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TWO-PHASE EXPERIMENTAL HEAT TRANSFER STUDIES ON A WATER-DIESEL SYSTEM IN A 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 diesel and water were experimentally studied in a 1:2 shell and tube heat exchanger. The data on pure water and diesel were fitted to an equation of the form. $h_{1\varphi} = a\,N_{Re}^{m}$ .The two-phase multiplier, Φ_L, was related to the Lockhart Martinelli (L-M) parameter, χ_{tt}^2, using the two-phase data and a correlation $\Phi_L = b+c(\chi_{tt}^2)+d/(\chi_{tt}^2)^2$ was established. The two-phase heat transfer coefficient was calculated based on the coefficients 'a' and 'm' for pure diesel and pure water along with Φ_L and the L-M parameter. The calculated values of the two-phase heat transfer coefficient $h_{2\varphi}$ based on pure diesel and pure water suggest that diesel is a better reference fluid since the average error is much smaller 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 has gained importance over the years. A better understanding of the rates of momentum and heat transfer in multiphase 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 the Reynolds number and Nusselt number.

Considerable research is being pursued in two-phase flow particularly in the area of fluid dynamics. Lockhart *et al*. (1949) 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*. (1972) 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 (L-M) for all regimes. Subsequently, 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*., 1980; Vijayarangan *et al*., 2007; Xiuzhong *et al*., 2005), horizontal tube (Rani Hemamalini *et al*.,

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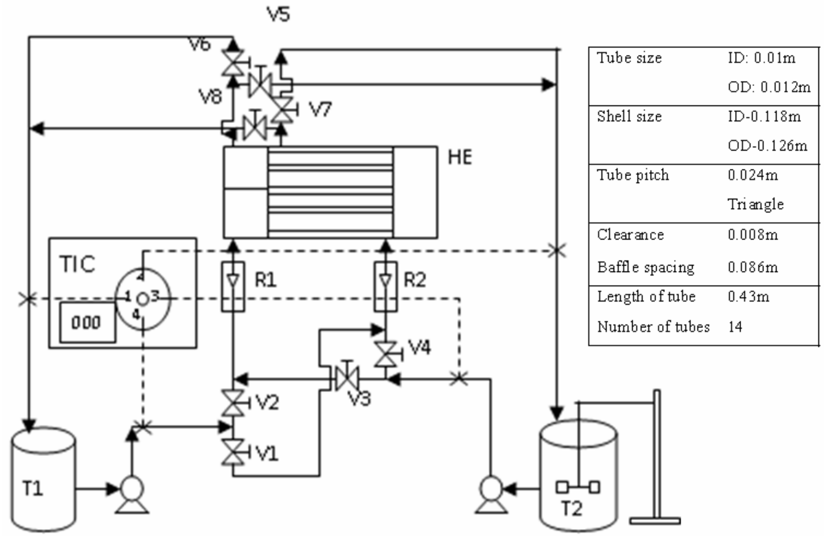
2005;), vertical and horizontal tube (Benbelk A. Shannak., 2008), across staggered rod bundles (Dowlati *et al*., 1992), helicoidal pipes (Awwad *et al*., 2000), etc. The heat transfer for gas-liquid flow in a plate type heat exchanger has also been investigated (Vlasogiannis *et al*., 2002). Ramachandran *et al*. (2006) conducted two-phase experiments in a compact heat exchanger and developed heat transfer correlations for two-phase heat transfer involving liquid-liquid systems. Ramachandran *et al*. (2008) developed a model for predicting the two-phase heat transfer coefficient of liquid-liquid systems using single phase data.

In this work, we propose a model formulation analogous to the L-M parameter model for heat transfer involving a liquid-liquid mixture. However, the study of heat transfer involving two immiscible liquids in a shell and tube heat exchanger has not been extensively studied. 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-diesel 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 relations between the Lockhart-Martinelli parameter, the quality and the two-phase multiplier were developed based on the experimental data. The work is confined to laminar flow in the present study.

EXPERIMENTAL SECTION

A schematic diagram of the 1-2 pass shell and tube heat exchanger experimental setup is shown in Figure 1, which gives in detail the size and specifications of all the units involved. Triangular pitch was used for the arrangement of tubes. Heating fluid and process fluid were pumped through the tube and shell side of the heat exchanger, respectively, using 0.25 HP pumps. Water was heated using a 2 kW heater and 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. Pumping continued through both the channels until a steady state was obtained with respect to the inlet and outlet temperatures of both the fluids. The flow rate was measured using Gallenkamp rotameters with an accuracy of ±0.1 LPM. The hot water flow rate was constantly maintained by rotameter R1 and circulated through the tube side, while the shell side test fluid mixture was metered through rotameter R2. The rotameters were calibrated before use. The flow rates of the two streams were adjusted using hand operated valves (2) and (4). The temperatures were recorded in the exit and inlet using RTD with an accuracy of ± 0.1°C. Six compositions (0% to 100% diesel) of the water-diesel system were used in the study. The two-phase system was kept in suspension using an agitator.



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. [solid lines - Flow; dotted lines - temperature sensor; 1, 4 – RTD's for inlet & outlet hot fluid; 2, 3 – RTD's for inlet & outlet cold fluid; R1, R2 – rotameters; V1, V2, V3, V4, V5, V6, V7, V8 – manual valves; HE – heat exchanger; TIC – temperature indicator controller; T1 – hot fluid storage tank; T2 – cold fluid storage tank].

CALCULATION METHODOLOGY

Tube Side

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

$$N_{Re} = \frac{vD_i\rho}{\mu} \tag{1}$$

$$N_{Nu} = 1.86\left\{\frac{N_{Re}N_{Pr}}{L/D_i}\right\}^{0.333} \tag{2}$$

$$h_{1t\phi} = \left(\frac{N_{Nu}k}{D_i}\right) \tag{3}$$

$$Q = m_h C_{ph}\left(T_{h2} - T_{h1}\right) \tag{4}$$

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

Shell Side

Various compositions of diesel and water were circulated at different flow rates. The heat transfer coefficients for the single phases were related to the Reynolds number using Equation (5) and the constants a and m established by regression analysis.

$$h_{1\phi} = aN_{Re}^{\ m} \tag{5}$$

The quality (X) is defined by Equation (6),

$$X = \frac{1}{\left[1 + \frac{(\rho_w V_w)}{(\rho_f V_f)}\right]} \tag{6}$$

The Reynolds number is calculated based on Equation (7) to (12):

$$\rho_m = \rho_f X + \rho_w (1 - X) \tag{7}$$

$$\mu_m = \mu_f X + \mu_w (1 - X) \tag{8}$$

$$A_S = \left(\frac{P_t - D_o}{P_t}\right) D_S B_S \tag{9}$$

$$G_S = \left(\frac{V_m \rho_m}{A_S}\right) \tag{10}$$

$$D_e = \frac{1.1}{D_o\left(P_t^{\ 2} - 0.91 D_o^{\ 2}\right)} \tag{11}$$

$$N_{Re} = \left(\frac{G_S D_e}{\mu_m}\right) \tag{12}$$

The correction factor (F_t) is a function of the shell and tube fluid temperatures and was correlated as a function of two dimensionless temperature ratios (Sinnott, 2000):

$$R = \frac{\left(T_{c1} - T_{c2}\right)}{\left(T_{h1} - T_{h2}\right)}, \qquad S = \frac{\left(T_{h2} - T_{h1}\right)}{\left(T_{c1} - T_{h1}\right)} \tag{13}$$

R is equal to the shell side fluid flow rate times the fluid mean specific heat divided by the tube side fluid flow rate times the tube side fluid specific heat.

S is a measure of the temperature efficiency of the exchanger.

The true temperature difference is expressed as:

$$\Delta T_m = F_t\, \Delta T_{lm} \tag{14}$$

The overall heat transfer coefficient (U) and process side heat transfer coefficient ($h_{2\varphi}$) are determined using Equation (15) and (16):

$$U = \frac{Q}{A_h\, \Delta T_m} \tag{15}$$

$$h_{2\phi} = \frac{1}{\left\{\left(\frac{1}{U}\right) - \left(\frac{D_o \ln\left(\frac{D_o}{D_i}\right)}{2\ k_w}\right) - \left(\frac{D_o}{D_i\ h_{1t\phi}}\right)\right\}} \tag{16}$$

The single phase heat transfer coefficient was related to the Lockhart-Martinelli parameter ($\chi_{tt}^{\ 2}$) using the slope ‘m’ of Equation (5).

$$\chi_{tt}^{\ 2} = \left(\frac{1 - X}{X}\right)^{2-m}\left(\frac{\rho_f}{\rho_f}\right)\left(\frac{\mu_w}{\mu_f}\right)^m \tag{17}$$

The ratio of the two-phase heat transfer coefficient to the single phase heat transfer coefficient is expressed as the two-phase multiplier (Φ_L):

$$\Phi_L = \frac{h_{2\phi}}{h_{1\phi}} \tag{18}$$

Equation (19) relates the two-phase multiplier to the L-M parameter:

$$\Phi_L = b + c\chi_{tt}^2 + \frac{d}{\chi_{tt}^2} \tag{19}$$

The error is defined by Equation (20) as,

$$\text{Error} = \left[\frac{h_{2\phi}(\exp) - h_{2\phi}(\text{cal})}{h_{2\phi}(\exp)}\right]100 \tag{20}$$

RESULTS AND DISCUSSION

Figure 2 shows the variation of the single and the two-phase heat transfer coefficients with Reynolds number for the shell side process fluid. It is seen that the two-phase data fall within the boundaries of the pure water and pure diesel 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, results in higher heat transfer coefficients.

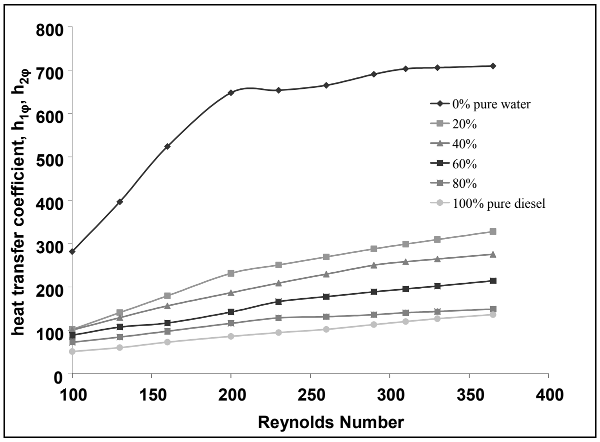


Figure 2: Variation of the heat transfer coefficient with Reynolds number for different diesel -water compositions.

Figures 3 and 4 show the single phase heat transfer coefficient ($h_{1\varphi}$) and Reynolds number relationship for pure diesel and pure water, respectively. The data for pure fluid (diesel or water) was fitted to Equation (5) by regression analysis and the resultant constants a and m for diesel and water are given in Table 1. Initially the L-M parameter correlation was used for predicting the pressure drop of gas-liquid two-phase systems and then the heat transfer coefficients for liquid-liquid two-phase flow were related to the L-M parameter (Ramachandran *et al.*, 2006, 2008) in Equation (17), where 'm' represents the power to which the Reynolds number is raised to determine the single phase heat transfer coefficient. The inlet and outlet temperatures of the shell side and tube side fluid are shown in Table 2 for different compositions. We maintained the inlet temperatures constant and measured the outlet temperatures once the heat exchanger attained the steady-state condition. The two-phase multiplier Φ_L (Equation (18)) and the L-M parameter (Equation (17)) are shown in Figures 5 and 6 for 80% composition of the diesel–water system based on pure diesel and pure water, respectively, and are related by the heat capacity (Equation (19)). The variation of the two-phase multiplier (Φ_L) with the L-M parameter (χ_{tt}^2) shows an increasing concave trend, while the $h_{1\varphi}$ of pure diesel is less than the heat transfer coefficient of the two-phase mixture. Because $h_{1\varphi}$ based on pure water is higher than $h_{2\varphi,}$ the trend between Φ_L and χ_{tt}^2 is upwardly concave. The constants b, c and d of the heat capacity correlation (Equation (19)) are given in Table 3 based on pure diesel and pure water as the reference fluid. The relationship of quality to the L-M parameter and the two-phase multiplier are shown in Figures 7 and 8. An increasing L-M parameter (χ_{tt}^2) for the diesel-water system denotes a decrease in quality(X) and implies an increase in the two-phase multiplier (Φ_L). As the proportion of the second phase increases, with a consequent decrease in the proportion of water, the viscosity of the mixture increases and the thermal conductivity, density and specific heat decrease. This brings down the heat transfer coefficient and hence the two phase multiplier decreases with quality. Tables 4 and 5 compare the two-phase heat transfer coefficients calculated based on pure diesel and pure water as the reference fluid. Table 6 summarizes the average absolute deviation of the two-phase heat transfer coefficients calculated using water and diesel as reference liquids for the data in Tables 4 and 5.

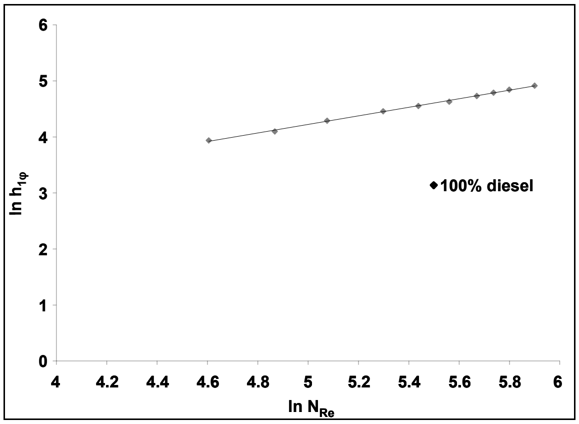


Figure 3: Plot between ln N_{Re} and ln $h_{1\varphi}$ (heat transfer coefficient of pure diesel).

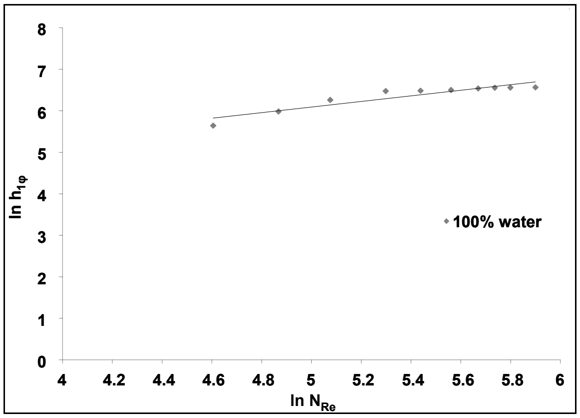


Figure 4: Plot between ln N_{Re} and ln $h_{1\varphi}$ (heat transfer coefficient of pure water).

Table 1: Correlation constants a and m for the pure diesel and pure water systems.

Mass percentage of diesel	a	m
0	15.135	0.674
100	1.501	0.763

Table 2: Inlet and outlet temperatures for different compositions of cold side and hot side fluids

N_{Re} of tube side	100% pure water				N_{Re} of tube side	20% diesel-water			
	T_{c1}	T_{c2}	T_{h1}	T_{h2}		T_{c1}	T_{c2}	T_{h1}	T_{h2}
1106	304	321.6	343	331.8	1168	304	316.4	343	338.8
1104	304	314.0	343	330.2	1141	304	314.0	343	335.2
1101	304	310.8	343	329.5	1132	304	311.4	343	334.0
1099	304	309.1	343	329.1	1126	304	310.0	343	333.2
1097	304	308.1	343	328.8	1120	304	309.0	343	332.4
1095	304	307.3	343	328.5	1118	304	308.4	343	332.0
1094	304	306.8	343	328.3	1113	304	308.0	343	331.4
1092	304	306.3	343	328.2	1110	304	307.6	343	330.9
1091	304	306.0	343	328.1	1106	304	307.3	343	330.4
1090	304	305.7	343	327.9	1103	304	307.1	343	329.9
N_{Re} of tube side	40% diesel- water				N_{Re} of tube side	60% diesel-water			
	T_{c1}	T_{c2}	T_{h1}	T_{h2}		T_{c1}	T_{c2}	T_{h1}	T_{h2}
1172	304	316.4	343	339.4	1178	304	316.0	343	340.1
1152	304	313.2	343	336.8	1162	304	312.8	343	338.1
1142	304	311.3	343	335.4	1157	304	310.5	343	337.4
1135	304	310.1	343	334.4	1147	304	309.9	343	336.1
1131	304	309.0	343	333.9	1143	304	309.0	343	335.5
1128	304	308.4	343	333.5	1140	304	308.4	343	335.1
1125	304	308.0	343	333.0	1137	304	308.0	343	334.7
1122	304	307.6	343	332.6	1134	304	307.6	343	334.3
1119	304	307.3	343	332.2	1130	304	307.4	343	333.8
1118	304	307.0	343	332.1	1129	304	307.1	343	333.6
N_{Re} of tube side	80% diesel- water				N_{Re} of tube side	100% pure diesel			
	T_{c1}	T_{c2}	T_{h1}	T_{h2}		T_{c1}	T_{c2}	T_{h1}	T_{h2}
1183	304	315.5	343	340.8	1188	304	315.3	343	341.4
1171	304	312.3	343	339.3	1178	304	313.0	343	340.2
1165	304	310.6	343	338.5	1177	304	309.9	343	340.0
1159	304	309.7	343	337.7	1171	304	309.5	343	339.2
1154	304	309.0	343	337.0	1166	304	308.9	343	338.6
1153	304	308.3	343	336.9	1163	304	308.6	343	338.2
1151	304	307.9	343	336.6	1161	304	308.2	343	337.9
1149	304	307.5	343	336.4	1157	304	308.0	343	337.4
1147	304	307.2	343	336.1	1154	304	307.8	343	337.0
1145	304	307.0	343	335.8	1152	304	307.5	343	336.7

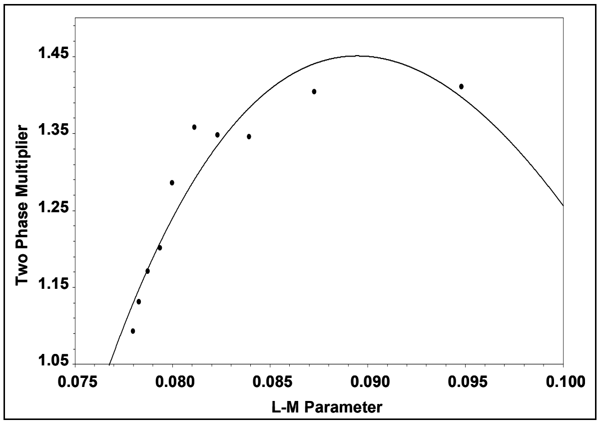


Figure 5: Variation of the Two-Phase Multiplier (Φ_L) with the L-M Parameter (χ_{tt}^2) for the 80% diesel-water system based on pure diesel

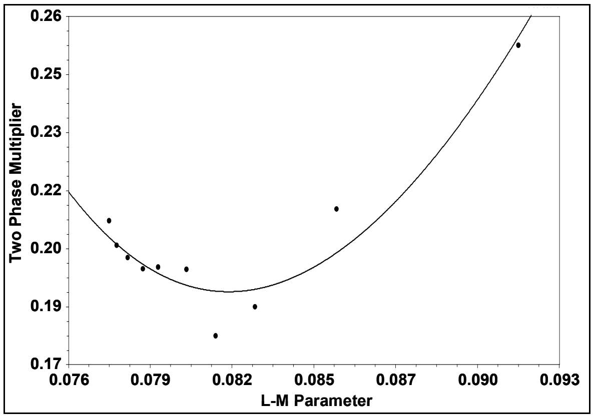


Figure 6: Variation of the Two Phase Multiplier (Φ_L) with the L-M Parameter (χ_{tt}^2) for the 80% diesel -water system based on pure water

Table 3: The correlation constants b, c and d in Eq. (19) for varying diesel-water compositions

Composition of diesel	Pure diesel			Pure Water		
	b	c	d	b	C	d
20%	30.8	-14	-16.9	-7.22	2.5	10.3
40%	15.2	-17	-1.12	-7.89	8.38	1.16
60%	7.06	-14.5	-0.105	-8.6	23.1	0.191
80%	17.7	-121	-0.043	-4.88	41.5	0.011

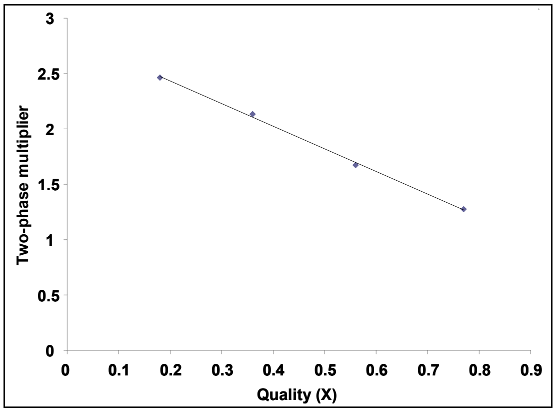


Figure 7: Plot between Quality(X) and Two-phase multiplier(Φ_L) based on pure diesel for the water-diesel system

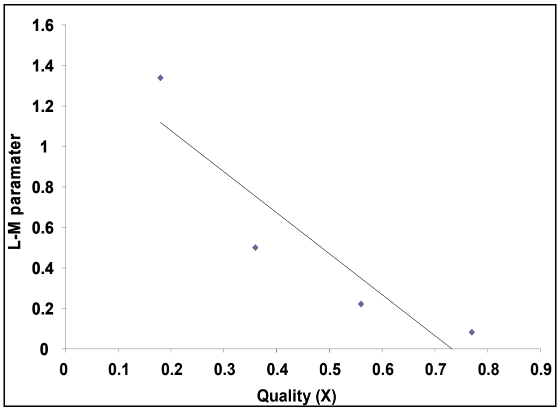


Figure 8: Plot between Quality(X) and the L-M Parameter(χ_{tt}^2) based on pure diesel for the water-diesel system

Table 4: Comparison of experimental and calculated values of two-phase heat transfer coefficients for 20% and 40% diesel-water systems

N_{Re} of shell side	$h_{2\varphi exp}$	20% diesel-water		$h_{2\varphi exp}$	40% diesel-water	
		$h_{2\varphi cal}$ based on pure diesel	$h_{2\varphi cal}$ based on pure water		$h_{2\varphi cal}$ based on pure diesel	$h_{2\varphi cal}$ based on pure water
100	102.22	102.08	110.60	100.71	101.49	104.09
130	141.02	145.55	141.04	129.36	131.71	120.75
160	179.82	190.37	192.60	156.61	162.06	160.96
200	231.55	226.61	253.23	186.82	191.49	207.89
230	250.91	247.33	270.28	209.12	208.93	222.54
260	269.49	264.30	285.43	229.71	223.74	235.19
290	288.09	290.62	304.16	250.31	246.57	250.91
310	298.97	305.47	318.12	258.40	259.90	262.83
330	309.45	320.06	325.81	264.61	273.00	269.56
365	327.79	341.85	332.10	275.47	291.59	277.10

Table 5: Comparison of experimental and calculated values of two-phase heat transfer coefficients for 60% and 80% diesel-water systems.

N_{Re} of shell side	$h_{2\varphi exp}$	60% diesel-water		$h_{2\varphi exp}$	80% diesel-water	
		$h_{2\varphi cal}$ based on pure diesel	$h_{2\varphi cal}$ based on pure water		$h_{2\varphi cal}$ based on pure diesel	$h_{2\varphi cal}$ based on pure water
100	88.93	89.49	89.26	72.39	72.42	72.60
130	107.69	105.57	93.00	84.57	87.63	79.01
160	117.03	125.27	121.05	98.12	101.89	99.15
200	142.36	147.08	152.88	116.30	116.40	122.13
230	166.37	159.61	161.75	128.88	123.77	124.15
260	177.84	170.36	171.27	131.58	128.25	128.31
290	188.88	187.42	183.18	136.24	138.53	134.88
310	195.55	197.27	192.52	140.54	142.93	139.35
330	202.17	207.46	196.39	143.65	147.59	141.54
365	214.48	221.45	202.50	149.10	156.08	143.54

Table 6: Average absolute deviation of $h_{2\varphi}$ based on pure water and pure diesel

Composition of diesel	Average absolute deviation based on	
	Pure diesel	Pure water
20%	2.549	5.692
40%	2.237	3.730
60%	2.877	4.434
80%	2.470	2.633

CONCLUSION

Two-phase flow through a 1-2 pass shell and tube exchanger using a water-diesel system was studied. The correlations between X, Φ_L and χ_{tt}^2 will be useful for predicting two-phase heat transfer coefficients using pure phase thermo-physical properties. The correlation developed for the diesel-water system is useful for identifying heat transfer coefficients of two-phase systems for the range of Reynolds number studied. Based on the summary in Table 6, it can be concluded that, for this system, diesel is a better reference fluid compared to water since the average absolute deviation varies from 2.24 to 2.88 percent compared to water (2.63 to 5.69 percent). Further studies on Palm oil-Water, Nitrobenzene-Water, Oleic acid-Water and Castor oil-Water are being carried out to verify whether Palm oil, Nitrobenzene, Oleic acid and Castor oil are also better reference fluids compared to water. The specific reason for diesel being a better reference fluid should be clarified by this comprehensive study of similar systems.

NOMENCLATURE

a, m	constants for pure water and pure diesel in Equation (5)	
A_h	heat transfer area	m^2
A_s	cross flow area	m^2

b, c, d	constants of the heat capacity correlation Equation (19)	
B_s	baffle spacing	m
Cp_h	specific heat of hot water	J/kg K
D_i	inner diameter of the tube	m
D_o	outer diameter of the tube	m
D_s	inner diameter of the shell	m
D_e	equivalent diameter	
F_t	temperature correction factor	
G_s	mass velocity	kg/m^2 s
$h_{1\varphi}$	heat transfer coefficient of pure diesel/pure water	W/m^2 K
$h_{2\varphi}$	two-phase heat transfer coefficient	W/m^2 K
$h_{1t\varphi}$	tube side (hot water) heat transfer coefficient	W/m^2 K
k	thermal conductivity of hot water	W/m K
k_w	thermal conductivity of the tube wall material	W/m K
L	length of tube	m
m_h	flow rate of hot water	kg/s
N_{Nu}	Nusselt number	
N_{Pr}	Prandtl number	
N_{Re}	Reynolds number	
Pt	tube pitch (m)	
R, S	dimensionless temperature ratios	
T_{h1}	inlet temperature of hot water on the tube side	K
T_{h2}	outlet temperature of hot water on the tube side	K
T_{c1}	inlet temperature of cold fluid on the shell side	K
T_{c2}	outlet temperature of cold fluid on the shell side	K
v_f	volumetric flow rate of diesel	m^3/s
v_m	flow rate of a diesel-water mixture	m^3/s
v_w	volumetric flow rate of water	m^3/s
X	quality parameter for the two-phase system	

Greek Letters

χ_{tt}^2	Lockhart-Martinelli (L-M) parameter	
Φ_L	two phase multiplier	
ΔT_{lm}	logarithmic mean temperature	K
ΔT_m	true temperature difference	K
v	velocity of hot water	m/s
μ	viscosity of hot water	kg/m s
μ_w	viscosity of water	kg/m s
μ_f	viscosity of diesel	kg/m s
μ_m	viscosity of diesel-water mixture	kg/m s
ρ	density of hot water	
ρ_w	density of water	kg/m^3
ρ_f	density of diesel	kg/m^3
ρ_m	density of diesel-water mixture	kg/m^3

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