CHAPTER 3: EXPERIMENTAL

3.1 : General

The details regarding the experimental design & shell and tube heat exchanger fabricated for the study are discussed in this chapter. The experimental procedure and the methodology adopted for the calculation of the various parameters are also dealt with. This work investigates heat transfer between hot water (single phase) and two-phase (liquid-liquid) process stream. Seven two-phase liquid-water systems have been investigated. These are Kerosene-water, Diesel-water, Nitro benzene-water, Oleic acid-water, Palm oil-water, Octane-water and Dodecane-water. The range of thermo physical & transport properties of various pure liquids used for formulation of two-phase, liquid-liquid systems are given in Table 3.1.

Table 3.1: Range of properties investigated

<table>
<thead>
<tr>
<th>Property</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>viscosity ( \mu )</td>
<td>( 0.001 &lt; \mu &lt; 0.02 ) kg/ms</td>
</tr>
<tr>
<td>density ( \rho )</td>
<td>( 678 &lt; \rho &lt; 1199 ) kg/m³</td>
</tr>
<tr>
<td>thermal conductivity ( k )</td>
<td>( 0.129 &lt; k &lt; 0.624 ) W/mK</td>
</tr>
<tr>
<td>heat capacity ( Cp )</td>
<td>( 1418 &lt; Cp &lt; 4187 ) J/kgK</td>
</tr>
<tr>
<td>Prandtl number ( Pr )</td>
<td>( 3.75 &lt; Pr &lt; 67 )</td>
</tr>
</tbody>
</table>

3.2 : Experimental setup

The photograph and schematic diagram of the heat exchanger experimental setup with other accessories are shown in Figure 3.1 and 3.2. The specifications of 1-2 shell and tube exchanger in detail are given in Table 3.2. This experimental setup was fabricated by Mahesh industries, Trichy and commissioned in the Chemical Engineering Department. Necessary instrumentation for measurement and control was also provided.
Figure 3.1: Photographs of 1-2 shell and tube heat exchanger with accessories
Figure 3.2: A schematic diagram of the experimental set-up

Table 3.2: Specifications of shell and tube heat exchanger (experimental set-up)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube size</td>
<td>ID=10 mm ; OD=12 mm</td>
</tr>
<tr>
<td>Shell size</td>
<td>ID=118 mm ; OD=126 mm</td>
</tr>
<tr>
<td>Number of tubes</td>
<td>14</td>
</tr>
<tr>
<td>Tube side passes</td>
<td>2</td>
</tr>
<tr>
<td>Shell side passes</td>
<td>1</td>
</tr>
<tr>
<td>Baffle spacing</td>
<td>86 mm</td>
</tr>
<tr>
<td>Length of tube</td>
<td>43 mm</td>
</tr>
<tr>
<td>Tube pitch</td>
<td>15 mm</td>
</tr>
</tbody>
</table>
The set-up consists of the following accessories:

(i). 1-2 shell and tube heat exchanger,

(ii). process fluid storage tank,

(iii). hot water tank,

(iv). auxiliary cooling tank fitted with helical coil,

(v). mono block pump,

(vi). gear pump,

(vii). rotameters,

(viii). electrical heater,

(ix). temperature controller with indicator and

(x). agitator.

The heat exchanger used here is a 1-2 shell tube heat exchanger. The shell of heat exchanger shell has been fabricated using mild steel pipe of 118 mm ID and 126 mm OD. This shell has been insulated with two layers of asbestos rope wound around it and covered with a paste of magnesia and asbestos powder to minimize heat lost from the shell. The tubes were made of stainless steel with 10 mm I.D. and 12 mm O.D. The length of the tube is limited to 0.43 m; this also limits the length of the shell. Since the fluids used were very clean, the chosen tube pitch arrangement within the shell side of heat exchanger was triangular. A schematic view of triangular pitch arrangement is shown in Figure 3.3. The shortest centre-to-centre distance between the adjacent tubes is known as tube pitch. The triangular pitch arrangements incorporate a larger number of tubes in a given shell diameter than with a square pitch. The tubes were arranged with
0.008 m clearance and 0.015 m triangular pitch. The shortest distance between two tubes is called clearance.

Tube sheet is essentially a flat circular plate with a provision for making gasketed joint, around the periphery. Fourteen holes were drilled in the tube sheet according to the pitch requirements and outside diameter of the tube. A tube sheet of 3 mm thickness was chosen as the tubes were 12 mm in outside diameter. Such tube sheets were welded near both ends of the shell. This separates area of channel cover from shell. The tubes placed in the tube bundle inside the shell were welded to the tube sheet. The tube sheet acts as a partition between shell side and tube side fluids.

Figure 3.3: Tube sheet triangular pitch of tubes
Baffles are commonly employed within the shell to increase the rate of heat transfer by promoting turbulence of the shell side fluid and also act as structural supports for tubes and dampers against vibration. The baffles cause the fluid to flow through shell at right angles to the axes of the tubes. To avoid bypassing of the shell side fluid, the clearance between the baffles and shell & baffles and tubes must be minimum. The schematic view of the baffles arrangement is given Figure 3.4. The centre-to-centre distance between adjacent baffles is known as baffle pitch or spacing. The baffle spacing should not be greater than the inside diameter of the shell and should not be less than one-fifth of the inside diameter of the shell. The optimum baffle spacing is 0.3 to 0.5 times the shell diameter. Various transverse baffles used are segmental disc and ring and orifice, etc. The segmental baffles are most commonly used one. The segmental baffle is a drilled circular
disc of sheet metal with one side cut away. When the height of the baffle is 75% of the inside diameter of the shell, it is called as 25% cut segmental baffle. 25% cut segmental baffle is the optimum one giving good heat transfer rates without excessive pressure drop. The baffles were drilled to have the number of holes according to 14 tubes designed and matched with the number of holes drilled in tube sheet. Once the tubes were inserted into the holes provided in the 25% cut segmental baffles, the 5 baffles were placed inside shell with spacing 86 mm.

Tie rods are used to hold the baffles in place, with spacers to locate the baffles. Tie rods are fixed at one end in the tube sheet by making blind holes. A 5 mm diameter of tie rod made of stainless steel was placed in the centre of entire length of the shell.

With the help of passes (flow path), we can change the direction of flow in the shell and tubes. Passes are generally used to obtain higher velocities and longer paths for a fluid to travel, without increasing the length of exchanger. This leads to high heat transfer rates. The passes on the shell side are single pass, two pass and single split pass. The passes on the tube side are one, two, four and six up to twelve. Passes on the tube side are formed by the partitions placed in the shell cover and channels. When we use single partition on the tube side, a tube side fluid flows twice through a heat exchanger. In this case, the pass partition divides the tubes equally in two sections. It is provided in the channel so that inlet and outlet for the tube side fluid are provided on the same channel.

The service (hot) fluid used here is water, stored in a 25 L vessel made of stainless steel. A 4 kW electrical heater was placed inside a heating tank. The heating surface was made of nichrome and copper material. This was placed in the hot-water tank by drilling hole at the bottom side and welding another end of heater with the tank. A thermocouple,
connected to digital temperature indicator cum controller, was used to control and measure the temperature of hot water. The hot water temperature could be maintained within ± 0.1°C of the desired temperature. The specifications of electrical heater are given in the Table 3.3:

Table 3.3: Specifications of electrical heater

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>4 kW</td>
</tr>
<tr>
<td>Coil diameter</td>
<td>10 mm</td>
</tr>
<tr>
<td>Length of coil</td>
<td>300 mm</td>
</tr>
</tbody>
</table>

For maintaining the inlet temperature of process fluid during recycling, a stirred tank fitted with helical coil has been used with process fluid flowing inside the coil and cold water surrounding the coil in the tank. The specifications of stirred tank fitted with helical coil for this purpose are given in the Table 3.4:

Table 3.4: Specifications of stirred tank with helical coil

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank capacity</td>
<td>30 L</td>
</tr>
<tr>
<td>Coil diameter</td>
<td>70 mm</td>
</tr>
<tr>
<td>Coil wire thickness</td>
<td>2 SWG</td>
</tr>
<tr>
<td>Diameter of copper piping</td>
<td>20 mm</td>
</tr>
<tr>
<td>Length of copper piping</td>
<td>1.5 m</td>
</tr>
</tbody>
</table>

The cold fluid was stored in a separate stainless steel tank of 25 L capacity. Proportional quantities of the test fluid and demineralized water were charged into this tank to obtain the experimental range of mass fractions (0 to 1). The two-phase system was kept in suspension using an agitator. Vigorous agitation was maintained to avoid stratification
and separation of the fluids and to obtain a uniform mixture. The heating fluid and process fluid were pumped through the tube and shell side of the heat exchanger using 0.25 HP mono pumps (hot water, low-viscous systems) and 1.5 HP gear pump (for high viscous liquids).

The flow rate was measured using rotameters with an accuracy of ± 0.1 LPM. The rotameters R1 and R2 were used to measure and maintain the flow rates in tube side and shell side respectively. The hot water rotameter has a measuring range of 0-500 LPH. On the cold side fluid side, a rotameter with the same measuring range was used for Water, Kerosene, Diesel, Nitrobenzene, Octane and Octane. For Palm oil and Oleic acid, another rotameter with measuring range of 0-1000 LPH was used. The calibration of the rotameter was carried out by measuring the volume of the fluid output per unit time and correlating the same with the rotameter scale reading. The calibration plot of the rotameter is given in Figure 3.5.

The flow rates of the two streams were adjusted using hand operated valves (1) and (4) prior to rotameter. The temperature of the hot fluid was maintained constant at 70°C in the tank using suitable thermostats with an accuracy of ± 0.1°C. Four RTD’s were provided at the two inlet and outlet streams of both shell and tube side to facilitate the measurement of temperatures. One more RTD was inserted in cold fluid tank to measure the inlet temperature of cold fluid in the tank and another RTD was placed in the helical coil tank to monitor the coolant temperature in the outside of coil arrangement. The terminal lugs of the RTD’s were connected to a six-way digital temperature indicator. The temperatures were recorded in the exit and inlet ends using Resistance Temperature Detector with an accuracy of ± 0.1°C.
3.3 : Process flow diagram

Figure 3.6 gives the flow configuration of process fluid in shell side and the hot water (service fluid) flowing in the tube side where as the Figure 3.7 shows the flow sheeting for two-phase flow in tube side and hot water in the shell side.
Figure 3.6: Piping arrangement diagram for shell side two-phase flow

Figure 3.7: Piping arrangement diagram for tube side two-phase flow
3.4 : Experimental procedure

In the present work, experiments were carried out in a shell and tube heat exchanger with hot water as the heating fluid (service fluid) and two-phase system of different fluids in different ratio as the cold fluid (process fluid). The present work investigates seven liquid-water systems viz. Kerosene, Diesel, Nitro benzene, Oleic acid, Palm oil, Octane and Dodecane in varying proportions and flow rates with water as second phase in the shell and tube heat exchanger. The ranges of variables investigated in the present study are given in Table 3.5. A wide range of parameters has been taken into account for the study of two-phase liquid-liquid immiscible flow systems.

The two-phase side rotameter was calibrated for each experimental volume fraction before the experimental run. The inlet and outlet temperatures of both service and process fluids were measured using RTD’s with digital display.

<table>
<thead>
<tr>
<th>S.no</th>
<th>Variables</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Composition of flow systems</td>
<td>20%, 40%, 60%, 80% and 100%</td>
</tr>
<tr>
<td>2</td>
<td>Mass flow rate of cold fluid</td>
<td>0.0088 kg/s to 0.2412 kg/s (shell side)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0043 kg/s to 0.1062 kg/s (tube side)</td>
</tr>
<tr>
<td>3</td>
<td>Cold fluid outlet temperature</td>
<td>34.2 to 52.5 °C (shell side)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>35.6 to 56.9 °C (tube side)</td>
</tr>
</tbody>
</table>
### Table 3.6: Summary of valve position for two-phase flow in tube side and shell side

<table>
<thead>
<tr>
<th>Flow Configuration</th>
<th>Valves</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube side-Process fluid (Two-phase)</td>
<td>V1</td>
<td>V2</td>
<td>V3</td>
<td>V4</td>
<td>V5</td>
<td>V6</td>
<td>V7</td>
<td>V8</td>
</tr>
<tr>
<td>Shell side-Service fluid</td>
<td>Opened</td>
<td>Closed</td>
<td>Opened</td>
<td>Closed</td>
<td>Opened</td>
<td>Closed</td>
<td>Opened</td>
<td>Closed</td>
</tr>
<tr>
<td>Tube side-Service fluid</td>
<td>Closed</td>
<td>Opened</td>
<td>Closed</td>
<td>Opened</td>
<td>Closed</td>
<td>Opened</td>
<td>Closed</td>
<td>Opened</td>
</tr>
<tr>
<td>Shell side-Process fluid (Two-phase)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The status of valves for supply of process fluid in shell side and tube side are given in Table 3.6. The service fluid side inlet temperature and flow rate were kept steady. The inlet temperature of process fluid was maintained constant by passing the liquid through helical coil where helical coil is submerged in cold water. The temperatures were monitored at the four ends using Resistance Temperature Detector (RTD). The two-phase side flow rate was varied and the temperatures of inlet and outlet fluids were measured for each selected flow rate after steady state was reached. Experimental runs with pure liquids in the process side were also carried out. Fouling possibilities were eliminated by cleaning both process side and service side with hot water before each run.
3.5 : Calculation methodology

3.5.1: Case 1. Process fluid in shell side and service fluid in tube side:

Tube side (hot water):

3.5.1.1: Mass flow rate of hot water in tube side

\[ m_{ht} = V_{ht} \rho_{ht} \] (01)

3.5.1.2: Tube side heat transfer rate

\[ Q_{ht} = m_{ht} C_{pht} (T_{h2} - T_{h1}) \] (02)

Shell side (Two-phase fluid):

3.5.1.3: Cross flow area

\[ A_s = \left( \frac{(P_t - D_o)}{P_t} \right) D_s B_s \] (03)

The term \( (P_t - D_o)/P_t \) is ratio of the clearance between tubes and the total distance between tube centers (Sinnott., 2003).

Velocity of shell side process fluid is calculated by following expression

\[ u_{ts} = \frac{V_{ts}}{A_s} \] (04)

3.5.1.4: For two-phase studies, the properties of the mixture of water and liquid (second phase) are taken as weighted average of the test fluid properties at respective temperatures (Jagadeesh., 2010; Reid., 1977; Yaws., 1999; Kothandaraman., 2007). Two-phase properties can be found out by following formula

Two-phase density \( (\rho_{ts}) = \rho_p X_s + \rho_w (1 - X_s) \) (05)
Two-phase viscosity \( (\mu_{ts}) = \mu_{fs} X_s + \mu_{w} (1 - X_s) \) \quad (06)

Two-phase specific heat capacity \( (C_{p_{ts}}) = C_{p_{fs}} X_s + C_{p_{w}} (1 - X_s) \) \quad (07)

Two-phase thermal conductivity \( (k_{ts}) = k_{fs} X_s + k_{w} (1 - X_s) \) \quad (08)

Where \( X_s \) is quality parameter

It is a ratio between amount of single phase fluid (second component) to total amount of both cold water and second component.

\[
X_s = \frac{1}{\left(1 + \left(\frac{\rho_{fs} V_{fs}}{\rho_{w} V_{w}}\right)\right)} 
\]

\( 3.5.1.5: \) Mass velocity is calculated by this expression,

\[
G_s = \left(\frac{V_{ts} \rho_{ts}}{A_s}\right) 
\]

Where \( D_e \) - Equivalent Diameter

\[
D_e = \frac{1,1}{D_o} \left(\frac{P^2}{0.917D_o^2}\right) 
\]

\( 3.5.1.6: \) Mass flow rate of two-phase in shell side

\[
m_{ts} = V_{ts} \rho_{ts} 
\]
3.5.1.7: Two-phase heat transfer rate in shell side

\[ Q_{ts} = m_{ts} C_{p_{ts}} (T_{c2} - T_{c1}) \]  \hspace{1cm} (13)

3.5.1.8: Two-phase heat transfer coefficient

\[ h_{2s} = \frac{Q_{ts}}{(A_o \times LMTD)} \]  \hspace{1cm} (14)

The heat transfer area of shell side

\[ A_o = \pi D_o LN_t \]  \hspace{1cm} (15)

Logarithmic mean temperature

\[ LMTD = \left[ \frac{(T_{w1} - T_{c1}) - (T_{w2} - T_{c2})}{\ln \left( \frac{\frac{(T_{w1} - T_{c1})}{(T_{w2} - T_{c2})}}{\ln \left( \frac{T_{w1}}{T_{w2}} \right)} \right)} \right] \]  \hspace{1cm} (16)

Figure 3.8: Schematic diagram showing the temperatures used in calculation.

\[ T_{w1} = \frac{(T_{c1} + T_{h2})}{2} \quad \text{and} \quad T_{w2} = \frac{(T_{c2} + T_{h1})}{2} \]  \hspace{1cm} (17)
3.5.1.9: The shell side heat transfer coefficient for single phase is related to Reynolds number by the following formula (Ludwig., 2002).

\[ Nu_{1s} \propto Re^{0.55} Pr^{0.333} \]  

(18)

3.5.1.10: Lockhart-Martinelli parameter

\[ \chi_{ts}^2 = \left( \frac{1 - X_s}{X_s} \right)^{2-0.55} \left( \frac{\mu_{fs}}{\mu_{ws}} \right)^{0.55} \]  

(19)

3.5.1.11: Modified two-phase multiplier

Normally, two-phase multiplier is defined as the ratio of heat transfer coefficient in two-phase flow to heat transfer coefficient in single phase flow. In the present work, a modified two-phase multiplier has been introduced, as the ratio of Nusselt number in two-phase flow to Nusselt number in single phase flow, as shown below:

\[ \Phi_{ts} = \frac{Nu_{2s}}{Nu_{1s}} \]  

(20)

3.5.2: Case 2. Process fluid in tube side and service fluid in shell side:

Shell side (hot water):

3.5.2.1: Mass flow rate of hot water in shell side

\[ m_{hs} = V_{hs} \rho_{hs} \]  

(21)

3.5.2.2: Shell side heat transfer rate is calculated by following expression:

\[ Q_{hs} = m_{hs} C_{phs} (T_{h2} - T_{h1}) \]  

(22)
Tube side (Process fluid):

3.5.2.3: Velocity of tube side two-phase fluid is calculated by following expression

\[ u_{tu} = \frac{V_u}{A_t} \]  \hspace{1cm} (23)

Where total cross sectional area of tube

\[ A_t = \frac{\pi D_t^2}{4} \times \frac{N_f}{N_p} \]  \hspace{1cm} (24)

3.5.2.4: The properties of two-phase systems were estimated as detailed in section 3.5.1.4.

3.5.2.5: Mass flow rate of two-phase mixture

\[ m_{tu} = V_u \rho_u \]  \hspace{1cm} (25)

3.5.2.6: Two-phase heat Transfer Rate in tube side

\[ Q_{tu} = m_{tu} C_{pu} (T_{c2} - T_{c1}) \]  \hspace{1cm} (26)

3.5.2.7: The two-phase heat transfer coefficient

\[ h_{2t} = \frac{Q_u}{(A_t \times LMTD)} \]  \hspace{1cm} (27)

Where tube side heat transfer area

\[ A_t = \pi D_t LN_t \]  \hspace{1cm} (28)

Logarithmic mean temperature

\[ LMTD(\Delta T_{tu}) = \left[ \frac{(T_{w1} - T_{c1}) - (T_{w2} - T_{c2})}{\ln\left(\frac{(T_{w1} - T_{c1})}{(T_{w2} - T_{c2})}\right)} \right] \]  \hspace{1cm} (29)
3.5.2.8: The tube side Nusselt number for single phase is related to Reynolds number by following formula (Sinnott., 2003).

\[ Nu_{tl} \propto (Re Pr)^{0.333} \]  

(31)

3.5.2.9: Lockhart-Martinelli parameter

\[ \chi'' = \left( \frac{1 - X_t}{X_t} \right)^{2-0.333} \left( \frac{\rho_f}{\rho_w} \right)^{0.333} \left( \frac{\mu_w}{\mu_f} \right) \]  

(32)

Where \( X_t \) is quality parameter

\[ X_t = \frac{1}{1 + \frac{(\rho_w V_w)}{(\rho_f V_f)}} \]  

(33)

3.5.2.10: Modified two-phase multiplier

\[ \Phi_{_{L_t}} = \frac{Nu_{_{2t}}}{Nu_{_{tl}}} \]  

(34)