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Effect of Heat Transfer Studies on A Water-Palm Oil Two-Phase System in 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 palm oil and water were experimentally studied in a 1:2 shell and tube heat exchanger. The data on pure water and palm oil 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, $\chi_{tt}{}^2$, 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 palm oil 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 palm oil and pure water suggest that palm oil 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; Two phase multiplier.

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 gas-liquid 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. Later many researchers have used this approach for hydrodynamic and pressure drop studies in gas-liquid two phase flow in various geometries such as vertical tube (Spedding et al.[3], Vijayarangan et al.[4], Xiuzhong et al.[5]), horizontal tube (Rani Hemamalini et al.[6]), vertical and horizontal tube (Benbelk A. Shannak.[7]), across staggered rod bundles

(Dowlati et al.[8]), helicoidal pipes (Awwad et al.[9]), etc. Then the heat transfer on gas-liquid flow in plate type heat exchanger has been investigated (Vlasogiannis et al.[10]). Oliemans et al.[11] established a semi-emprical model for the core-annular flow of oil and water through pipeline. Bretta et al.[12] studied pressure drop for horizontal oil- water flow in small diameter tubes. Ramachandran et al.[13, 14] 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.

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-palm oil in different ratios as the heated fluid(process fluid) on 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.

EXPERIMENTAL SETUP AND PROCEDURE

A schematic diagram of the experimental setup is shown in figure1 which gives in detail the size and specifications of all the units involved. A photographic view of 1-2 shell and tube heat exchanger 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.

CALCULATION METHODOLOGY

Tube side:

In the tube side, the heating fluid (hot water) was circulated at constant rate. The tube side Reynolds number, Nusselt number, heat transfer coefficient and heat transfer rates were calculated using equations 1 to 4.

$$N_{Re} = \frac{v * D_i * \rho}{\mu} \quad \text{.......(01)}$$

$$N_{Nu} = 1.86\left\{\frac{(N_{Re} * N_{Pr})}{(L/D_i)}\right\}^{0.333} \quad \text{..........(02)}$$

$$h_{it\varphi} = \left(\frac{(N_{Nu} * k)}{D_i}\right) \quad \text{..........(03)}$$

$$Q = m_h * C_{ph} * (T_{h2} - T_{h1}) \quad \text{..........(04)}$$

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

The heat transfer coefficients for single phase were related to Reynolds number using equation 5 and the constants a and m established by regression analysis

$$h_{i\varphi} = a N_{Re}{}^{m} \quad \text{..........(05)}$$

Shell side:

Various compositions of palm oil and water at different flow rates were circulated. The parameters used are given in equations 6 to 18:

The quality (X) is defined by equation 6,

$$X = \frac{1}{\left[1 + \frac{(\rho_w * V_w)}{(\rho_f * V_f)}\right]} \quad \text{..........(06)}$$

The Reynolds number is calculated based on equations 7 to12:

$$Mixture\ density\ (\rho_m) = \rho_f X + \rho_w (1 - X) \quad \text{....(07)}$$

$$Mixture\ viscosity\ (\mu_m) = \mu_f X + \mu_w (1 - X) \quad \text{... ....(08)}$$

$$Cross\ flow\ area\ (A_s) = \left(\frac{(P_t - D_o)}{P_t}\right) * D_s * B_s \quad \text{..(09)}$$

$$Mass\ velocity\ (G_s) = \left(\frac{(V_m * \rho_m)}{A_s}\right) \quad \text{.......(10)}$$

$$Equivalent\ diameter\ (D_e) = \frac{1.1}{D_o * (P_t{}^2 - 0.91 D_o{}^2)} \quad \text{....(11)}$$

$$Reynolds\ number\ (N_{Re}) = \left(\frac{(G_s * D_e)}{\mu_m}\right) \quad \text{....(12)}$$

The overall heat transfer coefficient (U) in (W/m²k), process side heat transfer coefficient ($h_{2\varphi}$), Lockhart-Martinelli parameter ($\chi_{tt}{}^2$) and two phase multiplier (Φ_L) are calculated using equations 13 to 16:

$$U = \frac{Q}{(A_h * LMTDt)} \quad \text{.....(13)}$$

$$h_{2\varphi} = \frac{1}{\left\{\left(\frac{1}{U}\right)-\left(\frac{D_o \cdot \ln\left(\frac{D_o}{D_i}\right)}{2 \cdot k_W}\right)-\left(\frac{D_o}{D_i \cdot h_{1t\varphi}}\right)\right\}} \quad \text{......(14)}$$

$$\chi_{tt}{}^2 = \left(\frac{1-X}{X}\right)^{2-m}\left(\frac{\rho_f}{\rho_w}\right)\left(\frac{\mu_w}{\mu_f}\right)^2 \quad \text{........(15)}$$

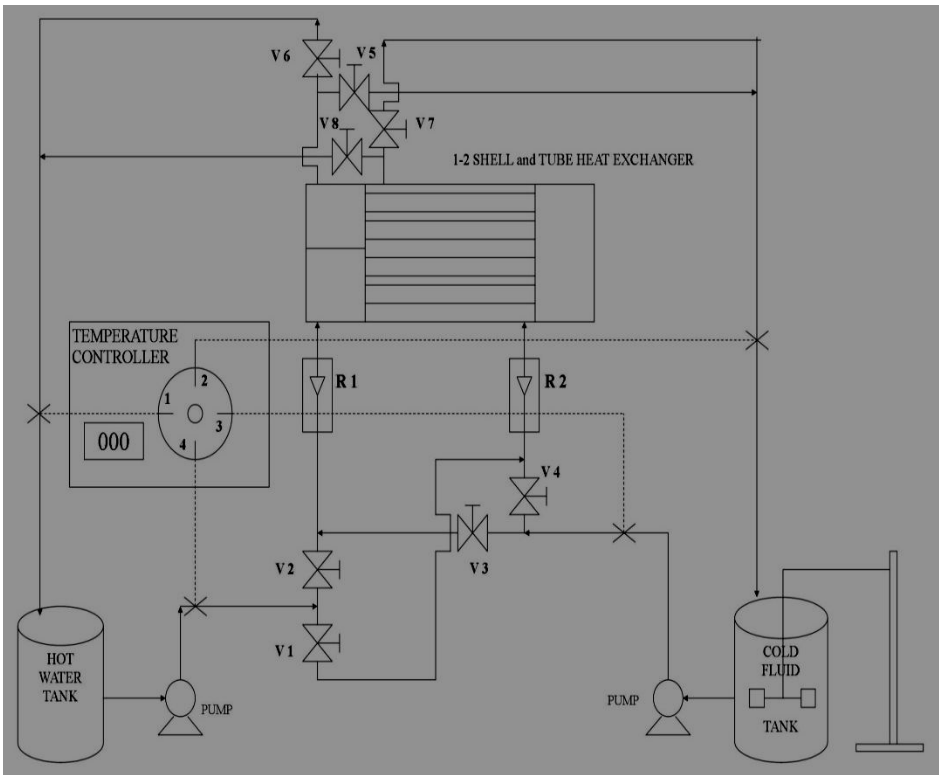
$$\Phi_L = \frac{h_{2\varphi}}{h_{1\varphi}} \quad \text{..............(16)}$$

Equation 17 relates the two phase multiplier to L-M parameter:

$$\Phi_L = \frac{b * \chi_{tt}{}^2}{c + \chi_{tt}{}^2} \quad \text{.. ....(17)}$$

Error is defined by equation18 as,

$$Error = \left[\frac{\left(h_{2\varphi}(exp) - h_{2\varphi}(cal)\right)}{h_{2\varphi}(exp)}\right] * 100 \text{..........(18)}$$



→ 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

Figure 1. A Systematic diagram of the experimental setup

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

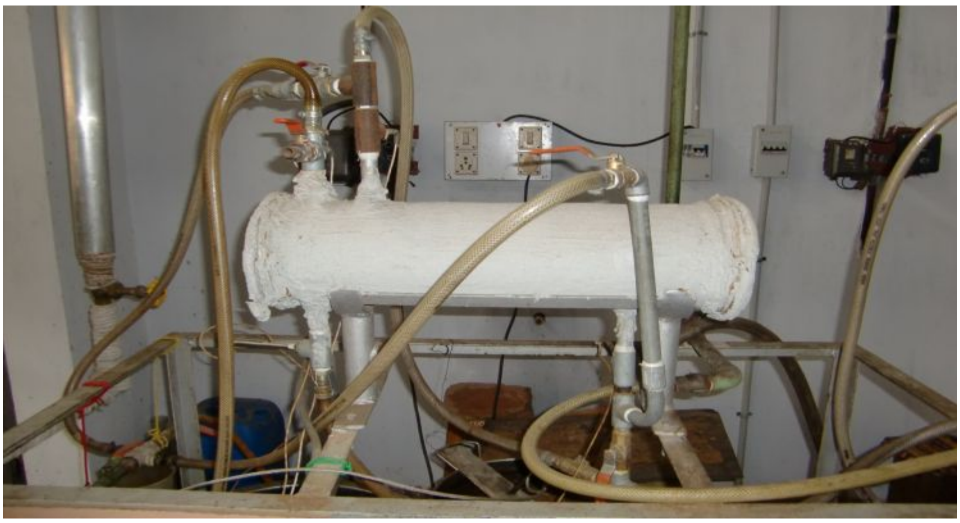


Figure 2: 1-2 Pass Shell and Tube Heat Exchanger

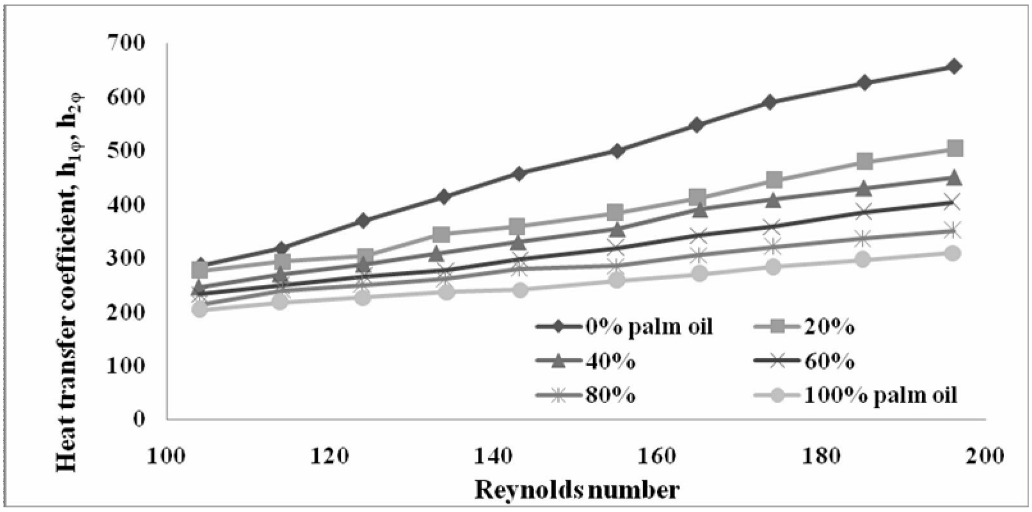


Figure 3: Variation of heat transfer coefficient with Reynolds number for different palm oil- water compositions.

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

Mass percentage of palm oil	a	m
0	0.537	1.354
100	9.757	0.651

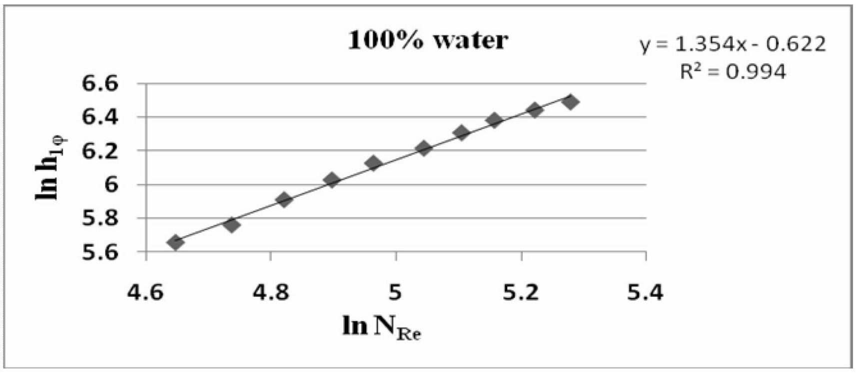


Figure 4: Plot between $\ln N_{Re}$ and $\ln h_{1\varphi}$(heat transfer coefficient of water)

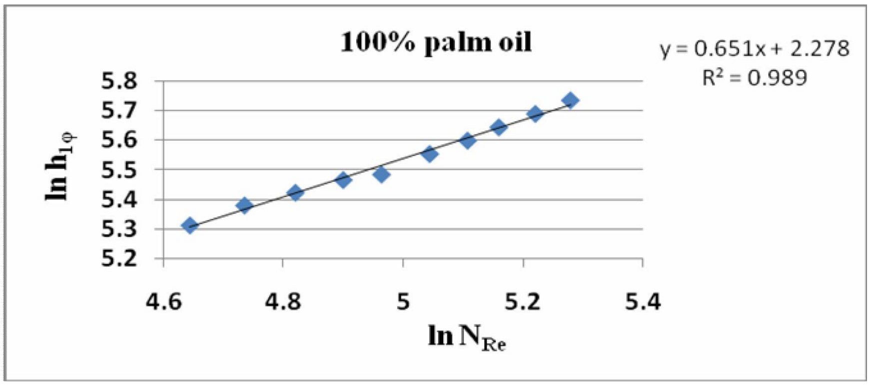


Figure 5: Plot between $\ln N_{Re}$ and $\ln h_{1\varphi}$(heat transfer coefficient of palm oil)

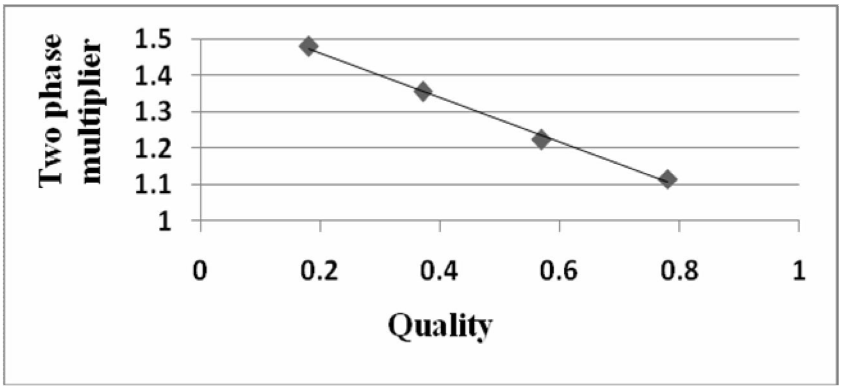


Figure 6: Plot between Quality (X) and Two-phase multiplier based on pure palm oil for water-palm oil system

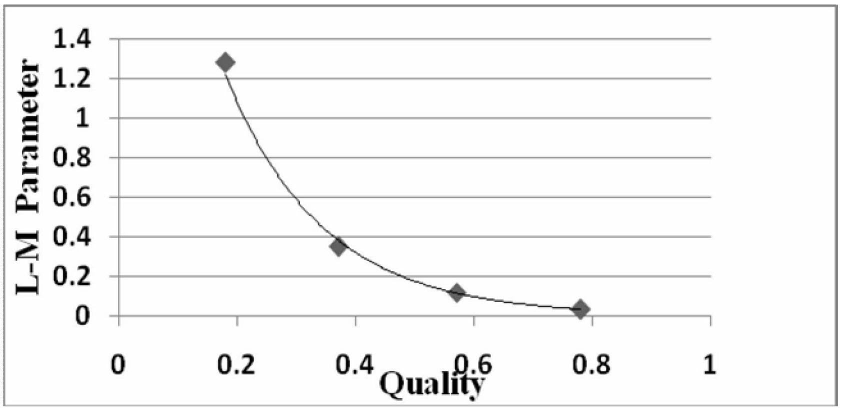


Figure 7: Plot between Quality (X) and L-M Parameter based on pure palm oil for water-palm oil system

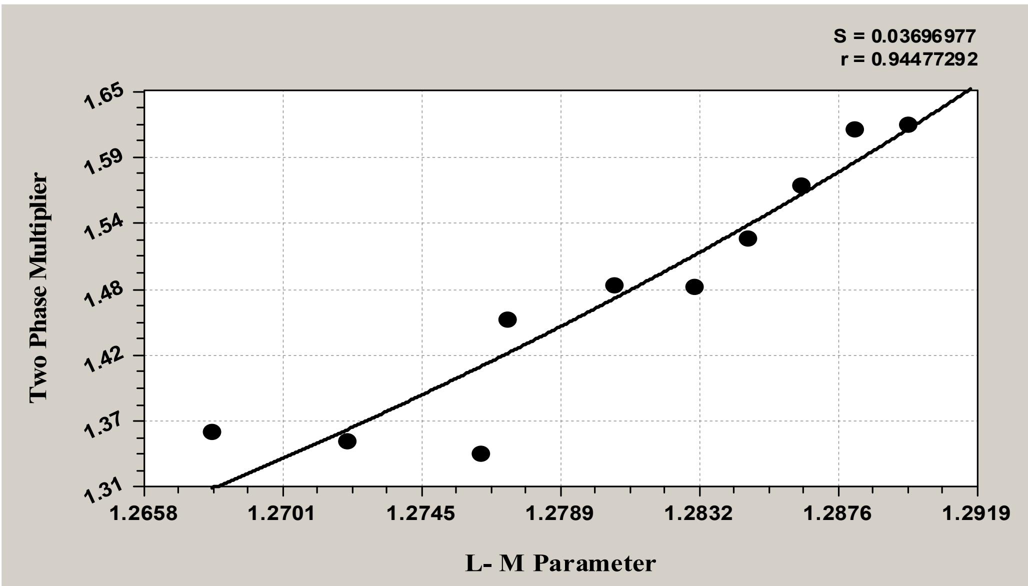


Figure 8: Variation of Two Phase Multiplier with L-M Parameter for 20% palm oil-water system based on pure palm oil

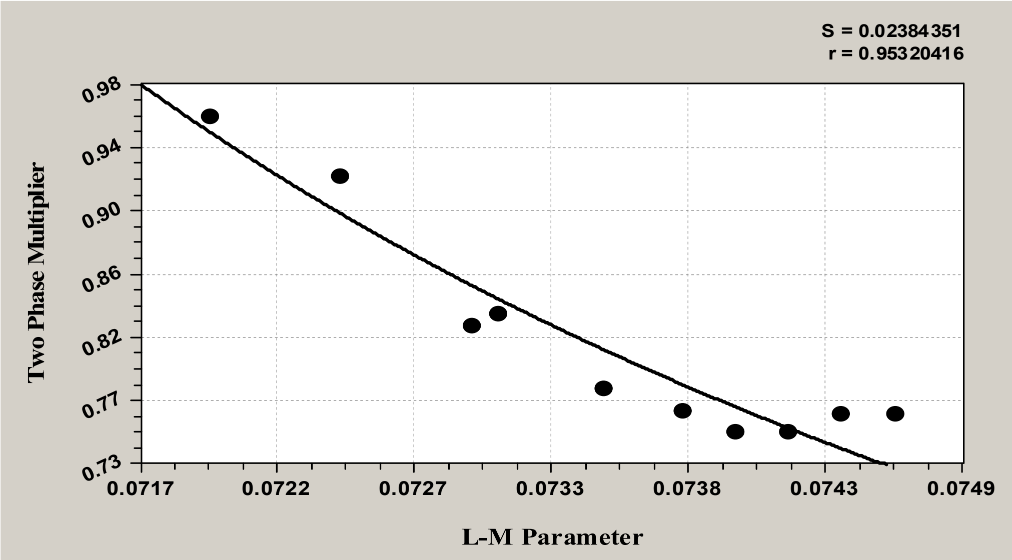


Figure 9: Variation of Two Phase Multiplier with L-M Parameter for 20% palm oil-water system based on pure water

Table 2: The correlation constants b and c in Eqn.17 for varying palm oil-water compositions

Composition of palm oil	Pure Palm oil		Pure Water	
	b	c	B	c
20%	-0.127	-1.390	0.098	-0.065
40%	-0.076	-0.366	0.062	-0.037
60%	-0.075	-0.124	0.038	-0.023
80%	-0.182	-0.036	0.025	-0.012

Table 3: Comparison of experimental and calculated values of two-phase heat transfer coefficients for 20% palm oil-water system

N_{Re}	$h_{2\varphi exp}$	Based on pure palm oil		Based on pure water	
		$h_{2\varphi cal}$	%error	$h_{2\varphi cal}$	%error
104	275.56	267.79	2.819	271.60	1.437
114	292.91	297.73	-1.649	284.02	3.032
124	303.36	323.34	-6.604	312.11	-2.882
134	344.13	340.27	1.123	346.97	-0.824
143	357.60	358.27	-0.186	368.01	-2.911
155	382.94	393.67	-2.803	390.30	-1.923
165	411.91	418.96	-1.710	419.88	-1.933
174	443.60	445.99	-0.537	443.64	-0.007
185	478.44	474.94	0.732	463.02	3.223
196	502.23	505.97	-0.742	477.16	4.991

Table 4: Comparison of experimental and calculated values of two-phase heat transfer coefficients for 40% palm oil-water system.

N_{Re}	$h_{2\varphi exp}$	Based on pure palm oil		Based on pure water	
		$h_{2\varphi cal}$	%error	$h_{2\varphi cal}$	%error
104	245.68	244.35	0.541	242.63	1.242
114	269.58	267.17	0.895	260.13	3.507
124	287.76	288.42	-0.228	287.69	0.026
134	308.13	307.99	0.043	313.42	-1.719
143	330.05	321.22	2.676	336.11	-1.835
155	353.73	352.48	0.354	356.65	-0.825
165	390.67	373.26	4.456	385.56	1.308
174	408.73	400.24	2.077	403.79	1.207
185	429.35	424.07	1.231	423.40	1.385
196	449.63	455.20	-1.240	432.69	3.768

Table 5: Comparison of experimental and calculated values of two-phase heat transfer coefficients for 60% palm oil-water system.

N_{Re}	$h_{2\varphi exp}$	Based on pure palm oil		Based on pure water	
		$h_{2\varphi cal}$	%error	$h_{2\varphi cal}$	%error
104	232.67	224.32	3.587	299.34	1.430
114	248.21	247.33	0.355	235.27	5.215
124	265.46	263.55	0.717	260.14	2.000
134	277.09	280.89	-1.369	279.13	-0.763
143	297.23	289.24	2.689	301.59	-1.468
155	318.02	316.64	0.432	315.57	0.770
165	341.48	334.90	1.927	338.89	0.759
174	357.86	354.27	1.003	357.46	0.112
185	384.85	374.84	2.599	372.44	3.224
196	403.76	396.71	1.745	383.17	5.099

Table 6: Comparison of experimental and calculated values of two-phase heat transfer coefficients for 80% palm oil-water system.

N_{Re}	$h_{2\varphi exp}$	Based on pure palm oil		Based on pure water	
		$h_{2\varphi cal}$	%error	$h_{2\varphi cal}$	%error
104	213.04	218.11	-2.376	230.01	-1.962
114	239.71	234.33	2.242	244.92	-2.173
124	250.19	246.76	1.372	263.39	-5.278
134	261.01	259.80	0.498	275.77	-5.619
143	279.90	265.87	5.014	294.64	-5.267
155	285.13	287.40	-0.795	302.01	-5.922
165	305.75	302.01	1.224	321.27	-5.076
174	320.10	317.39	0.845	335.84	-4.917
185	335.20	333.60	0.478	346.93	-3.499
196	351.13	350.70	0.122	354.04	-0.829

Table 7: Average absolute deviation of $h_{2\varphi}$ based on pure water and pure palm oil

Composition of palm oil	Average absolute deviation based on	
	Pure palm oil	Pure water
20%	1.891	2.317
40%	1.374	1.682
60%	1.643	2.082
80%	1.497	4.654

RESULTS AND DISCUSSION

Figure 3 shows the variation of single and two phase heat transfer coefficient with Reynolds number for the shell side process fluid. It is seen that the two-phase data falls within the boundaries of pure water and pure palm oil data. In addition, 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 data for pure fluid (palm oil or water) was fitted to equation 5 by regression analysis and the constants a & m for palm oil & water are given in Table 1. The figures 4 & 5 are shown $h_{1\varphi}$ and Reynolds number relationship for pure water and palm oil respectively. 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 (Ramachandran et al., 2006, 2008) in equation 17 where 'm' represents the power to which Reynolds number raised to determine single phase heat transfer coefficient. 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 palm oil-water system denotes a decrease in quality(X) and implies an increase in two phase multiplier (Φ_L). An increasing L-M parameter (χ_{tt}^2) for palm oil-water system denotes a decrease in quality(X) and implies an increase in two phase multiplier (Φ_L). 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. The two phase multiplier Φ_L (equation 16) and L-M parameter (equation 15) shown in figures 8 & 9 for 20% composition of palm oil–water system based on pure palm oil and pure water respectively, were related by equation 17. The variation of two phase multiplier (Φ_L) with L-M parameter (χ_{tt}^2) showed an increasing trend while the $h_{1\varphi}$ of pure palm oil was lesser than the heat transfer coefficient of two phase mixture. When the $h_{1\varphi}$ based on pure water was higher than the $h_{2\varphi}$, the trend between Φ_L and χ_{tt}^2 concave towards up. The constants b & c of fitted equation 17 were given in Table 2 based on palm oil & water as reference fluid. Tables 3 to 6 compared the experimental and theoretical two phase heat transfer coefficients based on pure palm oil and water as reference fluid. Table 7 summarizes the average absolute deviation of two phase heat transfer coefficient calculated using water and palm oil as reference liquids for the data in Tables 3 to 6.

CONCLUSION

Based on the summary in Table 7, it can be concluded that for this system palm oil is a better reference fluid compared to water since the average absolute deviation varies for 1.49 to 1.89 percent compared to water (1.68 to 4.65 percent). Further studies on diesel-water, nitrobenzene-water, oleic acid-water, kerosene-water and castor oil-water are being carried out to verify whether in these cases also diesel, nitrobenzene, oleic acid kerosene and castor oil are better reference fluids compared to water. The specific reason for palm oil 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 palm oil in equation(5)
b, c – constants of saturated growth correlation(17)
$h_{1\varphi}$ - heat transfer coefficient of pure palm oil/water (W/m²k)
$h_{2\varphi}$ - two-phase heat transfer coefficient (W/m²k)
$h_{1t\varphi}$ - tube 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 (m)
LMTDt – corrected logarithmic mean temperature difference (K)
A_h – heat transfer area (m^2)
m_h – flow rate of hot fluid (kg/s)
Cp_h – specific heat of hot fluid (J/kg k)
v – velocity of tube side liquid(m/s)
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(m^2/s)
μ_w - viscosity of water (kg/ms)
μ_f - viscosity of fluid (kg/ms)
ρ_w – density of water (kg/m^3)
ρ_f – density of fluid (kg/m^3)
ρ_m – density of mixture (kg/m^3)

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