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HEAT TRANSFER TO IMMISCIBLE LIQUID MIXTURES IN A SPIRAL PLATE HEAT EXCHANGER

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Abstract - This work presents new predictive correlations for heat transfer to immiscible liquid-liquid mixtures in a spiral plate heat exchanger. Liquid-liquid heat transfer studies were carried out in spiral plate heat exchangers for the water-octane, water-kerosene, and water-dodecane systems. For each composition of the mixture, the mass flow rate of the cold fluid was varied, keeping that of the hot fluid and the fluid inlet temperatures constant. Two-phase cold flow rates were in the laminar range, while the hot fluid flow was turbulent. Calculations of the LMTD (log mean temperature difference) correction factor showed that the flow was countercurrent. Heat transfer coefficients of the two-phase liquids were found to be strongly dependent on the composition of the liquid mixture and exhibited abrupt transitions as a function of the compositions. Given the absence of predictive correlations in the literature that sufficiently capture this composition-dependence, new empirical correlations were developed using part of the experimental data, with the composition of the cold fluid as an explicit variable. Statistical analysis of the regression yielded satisfactory results. The correlations were tested against the rest of the experimental data and were found to predict heat transfer coefficients within ± 15%. These preliminary studies should be useful in designing compact exchangers for handling two-phase water-organics mixtures.

Keywords: Liquid-Liquid mixture; Spiral plate heat exchanger; Countercurrent flow; Composition dependence; Two-phase heat transfer coefficient.

INTRODUCTION

Spiral plate heat exchangers have evinced significant interest owing to their compact size, large heat transfer surface area per unit volume, high heat transfer rates, lower fouling, operational flexibility and ease of maintenance. Multiphase flow involving liquid-liquid systems is encountered in an increasing number of important applications such as petroleum and petrochemicals, metal processing and other industries (Burmeister, 2006). Considerable research is being pursued in two-phase flow particularly in the area of fluid dynamics. However, there are few studies on heat transfer to liquid-liquid two-phase systems, especially after the 1970's. Further, most of the earlier studies were on direct-contact heat

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*To whom correspondence should be addressed transfer to a cold liquid by contacting a hot liquid (see below). Thus, there is a strong need for understanding fluid flow behavior and heat transfer to liquid-liquid two-phase mixtures in heat exchangers. A good understanding of the rates of momentum and heat transfer for liquid-liquid multiphase flow systems is a must for the optimal design of heat exchangers for such systems.

Experimental Studies on Liquid-Liquid Two-Phase Flows

There have been a number of studies involving oil-water two-phase flows in the literature. While reviewing them is not the focus of this work, a few representative works are discussed to illustrate the salient features of such flows. Trallero (1995) identified flow patterns for oil-water flows in horizontal pipes and developed a liquid-liquid flow pattern prediction model. Among the organic phases studied in the literature are kerosene (Zhao *et al*., 2006; Huang *et al*., 2007), Exxsol D140 (Lum *et al*., 2004; Lum *et al*., 2006), Exxsol D60 (Kumara *et al*., 2009), cyclohexane (Kashid and Agar, 2007), MACROL82 mineral oil (Salim *et al*., 2008), glycerine-water mixture (Lozano *et al*., 2008), diesel (Rodriguez and Oliemans, 2006) and Shell Vitrea 10 (Xu *et al*., 2010). Tap water and brine have been used as the aqueous phase. The flow regimes identified include smoothly stratified/parallel flow, wavy stratified flow, annular flow, three-layer flow, dispersed oil-in-water flow, dispersed water-in-oil flow, slug flow, monodispersed droplets flow, and droplets population flow. Generally, smoothly stratified flow is observed at low fluid velocities and gives rise to other flow patterns, depending on the relative fluid velocities, inclination or curvature, roughness, and the choice of the first liquid injected in the case of microchannels. In addition to flow patterns, pressure drop and water holdup (composition) have also been measured. The general observation has been that oil travels faster than water at most input compositions and velocities. The pressure gradient is found to be independent of composition and inclination reduced the pressure gradients. Further, two-phase pressure gradients are found to be lower than that of either single phase.

Heat Transfer to Liquid-Liquid Mixtures

One of the earliest studies on heat transfer to liquid-liquid mixtures was by Grover and Knudsen (1955), who observed that the overall heat transfer coefficient depended on the total mass flow rate but was independent of dispersed-phase volume fraction and inlet temperature. Gollan and Sideman (1970) measured the heat transfer coefficients for stratified laminar flow down an inclined plane to be of the order of 280 W/m^2-K. Somer *et al*. (1973) studied heat transfer to an immiscible liquid mixture for desalination of sea water, with the mineral oil Energol WM-2. They studied three regimes, namely, heat transfer to individual water drops, heat transfer to immiscible liquids in cocurrent turbulent flow without phase change, and heat transfer to immiscible liquids in cocurrent laminar and turbulent flow with evaporation of water. In the second regime, relevant to the present study, they measured the pressure drop and estimated the Fanning friction factor, and fit a correlation between Nusselt Number, Reynolds Number and Prandtl Number. However, they did not consider the effect of composition of the oil-phase on heat transfer in developing the correlation, despite observing that the dimensionless heat transfer coefficient of the mixture depended on the composition, in the form of the fraction of the surface area covered by oil. Comparisons with other published correlations revealed that there were large errors in predictions for the water-Energol WM-2 system. These results were observed for oil-in-water dispersions. They also examined water-in-oil systems (where the oil volume fraction was greater than 0.5), where they observed oil and water flowing as separate phases irrespective of composition or velocity. In this case, they could not observe any satisfactory correlation for the friction factor or heat transfer coefficient. Lang and Auracher (1996) studied the phase distribution and heat transfer in n-heptane-water mixtures flowing upward in a vertical tube, for different volumetric fractions of n-heptane, inlet velocities and inlet temperatures. An abrupt change in the heat transfer was observed from water-dominated heat transfer to n-heptane-dominated heat transfer at n-heptane volume fractions between 0.6 and 0.7. They developed a volumetric-fraction-based linear mixing rule to predict the two-phase heat transfer coefficient from single-phase data. On the other hand, using different mixing rules to treat the two-phase mixture as a single phase and using pure-fluid correlations gave poor results.

Heat transfer to liquid-liquid mixtures has received renewed interest in the context of enhancement of heat transfer in microreactors and micro-transport systems, and in the context of direct-contact heat transfer. While these are also not the focus of present work, a few representative works are discussed below for the insight they provide on liquid-liquid flow and heat transfer enhancement due to the flow patterns observed. Habchi and coworkers (Habchi *et al*., 2009; Habchi *et al*., 2009) examined liquid-liquid dispersion, droplet formation and breakup, and direct-contact heat transfer between immiscible liquids by facilitating mixing in straight flow, helically-coiled flow and twisted-pipe flow (chaotic advection) and in a high-efficiency vortex static mixer (Lemenand *et al*., 2010). Commercial-grade vegetable oil (Habchi *et al*., 2009; Habchi *et al*., 2009) and vaseline oil (Lemenand *et al*., 2010) were used as the organic phase. Chaotic advection generated in twisted pipe produced smaller and more homogeneous droplets than a helically coiled mixer. Simulations showed that chaotic advection caused fluid particles to randomly encounter zones of high shear and elongation rates, causing further breakup of droplets (Habchi *et al*., 2009). By introducing n-butanol in calculated quantities to modify the organic phase, it was observed that the reduction of continuous phase viscosity intensified the emulsification process, and enhanced mass transfer as well as providing a smaller droplet size distribution than in regular Dean flow. A phenomenological model for heat transfer was validated with experimental data (Lemenand *et al*., 2010) and longitudinal embedded vorticity was identified as the main intensification factor for heat transfer. Finally, using a microdispersion contactor, Wang *et al*. (2008) studied heat transfer microdispersing hot octane and hexane into cold water, by cross flow of the oil phase into water through a membrane. Significant enhancement in heat transfer was observed due to dispersion with up to a 15-20 increase in the volumetric heat transfer coefficients compared to a conventional dispersed system.

Heat Transfer in Spiral Heat Exchangers

Heat transfer in spiral exchangers and sizing methodologies for single-phase systems have been discussed in detail in the literature. Minton (1970) and Martin (1992) proposed correlations for heat transfer coefficients, friction factor and pressure drop, and presented algorithms for designing spiral heat exchangers. Picon-Nunez *et al*. (2007; 2009) developed a rapid design methodology for spiral plate heat exchangers on the basis of full utilization of pressure drop and heat utilization. Plate width and plate spacing are determined, and the final exchanger dimensions are then matched to standard dimensions. The approach uses empirical correlations for calculation of the heat transfer coefficients and friction factor based on the average curvature of the exchanger. Yan *et al*. (2008) examined design and economic analysis of three compact exchangers, viz., plate-fin, plate, and spiral plate heat exchangers. The criterion for optimization is minimum pressure drop for a given capacity. Material purchasing, equipment abrasion, and power consumption have also been studied. From an energetic point of view, all compact exchangers were found to be feasible.

Other similar compact geometries have also been examined: for instance, Adamski (2009) developed correlations to predict heat transfer coefficients and the Fanning friction factor for air flowing through a longitudinal flow spiral recuperator. He also examined the thermal efficiency of the exchanger. Naphon and Wongwises (2006) reviewed heat transfer and fluid flow studies in helically, spirally and otherwise coiled tubes and summarized predictions of single-phase heat transfer coefficients and friction factors in both single- and two-phase flows. They (Naphon and Wongwises, 2002; Naphon and Suwagrai, 2005; Naphon and Suwagrai, 2007) studied heat transfer with air/water mixtures in spirally coiled tubes of different curvature ratios under cooling and dehumidifying conditions; with constant wall temperature and constant radius the temperature profiles, heat transfer rate, heat transfer coefficients, and pressure drops were examined. These studies demonstrated an enhancement in the heat transfer and flow due to the effects of centrifugal force, and they proposed useful empirical correlations.

In some preliminary work, we studied heat transfer to dodecane-water mixtures (Ramachandran *et al*., 2006), palm oil-water mixtures (Ramachandran *et al*., 2008), nitrobenzene-water mixtures (Sathiyan *et al*., 2010) and diesel-water mixtures (Sathiyan *et al*., 2011) in spiral plate heat exchangers. Extending these studies, in this work, experiments have been conducted in a spiral plate heat exchanger with hot water as the hot fluid and immiscible two-phase mixtures of water and octane, kerosene and dodecane (any one) in different ratios and flow rates as the cold fluid. Experimental runs with single-phase fluids on the cold side have also been carried out. The heat transfer coefficients on the cold side (with two-phase flow) have been correlated with an average Dean Number, Prandtl Number and the composition of the immiscible mixtures. We show that, even with using linear mixing rules for all properties, by explicitly capturing the dependence of the heat transfer coefficient on the mixture composition, it is possible to predict the heat transfer behavior in liquid-liquid mixtures with good accuracy.

EXPERIMENTAL

The experimental setup consists of a spiral heat exchanger (Type LV, obtained from Alfa Laval, Pune, India), resistance temperature detectors (RTD), a rotameter, control valves, pumps and tanks as shown in Figure 1. The dimensions of the heat exchanger are given in the Table 1. The heating fluid used was demineralized water, heated in a stainless steel vessel by direct steam injection and agitated to maintain a uniform temperature. The cold fluid was stored in a different stainless steel tank. Weighed quantities of the organic phase (octane, kerosene, or dodecane) and demineralized water were charged into this tank to obtain the experimental range of mass fractions. The pure organic fluids (octane and dodecane) were of analytical reagent grade. Kerosene was obtained commercially as a blend. Agitation in the tank was maintained by bubbling air. Hot fluid was introduced into the center of the exchanger while the cold fluid was introduced from the outer radius. The flow through the heat exchanger was principally countercurrent, as established from the LMTD correction factor calculations. Two centrifugal pumps were used for circulation of the hot and cold fluid streams and the flow rate measured using calibrated rotameters. Online, calibrated resistance temperature detectors with digital indicators were used for the temperature measurements of the inlet and outlet streams of the hot and cold fluids.

The hot water inlet temperature and flow rate were kept steady. The two-phase side flow rate was varied, and for each flow rate, observations of all four temperatures and two flow rates were recorded after the steady state was reached. Experimental runs with pure liquids in the cold side were also carried out. Fouling possibilities were minimized by cleaning both cold side and hot side with hot water before each run.

Table 1: Dimensions of the spiral plate heat exchanger

Exchanger Details	Value
Flow length, m	10.926
Heat transfer area, m^2	2.24
Plate width, m	0.205
Plate spacing, m	0.005
Plate thickness, m	0.00063
Material of construction	SS 316

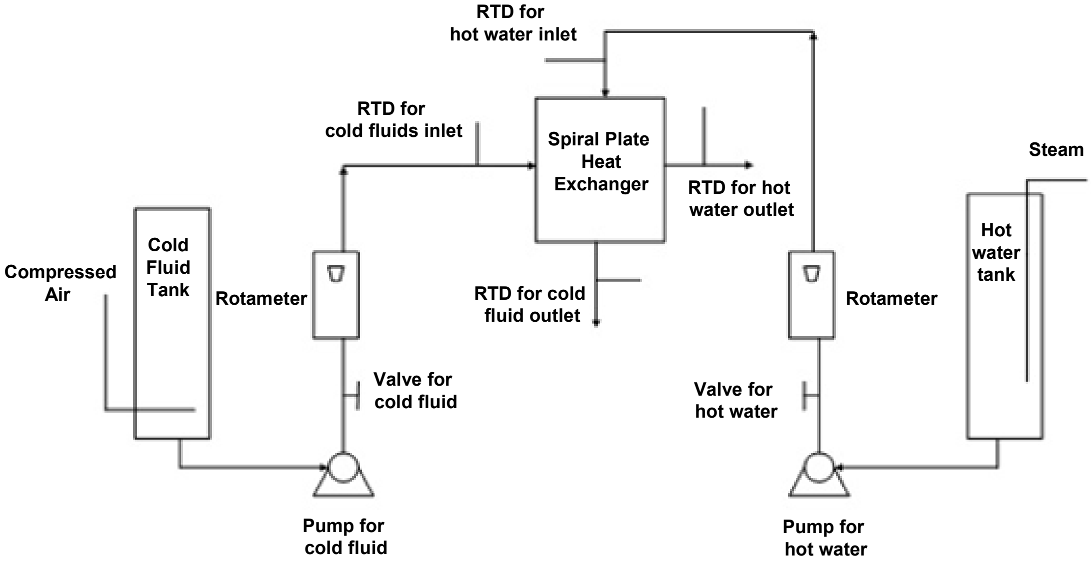

Figure 1: Schematic representation of the experimental apparatus

CALCULATION METHODOLOGY

Overall Heat Transfer Coefficient

The heat load was calculated using the expression

$$Q = M_{hf} Cp_{hf} \left(\Delta T\right)_{hf} = M_{cf} Cp_{cf} \left(\Delta T\right)_{cf} \qquad (1)$$

Using the heat load obtained from Equation (1), the overall heat transfer coefficient was obtained from the relation:

$$U = \frac{Q}{FA\left(\Delta T\right)_{lm}}. \qquad (2)$$

Here, F denotes the logarithmic mean temperature difference correction factor that accounts for differences arising from non-countercurrent operation. LMTD calculations using the model of Bes and Roetzel (1993) showed that this correction factor was very close to unity.

Nusselt Number and Heat Transfer Correlations

The hot fluid side heat transfer coefficient (h_h) was calculated using a correlation given in Perry *et al.*, (1998) rewritten to use Dean Number in place of Reynolds Number:

$$Nu = 0.104(De)^{0.8}(Pr)^{0.25}\left({}^{\mu}\!\big/_{\mu_{wl}} \right)^{0.17} \qquad (3)$$

where, Nu is the Nusselt Number given by:

$$Nu = \frac{h_{hf} d_e}{k_{hf}}, \qquad (4)$$

and the Dean Number used is computed for the average curvature of the spiral heat exchanger, in the absence of local curvature measurements, along the lines of Naphon and Wongwises (2002):

$$De = Re\sqrt{\frac{d_e}{d_{c,avg}}}, \qquad (5)$$

where d_e is the equivalent diameter, defined as:

$$d_e = \frac{2pW}{p+W}, \qquad (6)$$

where p and W are the plate width and plate spacing, respectively. The denominator of Equation (5), $d_{c,avg}$ is the average diameter of curvature of the spiral, given by the average of the minimum and the maximum diameters of the spiral in the exchanger $\left(d_{min} + d_{max}\right)/2$. In Equation (3), the term $\left(\mu / \mu_{wl}\right)^{0.17}$ is the Sieder-Tate correction factor to account for the evaluation of the Dean and Prandtl Numbers at the bulk temperature rather than at local temperatures. This effect is significant only when the temperature differences are large. For the conditions in our experiments, they are negligible and hence are not used.

The cold fluid side (two-phase side) heat transfer coefficient ($h_{2\phi}$) was then estimated from the overall heat transfer coefficient using

$$\frac{1}{U} = \frac{1}{h_{hf}} + \frac{t}{k_{ss}} + \frac{1}{h_{2\phi}}. \qquad (7)$$

The corresponding Nusselt Number of the two-phase cold fluid from Equation (7) (obtained from experiments, denoted as $Nu_{experimental}$) was estimated using the expression:

$$Nu_{experimental} = \left(h_{2\phi}\right)\left(\frac{d_e}{k}\right)_{cold\ side}. \qquad (8)$$

In developing predictive correlations for the cold-side two-phase heat transfer coefficient, the relevant variables are the following: $h_{2\phi}$, d_e, $k_{2\phi}$, $\rho_{2\phi}$, $\nu_{2\phi}$, $\mu_{2\phi}$, $Cp_{2\phi}$, and X. There are eight variables and four fundamental dimensions. Therefore, the number of dimensionless groups involved is four. They are the Nusselt Number (Nu), Dean Number (De), Prandtl Number (Pr), and the dimensionless composition, viz., mass fraction (X). Therefore, the general form of the correlations developed was:

$$Nu_{predicted} = a(De)^b (Pr)^c (X)^d, \qquad (9)$$

where, a, b, c and d are constants obtained from linear regression using Excel®.

Thermophysical and transport properties of the pure substances were calculated based on the correlations given in Yaws (1999). All two-phase properties were obtained using a linear mixing rule. It is important to note that the heat transfer coefficients measured and correlated are average values for the entire exchanger. Local coefficients are influenced by curvature and variations in composition, among other parameters. These effects are not considered in the present work.

RESULTS AND DISCUSSION

Single-Phase Results

The experimental results of single-phase studies are presented in the form of a plot between Dean Number and $h_{1\phi}$ in Figure 2. Re and $h_{1\phi}$ were correlated along with two-phase data by regression analysis. For single-phase systems, the mass fraction is equal to one and the correlation in Equation (3) reduces to: Nu = a $(De)^b$ $(Pr)^c$, with the constants shown in Table 2. For pure water, Equation (3) was used to predict $h_{1\phi}$. Results for the exchanger effectiveness are presented and discussed with two-phase systems.

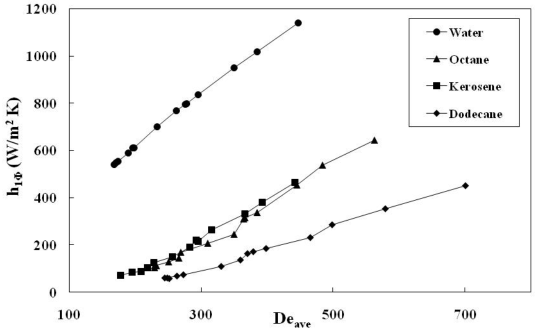

Figure 2: Variation of the heat transfer coefficient with Dean Number for single phase systems.

Table 2: Correlation constants for two-phase systems

System	a	b	c	d
Octane - Water	1.87E-06	1.96	1.20	-0.22
Kerosene -Water	2.03E-05	1.95	0.61	-0.55
Dodecane – Water	4.15E-06	2.21	0.57	-0.63

Two-Phase Results

Two-Phase Heat Transfer Coefficients

Figures 3(a) through 3(c) represent the two-phase heat transfer coefficients, $h_{2\phi}$, as a function of the Dean Number, De, for various compositions. It is to be noted that the Dean number used in these results is that for average curvature of the exchanger. Further, for two-phase systems, the Dean Number was based on the weighted-average of the thermo-physical properties of the fluids at the respective mean bulk temperatures. It is seen that there is enhancement of the heat transfer coefficient in the two-phase systems compared to the single-phase organic liquid. This enhancement is seen to be up to seven times the single-phase heat transfer coefficient in the case of dodecane, similar to results observed in microchannels by Asthana *et al*. (2011) and Janes *et al*. (2010), particularly for segmented two-phase flow. With curved channels such as in spiral plate heat exchangers, changes in flow patterns from smoothly stratified flow to more mixed flow are expected at lower velocities, resulting in enhanced heat transfer even at low velocities. While this study does not examine flow profiles in the exchanger, all measurements were made at velocities much less than that corresponding to the critical Reynolds Number. The maximum flow rate studied corresponds to a Reynolds Number of 3221, whereas the critical Reynolds Number for the exchanger studied is 6412. Even considering effects of curvature, it is not very likely that the flow patterns in the exchanger are dispersed one-phase-in-another. Therefore, the observed enhancements in heat transfer are most likely due to mixing achieved in wavy stratified, annular, three-layer, or slug flows, with small amounts of dispersion, if any. Unlike the observation of Knudsen and Grover (1955), the overall heat transfer coefficient is a strong function of composition, as are the film coefficients on the hot and cold side. This is consistent with the results of Somer *et al*. (1973) and Lang and Auracher (1996). The values of the overall heat transfer coefficients ranged from about 50 to 1000 W/m^2-K, consistent with the observations of Gollan and Sideman (1970). To further examine the effects of the two-phase nature of the cold fluid on heat transfer, heat transfer coefficients of the two-phase mixtures were normalized with respect to those of pure water and pure organic phase as follows:

$$\alpha = \frac{h_{2\phi} - h_{1\phi,o}}{h_{1\phi,w} - h_{1\phi,o}}. \tag{10}$$

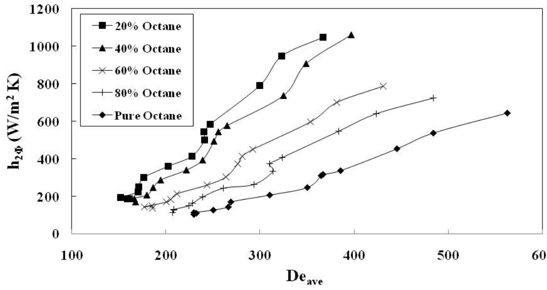

Figure 3(a): Variation of the heat transfer coefficient with Dean Number for the octane-water system.

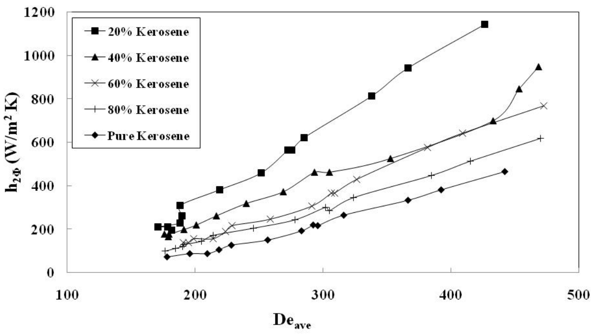

Figure 3(b): Variation of the heat transfer coefficient with Dean Number for the kerosene-water system.

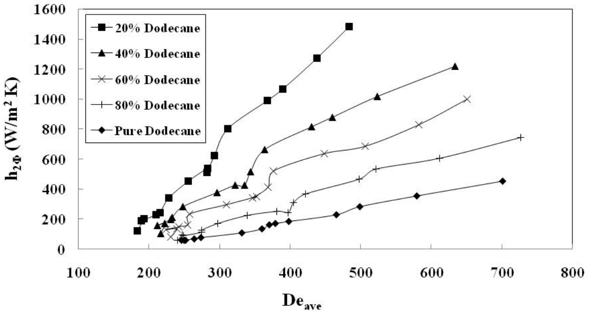

Figure 3(c): Variation of the heat transfer coefficient with Dean Number for the dodecane-water system.

For a fixed average inlet velocity of 0.15 m/s and an inlet temperature of 302 K, the behavior of the normalized heat transfer coefficient as a function of volume fraction of the organic phase is depicted in Figure 4.

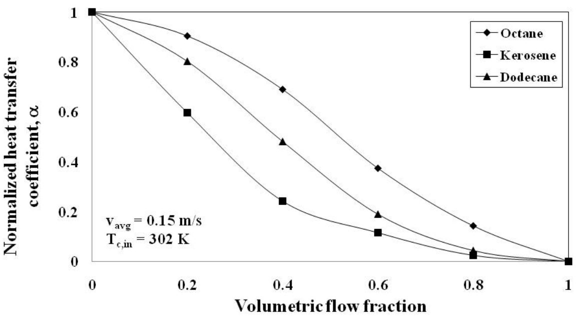

Figure 4: Variation of the normalized heat transfer coefficient with organic-phase volume fraction for all three systems.

Similar to the results of Lang and Auracher (1996) in turbulent flow, abrupt transitions in the heat transfer coefficients are observed even in laminar flow. This further underscores the influence of two-phase composition on heat transfer. It would be of interest to examine the possible relationship of the transitions of the heat transfer coefficients seen in Figure 4 with those in flow patterns in the liquid-liquid mixture. Also, it is seen that the heat transfer coefficient of kerosene is lower than that of octane and dodecane. This suggests that there may be interesting effects of blend composition on flow patterns and heat transfer, which merit further study.

Predictive Empirical Correlations

It is of interest to deduce predictive empirical correlations for heat transfer in two-phase liquid-liquid systems, which have value in the sizing of exchangers for handling two-phase liquid mixtures. For this purpose, the data were fitted by regression to Equation (9); the values obtained for a, b, c and d are given in Table 2. A statistical analysis was conducted to test the regression. The R^2 values for the three systems were found to be 0.9800, 0.9862 and 0.9365, respectively. Standard errors were found to be small. The statistical significance of the coefficients was tested by estimating the P-values, which indicated that the functional form chosen was appropriate. Residual analysis showed that the residuals obeyed a normal distribution. Only in the case of dodecane did there appear to be a possible non-random variation in the residuals vs. fitted value plot, indicating that there may be secondary, possibly flow-related, effects that were not captured by the correlation. However, since the R^2 of the fit is high, the correlation may still be used in a predictive manner. The results of statistical analysis for all three systems are compiled in Table 3 and the residual plots are in Figure 5. The correlations developed were then tested against new experimental data on the same systems. The calculated values of $h_{2\phi}$ based on these constants agreed with the experimental data within an error of ± 15%. The ranges of Dean Number and Prandtl Number for which the correlations are valid are given in Table 4. Similar to observations in other works (see, for example, Picon-Nunez *et al.*, 2009), correlations not developed for these fluids were uniformly poor at describing the experimental data. Deviations ranged from ± 25% to orders of magnitude. Even an attempt at deducing a single correlation for all three systems studied resulted in a poor fit. Based on our studies and other published results, it appears that the heat transfer coefficient in liquid-liquid two-phase systems depends significantly on the nature of the organic phase chosen. It is of interest to study this effect in more detail, for instance, by examining the dependence on the number of carbon atoms in the organic phase.

Table 3: Statistical analysis of regression in octane, kerosene and dodecane – water systems

S. No	System	P-values				R^2	S	n	σ
		a	B	C	d				
1	Octane-Water	8.19E-24	1.27E-24	1.06E-05	1.06E-06	0.9800	0.1008	35	0.5966
2	Kerosene-Water	1.34E-27	8.94E-30	1.50E-13	3.89E-12	0.9862	0.0745	35	0.4407
3	Dodecane-Water	1.49E-18	1.88E-22	0.0098	1.13E-05	0.9365	0.2103	39	1.3134

(S: Standard error; n: Number of observations; σ: Standard deviation)

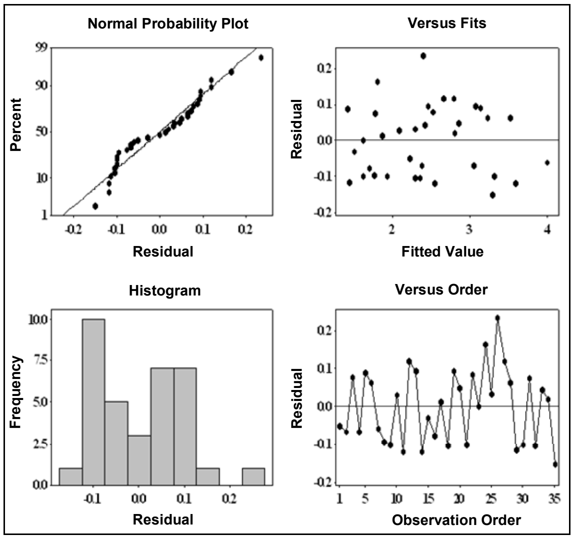

Figure 5(a): Residual plots for the octane-water system.

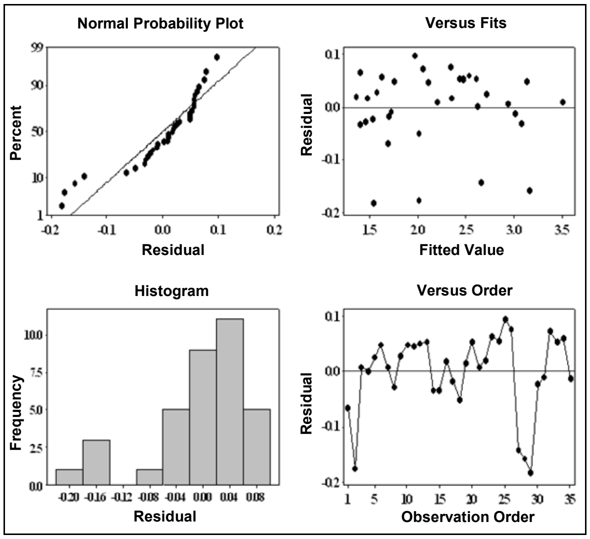

Figure 5(b): Residual plots for the kerosene-water system.

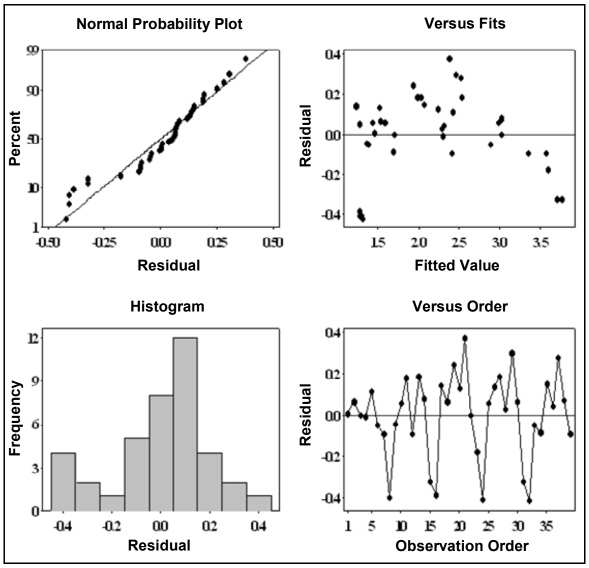

Figure 5(c): Residual plots for the dodecane-water system.

Table 4: Ranges of De and Pr

System	De_{ave}	Pr
Water	168 < De < 447	4.68 < Pr < 5.64
Octane - Water	152 < De < 562	4.98 < Pr < 7.90
Kerosene -Water	171 < De < 473	6.86 < Pr < 51.61
Dodecane - Water	183 < De < 727	5.49 < Pr < 18.96

Validity of the Correlations

Figures 6(a) through 6(c) show the comparison of the Nusselt Numbers obtained from the experiments, via Equation (8), with those calculated from the correlations, Equation (9).

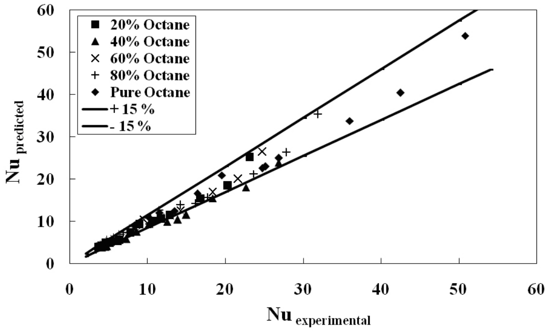

Figure 6(a): Comparison of Nu $_{\text{experimental}}$ with Nu $_{\text{predicted}}$ for the octane-water system.

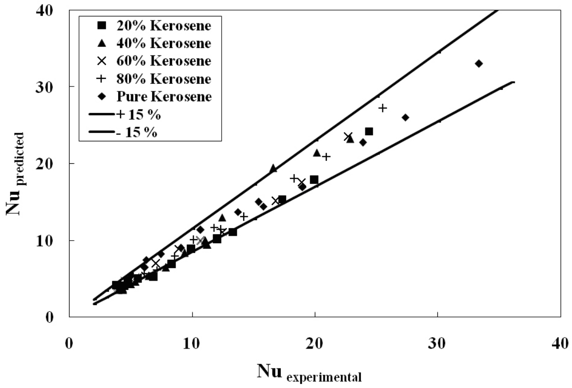

Figure 6(b): Comparison of Nu $_{\text{experimental}}$ with Nu $_{\text{predicted}}$ for the kerosene-water system.

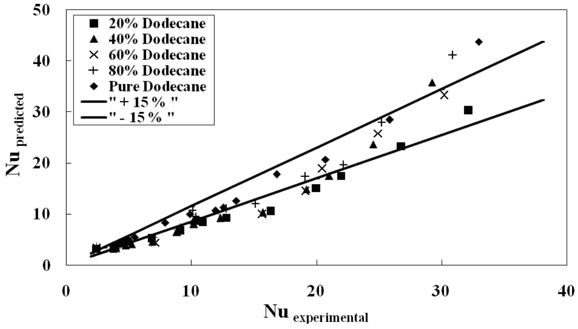

Figure 6(c): Comparison of Nu $_{\text{experimental}}$ with Nu $_{\text{predicted}}$ for the dodecane-water system.

The predicted Nusselt Numbers are within ± 15% of the experimental values. Observed discrepancies between the measured data and calculated results may be due to the uncertainties of the correlation and the approximation of only considering average properties of the two-phase mixture, thereby simplifying the functional form. The correlations seem to work best for low-molecular-weight non-polar hydrocarbon species. Correlations for octane and kerosene show the best results. Further studies are needed to develop better correlations for two-phase convective transfer of polar systems, aromatics, and highly viscous liquids.

It should be noted that the two-phase cold-fluid Nusselt Number is highly sensitive to errors in the prediction of the hot side heat transfer coefficient. Within the range and accuracy of the experimental data presented herein, if a correlation different than that given in Equation (3) were used to estimate the hot side heat transfer coefficient, different empirical correlations would result for the cold side Nusselt Number. Therefore, to use the correlations to predict two-phase heat transfer coefficients in these liquid-liquid systems, it is important to use Equation (8) to estimate the hot side heat transfer coefficient. In other words, Equation (3) and (9) together form a pair of correlations that can be used predictively.

Experimental determination of two-phase heat transfer coefficients and the development of predictive correlations are the first step towards initiating detailed studies on various aspects of liquid-liquid two-phase momentum and heat transfer, not limited to:

- Flow patterns in the two-phase mixtures;
- More appropriate definitions of the relevant dimensionless groups;
- Local heat transfer studies;
- Effects of curvature of the spiral plate heat exchanger on momentum and heat transfer in liquid-liquid two-phase mixtures.

These studies are expected to lead to better design capabilities for compact heat exchangers handling liquid-liquid two-phase mixtures.

CONCLUSIONS

Preliminary studies have been initiated on heat transfer in liquid-liquid two-phase mixtures of water and octane, kerosene or dodecane on the cold side of a spiral plate heat exchanger. The flow in the exchanger is determined to be largely countercurrent. Based on the inlet and the outlet temperatures and the flow rates of the hot and the cold streams, heat transfer coefficients have been estimated, and new correlations for liquid-liquid two-phase heat transfer have been developed, as an additional function of composition of the mixture. The heat transfer coefficient is a strong function of the composition of the two-phase mixture, exhibits abrupt transitions as the mixture composition varies, and is poorer in mixtures with more organic fluid. Regression analysis was performed and the resultant correlations faithfully reproduced the variations observed in the experiments, predicting the experimental heat transfer behavior within ± 15%.

NOMENCLATURE

A	area of heat transfer	m^2
p	plate spacing	m
Cp_h	specific heat	J/kg K
De	Dean Number	
d_e	equivalent diameter of the flow channel	m
F	logarithmic mean temperature difference correction factor	
h_h	heat transfer coefficient	W/m^2 K
$h_{1\phi}$	heat transfer coefficient	W/m^2 K
$h_{2\phi}$	heat transfer coefficient	W/m^2 K
k_h	thermal Conductivity	W/m K
k_{ss}	thermal Conductivity of the wall	W/m K
M_s	mass flow rate	kg/s
Nu	Nusselt Number	
Pr	Prandtl Number	
Q	heat transferred	W
Re	Reynolds Number	
t	wall thickness of the spiral plate	m
U	overall heat transfer coefficient	W/m^2 K
V	velocity of fluid flow	m/s
W	plate width	m
X	mass fraction of the organic component in the liquid-liquid two-phase mixture	

Greek Symbols

α	normalized heat transfer coefficient	
$(\Delta T)_h$	temperature drop of hot fluid	K
$(\Delta T)_c$	temperature drop of cold fluid	K
$(\Delta T)_{ln}$	logarithmic mean temperature difference between hot and cold fluid	K
μ	viscosity of fluid	kg/m-s
ρ	density of fluid	kg/m^3
ϕ	phase of liquid based on single and two-phase	

Subscripts

1ϕ	single-phase fluid
2ϕ	two-phase fluid
a,b,c,d	correlation coefficients
hf	hot fluid side
cf	cold fluid side
o	pure organic phase
w	pure water
wl	wall

REFERENCES

Adamski, M., Heat transfer correlations and NTU number for the longitudinal flow spiral recuperators. App. Therm. Eng., 29, 591-596 (2009).

Asthana, A., Zinovik, I., Weinmueller, C. and Poulikakos, D., Significant Nusselt number increase in microchannels with a segmented flow of two immiscible liquids: An experimental study. Int. J. Heat Mass Trans., 54, 1456-1464 (2011).

Bes, TH. and Roetzel, W., Thermal theory of the spiral heat exchanger. Int. J. Heat Mass Trans., 35, 765-773 (1993).

Burmeister, L. C., Effectiveness of a spiral-plate heat exchanger with equal capacitance rates. J. Heat Trans., 128, 295-301 (2006).

Gollan, A. and Sideman, S., Direct contact heat transfer with change of phase: Stratified flow of immiscible films on negative slopes. Chem. Eng. Prog. Symp., 66, No. 102, 55-61 (1970).

Grover, S. S. and Knudsen, J. G., Heat transfer between immiscible liquids. Chem. Eng. Prog. Symp., 51, 71-73 (1955).

G-Yan, Z., En, W. and S.-Tung, Tu., Techno-economic study on compact heat exchangers. Int. J. Ener. Res., 32, 1119-1127 (2008).

Habchi, C., Lemenand, T., Valle, D. D. and Peerhossaini, H., Liquid/liquid dispersion in a chaotic advection flow. Int. J. Multi. Flow, 35, No. 6, 485-497 (2009).

Habchi, C., Ouarets, S., Lemenand, T., Valle, D. D., Bellettre, J. and Peerhossaini, H., Influence of viscosity ratio on droplets formation in a chaotic advection flow. Int. J. Chem. Reac. Eng., 7, A50 (2009).

Huang, S. F., Zhang, X. G., Wang, D. and Lin, Z. H., Water holdup measurement in kerosene-water two-phase flows. Meas. Sci. Tech., 18, 3784-3794 (2007).

Janes, N., Muzychka, Y. S., Guy, B., Walsh, E. J. and Walsh, P., Heat transfer in gas-liquid and liquid-liquid two phase plug flow systems. Proceedings of 12th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (2010).

Kashid, M. N. and Agar, D. W., Hydrodynamics of liquid-liquid slug flow capillary micro-reactor: Flow regimes, slug size and pressure drop. Chem. Eng. J., 131, 1-13 (2007).

Kumara, W. A. S., Halvorsen, B. M. and Melaaen, M. C., Pressure drop, flow pattern and local water volume fraction measurements of oil–water flow in pipes. Meas. Sci. Tech., 20, 1-18 (2009).

Lang, P. and Auracher, H., Heat transfer to nonmiscible liquid-liquid mixtures flowing in a vertical tube. Exp. Therm. Fluid Sci., 12, No. 3, 364-372 (1996).

Lemenand, T., Durandal, C., Valle, D. D. and Peerhossaini, H., Turbulent direct-contact heat transfer between two immiscible fluids. Int. J. Ther. Sci., 49, No. 10, 1886-1898 (2010).

Lozano, A., Barreras, F., Fueyo, N. and Santodomingo, S., The flow in an oil/water plate heat exchanger for the automotive industry. App. Therm. Eng., 28, 1109-1117 (2008).

Lum, J. Y.-L., Al-Wahaibi, T. and Angeli, P., Upward and downward inclination oil-water flows. Int. J. Multi. Flow, 32, 413-435 (2006).

Lum, J. Y.-L., Lovick, J. and Angeli, P., Low inclination oil-water flows. Can. J. Chem. Eng., 82, 303-315 (2004).

Martin, H., Heat exchangers. Hemisphere Publication Corporation, 73-82 (1992).

Minton, P. E., Designing spiral heat exchangers. Chemical Engineering, May 4, 103-112 (1970).

Naphon, P. and Suwagrai, J., A study of the heat transfer characteristics of a compact spiral coil heat exchanger under wet surface conditions. J. Exp. Ther. Flu., Sci., 29, 511-521 (2005).

Naphon, P. and Suwagrai, J., Effect of curvature ratios on the heat transfer and flow development in the horizontal spirally coiled tubes. Int. J. Heat Mass Trans., 50, 444-451 (2007).

Naphon, P. and Wongwises, S. A., A review of flow and heat transfer characteristics in curved tubes. Renew. Sust. Ener. Rev., 10, 463-490 (2006).

Naphon, P. and Wongwises, S. A., An experimental study on the in-tube convective heat transfer coefficients in a spiral coil heat exchanger. Int. Comm. Heat Mass Trans., 29, No. 6, 797-809 (2002).

Perry, R. H., Green, D. W. and Maloney, J. O., Perry's Chemical Engineers' Handbook. 7th Edition, 11.55-11.56 (1998).

Picon-Nunez, M., Canizalez-Davalos, L. and Medina-Flores, J. M., Alternative sizing methodology for compact heat exchangers of the spiral type. Heat Trans. Eng., 30, No. 9, 744-750 (2009).

Picon-Nunez, M., Canizalez-Davalos, L., Martinez-Rodriguez, G. and Polley, T. G., Shortcut design approach for spiral heat exchangers. Trans. IChemE, Part C, 85, No. C4, 322-327 (2007).

Ramachandran, S., Kalaichelvi, P. and Sundaram, S., Heat transfer studies for two-phase flow in a spiral plate heat exchanger. J. Univ. Chem. Tech. Met., 41, No. 4, 439-444 (2006).

Ramachandran, S., Kalaichelvi, P. and Sundaram, S., Heat transfer studies in a spiral plate heat exchanger for water-palm oil two phase system. Braz. J. Chem. Eng., 25, No. 3, 483-490 (2008).

Rodriguez, O. M. H. and Oliemans, R. V. A., Experimental study on oil-water flow in horizontal and slightly inclined pipes. Int. J. Multi. Flow, 32, 323-343 (2006).

Salim, A., Fourar, M., Pironon, J. and Sausse, J., Oil-water two-phase flow in micro-channels: flow patterns and pressure drop measurements. Can. J. Chem. Eng., 86, 978-988 (2008).

Sathiyan, S., Rangarajan, M. and Ramachandran, S., An experimental study of spiral-plate heat exchanger for nitrobenzene-water two-phase system. Bulg. Chem. Comm., 42, No. 3, 205-209 (2010).

Sathiyan, S., Rangarajan, M. and Ramachandran, S., Studies of heat transfer for water-diesel two-phase system in a spiral heat exchanger. Chem. Biochem. Eng. Quar., 25, No. 2, 195-201 (2011).

Somer, T. G., Bora, O., Kaymakcalan, O., Ozmen, S. and Arikan, Y., Heat transfer to an immisible liquid mixture and between liquids in direct contact. Desalination, 13, No. 3, 231-249 (1973).

Trallero, J. L., Oil-water flows in horizontal pipes. PhD Thesis, the University of Tulsa, Oklahoma (1995).

Wang, K., Lu, Y., Shao, H. and Luo, G., Heat transfer performance of a liquid-liquid microdispersed system. Ind. Eng. Chemi. Res., 47, No. 23, 9754-9758 (2008).

Xu, M., Xiong, R. H., Li, Y. F., Yang, J. M., Luo, X., Yu, Y. B. and Zhao, T. Z., Pattern transition and holdup behaviors of horizontal oil-water pipe flow. 7th International Conference on Multiphase Flow, ICMF 2010, Tampa FL (2010).

Yaws, C. L., Chemical Properties Handbook. McGraw-Hill, New York (1999).

Zhao, Y., Chen, G. and Yuan, Q., Liquid-liquid two-phase flow patterns in a rectangular microchannel. AIChE Journal, 52, No. 12, 4052-4060 (2006).