NANYANG TECHNOLOGICAL UNIVERSITY

SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

E3.5/E3.1AE HEAT EXCHANGER

HEAT TRANSFER LAB

VENUE: N3-B2A-01

NAME OF STUDENT: ______________________________ LAB SUB-GROUP:______________

MATRIC NO:____ DATE: _____________________

NAME OF SUPERVISOR: ____

GRADE: _____________________________

NOTE: THIS TITLE PAGE SHOULD BE ATTACHED TO ALL REQUIRED MATERIAL FOR THIS EXPERIMENT BEFORE SUBMISSION.

E3.5/E3.1AE HEAT EXCHANGER

SUMMARY

I) Area of Study

Thermodynamics, Fluid Mechanics, Heat Transfer

Students are advised to read the relevant chapters on heat exchangers from any of the texts in the list of references at least two days <u>before</u> the start of their experiments.

II) Learning Objectives

By completing this project, students will be able to learn about

a. Theoretical Models, Principles and Concepts

Heat conduction and heat convection
Heat exchangers in parallel flow and counter flow

b. Experimental Techniques

Temperature and flow rate measurements

c. Instrumentation

Heat exchanger manufactured by P.A. Hilton Ltd, UK.

d. Data Analysis

Temperature readings
Flow rate readings
Data Conversion
Error analysis

E3.5/E3.1AE HEAT EXCHANGER

1 INTRODUCTION

In many applications it is necessary to transfer heat from a hot fluid to a cold fluid and a wide variety of "heat exchangers" have been developed for this purpose. Heat exchangers can be classified based on the relative directions of the flow of the hot and cold fluids: parallel flow (when both the fluids move in the same direction); counter flow (when the fluids move in parallel but in opposite direction); and cross flow (when the directions of flow are mutually perpendicular).

The parameters which affect the performance of a heat exchanger are the mass flow rates, specific heats, inlet and outlet temperatures of the hot and cold fluids, surface area available for heat transfer, thermal conductivity of the tube material, the tube thickness, and the convective heat transfer coefficients on the inside and outside surface of the tubes. The effect of the last four quantities can be combined into a single quantity, the overall heat transfer coefficient.

2 OBJECTIVES

The objective of this experiment is to compare the thermal performance of a concentric tube heat exchanger (also known as a double pipe heat exchanger) operated in parallel and counter flow and to determine for counter flow, the effect of fluid velocity on the convective heat transfer coefficients inside and outside the inner tube and the overall heat transfer coefficient.

3. THEORY

Heat is transferred whenever a temperature gradient exists. The three well-known modes of heat transfer, i.e., (1) conduction, (2) convection, and (3) radiation, can operate separately or simultaneously. Within a heat exchanger, heat transfer between fluids is through a combination of conduction and convection. Radiation is important only at high temperatures. At moderate to low temperatures, however, its effect is usually small.

Conduction is the mode of heat transfer through solids or fluids, in which there is no movement of the fluid in the direction of heat flow.

For simplicity, it is assumed that the curvature effects of a tube wall are negligible and the tube wall can be approximated as a plane wall. ***Fourier's law*** gives the relationship between heat conduction rate at any position x and its temperature gradient in one-dimensional (1-D) heat conduction as

$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \qquad (1)$$

where $\dot{Q}_{cond}$ = heat conduction rate (W)

k = thermal conductivity of the wall material (W/m·K)

A = area normal to the direction of heat flow (m^2)

$\frac{dT}{dx}$ = temperature gradient (K/m)

Under steady-state conditions, no heat generation and constant properties, the one-dimensional heat conduction through a plane wall results in a constant temperature gradient and the heat conduction rate across the wall is given by

$$\dot{Q}_{cond} = \frac{kA(T_1 - T_2)}{\Delta x} \qquad (2)$$

where Δx = thickness of the wall (m)
T_1, T_2 = temperatures on the left and right faces of the plane wall (°C)

It can be seen that the ***thermal resistance for conduction*** across a plane wall is

$$R_{cond} = \frac{T_1 - T_2}{\dot{Q}_{cond}} = \frac{\Delta x}{kA} \qquad (3)$$

Convection is the mode in which heat is transferred through a fluid system by the motion of the fluid. *"Forced convection"* occurs when the motion of the fluid is caused by a mechanical means such as a pump. *"Natural convection"* occurs when the motion of the fluid is caused by the heating process, e.g., by buoyancy.

According to the flow rate of the fluid in the heat exchanger, and the resulting Reynolds number, flow in the bulk of the fluid may be *"Laminar"* or *"Turbulent"*. In laminar flow, i.e., when Reynolds number is low, the fluid flows in a number of filaments which do not mix whereas in turbulent flow, there is mixing and generation of recirculating pockets of fluids called eddies.

At higher Reynolds numbers, the ordered laminar flow breaks down and is replaced *by* random and turbulent flow. The movement within the fluid now rapidly distributes the heat transferred from the walls. However, even when the bulk of the fluid has vigorously turbulent flow, turbulence within the boundary layer against the walls is greatly suppressed. Consequently, heat transfer within the **boundary layer** is again mainly due to **conduction**. Forced convection in turbulent flow gives better heat transfer in a heat exchanger.

For external flow, the rate of convective heat transfer from a surface to a fluid is given by Newton's law of cooling

$$\dot{Q}_{conv} = hA(T_s - T_\infty) \qquad (4)$$

where Q = convective heat transfer rate (W)
h = average convective heat transfer coefficient (W/m^2·K)
A = heat transfer area (m^2)
T_s = temperature of the surface (°C)
T_∞ = free stream temperature of the fluid (°C)

In general, the ***thermal resistance for convection*** is given by

$$R_{conv} = \frac{T_s - T_\infty}{\dot{Q}_{conv}} = \frac{1}{hA} \qquad (5)$$

Note that for flow in a pipe, i.e., internal flow, T_∞ is replaced by T_m the mean temperature of the fluid at any section of the pipe and Newton's law of cooling is written in terms of the heat flux as

$$\dot{q}_{conv} = h_{local}\left(T_s - T_\infty\right) \tag{6}$$

where $\dot{q}_{conv}$ = convective heat transfer flux (W/m^2)

h_{local} = local convective heat transfer coefficient (W/m^2·K) at a section

T_s = temperature of the surface (°C)

T_m = mean temperature of the fluid at a section (°C)

In a typical heat exchanger, heat is transferred from a hot fluid, through a separating wall, to a colder fluid. Heat is driven through three resistances in series given by

$$\sum R = R_{conv,h} + R_{cond,wall} + R_{conv,c} = \frac{1}{h_h A_h} + \frac{\Delta x}{kA} + \frac{1}{h_c A_c} \tag{7}$$

where the subscripts *h* and *c* denote the hot and cold fluids, respectively.

The rate of heat transfer is then given by

$$\dot{Q} = \frac{T_h - T_c}{\sum R} = \frac{T_h - T_c}{\dfrac{1}{h_h A_h} + \dfrac{\Delta x}{kA} + \dfrac{1}{h_c A_c}} \tag{8}$$

If the tube wall of the heat exchanger is thin, we may assume that all the areas are equal such that, $A_h \approx A_c \approx A \approx A_m$. Equation (8) can then be written as

$$\dot{Q} = UA_m\left(T_h - T_c\right) \tag{9}$$

where $U = \dfrac{1}{\dfrac{1}{h_h} + \dfrac{\Delta x}{k} + \dfrac{1}{h_c}}$ is the overall heat transfer coefficient (W/m^2·K)

A_m = mean heat transfer mean area (m^2)

T_h = temperature of hot fluid °C

T_c = temperature of cold fluid °C

The conduction thermal resistance of the tube wall is usually insignificant compared to the other two resistances and is often ignored. It can be seen that an accurate prediction of the convective heat transfer coefficients is most important when designing a heat exchanger.

However, Eq. (9) cannot be used to calculate the rate of heat exchanger in a heat exchanger because the temperature difference between the two streams and between the metal wall and each stream vary according to the position within the heat exchanger. For example in parallel flow of a concentric tube heat exchanger, the typical fluid temperature distribution is shown in Fig. 1.

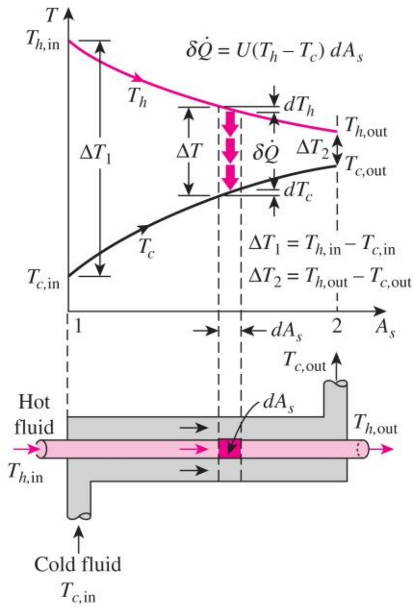

Figure 1: Typical variation of fluid temperatures in a parallel flow concentric tube heat exchanger. Source: Çengel and Ghajar [1]

Heat transfer calculations are eased if a **mean value of the local temperature differences** can be found. It can be shown that for a concentric tube heat exchanger, the appropriate mean temperature difference between the two streams of fluid is the ***log mean temperature difference*** given by

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln \dfrac{\Delta T_2}{\Delta T_1}} \tag{10}$$

Based on the labelling of the temperatures in this equipment,

$$\Delta T_{lm} = \frac{(T_3 - T_7) - (T_6 - T_{10})}{\ln\left(\dfrac{T_3 - T_7}{T_6 - T_{10}}\right)} \tag{11}$$

where the definitions of the subscripts are given in Table 1.

A detailed analysis of ΔT_{lm} together with its validity and application can be found in standard heat transfer texts [1, 2].

The rate of heat transfer is then given by

$$\dot{Q} = UA_m \Delta T_{lm} \tag{12}$$

By measuring the temperatures and the mass flow rates of both streams, the following may be calculated.

(i) Overall rate of heat transfer from the hot stream to the cold stream

$$\dot{Q}_h = \dot{m}_h c_p (T_3 - T_6) \tag{13}$$

where c_p is the specific heat (4.18 kJ/kg·K for water) and $\dot{m}_h$ is the mass flow rate of hot water as defined in Table 1.

(ii) Overall rate of heat transfer to the cold stream from the hot stream

$$\dot{Q}_c = \dot{m}_c c_p (T_{10} - T_7) \qquad \text{for parallel flow} \qquad (14)$$

$$\dot{Q}_c = \dot{m}_c c_p (T_7 - T_{10}) \qquad \text{for counter flow} \qquad (15)$$

Note: Any discrepancy between the two heat transfer rates will be due to either observation (human error) or instrument error (allowing insufficient time for stability to be reached) or heat losses to the environment.

(iii) Overall heat transfer coefficient

$$U = \frac{\dot{Q}_h}{A_m \Delta T_{lm}} = \frac{\dot{Q}_h}{\dfrac{(T_3 - T_7) - (T_6 - T_{10})}{\ln\left(\dfrac{T_3 - T_7}{T_6 - T_{10}}\right)} A_m} \qquad (16)$$

(iv) Average convective heat transfer coefficient between the inner surface of tube and the hot stream

$$h_h = \frac{\dot{Q}_h}{A_h \Delta T_{lm,h}} = \frac{\dot{Q}_h}{A_h \dfrac{(T_3 - T_1) - (T_6 - T_2)}{\ln\left(\dfrac{T_3 - T_1}{T_6 - T_2}\right)}} \qquad (17)$$

(v) Average convective heat transfer coefficient between the outer surface of tube and the cold stream

$$h_h = \frac{\dot{Q}_c}{A_c \Delta T_{lm,c}} = \frac{\dot{Q}_c}{A_c \dfrac{(T_1 - T_7) - (T_2 - T_{10})}{\ln\left(\dfrac{T_1 - T_7}{T_2 - T_{10}}\right)}} \qquad (18)$$

4. EQUIPMENT

4.1 Equipment List

A water to water turbulent flow concentric tube heat exchanger manufactured by P.A. Hilton Ltd. will be used for the investigation. A schematic diagram of the unit is attached to the workbench.

Heat Exchanger

This is of the double pipe configuration with hot water flowing through the central tube while cooling water flows through the annular space. The heat exchanger has been divided into three equal sections to allow examination of the intermediate stream temperatures. Thermocouples are installed to sense the stream temperatures and the inner tube wall temperature at the four stations.

Hot Water Circuit

Hot water provided by a heater (electrical resistance type) is fed into the upper end of the central tube of the heat exchanger. Water cools as it flows through the heat exchanger, and on leaving passes through a pump which provides the circulating head. The water then flows through either a high or a low flow meter (according to the flow rate) and then back to the water heater, where it is reheated. A plastic mesh screen is fitted in the heater tank to assist de-aeration. A drain on the lower right-hand side of the panel allows draining of the hot water circuit if required.

Cold Water Circuit

Mains cold water passes through a flow control valve and flow meter to a quick release union on the face of the panel. A similar quick release union is connected to the central water drain point. Flexible hoses connecting the annulus at either end of the heat exchanger can be connected to either of these unions. In this way, the cooling water can be set to flow in a parallel or counter direction.

Control

Valves are provided to control the flow rate of the hot and cold streams of water. An electronic control regulates the power input to the water heater, and a thermostat senses the temperature in the water heater and limits the water temperature to approximately 85°C.

Temperature

A digital thermometer with a selector switch displays the temperature sensed by the thermocouples placed on the surfaces and within the fluid streams.

4.2 Equipment technical data

Heat Exchanger	*Core tube*	Material: Copper
		External diameter: 9.5 mm
		Internal diameter: 7.9 mm
		Length: 3 × 350 mm
		External heat transfer area: 0.031 m^2
		Internal heat transfer area: 0.0261 m^2
		Mean heat transfer area A_m: 0.0288 m^2
		Flow area: 49×10^{-6} m^2
	Outer tube	Material: Copper
		External diameter: 12.7 mm
		Internal diameter: 11.1 mm
		Annulus flow area: 25.9×10^{-6} m^2

5. EXPERIMENT PROCEDURE

Parallel flow

Connect the heat exchanger for parallel flow. Check that the heater tank contains water to the correct level. Fully open the "high" flow valve, switch on the mains and heater and raise the hot water temperature inlet (T_3) to about 65°C. Reduce the hot water flow rate to about 50 g/s and set the cold water flow rate to about 20 g/s. Set the heater control so that T_3 is steady at about 65°C. Proceed to take the measurements set out in Table 1.

<u>Counter flow</u>
Quickly switch off the mains and <u>turn off</u> the cold water control valve. Reverse the direction of cold water flow through the heat exchanger by reversing the cooling water and drain tubes. <u>Switch on</u> the mains, and reset the hot and cold water flow rates to as close as possible to the same values as in above. (The actual values are not important but for a strict comparison, the flow rates and initial temperatures must be the same in both the parallel and counter flow configurations). Repeat the measurements previously made.

<u>Effect of the fluid velocity on the surface heat transfer coefficients</u>
Ensure that the heat exchanger is connected for counter flow. Check that the heater tank contains water to the correct level. Fully open the "high flow" valve, switch on the mains and heater and raise the hot water temperature (T_3) to about 65°C. Adjust the cold water to bring the mean hot water $[T_3 + T_6]/2$ to about 65°C. Allow conditions to stabilise, then proceed to take measurements set out in Table 2.

Reduce the hot water flow rate to about 80% of the initial value without changing the cold water flow rate. Use the heater control to bring the mean hot water temperature back to the original value. Allow conditions to stabilise, then repeat the measurements. Repeat experiment with hot water flow rates of about 60%, 40% and 20% of the initial value.

6. RESULTS AND DISCUSSION

<u>Parallel and counter flow</u>
Plot the temperature distributions of the metal wall, the hot and cold streams and discuss the trends. Compare the rate of heat transferred for the two flow arrangements and explain the calculated discrepancies.

<u>Effect of fluid velocity on the convective heat transfer coefficients and the overall heat transfer coefficient</u>
Plot, for a constant velocity in the annulus, the convective heat transfer coefficients inside and outside the tube and the overall heat transfer coefficient against the tube water velocity. Comment on your results.

<u>Sample calculations</u>
Show sample calculations and verify that they are the same as those generated by the spreadsheet programme in the laboratory's personal computer.

<u>Observations</u>
Note down in your log sheet the experimental uncertainties associated with each measuring instrument or sensor. Record the time taken for the readings to stabilise.

Table 1 Parallel flow and Counter flow

Test	Parallel flow	Counter flow
Metal wall at inlet, T_1 (°C)		
Metal wall at exit, T_2 (°C)		
Hot stream at inlet, T_3 (°C)		
Hot stream 1st intermediate, T_4 (°C)		
Hot stream 2nd intermediate, T_5 (°C)		
Hot stream at exit, T_6 (°C)		
Cold stream entry/exit, T_7 (°C)		
Cold stream intermediate, T_8 (°C)		
Cold stream intermediate, T_9 (°C)		
Cold stream entry/exit, T_{10} (°C)		
Hot water flow rate, $\dot{m}_h$ (kg/s)		
Cooling water flow rate, $\dot{m}_c$ (kg/s)		
Heat transfer rate from hot water, $\dot{Q}_h$ (W)		
Heat transfer rate to cold water, $\dot{Q}_c$ (W)		

Table 2 Effect of fluid velocity on the convective heat transfer coefficients (Counter flow)

Test	1 (100%)	2 (80%)	3 (60%)	4 (40%)	5 (20%)
Metal wall at inlet, T_1 (°C)					
Metal wall at exit, T_2 (°C)					
Hot stream at inlet, T_3 (°C)					
Hot stream 1st intermediate,T_4 (°C)					
Hot stream 2nd intermediate, T_5 (°C)					
Hot stream at exit, T_6 (°C)					
Cold stream entry/exit, T_7 (°C)					
Cold stream intermediate, T_8 (°C)					
Cold stream intermediate, T_9 (°C)					
Cold stream entry/exit, T_{10} (°C)					
Hot water flow rate, $\dot{m}_h$ (kg/s)					
Cooling water flow rate, $\dot{m}_c$ (kg/s)					
Overall heat transfer coefficient, U (W/m^2·K)					
Average convective heat transfer coefficient inside the inner tube, h_h (W/m^2·K)					
Average convective heat transfer coefficient in the annulus between the tubes, h_c (W/m^2·K)					

7. REFERENCES

1. Çengel, Y.A. and Ghajar, A. *Heat and Mass Transfer: Fundamentals and Applications*, 5th Edition (SI Units), Chapter 11, McGraw-Hill, 2015.
2. Incropera, F.P., DeWitt, D.P., Bergman, T.L. and Lavine, A.S. *Principles of Heat and Mass Transfer*, 7th Edition (SI Units), Chapter 11, John Wiley & Sons, 2013.

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EXPERIMENT: E3.5/E3.1AE - HEAT EXCHANGER

LOG SHEET

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