CHAPTER

FOUR

HEAT TRANSFER

4.1. Determination of Overall Heat Transfer Coefficient in a Tubular Heat Exchanger

4.2. Determination of Overall Heat Transfer Coefficient in a Plate Type Heat Exchanger

4.3. Determination of Overall Heat Transfer Coefficient in a Shell and Tube Heat Exchanger

4.4. Determination of Heat Transfer Rate in Boiling and Condensation

4.5. Heat Transfer in Extended Surfaces

4.1. DETERMINATION OF OVERALL HEAT TRANSFER COEFFICIENT IN A TUBULAR HEAT EXCHANGER

Keywords: *Tubular heat exchanger, heat transfer coefficient, heat transfer area, heat transfer efficiency.*

Before the experiment: *Read the booklet carefully. Be aware of the safety precautions.*

4.1.1. Aim

To determine the heat transfer coefficient of a tubular heat exchanger both experimentally and theoretically in order to find the efficiency of the heat exchanger.

4.1.2. Theory

The process of heat exchange between two fluids that are at different temperatures and separated by a solid wall occurs in many engineering applications. The device used to implement this exchange is called a heat exchanger, and specific applications may be found in space heating and air-conditioning, power production, waste heat recovery and chemical processing. The flow of heat from a fluid through a solid wall to another fluid is often encountered in chemical engineering practice. The heat transferred may be latent heat accompanying phase changes such as condensation or vaporization, or it may be sensible heat coming from increasing or decreasing the temperature of a fluid without phase change [1]. Heat transfer is the movement of energy due to a temperature difference. There are three physical mechanisms of heat transfer; conduction, convection, radiation. All three modes may occur simultaneously in problems of practical importance.

4.1.2.1. Conduction

Heat conduction is the transfer of heat from one part of a body to another part of the same body, or from one body to another body in physical contact with it, without appreciable displacement of the particles of the body. Energy transfer by conduction is accomplished in two ways. The first mechanism is that of molecular interaction, in which the greater motion of a molecule at a higher energy level (temperature) imparts energy to adjacent molecules at lower energy levels. This type of transfer is present, to some degree, in all systems in which a temperature gradient exists and in which molecules of a solid, liquid, or gas are present. The second mechanism of conduction heat transfer is by “free” electrons. The free-electron mechanism is significant primarily in pure-metallic solids; the concentration of free electrons varies considerably for alloys and becomes very low for nonmetallic solids. The distinguishing feature of conduction is that it takes place within the boundaries of a body, or across the boundary of a body into another body placed in contact with the first, without an appreciable displacement of the matter comprising the body [2, 3].

4.1.2.2. Convection

Heat transfer by convection occurs in a fluid by the mixing of one portion of the fluid with another portion due to gross movements of the mass of fluid. The actual process of energy transfer from one fluid particle or molecule to another is still one of conduction, but the energy may be transported from one point in space to another by the displacement of the fluid itself. Convection can be further subdivided into free convection and forced convection. If the fluid is made to flow by an external agent such as a fan or pump, the process is called “forced convection”. If the fluid motion is caused by density differences which are created by the temperature differences existing in the fluid mass, the process is termed “free convection”, or “natural convection”. The motion of the water molecules in a pan heated on a stove is an example of a free convection process. The important heat transfer problems of condensing and boiling are also examples of convection, involving the additional complication of a latent heat exchange. It is virtually impossible to observe pure heat conduction in a fluid because as soon as a temperature difference is imposed on a fluid, natural convection currents will occur due to the resulting density differences [3].

4.1.2.3. Radiation

Thermal radiation describes the electromagnetic radiation that is emitted at the surface of a body which has been thermally excited. This electromagnetic radiation is emitted in all directions; and when it strikes another body, part may be reflected, part may be transmitted, and part may be absorbed. Thus, heat may pass from one body to another without the need of a medium of transport between them. In some instances there may be a separating medium, such as air, which is unaffected by this passage of energy. The heat of the sun is the most obvious example of thermal radiation.

4.1.2.4. Heat Exchangers

Heat exchangers are typically classified according to flow arrangement and type of construction. In the first classification, flow can be countercurrent or cocurrent (also called parallel). Heat exchangers can also be classified based on their configuration as tubular, plate and shell & tube heat exchangers. The tubular heat exchanger, sometimes called a double-pipe heat exchanger, is the simplest form of heat exchanger and consists of two concentric (coaxial) tubes carrying the hot and cold fluids. Heat is transferred to/from one fluid in the inner tube from/to the other fluid in the outer annulus across the metal tube wall that separates the two fluids [2].

4.1.2.5. Cocurrent and Countercurrent Flow

In the countercurrent flow heat exchangers, the fluids enter at opposite ends, flow in opposite directions, and leave at opposite ends. The temperatures are denoted as follows:

T_1: Temperature of entering hot fluid, °C

T_2: Temperature of mid-position hot fluid, °C

T_3: Temperature of leaving hot fluid, °C

T_4: Temperature of entering cold fluid, °C

T_5: Temperature of mid-position cold fluid, °C

T_6: Temperature of leaving cold fluid, °C

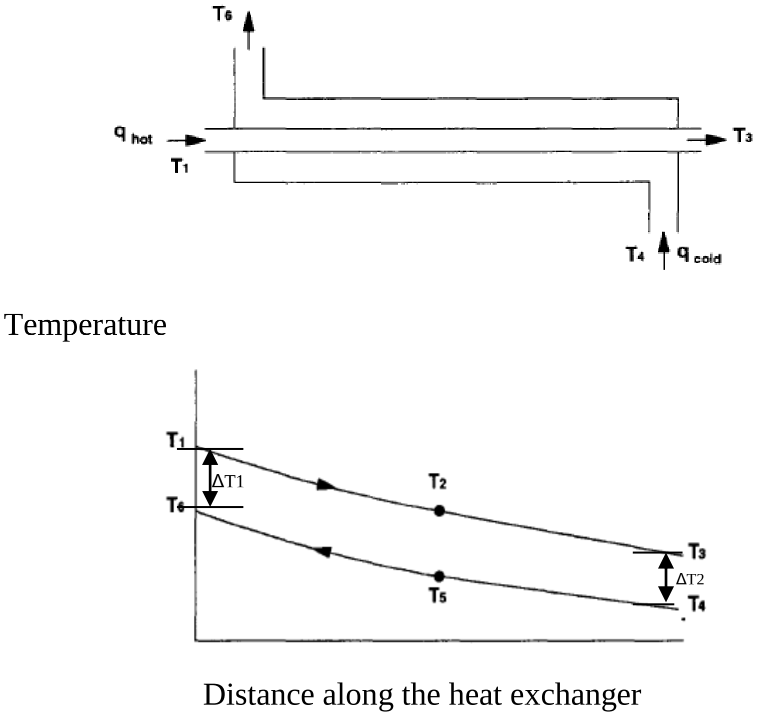

Figure 4.1.1. Countercurrent flow heat exchanger [3].

The approaches are:

$$T_1 - T_6 = \Delta T_1 \tag{4.1.1}$$

$$T_3 - T_4 = \Delta T_2 \tag{4.1.2}$$

In the cocurrent flow (parallel flow) heat exchanger the hot and cold fluids enter at the same end, flow in the same direction, and leave at the same end. The temperature practices across the tube length are shown in the below figure.

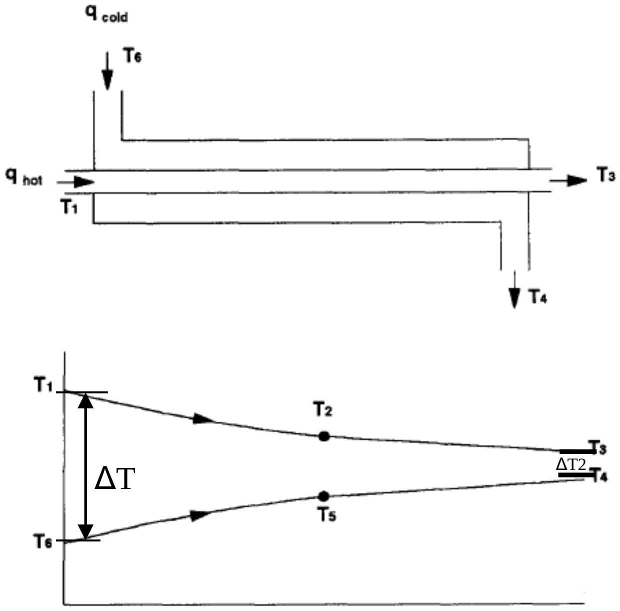

Figure 4.1.2. Cocurrent flow heat exchanger [3].

The approaches are:

$$T_1 - T_6 = \Delta T_1 \tag{4.1.3}$$

$$T_3 - T_4 = \Delta T_2 \tag{4.1.4}$$

Cocurrent flow is rarely used in a single-pass heat exchanger, because, as inspection of Figures 4.1.1 and 4.1.2 will show, it is not possible with this method of flow to bring the exit temperature of one fluid close to the entrance temperature of the other, and the heat that can be transferred is less than that possible in countercurrent flow. Parallel flow is used in special situations where it is necessary to limit the maximum temperature of the cooler fluid or where it is important to change the temperature of at least one fluid rapidly. In the multipass heat exchangers, parallel flow is used in same passes, largely for mechanical reasons, and the capacity and approaches obtained are thereby affected [3].

4.1.2.6. Enthalpy Balances in Heat Exchangers

To design or predict the performance of a heat exchanger, it is essential to determine the heat lost to the surrounding for the analyzed configuration. A parameter can be defined to quantify the percentage of losses or gains. Such a parameter may readily be obtained by applying overall energy balances for hot and cold fluids. In heat exchangers there is no shaft work, and mechanical-potential and mechanical-kinetic energies are small in comparison with the other terms in the energy-balance equation. If Q_e is the heat power emitted from hot fluid, while Q_a is the heat power absorbed by cold fluid, and also if constant specific heats are assumed [4];

$$Q_e = \dot{m}_h\left(h_{h,i} - h_{h,o}\right) = \dot{m}_h C_{p_h}\left(T_{h,i} - T_{h,o}\right) \tag{4.1.5}$$

$$Q_a = \dot{m}_c\left(h_{c,i} - h_{c,o}\right) = \dot{m}_c C_{p_c}\left(T_{c,i} - T_{c,o}\right) \tag{4.1.6}$$

where,

$\dot{m}_h$, $\dot{m}_c$: mass flow rate of hot and cold fluid, respectively.

$h_{h,i}$, $h_{h,o}$: inlet and outlet enthalpies of hot fluid, respectively.

$h_{c,i}$, $h_{c,o}$: inlet and outlet enthalpies of cold fluid, respectively.

$T_{h,i}$, $T_{h,o}$: inlet and outlet temperatures of hot fluid, respectively.

$T_{h,i}$, $T_{h,o}$: inlet and outlet temperatures of cold fluid, respectively.

C_{p_h}, C_{p_c} : specific heats of hot and cold fluid, respectively.

$$Heat\ power\ gain\ or\ loss = |Q_e| - |Q_a| \tag{4.1.7}$$

Percentage P of losses or gains is

$$P = \frac{|Q_a|}{|Q_e|} \times 100 \tag{4.1.8}$$

If the heat exchanger is well insulated, Q_e and Q_a should be equal. Then, the heat lost by the hot fluid is gained by the cold fluid; $Q_a = -Q_e$

In practice these differ due to heat losses or gains to/from the environment. If the average cold fluid temperature is above the ambient air temperature then heat will be lost to the surroundings resulting in P < 100%. If the average cold fluid temperature is below the ambient temperature, heat will be gained resulting P > 100%.

4.1.2.7. Rate of Heat Transfer

Heat transfer calculations are based on the area of the heating surface and are expressed in kg per cubic second of surface through which the heat flows. The rate of heat transfer per unit area is called the heat flux. In many types of heat transfer equipment, the transfer surface is the surface area of the tube. Heat flux may then be based either on the inside area or the outside area of the tubes. Although the choice is arbitrary, it must be clearly stated, because the magnitude of the heat fluxes will not be the same for the two choices.

4.1.2.8. Average Temperature of Fluid Stream

When a fluid is being heated, the temperature of the fluid is a maximum at the wall of the heating surface and decreases toward the center of the stream. If the fluid is being cooled, the temperature is a minimum at the wall and increases toward the center. Because the temperature difference between the hot and cold fluid streams varies along the length of the heat exchanger it is necessary to derive an average temperature difference (driving force) from which heat transfer calculations can be performed [4]. This average temperature difference is called the Logarithmic Mean Temperature Difference (LMTD) ΔT_{lm} [5].

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{4.1.9}$$

4.1.2.9. Overall Heat Transfer Coefficient

It can be expected that the heat flux may be proportional to a driving force. In heat flow, the driving force is taken as T_h - T_c where T_h is the average temperature of the hot fluid and T_c is that of the cold fluid. The quantity T_h - T_c is the overall temperature difference. It is denoted by ΔT. It is clear from Figure 4.1.1, that T can vary considerably from point to point along the tube, and therefore since the heat flux is proportional to ΔT, the flux also varies with tube length. It is necessary to start with a differential equation, by focusing attention on a differential area dA through which a differential heat flow dq occurs under the driving force of a local value of ΔT. The local flux is then dx/dA and is related to the local value of ΔT by the equation [4]:

$$\frac{dq}{dA} = U\Delta T = U(T_h - T_c) \tag{4.1.10}$$

The quantity U, defined by Eq. 4.1.10 as a proportionality factor between dq/dA and ΔT, is called the local overall heat-transfer-coefficient. To complete the definition of U in a given case, it is necessary to specify the area. If A is taken as the outside tube area A_o, U becomes a coefficient based on that area and is written U_o. Likewise, if the inside area A_i is chosen, the coefficient is also based on that area and is denoted by U_i. Since ΔT and dq are independent of the choice of area, it follows that

$$\frac{U_o}{U_i} = \frac{dA_i}{dA_o} = \frac{D_i}{D_o} \tag{4.1.11}$$

where D_i and D_o are the inside and outside tube diameters, respectively. To apply Eq. 4.1.10 to the entire area of a heat exchanger, the equation must be integrated. The assumptions are [5]:

1. The overall coefficient U is constant.
2. The specific heats of the hot and cold fluids are constant.
3. Heat exchange with the surroundings is negligible.
4. The flow is steady and parallel or countercurrent, as shown in Figures 4.1.1 and 4.1.2

The most questionable of these assumptions is that of a constant overall coefficient. The coefficient does in fact vary with the temperatures of the fluids, but its change with temperature is gradual, so that when the temperature ranges are moderate, the assumption of constant U is not seriously in error.

Assumptions 2 and 4 imply that if T_c and T_h are plotted against q, straight lines are obtained. Since T_c and T_h vary linearly with q, ΔT does likewise, and d(ΔT)/dq the slope of the graph of ΔT vs. q, is constant. Therefore:

$$\frac{dT}{dq} = \frac{(\Delta T_2 - \Delta T_1)}{q_T} \tag{4.1.12}$$

where ΔT_1 and ΔT_2 are the approaches and q_T is the rate of heat transfer in the entire exchanger. Elimination of dq from Eq. 4.1.10 and 4.1.12 gives:

$$\frac{dT}{U\Delta T dA} = \frac{(\Delta T_2 - \Delta T_1)}{q_T} \tag{4.1.13}$$

The variables ΔT and A can be separated, and if U is constant, the equation can be integrated over the limits A_T and 0 for A and ΔT_2 and ΔT_1 for ΔT, where A_T is the total area of the heat-transfer surface.

Thus,

$$\int_{\Delta T_1}^{\Delta T_2} \frac{d(\Delta T)}{\Delta T} = \frac{U(\Delta T_2 - \Delta T_1)}{q_T} \int_{O}^{A_T} dA \tag{4.1.14}$$

or,

$$\ln\left(\frac{\Delta T_2}{\Delta T_1}\right) = \frac{U(\Delta T_2 - \Delta T_1)}{q_T \cdot A_T} \tag{4.1.15}$$

Then,

$$q_T = U \cdot A_T \cdot \frac{(\Delta T_2 - \Delta T_1)}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} = U \cdot A_T \cdot \Delta T_{lm} \tag{4.1.16}$$

Total heat transfer surface area in the tubular heat exchanger is defined as

$$A_T = \frac{2\pi D_i L + 2\pi D_o L}{2} \tag{4.1.17}$$

4.1.2.10. NTU Method

The number of transfer units (NTU) method is used to calculate the theoretical overall heat transfer coefficient (U) by using effectiveness charts. In addition to the effectiveness, the ratio of C_{min}/C_{max} is needed (C_{min} is the smaller of the two heat capacity rates C_c and C_h and C_{max} is the higher one). From the effectiveness graphs, the intersection point of the ratio C_{min}/C_{max} and effectiveness value gives the NTU value [5]. The effectiveness:

$$\varepsilon = C_h\,(T_{h,i} - T_{h,o}) \,/\, C_{min}(T_{h,i} - T_{c,i}) \tag{4.1.18}$$

$$\varepsilon = C_c(T_{c,o} - T_{c,i}) \,/\, C_{min}(T_{h,i} - T_{c,i}) \tag{4.1.19}$$

Then the theoretical heat transfer coefficient value (U) is calculated by the following equation,

$$NTU = (UA)/C_{min} \tag{4.1.20}$$

$$U = ((NTU)C_{min})/A \tag{4.1.21}$$

The heat transfer coefficients change due to alterations in fluid flow rates and inlet fluid temperatures. Those may either be calculated experimentally or theoretically through LMTD and NTU methods.

4.1.3. Experimental Setup

The apparatus used in this experiment is shown in Figure 4.1.3:

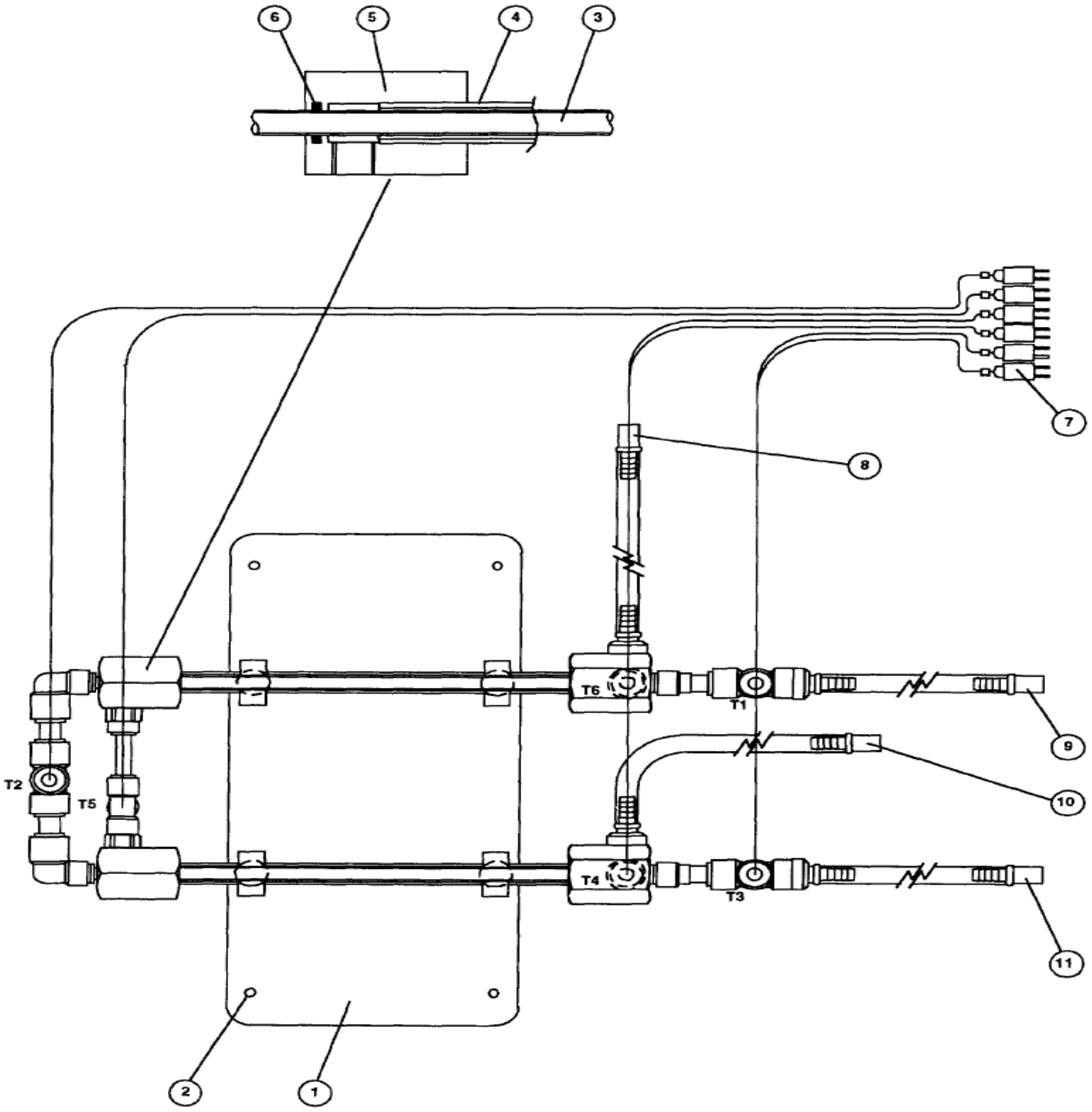

Figure 4.1.3. Schematic diagram of the tubular heat exchanger.

1.) PVC base plate
2.) Holes
3.) Inner stainless steel tube
4.) Acrylic outer tube
5.) PVC housings

6.) O rings
7.) Thermocouple plug
8.) Cold water outlet
9.) Hot water inlet
10.) Cold water inlet
11.) Hot water outlet

Inner diameter of tubes = 0.0083 m

Outer diameter of tubes = 0.0095 m.

Length of the tubes = 0.66 m.

4.1.4. Procedure

1. Open the inlet valve for cold water in the countercurrent flow and adjust water flow rate to a constant value less than 1 L/min.
2. Fill the hot water tank with distilled water.
3. Turn on the inlet valve for hot water and by using computer adjust the temperature to 35 °C.
4. Open hot water valve and adjust water flow rate to 1 L/min.
5. When the system has reached steady-state; record the flow rates, inlet and outlet temperatures of hot and cold water.
6. Repeat the experiment for 2 L/min and 2.5 L/min of hot water flow rate without changing water tank temperature.
7. Repeat the experiment for hot water tank temperature, 50 °C.
8. Repeat the experiment using cocurrent flow.

Safety Issues: Before starting the experiment, be sure that all the water valves are connected to the system and turned open. Fill the hot water tank with distilled water to the level that reaches to the thermocouple. At the end of the experiment, be sure that all water valves are closed and the heat exchanger system is turned off.

4.1.5. Report Objectives

1. Use the recorded inlet/outlet temperatures of streams and their corresponding flow rates to calculate the heat absorbed and heat emitted. Calculate the efficiency.
2. Calculate the overall heat transfer coefficient, U experimentally by LMTD Method.
3. Use NTU (number of transfer units) method to calculate theoretical value of U and compare with the one obtained as a result of experimental calculations.

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4.2. DETERMINATION OF OVERALL HEAT TRANSFER COEFFICIENT IN A PLATE TYPE HEAT EXCHANGER

Keywords: *Plate heat exchanger, heat transfer coefficient, heat transfer area, heat transfer efficiency.*

Before the experiment: *Read the booklet carefully and familiarize yourself with the equipment. Be aware of the safety precautions.*

4.2.1. Aim

To observe the effect of fluid flow rates on overall heat transfer coefficient of a plate heat exchanger.

4.2.2. Theory

The process of heat exchange between two fluids that are at different temperatures and separated by a solid wall occurs in many engineering applications. The device used to implement this exchange is called a heat exchanger, and specific applications may be found in space heating and air-conditioning, power production, waste heat recovery and chemical processing. The flow of heat from a fluid through a solid wall to a coated fluid is often encountered in chemical engineering practice. The heat transferred may be latent heat accompanying phase changes such as condensation or vaporization, or it may be sensible heat coming from increasing or decreasing the temperature of a fluid without phase change [1].

Heat transfer is the movement of energy due to a temperature difference. There are three physical mechanisms of heat transfer; conduction, convection, radiation.

Heat exchangers are typically classified according to flow arrangement and type of construction [2].

4.2.2.1. Classification of heat exchangers according to the type of construction

According to their configuration, heat exchangers can be labeled as tubular, plate and shell & tube heat exchangers [2].

Tubular Heat Exchangers

A tubular heat exchanger, consisting of a pipe and a jacket around it, is the simplest heat exchanger mainly used for small flow rates of fluid. The fluid which is desired to be heated or cooled flows inside the pipe, while the other fluid flows in the jacket. Heat is exchanged from hot fluid to cold fluid through the walls [2,3].

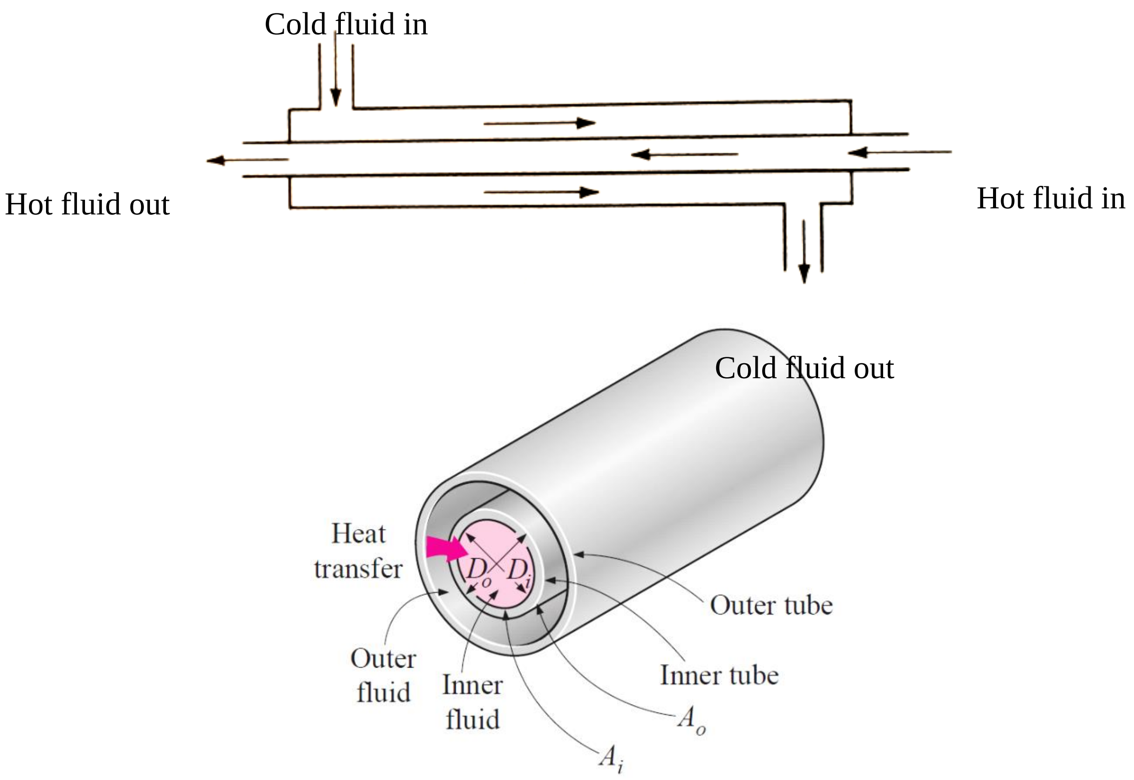


Figure 4.2.1. Basic flow arrangement for a tubular heat exchanger [3].

Shell & Tube Heat Exchangers

Approximately 70-80% of the heat exchanger market is held by the shell-and-tube type heat exchanger. It is largely favored due to its long performance history, relative simplicity, and its wide temperature and pressure design ranges. In essence, a shell-and-tube exchanger is a pressure vessel with many tubes inside. One process fluid flows through the tubes of the exchanger while the other flows outside of the tubes within the shell. The tube side and shell side fluids are separated by a tube sheet. Specific heat exchangers differ in the number of shell passes and the number of tube passes. The simplest form, which involves single tube and shell passes, is shown in Figure 4.2.2. Baffles are usually installed to increase the convective heat transfer coefficient of the shell-side fluid by inducing turbulence and a cross-flow velocity component. As such, shell-and-tube heat exchangers have neither pure counter-flow nor pure cross-flow, and the thermal analysis can be quite complex [2,3].

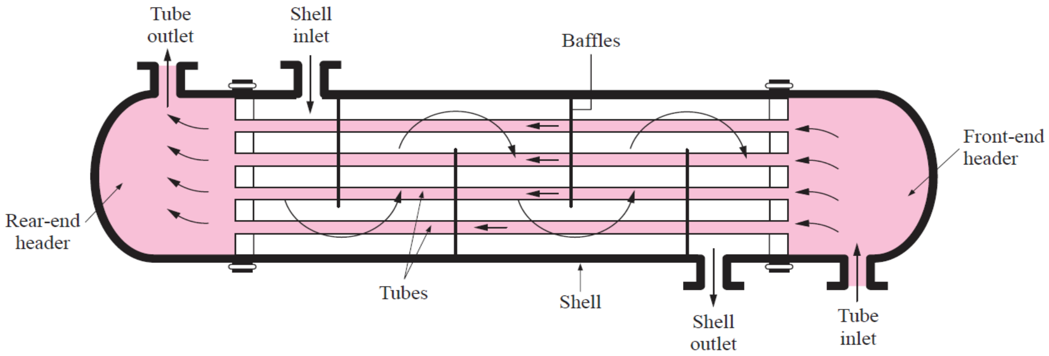


Figure 4.2.2. Basic flow arrangement for shell-and-tube heat exchangers [3].

Plate Heat Exchangers

Plate heat exchangers use metal plates to transfer heat between two fluids. They provide a larger surface area for heat transfer compared to conventional shell and tube heat exchangers, which greatly increases the speed of temperature change. The plates, made of materials such as stainless steel, aluminum and titanium, are attached in a large frame by rubber gaskets that are placed between each plate as shown in Figure 4.2.3. There are four flow ports on each plate of which one top and one bottom ports are blocked by the gasket. For the next plate the other two ports are blocked.

Plate heat exchangers are used commonly in the food and beverage industries. The advantages of plate heat exchangers are lower material costs and space requirement, easy maintenance, lighter weight and greater flexibility for changes such as plate addition. Also, they can also operate in very low temperatures compared to shall & tube heat exchangers. On the other hand, they are not very suitable for very temperatures higher than 200 °C, viscosity more than 10 Pa.s and pressures higher than 20 bar [4].

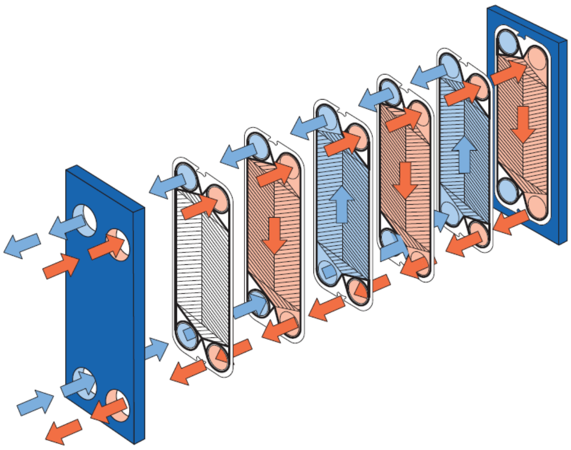


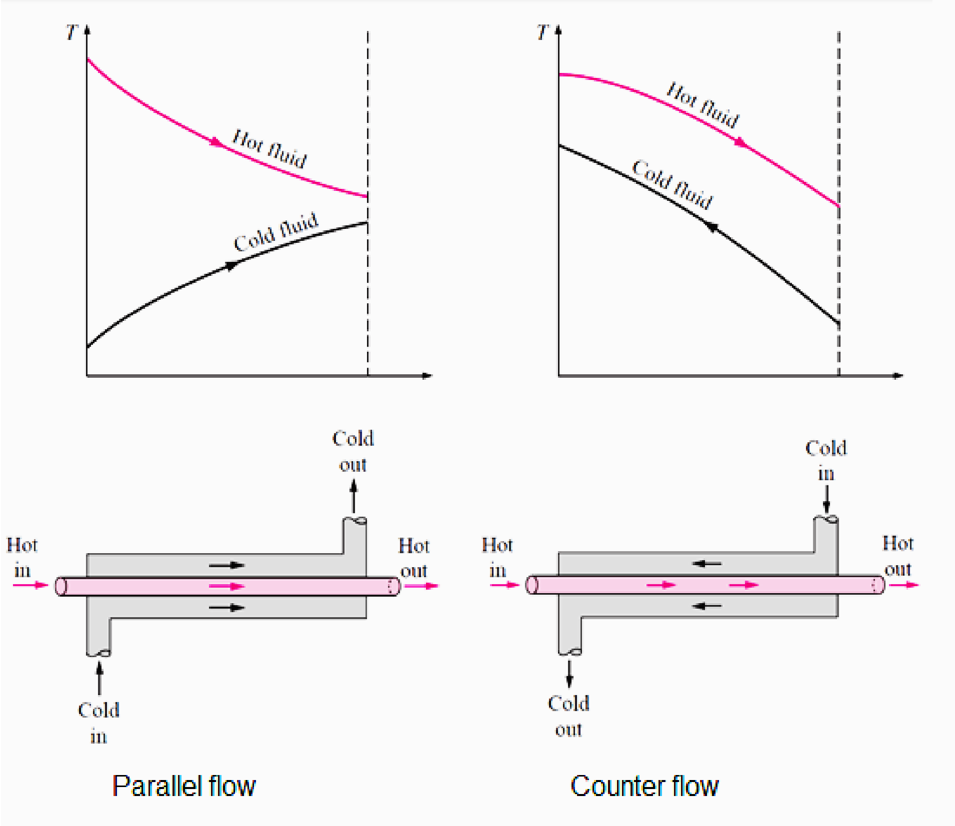
Figure 4.2.3. Basic flow arrangement for plate heat exchangers [5].

The main advantages of plate heat exchangers over shell and tube heat exchangers are

- high overall heat transfer coefficient
- low cost
- lower space requirement
- easy maintenance
- less weight
- lower heat loss

4.2.2.2. Classification of heat exchangers according to the flow arrangement

Flow can be countercurrent or cocurrent (also called parallel).

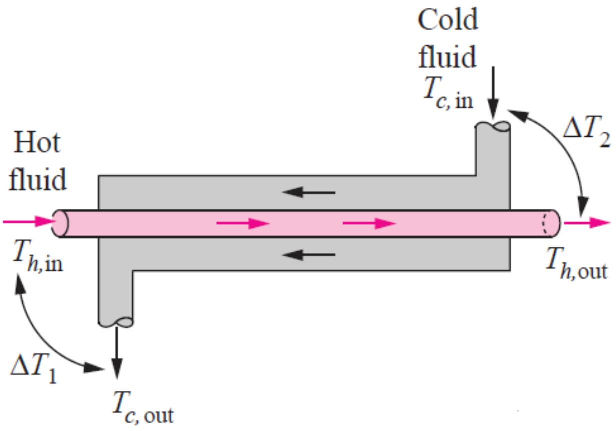


Parallel flow

Counter flow

Figure 4.2.4. Cocurrent (parallel) and countercurrent flow [3].

In the countercurrent the fluids enter at opposite ends, flow in opposite directions, and leave at opposite ends. The temperature-length curves for this case are shown in Figure 4.2.4.

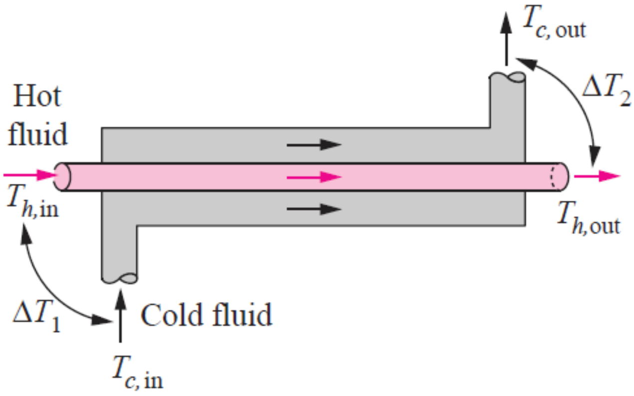


$$\Delta T_1 = T_{h,in} - T_{c,out}$$

$$\Delta T_2 = T_{h,out} - T_{c,in}$$

Figure 4.2.5. ΔT_1 and ΔT_2 expressions in counter flow arrangement.

In the cocurrent flow (parallel flow) the hot and cold fluids enter at the same end, flow in the same direction, and leave at the same end. The temperature-length curves for this case are shown in Figure 4.2.4.



$$\Delta T_1 = T_{h,in} - T_{c,in}$$

$$\Delta T_2 = T_{h,out} - T_{c,out}$$

Figure 4.2.6. ΔT_1 and ΔT_2 expressions in parallel flow arrangement [2].

Cocurrent flow is rarely used in a single-pass heat exchanger, because, as inspection of Figure 4.2.4 will show, it is not possible with this method of flow to bring the exit temperature of one fluid nearly to the entrance temperature of the other, and the heat that can be transferred is less than that possible in countercurrent flow. Parallel flow is used in special situations where it is necessary to limit the maximum temperature of the cooler fluid or where it is important to change the temperature of at least one fluid rapidly [3].

4.2.2.3. Energy Balances in Heat Exchangers

The energy balances to calculate rate of heat transfer are subject to following assumptions,

1. There is no heat exchange between the surroundings and the fluids.
2. Axial conduction in the tubes is negligible.
3. Fluid specific heats are constant at average temperature values of inlet and outlet temperatures.
4. Potential and kinetic energy changes are negligible.
5. The overall heat transfer coefficient is constant [2].

Since there is no shaft work in heat exchangers, the energy balance equation for heat power emitted from the hot fluid becomes,

$$Q_E = \dot{m}_h c_{p,h}\left(T_{h,i} - T_{h,o}\right) \tag{4.2.1}$$

where $\dot{m}_h$ is the hot fluid flow rate, $T_{h,i}$ and $T_{h,o}$ are the inlet and outlet hot fluid temperatures, respectively. Heat Rate of heat absorbed is given by,

$$Q_A = \dot{m}_c c_{p,c}\left(T_{c,i} - T_{c,o}\right) \tag{4.2.2}$$

where $\dot{m}_c$ is the hot fluid flow rate, $T_{c,i}$ and $T_{c,o}$ are the inlet and outlet hot fluid temperatures, respectively [2,3]. If the insulation of the heat exchanger is perfect, the heat power emitted from the hot fluid is equal to the heat power absorbed by the cold fluid. However, since perfect insulation is not achieved, heat power lost or gained is calculated by,

$$|Q_E| - |Q_A| \tag{4.2.3}$$

Percentage of loss or gain of heat power is given by,

$$P = \frac{|Q_A|}{|Q_E|} \times 100 \tag{4.2.4}$$

In practice these differ due to heat losses or gains to/from the environment. If the average cold fluid temperature is above the ambient air temperature then heat will be lost to the surroundings resulting in P < 100%. If the average cold fluid temperature is below the ambient temperature, heat will be gained resulting P > 100%.

4.2.2.4. Rate of Heat Transfer

Heat transfer calculations are based on the area of the heating surface and are expressed in kJ per second per square meter of surface through which the heat flows. The rate of heat transfer per unit area is called the heat flux. In many types of heat transfer equipment the transfer surfaces are constructed from tubes or pipe. Heat fluxes may then be based either on the inside area or the outside area of the tubes. Although the choice is arbitrary, it must be clearly stated, because the numerical magnitude of the heat fluxes will not be the same for the two choices [2].

4.2.2.5. Average Temperature of Fluid Stream

When a fluid is being heated, the temperature of the fluid is a maximum at the wall of the heating surface and decreases toward the center of the stream. If the fluid is being cooled, the temperature is a minimum at the wall and increases toward the center. Because the temperature difference between the hot and cold fluid streams varies along the length of the heat exchanger it is necessary to derive an average temperature difference (driving force) from which heat transfer calculations can be performed. This average temperature difference is called the Logarithmic Mean Temperature Difference (LMTD) ΔT_{lm}. [2,3]

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \qquad (4.2.5)$$

Where ΔT_1 and ΔT_2 are defined above for both co-current and countercurrent flow arrangements.

4.2.2.6. Overall Heat Transfer Coefficient

4.2.2.6.1. LMTD Method

The overall heat transfer coefficient, U, may change because of variations in flow conditions and fluid properties. However, in many applications, it is reasonable to work with an average value of U [2] LMTD method is very useful for determining the size of heat exchanger when mass flow rate and the inlet and outlet temperatures of fluids are known [3]. A proper differential equation which relates differential area dA through which a differential heat flow dq occurs under the driving force of a local value of ΔT is as follows,

$$\frac{dq}{dA} = U\Delta T = U(T_h - T_c) \qquad (4.2.6)$$

With these assumptions, when the graph of T_c and T_h versus q is plotted, straight lines are obtained, which implies that $\frac{d(\Delta T)}{dA}$ is constant

$$\frac{dT}{dq} = \frac{(\Delta T_2 - \Delta T_1)}{q_T} \tag{4.2.7}$$

where q_T is the rate of heat transfer in the entire heat exchanger. Using Equation 4.2.8

$$\frac{dT}{U\Delta T dA} = \frac{(\Delta T_2 - \Delta T_1)}{q_T} \tag{4.2.8}$$

$$\int_{\Delta T_1}^{\Delta T_2} \frac{d(\Delta T)}{\Delta T} = \frac{U(\Delta T_2 - \Delta T_1)}{q_T} \int_0^A dA \tag{4.2.9}$$

$$\ln\left(\frac{\Delta T_2}{\Delta T_1}\right) = \frac{U(\Delta T_2 - \Delta T_1)}{q_T A} \tag{4.2.10}$$

$$q_T = \frac{UA(\Delta T_2 - \Delta T_1)}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} = UA\Delta T_{lm} \tag{4.2.11}$$

4.2.2.6.2. Number of Transfer Units (NTU)Method

In 1955, Kays and London found the effectiveness-NTU (or NTU) method. NTU method facilitates heat exchanger analysis. Heat transfer effectiveness ε is defined as;

$$\varepsilon = \frac{\dot{Q}}{Q_{max}} = \frac{Actual\ heat\ transfer\ rate}{Maximum\ possible\ heat\ transfer\ rate} \tag{4.2.12}$$

$$\dot{Q} = C_c\left(T_{c,out} - T_{c,in}\right) = C_h\left(T_{h,in} - T_{h,out}\right) \tag{4.2.13}$$

where, $C_c = \dot{m}_c c_{p,c}$ and $C_h = \dot{m}_c c_{p,h}$. If,

$$\mathrm{C}_c < C_h\text{:}\ Q_{max} = C_c(T_{h,in} - T_{c,in}) \tag{4.2.14}$$

$$\mathrm{C}_h < C_c\text{:}\ Q_{max} = C_h(T_{h,in} - T_{c,in}) \tag{4.2.15}$$

The number of transfer units (NTU) is a dimensionless parameter and defined as:

$$NTU = \frac{UA}{C_{min}} \tag{4.2.16}$$

where, C_{min} is the smaller of C_c and C_h. In the heat exchanger another dimensionless parameter is the capacity ratio c.

$$c = \frac{C_{min}}{C_{max}} \qquad (4.2.17)$$

Effectiveness of a heat exchanger is a function of NTU and capacity ratio, c. [2]

$$\varepsilon = \text{function}(NTU, c) \qquad (4.2.18)$$

4.2.3. Experimental Setup

The apparatus used in this experiment is shown in Fig. 4.2.7 and Fig. 4.2.8:

Number of active plates : 5

Plate overall dimensions : 75 mm x 115 mm

Projected heat transmission area: 0.008 m^2 per plate

Figure 4.2.7. Armfield plate type heat exchanger.

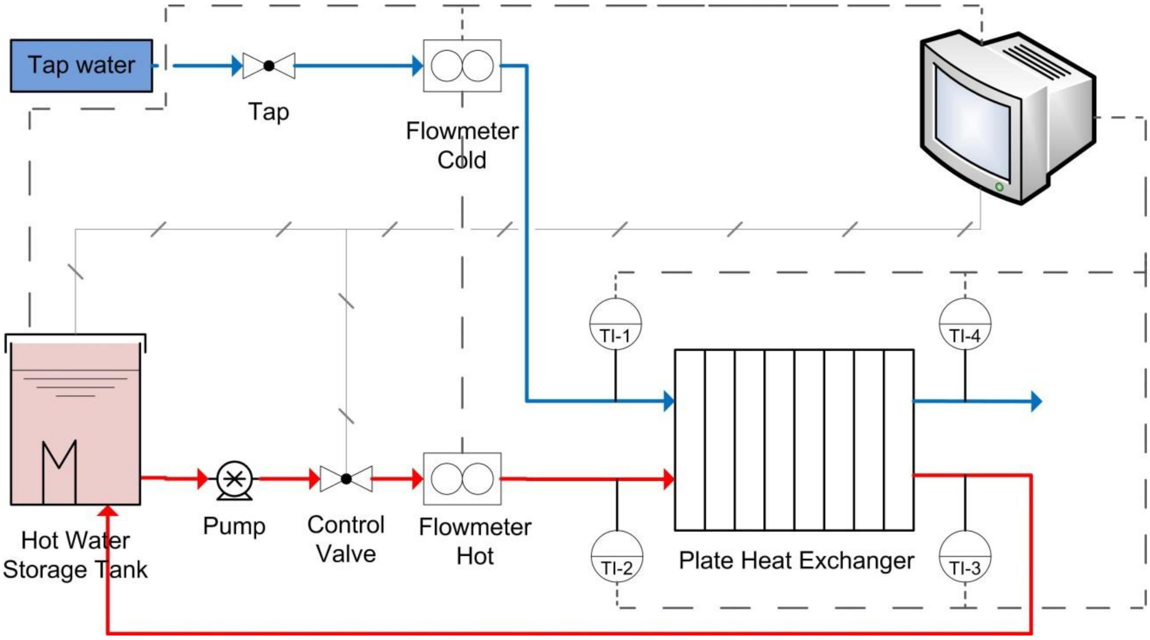


Figure 4.2.8. Flow diagram of experimental apparatus.

4.2.4. Procedure

1. Open the tap for cold water inlet and adjust water flow rate to a desired value.
2. Fill the hot water tank with distilled water.
3. Turn on the hot water tank and adjust the temperature to a desired value.
4. Open hot water valve and adjust water flow rate to a desired value.
5. When the system has reached the steady-state; record the flow rates and inlet and outlet temperatures of hot and cold water.
6. Repeat the experiment for different flow rates of hot and cold water without changing water tank temperature.
7. Repeat the experiment for different hot water tank temperatures.
8. Repeat the experiment for cocurrent flow.

Safety Issues: In this experiment hot and cold water are used. There is a chance of a pipe bursting or a valve leaking water causing water to spray around the area of the heat exchanger. Wet surface may cause slips or falls. While admitting cold and hot water to the system, open the valves cautiously and check all connections for possible leaks. At the end of the experiment, be sure that all electronic parts are turned off and the water valves are closed. For serious injuries get medical attention.

4.2.5. Report Objectives

1. Use the recorded inlet/outlet temperatures of streams and their corresponding flow rates to calculate the heat absorbed and heat emitted. Calculate the effectiveness.
2. Calculate the overall heat transfer coefficient, U by LMTD method.
3. Use NTU (number of transfer units) method to calculate theoretical value of U and compare with the one obtained as a result of experimental calculations.

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4.3. DETERMINATION OF OVERALL HEAT TRANSFER COEFFICIENT IN A SHELL AND TUBE HEAT EXCHANGER

Keywords: *Shell and tube exchanger, heat transfer coefficient, effect of inlet temperature and flow rate, concurrent, countercurrent, NTU method.*
Before the experiment: *Read the booklet carefully. Be aware of the safety precautions.*

4.3.1. Aim

To measure the heat transfer coefficient of a single-pass shell and tube heat exchanger.

4.3.2. Theory

In the majority of chemical processes heat is either given out or absorbed, and in a very wide range of chemical plants, chemical engineers are involved in heating and cooling fluids. Thus in furnaces, evaporators distillation units, dryers, and reaction vessels one of the major problems is that of transferring heat at the desired rate. Alternatively, it may be necessary to prevent the loss of heat from a hot vessel or steam pipe. The control of the flow of heat in the desired manner is a key in chemical engineering practice. Heat transfer processes can be categorized into three basic modes, namely conduction, convection and radiation. All three modes may occur simultaneously in problems of practical importance [1].

4.3.2.1. Convection

Convection is the term applied to the heat transfer mechanism that occurs in a fluid by the mixing of one portion of the fluid with another portion due to gross movements of the mass of fluid. The actual process of energy transfer from one fluid particle or molecule to another is still one of conduction, but the energy may be transported from one point in space to another by the displacement of the fluid itself. The fluid motion may be caused by external means, e.g., by a fan, pump, etc., in which case the process is called “forced convection”. If the fluid motion is caused by density differences which are created by the temperature differences existing in the fluid mass, the process is termed “free convection”, or “natural convection”. The motion of the water molecules in a pan heated on a stove is an example of a free convection process. The important heat transfer problems of condensing and boiling are also examples of convection, involving the additional complication of a latent heat exchange. It is virtually impossible to observe pure heat conduction in a fluid because as soon as a temperature difference is imposed on a fluid, natural convection currents will occur due to the resulting density differences [2].

4.3.2.2. Countercurrent and Co-Current Flow

The principles of heat transfer find application most commonly in the design of heat exchanger units for the exchange of heat between two fluid streams at different levels of temperatures while keeping them from mixing. Heat exchangers are arrangements of surfaces separating the fluids between which heat transfer takes place. These surfaces are heated by one fluid and cooled by the other [3].

If the two fluids enter at different ends of the exchanger and pass in opposite directions through the unit, this is called countercurrent flow. The temperature-length curves for this case are shown in Figure 4.3.1. The four terminal temperatures are denoted as follows:

$T_{h,i}$: temperature of entering hot fluid, °C
$T_{h,o}$: temperature of leaving hot fluid, °C
$T_{c,i}$: temperature of entering cold fluid, °C
$T_{c,o}$: temperature of leaving cold fluid, °C

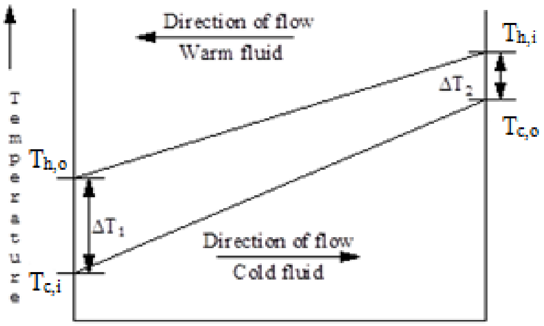


Figure 4.3.1. Countercurrent flow.

The approaches are [4]:

$$T_{h,o} - T_{c,i} = \Delta T_1 \tag{4.3.1}$$

$$T_{h,i} - T_{c,o} = \Delta T_2 \tag{4.3.2}$$

If the two fluids enter at the same end of the exchanger and flow in the same direction to the other end, the flow is called cocurrent flow. The temperature-length curves for cocurrent flow area shown in Figure 4.3.2.

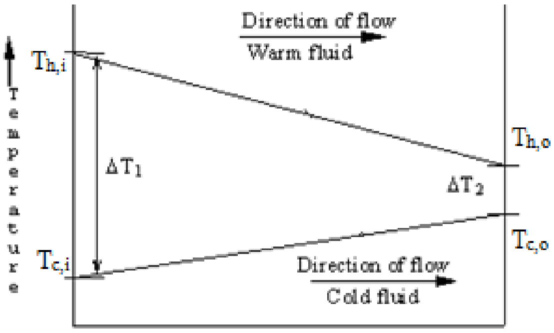


Figure 4.3.2. Cocurrent flow.

The approaches are [4]:

$$T_{h,i} - T_{c,i} = \Delta T_1 \quad (4.3.3)$$

$$T_{h,o} - T_{c,o} = \Delta T_2 \quad (4.3.4)$$

Cocurrent flow is rarely used because, as inspection of Figures 4.3.1 and 4.3.2 will show, it is not possible with this method of flow to bring the exit temperature of one fluid close to the entrance temperature of the other, and the heat that can be transferred is less than that possible in countercurrent flow. Cocurrent flow is used in special situations where it is necessary to limit the maximum temperature of the cooler fluid or where it is important to change the temperature of at least one fluid rapidly [4].

4.3.2.3. Enthalpy Balances in Heat Exchangers

In heat exchangers there is no shaft work, and mechanical-potential and mechanical-kinetic energies are small in comparison with the other terms in the energy-balance equation. Thus, for one stream through the exchanger [4]:

$$\dot{m}(H_o - H_i) = q \quad (4.3.5)$$

where $\dot{m}$: flow rate of stream, kg/hr

q : Q/t, heat flow into stream, W

H_i, H_o : enthalpies of stream at entrance and exit, respectively, J/kg

Equation (4.3.5) may be written for each stream flowing through the exchanger. It is customary to neglect heat flow between the shell side of the heat exchanger and the ambient air as well as the heat transfer through the walls of the tubes from the hot fluid to the cold fluid. Under these assumptions, the heat lost by the hot fluid is gained by the cold fluid, and

$$-q_h = q_c \tag{4.3.6}$$

If constant specific heats are assumed, the overall enthalpy balance for a heat exchanger becomes:

$$\dot{m}_h C_{p,h}\left(T_{h,i} - T_{h,o}\right) = \dot{m}_c C_{p,c}\left(T_{c,o} - T_{c,i}\right) = q \tag{4.3.7}$$

4.3.2.4. Average Temperature of Fluid Stream

When a fluid is being heated or cooled, the temperature will vary throughout the cross-section of the stream. If the fluid is being heated, the temperature of the fluid is at maximum at the wall of the heating surface and decreases toward the center of the stream. If the fluid is being cooled, the temperature is a minimum at the wall and increases toward the center. Because of these radial temperature gradients, it is necessary to define what is meant by the temperature of the stream. It is agreed that it is the temperature that would be attained if the entire fluid stream flowing across the section in question were withdrawn and mixed adiabatically to uniform temperature. The temperature so defined is called the average stream temperature. The temperatures plotted in Figures 4.3.1 and 4.3.2 are all average stream temperatures [3].

4.3.2.5. Overall Heat Transfer Coefficient

It can be expected that the heat flux may be proportional to a driving force. In heat flow, the driving force is taken as T_h - T_c where T_h is the average temperature of the hot fluid and T_c is that of the cold fluid. The quantity T_h - T_c is the over-all temperature difference. It is denoted by ΔT. It is clear from Figure 4.3.1 that T can vary considerably from point to point along the tube, and therefore since the heat flux is proportional to ΔT, the flux also varies with tube length. It is necessary to start with a differential equation, by focusing attention on a differential area dA through which a differential heat flow dq occurs under the driving force of a local value of ΔT. The local flux is then dx/dA and is related to the local value of ΔT by the equation [4]:

$$\frac{dq}{dA} = U\Delta T = U(T_h - T_c) \tag{4.3.8}$$

The quantity U, defined by Equation (4.3.8) as a proportionality factor between dq/dA and ΔT, is called the local overall heat-transfer-coefficient.

When ΔT_1 and ΔT_2 are close, their arithmetic average may be used for ΔT. When the difference between ΔT_1 and ΔT_2 is more than 40 percent, the logarithmic mean temperature difference should always be used. For all flow types including countercurrent flow, cocurrent flow, or multipass flow, logarithmic mean temperature difference can be used in order to calculate ΔT [3]:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{4.3.9}$$

The assumptions for the calculation of overall heat transfer coefficient are [4]:

1. The overall coefficient U is constant.
2. The specific heats of the hot and cold fluids are constant.
3. Heat exchange with the surroundings is negligible.
4. The flow is steady.

4.3.2.6. NTU Method

The number of transfer units (NTU) method is used to calculate the theoretical overall heat transfer coefficient (U) by using effectiveness charts [3]. In addition to the effectiveness, the ratio of C_{min}/C_{max} is needed (C_{min} is the smaller of the two heat capacity rates C_c and C_h and C_{max} is the higher one). From the effectiveness graphs, the intersection point of the ratio C_{min}/C_{max} and effectiveness value gives the NTU value [3]. The effectiveness [3]:

$$\varepsilon = C_h\,(T_{h,i} - T_{h,o})\,/\,C_{min}(T_{h,i} - T_{c,i}) \tag{4.3.10}$$

$$\varepsilon = C_c(T_{c,o} - T_{c,i})\,/\,C_{min}(T_{h,i} - T_{c,i}) \tag{4.3.11}$$

Then the theoretical heat transfer coefficient value (U) is calculated by the following equation [3],

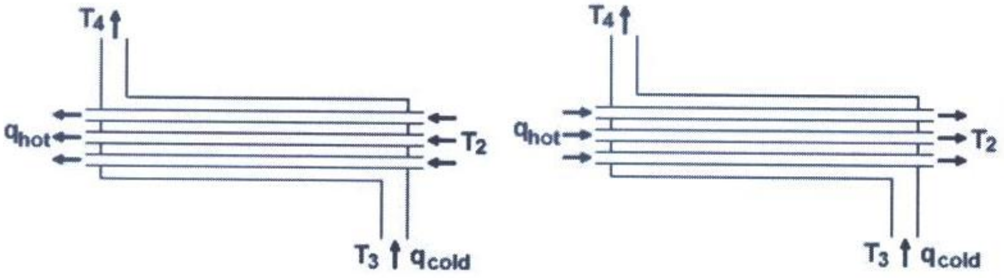
$$NTU = \frac{UA}{C_{min}} \tag{4.3.12}$$

$$U = \frac{NTU \times C_{min}}{A} \tag{4.3.13}$$

The heat transfer coefficients change in case of alterations in fluid flow rates and inlet fluid temperatures. Those may either be calculated experimentally through log mean temperature difference (LMTD) or theoretically through number of transfer units (NTU) method.

4.3.3. Experimental Setup

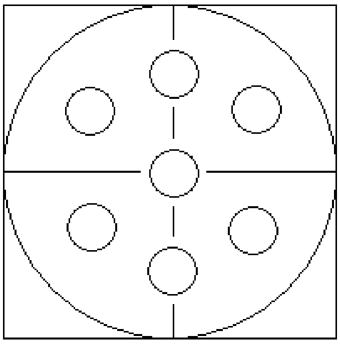
The apparatus used in this experiment is shown in Figure 4.3.3:



Cocurrent Flow

Countercurrent Flow

Length of each tube = 14.4 cm
Number of tubes = 7
Inner diameter of an inner tube = 0.515 cm
Outer diameter of an inner tube = 0.635 cm



Cross section of tubular bundle

Figure 4.3.3. Schematic diagram of the heat exchanger.

4.3.4. Procedure

1. Open the inlet valve for cold water and adjust the water flow rate to a desired value.
2. Fill the hot water tank with distilled water.
3. Turn on the hot water tank and adjust the temperature to a desired value.
4. Open hot water valve and adjust water flow rate to a desired value.

5. When the system has reached steady-state; record the flow rates and inlet and outlet temperatures of hot and cold water.
6. Fix cold water flow rate at 1 L/min throughout the experiment.
7. Repeat the experiment for 3 different flow rates of hot water without changing water tank temperature.
8. Repeat the experiment for 3 different hot water tank temperatures without changing water flow rates.
9. Repeat the experiment for cocurrent flow.

Safety Issues: Before starting the experiment, be sure that all the water valves are connected to the system and turned open. Fill the hot water tank with distilled water to the level that reaches to the thermocouple. At the end of the experiment, be sure that all water valves are closed and the heat exchanger system is turned off.

4.3.5. Report Objectives

1. For each case calculate the experimental value of overall heat transfer coefficient.
2. Discuss the effect of process variables, i.e. hot water flow rate, temperature difference and pattern of flow on heat transfer coefficient.
3. Using NTU method, calculate the theoretical value of overall heat transfer coefficient. Calculate and discuss the error.

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4.4. DETERMINATION OF HEAT TRANSFER RATE IN BOILING AND CONDENSATION

Keywords: *Boiling, convective boiling, nucleate boiling, film boiling, heat transfer rate, heat transfer coefficient, heat flux, filmwise condensation, current, potential difference.*
Before the experiment: *Read the booklet carefully. Be aware of the safety precautions.*

4.4.1. Aim

The object of this experiment is to improve the understanding of boiling and condensing heat transfer and enables both a visual and analytical study of these processes. In the first part of the experiment, the convective, nucleate and film boiling phenomena are observed. In the second part of the experiment, heat flux and heat transfer coefficient values are calculated and compared for constant cooling flow rate, constant pressure and constant potential difference conditions.

4.4.2. Theory

Boiling and condensation are vital links in the transfer of heat from a hot to a colder region in countless applications, e.g., thermal and nuclear power generation in steam plants, refrigeration, refining, heat transmission, etc [1].

4.4.2.1. Boiling

When a liquid at saturation temperature is in contact with the surface of a solid (usually metal) at a higher temperature, heat is transferred to the liquid and a phase change (evaporation) of some of the liquid occurs. The nature and rate of this heat transfer change considerably as the temperature difference between the metal surface and the liquid is increased [1].

Although *boiling* is a process familiar to everyone, the production of vapor bubbles is a very interesting and complex process. Due to surface tension, the vapor inside a bubble must be at a higher pressure than the surrounding liquid. The pressure difference increases as the diameter of the bubble decreases, and is insignificant when the bubble is large [1].

However, when the bubble is minute, an appreciable pressure difference exists. The pressure inside the bubble is the vapor pressure corresponding with the temperature of the surrounding liquid. Thus, when no bubbles exist (or are very small) it is possible for the liquid temperature in the region of the heat transfer surface to be well above the temperature of the bulk of the liquid. (This will be close to the saturation temperature corresponding with the pressure at the free liquid-vapor interface). The formation of the bubbles normally associated with boiling is influenced by the foregoing [1].

4.4.2.1.1. Convective Boiling

When the heating surface temperature is slightly hotter than the saturation temperature of the liquid, the excess vapor pressure is unlikely to produce bubbles. The locally warmed liquid expands and convection currents carry it to liquid-vapor interface where evaporation takes place and thermal equilibrium is restored. Thus, in this mode, evaporation takes place at small temperature differences and with no bubble formation [1].

4.4.2.1.2. Nucleate Boiling

As the surface becomes hotter, the excess of vapor pressure over local liquid pressure increases and eventually bubbles are formed. These occur at nucleating points on the hot surface where minute gas pockets, existing in surface defects from the nucleus for the formation of a bubble. As soon as a bubble is formed, it expands rapidly as the warmed liquid evaporates into it. The buoyancy detaches the bubble from the surface and another starts to form [1].

Nucleate boiling is characterized by vigorous bubble formation and turbulence. Exceptionally high heat transfer rates and heat transfer coefficients with moderate temperature differences occur in nucleate boiling, and in practical applications, boiling is nearly always in this mode [1].

4.4.2.1.3. Film Boiling

Above a critical surface-liquid temperature difference, it is found that the surface becomes vapor locked and the liquid is unable to wet the surface. When this happens there is a considerable reduction in heat transfer rate and if the heat input to the metal is not immediately reduced to match the lower ability of the surface to transfer heat, the metal temperature will rise until radiation from the surface plus the limited film boiling heat transfer, is equal to the energy input [1].

If the energy input is in the form of work (including electrical energy) there is no limit to the temperature which could be reached by the metal and its temperature can rise until a failure or a burn out occurs. If the source is radiant energy form, for example, a combustion process, a similar failure can occur, and many tube failures in the radiant section of advanced boilers are attributed to this cause. Immersion heaters must be obviously designed with sufficient area so that the heat flux never exceeds the critical value [1].

4.4.2.2. Condensing Heat Transfer

Condensation of a vapor onto a cold surface may be filmwise or dropwise. When filmwise condensation occurs, the surface is completely wetted by the condensate and condensation is onto the outer layer of the liquid film, the heat passing through the film and into the surface largely by conduction [1].

By treating a surface with a suitable compound it may be possible to promote dropwise condensation. When this occurs, the surface is not wetted by the liquid and the surface becomes covered with beads of liquid which coalesce to form drops which then fall away leaving the surface bare for a repetition of the action [1].

Heat transfer coefficients with dropwise condensation are higher than with filmwise owing to the absence of the liquid film. Boiling and condensating heat transfer are indispensable links in the production of power, all types of refining and chemical processes, refrigeration, heating systems, etc. There is a constant pressure for more compact heat transfer units with high heat transfer rates and a clear understanding of the boiling and condensing processes is essential for every mechanical and chemical engineer [1].

4.4.2.3. Heat Flux and Surface Heat Transfer Coefficient

Heat transfer could be determined via Newton’s Law of Cooling [1], which is given as follows.

$$Q = hA(T_{metal} - T_{liquid}) \tag{4.1}$$

where,
Q: Heat transfer, W
A: Area of the metal surface, m^2

h: Heat transfer coefficient, $W.m^{-2}.°C^{-1}$
T_{metal}: Temperature of the metal, °C
T_{liquid}: Temperature of the liquid, °C

Power is mostly defined as the rate of energy change with time. The power is simply depends of current, which is the rate of charge flow past a given area called electric current, and potential difference. The power is determined as follows.

$$P = I \times V \tag{4.2}$$

In many heat transfer applications it is important to know the rate at which heat is transferred from a hot surface to the surrounding fluid, at a given temperature difference. This rate is expressed by the *heat flux* and is expressed in Wm^{-2} [2].

$$Heat\ flux = q'' = \frac{Q}{A} \tag{4.3}$$

For many design purposes it is more convenient to express the thermal performance of a surface / fluid combination in terms of the heat flux per degree of temperature difference - i.e., *surface heat transfer coefficient* and is expressed in $Wm^{-2}K^{-1}$. In boiling heat transfer both the heat flux and the surface heat transfer coefficient are extremely high compared with other types of heat transfer [2].

4.4.2.4. Overall Heat Transfer Coefficient

The overall heat transfer coefficient could be used to determine the total heat transfer through a heat exchanger or a system. The overall heat transfer coefficient depends on the heat transfer area, log mean temperature difference of the system and rate of heat transfer. The formulation is given as follows.

$$Q = UA\Delta T_{lm} \tag{4.4}$$

where,

Q: Heat transfer, W

A: Area of the metal surface, m^2

U: Overall heat transfer coefficient, $W.m^{-2}.°C^{-1}$

ΔT_{lm}: Log mean temperature difference, °C

The heat transfer could be obtained by following formula.

$$Q = mc_p(T_{outlet} - T_{inlet}) \tag{4.5}$$

where,

m: Mass flow, g

c_p: Heat capacity, $J.K^{-1}$

T_{inlet}: Temperature of inlet stream, °C

T_{outlet}: Temperature of outlet stream, °C

For the calculation of the log mean temperature difference, the following formula is used;

$$\Delta T_{lm} = \frac{(\Delta T_2 - \Delta T_1)}{ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} \tag{4.6}$$

where,

$$\Delta T_1 = T_{saturation} - T_{inlet} \tag{4.7}$$

$$\Delta T_2 = T_{saturation} - T_{outlet} \tag{4.8}$$

4.4.2.5. Saturation Pressure

During the boiling, liquid vapor equilibrium is reached for a closed system after adequate time is passed. At equilibrium, the vapor and liquid amounts are not changed. To determine the vapor pressures, Antoine equation could be utilized, which is demonstrated as follows [3].

$$ln\, P_{sat}(kPa) = A - \frac{B}{T(°C) + C} \tag{4.9}$$

4.4.3. Experimental Setup

A high watt density electric heating element in a copper sleeve submerged in the liquid is mounted horizontally in a vertical glass cylinder. The temperature of the copper sleeve is measured by a thermocouple and digital indicator.

The electrical input to the heater may be varied from 0 to approximately 300 W by a variable transformer, the actual heat transfer rate being obtained from the product of the voltmeter and ammeter readings.

A controller incorporated in the temperature indicator, switches off the electrical input if the temperature of the heating surface exceeds a pre-set value.

A cooling water flow meter used in conjunction with glass thermometers measuring the cooling water temperatures, enables the rate of heat transfer at the condenser to be measured. The logarithmic mean temperature difference may also be determined. Glass thermometers are also mounted inside the glass cylinder to indicate the temperature of the liquid and vapor.

The apparatus used in this experiment is shown in Figure 4.1.1. The dimensions and properties of the equipment that will be used in the experiment are given as follows.

Table 4.4.1. Unit specifications.

Fluid	Methylene Chloride (CH_2Cl_2)
Quantity of fluid	Liquid level to be not less than 50 mm above heating element, approximately 0.55 liter.
Condenser surface area	0.032 m^2
Maximum permitted surface temperature	270°C
Heater cut out temperature	220°C
Dimensions of heating surface	Effective length = 29.5 mm Diameter = 12.7 mm Surface area = 0.0013 m^2 (including area of end)
Dimensions of glass chamber	Nominal internal diameter = 80 mm Length = 300 mm Volume = 0.0015 m^3

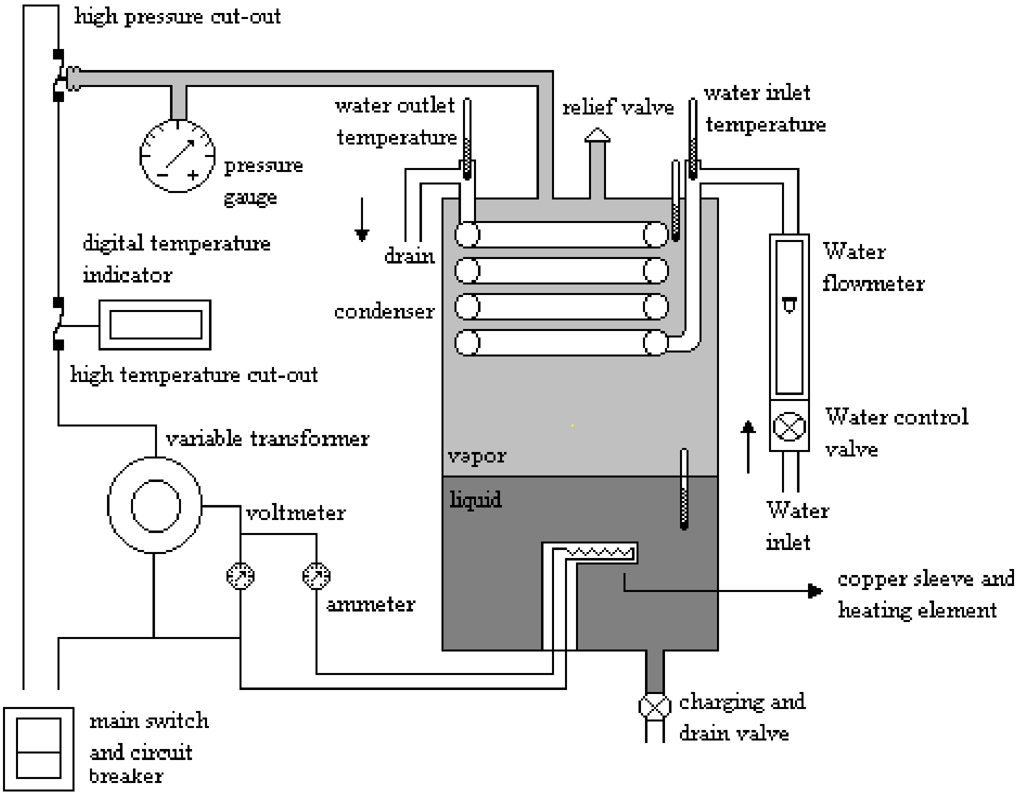

Figure 4.4.1. Boiling heat transfer unit.

4.4.4. Procedure

1. Turn on the electrical and water supplies and adjust both to low settings. Allow the digital thermometer to stabilize.
2. Observe the three types of boiling; convective boiling, nucleate boiling, film boiling by increasing the power input at between 200 and 300W.
3. At constant flow rate, by changing the voltage between 50 V and 175 V (50, 75, 100, 125,150, 175), record the temperatures of liquid, metal, saturation, inlet and outlet, voltage and gauge pressure.
4. At constant voltage, by changing the flow rate between 10 g/sec and 50 g/sec (10, 20, 30, 40, 50), record the temperatures of liquid, metal, saturation, inlet and outlet, flow rate and gauge pressure.
5. In each run, in order to attain the liquid and vapor equilibrium, 3-5 minutes should be waited.

Safety Issues: Before the experiment, be sure that the cooling water is connected and ready for use, the pressure and temperature of the methylene chloride agree with those at saturation conditions and the digital temperature indicator is showing the same temperature as the liquid thermometer. Methylene chloride is present in a closed vessel and it is unlikely to come into contact with the substance. In case of eye contact, check for and remove any contact lenses, immediately flush eyes with running water for at least 15 minutes, keeping eyelids open and get medical attention immediately [4]. In case of skin contact, immediately flush skin with plenty of water, cover the irritated the skin with an emollient and get medical attention [4]. In case of inhalation, remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen [4]. After the experiment, be sure that the boiling heat transfer unit is turned off and the cooling water is not running.

4.4.5. Report Objectives

1. Discuss in detail boiling phenomena using the visual aspects you obtained referring to the theory.
2. Determine heat transfer rate, heat flux, surface to liquid temperature difference and surface heat transfer coefficient for each measurement. Construct the graphs for the following relations on log-log basis: heat flux vs surface to liquid temperature difference, surface heat transfer coefficient vs surface to liquid temperature difference.
3. Determine heat addition and removal rates, heat loss to the surrounding and overall heat transfer coefficient for each measurement. Construct overall heat transfer coefficient vs log mean temperature difference graphs on log-log basis.
4. Construct the saturation temperature vs saturation pressure graph.

References

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APPENDIX A: Raw Data Sheet

Table A.1. Raw data for constant voltage.

Water flowrate (g/s)	**T_m (°C)**	**T_{liq} (°C)**	**T_{sat} (°C)**	**T_{in} (°C)**	**T_{out} (°C)**	**V (V)**	**I (A)**

Table A.2. Raw data for constant water flowrate.

Water flowrate (g/s)	**T_m (°C)**	**T_{liq} (°C)**	**T_{sat} (°C)**	**T_{in} (°C)**	**T_{out} (°C)**	**V (V)**	**I (A)**

4.5. HEAT TRANSFER IN EXTENDED SURFACES

Keywords: *Heat conduction, natural convection, thermal conductivity, heat transfer coefficient, fin.*

Before the experiment: *Read the booklet carefully. Be aware of the safety precautions.*

4.5.1. Aim

The object of this experiment is to calculate the thermal conductivity of a steel rod and brass rod given the thermal conductivity of an aluminum rod of the same geometry and thereby providing an application of steady state fin heat transfer. Only natural convection is considered here.

4.5.2. Theory

Heat transfer is the transfer of energy that occurs as a result of a driving force, which is called temperature difference. There are three mechanisms by which heat transfer can occur: conduction, convection or radiation [1].

In conduction, heat can be conducted through solids, liquids, and gases. The heat is conducted by the transfer of the energy of motion between adjacent molecules. In a gas the “hotter” molecules, which have greater energy and motions, impart energy to the adjacent molecules at lower energy levels. This type of transfer is present to some extent in all solids, gases or liquids in which a temperature gradient exists. In conduction, energy can also be transferred by free electrons, which is quite important in metallic solids. Examples of heat transfer mainly by conduction are heat transfer through walls of exchangers or a refrigerator, heat treatment of steel forgings, freezing of the ground during the winter, and so on.

Convection implies transfer of heat due to bulk transport and mixing of macroscopic elements of liquid or gas. Because motion of a fluid is involved, heat transfer by convection is partially governed by the laws of fluid mechanics. If convection is induced by density differences resulting from temperature differences within the fluid, it is said to be natural convection. However, if the motion of the fluid is the result of an outside force, as might be exerted by a pump impeller, then it is called forced convection [2].

Natural convection heat transfer occurs when a solid surface is in contact with a gas or liquid, which is at a different temperature from the surface. Density differences in the fluid arising from the heating process provide the buoyancy force required to move the fluid. Free or natural convection is observed as a result of the motion of the fluid. An example of heat transfer by natural convection is a hot radiator used for heating a room. Cold air encountering the radiator is heated and rises in natural convection because of buoyancy forces. An important heat transfer system occurring in process engineering is the transfer of heat from a hot vertical plate to a gas or liquid adjacent to it by natural convection [3].

4.5.2.1. Convective Heat Transfer Coefficient

When the fluid outside the solid surface is in forced or natural convective motion, the rate of heat transfer from the solid to the fluid, or vice versa, is expressed by the following equation:

$$q = h\,A\,(\,T - T_a\,) \tag{4.5.1}$$

where q is the heat transfer rate in W, A is the area in m^2, T is the temperature of the solid surface in K, T_a is the average or bulk temperature of the fluid flowing by in K, and h is the convective heat transfer coefficient in W/m^2. K.

The convective heat transfer coefficient, h, is a function of the system geometry, fluid properties, flow velocity, and temperature difference. Empirical correlations are used to predict this coefficient, since it often cannot be predicted theoretically. When a fluid flows by a surface there is a thin, almost stationary layer or film of fluid adjacent to the wall which presents most of the resistance to the heat transfer. The resistance caused by this film is often called a film coefficient [4].

4.5.2.2. Thermal Conductivity

Thermal conductivity is, a property of the material and it is a function of temperature and pressure. The thermal conductivity of an ideal gas is independent of pressure. Thermal conductivities of gases, liquids, and solids are moderately dependent on temperature. In general, an increase in temperature causes the conductivity of a gas to increase and the conductivity of a solid or liquid to decrease. However, there are many exceptions to these generalizations; in fact, there are some substances for which conductivities pass through maxima or minima with change in temperature. In considering the thermal conductivities, the magnitudes of the values decrease markedly as they are considered in the order of decreasing density [4].

4.5.2.3. Effects of Fins on Heat Transfer

The use of fins or extended surfaces on the outside of a heat exchanger pipe wall to give relatively high heat transfer coefficients in the exchanger is quite common. They increase the total amount of heat transfer by increasing the heat transfer area. An automobile radiator is such a device, where hot water passes inside through a bank of tubes and loses heat to air. On the outside of the tubes, extended surfaces receive heat from the tube walls and transmit it to the air by forced convection.

In this experiment, long aluminum and steel cylindrical rods of uniform diameter are used as fins.

Consider a long cylindrical rod of uniform diameter (D), heated on one end and exposed to air throughout its length. The temperature (T) is assumed to be a function of x. The thermal conductivity (k) and the heat transfer coefficient (h) are assumed to be constant. By denoting the perimeter of the cylinder as P, eqn. (4.5.2) is written [4]

$$\underbrace{Q_x}_{Heat\,conducted\,in} - \underbrace{Q_{x+\Delta x}}_{Heat\,conducted\,out} - \underbrace{h(P\Delta x)(T-T_a)}_{Convected\,heat} = \underbrace{A\Delta x\rho C_p \frac{\partial T}{\partial t}}_{Heat\,accumulated} \tag{4.5.2}$$

using the Fourier's heat conduction law

$$Q = -k\,A\frac{\partial T}{\partial x} \tag{4.5.3}$$

for steady state, the following ODE is obtained

$$\frac{d^2T}{dx^2} = \left(\frac{4h}{kD}\right)(T-T_a) \tag{4.5.4}$$

The following relation is obtained by solving the above ODE,

$$\frac{(T-T_a)}{(T_s-T_a)} = \exp\left(-\sqrt{\frac{4h}{kD}}\,x\right) \tag{4.5.5}$$

4.5.3. Experimental Setup

The apparatus used in this experiment is shown in Figure 4.5.1.

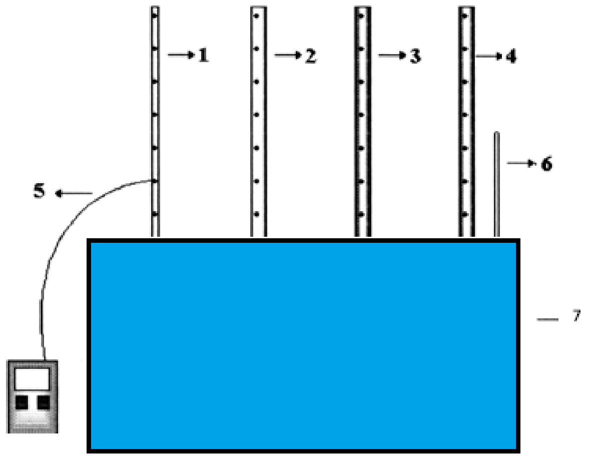

Figure 4.5.1. Experimental set up of heat transfer.

1.) Aluminum rod (D = 12 mm)
2.) Aluminum rod (D = 24 mm)
3.) Steel rod (D = 24 mm)
4.) Brass rod (D = 24 mm)
5.) Thermocouple
6.) Thermometer
7.) Water bath

4.5.4. Procedure

1. Set the temperature of the water bath to the desired value (above 60 ˚C).
2. Before the experiment is performed, check the temperature of the water bath whether is reached steady state or not, and record it as T_s.
3. Check the temperature of the rod to see if steady state has been achieved.
4. Note the temperatures shown on each thermocouple for each rod. Be careful to allow the readings to reach equilibrium before recording the temperature.
5. Make sure to record the room temperature for each run as T_a. Do not take the room temperature near the water bath.

Safety Issues: Avoid direct contact with hot rods. Be sure of that water tank is unplugged at the end of the experiment.

4.5.5. Report Objectives

1. Using the Fourier's heat conduction law show that

$$\frac{(T-T_a)}{(T_s-T_a)} = \exp\left(-\sqrt{\frac{4h}{kD}}\,x\right)$$

where

T_a = ambient temperature

T_s = temperature of heat source

Use the following boundary conditions:

$T = T_s$ at $x = 0$

$T \rightarrow T_a$ as $x \rightarrow \infty$

2. Prepare a table for $(T - T_a) / (T_s - T_a)$ as a function of $x(4 / kD)^{1/2}$ for both aluminum rods from the obtained data. Use the temperature indicated by the thermocouple number one as T.

3. Determine "h" for both aluminum rods from a graph of $\ln\{ (T - T_a) / (T_s - T_a) \}$ versus $x(4 / kD)^{1/2}$.

4. Determine "k" for each rod, steel and brass, from a graph of $\ln\{ (T - T_a) / (T_s - T_a) \}$versus $x(4h / D)^{1/2}$. Use the value of h obtained for the aluminum rod which has 24 mm diameter.

5. Discuss the effect of geometry on heat transfer coefficient and compare the experimental heat transfer coefficient with the one in literature.

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