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Effect of Two-phase Heat Transfer Characteristics in Developing Two-Phase Parameter Correlation for Immiscible Liquid Systems

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ABSTRACT

The heat transfer involving two-phase immiscible systems is gaining importance in petrochemical and allied industries. In the present study, varying compositions of two-phase liquid systems were experimentally studied in a shell and tube heat exchanger. The objective of this study is to establish a two-phase parameter correlation to predict two-phase heat transfer coefficient which would be vital for the optimal design of heat transfer equipment. A new two-phase parameter called modified two-phase multiplier (MTPM) has been proposed and correlated with Lockhart-Martinelli parameter and Quality for different compositions of liquid-water systems. The experimental data was statistically analyzed to develop a correlation for two-phase liquid systems on tube side. The developed correlation predicts MTPM and two-phase heat transfer coefficient from single phase data with a maximum error of ±15 % for 7 different two-phase liquid systems.

Keywords: Two-phase flow, Heat transfer, Lockhart-Martinelli parameter, Quality, Modified two-phase multiplier

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INTRODUCTION

Understanding of momentum and heat transfer in two-phase flow is essential for designing best feasible heat transfer equipment used particularly in petrochemical and allied industries.

Many researchers had used the empirical Lockhart-Martinelli approach [1] for describing hydrodynamic and pressure drop studies in gas-liquid two-phase flow for various geometries [2] – [7]. Chisholm and Laird [8] developed the general correlation between the L-M 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 [9] – [11], microchannels [12], [13], horizontal and annular piping [14] – [17], inclined pipe [18], [19].

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 [20], agitated vessel with helical coil [21], direct contact heat exchanger [22] and shell and tube heat exchanger [23] - [29].

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[30]. The coefficient and exponent were used in the calculation of L-M parameter. Subsequently, a model was developed relating L-M 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. Though the two-phase heat transfer characteristics in chosen equipment had been studied in detail, very few studies had been conducted for 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.

MATERIALS AND METHODS

The 1-2 pass shell and tube heat exchanger used for heat transfer experiments is described in our earlier work [23] - [27] and its process flow diagram is shown in Figure 1. In the present work, experiments were carried out in a shell and tube heat exchanger with supplying hot water as the heating fluid in shell side and two-phase system of different fluids in tube side as the 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 with water as second phase. V1, V2, V3 and V4 are manual valves used to adjust the flow rates of hot and cold streams. An agitator was used to ensure constant mixing of two fluids in the reservoir.

This experimental design yielded 7 two-phase systems with 4 compositions (20%, 40%, 60%, 80% and 100%) each leading to 28 different two-phase systems. The flow rate of process fluid investigated in tube side of the exchanger is from 0.0043 to 0.1062 kg/s. 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.

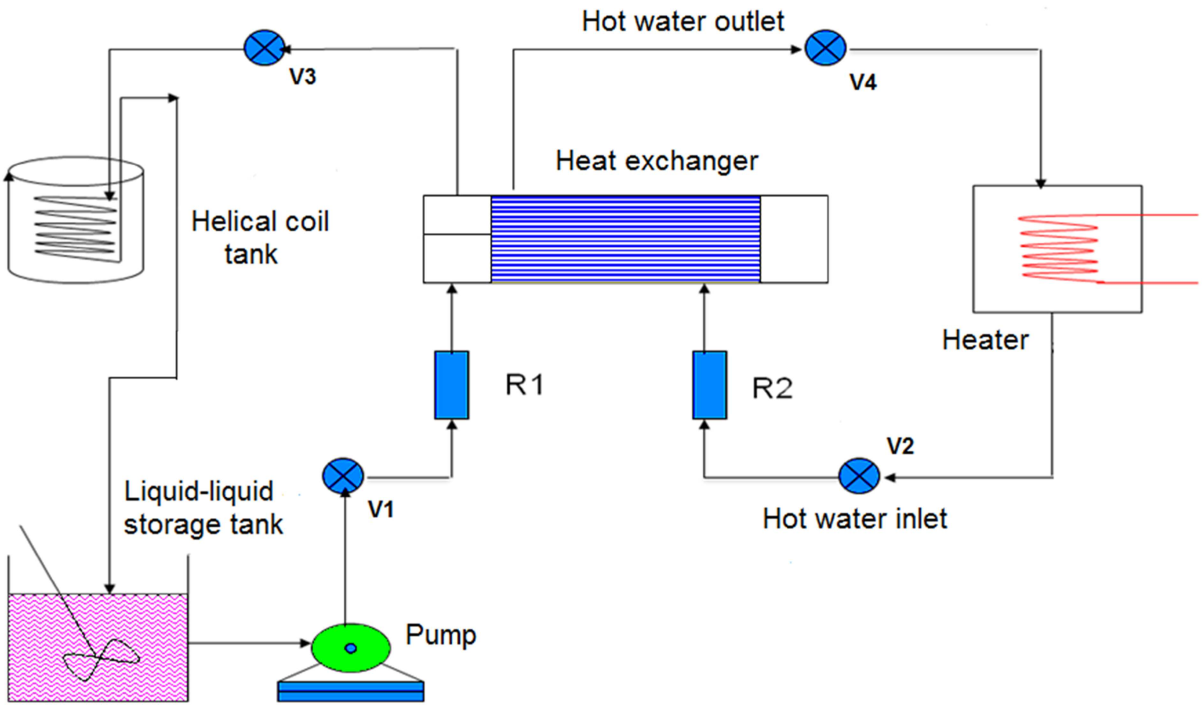

Figure 1: The process flow diagram

1. Calculation methodology

3.1: Shell side (hot water):

3.1.1**:** Mass flow rate of hot water in shell side is given by

$$m_{hs} = V_{hs}\rho_{hs} \tag{1}$$

3.1.2**:** Shell side heat transfer rate is calculated using the following expression:

$$Q_{hs} = m_{hs}c_{p_{hs}}\left(T_{h2} - T_{h1}\right) \tag{2}$$

m_{hs}, Cp_{hs} - Mass flow rate (kg/s) and Specific heat (J/kg K) of hot water.
T_{h1}, T_{h2} - Inlet and Outlet temperature of hot water, K

3.2: Tube side (Process fluid):

3.2.1**:** Velocity of single-phase fluid is calculated as

$$u_{1t} = \frac{V_{1t}}{A_t} \qquad (3)$$

The total cross sectional area of tubes (A_t) is

$$A_t = \frac{\pi D_i^2}{4} \times \frac{N_t}{N_p} \qquad (4)$$

N_t, N_p - Number of tubes and Number of passes

3.2.2**:** Mass flow rate of fluid is given by

$$m_{1t} = V_{1t}\,\rho_{1t} \qquad (5)$$

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

$$Q_{1t} = m_{1t} c_{p_{1t}} \left(T_{c2} - T_{c1}\right) \qquad (6)$$

m_{1t}, Cp_{1t} - Mass flow rate (kg/s) and Specific heat (J/kg K) of single-phase fluid.
T_{c1}, T_{c2} - Inlet and Outlet temperature of cold fluid in tube side, K

3.2.4**:** The tube side Nusselt number for single phase is related to Reynolds number by following formula [31].

$$Nu_{1t}\ \alpha\ (\mathrm{Re}\,\mathrm{Pr})^{0.333} \qquad (7)$$

3.2.5**:** Lockhart-Martinelli parameter is calculated as

$$\chi_{tt}^{\ 2} = \left(\frac{1-X_t}{X_t}\right)^{2-0.333} \left(\frac{\rho_{ft}}{\rho_{wt}}\right)\left(\frac{\mu_{wt}}{\mu_{ft}}\right)^{0.333} \qquad (8)$$

ρ_{wt}, ρ_{ft} - Density of cold water and pure liquid in tube side (kg/m³)

μ_{wt}, μ_{ft} - Viscosity of cold water and pure liquid in tube side (kg/ms)

Where X_t is quality parameter for two-phase fluid in tube side given by

$$X_t = \frac{1}{\left(1 + \frac{(\rho_{wt} V_{wt})}{(\rho_{ft} V_{ft})}\right)} \qquad (9)$$

3.2.7**:** Modified two-phase multiplier for tube side flow of two-phase stream is given by

$$\Phi_{Lt} = \frac{Nu_{2t}}{Nu_{1t}} \qquad (10)$$

RESULTS AND DISCUSSION

1.1. 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_{Lt}) of two-phase process stream, when it was supplied through the tube-side. It is observed from Figure 2 that the modified two-phase multiplier increased with increase in its quality. Φ_{Lt} relates single phase Nusselt number (Nu_{1t}) and two-phase Nusselt number (Nu_{2t}) as shown in Eq. (10). Φ_{Lt} 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 while thermal conductivity, density and specific heat decrease. At the same time, this increases the Nusselt number (Nu_{2t}) and hence the modified two-phase multiplier increases with the quality.

Figure 2 also compares the Φ_{Lt} based on 100% kerosene and based on 100% water. Since the single phase Nusselt number of water was lower than the single phase Nusselt number of kerosene, the Φ_{Lt} based on pure water was greater for a fixed quality of kerosene-water system. The variation of the Φ_{Lt} 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.

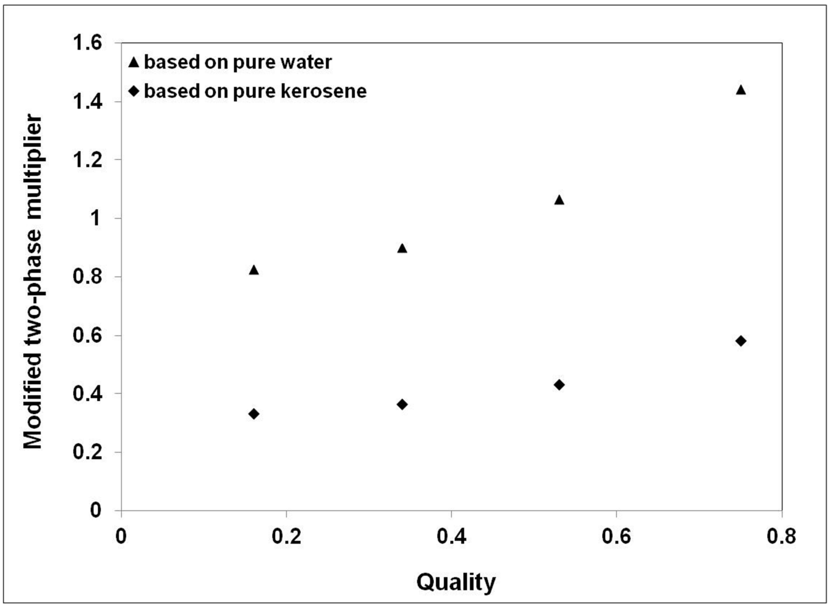

Figure 2: Variation between Modified two-phase multiplier and Quality for kerosene-water system in tube side

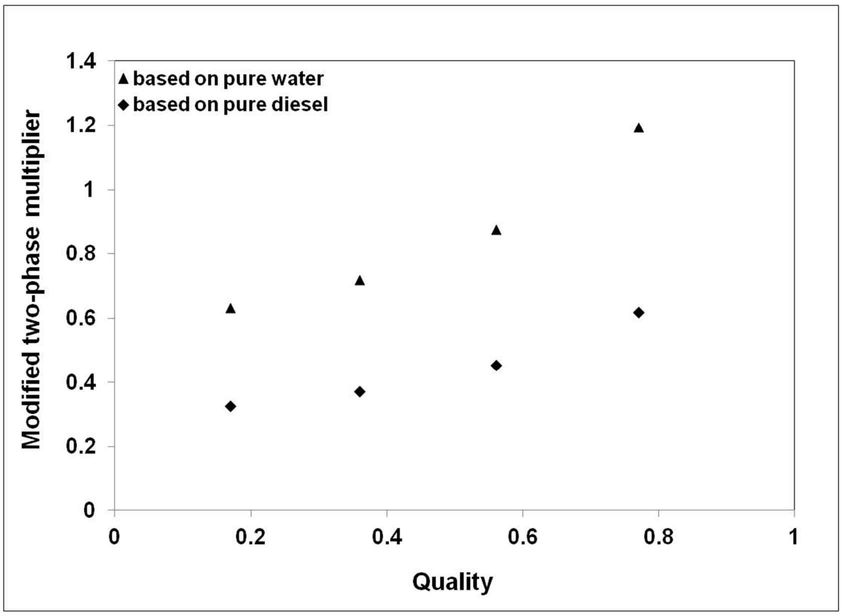

Figure 3: Variation between Modified two-phase multiplier and Quality for diesel-water system in tube side

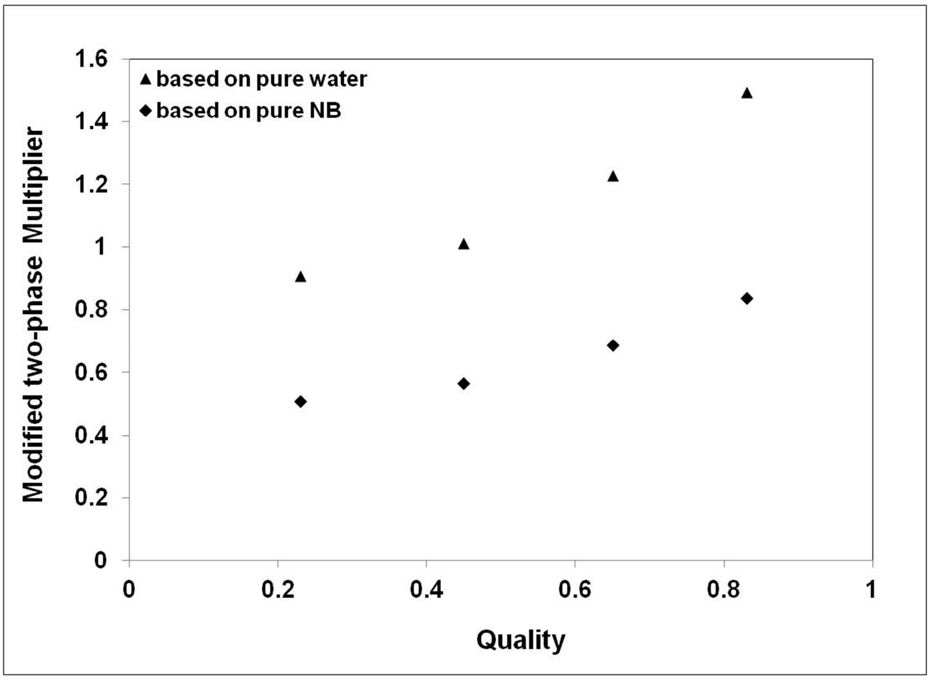

Figure 4: Variation between Modified two-phase multiplier and Quality for NB-water system in tube side

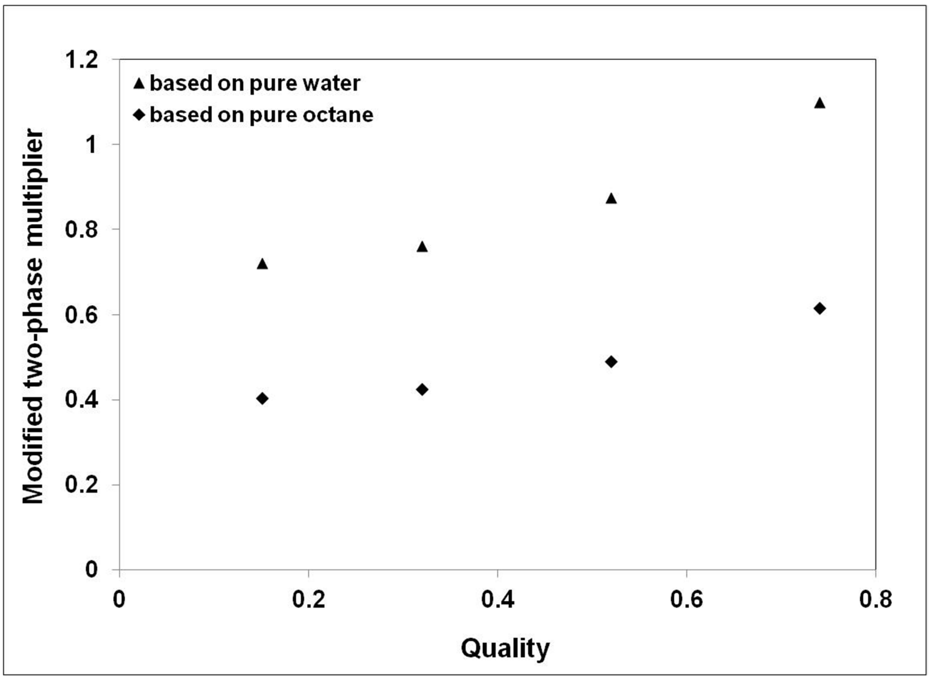

Figure 5: Variation between Modified two-phase multiplier and Quality for octane-water system in tube side

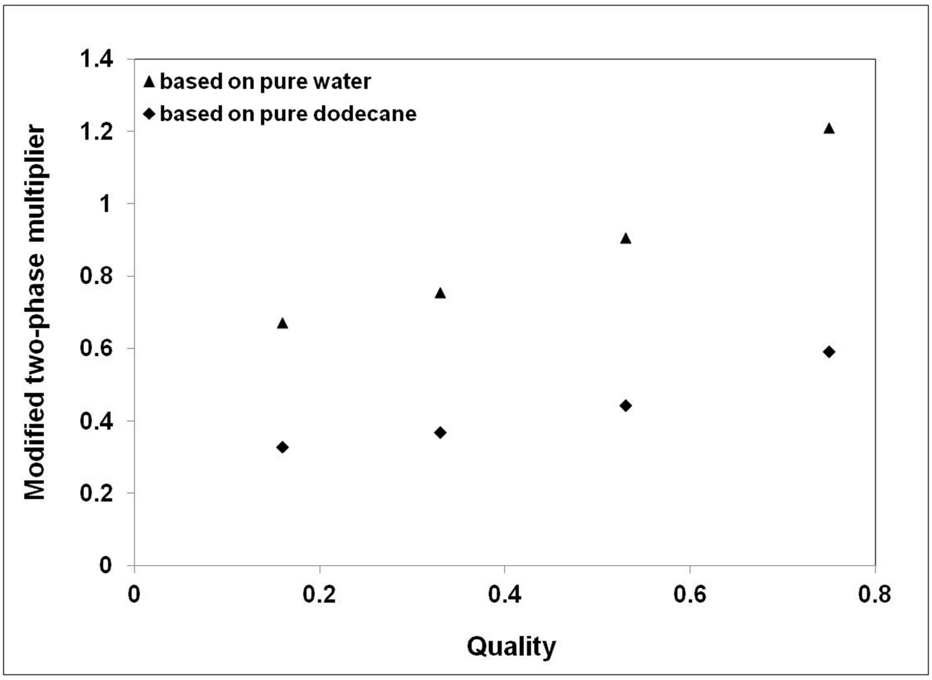

Figure 6: Variation between Modified two-phase multiplier and Quality for dodecane-water system in tube side

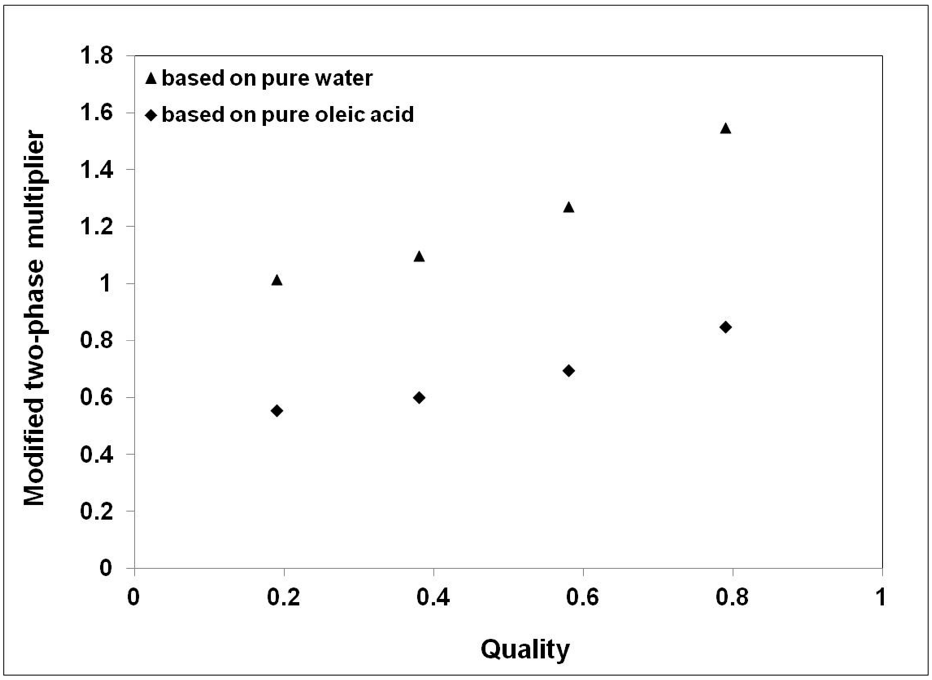

Figure7: Variation between Modified two-phase multiplier and Quality for oleic acid-water system in tube side

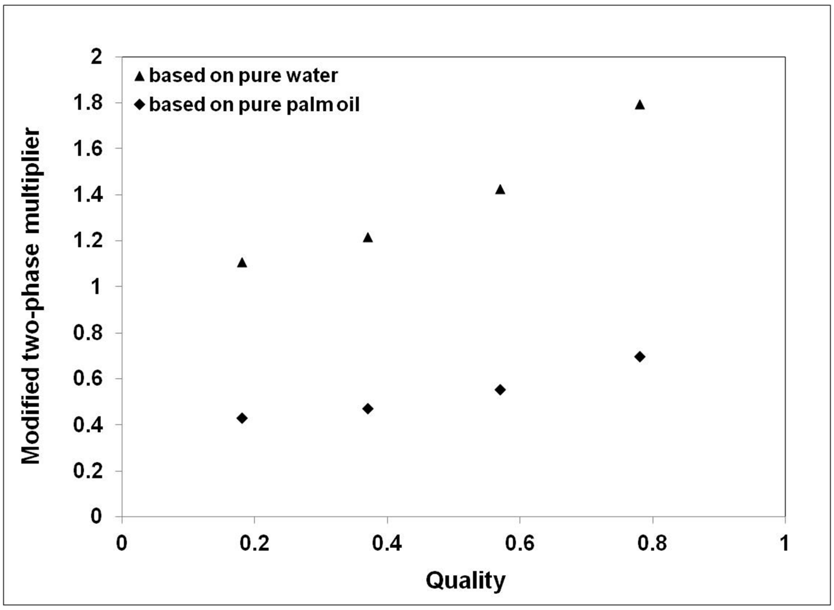

Figure 8: Variation between Modified two-phase multiplier and Quality for palm oil-water system in tube side

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

Figure 9 shows the effect of quality on L-M parameter (χ_{tt}^2) of two-phase process stream, when it was supplied through the tube side. Figure 9 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 9 that the L-M parameter decreased with increase in quality for kerosene-water as process stream. The single phase exponent is useful in determining 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 was calculated using the exponent value 'm_t' as 0.333 [31] which represent the power to which Reynolds number is raised for single phase data. The L-M parameter 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.(8).

From the definition, L-M parameter 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 L-M parameter. Due to relatively 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 values of L-M parameter. Similar behavior has been observed for other two-phase process streams also as shown in Figure 9.

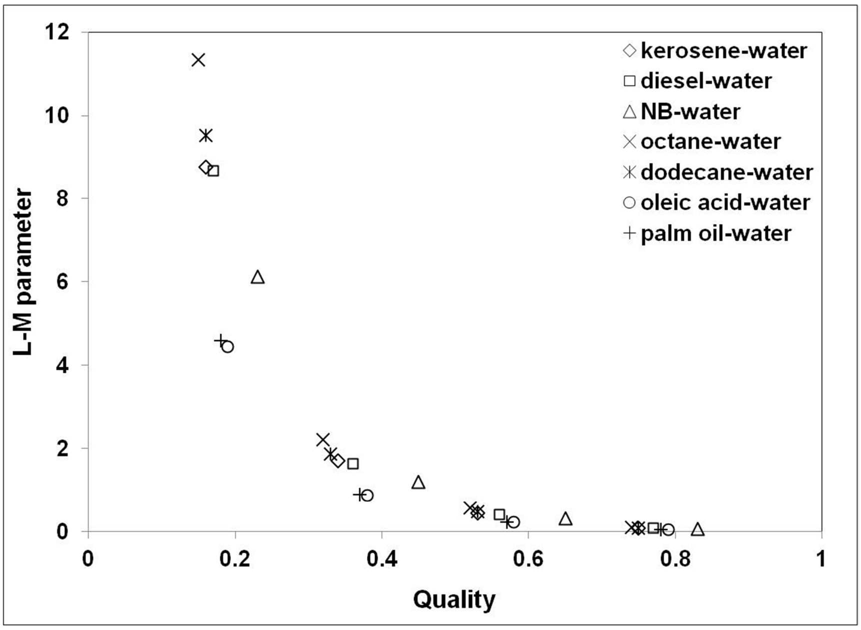

Figure 9: Variation between Quality and L-M parameter for seven liquid-water systems in tube side

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

Figures 10 to 16 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 tube-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.

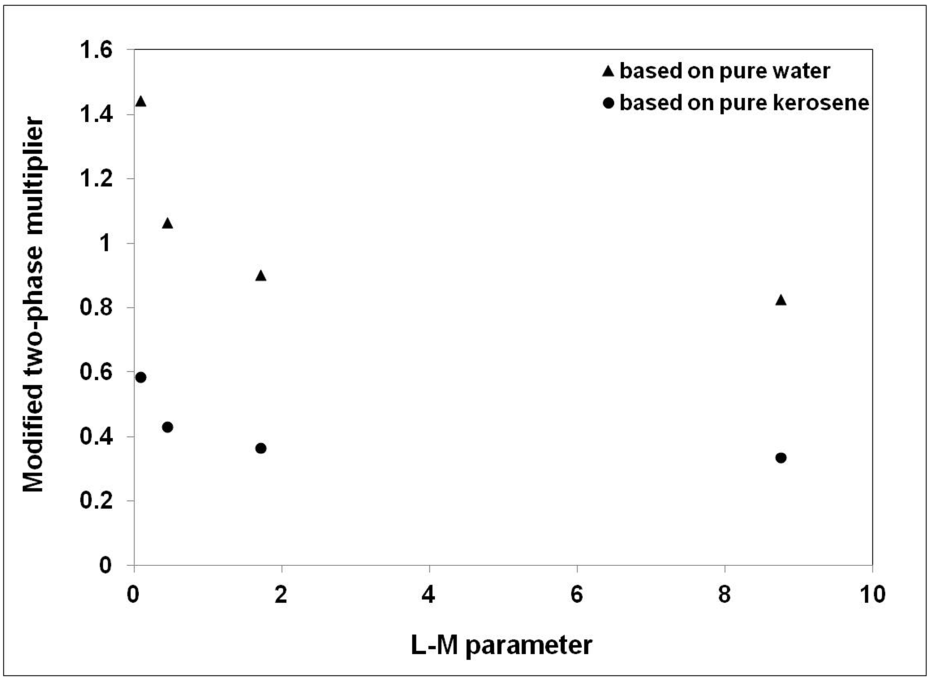

Figure 00: Variation between L-M parameter and Modified two-phase multiplier for kerosene-water system in tube side

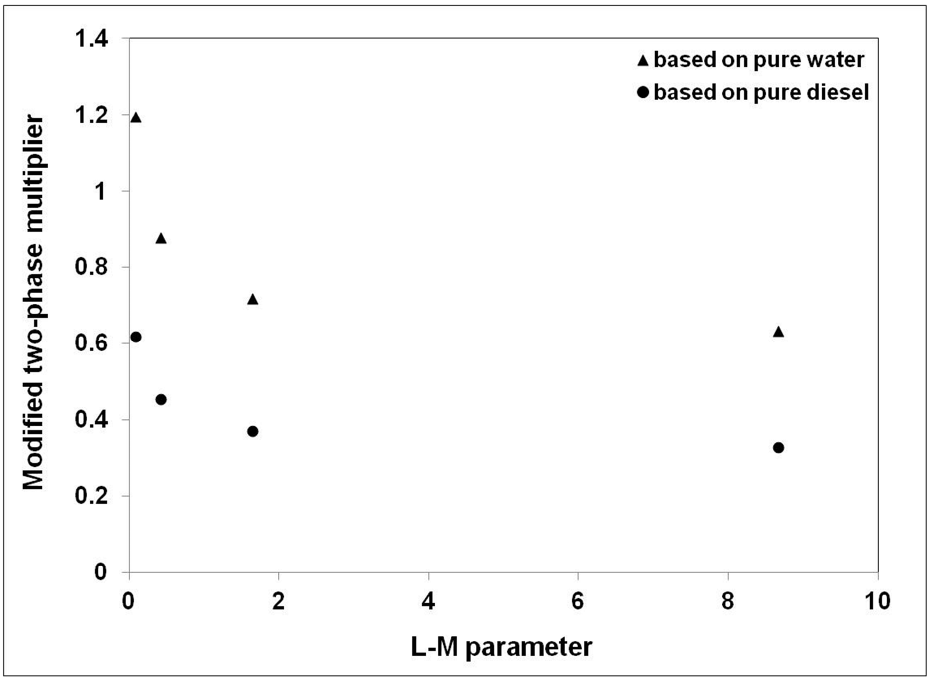

Figure 11: Variation between L-M parameter and Modified two-phase multiplier for diesel-water system in tube side

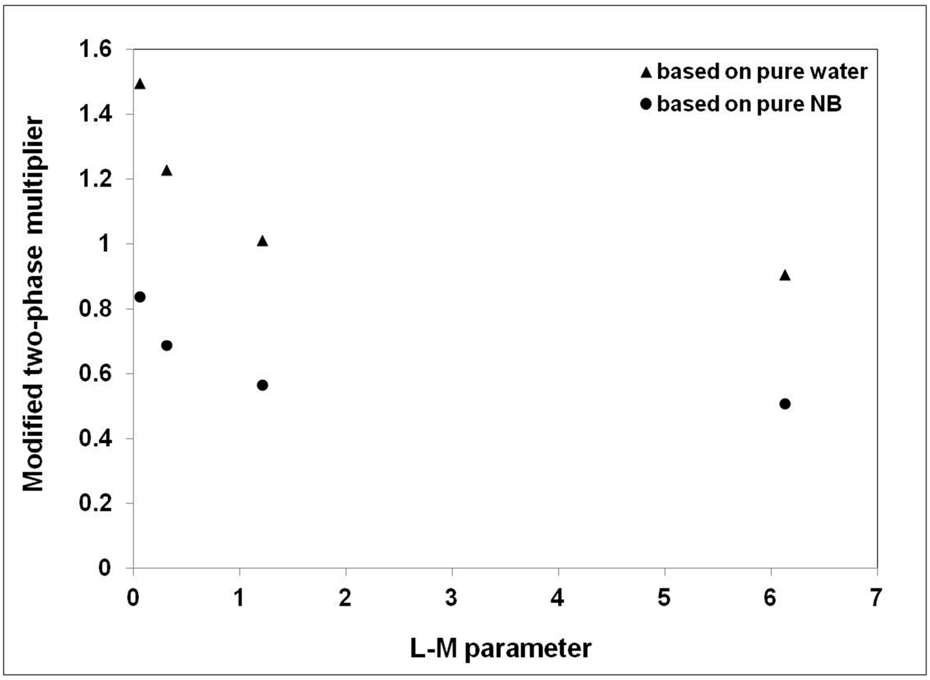

Figure 12: Variation between L-M parameter and Modified two-phase multiplier for NB-water system in tube side

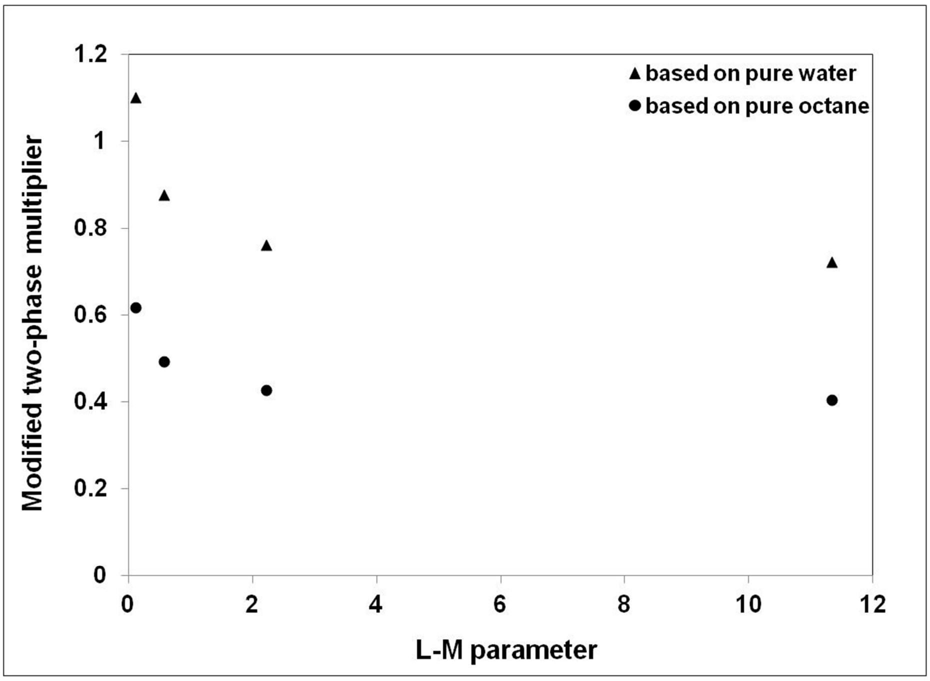

Figure 13: Variation between L-M parameter and Modified two-phase multiplier for octane-water system in tube side

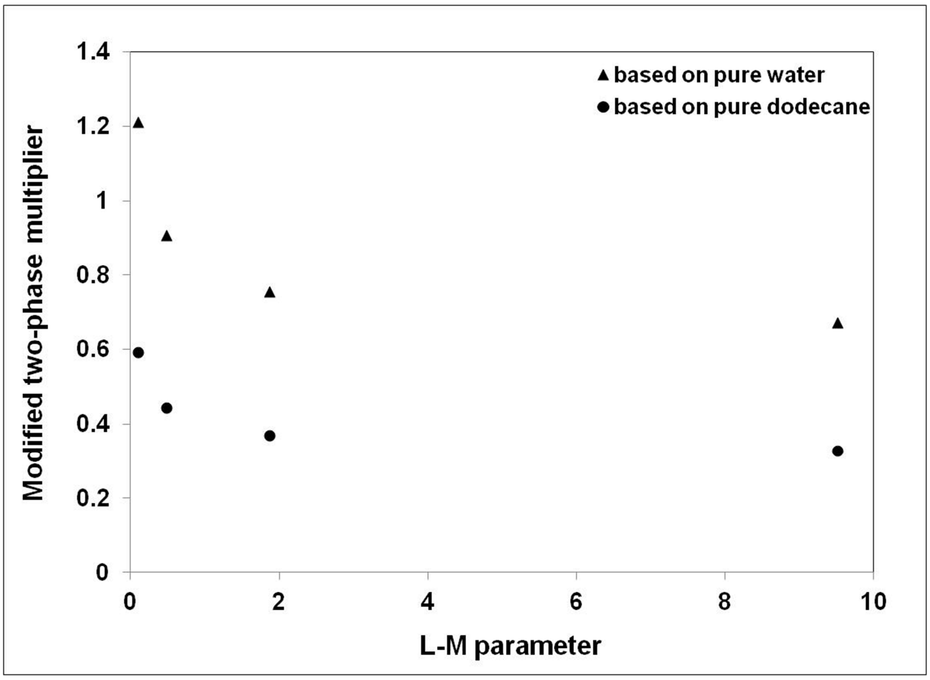

Figure 14: Variation between L-M parameter and Modified two-phase multiplier for dodecane-water system in tube side

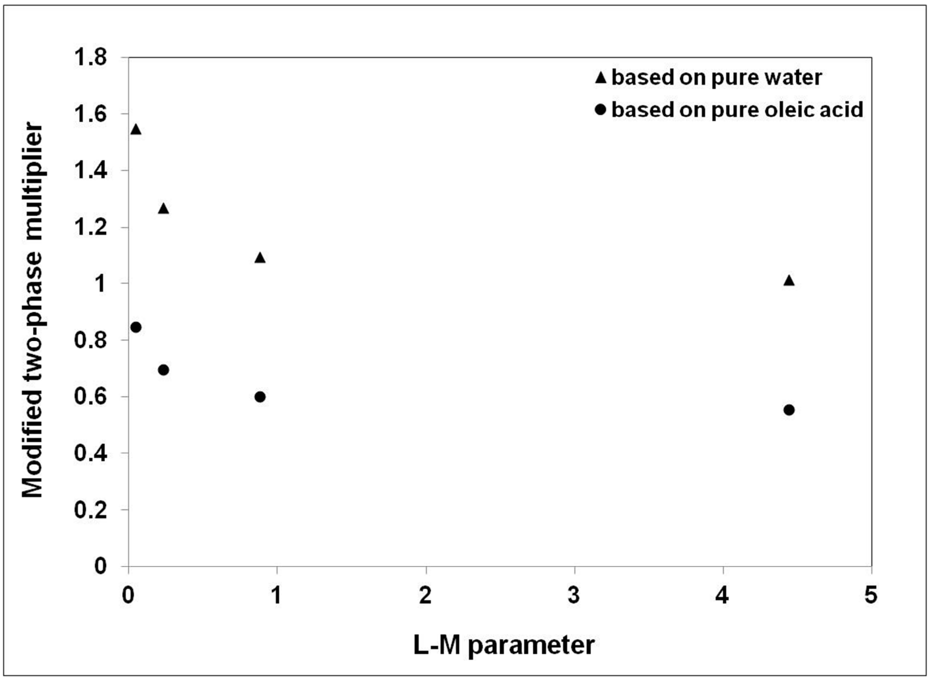

Figure 15: Variation between L-M parameter and Modified two-phase multiplier for oleic acid-water system in tube side

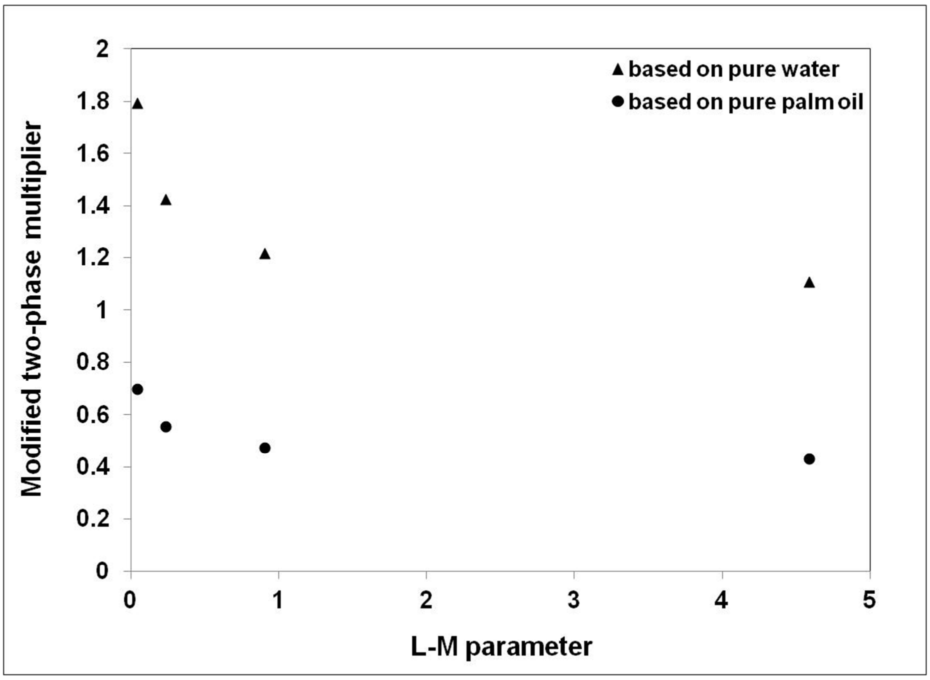

Figure 16: Variation between L-M parameter and Modified two-phase multiplier for palm oil-water system in tube side

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

A correlation between the modified two-phase multiplier (Φ_{Lt}), Quality (X_t) and L-M parameter (χ_{tt}^2) 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:

$$\Phi_{Lt} = 0.682 \left(X_t\right)^{-0.226} \left(\chi_{tt}^2\right)^{-0.409} \quad (11)$$

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.

The coefficient and two exponents of Eq. (11) 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 0.027 to 13.803 and modified two-phase multiplier range from 0.633 to 1.801.

Figure 17 shows the comparison between the experimental values of modified two-phase multiplier and those calculated using Eq. (11). It is evident from Figure 17 that the Eq. (11) predicts the modified two-phase multiplier for seven liquid-liquid systems within ± 15% error conveying 28 various water-organic liquid compositions. Table 1 presents the statistics and the range of variables for Eq.(11).

Table 1: The range of variables investigated for modified two-phase multiplier correlation in tube side

Dimensionless variables	Range of values
Standard deviation in modified two-phase multiplier	0.095
Coefficient of variation (%)	8.167
Mean error (%)	6.564
Index of correlation	0.934

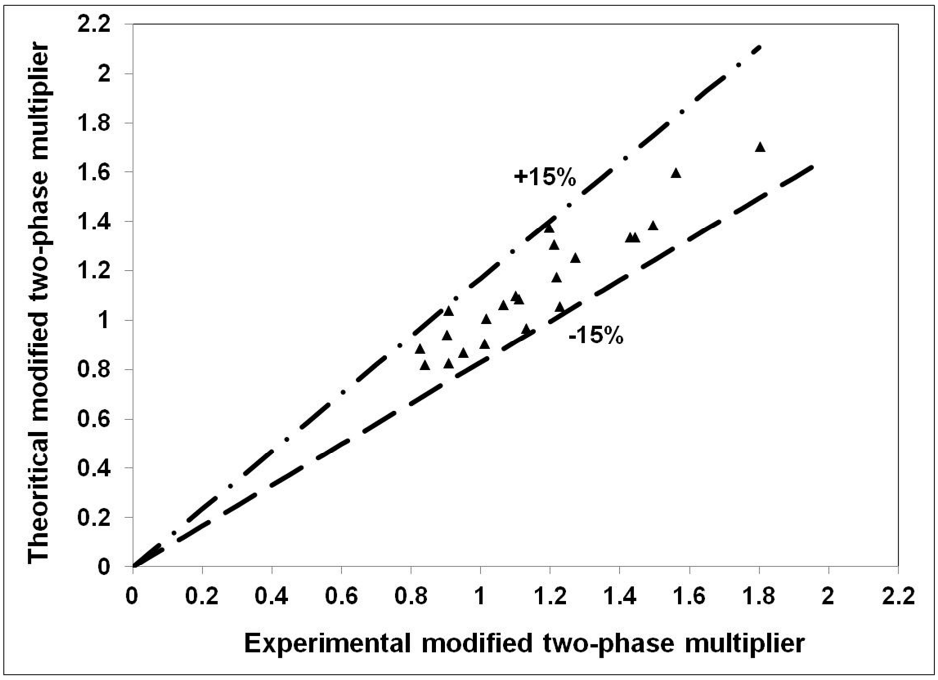

Figure 17: Variation between experimental and calculated modified two-phase multiplier based on the developed two-phase correlation in tube side

CONCLUSION

Experimental two-phase heat transfer studies were conducted in a shell and tube heat exchanger. The correlation obtained between X_{tt}, Φ_{Lt} and χ^2_{tt} for different compositions of liquid-water systems based on pure water, will be useful in predicting two-phase heat transfer coefficients using pure phase thermo-physical properties. The predicted values can be used for designing heat exchangers for a specific two-phase duty in the Reynolds numbers range investigated. Based on the summary in Table 1, 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 in tube side with a maximum error of ± 15 % for wide range of data points covering 7 different two-phase systems.

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