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An Experimental Solution of Two-Phase Parameter Correlation Involving Heat Transfer Characteristics for Liquid-Liquid Flow

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Abstract : In petrochemical and allied industries, the commonly encountered two-phase flow is simultaneous flow of two immiscible phases. In the present work, experiments were conducted in a shell and tube heat exchanger with hot water as the heating fluid and different compositions of two-phase system as the process fluid. A new parameter called modified two-phase multiplier (MTPM) has been proposed and correlated with Lockhart-Martinelli parameterand Quality for different compositions of liquid-water systems.The experimental data was statistically analyzed to develop a correlation for MTPM of two-phase liquid systems on shell side. The developed correlation predicts MTPM of two-phase liquid systems as well as two-phase heat transfer coefficients from single phase data with a maximum error of ±10 % for 7 different two-phase liquid systems.
Keywords : Two-phase flow, Heat transfer, Lockhart-Martinelli parameter,Quality, Modified two-phase multiplier, Nusselt number.

1. Introduction

Considerable research has been carried on two-phase flow, particularly in the area of fluid dynamics and heat transfer. Many researchers had used the empirical L-M approach[1] established by Lockhart *et al.* for describing hydrodynamic and pressure drop studies in gas-liquid two-phase flow for various geometries[2,3,4]. Chisholm[5]developed the general correlation between the Lockhart-Martinelli parameter and the two–phase multiplier for pressure drop first time on liquid-liquid two-phase flow in circular tube. Similar kind of studies have been carried out on liquid–liquid systems in various geometries such as horizontal piping[6,7], microchannels[8,9], horizontal and annular piping[10,11], inclined pipe[12,13].

In the recent years, studies on heat transfer involving two-phase liquid - liquid systems have been reported in many heat exchange equipments, such as spiral plate heat exchanger[14], direct contact heat exchanger[15] and shell and tube heat exchanger[16-22].

In the previous studies, heat transfer coefficient was correlated with Reynolds number in power-law fashion for each composition of two-phase, liquid-liquid systems[23]. The coefficient and exponent were used in the calculation of Lockhart-Martinelli parameter. Subsequently, a model was developed relating Lockhart-Martinelli parameter and two-phase multiplier which could be used for prediction of two-phase heat transfer coefficient based on each composition of liquid-water systems. While heat transfer in two-phase flow systems in selected heat transfer equipment had been studied in detail, very few studies had been conducted on determining the heat transfer and flow behavior in shell and tube heat exchangers.

From the survey of literature, it is evident that much of the research in liquid-liquid systems has been predominantly on the fluid dynamics area with relatively fewer works on heat transfer. This paper reports the development of a correlation for MTPM for the instance of heat transfer between a single phase stream and a two-phase stream for a reasonably wide variety of liquids constituting two phases.

2. Experimental

The 1-2 pass shell and tube heat exchanger used for heat transfer experiments is described in our earlier work[16-20]and a process flow diagram is shown in Figure 1. The hot water and two-phase liquids were pumped to the heat exchanger using 0.25 HP pumps andthe flow rates were measured using calibrated rotameters.V1, V2, V3 and V4 are manual valves used to adjust the flow rates of hot and cold streams. A thermostat was used to maintain the temperature of hot water. An agitator was used to maintain the uniform concentration of two-phase stream in the reservoir. Seven liquid-water systems viz. Kerosene-water, Diesel-water, Nitro benzene-water, Oleic acid-water, Palm oil-water, Octane-water and Dodecane-water in varying proportions were used for experiments. This experimental design yielded 7 two-phase systems with 4 compositions each leading to 28 different two-phase systems. The range of variables investigated isgiven in Table 1. The wide range of thermo-physical & transport properties of various pure liquids used for formulation of two-phase, liquid-liquid systems are dealt in this study.

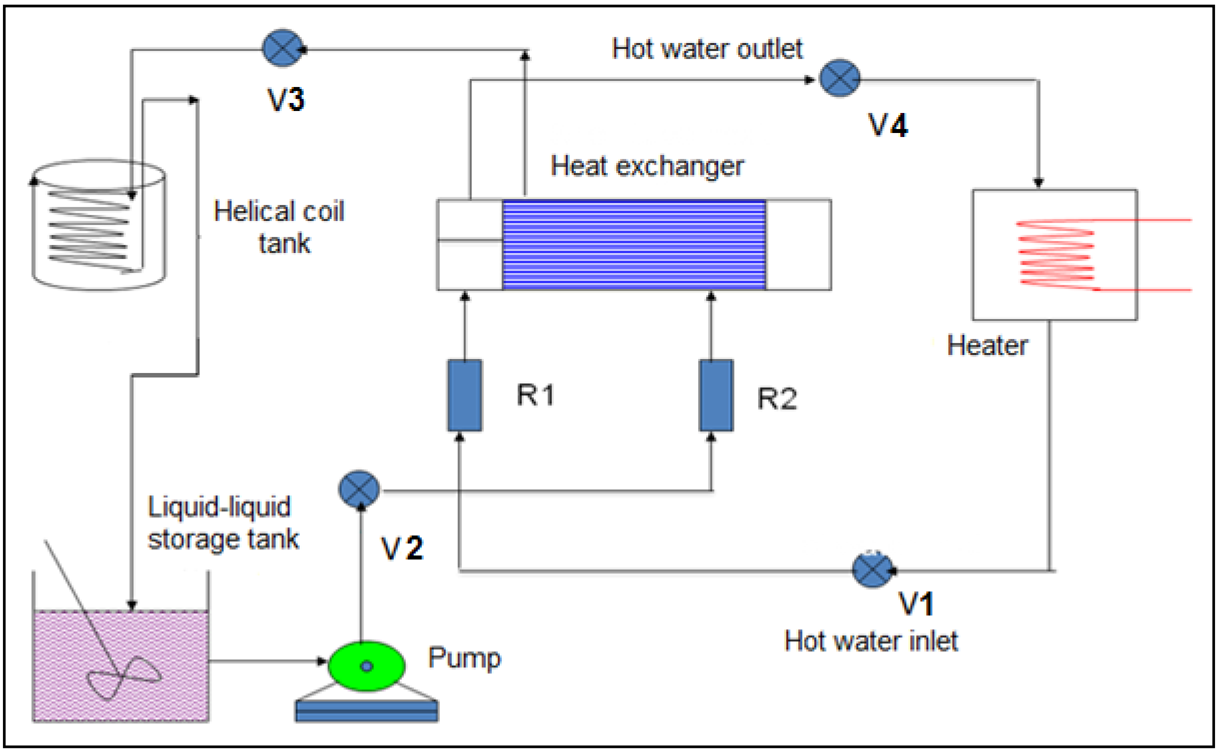

Figure 1: Theproc

Table 1: Range of variables investigated

S.no	Variables	Values
1	Composition of two-phase systems (as volume percentage of organic phase)	20%, 40%, 60%, 80% and 100%
2	Mass flow rate of cold fluid in shell side	0.0088 kg/s to 0.2412 kg/s

3. Calculation methodology

3.1: Tube side (hot water):

3.1.1: Tube side heat transfer rate is calculated as follows:

$$Q_{ht} = m_{ht} Cp_{ht} \left(T_{h2} - T_{h1}\right) \quad (1)$$

3.2: Shell side (Process fluid):

3.2.1: Cross flow area is given by

$$A_s = \left(\frac{(P_t - D_o)}{P_t}\right) D_s B_s \quad (2)$$

Velocity of shell side fluid is calculated as

$$u_{1s} = \frac{V_{1s}}{A_s} \quad (3)$$

3.2.2: $X_s$is related to volumetric flow rate of organic phase and water phase as:

$$X_s = \frac{1}{\left(1 + \frac{(\rho_{ws} V_{ws})}{(\rho_{fs} V_{fs})}\right)} \quad (4)$$

V_{ws}, V_{fs} - volumetric rate of cold water and pure liquid in shell side, m^3/s

ρ_{ws}, ρ_{fs} - Density of cold water and pure liquid in shell side (kg/m^3)

3.2.3: Shell side heat transfer rate is related to temperature rise of single-phase stream as

$$Q_{1s} = m_{1s} Cp_{1s} \left(T_{c2} - T_{c1}\right) \quad (5)$$

3.2.4: The shell side heat transfer coefficient for single phase is related to Reynolds number by the following formula[24].

$$Nu_{1s} \ \alpha \ \mathrm{Re}^{0.55} \, \mathrm{Pr}^{0.333} \quad (6)$$

3.2.5: Lockhart-Martinelli parameter is related to quality parameter, density and viscosity of the two-phases as follows:

$$\chi_{ts}^{2} = \left(\frac{1-X_s}{X_s}\right)^{2-0.55}\left(\frac{\rho_{fs}}{\rho_{ws}}\right)\left(\frac{\mu_{ws}}{\mu_{fs}}\right)^{0.55} \quad (7)$$

μ_{ws}, μ_{fs} - Viscosity of cold water and pure liquid in shell side (kg/ms)

3.2.6: Modified two-phase multiplier

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:

$$\Phi_{Ls} = \frac{Nu_{2s}}{Nu_{1s}} \quad (8)$$

4. Results & Discussion

4.1. Effect of Quality on Modified Two-phase Multiplier for the process fluid:

Figures 2 to 8 show the effect of quality on modified two-phase multiplier (Φ_{Ls}) of two-phase process stream, when it was supplied through the shell-side. Figure 2 has been drawn for different compositions of kerosene-water system as the process stream. It is observed from Figure 2 that the modified two-phase multiplier increased with increase in its quality.As the proportion of the second phase increases and a consequent decrease in the proportion of water, the viscosity of the mixture increases while thermal conductivity, density and specific heat decrease. At the same time, this increases the Nusselt number (Nu_{2s}) and hence the modified two-phase multiplier increases with the quality.

ess flow diagram

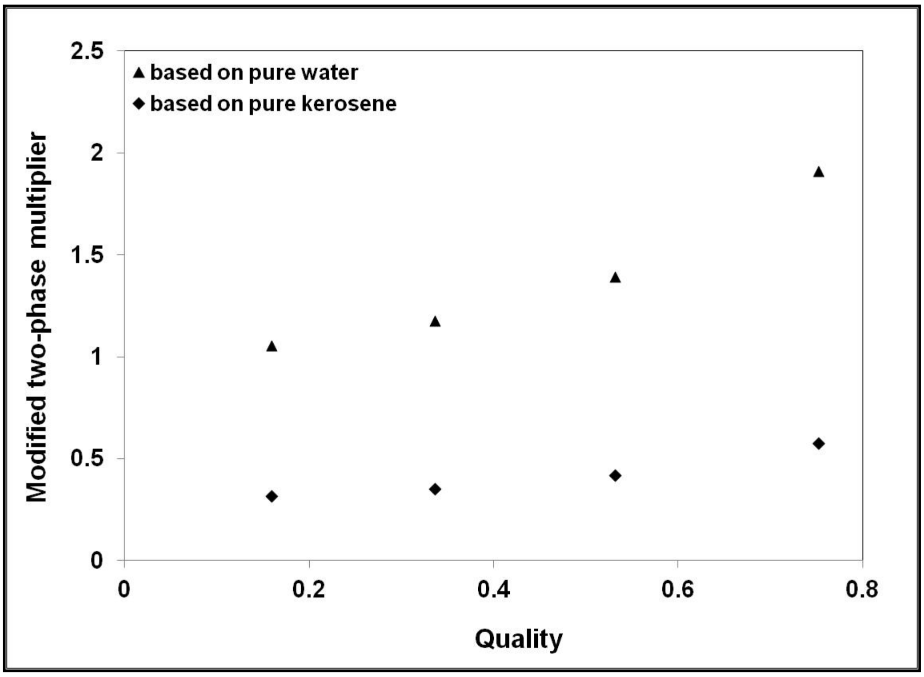

Figure 2: Variation between Quality and Modified two-phase multiplier for kerosene-water system in shell side

Figure 2 also compares the modified two-phase multiplier based on 100% kerosene and based on 100% water. Since the single phase Nusselt number (Nu_{1s}) of water was lower than the single phase Nusselt number (Nu_{1s}) of kerosene, the modified two-phase multiplier based on pure water was greater for a fixed quality of kerosene-water system. The variation of the modified two phase multiplier with quality is a linear relationship with a positive slope. Similar trend is seen for all other two-phase systems studied also as shown in Figures 3 to 8.

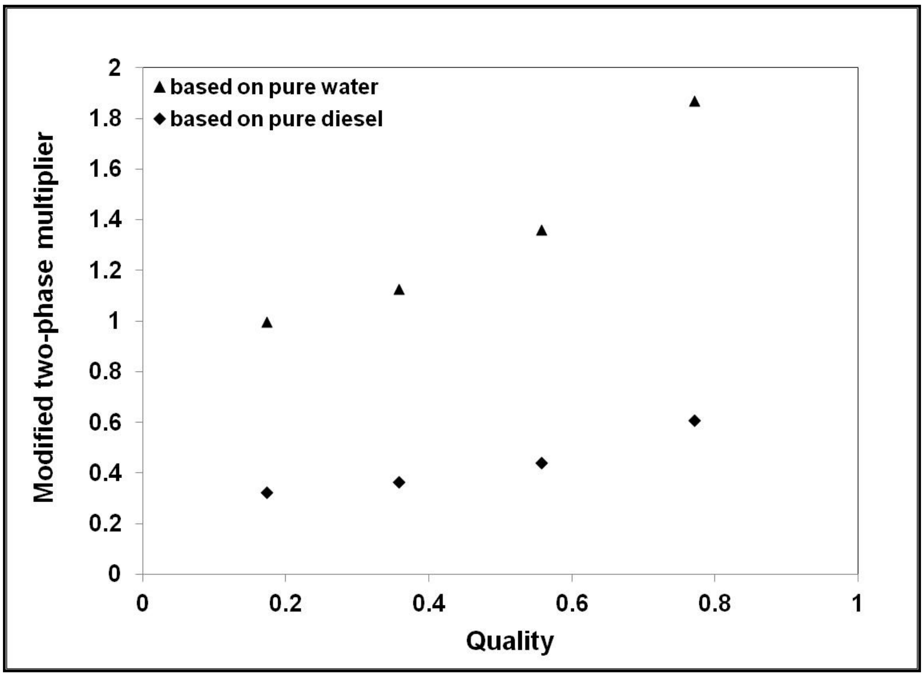

Figure 3: Variation between Quality and Modified two-phase multiplier for diesel-water system in shell side

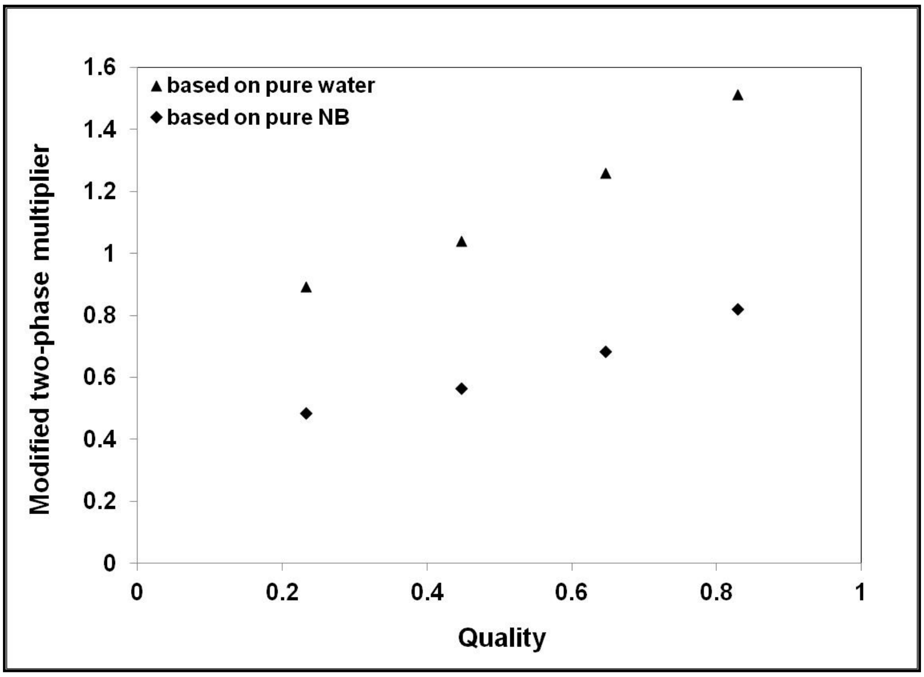

Figure 4: Variation between Quality and Modified two-phase multiplier for NB-water system in shell side

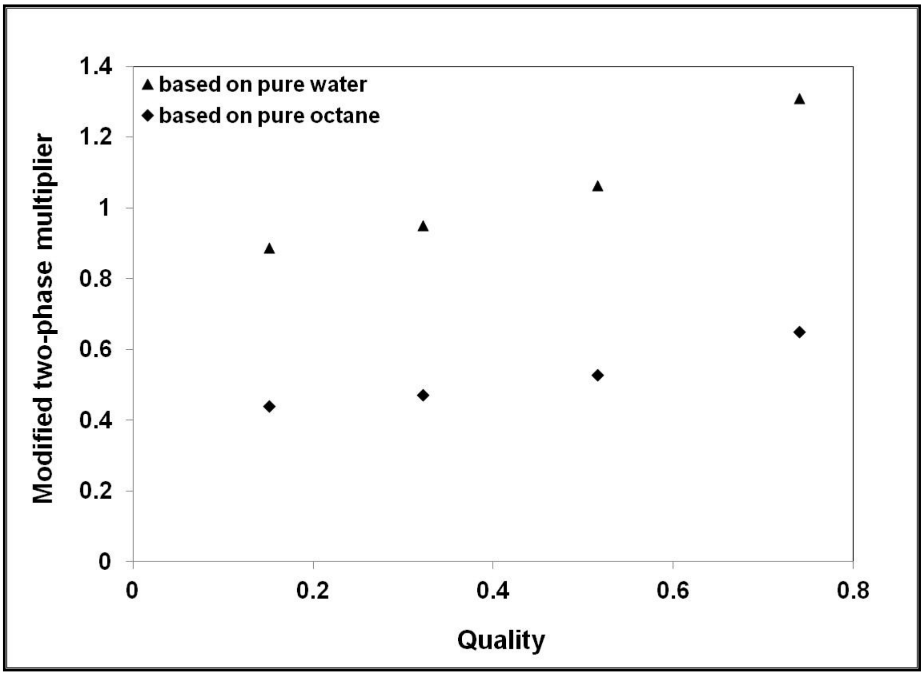

Figure 5: Variation between Quality and Modified two-phase multiplier for octane-water system in shell side

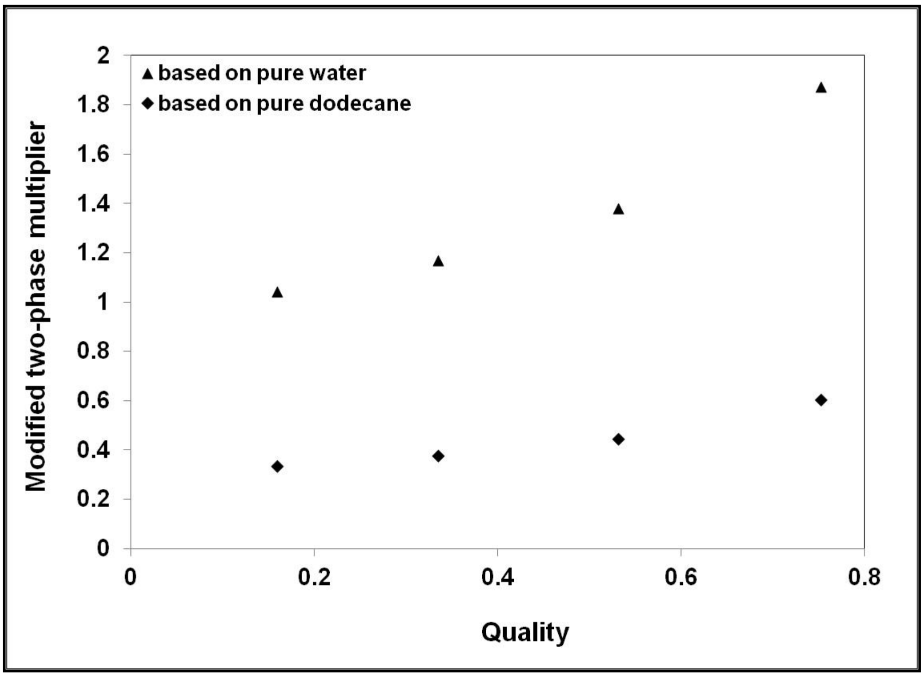

Figure 6: Variation between Quality and Modified two-phase multiplier for dodecane-water system in shell side

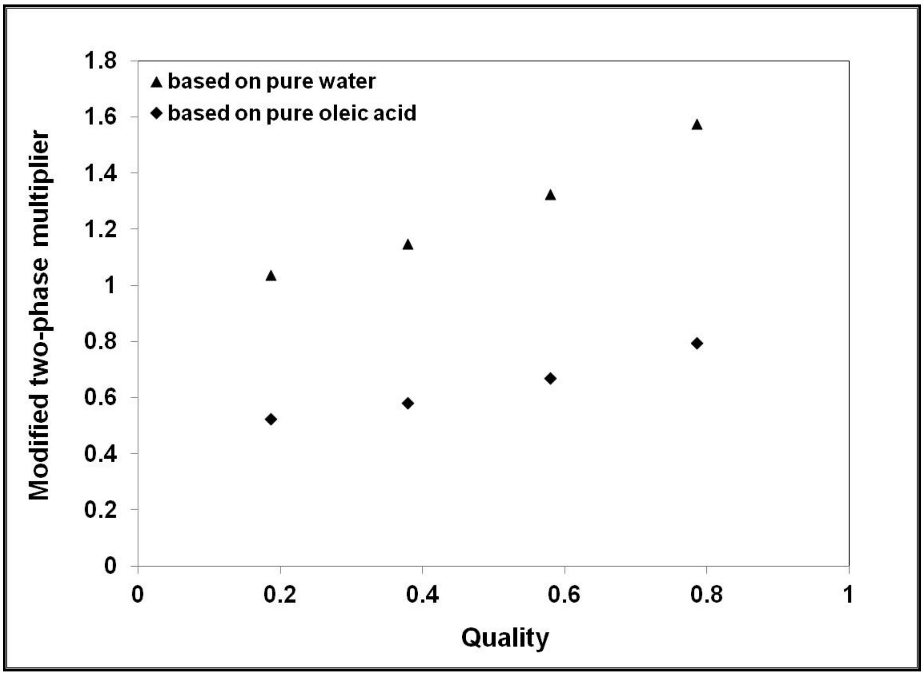

Figure 7: Variation between Quality and Modified two-phase multiplier for oleic acid-water system in shell side

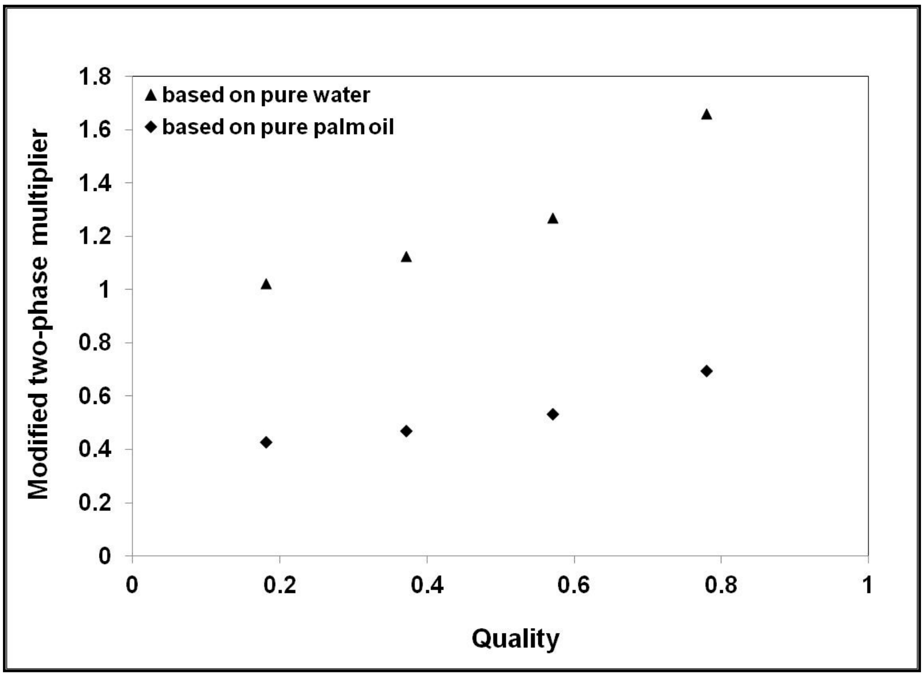

Figure 8: Variation between Quality and Modified two-phase multiplier for palm oil-water system in shell side

4.2. Effect of quality on L-M parameter for the process stream in shell side:

Figure 9shows the effect of quality on L-M parameter (χ_{ts}^2) of two-phase process stream, when it was supplied through the shell-side. Figure 9has 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 9 that the LMP decreased with increase in quality for kerosene-water as process stream. The single phase exponent is useful in determining LMP from single phase data. The LMP is calculated based on the exponent value of Reynolds number for pure water and pure liquid. The LMP was calculated using the exponent ‘m’ as 0.55which represents the power to which Reynolds number is raised for single phase data[24] .The LMP 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.(7).

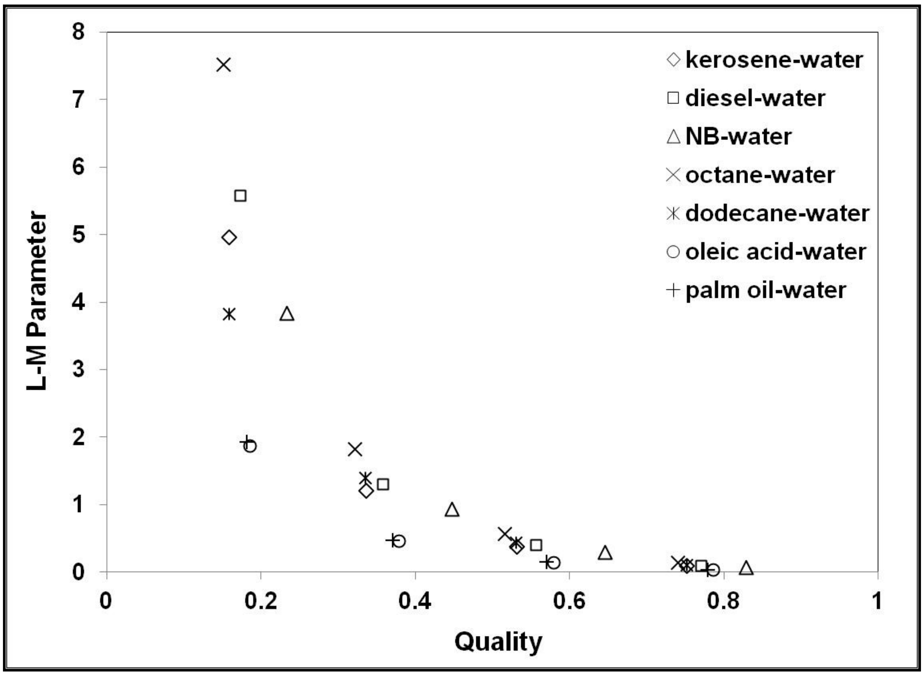

Figure 9: Variation between Quality and L-M parameter for seven liquid-water systems in shell side

From the definition, LMP has as 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 LMP. Due to relatively wide range of the viscosity of the test fluids, the range of LMP variations are also large. As expected the high viscosity fluids such as palm oil, oleic acid, have low values of LMP. Similar behavior has been observed for other two-phase process streams also as shown in Figure 9.

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

Figures 10 to 16show 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 10 has been drawn between modified two-phase multiplier and L-M parameter for different compositions of kerosene-water system. It is observed from Figure 10 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 10 that the modified two-phase multiplier increases with quality. Hence, with increase in L-M parameter, the modified two-phase multiplier decreases due to decrease in quality 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 11 to 16.

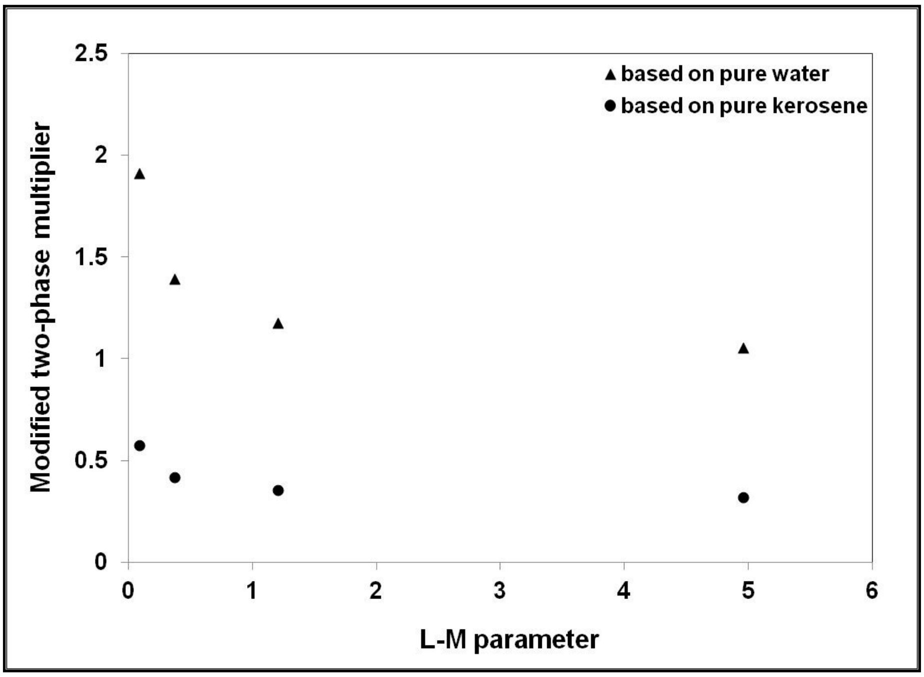

Figure1: Variation between L-M parameter and Modified two-phase multiplier for kerosene-water system in shell side

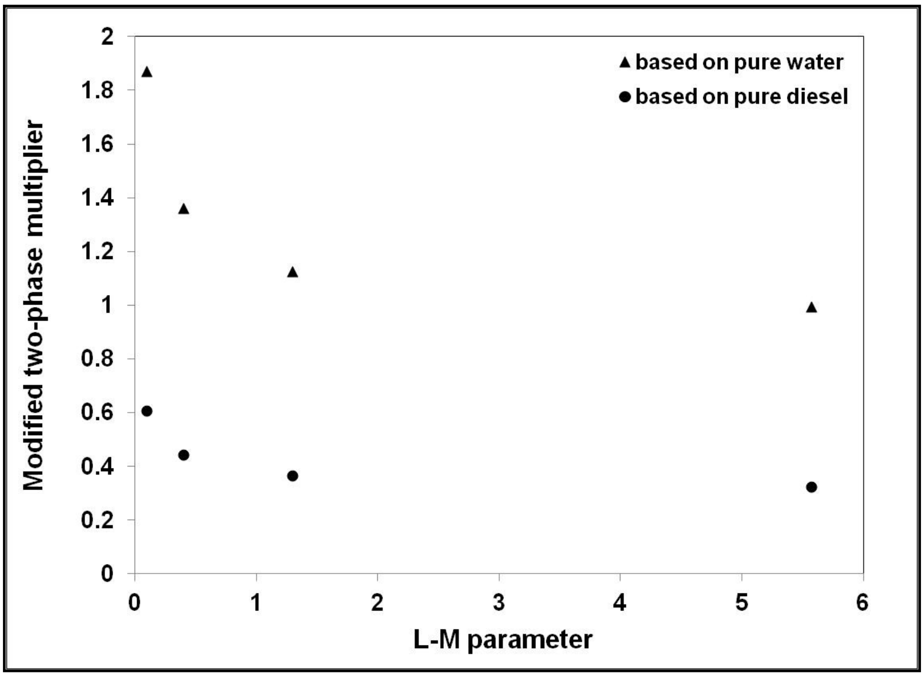

Figure2: Variation between L-M parameter and Modified two-phase multiplier for diesel-water system in shell side

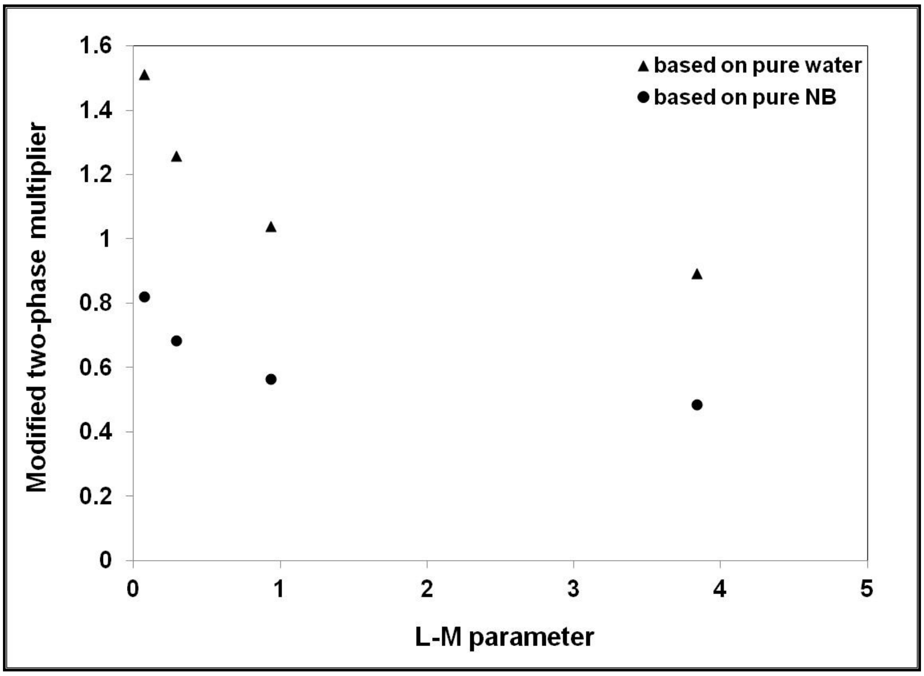

Figure3: Variation between L-M parameter and Modified two-phase multiplier for NB-water system in shell side

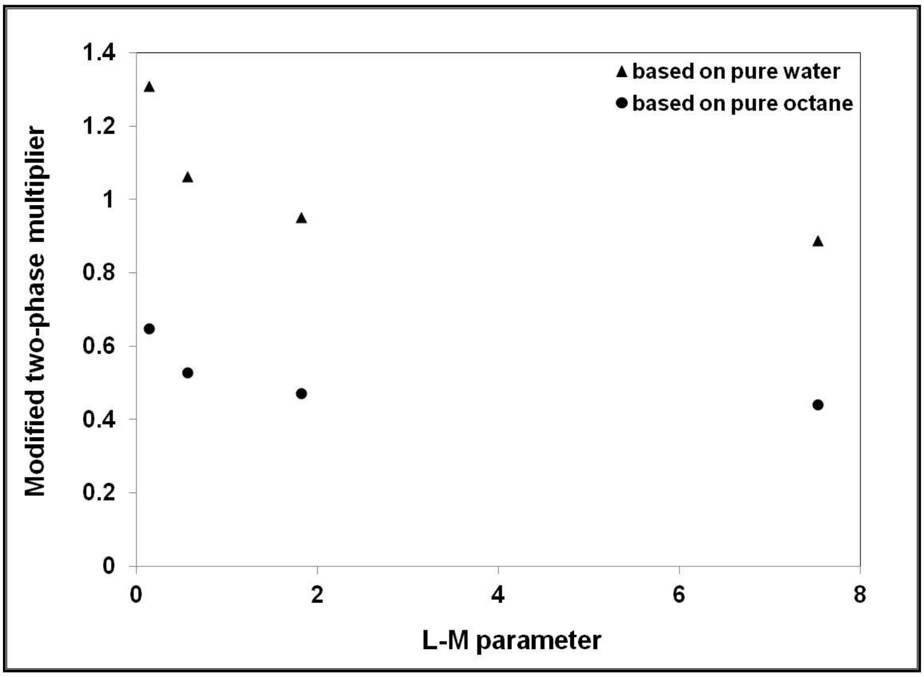

Figure4: Variation between L-M parameter and Modified two-phase multiplier for octane-water system in shell side

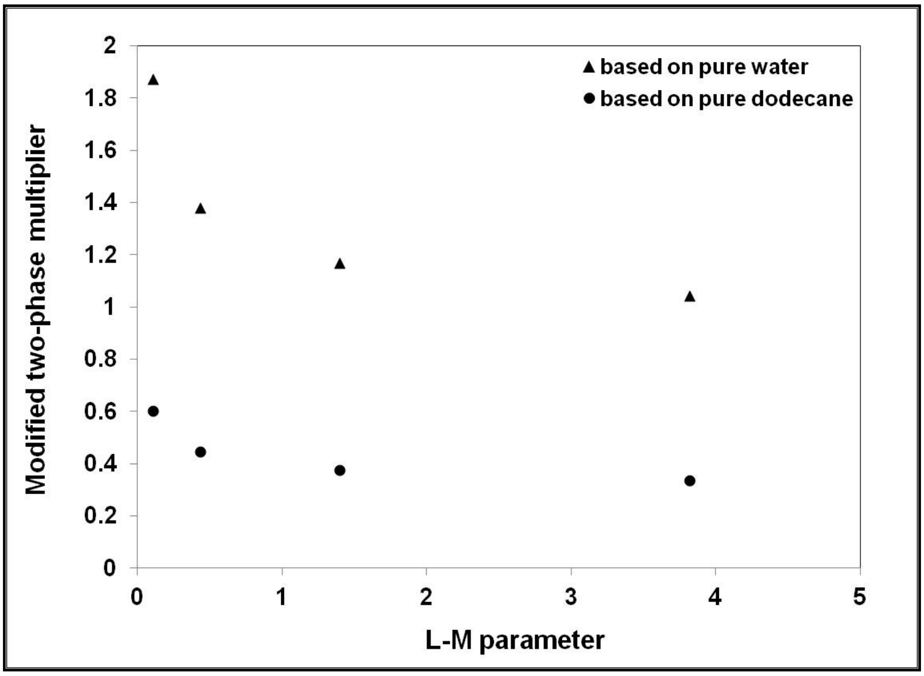

Figure5: Variation between L-M parameter and Modified two-phase multiplier for dodecane-water system in shell side

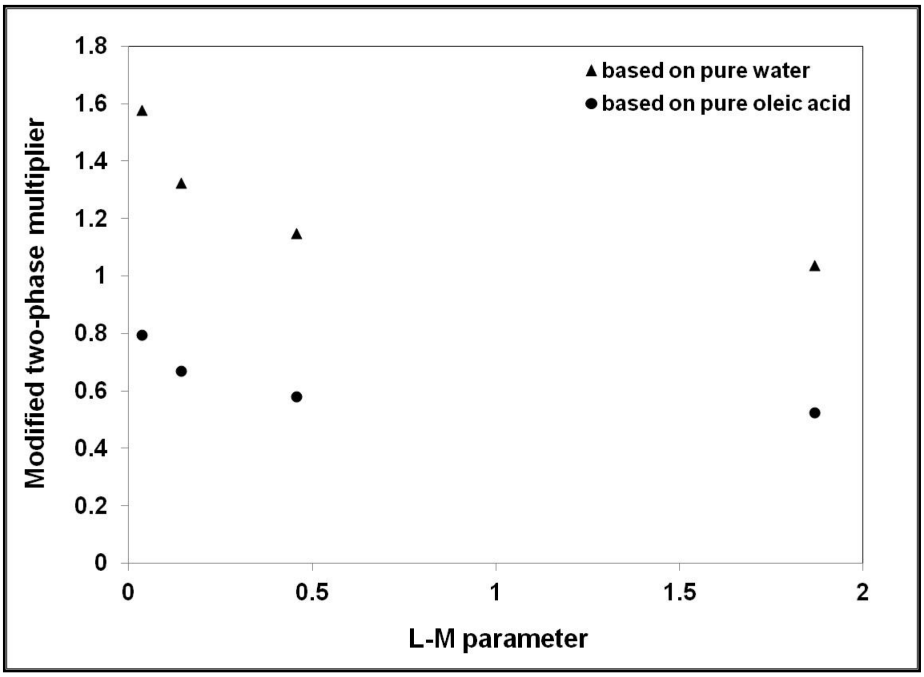

Figure6: Variation between L-M parameter and Modified two-phase multiplier for oleic acid-water system in shell side

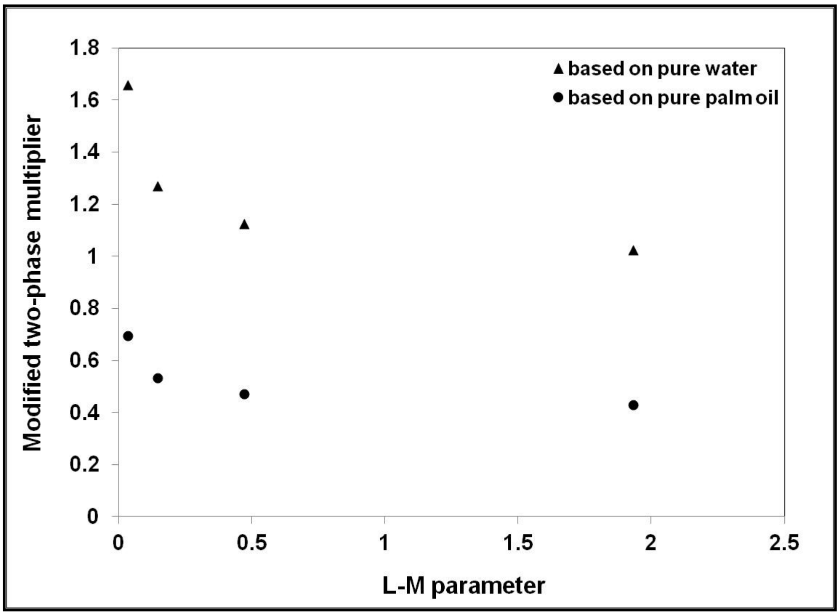

Figure7: Variation between L-M parameter and Modified two-phase multiplier for palm oil-water system in shell side

4.4: Modified two-phase multiplier, Quality and L-M parameter correlations

A correlation between the modified two-phase multiplier (Φ_{Ls}), Quality (X_s) and L-M parameter (χ_{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:

$$\Phi_{Ls} = 1.433\left(X_s\right)^{-0.028}\left(\chi_{ts}^2\right)^{0.193} \qquad (9)$$

Water has been chosen as the reference as it was the common phase for all liquid-liquid systems investigated. A comparison of experimental modified two-phase multiplier and that predicted using Eq. (9) is shown in Figure 17. It is evident from Figure 17 that the Eq. (9) predicts the modified two-phase multiplier for seven process streams within ± 10% error for about 22 various water-organic liquid compositions. Table 2 presents the statistics and the range of variables for Eq.(9).

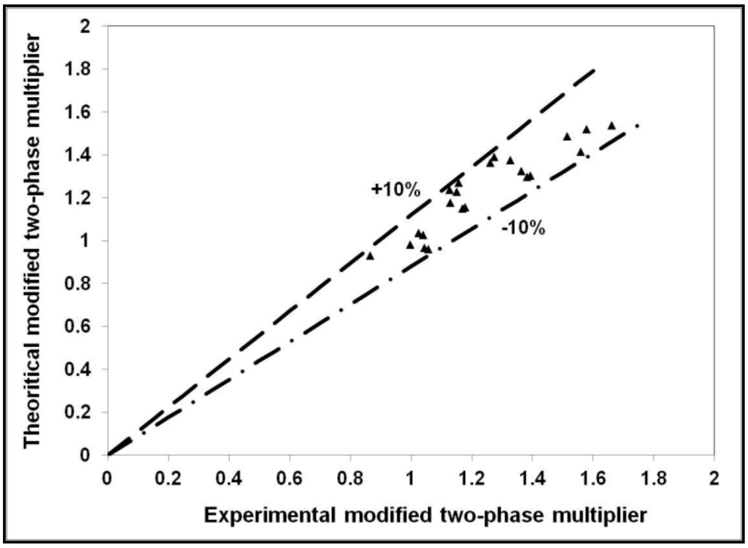

Figure8: Variation between experimental and calculated modified two-phase multiplier based on the developed two-phase correlation in shell side

Table 2: The range of variables investigated for modified two-phase multiplier correlation in shell side

Dimensionless variables	Range of values
Quality	0.151 to 0.829
L-M parameter	0.023 to 10.627
Modified two-phase multiplier	0.864 to 1.913
% error deviation in modified two-phase multiplier	- 9.021 to + 9.952
Standard deviation in modified two-phase multiplier	0.081
Coefficient of variation (%)	6.527
Mean error (%)	5.457
Index of correlation	0.925

5. Conclusion

The heat transfer involving two-phase immiscible systems in a 1-2 pass shell tube heat exchanger were studied experimentally. The choice of these organic process liquids facilitated experimental studies covering wide range of thermo-physical properties. The modified two-phase multiplier increases with quality and decreases with L-M parameter in non-linear fashion for all the two-phase systems investigated in the laminar flow regime. A correlation between the modified two-phase multiplier (Φ_{Ls}), Quality (X_s) and L-M parameter (χ_{ls}^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. The predicted values can be used for the design of heat exchangers for a specific two-phase duty in the Reynolds numbers range investigated. Based on the summary in Table 2, it can be concluded that water is a better reference fluid compared to other organic liquids. The developed correlation predicts the MTPM for two-phase liquid system with a maximum error of ± 10 % for wide range of data points covering 7 different two-phase systems.

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