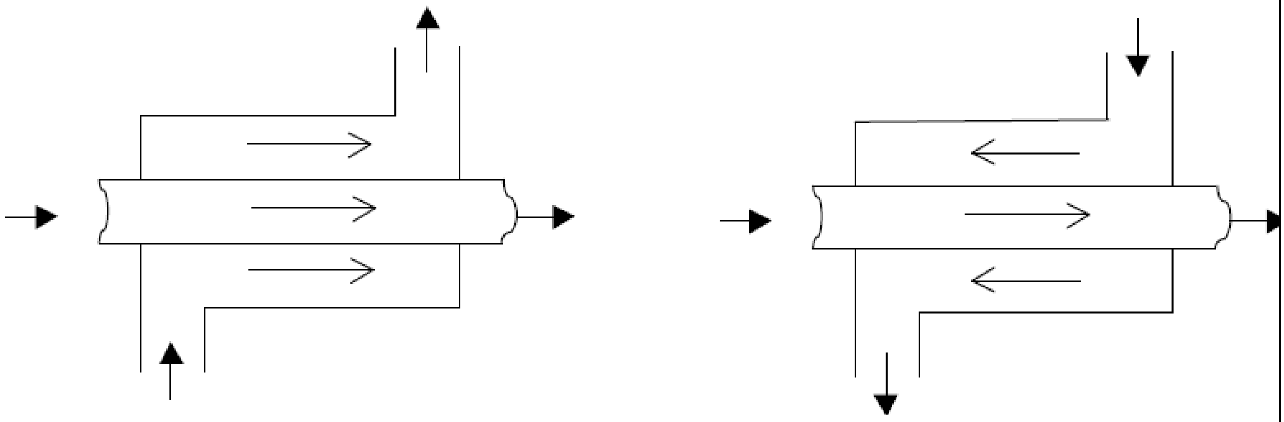


Figure 13.3: Parallel and counter parallel flow

13.4.2 Jacketed And Vessel Heat Exchanger

In chemical engineering, a jacketed vessel is a container that is designed for controlling the temperature of its contents, by using a cooling or heating "jacket" around the vessel through which a cooling or heating fluid is circulated. A jacket is a cavity external to the vessel that permits the uniform exchange of heat between the fluid circulating in it and the walls of the vessel.

13.4.3 Overall Heat-Transfer Coefficient

The overall heat-transfer coefficient U is defined by the relation

$$q=UA\Delta T_{overall}$$

Although final heat-exchanger designs will be made on the basis of careful calculations of U, it is helpful to have a tabulation of values of the overall heat-transfer coefficient for various situations that may be encountered in practice

13.4.4 The Log Mean Temperature Difference (LMTD)

Being $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ in parallel flow

$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ in countercurrent flow.

$$T_{lm}=\frac{(\Delta T1)-(\Delta T2)}{\ln[\frac{\Delta T1}{\Delta T2}]}$$

13.4.5 Effectiveness-Ntu Method

$$\text{Effectiveness}=\frac{\text{Actual heat transfer}}{\text{Maximum possible heat transfer}}$$

13.4.6 Capacity coefficient

Capacity coefficient will be defined as (CR)

$$C_r=\frac{C_{min}}{C_{max}}=\ldots\ldots\ldots\frac{w/k}{w/k}$$

Mass flow rate multiplied by specific heat) C_h and C_c for the hot and cold fluids respectively, and denoting the smaller one as C_{min}

13.4.7 Reynolds number

In fluid mechanics, the Reynolds number (Re) is a dimensionless quantity that is used to help predict similar flow patterns in different fluid flow situations. The Reynolds number is defined as the ratio of momentum forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. They are also used to characterize different flow regimes within a similar fluid, such as laminar or turbulent flow

1) Laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion;
2) Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic eddies, vortices and other flow instabilities.

13.5 Objective: 01

To study the Global energy balance in the Turbulent Flow exchanger and heat losses.

13.5.1 Procedure

1. Verify that valves are opened and that parallel flux configuration is been set.
2. Verify that the heating tank is filled with water over the level switch.
3. Verify that the AV9 valve is opened while the AV10 valve is closed.
4. Turn on the pump and the resistance (the equipment power supply).
5. Fix the tank temperature in 50 ºC (ST16).
6. Fix the hot water flow at about 3 l/min (SC1) and adjust the cold water flow so stationary operating conditions are reached keeping the temperature in the tank constant.
7. Start the stirrer.
8. Write down temperature and flow measurements on the experimental sheet.
9. Repeat steps 5 and 6 for different temperatures of the water tank: 45 ºC, 55ºC and 60 ºC.
10. Once the measures have been taken you may calculate the heat transferred by the hot water, the heat absorbed by the cold water, heat losses, the logarithmic average temperature differences and the global exchange heat coefficient.

13.5.2 Observations

	TEST 1	TEST 2	TEST 3	TEST 4
ST16	45	50	55	60
ST1 (°C)				
ST2 (°C)				
ST3 (°C)				
ST4 (°C)				
ST5 (°C)				
SC1 (l/min)	3	3	3	3
SC2 (l/min)				
Volume of the vessel (l)	5.5	5.5	5.5	5.5
Speed of Rotation (rpm)	Maximum	Maximum	Maximum	Maximum

Table 13.2: Measurement of temperatures in jacketed and vessel heat exchangers

13.5.3 Calculated Data

	TEST 1	TEST 2	TEST 3	TEST 4
q_h (w)				
q_c (w)				
q_l (w)				
ΔT_{lm} (K)				
U (w/m^{2}k)				

Table 13.3: Overall heat transfer coefficient jacketed and vessel heat exchangers

13.5.4 Specimen Calculation

13.5.4.1 Heat transferred by hot water (q_h)

$$q_h = m_h \, Cp_h \, (T_{h,i} - T_{h,o})$$

13.5.4.2 Heat absorbed by the cold water (q_c)

$$q_c = m_c\, Cp_c\, (T_{c,o} - T_{c,i})$$

Where m_h and m_c are the mass expenses, and Cp_h and Cp_c are the specific heats of the hot and cold fluids

Note: Theoretically q_h should equal q_c but due to environmental energy losses and to instrumental and observation measurement errors, they are not always equal

13.5.4.3 Heat losses (q_l)

$$q_{l} = q_{h} - q_{c}$$

13.5.4.4 Logarithmic average temperatures difference between hot and cold water (ΔT_{lm})

Being $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ in parallel flow
$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ in countercurrent flow.

$$T_{lm} = \frac{(\Delta T1) - (\Delta T2)}{\ln[\frac{\Delta T1}{\Delta T2}]}$$

13.5.4.5 Global heat transfer coefficient (U)

$$q = U\, A\, DT_{lm}$$

Global Heat Transfer Coefficient multiplied by the Transfer Area will be

$$U.\, A = \frac{Q_h}{\Delta T_{lm}}$$

Note: U can be calculated obtaining an average value of the heat transfer area: $A_m = 0.192$

13.6 Objective:02

Determination of the exchanger effectiveness. NTU method

13.6.1 Procedure

1. Verify that valves may be opened and parallel flow configuration has been set.
2. Verify that the heating tank is filled with water over the level switch.
3. Verify that the AV9 valve is opened and that AV10 valve is closed.
4. Turn on the pump and the resistance (equipment power supply).
5. Fix tank temperature at 60 ºC (ST16).
6. Start the stirrer.
7. Fix the hot water flow to about 3 l/min (SC1) and adjust the cold water flow at 1l/min.
8. Write down temperature and flow measurements on the experimental sheet.
9. Set the cold water at 2l/min (SC1).
10. Verify that 60ºC temperatures are kept in the tank and that the same hot and cold water flows set previously in step 5 are circulating.
11. Once the system is stabilized write down the temperature and flow measures on the experimental sheet.

12. Once the measures have been taken you may calculate the experimental effectiveness, theoretical effectiveness by the NTU method and the theoretical temperatures at the exchanger outlet.

13.6.2 Observations

	TEST 1	TEST 2
ST16	50	50
ST1 (°C)		
ST2 (°C)		
ST3 (°C)		
ST4 (°C)		
ST5 (°C)		
SC1 (l/min)	3	2
SC2 (l/min)		
Volume of the vessel (l)	5.5	5.5
Speed of Rotation (rpm)	Maximum	Maximum

Table 13.4: Measurement of temperatures for different properties in jacketed and vessel heat exchangers

13.6.3 Calculated Data

	TEST 1 Crosscurrent Flow	TEST 2 Parallel flow
ϵ		
q_h (W)		
ΔT_{lm} (K)		
U.A (w/k)		
NTU		
C_R		
ϵ_{NTU}		
$T_{h,\circ}$ (°C)		
$T_{c,o}$ (°C)		

Table 13.5: Effectiveness of jacketed and vessel heat exchangers

13.6.4 Specimen Calculations

13.6.4.1 Experimental effectiveness (ϵ)

The effectiveness is the quotient between the heat really exchanged and the maximum heat that could be transferred in an infinite area exchanger in a crosscurrent flow.

If $m_h Cp_h < m_c Cp_c$ $\quad \epsilon = \frac{(Th,i)-(Th,o)}{Th,i-Tc,o}$

$m_h Cp_h > m_c Cp_c$ $\quad \epsilon = \frac{(Tc,o)-(Tc,i)}{Th,i-Tc,i}$

13.6.4.2 Logarithmic average temperatures difference between hot and cold water (ΔT_{lm})

Being $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ in parallel flow
$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ in countercurrent flow.

$$T_{lm} = \frac{(\Delta T1)-(\Delta T2)}{\ln[\frac{\Delta T1}{\Delta T2}]}$$

13.6.4.3 Global heat transfer coefficient (U)

$$q = U\ A\ \Delta T_{lm}$$

Global Heat Transfer Coefficient multiplied by the Transfer Area will be

$$U.\ A = \frac{Q_h}{\Delta T_{lm}}$$

13.6.4.4 Number of transmission units

$$NTU = \frac{U.A}{(m.Cp)min}$$

Capacity coefficient is determined by

13.6.4.5 Capacity coefficient

$$Cr = \frac{(mCp)min}{(mCp)max} = \ldots\ldots\ldots \frac{w/k}{w/k}$$

Once the NTU and C_r are obtained, we can calculate the effectiveness, but depending if the flow is in crosscurrent or in parallel flow, we will have to use different expressions

$$\epsilon_{NTU} = \frac{1-e^{-NTU.(1+C_R)}}{1+C_R}$$ For Parallel flow

$$\epsilon_{NTU} = \frac{1-e^{-NTU.(1-C_R)}}{1-C_R \times e^{-NTU.(1-C_R)}}$$ For Crosscurrent flow

13.6.4.6 Temperatures at the exchanger outlet

From the experimental effectiveness (ε), previously calculated, the hot and the cold fluid temperatures at the exchanger outlet can be estimated

$$\left.\begin{aligned} Th,o &= Th,i - \varepsilon\,(Th,i - Tc,i) \\ Tc,o &= Tc,i + CR\,(Th,i - Th,o) \end{aligned}\right\}\quad \text{if} \qquad mh\cdot Cph < mc\cdot Cpc$$

$$\left.\begin{aligned} Tc,o &= Tc,i + \varepsilon\,(Th,i - Tc,i) \\ Th,o &= Th,i - CR\,(Tc,o - Tc,i) \end{aligned}\right\}\quad \text{if} \qquad mc\cdot Cpc < mh\cdot Cph$$

13.7 Conclusion

13.8 Statistical Analysis

For overall heat transfer coefficient “U”

1) $x_{avg} = \frac{x_1 + x_2 + x_3}{n}$
2) $S_x = \sqrt{\frac{1}{n-1}\left((x_1 - x_{avg})^2 + (x_2 - x_{avg})^2 + (x_3 - x_{avg})^2\right)}$

13.9 Graph

Represent temperatures distribution. For that purpose you may represent on y- axis the values for hot and cold water temperatures in ºC (T); and the position along the exchanger in meters on the x-axis. You may consider that the exchanger length is roughly the same as the jacket perimeter and that we may have two points of measure as well:

Cold water: ST2 at x=0, ST6 at x= L
Hot water: ST3 at x=0, ST5 at x=

13.10 Questions

1) What is the difference between the temperature distribution for parallel and crosscurrent flow in jacketed and vessel heat exchanger
2) What is Global heat transference coefficient
3) What is Logarithmic temperatures mean difference
4) What is difference of jacketed and vessel heat exchanger from other heat exchangers
5) What is reynold number
6) What is Nusset number

13.11 Comments

Table of water Properties

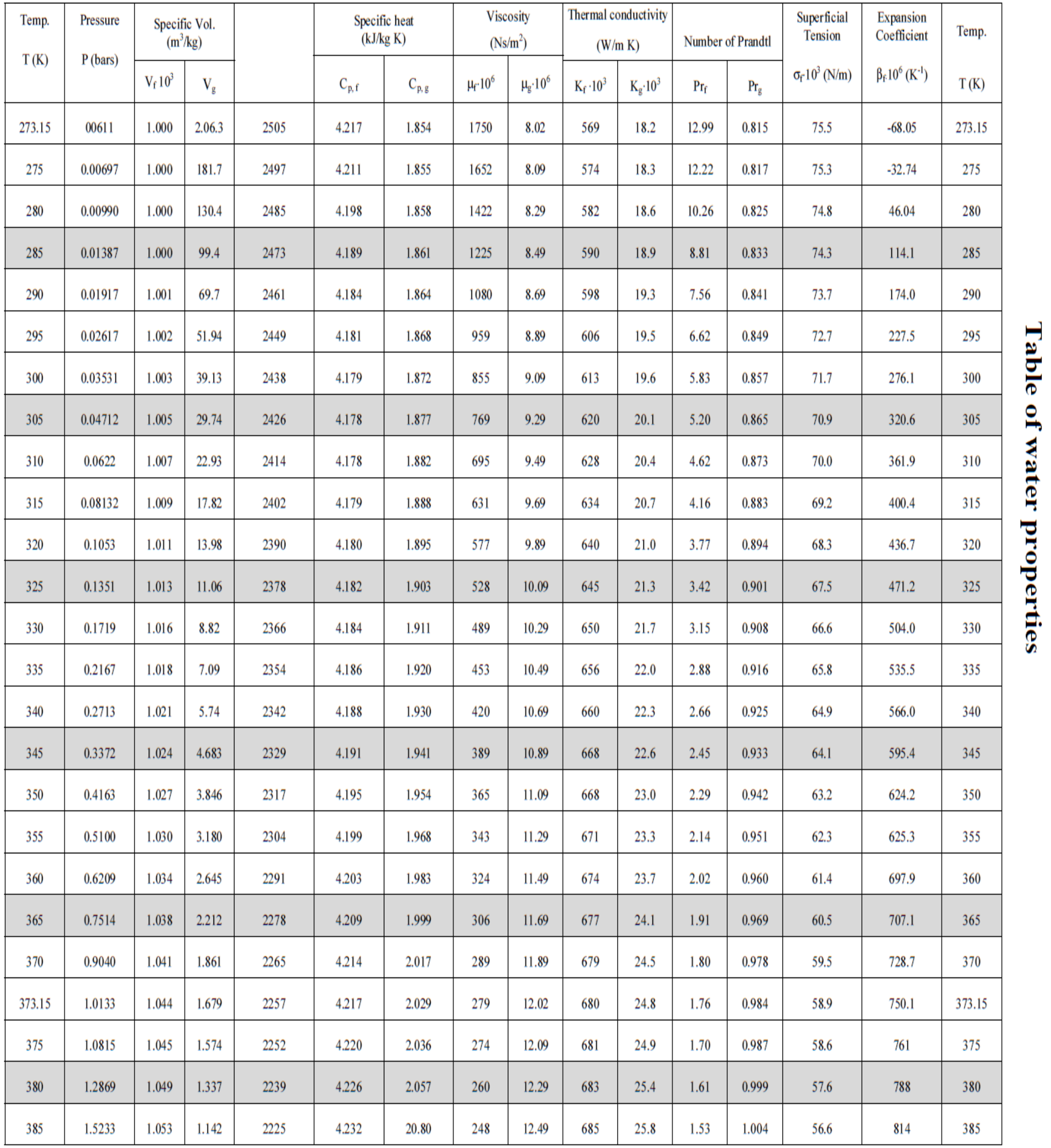


Table of water properties

Temp. T (K)	Pressure P (bars)	Specific Vol. (m^3/kg)			Specific heat (kJ/kg K)		Viscosity (Ns/m^2)		Thermal conductivity (W/m K)		Number of Prandtl		Superficial Tension	Expansion Coefficient	Temp.
		$V_f 10^3$	V_g		$C_{p,f}$	$C_{p,g}$	$\mu_f \cdot 10^6$	$\mu_g \cdot 10^6$	$K_f \cdot 10^3$	$K_g \cdot 10^3$	Pr_f	Pr_g	$\sigma_f 10^3$ (N/m)	$\beta_f 10^6$ (K^{-1})	T (K)
273.15	00611	1.000	2.06.3	2505	4.217	1.854	1750	8.02	569	18.2	12.99	0.815	75.5	-68.05	273.15
275	0.00697	1.000	181.7	2497	4.211	1.855	1652	8.09	574	18.3	12.22	0.817	75.3	-32.74	275
280	0.00990	1.000	130.4	2485	4.198	1.858	1422	8.29	582	18.6	10.26	0.825	74.8	46.04	280
285	0.01387	1.000	99.4	2473	4.189	1.861	1225	8.49	590	18.9	8.81	0.833	74.3	114.1	285
290	0.01917	1.001	69.7	2461	4.184	1.864	1080	8.69	598	19.3	7.56	0.841	73.7	174.0	290
295	0.02617	1.002	51.94	2449	4.181	1.868	959	8.89	606	19.5	6.62	0.849	72.7	227.5	295
300	0.03531	1.003	39.13	2438	4.179	1.872	855	9.09	613	19.6	5.83	0.857	71.7	276.1	300
305	0.04712	1.005	29.74	2426	4.178	1.877	769	9.29	620	20.1	5.20	0.865	70.9	320.6	305
310	0.0622	1.007	22.93	2414	4.178	1.882	695	9.49	628	20.4	4.62	0.873	70.0	361.9	310
315	0.08132	1.009	17.82	2402	4.179	1.888	631	9.69	634	20.7	4.16	0.883	69.2	400.4	315
320	0.1053	1.011	13.98	2390	4.180	1.895	577	9.89	640	21.0	3.77	0.894	68.3	436.7	320
325	0.1351	1.013	11.06	2378	4.182	1.903	528	10.09	645	21.3	3.42	0.901	67.5	471.2	325
330	0.1719	1.016	8.82	2366	4.184	1.911	489	10.29	650	21.7	3.15	0.908	66.6	504.0	330
335	0.2167	1.018	7.09	2354	4.186	1.920	453	10.49	656	22.0	2.88	0.916	65.8	535.5	335
340	0.2713	1.021	5.74	2342	4.188	1.930	420	10.69	660	22.3	2.66	0.925	64.9	566.0	340
345	0.3372	1.024	4.683	2329	4.191	1.941	389	10.89	668	22.6	2.45	0.933	64.1	595.4	345
350	0.4163	1.027	3.846	2317	4.195	1.954	365	11.09	668	23.0	2.29	0.942	63.2	624.2	350
355	0.5100	1.030	3.180	2304	4.199	1.968	343	11.29	671	23.3	2.14	0.951	62.3	625.3	355
360	0.6209	1.034	2.645	2291	4.203	1.983	324	11.49	674	23.7	2.02	0.960	61.4	697.9	360
365	0.7514	1.038	2.212	2278	4.209	1.999	306	11.69	677	24.1	1.91	0.969	60.5	707.1	365
370	0.9040	1.041	1.861	2265	4.214	2.017	289	11.89	679	24.5	1.80	0.978	59.5	728.7	370
373.15	1.0133	1.044	1.679	2257	4.217	2.029	279	12.02	680	24.8	1.76	0.984	58.9	750.1	373.15
375	1.0815	1.045	1.574	2252	4.220	2.036	274	12.09	681	24.9	1.70	0.987	58.6	761	375
380	1.2869	1.049	1.337	2239	4.226	2.057	260	12.29	683	25.4	1.61	0.999	57.6	788	380
385	1.5233	1.053	1.142	2225	4.232	20.80	248	12.49	685	25.8	1.53	1.004	56.6	814	385