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Two-Phase Experimental Studies on a Oleic Acid-Water System in Shell side - Shell and Tube Heat Exchanger

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Abstract: Two phase heat transfer involving two immiscible systems is gaining importance in petrochemical and allied industries. Varying compositions of oleic acid and water were experimentally studied in a 1:2 shell and tube heat exchanger. The data on pure water and oleic acid were fitted to an equation of the form $h_{1\varphi} = a\ N_{Re}^{m}$. The two phase multiplier,Φ_L, was related to Lockhart Martinelli(L-M) parameter, χ_{tt}^2, using the two phase data and a correlation $\Phi_L = b^*\ \chi_{tt}^2 / c+ \chi_{tt}^2$ was established. The two phase heat transfer coefficient was calculated based on the coefficients 'a' and 'm' for pure oleic acid and pure water along with Φ_L and L-M parameter. The calculated values of two phase heat transfer coefficient $h_{2\varphi}$ based on pure oleic acid and pure water suggest that oleic acid is a better reference fluid since the average error is much lesser compared to pure water as reference.
Keywords: Heat transfer coefficient; Shell and tube heat exchanger; Two-phase flow; Lockhart -Martinelli parameter.

INTRODUCTION

In process industries, two phase flow is gaining importance over the years. A better understanding of the rates of momentum and heat transfer in multi phase flow is a must for the optimum design of heat exchangers. Since experimentation in two phase flow is cumbersome, heat transfer coefficient correlations are being developed using pure fluid thermo-physical properties, dimensionless numbers such as Reynolds number and Nusselt number.

Considerable research is being pursued in two phase flow particularly in the area of fluid dynamics. Lockhart et al.[1] carried out the first detailed study in two phase flow and proposed a correlation for isothermal two component flow in pipes. Thorbjon et al.[2] presented a theoretical method for predicting the hold up in stratified and wavy two phase flow. This theoretical solution agrees well with the generalized empirical solution developed by Lockhart and Martinelli for all regimes. Oliemans et al.[3] established a semi-emprical model for the core-annular flow of oil and water through pipeline. Dowlati et al.[4] correlated the two phase friction multiplier with the Martinelli parameter for flow across horizontal and staggered rod bundles. Bretta et al.[5] studied pressure drop for horizontal oil- water flow in small diameter tubes. Awwad et al.[6] investigated air-water two phase flow in horizontal helicoidal pipes of varying configurations. It was found that the pressure drop multiplier relates strongly to the superficial velocities of air or water. He has developed correlation for two phase flow in the horizontal pipes based on experimental data. Vlasogiannis et al.[7] tested a plate heat exchanger for two phase flow using an air-water mixture as the cold stream. Rani Hemamalini et al.[8] conducted an experimental study on two phase flow through a pipe and control valve in series for air-palm oil system. They concluded that based on single phase flow through the pipe-valve system, it is possible to predict the pressure drop for two phase flow. Ramachandran et al.[9, 10] conducted two phase experiment in a compact heat exchanger and developed heat transfer correlations for predicting two phase heat transfer involving liquid-liquid systems using single phase data. Alagesan et al.[11] investigated the two-phase heat transfer coefficient of liquid-liquid systems and established a new heat transfer correlation for two-phase systems, predict data within the absolute deviation range 3.88% to 9.92%.

However the field, which has received relatively less attention, is the study of heat transfer involving two immiscible liquids in a shell and tube heat exchanger. 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 mixtures of water-oleic acid in different ratios as the heated fluid(process fluid) in the shell side. The heat transfer coefficients on the shell side were correlated with Reynolds numbers and the relation between Lockhart-Martinelli parameter and quality was developed based on the experimental data. The work is confined to laminar flow in the present study.

MATERIALS AND METHODS

A schematic diagram of the experimental setup is shown in figure1. The heat exchanger used in the experiment was a 1-2 pass shell and tube heat exchanger with heat transfer area of $0.2269 m^2$. Triangular pitch was used for the arrangement of tubes. The heat exchanger has a shell with 0.118m ID and 0.126m OD. There were 14 tubes with 0.01m ID and 0.012m OD and each tube has 0.43m length. The clearance, tube pitch and baffle spacing are 0.008m, 0.024m and 0.086m respectively. Heating fluid and process fluid were pumped through the tube and shell side of the heat exchanger respectively using 0.25HP pumps. The flow rate was measured using Gallenkamp rotameters with an accuracy of ±0.1 LPM. The rotameters were calibrated before use. The flow rates of the two streams were adjusted using hand operated valves (2) and (4). The temperature of the hot fluid was maintained constant at 70^oC in the tank using suitable thermostats with an accuracy of ± 0.5^oC. The temperatures were recorded in the exit and inlet using RTD with an accuracy of ± 0.1^oC. The two phase mixture was kept in suspension using an agitator.

CALCULATION METHODOLOGY

The heat transfer coefficients for single phase were related to Reynolds number using equation 1 and the constants a and m established by regression analysis

$$h_{1\varphi} = a\, N_{Re}^{m}$$

The quality parameter (X) is defined by equation 2,

$$X = 1/ [1+ (\rho_w * v_w)/ (\rho_f * v_f)]$$

The overall heat transfer coefficient (U) in (W/m^2k), process side heat transfer coefficient ($h_{2\varphi}$), Lockhart-Martinelli parameter (χ_{tt}^2) and two phase multiplier (Φ_L) are calculated using equations 3 to 6:

$$U = Q/ (A_h * LMTDt) \quad \ldots\ldots(03)$$

$$h_{2\varphi}=1/[(1/U)-(Do*\ln(Do/Di)/2*k_w-(Do/Di*h_{1t\varphi}) \quad \ldots\ldots(04)$$

$$\chi_{tt}^2 = [1-X/ X]^{2-m}(\rho_f / \rho_w)(\mu_w/\mu_f)^m$$

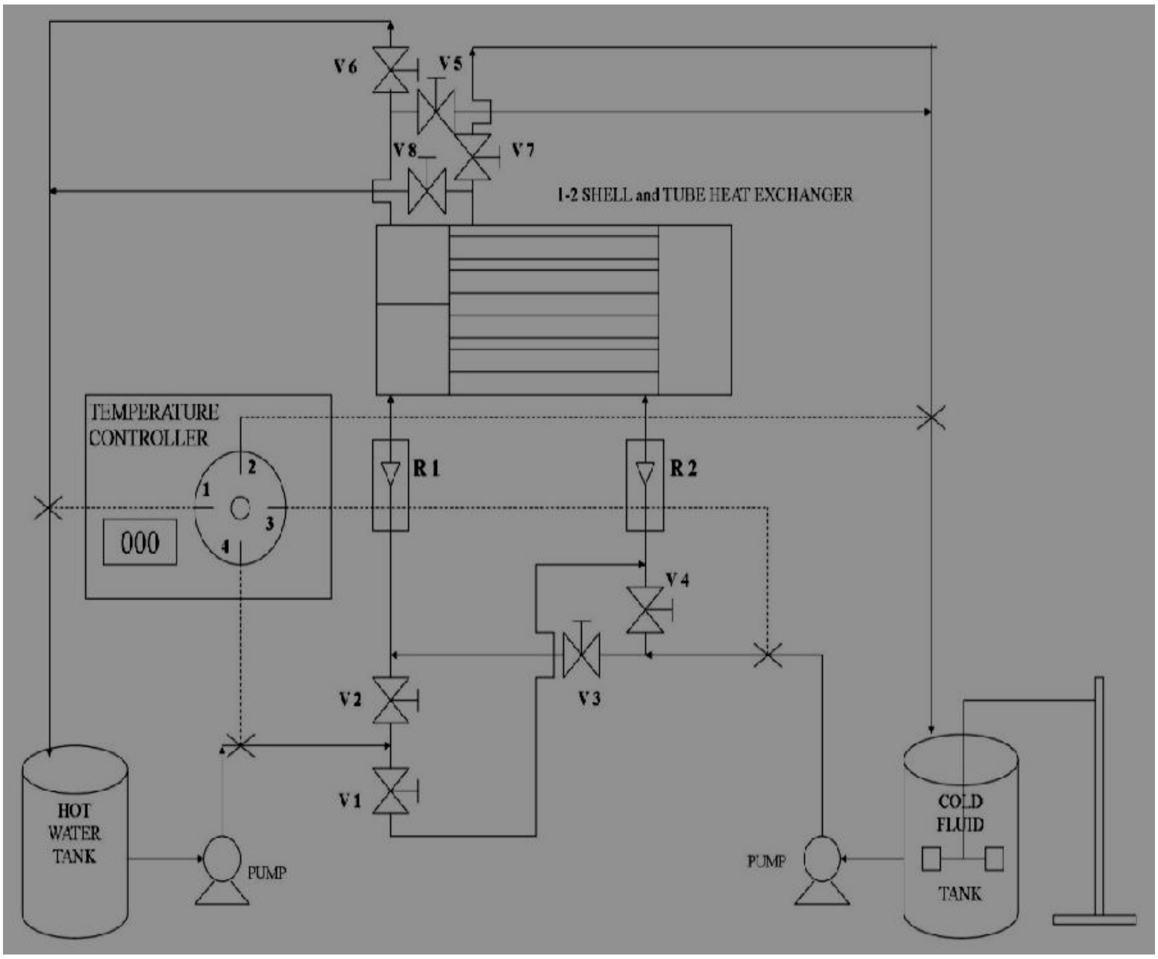
Ratio between two phase and single phase heat transfer coefficient is given as:

$$\Phi_L = h_{2\varphi} / h_{1\varphi}$$

Equation 7 relates the two phase multiplier to L-M parameter:

$$\Phi_L = b* \chi_{tt}^2 / c+ \chi_{tt}^2$$

Figure 1: Schematic view of experimental set up



⟶ Flow
----▸ Temperature sensor

1, 4 – RTD's for inlet & outlet hot fluid
3, 2 – RTD's for inlet & outlet cold fluid
R 1,R 2 – Rotameters
V1, v2, v3, v4, v5, v6, v7, v8 – Manual valves

Table 1: Correlation constants a and m for pure oleic acid and pure water system

Mass percentage of pure system	a	m
100% Water	6.007	0.796
100% Oleic acid	4.581	0.889

Table 2: The correlation constants b and c for varying oleic acid-water compositions

Composition of oleic acid	Pure oleic acid		Pure Water	
	b	c	b	c
20%	-0.15	-0.76	0.07	-0.43
40%	-0.09	-0.23	0.04	-0.15
60%	-0.09	-0.08	0.02	-0.06
80%	-0.21	-0.03	0.02	-0.02

Table 3: Comparison of experimental and calculated values of two-phase heat transfer coefficients for 20% and 40% composition of oleic acid-water system:

N_{Re}	20% oleic acid-water			40% oleic acid-water		
	$h_{2\varphi exp}$	$h_{2\varphi\ cal}$ based on oleic acid	$h_{2\varphi\ cal}$ based on water	$h_{2\varphi exp}$	$h_{2\varphi\ cal}$ based on oleic acid	$h_{2\varphi\ cal}$ based on water
104	272.09	265.83	268.51	245.68	256.06	235.48
114	290.08	286.82	283.66	269.38	277.24	248.89
124	300.43	312.30	311.00	287.76	300.44	276.01
134	339.42	332.43	341.88	308.13	322.51	301.19
143	353.87	347.75	365.93	330.05	337.33	323.48
155	378.82	382.69	387.62	353.73	371.21	343.72
165	407.31	407.69	416.66	390.67	393.65	371.82
174	438.46	434.45	439.91	408.73	417.53	394.95
185	472.65	463.15	458.77	429.35	449.30	409.06
196	496.00	493.96	472.43	449.63	476.93	423.69

Table 4: Comparison of experimental and calculated values of two-phase heat transfer coefficients for 60% and 80% composition of oleic acid-water system:

N_{Re}	60% oleic acid-water			80% oleic acid-water		
	$h_{2\varphi exp}$	$h_{2\varphi\ cal}$ based on oleic acid	$h_{2\varphi\ cal}$ based on water	$h_{2\varphi exp}$	$h_{2\varphi\ cal}$ based on oleic acid	$h_{2\varphi\ cal}$ based on water
104	230.83	230.40	230.14	211.98	220.75	236.99
114	246.87	246.00	241.22	238.45	231.61	252.02
124	263.99	262.83	265.48	248.85	244.18	270.39
134	275.53	281.53	283.63	259.68	258.05	282.51
143	295.50	290.30	305.84	278.33	264.24	301.55
155	316.11	318.62	318.82	283.53	285.95	308.55
165	339.36	337.43	341.77	303.98	300.65	327.96
174	355.59	357.41	359.89	318.20	316.13	342.56
185	382.30	378.66	374.36	333.17	332.44	353.61
196	401.02	401.30	384.54	348.95	349.66	360.59

Table 5: Average absolute deviation of $h_{2\varphi}$ based on pure water and pure oleic acid

Composition of oleic acid	Average absolute deviation based on	
	Pure oleic acid	Pure water
20%	1.56	2.38
40%	3.69	4.17
60%	0.78	1.86
80%	1.76	7.71

RESULTS AND DISCUSSION

Figure 2 shows the variation of single and two phase heat transfer coefficient with Reynolds number for the shell side process fluid. The data for pure fluid (oleic acid or water) was fitted to equation 1 by regression analysis and the constants a & m for oleic acid & water are given in Table 1.

The relation of quality with respect to L-M parameter and two phase multiplier based on both pure water and pure oleic acid systems are shown in Figures.3, 4, 5 and 6. As the proportion of the second phase increases and a consequent decrease in the proportion of water, the viscosity of the mixture increases and then the thermal conductivity, density and specific heat decrease.

This brings down the heat transfer coefficient and hence the two phase multiplier decreases with quality.

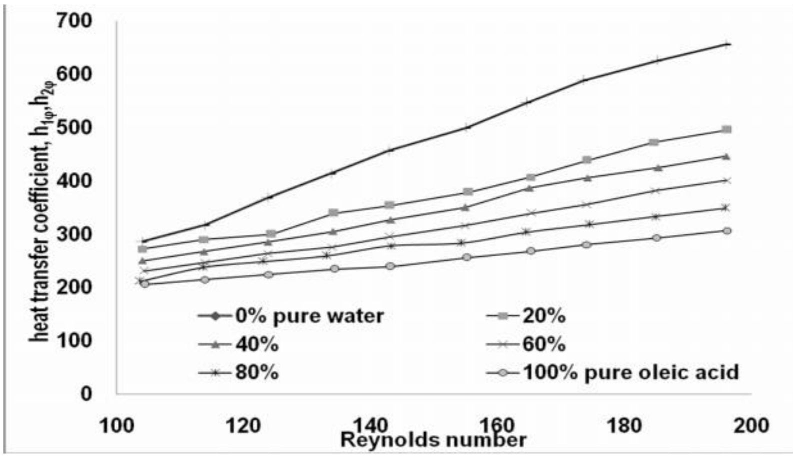


Figure 2: Variation of heat transfer coefficient with Reynolds number for different oleic acid-water compositions.

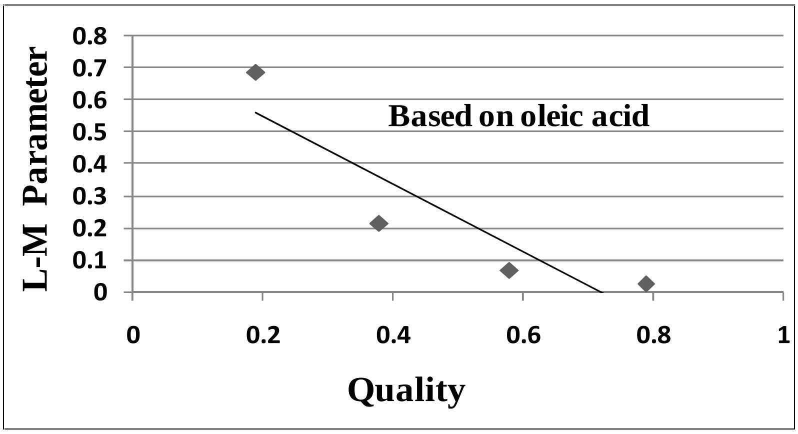


Figure 3: Plot between Quality (X) and L-M Parameter based on pure oleic acid

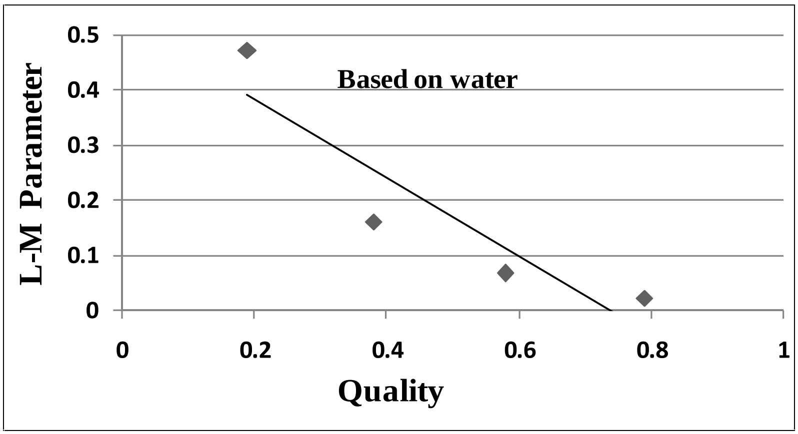


Figure 4: Plot between Quality (X) and L-M Parameter based on pure water

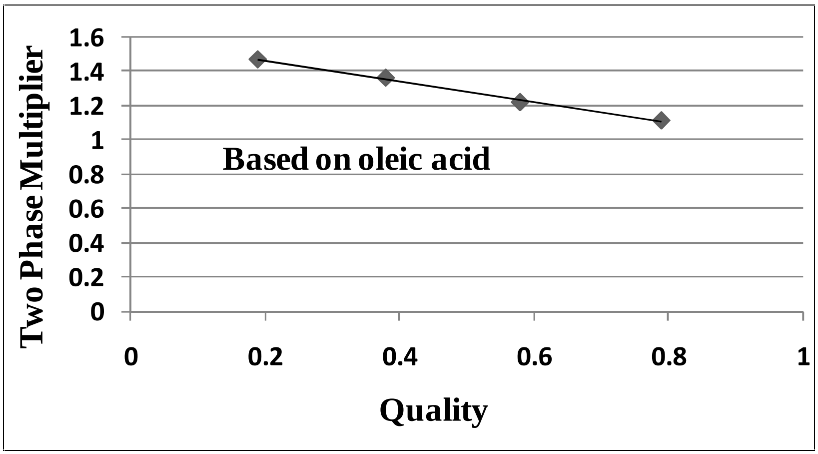


Figure 5: Plot between Quality (X) and Two-phase multiplier based on pure oleic acid

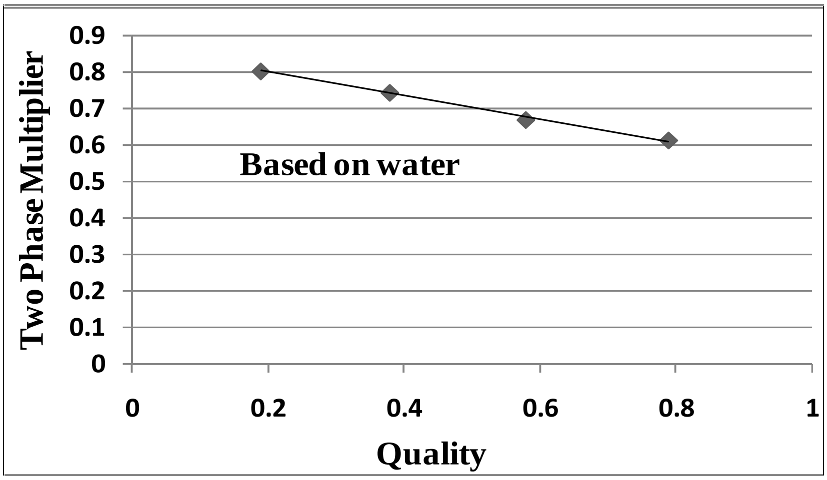


Figure 6: Plot between Quality (X) and Two-phase multiplier based on pure water

An increasing L-M parameter (χ_{tt}^2) for oleic acid - water system denotes a decrease in quality(X) and implies an increase in two phase multiplier (Φ_L). Initially L-M parameter correlation used for predicting pressure drop of gas-liquid two phase systems and then the heat transfer coefficients in liquid-liquid two phase flow were related to L-M parameter [9, 11] in equation 5 where 'm' represents the power to which Reynolds number raised to determine single phase heat transfer coefficient.

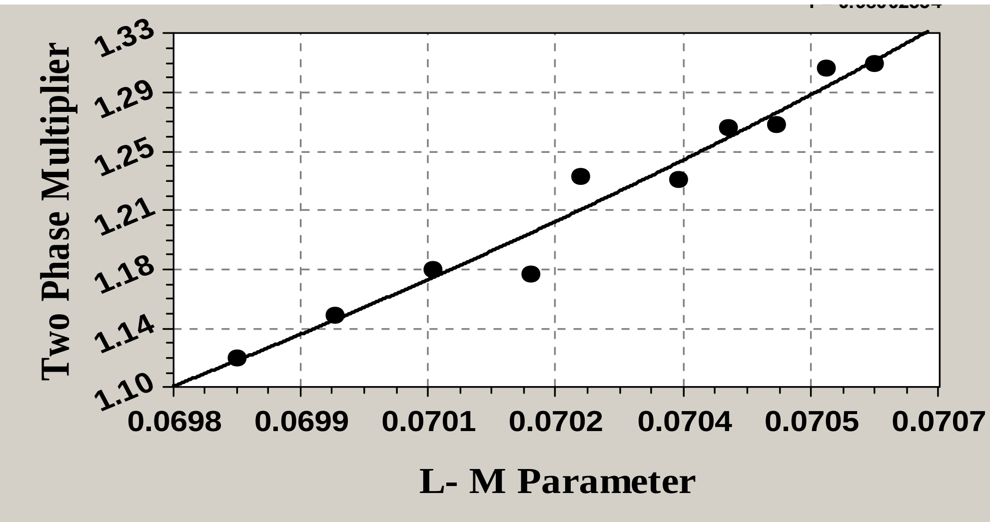


Figure 7: Variation of Two Phase Multiplier with L-M Parameter for 60% oleic acid-water system based on pure oleic acid

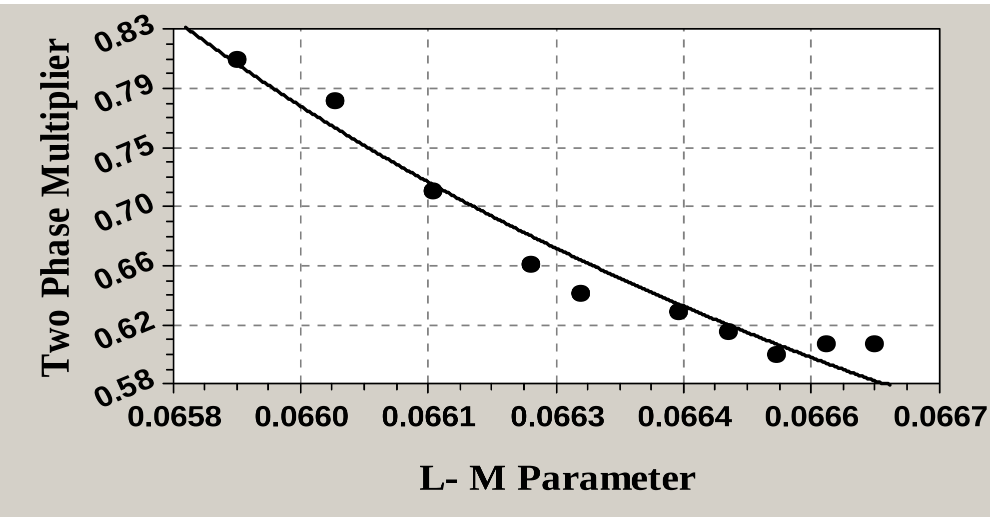


Figure 8: Variation of Two Phase Multiplier with L-M Parameter for 60% oleic acid-water system based on pure water

The two phase multiplier Φ_L (equation 6) and L-M parameter (equation 5) shown in figures 7 & 8 are related by equation 7. The variation of two phase multiplier (Φ_L) with L-M parameter (χ_{tt}^2) shows an increasing trend when it is based on pure oleic acid as reference fluid. Since the pure water heat transfer coefficient is always higher than two phase heat transfer coefficient, the two phase multiplier decreases with L-M parameter when it is based on pure water system.The constants b & c of equation 7 are given in Table 2 based on oleic acid & water as reference fluid. Tables 3 & 4 compare the two phase heat transfer coefficient calculated based on pure oleic acid and water as reference fluid. Table 5 summarizes the average absolute deviation of two phase heat transfer coefficient calculated using water and oleic acid as reference liquids for the data in Tables 3 & 4.

CONCLUSION

Two-phase flow through a 1-2 shell and tube exchanger using water-oleic acid system was studied. The correlations between X, Φ_L and χ_{tt}^2, will be useful in predicting two-phase heat transfer coefficients using pure phase thermo-physical properties. 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 5, it can be concluded that for this system oleic acid is a better reference fluid compared to water since the average absolute deviation varies for 0.78 to 3.69 percent compared to water (1.86 to 7.71 percent). Further studies on Diesel-Water, Nitrobenzene-Water, Palm oil-Water and Castor oil-Water are being carried out to verify whether in these cases also Diesel, Nitrobenzene, Palm oil and Castor oil are better reference fluids compared to water. The specific reason for oleic acid being a better reference can be arrived at after a comprehensive study of all similar systems.

NOMENCLATURE

a, m -constants for pure water and pure oleic acid in equation(1)

b, c -constants of saturated growth correlation (7)

$h_{1\varphi}$ -heat transfer coefficient of pure oleic acid/water (W/m²k)

$h_{2\varphi}$ -two-phase heat transfer coefficient (W/m²k)

$h_{1t\varphi}$ – tube side heat transfer coefficinet (W/m²k)

v_f _- volumetric flow rate of fluid (m³/s)

v_w - volumetric flow rate of water (m³/s)

k_w - thermal conductivity of the tube wall material (W/mK)

v_m - flow rate of a mixture (m³/s)

LMTDt -corrected logarithmic mean temperature difference (K)

A_h – heat transfer area (m²)

D_i – Inner diameter of the tube (m)

D_o – outer diameter of the tube (m)

Greek letters

χ_{tt}^2 - Lockhart-Martinelli (L-M) parameter

Φ_L – two-phase multiplier

μ_w - viscosity of water (kg/ms)

μ_f - viscosity of oleic acid (kg/ms)

ρ_w – density of water (kg/m³)

ρ_f – density of oleic acid (kg/m³).

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