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An experimental study of spiral-plate heat exchanger for nitrobenzene-water two-phase system

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This paper presents the results of two-phase (immiscible liquids) heat transfer studies, conducted using a spiral plate heat exchanger. Experimental studies were conducted using hot water as the service fluid. The two-phase system of nitrobenzene-water in different mass fractions and flow rates was studied as a cold process fluid. The two phase heat transfer coefficients were correlated with Reynolds numbers, Prandtl number, and by the following equation $Nu = a. (Re)^{b}. (Pr)^{c}. (X)^{d}$, adopting an approach available in the literature for the two-phase flows. The data obtained from the experimental study are compared with the theoretical predictions. The predicted coefficients showed a spread of ± 15 % in the laminar range. This new correlation for predicting Nusselt number may be used for practical applications.

Keywords: Spiral plate heat exchanger, two- phase flow, single-phase heat transfer coefficients, two-phase heat transfer coefficients, Nusselt number, Reynolds number

INTRODUCTION

The heat exchanger is a device where energy is transferred from one fluid to another across a solid surface. With rising equipment costs and increasingly stringent space constraints, compact heat exchangers are gaining a larger portion of the heat exchanger market. Spiral plate heat exchangers are extremely compact, fitting a large heat transfer surface area into a small volume, have higher heat transfer rates, less fouling, operational flexibility, and are easy to maintain. An important feature of spiral plate exchangers is its capacity to handle high viscosity and highly suspended liquids, exhibiting lower tendency to fouling. This type of exchanger is common in the paper, petrochemical, food, and sugar industries with applications in evaporation and condensation.

Simultaneous flow of two or more immiscible fluids is one of the different types of multiphase flows that occur widely in the industry, in environmental, chemical and biochemical processes. Heat transfer in liquid-liquid systems is frequently encountered in metal processing, the petrochemical and other industries. For improved heat exchanger designs, it is critical to gain better understanding of the momentum and heat transferring in the multiphase flow processes where fluids of different thermophysical properties are involved.

Jha and Rao [1] have studied the outside-film and inside-film heat transfer coefficients in an agitated vessel. They have derived an equation to predict the Nusselt number based on the geometry of the helical coil and the location of the agitator. Kalb and Seader [2] have performed numerical studies for uniform wall heat flux with peripherally uniform wall temperature for Dean numbers in the range of 1-1200, Prandtl numbers of 0.005-1600, and curvature ratios of 10 to 100 for fully developed velocity and temperature fields. Yao and Berger [3] have studied the effects of buoyancy forces on fully developed laminar flow with constant heat flux. Their studies have been based on the Boussinesq approximation for the buoyancy forces and analyzed for both horizontally and vertically oriented curved pipes. The heat transfer to a helical coil in an agitated vessel has been studied by Havas *et al*. [4], and a correlation has been developed for the outer Nusselt number based on a modified Reynolds number, Prandtl number, viscosity ratio, and the tube diameter to the vessel diameter ratio.

Lemenand and Peerhossaini [5] have developed a correlation for Nusselt number based on the Reynolds number, Prandtl number, and the number of bends in the pipe. Their study shows that

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the Nusselt number slightly drops off with the increase of bend number. Gut *et al*. [6] have developed a parameter estimation procedure for plate heat exchangers that handles experimental data from multiple configurations. Hemamalini *et al*. [7] have developed correlations for the prediction of the pressure drop in a two-phase flow based on pure component density, gas and liquid flow rates in a horizontal pipe and a control valve, in series for an air/palm oil two-phase flow. Shah [8] has summarized the advances in compact heat exchangers related to two-fluid exchanger effectiveness, NTU results for highly complex flow arrangements, heat transfer, pressure drop analyses, CFD role in the design, analysis of header and manifold design, recuperator design procedure, design data for compact heat exchanger, and thermodynamic modeling and analysis.

Paisarn and Jamnean [9] have experimentally investigated the effect of curvature ratios on the heat transfer and flow development in horizontal spirally coiled tubes. In their work, the turbulence flow and the heat transfer have been simulated by using the k-ε standard turbulence model. The centrifugal force is seen to have significant effects on the enhancements of heat transfer and pressure drop. Marchitto *et al*. [10] have carried out experiments on a horizontal cylindrical two-phase flow header supplying sixteen vertical channels and have analyzed the effects of nozzles and of orifices placed upstream of the header and connecting it to the channels. Their experimental results show that the operating conditions exert a strong influence on the structure of the two-phase flow pattern inside the header, and therefore on the flow distribution to the channels.

In this study, heat transfer investigations were carried out using a spiral plate heat exchanger with water as the hot fluid, and nitrobenzene and two-phase mixtures of nitrobenzene-water immiscible liquid mixture as the cold fluids. Single- and two-phase heat transfer coefficients were obtained for the cold side from the experiments. Predictive correlations were developed for the cold-side (two-phase fluid) heat transfer coefficient.

EXPERIMENTAL

Experimental set-up and procedure

A schematic diagram of the experimental setup is shown in Fig. 1. The heat exchanger, used in the experiment, was a spiral plate heat exchanger, manufactured by Alfa Laval (India) Ltd., Pune,

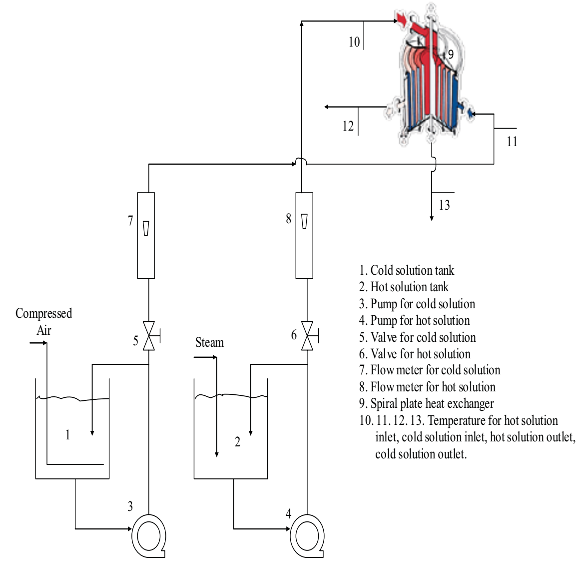

Fig. 1. Schematic diagram of the experimental set-up.

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 (cold-side) fluid was stored in a separate stainless steel tank. Weighed quantities of nitrobenzene and demineralized water were charged into this tank to obtain the experimental range of nitrobenzene mass fractions (0, 20, 40, 60, 80 and 100%). The agitation in the tank was maintained by air bubbling. Centrifugal pumps were used for the circulation of the two streams of fluids. The two-phase rotameters were calibrated for each experimental mass fraction before the experimental run. Online calibrated resistance temperature detectors with digital indicators were used for temperature measurements of the inlet and outlet streams of the service and process fluids.

The service-fluid-side inlet temperature and the 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 were also carried out. The service and process fluid flow paths of heat exchanger are shown in Fig. 2. The heat-transfer performance of the spiral plate heat exchangers mainly depends on mass flow rate of the fluid, flow area and logarithmic temperature difference between entering and leaving fluid streams.

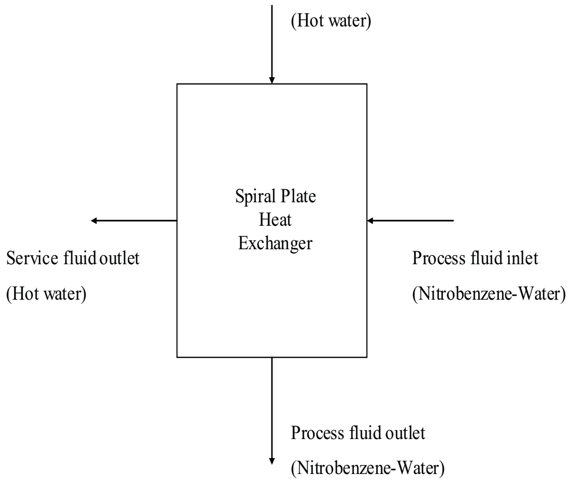

Figure 2: Service and process fluid flow paths of the heat exchanger

Calculation methodology

The heat load is calculated using the expression:

$$Q = M_h Cp_h (\Delta T)_h ; \quad (1)$$

M_h – Mass flow rate of the hot fluid, kg/s
Cp_h – Specific heat of the hot fluid, J/kg K
$(\Delta T)_h$ – Temperature drop of the hot fluid, K.

Using equation (1), the overall heat transfer coefficient is obtained from the relation:

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

U – Overall heat transfer coefficient, W/m^2 K
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 calculated using the following equation [11]:

$$Nu = 0.0315(Re)^{0.8} (Pr)^{0.25} ; \quad (3)$$

Nu is the Nusselt number, given by

$$Nu = \frac{h_h d_e}{k_h} ; \quad (4)$$

h_h – Hot-side heat-transfer coefficient, W/m^2 K
d_e – Equivalent diameter of the flow channel, m
k_h – Thermal conductivity of the hot fluid, W/m K

The cold-fluid-side (two-phase side) heat-transfer coefficient ($h_{2\phi}$) is estimated using the expression, where the results from Eqs. (2) to (4) are used.

$$\frac{1}{U} = \frac{1}{h_h} + \frac{t}{k_{ss}} + \frac{1}{h_{2\varphi}} ; \quad (5)$$

t – wall thickness of the spiral plate, m
k_{ss} – thermal conductivity of the wall, W/m K
$h_{2\phi}$ – heat transfer coefficient of the two-phase fluid, W/m^2 K.

The experimental Nusselt number, for the two-phase cold fluid, is estimated based on the two-phase heat-transfer coefficient from Eq. (5) using the expression

$$Nu_{experimental} = (h_{2\varphi})_{hotside} (d_e/k)_{cold\ side} . \quad (6)$$

In developing a predictive correlation for the cold-side two-phase heat-transfer coefficient, $h_{2\phi}$, d_e, $k_{2\phi}$, $\rho_{2\phi}$, $v_{2\phi}$, $\mu_{2\phi}$, $Cp_{2\phi}$ and X are the eight relevant variables, assuming average properties assigned to the two-phase system. There are four fundamental dimensions. That is why, four is the number of the dimensionless groups involved. These groups are the Nusselt number (*Nu*), Reynolds number (*Re*), Prandtl number (*Pr*), and the mass fraction (*X*). Therefore, the general form of the correlations developed is

$$Nu_{\text{predicted}} = a(\text{Re})^b (\text{Pr})^c (X)^d , \quad (7$$

where *a*, *b*, *c,* and *d* are constants, obtained from linear regression using MS Excel. The thermo-physical properties of the pure substances were calculated based on the correlations given in Yaws [12]. The two-phase properties were obtained using a linear mixing rule.

RESULTS AND DISCUSSION

Single-phase flow

The experimental results of single-phase studies are presented in the form of a plot between Reynolds Number and $h_{1\phi}$ in Fig. 3. The relation between Re and $h_{1\phi}$ (heat transfer coefficient for pure nitrobenzene, W/m^2 K) were correlated by regression analysis in the form given in Eq. (7). For pure water, equation (3) was used to predict $h_{1\phi}$.

Two-phase flow

Two-phase studies were carried out with different mass fractions of nitrobenzene in water (20%, 40%, 60% and 80%). Fig. 4 represents the two-phase heat transfer coefficients, $h_{2\phi}$ as a function of Reynolds number for various compositions. For two-phase systems, the Reynold's number is based on the weighted-average thermophysical properties of the fluids at the respective mean bulk temperatures. The obtained data are fitted by regression to the correlation given in equation (7), and the values of *a*, *b*, *c,* and *d* are given in Eq. (8):

$$Nu_{\text{predicted}} = 1.7311\times 10^{-6} (Re)^{1.6947} (Pr)^{1.1767} (X)^{-0.6860} \quad (8)$$

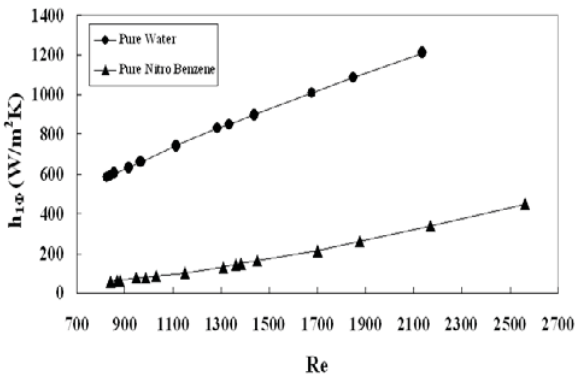

Fig. 3. Variation of heat transfer coefficient with Re for single phase system.

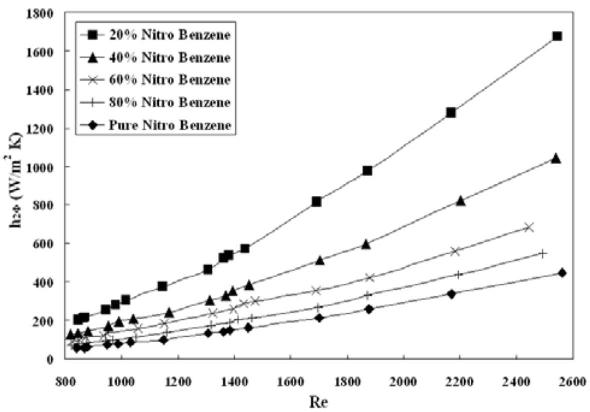

Fig. 4. Variation of Heat Transfer Coefficient with Re for Nitrobenzene -Water System

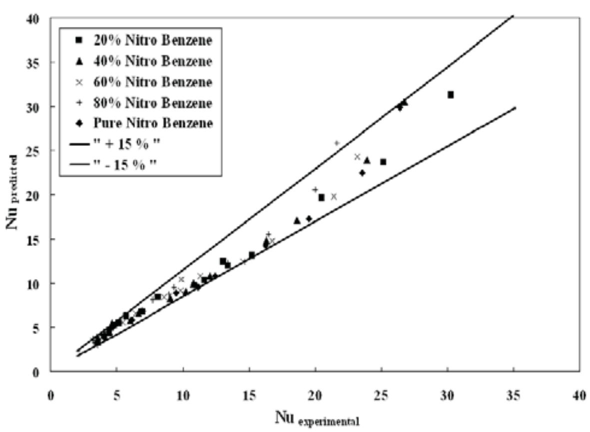

Fig. 5. Comparison of $Nu_{experimental}$ with $Nu_{predicted}$ for nitrobenzene-water system.

The developed correlations were tested against new experimental data of the same system (comparison of the results from equations 6 and 8). The calculated values of $h_{2\phi}$, based on these constants, agreed with the experimental data within an error of ± 15 %. Table 1 shows the ranges of Reynolds and Prandtl numbers for which the correlations are valid.

Table 1 Ranges of Re and Pr.

System	Re	Pr
Water	826 < Re < 2135	4.68 < Pr < 5.64
Nitrobenzene/ Water	819 < Re < 2561	6.59 < Pr < 17.42

Fig. 5 shows the comparison between the Nusselt numbers, obtained from the conducted experiments and the numbers, calculated from the developed correlations. The predicted Nusselt numbers are within ± 15% of the experimental values. Observed discrepancies between the measured data and the calculated results may be due to the uncertainties of the correlation and also due to the assignment of average properties for the two-phase mixtures. Further studies are needed to develop better correlations for two-phase convective transfer of polar systems, aromatics, and highly viscous liquids.

CONCLUSIONS

This paper presents experimental data from measurement of the heat transfer coefficient of a mixture of water and nitrobenzene in a spiral plate heat exchanger. The obtained data from the experimental study are compared with the theoretical prediction. New correlations are proposed based on the experimental data, which may be used for practical applications. Further work at higher Reynolds number and for different two-phase systems is in progress.

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ЕКСПЕРИМЕНТАЛНО ИЗСЛЕДВАНЕ НА РАБОТАТА НА ТОПЛООБМЕННИК СЪС СПИРАЛНИ ПЛАСТИНИ ПРИ ДВУ-ФАЗНАТА СИСТЕМА ВОДА-НИТРОБЕНЗЕН

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(Резюме)

В работата са представени резултати от изследване на топлообмена в топлообменник със пирални пластини за дву-фазна система от две несмесващи се течности. Като носещ флуид при изследванията е използвана гореща вода. Като студен флуид е използвана сместа от вода и нитробензен при различни масови съотношения и дебити. Коефициентите на топлообмен за двете фази са корелирани с числата на Рейнолдс и Прандтл по уравнението $Nu = a. (Re)^{b}. (Pr)^{c}. (X)^{d}$. Получените експериментални резултати показват, че при ламинарни режими опитните данни са в съгласие с изведеното уравнение в границите на разсейване от ± 15 % . Тази нова зависимост позволява изчисляването на числото на Нуселт за практически важни случаи.