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Experimental Heat Transfer Correlations For A Liquid-Liquid Two Phase System In A Compact Heat Exchanger

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ABSTRACT

Heat transfer using new generation compact heat exchangers in two-phase process streams are increasingly encountered in process industries. Investigation of the rates of momentum and heat transfer for two phase systems is a must for an optimal design of the heat exchanger. Experimental studies in laminar range were conducted in a spiral plate heat exchanger with hot water as the heating fluid and the two-phase mixture of water-nitrobenzene in different mass fractions and flow rates as the process fluid. The experimental heat transfer coefficients on the process side were correlated with Reynolds numbers and were fitted into an equation $h = a\,Re^{m}$, adopting an approach available in literature for two phase fluid flow studies. The heat transfer coefficients were also related to the mass fraction of nitrobenzene 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 - φ_L) was correlated with the Lockhart Martinelli parameter (χ_{tt}^2) in the form $\varphi_L=1+C/\chi_{tt}+1/\chi_{tt}^2$. This correlation enables calculation of the two-phase heat transfer coefficients using single-phase data. The calculated coefficients showed a variance of ± 8 % over the experimental values.

KEYWORDS

Heat transfer coefficient;
Spiral heat exchanger;
Two-phase mixture;
Reynolds number;
Two-phase multiplier;
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 equipment include higher heat transfer coefficient, 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. 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. 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[1-11].

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 exchanger with hot water as the service fluid and two-phase mixtures of water and nitrobenzene in different ratios and flow rates as the cold process fluid. Experimental runs with single-phase fluids (pure water and pure nitrobenzene) 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 based on heat transfer coefficients of pure fluid and two-phase mixture correlated well with the Lockhart-Martinelli Parameter (L-M Parameter). This enables prediction of the two-phases, service side coefficients (for the range of Reynolds numbers studied) using single-phase data. The predicted coefficients showed a variance of ± 8 % over the experimental values

EXPERIMENTAL

Equipment and procedure

A schematic diagram of the experimental setup is shown in figure1.

The heat exchanger used in the experiment was a spiral plate heat exchanger manufactured by Alfa Laval (India) Ltd., Pune, India – Type 1V with a heat transfer area of 2.24 m^2 and a channel spacing of 5 mm.

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 commercial nitrobenzene and demineralized water were charged into this tank to obtain the experimental range of mass fractions of nitrobenzene (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, nitrobenzene) 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 deteregent solution on both the process and service side followed by rinse pumping with pure hot water.

Calculation methodology

The heat load (Q, Watts) is calculated using the

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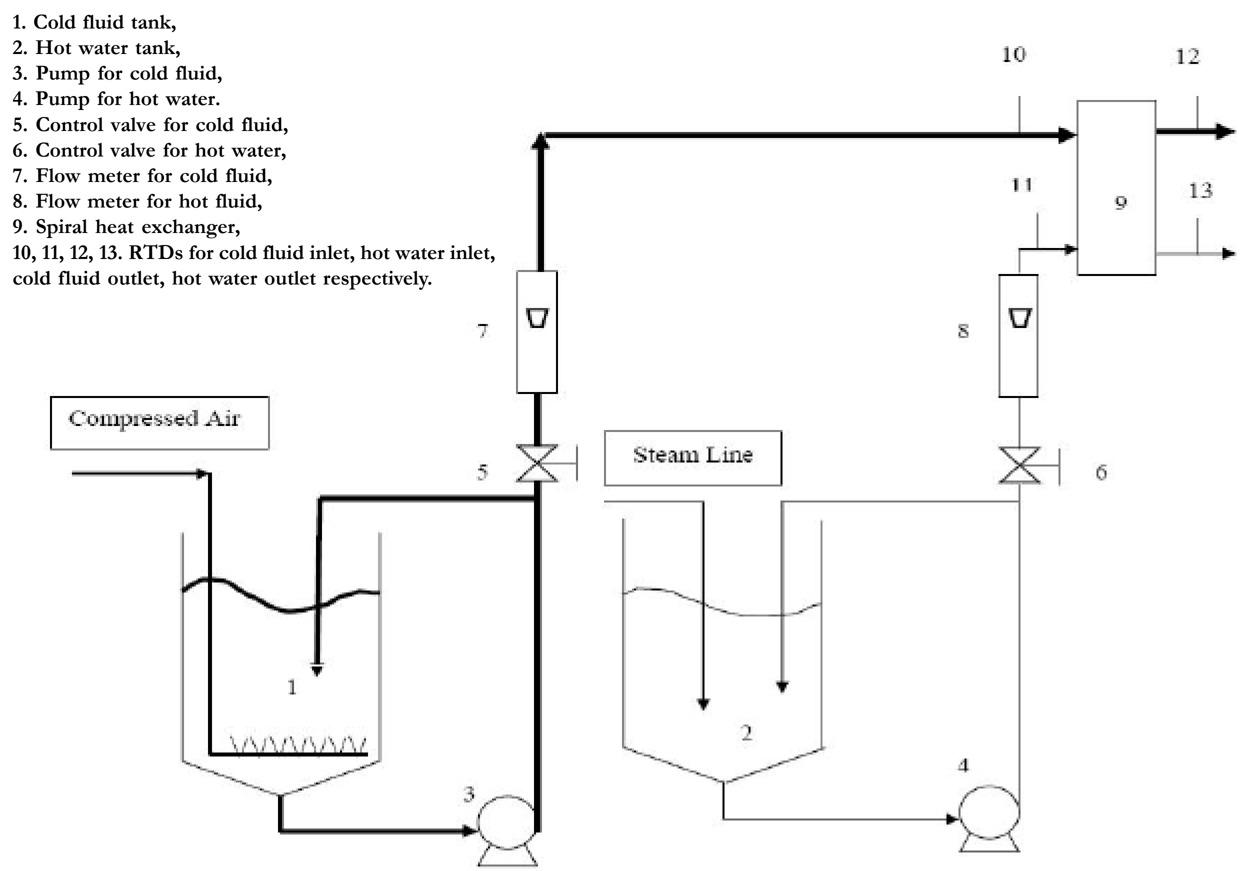

Figure 1: Schematic diagram of the experimental setup

expression

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

M_h - Mass flow rate of hot fluid, kg s^{-1},
Cp_h - Specific heat of hot fluid, J kg^{-1} K^{-1}
$(\Delta T)_h$ - Temperature drop of hot fluid, K

The overall heat transfer coefficient(U, W m^{-2} K^{-1}) is obtained from the relation

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

A–Area of Heat Transfer, m^2 $(\Delta T)_{lm}$ - Logarithmic mean temperature difference, K

The hot fluid side heat transfer coefficient (h_h) is estimated using the following equation since the flow was laminar.

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

where Nu is the Nusselts number given by

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

and Gz is the Gratez number given by

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

d_e – equivalent diameter of the flow channel, m,
k_h - thermal conductivity of hot fluid, Wm^{-1} K^{-1},
L–Length of the flow channel, m

The cold side (two phase side) heat transfer coefficient ($h_{2\varphi}$) is calculated using the expression

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

t-wall thickness of the spiral plate, m,
k_{ss} – thermal conductivity of the wall, Wm^{-1} K^{-1}

The quality parameter X is defined as

$$X = \frac{1}{1+\varrho_w Q_w/\varrho_f Q_f} \tag{7}$$

ρ_f - density of nitrobenzene, kg m^{-3},
Q_f - volumetric flow rate of nitrobenzene, m^3 s^{-1}
ρ_w - density of water, kg m^{-3},
Q_w - volumetric flow rate of water, m^3 s^{-1}

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

$$\chi_{tt}^2 = \left(\frac{1-X}{X}\right)^{2-m}\left(\frac{\varrho_f}{\varrho_w}\right)\left(\frac{\mu_w}{\mu_f}\right)^m \tag{8}$$

μ_w is the viscosity of water,

μ_f is the viscosity of nitrobenzene, N s m $^{-2}$

The factor m is obtained from the correlation

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

a, m – correlation constants

The two phase multiplier φ_L is defined as

$$\varphi_L = h_{2\varphi} / h_{1\varphi} \tag{10}$$

$h_1\varphi$-heat transfer coefficient of pure nitrobenzene, $Wm^{-2} K^{-1}$

RESULTS AND DISCUSSION

Single phase results

The experimental results of single phase studies are presented in the form of a plot between Reynolds number (Re) 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 & m are given in TABLE 1

Two phase results

Two phase studies were carried out with different mass fractions of nitrobenzene in water (20%, 40%, 60%, and 80%). Figure 2 also presents the two phase 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 1. The calculated values of $h_{2\varphi}$ based on these constants agreed with the experimental data with an error of ± 15 %

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

The variation of φ_L Vs χ_{tt}^2 was fitted into a correlation given in equation 11

$$\varphi_L = -1.93 + \frac{6.1}{\chi_{tt}} - \frac{1.93}{\chi_{tt}^2} \tag{11}$$

The experimental heat transfer coefficients ($h_2\varphi$) and their corresponding calculated values based on equation 11 is given in TABLE 2. It is seen from this table that the error ranges between ± 8 %. The results were re-ascertained by conducting validation runs.

Equation 11 can be rewritten as

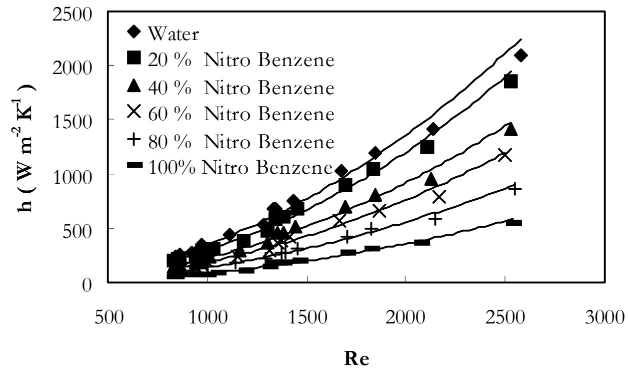

Figure 2: Variation of heat transfer coefficient with Re for nitrobenzene–water system

TABLE 1: Correlation constants a and m for nitrobenzene–water system

Mass percent of nitrobenzene	a	m
0	0.0005	1.9432
20	0.0004	2.0451
40	0.00046	2.0272
60	0.00023	2.0266
80	0.00014	2.0344
100	0.00009	2.085

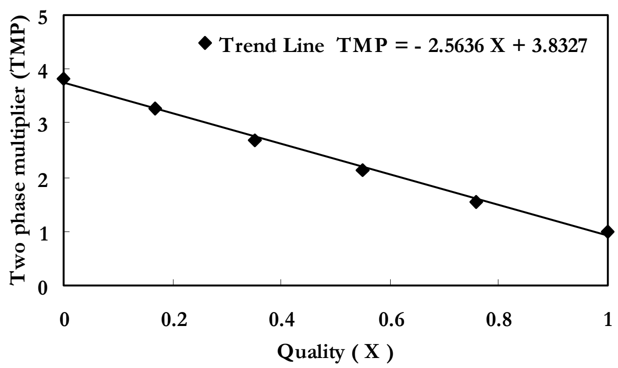

Figure 3: Variation of the two phase multiplier (φ_L) with Quality (X)

$$\varphi'_L = 1 - \frac{3.16}{\chi_{tt}} + \frac{1}{\chi_{tt}^2} \tag{12}$$

where φ'_L is the modified two phase multiplier for water - nitrobenzene system. This modified two phase multiplier is expressed as

$$\varphi'_L = -\frac{\varphi_L}{1.93} \tag{13}$$

Equation 13 is of the form

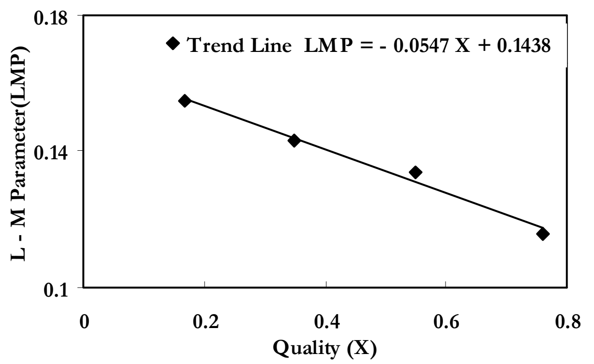

Figure 4: Variation of L-M parameter (χ_{tt}^2) with quality (X)

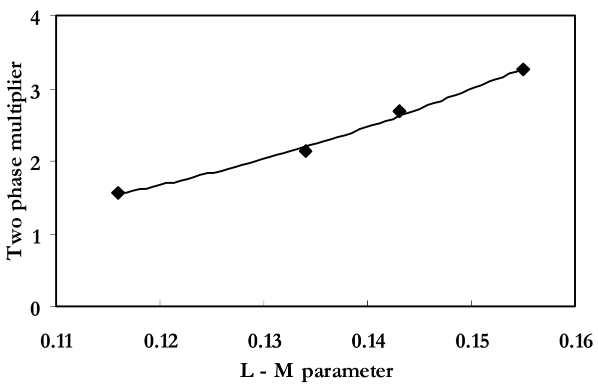

Figure 5: Variation of the two phase multiplier (φ_L) with L-M parameter (χ_{tt}^2)

$$\varphi_L = 1 + \frac{C}{\chi_{tt}} + \frac{1}{\chi_{tt}^2} \tag{14}$$

suggested by Chisholm and Laird [11]. The value of C is -3.16 for water-nitrobenzene two phase system.

CONCLUSION

Two phase flow studies were conducted in a spiral plate heat exchanger using water - nitrobenzene system. Heat transfer coefficients were related to the quality of the two phase systems. The correlations between X, φ_L and χ_{tt}^2 show a good agreement with experimental data. These correlations can be used for the calculation of two phase heat transfer coefficients from single phase data .This is 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 these correlations. Further work at higher Re and for different two phase systems is in progress in this laboratory.

TABLE 2: Experimental and calculated heat transfer coefficients for nitrobenzene – water system

Re	$h_{2\varphi}$ for 20% nitrobenzene – water system (W m^{-2} K^{-1})		% Error
	Experimental	Calculated	
842	222.6	208.4	+ 6.4
990	295.9	316.7	- 7.0
1474	729.6	705.4	+3.3
2539	2236.6	2109.1	+ 5.7
Re	$h_{2\varphi}$ for 40% nitrobenzene – water system (W m^{-2} K^{-1})		% Error
	Experimental	Calculated	
845	169.8	181.2	- 6.7
1029	264.3	244.4	+ 7.5
1669	760.3	712.4	+ 6.3
2154	1046.9	1020.7	+ 2.5
Re	$h_{2\varphi}$ for 60% nitrobenzene – water system (W m^{-2} K^{-1})		% Error
	Experimental	Calculated	
877	145.6	139.2	+ 4.4
1144	269.6	248.4	+ 7.9
1657	619.2	656.5	- 6.0
2465	1286.3	1372.1	- 6.7
Re	$h_{2\varphi}$ for 80% nitrobenzene – water system (W m^{-2} K^{-1})		% Error
	Experimental	Calculated	
856	104.6	97.5	+ 6.8
1167	187.5	195.6	- 4.3
1834	540.2	582.6	- 7.8
2561	954.2	992.3	- 4.0

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