CHAPTER 4: RESULTS AND DISCUSSION

4.1 : Development of correlation between two-phase parameters for the process fluid:

4.1.1 : Effect of Reynolds number on single phase and two-phase heat transfer coefficient

The variation of heat transfer coefficient of single phase and two-phase process stream of varying compositions as a function of Reynolds number in shell side of heat exchanger have been showed in Figures 4.1 to 4.7 for kerosene-water, diesel-water, nitrobenzene-water, octane-water, dodecane-water, oleic acid-water and palm oil-water systems respectively. Figures 4.1 to 4.7 also show the effect of Reynolds number on single phase heat transfer coefficient of 100% water, 100% kerosene, 100% diesel, 100% nitrobenzene, 100% octane, 100% dodecane, 100% oleic acid and 100% palm oil systems as the process stream, when it was supplied through the shell-side. It is observed from Figure 4.1 that the heat transfer coefficient of process stream increases with increase in its Reynolds number. For a process stream of fixed composition, higher Reynolds number indicates higher velocity and hence higher mass flow rate of process stream. Hence the heat transfer coefficient of process fluid increases with increase in Reynolds number. The heat transfer coefficient of 100% water as process stream is higher than that of 100% kerosene as process stream for the same Reynolds number. The heat transfer coefficient for two-phase process streams lies between the heat transfer coefficient of 100% water and 100% kerosene as process stream.

It is seen that the two-phase data falls within the boundaries of pure water and pure liquid data. As the composition of water on second phase increases, the two-phase heat transfer
coefficient increase for the range of Reynolds number studied due to increase in thermal conductivity of water. In the experiments conducted, the Reynolds number were directly proportional to the flow rate/velocity since all other parameters were constant for a given quality and mean bulk temperature. The viscosities of kerosene-water systems are higher than the viscosity of water. Hence to maintain the same Reynolds number, higher velocity and hence higher mass flow rate must be used for kerosene-water system. This leads to increase in heat capacity, which in turn reduces the temperature rise. The second phase fluid (the first and common phase being water) has higher viscosity and lower thermal conductivity, which lower the heat transfer coefficient. Similar behavior has been observed for other single phase and two-phase process streams also as shown in Figures 4.2 to 4.7. The increase in agitation enhances the uniformity of the two-phase system thus preventing stratification of the phases. Hence the overall physical properties of the mixture remain uniform throughout the flow channel. A non-uniform mixture will result in segregated areas of higher heat transfer coefficients (water rich zones) and lower heat transfer coefficients (test-fluid rich zones). The uniformity of the two-phase system coupled with increased convective currents driven by higher flow velocities results in a higher heat transfer coefficients. This explains the observed behavior in the trend of increasing heat transfer coefficient with Reynolds number for all the systems investigated.
Figure 4.1: Variation of the heat transfer coefficient with Reynolds number for different kerosene-water compositions in shell side

Figure 4.2: Variation of the heat transfer coefficient with Reynolds number for different diesel-water compositions in shell side
Figure 4.3: Variation of the heat transfer coefficient with Reynolds number for different nitrobenzene-water compositions in shell side

Figure 4.4: Variation of the heat transfer coefficient with Reynolds number for different octane-water compositions in shell side
Figure 4.5: Variation of the heat transfer coefficient with Reynolds number for different dodecane-water compositions in shell side

Figure 4.6: Variation of the heat transfer coefficient with Reynolds number for different oleic acid-water compositions in shell side
Figure 4.7: Variation of the heat transfer coefficient with Reynolds number for different palm oil -water compositions in shell side.

Figures 4.8 to 4.14 show the influence of tube side Reynolds number on single phase and two-phase heat transfer coefficient of process fluid supplied in the tube side. Figures 4.8 to 4.14 are similar to the behavior of Figures 4.1 to 4.7.
Figure 4.8: Variation of the heat transfer coefficient with Reynolds number for different kerosene -water compositions in tube side

Figure 4.9: Variation of the heat transfer coefficient with Reynolds number for different diesel -water compositions in tube side
Figure 4.10: Variation of the heat transfer coefficient with Reynolds number for different nitrobenzene -water compositions in tube side

Figure 4.11: Variation of the heat transfer coefficient with Reynolds number for different octane -water compositions in tube side
Figure 4.12: Variation of the heat transfer coefficient with Reynolds number for different dodecane-water compositions in tube side

Figure 4.13: Variation of the heat transfer coefficient with Reynolds number for different oleic acid-water compositions in tube side
4.1.2: Development of correlation between single phase Nusselt number and Reynolds number

Figures 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4.21 and 4.22 show the single phase Nusselt number ($\text{Nu}_{1s}$) and Reynolds number relationship for pure water, pure kerosene, pure diesel, pure nitrobenzene, pure octane, pure dodecane, pure oleic acid and pure palm oil respectively. Figure 4.15 has been drawn for 100% compositions of water system as the process stream, when it was supplied through shell side. Figure 4.15 shows that the single phase Nusselt number ($\text{Nu}_{1s}$) of 100% water increases with increasing Reynolds number linearly. Since the single phase Nusselt number of 100% water show a increase with Reynolds number and Prandtl number range investigated, the experimental data for pure phase was fitted to Eqn.(18) (Ludwig., 2002) and the relevant exponents are given in the plot of 100% water system, where the exponent value of 0.55 represents the power to
which Reynolds number is raised. Similar linear behavior has been observed for other single phase systems such as 100% kerosene, 100% diesel, 100% nitrobenzene, 100% octane, 100% dodecane, 100% oleic acid and 100% palm oil also as shown in Figures 4.16 to 4.22. The increase in velocity of single phase process stream especially in a shell side baffle surface leads to increase of axial and vertical mixing. 100% water gives higher heat transfer coefficient and lower Nusselt number because of its high thermal conductivity, low viscosity and also has the maximum logarithmic mean temperature difference. The single phase exponent is useful in determining two-phase parameter (i.e. L-M parameter) from single phase data. The L-M parameter is calculated based on the exponent value of Reynolds number for pure water and pure liquid. The L-M parameter \((\chi_{ts})^2\) refers with respect to Quality of the two-phase system and it is defined as the ratio between density of pure liquid to pure water and ratio between viscosity of pure water to pure liquid as shown in Eqn.(19). Another two-phase parameter named modified two-phase multiplier is the ratio between two-phase Nusselt number and single phase Nusselt number. Both L-M parameter and modified two-phase multiplier are significant in obtaining two-phase data from single phase data.
Figure 4.15: Plot between Nusselt number and $Re^{0.55}Pr^{0.333}$ for pure water in shell side.

Figure 4.16: Plot between Nusselt number and $Re^{0.55}Pr^{0.333}$ for pure kerosene in shell side.
Figure 4.17: Plot between Nusselt number and $\text{Re}^{0.55}\text{Pr}^{0.333}$ for pure diesel in shell side

Figure 4.18: Plot between Nusselt number and $\text{Re}^{0.55}\text{Pr}^{0.333}$ for pure nitrobenzene in shell side
Figure 4.19: Plot between Nusselt number and $\text{Re}^{0.55}\text{Pr}^{0.333}$ for pure octane in shell side

Figure 4.20: Plot between Nusselt number and $\text{Re}^{0.55}\text{Pr}^{0.333}$ for pure dodecane in shell side
Figure 4.21: Plot between Nusselt number and $\text{Re}^{0.55}\text{Pr}^{0.333}$ for pure oleic acid in shell side

Figure 4.22: Plot between Nusselt number and $\text{Re}^{0.55}\text{Pr}^{0.333}$ for pure palm oil in shell side
Figures 4.23 to 4.30 show the influence of tube side Reynolds number on Nusselt number of single phase fluid supplied in the tube side. The tube side experimental data for pure water, pure kerosene, pure diesel, pure nitrobenzene, pure octane, pure dodecane, pure oleic acid and pure palm oil were fitted linearly to Eq.(31) by taking the exponent as 0.333 for Reynolds number for all single phase systems (Sinnott., 2003). Figure 4.23 shows good agreement with the correlation for single phase Nusselt number for fluid flow inside tube (Sinnott., 2003). Figures 4.24 to 4.30 are similar to the behavior of Figures 4.15 to 4.22.

![Plot between Nusselt number and (RePr)^0.333 for pure water in tube side](image)

Figure 4.23: Plot between Nusselt number and (RePr)^0.333 for pure water in tube side
Figure 4.24: Plot between Nusselt number and \((RePr)^{0.333}\) for pure kerosene in tube side

\[
R^2 = 0.990
\]

100% kerosene

Figure 4.25: Plot between Nusselt number and \((RePr)^{0.333}\) for pure diesel in tube side

\[
R^2 = 0.988
\]

100% diesel
Figure 4.26: Plot between Nusselt number and \((RePr)^{0.333}\) for pure nitrobenzene in tube side

Figure 4.27: Plot between Nusselt number and \((RePr)^{0.333}\) for pure octane in tube side
Figure 4.28: Plot between Nusselt number and $(RePr)^{0.333}$ for pure dodecane in tube side

Figure 4.29: Plot between Nusselt number and $(RePr)^{0.333}$ for pure oleic acid in tube side
4.1.3: Effect of quality on modified two-phase multiplier for the process fluid

Figures 4.31, 4.32, 4.33, 4.34, 4.35, 4.36 and 4.37 show the effect of quality on modified two-phase multiplier ($\Phi_{LS}$) of two-phase process stream, when it was supplied through the shell-side. Figure 4.31 has been drawn for different compositions of kerosene-water system as the process stream. It is observed from Figure 4.31 that the modified two-phase multiplier increases with increase in its quality. The modified two-phase multiplier ($\Phi_{LS}$) relates single phase Nusselt number ($Nu_{1s}$) and two-phase Nusselt number ($Nu_{2s}$) as shown in Eq. (20). The modified two-phase multiplier ($\Phi_{LS}$) is determined based on the single phase data (i.e. either from 100% water data or 100% kerosene data).

As the proportion of the second phase increases and a consequent decrease in the proportion of water, the viscosity of the mixture increases, thermal conductivity, density
and specific heat decrease. At the same time, this increases the Nusselt number ($\text{Nu}_{2s}$) and hence the modified two-phase multiplier increases with the quality studied. Salcudean. (1983) has reported that the increase of two-phase multiplier with quality for the air-water two-phase flow systems could be attributed to the increase in turbulence with the increase in proportion of air. In this investigation, the test fluids added have a higher viscosity and hence contribute to lowering the turbulence which eventually reduces the two phase multiplier.

Figure 4.31 also compares the modified two-phase multiplier ($\Phi_{Ls}$) based on 100% kerosene and based on 100% water. Since the single phase Nusselt number ($\text{Nu}_{1s}$) of water is always lower than the single phase Nusselt number ($\text{Nu}_{1s}$) of kerosene, the modified two-phase multiplier ($\Phi_{Ls}$) based on pure water is greater for a fixed quality of kerosene-water system. The variation of the modified two phase multiplier ($\Phi_{Ls}$) with quality is a linear relationship with a positive slope. Similar trend is seen in all other two-phase systems studied also as shown in Figures 4.32 to 4.37.
Figure 4.31: Variation between Quality and Modified two-phase multiplier for kerosene-water system in shell side

Figure 4.32: Variation between Quality and Modified two-phase multiplier for diesel-water system in shell side
Figure 4.33: Variation between Quality and Modified two-phase multiplier for NB-water system in shell side

Figure 4.34: Variation between Quality and Modified two-phase multiplier for octane-water system in shell side
Figure 4.35: Variation between Quality and Modified two-phase multiplier for dodecane-water system in shell side

Figure 4.36: Variation between Quality and Modified two-phase multiplier for oleic acid-water system in shell side
Figures 4.38 to 4.44 show the influence of quality on modified two-phase multiplier of two-phase process stream, when it was supplied through the tube side. Figures 4.38 to 4.44 are similar to the behavior of Figures 4.31 to 4.37.
Figure 4.38: Variation between Modified two-phase multiplier and Quality for kerosene-water system in tube side

Figure 4.39: Variation between Modified two-phase multiplier and Quality for diesel-water system in tube side
Figure 4.40: Variation between Modified two-phase multiplier and Quality for NB-water system in tube side

Figure 4.41: Variation between Modified two-phase multiplier and Quality for octane-water system in tube side
Figure 4.42: Variation between Modified two-phase multiplier and Quality for dodecane-water system in tube side

Figure 4.43: Variation between Modified two-phase multiplier and Quality for oleic acid-water system in tube side
4.1.4 : Effect of quality on L-M parameter for the process stream

Figure 4.45 shows the effect of quality on L-M parameter ($\chi_{ls}^2$) of two-phase process stream, when it was supplied through the shell-side. Figure 4.45 has been drawn for different compositions of kerosene-water, diesel-water, nitrobenzene-water, octane-water, dodecane-water, oleic acid-water and palm oil-water systems. It is observed from Figure 4.45 that the L-M parameter decreases with increase in quality for kerosene-water as process stream. The L-M parameter ($\chi_{ls}^2$) was calculated using the exponent ‘m’ as 0.55. The L-M parameter ($\chi_{ls}^2$) is related to quality, ratio between density of pure kerosene to pure water and ratio between viscosity of pure water to pure kerosene as shown in Eq.(19).
From the definition, L-M parameter has an inverse relation with the viscosity of the kerosene-water system. As the quality increases, the viscosity of the kerosene-water process stream increases leading to a decrease in the value of L-M parameter. Since the viscosity term is raised to the power of the correlation constant ‘ms’, the impact of the two-phase viscosity on the value of the L-M parameter is very large. Due to the wide range of the viscosity of the test fluids, the range of L-M parameter variations are also large. As expected the high viscosity fluids such as Palm oil, Oleic acid, have low range of L-M parameter. Similar behavior has been observed for other two-phase process streams also as shown in Figure 4.45.

Figure 4.45: Variation between Quality and L-M parameter for seven liquid-water systems in shell side
Figure 4.46 shows the influence of quality on L-M parameter of two-phase process stream, when it was supplied through the tube side. The L-M parameter \(\chi_{t}^{2}\) was calculated using the exponent value ‘m’ as 0.333. The Figure 4.46 is qualitatively similar to that of Figure 4.45.

![Graph showing the variation between L-M parameter and quality for seven liquid-water systems in tube side.](image)

**Figure 4.46: Variation between L-M parameter and Quality for seven liquid-water systems in tube side**

4.1.5 : Effect of L-M parameter on Modified two-phase multiplier

Figures 4.47, 4.48, 4.49, 4.50, 4.51, 4.52 and 4.53 show the effect of L-M parameter of two-phase process stream on modified two-phase multiplier, when the two-phase process fluid was supplied through the shell-side. Figure 4.47 has been drawn between modified two-phase multiplier and L-M parameter for different compositions of kerosene-water
system. It is observed from Figure 4.47 that the modified two-phase multiplier is inversely proportional to L-M parameter. An increasing L-M parameter for a kerosene-water system denotes decrease in quality. It may be recalled from Figure 4.31 that the modified two-phase multiplier increases with quality. Hence, with increase in L-M parameter, the modified two-phase multiplier decreases for a particular two-phase system. The variation of modified two-phase multiplier with L-M parameter is not linear and obeys power law model. Similar behavior has been observed for other two-phase process streams also as shown in Figures 4.48 to 4.53.

![Graph showing variation between L-M parameter and Modified two-phase multiplier for kerosene-water system in shell side](image)
Figure 4.48: Variation between L-M parameter and Modified two-phase multiplier for diesel-water system in shell side

Figure 4.49: Variation between L-M parameter and Modified two-phase multiplier for NB-water system in shell side
Figure 4.50: Variation between L-M parameter and Modified two-phase multiplier for octane-water system in shell side

Figure 4.51: Variation between L-M parameter and Modified two-phase multiplier for dodecane-water system in shell side
Figure 4.52: Variation between L-M parameter and Modified two-phase multiplier for oleic acid-water system in shell side

Figure 4.53: Variation between L-M parameter and Modified two-phase multiplier for palm oil-water system in shell side
A correlation between the modified two-phase multiplier ($\Phi_{Ls}$), Quality ($X_s$) and L-M parameter ($\chi_{ts}^2$) for different compositions of liquid-water systems based on pure water, for the two-phase process stream flowing through the shell side is obtained as follows:

$$\Phi_{Ls} = 0.947 \left( X_s \right)^{0.214} \left( \chi_{ts}^2 \right)^{-0.248}$$  \hspace{1cm} (35)

A comparison of experimental modified two-phase multiplier and that predicted using Eq. (35) is shown in Figure 4.54. It is evident from Figure 4.54 that the Eq. (35) predicts the modified two-phase multiplier for seven process streams within ± 14% error for about 200 data points.

The range of dimensionless variables average absolute deviation of modified two-phase multiplier for different compositions all two-phase systems based on water and coefficient of variation are shown in Table 4.1.

![Figure 4.54: Variation between experimental and calculated modified two-phase multiplier based on the developed two-phase correlation in shell side](image-url)
Table 4.1: The range of variables investigated for modified two-phase multiplier correlation in shell side

<table>
<thead>
<tr>
<th>Dimensionless variables</th>
<th>Range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality</td>
<td>0.151 to 0.829</td>
</tr>
<tr>
<td>L-M parameter</td>
<td>0.070 to 7.525</td>
</tr>
<tr>
<td>Modified two-phase multiplier</td>
<td>0.888 to 1.873</td>
</tr>
<tr>
<td>% error deviation in modified two-phase multiplier</td>
<td>-10.572 to + 13.293</td>
</tr>
<tr>
<td>Standard deviation in modified two-phase multiplier</td>
<td>0.084</td>
</tr>
<tr>
<td>Coefficient of variation (%)</td>
<td>6.843</td>
</tr>
</tbody>
</table>

Figures 4.55 to 4.61 show the influence of L-M parameter on modified two-phase multiplier of two-phase process stream, when it was supplied through the tube side. Figures 4.55 to 4.61 are qualitatively similar to that of Figures 4.47 to 4.53.

Figure 4.55: Variation between L-M parameter and Modified two-phase multiplier for kerosene-water system in tube side
Figure 4.56: Variation between L-M parameter and Modified two-phase multiplier for diesel-water system in tube side

Figure 4.57: Variation between L-M parameter and Modified two-phase multiplier for NB-water system in tube side
Figure 4.58: Variation between L-M parameter and Modified two-phase multiplier for octane-water system in tube side

Figure 4.59: Variation between L-M parameter and Modified two-phase multiplier for dodecane-water system in tube side
Figure 4.60: Variation between L-M parameter and Modified two-phase multiplier for oleic acid-water system in tube side

Figure 4.61: Variation between L-M parameter and Modified two-phase multiplier for palm oil-water system in tube side
A correlation between the modified two-phase multiplier (ΦLt), Quality (Xt) and L-M parameter (χt2) for different compositions of liquid-water systems based on pure water, for the two-phase process stream flowing on the tube side is obtained as follows:

\[
\Phi_{Lt} = 0.448 (X_t)^{-0.708} (\chi_t^2)^{0.365}
\]  
(36)

A coefficient and two exponents of Eq. (36) have been evaluated by regression analysis for the present experimental data having Quality range from 0.16 to 0.83, L-M parameter range from 0.045 to 9.511 and modified two-phase multiplier range from 0.633 to 1.549. Figure 4.62 shows the comparison between the experimental values of modified two-phase multiplier and those calculated using Eq. (36). It is evident from Figure 4.62 that the Eq. (36) predicts the modified two-phase multiplier for seven liquid-liquid systems within ± 13% error for about 200 data points.
4.2: Development of correlation for predicting heat transfer coefficient of two-phase liquid-liquid systems

Nusselt number, Reynolds number and Prandtl number have been widely used to correlate heat transfer coefficient in heat transfer involving single phase. An overall generalized empirical correlation in terms of dimensionless groups relating the heat transfer coefficient with fundamental thermo-physical properties of the two-phase, liquid-liquid system will be useful. Since the system used was two-phase, both the phases interact with tube surface as well as with each other in contrast to single phase system, where the only interaction was between the fluid and the tube surface. Further with the increase in dispersed phase holdup in water, the heat transfer coefficient was found to decrease. The effect of second phase on the heat transfer rate to the two-phase liquid systems depends largely on the properties of the boundary layers formed at the interface.

In developing predictive correlations for the cold-side two-phase heat transfer coefficient, the effect of composition has to be accounted for. Using weighted-average two-phase properties, dimensional analysis indicates that there are four dimensionless groups in the system. The dimensionless numbers identified are Nusselt number (Nu), Reynolds number (Re), Prandtl number (Pr), and the quality (X) as follows:

\[
N_{Re} = \left( \frac{G_s D_c}{\mu_{ts}} \right) 
\]

\[
N_{Pr} = \left( \frac{C P_{ts} \mu_{ts}}{k_{ts}} \right) 
\]

\[
N_{Nu} = \left( \frac{h_{ts} D_c}{k_{ts}} \right) 
\]
Two-phase heat transfer coefficient may be considered to be a function of Reynolds number (Re), Prandtl number (Pr) and quality (X) for shell side as given below:

\[ Nu = r_1 \text{Re}^{r_2} \text{Pr}^{r_3} X^{r_4} \]  \hspace{1cm} (40)

Power law type function was assumed, following the Nusselt number correlations for single phase heat transfer. The coefficient \((r_1)\) and exponents \((r_2, r_3\) and \(r_4)\) have been evaluated by regression analysis for the present experimental data having Prandtl number range from 3.74 to 67.38, Reynolds number range from 54.12 to 102.25 and Nusselt number range from 2.56 to 10.20.

Therefore, the general form of the correlation developed by fitting experimental data of all two-phase systems in shell side was

\[ Nu = 0.72 \text{Re}^{0.52} \text{Pr}^{0.027} X^{0.227} \]  \hspace{1cm} (41)

The calculated values of two-phase heat transfer coefficients based on the Eq. (41) for different compositions of liquid-water systems are compared with experimental two-phase heat transfer coefficient. Figure 4.63 shows the comparison between experimental and calculated data with an average absolute deviation ranging ± 14 percent and predicts the established correlation with the coefficient of variation 7.66%.
Similarly, the dimensionless numbers for process fluid in tube side are defined as follows:

**Nusselt number**

\[ N_{Nu} = \left( \frac{h_t D_t}{k_u} \right) \]  

(42)

**Prandtl number**

\[ N_{Pr} = \left( \frac{C_p u A_{u}}{k_u} \right) \]  

(43)

**Reynolds number**

\[ N_{Re} = \frac{u_A D_t A_{tu}}{\mu_u} \]  

(44)
The following correlation was obtained for prediction of Nusselt number for heat transfer in two-phase, liquid-liquid systems, when the same is supplied on tube side:

\[ \text{Nu} = 0.179 \, \text{Re}^{0.596} \, \text{Pr}^{0.213} \, X^{0.148} \]  

(45)

The constants in Eq.(45) were obtained by regression analysis of the present experimental data having Prandtl number range from 4.12 to 67.09, Reynolds number range from 102.02 to 197.12 and Nusselt number range from 2.53 to 9.88.

The predicted two-phase Nusselt numbers for 20%, 40%, 60% and 80% compositions of all two-phase systems were found to be within average absolute deviation of ± 15 percent of the experimental two-phase Nusselt numbers (Figure 4.64). The coefficient of variation for 220 data points, covering seven liquid-liquid systems was found to be 8.13%.

![Figure 4.64: Variation between experimental and calculated two-phase Nusselt number based on the developed two-phase correlation in tube side](image-url)
4.3 : Development of correlations for predicting thermal effectiveness of two-phase systems:

4.3.1 : Effect of Reynolds number on thermal effectiveness of process fluid

Thermal effectiveness, defined as the ratio of actual to theoretical maximum heat transfer rate, helps in accessing the performance of the heat exchanger. In the present work, the effect of operating conditions (flow rate and temperature) on thermal effectiveness of a shell and tube heat exchanger is studied. Figure 4.65 shows the effect of Reynolds number on thermal effectiveness of process stream, when it was supplied through the shell-side. Figure 4.65 has been drawn for different compositions of kerosene-water system as the process stream. It is observed from Figure 4.65 that the thermal effectiveness of process stream decreases with increase in its Reynolds number. For a process stream of fixed composition, higher Reynolds number indicates higher velocity and hence higher mass flow rate of process stream. Though heat transfer coefficient is expected to increase with velocity of process stream, the higher heat capacity (product of mass flow rate and specific heat) of process stream leads to reduction in its temperature rise. Hence thermal effectiveness of process fluid decreases with increase in Reynolds number.

The thermal effectiveness of 100% water as process stream is higher than that of 100% kerosene as process stream for the same Reynolds number. The thermal effectiveness for two-phase process streams lies between the thermal effectiveness of 100% water and 100% kerosene as process stream. The viscosities of kerosene-water mixtures are higher than the viscosity of water. Hence to maintain the same Reynolds number, higher velocity and hence higher mass flow rate must be used for kerosene-water system. This leads to increase in heat capacity, which in turn reduces the temperature rise. Pure
kerosene has the highest viscosity among kerosene-water systems and has the lowest thermal effectiveness due to increase of velocity required to maintain the desired Reynolds number. Similar behavior has been observed for other two-phase process streams also as shown in Figures 4.66 to 4.71.

Figure 4.65: Influence of Reynolds number on Thermal effectiveness of kerosene-water system supplied in the shell side.
Figure 4.66: Influence of Reynolds number on Thermal effectiveness of diesel-water system supplied in the shell side.

Figure 4.67: Influence of Reynolds number on Thermal effectiveness of palm oil-water system supplied in the shell side.
Figure 4.68: Influence of Reynolds number on Thermal effectiveness of oleic acid-water supplied in the shell side.

Figure 4.69: Influence of Reynolds number on Thermal effectiveness of NB-water supplied in the shell side.
Figure 4.70: Influence of Reynolds number on Thermal effectiveness of dodecane-water supplied in the shell side.

Figure 4.71: Influence of Reynolds number on Thermal effectiveness of octane-water supplied in the shell side.
Figures 4.72 to 4.78 show the influence of tube side Reynolds number on thermal effectiveness of process fluid supplied in the tube side. Figures 4.72 to 4.78 are similar to the behavior of Figures 4.65 to 4.71.

Figure 4.72: Influence of Reynolds number on Thermal effectiveness of kerosene-water supplied in the tube side
Figure 4.73: Influence of Reynolds number on Thermal effectiveness of diesel-water supplied in the tube side.

Figure 4.74: Influence of Reynolds number on Thermal effectiveness of palm oil-water supplied in the tube side.
Figure 4.75: Influence of Reynolds number on Thermal effectiveness of oleic acid-water supplied in the tube side.

Figure 4.76: Influence of Reynolds number on Thermal effectiveness of NB-water supplied in the tube side.
Figure 4.77: Influence of Reynolds number on Thermal effectiveness of dodecane-water supplied in the tube side.

Figure 4.78: Influence of Reynolds number on Thermal effectiveness of octane-water supplied in the tube side.
4.3.2 : Effect of velocity ratio on thermal effectiveness of process fluid

Figure 4.79 shows the effect of shell-side velocity (process stream velocity) to tube-side velocity (hot stream velocity) on thermal effectiveness of process stream, when it was supplied through shell side. Figure 4.79 has been drawn for different compositions of kerosene-water system as the process stream. Thermal effectiveness of process fluid at different ratios of process stream to hot steam velocities was obtained by performing heat transfer experiments with different flow rates of process fluid at a constant flow rate of hot stream. It is observed from Figure 4.79 that the thermal effectiveness of process stream decreases with increase in its velocity ratio for all compositions of two-phase system. Similar behavior has been observed for other two-phase systems as shown in Figures 4.80 to 4.85.

![Figure 4.79: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of kerosene-water system supplied in the shell side](image)
Figure 4.80: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of diesel-water system supplied in the shell side.

Figure 4.81: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of palm oil-water system supplied in the shell side.
Figure 4.82: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of oleic acid-water system supplied in the shell side.

Figure 4.83: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of NB-water system supplied in the shell side
Figure 4.84: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of dodecane-water system supplied in the shell side

Figure 4.85: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of octane-water system supplied in the shell side
Figures 4.86 to 4.92 show the influence of shell side to tube side velocity ratio on thermal effectiveness of process fluid supplied in the tube side. Figures 4.86 to 4.92 are similar to the behavior of Figures 4.79 to 4.85.

**Figure 4.86:** Influence of Shell side to tube side velocity ratio on Thermal effectiveness of kerosene-water system supplied in the tube side
Figure 4.87: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of diesel-water system supplied in the tube side

Figure 4.88: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of palm oil-water system supplied in the tube side
Figure 4.89: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of oleic acid-water system supplied in the tube side

Figure 4.90: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of NB-water system supplied in the tube side
Figure 4.91: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of dodecane-water system supplied in the tube side

Figure 4.92: Influence of Shell side to tube side velocity ratio on Thermal effectiveness of octane-water system supplied in the tube side
To understand this observation, one may derive an expression relating thermal effectiveness and velocity ratio as follows:

Thermal effectiveness of process stream is

$$E = \frac{(T_{co} - T_{ci})}{(T_{hi} - T_{ci})}$$ (46)

Rewriting Eq. (46) in terms of heat transfer rate and heat capacity,

$$E = \frac{Q}{(mCp)_{cold}(T_{hi} - T_{ci})}$$ (47)

For fixed heat exchanger geometry, heat transfer rate may be expressed as the product of overall heat transfer coefficient, heat transfer area and driving force. Accordingly Eq. (47) becomes,

$$E = \frac{UA\Delta T}{(mCp)_{cold}(T_{hi} - T_{ci})}$$ (48)

Neglecting the heat transfer resistance in the tube wall, overall heat transfer coefficient may be related to shell side and tube side heat transfer coefficients, $h_o$ and $h_i$ respectively. Therefore, Eq. (48) becomes

$$\frac{1}{U} = \frac{1}{h_o} + \frac{1}{h_i}$$ (49)

$$U = \frac{h_o h_i}{h_o + h_i}$$ (50)

Substituting Eq. (50) in Eq. (48)

$$E = \frac{h_o h_i \Delta T}{(h_o + h_i)(mCp)_{cold}(T_{hi} - T_{ci})}$$ (51)
If shell side and tube side velocities are ‘v’ and ‘u’ respectively, Eq. (51) may be written for the two-phase on the shell-side as follows, accounting heat transfer coefficient-velocity relationship in the power law form,

\[
E = \frac{v^n u^m A \Delta T}{(v^n + u^m)(T_{hi} - T_{ci})(\rho \alpha ACp)_{cold}}
\]

(52)

In Eq. (52), m & n are exponents in \( h_i = m_i u^m \) and \( h_o = n_i v^n \)

Eq. (52) becomes

\[
E = \frac{v^{n-1} u^m A \Delta T}{(v^n + u^m)(T_{hi} - T_{ci})(\rho \alpha ACp)_{cold}}
\]

(53)

For a constant tube side fluid velocity (u), Eq. (53) may be simplified as follows:

\[
E\alpha = \frac{1}{v \left[ 1 + k \left( \frac{v}{u} \right)^{-\alpha} \right]}
\]

(54)

where k is \( u^{m-n} \), constant at constant tube side velocity.

From Eq. (54), it is evident that the thermal effectiveness decreases with ‘v’ or (v/u) ratio. The rate of decrease depends on ‘n’ in heat transfer coefficient-shell side velocity relationship.

Figures 4.86 to 4.92 show the influence of shell-side to tube-side velocity ratio on thermal effectiveness of process fluid when supplied in the tube side. It may be observed from Figure 4.86 to 4.92 that the thermal effectiveness of two-phase liquid system increases with increase in shell-side to tube-side velocity ratio, for all the two-phase
systems when they are supplied inside the tubes. This observation may be explained as follows:

For constant shell side velocity, but varying tube-side velocities for two-phase system flowing inside the tubes, Eq. (51) may be modified as follows:

\[
E = \frac{v^n u^m A\Delta T}{(v^n + u^m)(T_{hi} - T_{ci})(u\rho ACp)_{cold}}
\]  

(55)

\[
E \propto \frac{u^m}{\left[\frac{v^n}{u^n} + 1\right]} u
\]

(56)

From Eq. (56), it is clear that the thermal effectiveness depends upon ‘u’ for a constant ‘v’. Increase in tube side velocity (u) results in lower value of thermal effectiveness. In other words, with increase in (v/u) ratio, the thermal effectiveness increases when the two-phase system is supplied inside the tubes and when the shell side fluid velocity is constant. This is also evident from Figures 4.86 to 4.92.

4.3.3 : Thermal effectiveness correlations for two-phase systems

The thermal effectiveness is a suitable means of assessing the thermal performance of the heat exchanger. The method of thermal effectiveness is based on the effectiveness of a heat exchanger in transferring a given amount of heat. Since the mass flow rate and specific heat of both fluids play major role in most industrial heat exchangers, thermal effectiveness is related to heat capacity ratio of cold fluid to hot water.
Thermal effectiveness may be considered to be a function of Reynolds number (Re), Prandtl number (Pr) and heat capacity ratio (F) as shown below:

\[ E = k_o F^b \Re^c \Pr^d \]

(57)

Power law type function was assumed, following the conventional correlations for heat transfer coefficient and Nusselt number. Tube diameter and two phase velocity were taken as characteristic dimension and characteristic velocity in Reynolds number. Heat capacity ratio is the ratio of heat capacity of the two-phase fluid to the heat capacity of single phase fluid (hot fluid in this case).

The regression equations for thermal effectiveness (E) for the two-phase liquid-liquid systems were obtained using Minitab-15 as follows:

\[ E = 9.583 F^{-0.73} \Re^{0.274} \Pr^{-0.128} \] for two-phase systems in shell side

(58)

\[ E = 17.29 F^{-0.452} \Re^{0.159} \Pr^{-0.22} \] for two-phase systems in tube side

(59)

Figure 4.93 and Figure 4.94 show the comparison between the experimental values of thermal effectiveness and those calculated using Eqs. (58) & (59) respectively. It is evident from Figures 4.93 and 4.94 that the Eqs. (58) and (59) predict the thermal effectiveness for the two-phase within ± 14% error for seven liquid-liquid systems for about 260 data points.
Figure 4.93: Variation between experimental and predicted values of thermal effectiveness for different compositions of liquid-liquid systems in shell side

Figure 4.94: Variation between experimental and predicted values of thermal effectiveness for different compositions of liquid-liquid systems in tube side