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TWO PHASE HEAT TRANSFER STUDIES ON LIQUID-LIQUID SYSTEM IN TUBE SIDE SHELL AND TUBE HEAT EXCHANGER

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ABSTRACT

Heat transfer studies on immiscible systems are vital in petrochemical and allied industries. Two phase systems water – oleic acid and water – palm oil of varying compositions were experimentally studied in a 1:2 shell and tube heat exchanger. The data fitted to an equation of the form $N_{Nu}= n\ N_{Re}^{k}$ with an average absolute deviation ranging between 3.882 and 9.921 percent where n and k are functions of composition of the systems studied. 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 $h_{2\varphi}$ for both systems were recalculated based on the above correlation and found that water as better reference fluid gave the least error ranging between 2.193 and 6.313 percent for both the systems.

Keywords: *Heat Transfer Coefficient; Shell And Tube Heat Exchanger; Two Phase Flow; Lockhart Martinelli Parameter;Two Phase Multiplier.*

1. 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. Spedding et al.[3] developed regime maps for air-water two phase flow for both downward and upward flow. Oliemans et al.[4] established a semi-emprical model for the core-annular flow of oil and water through pipeline. Dowlati et al.[5] correlated the two phase friction multiplier with the Martinelli parameter for flow across horizontal and staggered rod bundles. Bretta et al.[6] studied pressure drop for horizontal oil- water flow in small diameter tubes. Awwad et al.[7] 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.[8] tested a plate heat exchanger for two phase flow using an air-water mixture as the cold stream. Ede et al.[9] recorded data on the local heat transfer coefficient in a straight pipe. Spalding et al.[10] presented a rigorous theoretical analysis of the heat and mass transfer occurring at an element of the interface separating the liquid and gaseous phases of a binary mixture. Rani Hemamalini et al.[11] 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. Xiuzhong et al.[12]analyzed two phase flow characteristics

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with experimental data which shows that the phase distribution patterns in the vertical large diameter pipe can be divided into two basic patterns namely, wall peak and core peak. Ramachandran et al.[13] conducted two phase experiment in a compact heat exchanger and developed heat transfer correlations for two phase heat transfer involving liquid-liquid systems. Vijayarangan, et al.[14] developed a model for prediction of pressure drop in heated tube and suggested methods to determine the pressure gradient and void fraction. Benbelk A. Shannak[15] conducted experiments and proposed model for air-water two phase flow frictional pressure drop of vertical, horizontal smooth and relatively rough pipes.

The study of heat transfer involving two immiscible liquids in a shell and tube heat exchanger has not been extensively studied. 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 and water- palm oil in different ratios as the heated fluid(process fluid) on the tube side. The heat transfer coefficients on the tube side were correlated with Reynolds numbers and the relation between Lockhart-Martinelli parameter and quality was developed based on the experimental data. The correlation between Nusselt number and Reynolds number were developed for different compositions of two phase systems. The work is confined to laminar flow in the present study.

2. EXPERIMENTAL SECTION

A schematic diagram of the 1-2 shell and tube heat exchanger is shown in figure 1 which gives in detail the size and specifications of all the units involved. A photographic view with accessories is shown in Figure 2. Heating fluid and process fluid were pumped through the tube and shell side of the heat exchanger respectively using 0.25 HP 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°C in the tank using suitable thermostats with an accuracy of ± 0.5°C. The temperatures were recorded in the exit and inlet using RTD with an accuracy of ± 0.1°C. The two phase system was kept in suspension using an agitator.

3. CALCULATION METHODOLOGY

Shell side:

In the shell side, the heating fluid (hot water) was circulated at constant rate. The shell side Reynolds number, heat transfer coefficient and heat transfer rates were calculated using equations 1 to 6.

$$\text{Cross flow area } (A_s) = \left(\frac{(P_t - D_o)}{P_t}\right) * D_s * B_s \qquad \ldots(01)$$

$$\text{Mass velocity } (G_s) = \left(\frac{(V_w * \rho)}{A_s}\right) \qquad \ldots\ldots\ldots(02)$$

$$\text{Equivalent diameter } (D_e) = \frac{1.1}{D_o \cdot (P_t^2 - 0.91 D_o^2)} \qquad \ldots\ldots\ldots(03)$$

$$\text{Reynolds number } (N_{Re}) = \left(\frac{(G_s * D_e)}{\mu_w}\right) \qquad \ldots\ldots\ldots(04)$$

$$Q = m_h * C_{ph} * (T_{h2} - T_{h1}) \qquad \ldots\ldots\ldots(05)$$

$$h_{1s\varphi} = \frac{Q}{A_h * (T_{hm} - T_w)} \qquad \ldots\ldots\ldots(06)$$

The properties μ, ρ, k are calculated based on the average of inlet and outlet temperatures.

Tube side:

The heat transfer coefficients for single phase were related to Reynolds number using equation 7 and the constants a and m established by regression analysis

$$h_{1\varphi} = a\, N_{Re}^{\ m} \qquad \ldots\ldots\ldots(07)$$

Various compositions of liquid(oleic acid, palm oil) and water at different flow rates were circulated. The parameters used for two phase flow are given by equations 8 to 17:

The quality parameter is defined by equation 8,

$$X = \frac{1}{\left[1 + \frac{(\rho_w \cdot V_w)}{(\rho_f \cdot V_f)}\right]} \qquad \ldots\ldots\ldots(08)$$

The Reynolds number is calculated based on equations 9 to11:

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Mixture density $(\rho_m)=\rho_f X+\rho_w(1-X)$

(09)

Mixture viscosity $(\mu_m)=\mu_f X+\mu_w(1-X)$

(10)

$$N_{Re}=\frac{u_m * D_i * \rho_m}{\mu_m}$$ ……….(11)

The overall heat transfer coefficient (U) in (W/m²k), process side heat transfer coefficient ($h_{2\varphi}$), Lockhart-Martinelli parameter (χ_{tt}^2) and two phase multiplier (Φ_L) are calculated using equations 12 to 16:

$$U_o=\frac{Q}{(A_h * LMTDt)}$$ ….(12)

$$h_{2\varphi}=\frac{1}{\left\{\left(\frac{1}{U_o}\right)-\left(\frac{D_o * \ln\left(\frac{D_o}{D_i}\right)}{2 * k_w}\right)-\left(\frac{D_o}{D_i * h_{1S\varphi}}\right)\right\}}$$.(13)

$$\chi_{tt}^2=\left(\frac{1-X}{X}\right)^{2-m}\left(\frac{\rho_f}{\rho_w}\right)\left(\frac{\mu_w}{\mu_f}\right)^2$$ ……….(14)

$$\Phi_L=\frac{h_{2\varphi}}{h_{1\varphi}}$$ ……..(15)

Equation 16 relates the two phase multiplier to L-M parameter:

$$\Phi_L=\frac{b * \chi_{tt}^2}{c+\chi_{tt}^2}$$ ……….(16)

Error is defined by equation17 as

$$Error=\left[\frac{(h_{2\varphi}(exp)-h_{2\varphi}(cal))}{h_{2\varphi}(exp)}\right] * 100$$ ……...(17)

Relation between N_{Nu} and N_{Re} for two phase data for different compositions fitted as

$$N_{Nu}=[0.019e^{2.203X}]Re^{(-0.319X+1.212)}$$ (18)

4. RESULTS AND DISCUSSION

Figures 3 & 4 show the variation of heat transfer coefficient of two phase fluid of varying compositions as a function of Reynolds number in tube side of heat exchanger for oleic acid-water, palm oil-water system respectively. It is seen that the two-phase data falls within the boundaries of pure water and pure liquid data. The increase in agitation enhances the uniformity of the two phase mixture thus preventing stratification of the phases. Hence the overall physical properties of the mixture remain uniform throughout the flow channel. The uniformity of the two phase mixture coupled with increased convective currents driven by higher flow velocities result in a higher heat transfer coefficients. The figure 5 is shown the single phase heat transfer coefficient ($h_{1\varphi}$) and Reynolds number relationship for pure water. The data for pure water was fitted to equation 7 by regression analysis and the constants a & m for water are given in Table 1.

The relation of quality with respect to L-M parameter and two phase multiplier are shown in figures 6 & 7. An increasing L-M parameter (χ_{tt}^2) for liquid-water system denotes a decrease in quality(X) and implies an increase in two phase multiplier (Φ_L). The two phase multiplier Φ_L (equation 15) and L-M parameter (equation 14) for different compositions of liquid-water systems based on pure water shown in figure 8 are related by equation 16. The variation of two phase multiplier (Φ_L) with L-M parameter (χ_{tt}^2) shows an increasing trend when the two phase heat transfer coefficient based on both pure liquid and pure water. The constants b & c of equation 16 are given in Table 2 based on water as reference fluid. ……...(15) ……...(16)

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. Figures 9 & 10 compare the two phase heat transfer coefficients calculated based on pure water as reference fluid for 20%, 40%, 60% and 80% compositions of oleic acid-water and palm oil-water systems respectively. Table 3 summarizes the average absolute deviation of two phase heat transfer coefficient calculated based on relation 16 developed with water as reference liquid. The calculated Nusselt number for 20%, 40%, 60% and 80% compositions of both liquid-water systems fitted with the range of Reynolds number investigated. The intercept(n) and slope(k) values of each fitted correlation for

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different compositions are given in Table 4. Figure 11 shows the plot between constants n, k and various compositions of two phase systems.

The equation 18 was established using the fitted values in figure 11. Tables 5 and 6 compare the theoretical and calculated values of two phase heat transfer coefficients based on the developed correlation 18 for different compositions of liquid-water systems. The average absolute deviation of two phase heat transfer coefficient calculated using the constants of relation 18 for the data in Tables 5 & 6 summarizes in Table 7.

5. CONCLUSION

It can be concluded from Table 3 that water is a better reference fluid to determine the two phase heat transfer coefficient for palm oil-water and oleic acid-water systems with an average absolute deviation varying from 2.193 to 6.313 percent. Table 7 suggests that a single equation of the form $N_{Nu}= (0.019\ e^{2.203x})\ N_{Re}^{(-0.319x+1.212)}$ can represent two phase data of varying compositions with an average absolute deviation ranging between 3.882 and 9.921percent. The developed correlation of liquid-water systems is useful in identifying heat transfer coefficients of two phase systems for the range of Reynolds number studied. Further work on Diesel-Water, kerosene-water, Nitrobenzene-Water and Castor oil-Water are being carried out.

6. NOMENCLATURE

a, m – constants for pure water and pure liquid in equation(7)
b, c – constants of saturated growth correlation(16)
n, k - intercept and slope values in equation (18)
$h_{1\varphi}$ - heat transfer coefficient of pure liquid /water (W/m²k)
$h_{2\varphi}$ - two-phase heat transfer coefficient (W/m²k)
$h_{1s\varphi}$ - shell side(hot water) heat transfer coefficient (W/m²k)
v_f - volumetric flow rate of fluid (m³/s)
v_w - volumetric flow rate of water (m³/s)
X - quality parameter for two-phase system
k_w - thermal conductivity of the tube wall material (W/mK)
v_m - flow rate of a mixture (m³/s)
D_s - shell inside diameter (m)
Pt - tube pitch (m)
B_s - baffle spacing
LMTDt – corrected logarithmic mean temperature difference (K)
A_h - heat transfer area (m²)
m_h - flow rate of hot fluid (kg/s)
Cp_h – specific heat of hot fluid (J/kg k)
u_m - velocity of mixture(m/s)
x - weight fraction of fluid
D_i - inner diameter of the tube (m)
D_o – outer diameter of the tube (m)
N_{Re} – Reynolds number
N_{Nu} – Nusselt number
N_{Pr} – Prandtl number
L - length of tube (m)

Greek letters

χ_{tt}^2 – Lockhart-Martinelli (L-M) parameter
Φ_L - two-phase multiplier
ν - kinematic viscosity of fluid(m²/s)
μ_w - viscosity of water (kg/ms)
μ_f - viscosity of fluid (kg/ms)
ρ_w - density of water (kg/m³)
ρ_f - density of fluid (kg/m³)
ρ_m - density of mixture (kg/m³)

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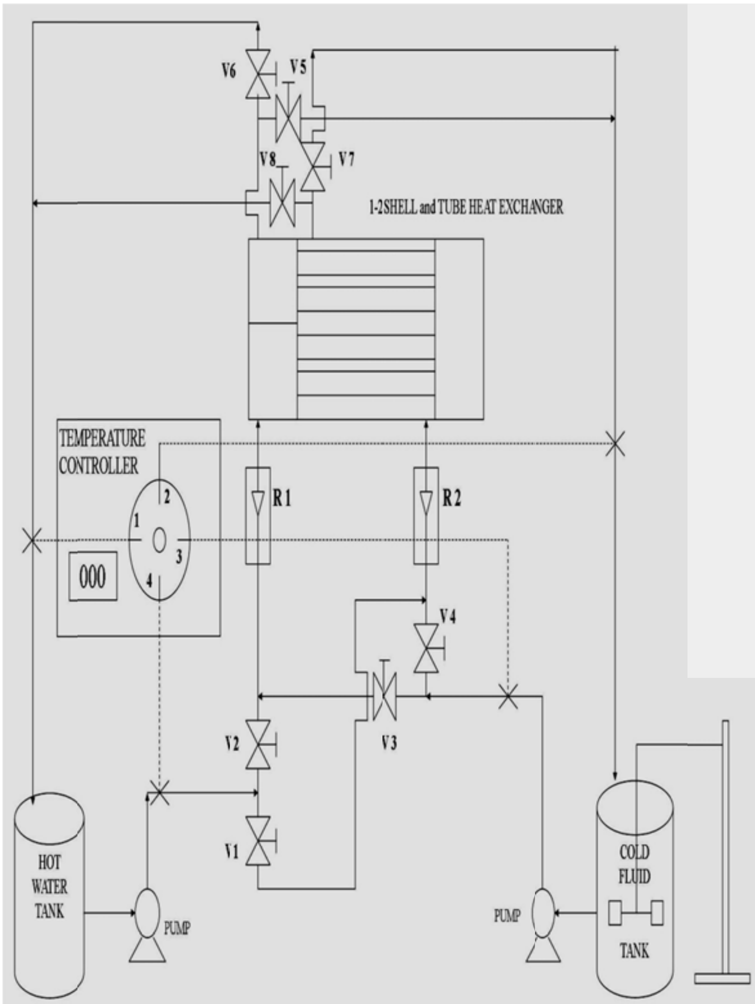
APPENDIX:



→ 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

Tube size	ID: 0.01m OD: 0.012m
Shell size	ID-0.118m OD-0.126m
Tube pitch	0.024m Triangle
Clearance	0.008m
Baffle spacing	0.086m
Length of tube	0.43m
Number of tubes	14

Figure 1. A Systematic diagram of the experimental setup

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Figure 2: 1-2 Shell and Tube Heat Exchanger with accessories.

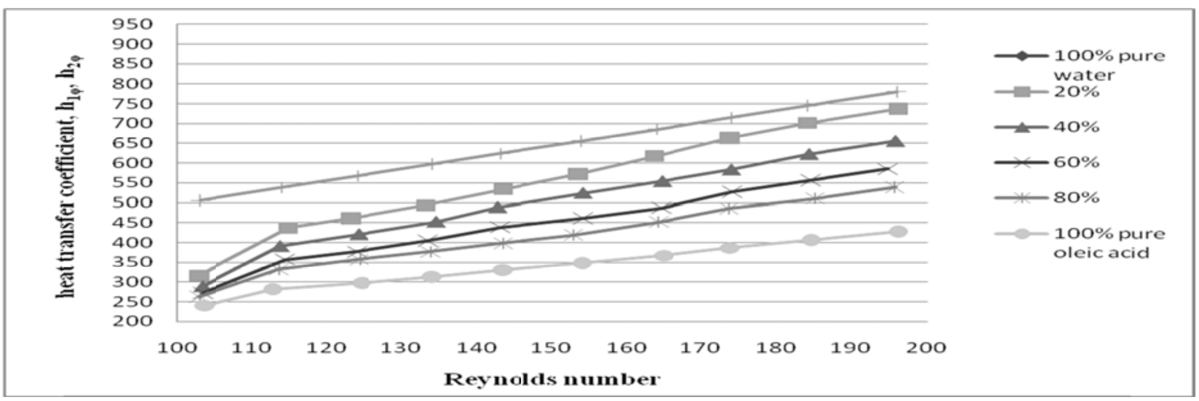

Figure 3: Variation of heat transfer coefficient with Reynolds number for different oleic acid-water compositions.

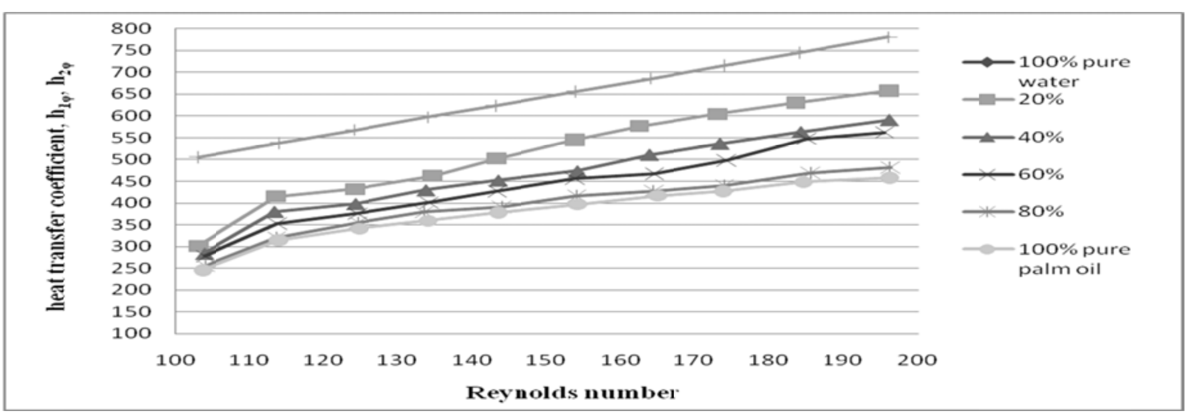

Figure 4: Variation of heat transfer coefficient with Reynolds number for different palm oil-water compositions.

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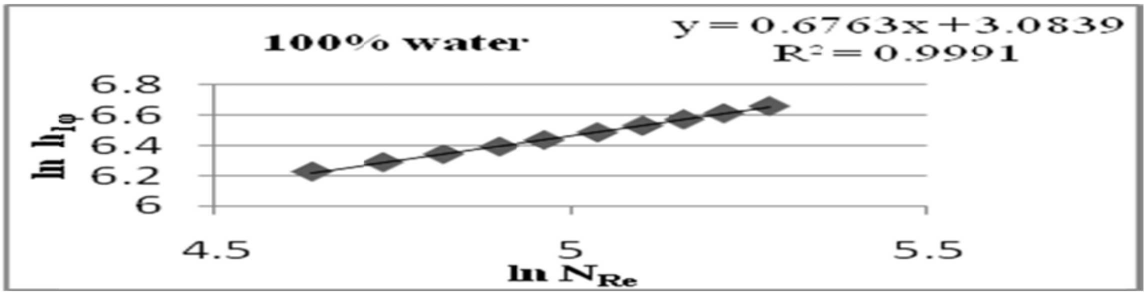

Figure 5: Plot between $\ln N_{Re}$ and $\ln h_{1\varphi}$(heat transfer coefficient of water)

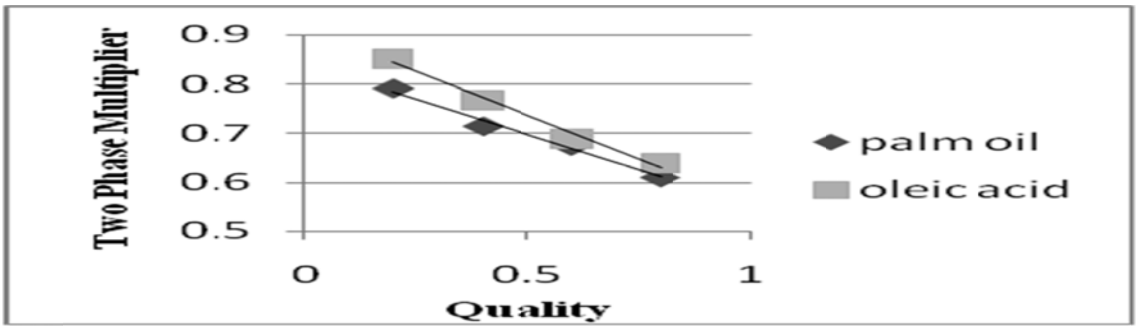

Figure 6: Plot between Quality (X) and Two-phase multiplier based on pure water

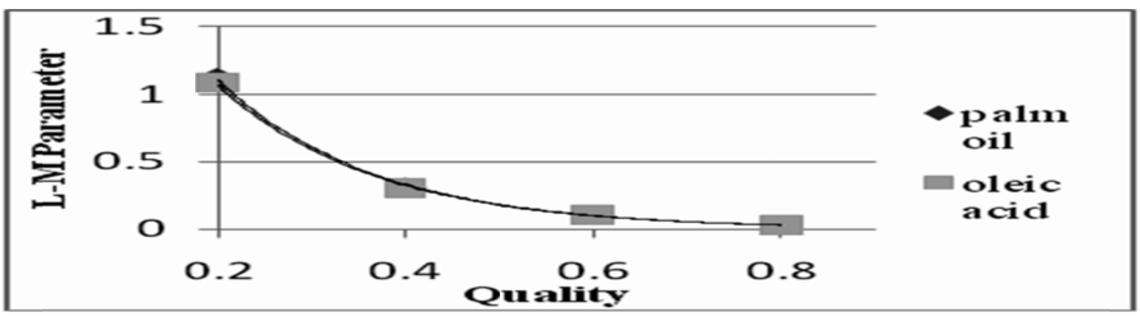

Figure 7: Plot between Quality (X) and L-M Parameter based on pure water

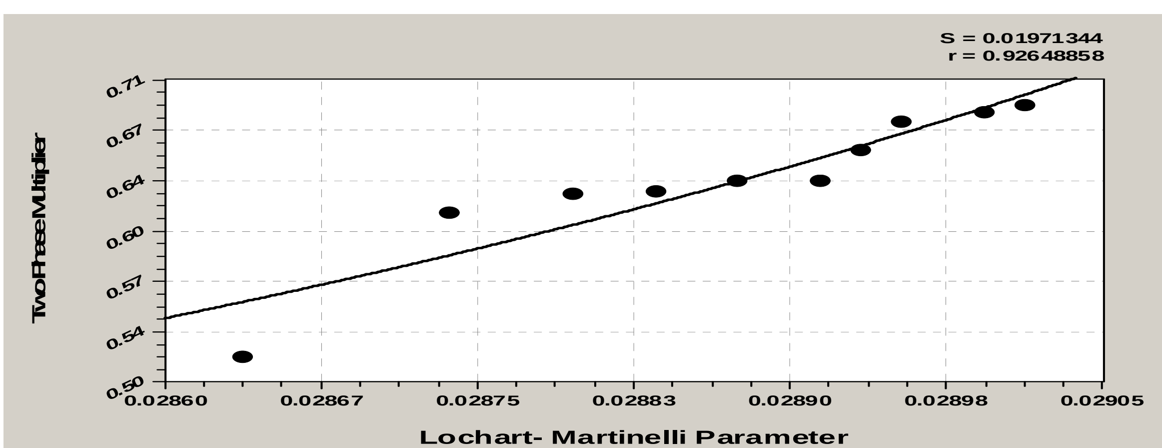

Figure 8: Variation of Two Phase Multiplier with L-M Parameter based on pure water

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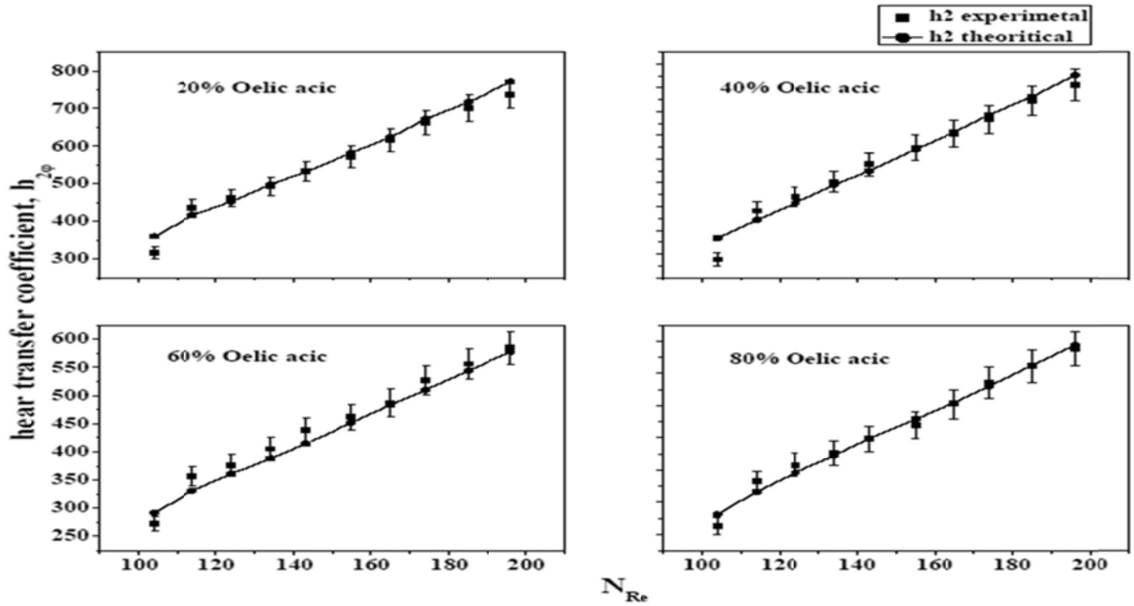

Figure 9: Comparison of experimental and calculated values of two-phase heat transfer coefficients for different compositions of oleic acid -water system based on pure water

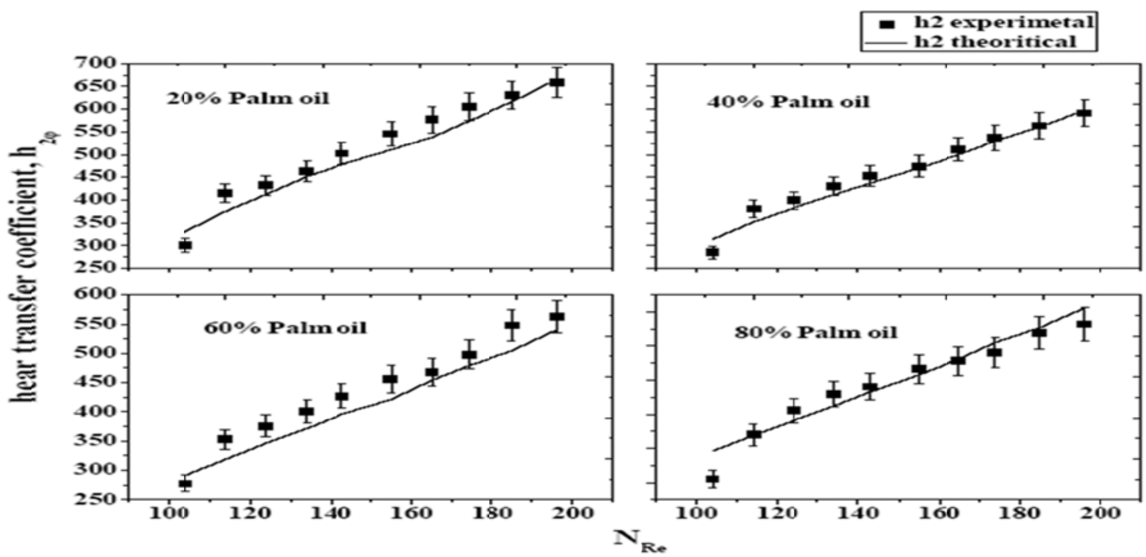

Figure 10: Comparison of experimental and calculated values of two-phase heat transfer coefficients for different compositions of palm oil-water system based on pure water

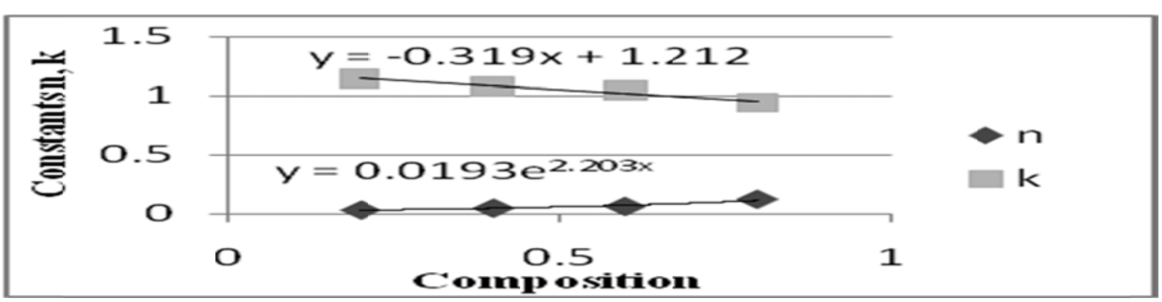

Figure 11: Plot between Composition and Constants n and k for liquid –water two phase systems

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

Mass percentage of water	a	m
100	21.780	0.676

Table 2: The correlation constants b and c in Eqn.16 for varying liquid-water compositions

Composition of liquid	Palm oil-water		Oleic acid-water	
	b	c	b	c
20%	-0.08	-1.26	-0.09	-1.20
40%	-0.67	-0.34	-0.06	-0.33
60%	-0.45	-0.12	-0.04	-0.11
80%	-0.08	-0.03	-0.04	-0.03

Table 3: Average absolute deviation of $h_{2\varphi}$ based on pure water for liquid-water systems

Composition of liquid	Average absolute deviation	
	Palm oil -water	Oleic acid -water
20%	5.275	3.273
40%	3.587	3.494
60%	6.313	3.770
80%	4.000	2.193

Table 4: Correlation constants n and k for different compositions of liquid-water systems

Composition of liquid	n	k
20%	0.031	1.147
40%	0.047	1.076
60%	0.062	1.044
80%	0.123	0.945

Table 5: Comparison of experimental and calculated values of two-phase heat transfer coefficients for different composition of oleic acid - water systems based on constants n & k.

N_{Re}	20% oleic acid		40% oleic acid		60% oleic acid		80% oleic acid	
	$h_{2\varphi exp}$	$h_{2\varphi cal}$	$h_{2\varphi exp}$	$h_{2\varphi cal}$	$h_{2\varphi exp}$	$h_{2\varphi cal}$	$h_{2\varphi exp}$	$h_{2\varphi cal}$
104	316.42	330.50	288.91	327.24	272.65	315.24	262.15	281.84
114	437.01	374.40	390.78	363.15	356.95	349.45	331.78	310.05
124	461.25	405.46	420.70	399.39	376.66	379.47	357.35	338.16
134	493.43	443.72	452.21	435.79	404.88	409.10	376.77	363.11
143	533.68	483.03	488.70	464.42	438.39	439.17	398.10	388.01
155	571.79	522.03	524.12	505.25	461.57	474.32	419.27	412.82
164	617.38	561.88	554.01	542.95	487.31	507.17	452.12	442.19
174	663.36	601.63	583.53	576.40	526.84	537.35	485.66	466.81
184	701.07	642.70	622.69	613.20	556.10	570.29	510.69	496.05
196	737.59	692.06	655.68	655.38	585.04	603.07	538.58	523.71

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Table 6: Comparison of experimental and calculated values of two-phase heat transfer coefficients for different composition of palm oil - water systems based on constants n & k.

N_{Re}	20% palm oil		40% palm oil		60% palm oil		80% palm oil	
	$h_{2\varphi exp}$	$h_{2\varphi cal}$	$h_{2\varphi exp}$	$h_{2\varphi cal}$	$h_{2\varphi exp}$	$h_{2\varphi cal}$	$h_{2\varphi exp}$	$h_{2\varphi cal}$
104	301.40	324.24	284.31	313.83	277.49	290.81	255.33	250.65
114	415.38	362.06	380.75	345.24	352.49	319.07	320.28	273.08
124	431.83	401.00	398.49	381.29	375.78	349.74	355.32	298.22
134	462.44	440.19	430.10	413.59	400.98	378.16	379.31	319.07
143	502.41	472.53	452.21	446.22	427.25	404.22	390.67	342.62
155	545.39	513.44	473.66	482.95	455.92	435.22	416.09	366.10
164	576.72	546.62	511.52	515.88	467.52	465.97	428.08	389.49
174	604.46	587.78	537.00	548.94	498.09	494.64	440.28	411.43
184	630.52	628.79	563.60	586.33	547.76	525.74	468.98	437.53
196	657.48	678.58	591.38	628.11	562.44	556.70	481.92	462.09

Table 7: Average absolute deviation of $h_{2\varphi}$ based on correlation 18 for different compositions of three liquid-water systems

Composition of liquid	Average absolute deviation	
	Palm oil-water	Oleic acid-water
20%	5.563	9.193
40%	4.447	4.238
60%	4.289	3.416
80%	9.921	3.882