Brazilian Journal
of Chemical
Engineering

ISSN 0104-6632
Printed in Brazil
www.abeq.org.br/bjche

Vol. 25, No. 03, pp. 483 - 490, July - September, 2008

HEAT TRANSFER STUDIES IN A SPIRAL PLATE HEAT EXCHANGER FOR WATER – PALM OIL TWO PHASE SYSTEM

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(Received: August 18, 2006 ; Accepted: March 04, 2008)

Abstract - Experimental studies were conducted in a spiral plate heat exchanger with hot water as the service fluid and the two-phase system of water – palm oil in different mass fractions and flow rates as the cold process fluid. The two phase heat transfer coefficients were correlated with Reynolds numbers (Re) in the form h = a Re^m, adopting an approach available in literature for two phase fluid flow. The heat transfer coefficients were also related to the mass fraction of palm oil for identical Reynolds numbers. The two-phase multiplier (ratio of the heat transfer coefficient of the two phase fluid and that of the single phase fluid) was correlated with the Lockhart Martinelli parameter in a polynomial form. This enables prediction of the two-phase coefficients using single-phase data. The predicted coefficients showed a spread of ± 10 % in the laminar range.

Keywords: Heat transfer coefficient; Two - phase flow; Lockhart Martinelli parameter.

INTRODUCTION

Conventional shell and tube heat exchangers have certain operational limitations. These are successfully addressed in compact exchangers such as plate / spiral type equipment. The advantages of these equipments include higher heat transfer rates, less fouling, operational flexibility, ease of maintenance and lower space requirement. They are also better suited to handle slurries, viscous liquids and can be operated where the approach temperatures are low.

In chemical industries, two phase flow is a process necessity. A better understanding of the rates of momentum and heat transfer in multi phase flow conditions is a must for the optimal design of the heat exchanger. (Ho et al., 1995). To simplify the complexities in design, transfer coefficient correlations are being developed using pure phase thermo-physical properties and system parameters like flow geometries and flow velocities. (Jensen, 1988; Gut et al., 2004) Considerable research is being pursued in two phase flow areas particularly in the area of fluid dynamics. The first detailed study in two phase flow was carried out by Lockhart and Martinelli in the year 1949. A number of such studies are cited in the references section (Naphlon and Wongwises., 2002; Manglik and Bergles, 1995; Downing and Gunol Kojasoy, 2002; Chen et al., 2004 Rani Hemamalini, et al., 2005).

However the field which has received relatively less attention is the study of heat transfer involving two phases (especially two immiscible liquids) in a compact heat exchanger. In the present work, experiments were done in a spiral plate heat

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*To whom correspondence should be addressed exchanger with hot water as the service fluid and two-phase mixtures of water and palm oil in different ratios and flow rates as the cold process fluid. Experimental runs with single-phase fluids (pure water and pure palm oil) on the process side were also carried out. The heat transfer coefficients on the cold side were correlated with Reynolds numbers. The heat transfer coefficients were then related to the quality for identical Reynolds numbers. The two-phase multiplier (φ_L) based on heat transfer coefficients of pure fluid and two-phase mixture correlated well with the Lockhart – Martinelli Parameter (L – M Parameter $-\chi_{tt}^2$). This enables prediction of the two-phase, service side coefficients (for the range of Reynolds numbers studied) using single-phase data. The predicted coefficients showed a variance of ± 10 % over the experimental values for the Laminar flow range.

MATERIALS AND METHODS

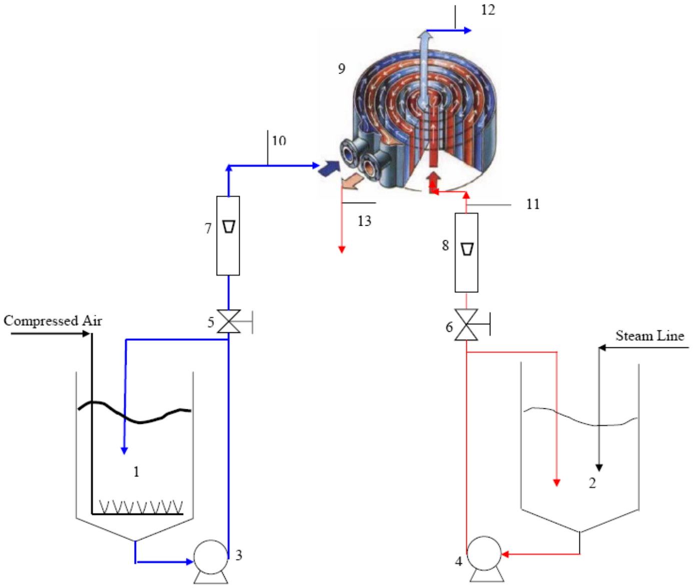
The heat exchanger dimensions are given in Table 1. The experimental setup is illustrated in Figure 1.

The service fluid used was water, heated in a stainless steel vessel by steam purging. A temperature controller was used to maintain the inlet temperature to the heat exchanger. The process fluid was stored in a separate stainless steel tank. Weighed quantities of food grade palm oil and demineralized water were charged into this tank to obtain the experimental range of mass fractions of palm oil (0% to 100%). Agitation in the tank was maintained by air bubbling. Two fractional horsepower centrifugal pumps were used for the circulation of the two streams of fluids. The two phase side rotameter was calibrated for each experimental mass fraction before the experimental run. Online, calibrated Resistance Temperature Detectors (RTDs) with digital indicators were used for the temperature measurements of the inlet and outlet streams of the service and process fluids.

The service fluid side inlet temperature and flow rate were kept steady. The two phase side flow rate was varied and for each selected flow rate observations of all four temperatures and two flow rates were recorded after steady state was reached. Experimental runs with pure liquids in the process side (water, palm oil) were also carried out. Fouling possibilities were eliminated by cleaning both process side and service side with hot water before each run. This was accomplished by pumping hot, mild detergent solution on both the process and service side followed by rinse pumping with pure hot water.

Table 1: Details of the Spiral Plate Heat Exchanger

Exchanger Details	Value
Channel size, (w x b), m	0.005 x 0.205
Plate thickness, m	0.00063
Flow Length, (L), m	10.926
Heat Transfer Area, m^2	2.24



1. Cold fluid tank
2. Hot water tank
3. Pump for cold fluid
4. Pump for hot water
5. Valve for cold fluid
6. Valve for hot water
7. Flow meter for cold fluid
8. Flow meter for hot fluid
9. Spiral heat exchanger
10. 11. 12. 13. RTDs for cold fluids inlet, hot water inlet, cold fluids outlet, hot water outlet

Figure 1: Schematic Diagram of the Experimental Setup

CALCULATION METHODOLOGY

a) The following basic relations were used for calculating the overall heat transfer coefficients and individual heat transfer coefficients on the single phase and two phase sides.

$$Q = M_h\ Cp_h\ (\Delta T\ )_h \tag{1}$$

$$U = Q\ /\ A\ (\Delta T)_{lm} \tag{2}$$

$$Nu = 2.0\ Gz^{0.33} \tag{3}$$

This correlation between Nusselt Number (Nu) and Graetz Number (Gz) is adopted from equation 12.25 in the book of McCabe et al. (2001)

$$Nu = h_h d_e / k_h \tag{4}$$

$$Gz = M_h\ Cp_h\ / k_h\ L \tag{5}$$

$$1\ /\ U = 1\ /\ h_h\ + t\ /\ k_{ss}\ + 1\ /\ h_{2Ø} \tag{6}$$

b) The Quality Parameter X is defined as

$$X = \frac{1}{1+\rho_w Q_w / \rho_f Q_f} \tag{7}$$

c) The Lockhart Martinelli (L – M) Parameter (χ_{tt}^2) is defined as

$$\chi_{tt}^2 = \left(\frac{1-X}{X}\right)^{2-m}\left(\frac{\rho_f}{\rho_w}\right)\left(\frac{\mu_w}{\mu f}\right)^m \tag{8}$$

d) The factor m is obtained from the correlation

$$h = aRe^m \tag{9}$$

e) The two phase multiplier $Ø_L$ is defined as

$$Ø_L = h_{2Ø}\ /\ h_{1Ø} \tag{10}$$

RESULTS AND DISCUSSION

Single Phase Results

The experimental results of single phase studies are presented in the form of a plot between Reynolds Number and $h_{1\varphi}$ in Figure 2. Re and $h_{1\varphi}$ were correlated by regression analysis in the form given in equation 9 and the values of a and m are given in Table 2.

Two Phase Results

Two phase studies were carried out with different mass fractions of palm oil in water (20%, 40%, 60%, and 80%). The experimental values of the inlet and outlet temperatures of the hot and cold fluids and the corresponding Re values are provided in Table 3.

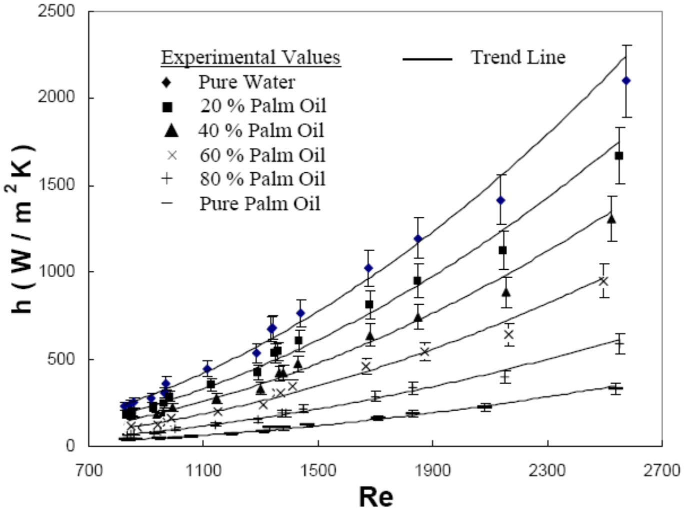


Figure 2: Variation of Heat Transfer Coefficient with Re for Water-Palm Oil System

Table 2: Correlation Constants a and m for Water - Palm Oil system

Palm Oil (%)	a	m
0	0.0004	1.9696
20	0.0003	1.9696
40	0.0002	2.0084
60	0.0001	2.0238
80	0.00008	1.991
100	0.00004	2.0518

Table 3: Experimental values of the inlet and outlet temperatures of the hot and cold fluid

100% Palm Oil

Sl.No	T_{h1} K	T_{h2} K	Re of Hot Water	T_{c1} K	T_{c2} K	Re of Cold Fluid
1	334	333	3401	303	333	833
2	334	332	3401	303	325	845
3	334	332	3401	303	325	862
4	334	332	3401	303	327	945
5	334	332	3401	303	329	1003
6	334	331	3350	303	324	1057
7	334	331	3350	303	328	1197
8	334	329	3302	303	319	1310
9	334	328	3302	303	319	1330
10	334	329	3302	303	325	1379
11	334	329	3302	303	327	1461
12	334	327	3257	303	325	1607
13	334	326	3257	303	324	1829
14	334	323	3159	303	317	2150
15	334	321	3127	303	316	2527

80 % Palm Oil

Sl.No	T_{h1} K	T_{h2} K	Re of Hot Water	T_{c1} K	T_{c2} K	Re of Cold Fluid
1	335	333	5449	303	328	833
2	335	333	5449	303	328	852
3	335	332	5361	303	319	869
4	335	332	5361	303	322	936
5	335	331	5361	303	315	952
6	335	331	5361	303	321	1009
7	335	330	5282	303	318	1147
8	335	329	5282	303	317	1293
9	335	328	5205	303	320	1376
10	335	327	5205	303	314	1390
11	335	327	5205	303	317	1449
12	335	325	5136	303	318	1719
13	335	323	5056	303	313	1824
14	335	321	4979	303	311	2157
15	335	321	4890	303	308	2549

60% Palm Oil

Sl.No	T_{h1} K	T_{h2} K	Re of Hot Water	T_{c1} K	T_{c2} K	Re of Cold Fluid
1	334	332	7062	303	329	842
2	334	331	6958	303	322	879
3	334	331	6958	303	323	853
4	334	330	6958	303	317	946
5	334	330	6958	303	320	975
6	334	329	6856	303	317	990
7	334	328	6856	303	315	1152
8	334	327	6765	303	317	1309
9	334	327	6765	303	323	1357
10	334	326	6765	303	318	1365
11	334	325	6660	303	317	1411
12	334	323	6559	303	318	1669
13	334	321	6461	303	313	1874
14	334	320	6461	303	314	2169
15	334	317	6402	303	312	2482

Continuation Table 3

40 % Palm Oil						
Sl.No	**T_{h1} K**	**T_{h2} K**	**Re of Hot Water**	**T_{c1} K**	**T_{c2} K**	**Re of Cold Fluid**
1	334	332	8822	304	330	839
2	334	331	8693	304	324	860
3	334	330	8693	304	316	855
4	334	329	8565	304	310	935
5	334	330	8693	304	321	962
6	334	329	8565	304	320	995
7	334	328	8565	304	319	1146
8	334	327	8541	304	319	1299
9	334	326	8541	304	319	1366
10	334	325	8320	304	316	1380
11	334	324	8320	304	315	1429
12	334	322	8194	304	314	1683
13	334	320	8071	304	312	1850
14	334	319	7951	304	312	2157
15	334	316	7876	304	310	2507
20 % Palm Oil						
Sl.No	**T_{h1} K**	**T_{h2} K**	**Re of Hot Water**	**T_{c1} K**	**T_{c2} K**	**Re of Cold Fluid**
1	337	334	10984	302	329	833
2	337	333	10984	302	323	851
3	337	333	10984	302	324	856
4	337	332	10817	302	319	927
5	337	332	10817	302	322	964
6	337	331	10817	302	321	983
7	337	330	10643	302	321	1130
8	337	329	10643	302	321	1293
9	337	328	10486	302	323	1351
10	337	327	10486	302	320	1361
11	337	326	10333	302	319	1434
12	337	325	10333	302	324	1618
13	337	323	10195	302	321	1850
14	337	320	9885	302	316	2146
15	337	317	9711	302	314	2523

Figure 2 also presents the two phase experimental heat transfer coefficients, $h_{2\varphi}$ as a function of Re. For the two phase system, Re is based on the weighted average thermo-physical properties of the fluids at the respective mean bulk temperatures. It is seen that the two phase data falls in between the values for the single phase. These data are fitted by regression to the correlation given in equation 9 and the values of a and m are given in Table 2. The calculated values of $h_{2\varphi}$ based on these constants agreed with the experimental data with an error of ± 15 % as shown in the trend lines in Figure 2.

The experimental data shown in figure 2 is used to calculate the values of the two phase multiplier (φ_L) and the L – M parameter (χ_{tt}^2).

Figures 3, 4 and 5 present the relations φ_L Vs X, χ_{tt}^2 Vs X and χ_{tt}^2 Vs φ_L respectively.

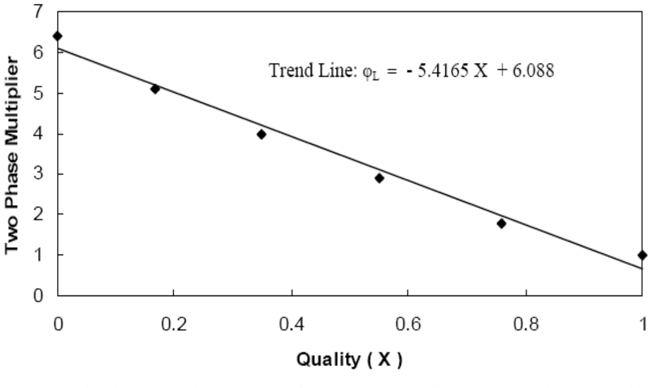


Figure 3: Variation of the Two Phase Multiplier (φ_L) with Quality (X)

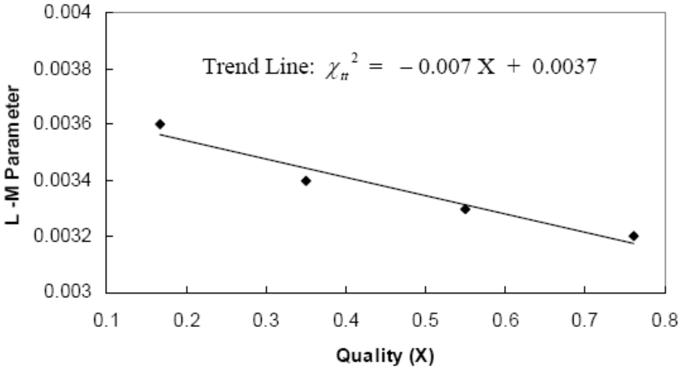


Figure 4: Variation of L – M Parameter (χ_π^2) with Quality (X)

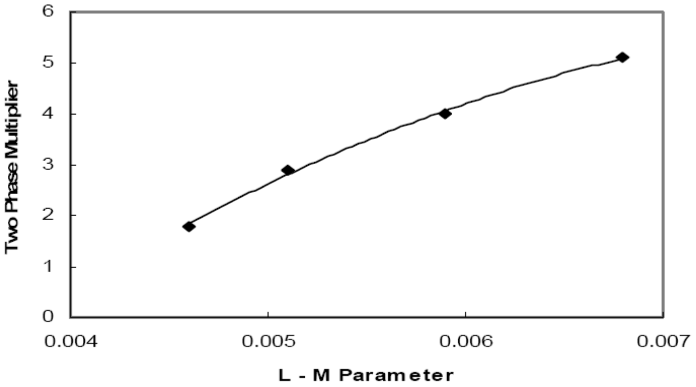


Figure 5: Variation of the Two Phase Multiplier (φ_L) with L - M Parameter (χ_π^2)

The variation of φ_L with χ_{tt}^2, shown in Figure 5 is represented by equation 11.

$$\varphi_L = -0.163 + \frac{3}{\chi_{tt}} - \frac{0.163}{\chi_{tt}^2} \quad (11)$$

The Correlation coefficients (R^2) for the trend equations in Figures 3, 4 and 5 are given in Table 4.

The experimental heat transfer coefficients ($h_{2\varphi}$) and their corresponding calculated values based on equation 11 for different quality values (X) and Reynolds Numbers and the corresponding % error are given in Table 5. It is seen from this Table that the error ranges between ± 10 % for the laminar range. The results were re-ascertained by conducting validation runs.

Equation 11 can also be rewritten as

$$\varphi_L = 1 - \frac{18.4}{\chi_{tt}} + \frac{1}{\chi_{tt}^2} \quad (12)$$

where φ_L' is the modified two phase multiplier for water – palm oil system. This modified two phase multiplier is expressed as

$$\varphi_L' = -\frac{\varphi_L}{0.163} \quad (13)$$

Equation 12 is of the form

$$\varphi_L = 1 + \frac{C}{\chi_{tt}} + \frac{1}{\chi_{tt}^2} \quad (14)$$

suggested by Chisholm and Laird (1958) .The value of C is - 18.4 for water - palm oil two phase system.

Table 4: Correlation Coefficients

Trend Line Equation	Correlation Coefficient (R^2)	Reference
$\varphi_L = 5.4165X + 6.088$	0.945	Figure 3
$\chi_{tt}^2 = -0.007X + 0.0037$	0.9542	Figure 4
$\varphi_L = -0.163 + \frac{3}{\chi_{tt}} - \frac{0.163}{\chi_{tt}^2}$	0.9515	Figure 5 (Equation 11)

Table 5: Experimental and Calculated Heat Transfer Coefficients for Water – Palm Oil System

Re	$h_{2\varnothing}$ for 20 % Palm Oil (W/m^2 K)		
	Experimental	**Calculated**	**% Error**
833	182.3	172.8	+ 5.2
983	284.6	306.2	- 7.6
1680	812.2	761	+ 6.3
2146	1125.9	1022.3	+ 9.2
2461	1304.1	1159.3	+ 11.1
Re	**$h_{2\varnothing}$ for 40 % Palm Oil (W/m^2 K)**		
	Experimental	**Calculated**	**% Error**
860	150	158.3	- 5.5
995	223.2	217	+ 2.8
1683	637	655.5	- 2.9
2157	883	946.6	- 7.2
2579	1111.4	1248.1	- 12.3
Re	**$h_{2\varnothing}$ for 60 % Palm Oil (W/m^2 K)**		
	Experimental	**Calculated**	**% Error**
845	103.7	97.2	+ 6.3
990	161.8	165.7	- 2.4
1666	461.8	456.3	+ 1.2
2165	640.2	697.2	- 8.9
2523	752.0	828.7	- 10.2
Re	**$h_{2\varnothing}$ for 80 % Palm Oil (W/m^2 K)**		
	Experimental	**Calculated**	**% Error**
833	64.3	60.4	+ 6.0
1000	100.4	92.7	+ 7.7
1830	335.3	319.2	+ 4.8
2150	397.4	407.3	- 2.5
2557	481.3	449.7	+ 6.5

CONCLUSION

Two phase flow studies were conducted in a spiral plate heat exchanger using water – palm oil system. Heat transfer coefficients were related to the quality of the two phase systems. The correlations between quality (X), φ_L and L – M parameter show a good agreement with experimental data. This correlation can be used for the prediction of two phase heat transfer coefficients and are useful in the design of heat exchangers for two phase duties in the Re and temperature ranges investigated. The validation experimental runs have demonstrated the reliability range of this correlation. Further work at higher Re and for different two phase systems is in progress in this laboratory.

NOMENCLATURE

a	Experimental correlation constant	(-)
b	Channel height	m
Cp_h	Specific heat of hot fluid	J/kg K
d_e	Equivalent diameter of the flow channel	m
h_h	Heat transfer coefficient on hot fluid side	W/m^2 K
$h_{1\varnothing}$	Heat transfer coefficient of pure palm oil	W/m^2 K
$h_{2\varnothing}$	Heat transfer coefficient of palm oil – water mixture	W/m^2 K
k_h	Thermal Conductivity of hot fluid	W/m K
k_{ss}	Thermal conductivity of the wall	W/ m K
L	Length of the Flow Channel	m
M_h	Mass flow rate of hot fluid	kg/s
m	Experimental correlation constant	(-)
Q	Heat transferred	W
Q_f	Volumetric Flow rate of palm oil	kg/s
Q_w	Volumetric Flow rate of water	kg/s
T_{h1}	Inlet Temperature of water	K
T_{h2}	Outlet Temperature of water	K
T_{c1}	Inlet Temperature of palm oil	K
T_{c2}	Outlet Temperature of palm oil	K
t	Wall thickness of the spiral	m

	plate	
U	Overall heat transfer coefficient	W/m^2 K
w	Channel width	m
X	Quality	(-)

Greek Letters

$\O_L$	Two Phase Multiplier	(-)
ρ_f	Density of palm oil	kg/m^3
ρ_w	Density of water	kg/ m^3
μ_f	Viscosity of palm oil	kg/ms
$\chi_{tt}{}^2$	Lockhart Martinelli parameter	(-)
$(\Delta T)_h$	Temperature drop of hot fluid	K
$(\Delta T)_{lm}$	Logarithmic Mean Temperature	(-)
	Difference between hot and cold fluid	K

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