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Development of correlations for thermal effectiveness of two-phase liquid – liquid systems in a tube side – shell and tube heat exchanger

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ABSTRACT

Experiments were carried out on heat transfer between hot water and various two-phase liquid mixtures in a custom-built 1-2 shell and tube heat exchanger. The two-phase liquid systems were chosen to represent wide range of thermo-physical and transport properties. The influence of mass flow rate of hot fluid & two-phase liquid mixture, composition of two-phase liquid mixture, flow geometry (tube/shell side) on thermal effectiveness of two-phase liquid mixture were comprehensively studied in laminar flow regime. The experimental data was statistically analyzed to develop a correlation for thermal effectiveness of two-phase liquid mixture on tube side. The developed correlation predicts thermal effectiveness of two-phase liquid mixture with a maximum error of ±15 % for 240 data points covering 7 different two-phase liquid systems.

Keywords: Two-phase liquid mixture, heat transfer, thermal effectiveness, correlation, Reynolds number, heat capacity ratio

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INTRODUCTION

Many industrial applications involve heat transfer in various multiphase systems viz., gas-liquid, liquid-liquid, liquid-solid and gas-solid. Heat transfer in flow boiling[1], pneumatic conveying and preheating in drying systems [2] – [7], cyclone heat exchanger [8], fluidized beds [9], etc. are some of the examples. Heat transfer in liquid-liquid two-phase systems is widely prevalent in petrochemical industries [10]. The presence of one liquid along with other liquid forming two-immiscible phases with different thermo-physical properties changes momentum and heat transfer characteristics. Hence the understanding of heat transfer in such two-phase systems is essential, which can be utilized for design and analysis of heat transfer equipment.

A survey of literature on the gas-liquid systems shows that considerable research has been carried out on the dynamics and heat transfer of two-phase flow [11] – [26]. Chisholm and Laird [27] developed the general correlation between the Lockhart-Martinelli parameter and the two–phase multiplier for pressure drop first time on liquid-liquid two-phase flow in circular tube. Similar kind of studies have been carried out on liquid–liquid systems in various geometries such as horizontal piping [28] – [30], microchannels [31] – [34], horizontal and annular piping [35] – [38], inclined pipe [39], [40]. Heat transfer studies on liquid-liquid systems have also been investigated in many heat exchange equipments such as spiral plate heat exchanger [41], shell and tube heat exchanger [42] – [46].

Thermal effectiveness is one of the means to assess the performance of a heat exchanger. In a plant heat exchanger, it is essential to know the exit temperature of hot and cold stream leaving the heat exchanger. Heat transfer coefficient calculated from fluid velocity and transport properties is widely used to determine heat transfer rate from which exit temperature can be calculated. However, a direct correlation between exit temperature of streams and thermo physical properties & fluid velocity, in terms of dimensionless numbers will be useful for easy prediction of stream temperatures. This paper reports the development of a correlation for thermal effectiveness for the instance of heat transfer between a single phase stream and a two-phase stream for a reasonably wide variety of liquids constituting two phases.

EXPERIMENTAL SECTION

The 1-2 pass shell and tube heat exchanger used for heat transfer experiments is described in our earlier work [42]-[46] and a schematic diagram is shown in Figure 1. Heat transfer area of 0.2269 m^2 was obtained by arranging 14 tubes (0.01 m ID and 0.012 m OD) in triangular pitch pattern. Each tube is 0.43 m long. The hot and cold fluids (hot water and two-phase liquid mixtures respectively) were pumped to the heat exchanger using 1/4 HP pumps and the flow rates were measured using calibrated rotameters with an accuracy of ±0.1 LPM. Flow rates of hot and cold streams were adjusted using hand operated valves. A thermostat (accuracy ~±0.5°C) was used to maintain the temperature of hot fluid (hot water). An agitator was used to ensure constant mixing of two fluids (in two-phase stream) in the reservoir. Seven liquid-water systems viz. Kerosene-water, Diesel-water, Nitro benzene-water, Oleic acid-water, Palm oil-water, Octane-water and Dodecane-water in varying proportions were used for experiments. This experimental design yielded 7 two-phase systems with 4 compositions each leading to 28 different two-phase mixtures. The range of variables investigated are given in Table 1. The range of thermo-physical & transport properties of various pure liquids used for formulation of two-phase, liquid-liquid systems are given in Table 2.

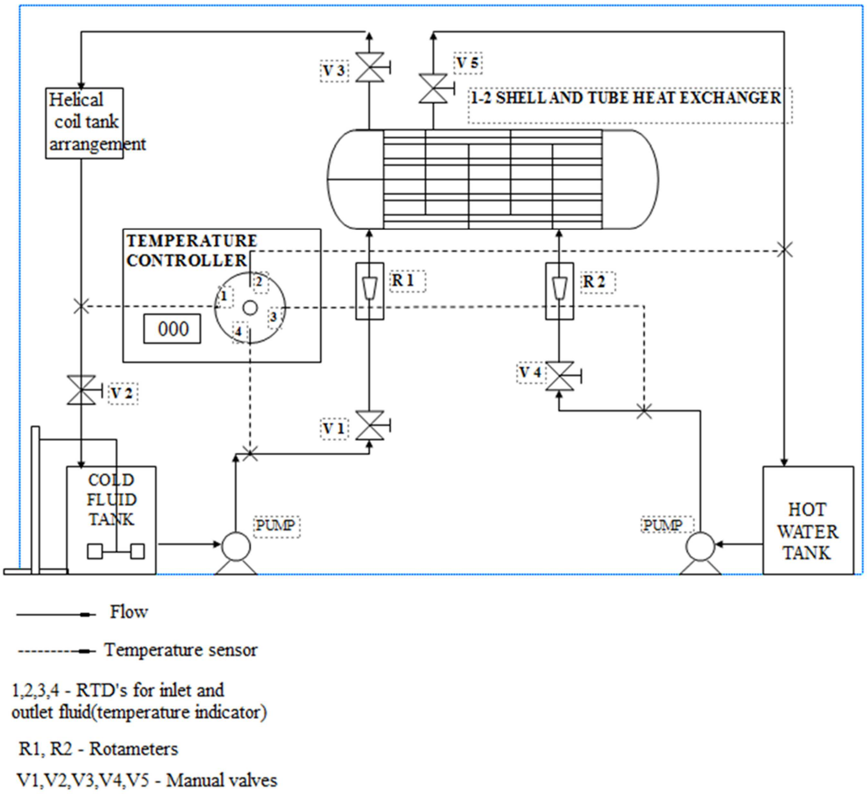

Figure 1: A schematic view of the experimental set-up

Table 1: Range of variables investigated

S.no	Variables	Values
1	Composition of two-phase systems (as volume percentage of organic phase)	20%, 40%, 60%, 80% and 100%
2	Mass flow rate of cold fluid	0.0088 kg/s to 0.2412 kg/s (shell side) 0.0043 kg/s to 0.1062 kg/s (tube side)

Table 2: Range of properties of two-phase systems investigated

S.No	Properties	Notation	Range	Unit
1	Dynamic viscosity	μ	0.001 to 0.05	kg/ms
2	Density	ρ	678 to 1199	kg/m^3
3	Thermal conductivity	k	0.129 to 0.624	W/mK
4	Specific heat	c_p	1418 to 4187	J/kgK
5	Prandtl number	N_{Pr}	3.75 to 67	Nil

RESULTS AND DISCUSSION

1.1. Effect of Reynolds number on thermal effectiveness of process fluid:
Figure 2 shows the effect of Reynolds number on thermal effectiveness of process stream, when it was supplied through the shell-side. Figure 2 has been drawn for different compositions of kerosene-water system as the process stream. It is observed from Figure 2 that the thermal effectiveness of process stream decreases with increase in its Reynolds number. For a process stream of fixed composition, higher Reynolds number indicates higher velocity and hence higher mass flow rate of process stream. Though heat transfer coefficient is expected to increase with velocity of process stream, the higher heat capacity (product of mass flow rate and specific heat) of process stream leads to reduction in its temperature rise. Hence thermal effectiveness of process fluid decreases with increase in Reynolds number.

The thermal effectiveness of 100% water as process stream is higher than that of 100 % kerosene as process stream for the same Reynolds number. The thermal effectiveness for two-phase process streams lies between the thermal effectiveness of 100 % water and 100 % kerosene as process stream. The viscosities of kerosene-water mixtures are higher than the viscosity of water. Hence to maintain the same Reynolds number, higher velocity and hence higher mass flow rate must be used for kerosene-water mixture. This leads to increase in heat capacity, which in turn reduces the temperature rise. Pure kerosene has the highest viscosity among kerosene-water systems and has the lowest thermal effectiveness due to increase heat capacity required to maintain the desired Reynolds number. Similar behavior has been observed for other two-phase process streams also as shown in Figures 3 to 8.

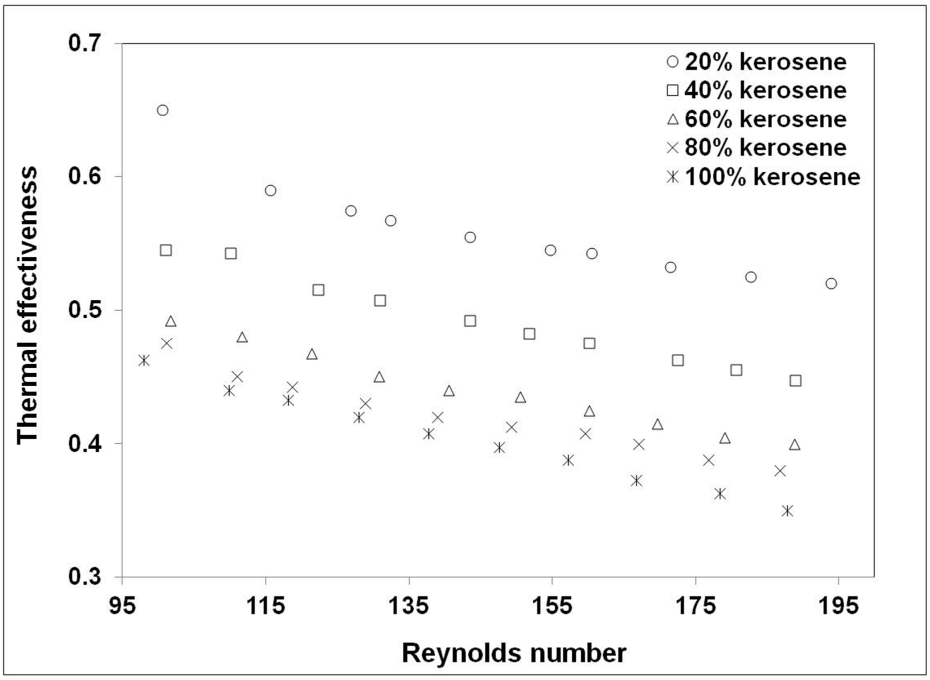

Figure 2: Influence of Reynolds number on Thermal effectiveness of kerosene-water system

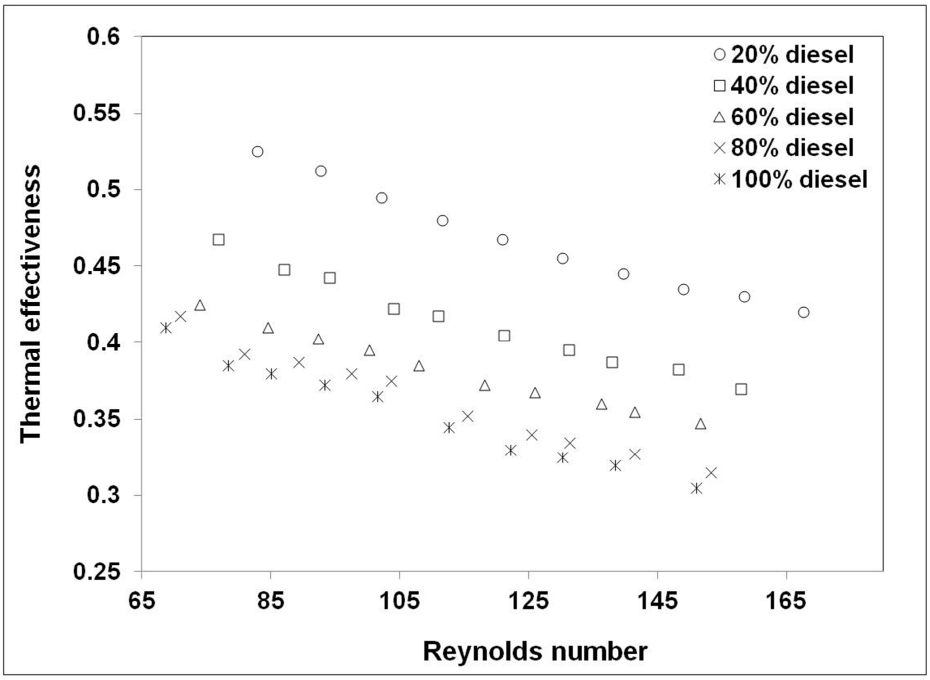

Figure 3: Influence of Reynolds number on Thermal effectiveness of diesel-water system

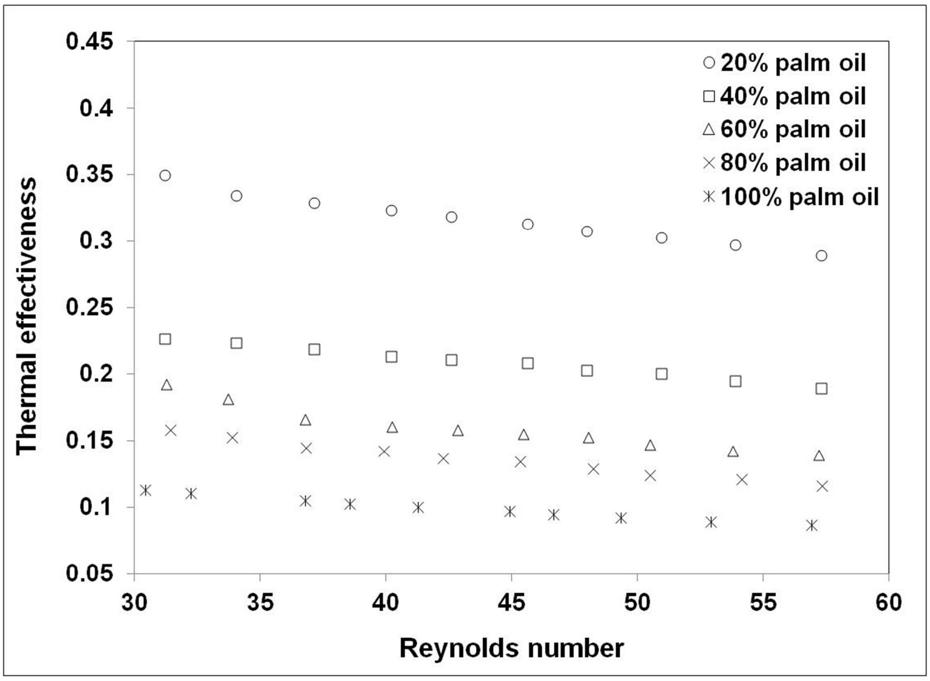

Figure 4: Influence of Reynolds number on Thermal effectiveness of palm oil-water system

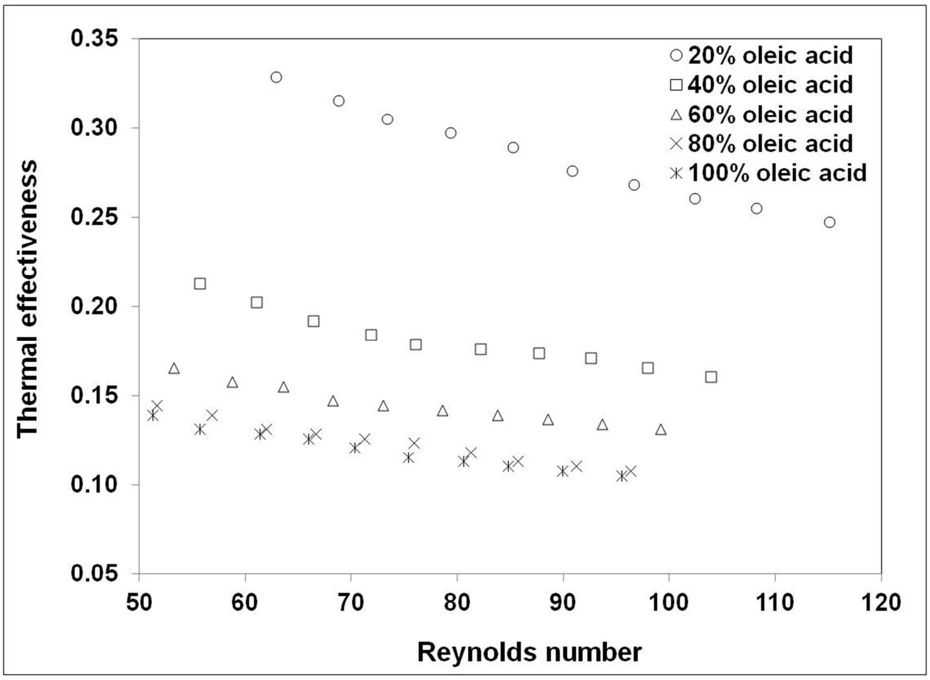

Figure 5: Influence of Reynolds number on Thermal effectiveness of oleic acid-water system

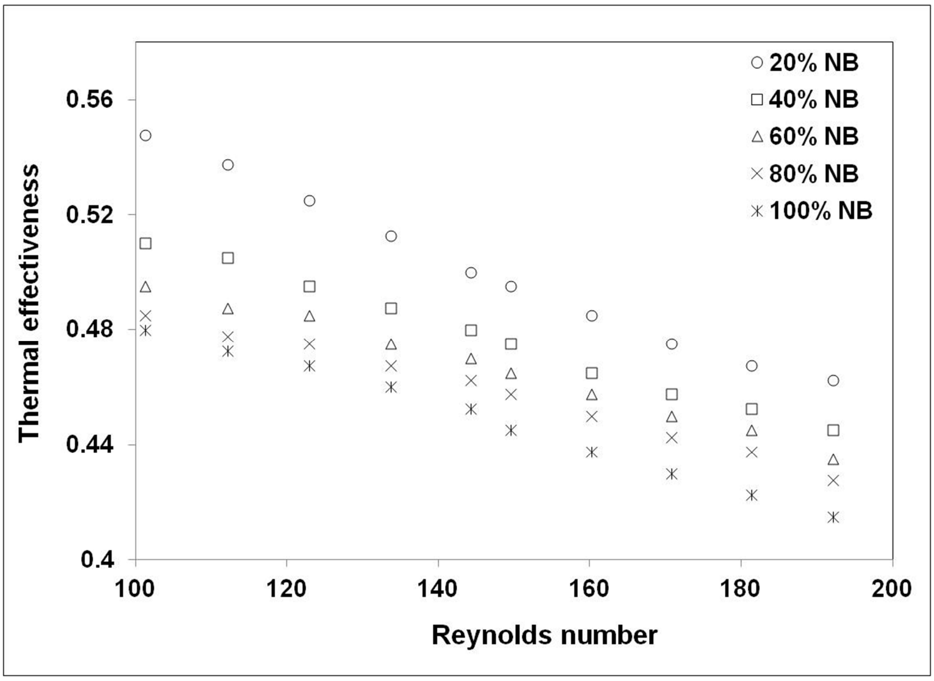

Figure 6: Influence of Reynolds number on Thermal effectiveness of NB-water system

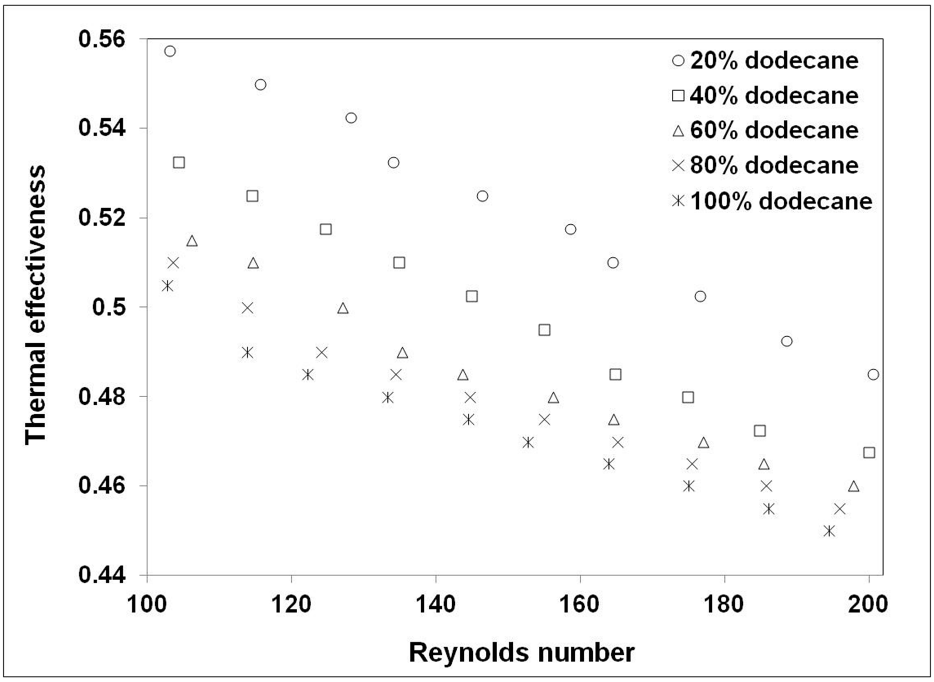

Figure 7: Influence of Reynolds number on Thermal effectiveness of dodecane-water system

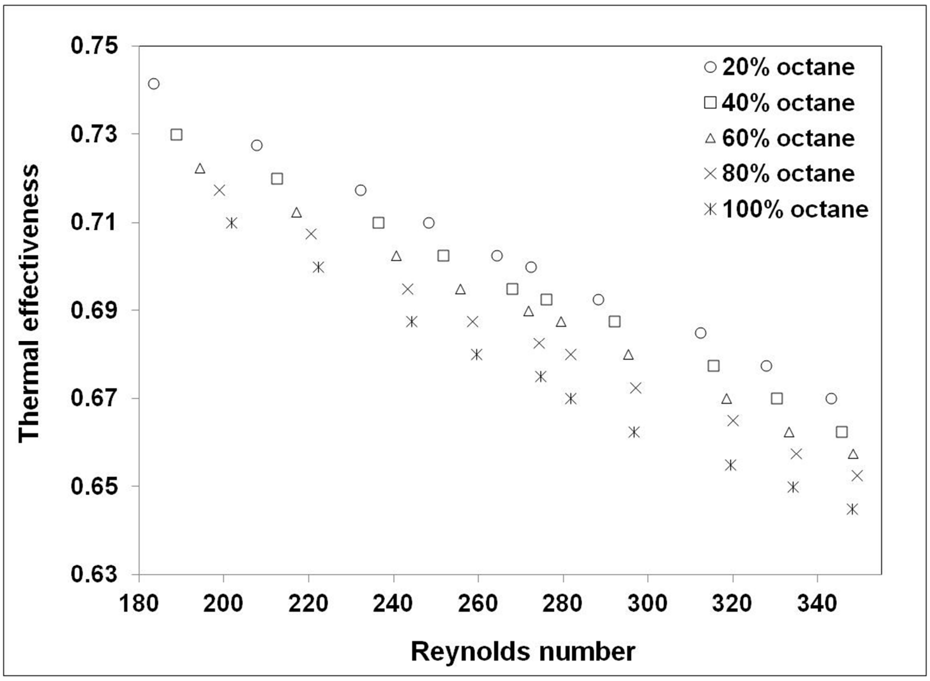

Figure 8: Influence of Reynolds number on Thermal effectiveness of octane-water system

1.2. Effect of velocity ratio on thermal effectiveness of process fluid in tube side:

Figure 9 shows the effect of shell-side velocity (process stream velocity) to tube-side velocity (hot stream velocity) on thermal effectiveness of process stream, when it was supplied through tube side. Figure 9 has been drawn for different compositions of kerosene-water system as the process stream. Thermal effectiveness of process fluid at different ratios of process stream to hot stream velocities was obtained by performing heat transfer experiments with different flow rates of process fluid at a constant flow rate of hot stream. It is observed from Figure 9 that the thermal effectiveness of process stream decreases with increase in its velocity ratio for all compositions of two-phase mixture. Similar behavior has been observed for other two-phase systems as shown in Figures 10 to 15.

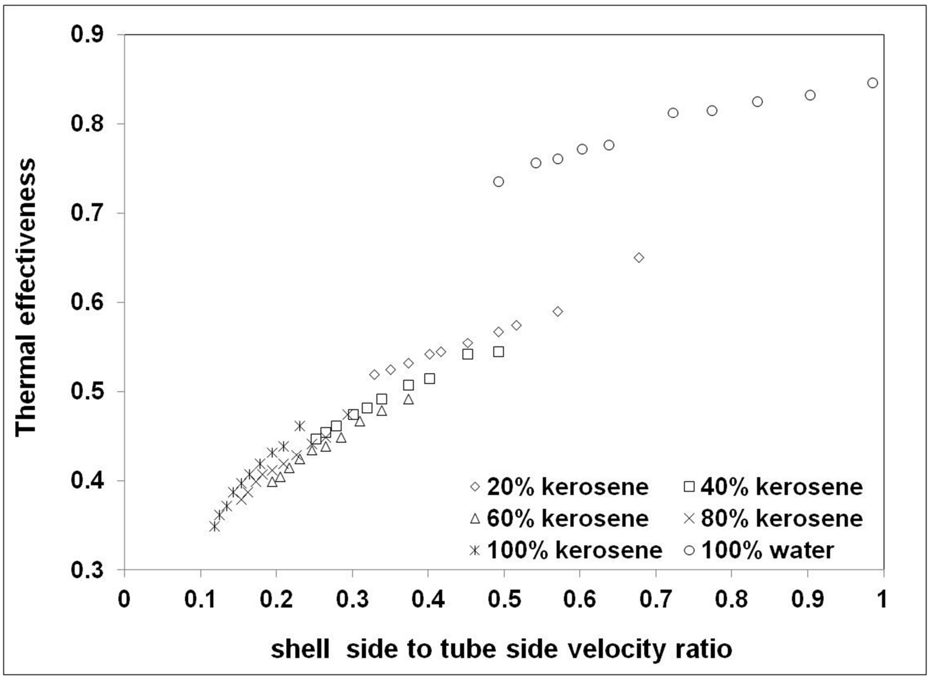

Figure 9: Influence of Shell side to tube side velocity ratio on thermal effectiveness of kerosene-water system

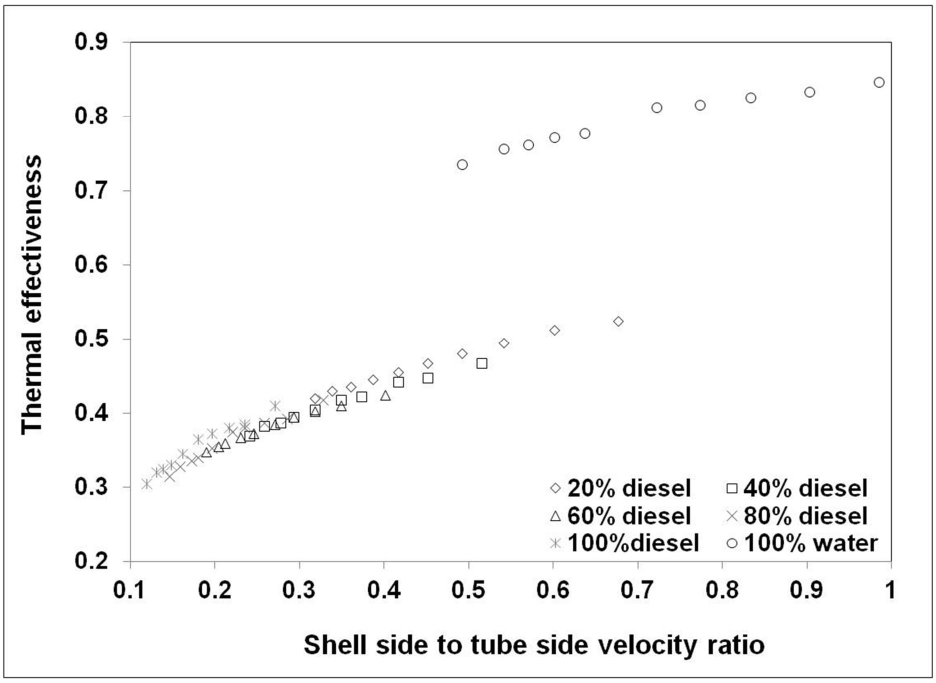

Figure 10: Influence of Shell side to tube side velocity ratio on thermal effectiveness of diesel-water system

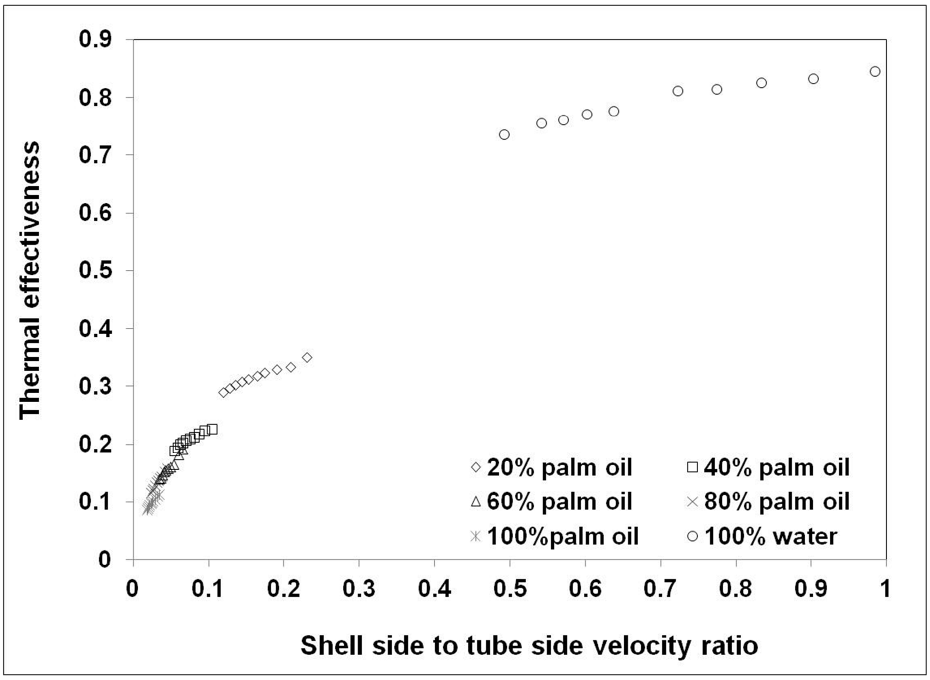

Figure 11: Influence of Shell side to tube side velocity ratio on thermal effectiveness of palm oil-water system

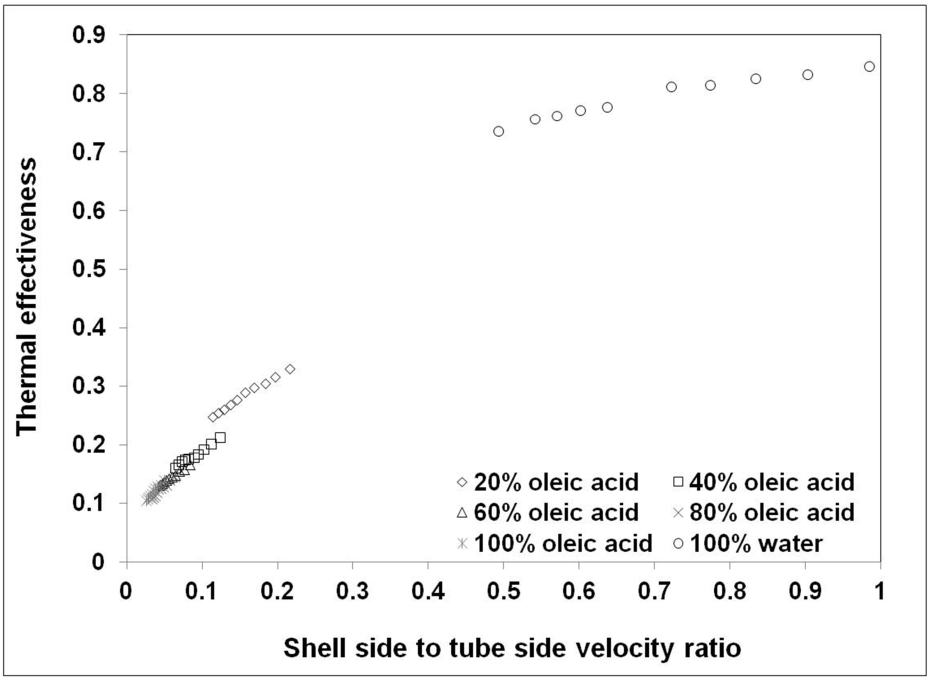

Figure 12: Influence of Shell side to tube side velocity ratio on thermal effectiveness of oleic acid-water system

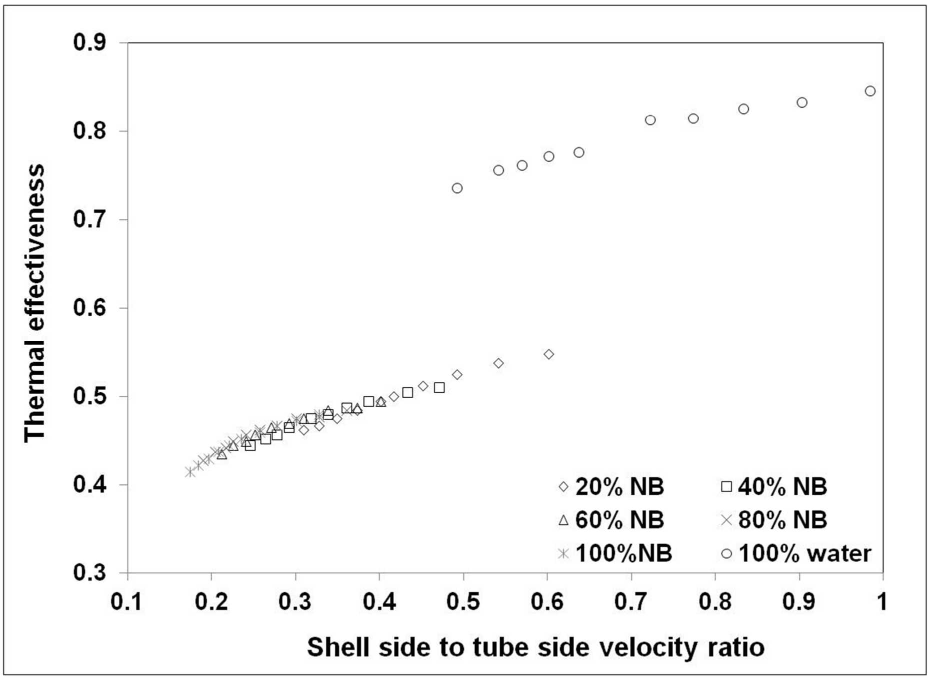

Figure 13: Influence of Shell side to tube side velocity ratio on thermal effectiveness of NB-water system

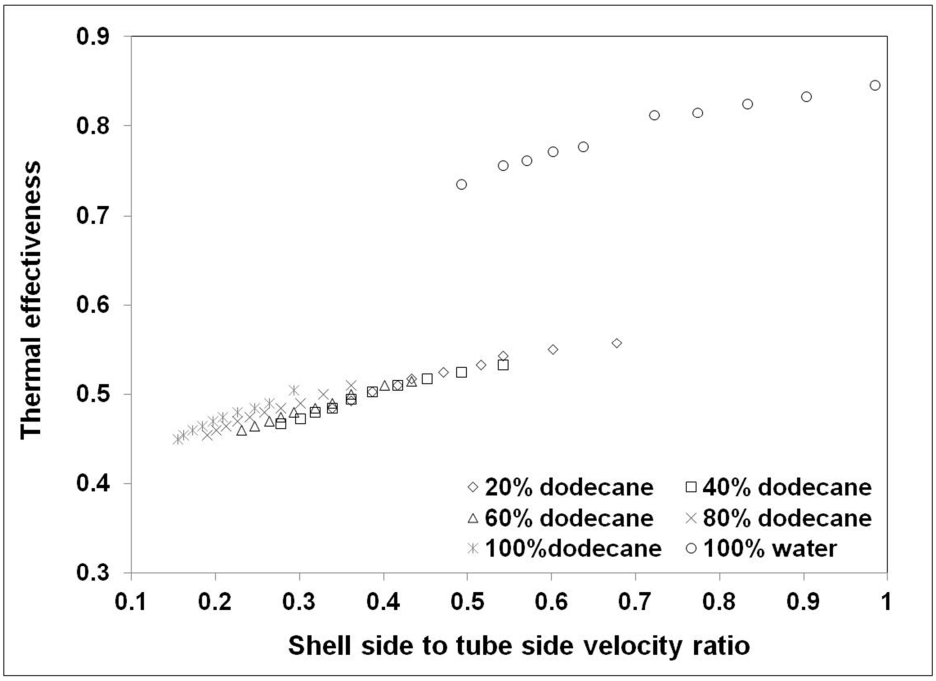

Figure 14: Influence of Shell side to tube side velocity ratio on thermal effectiveness of dodecane-water system

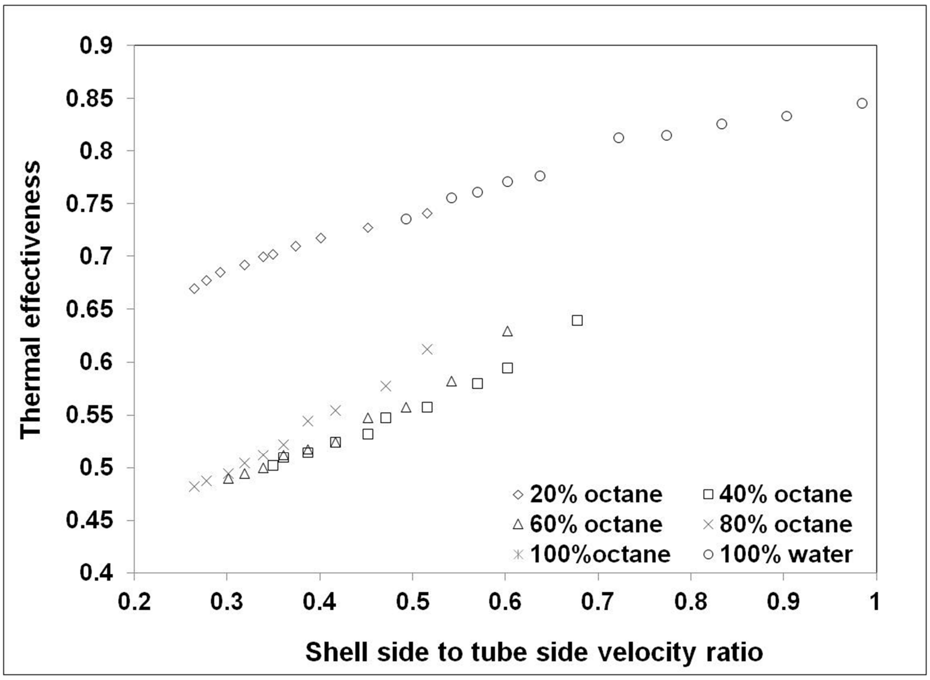

Figure 15: Influence of Shell side to tube side velocity ratio on thermal effectiveness of octane-water system

To understand this observation, one may derive an expression relating thermal effectiveness and velocity ratio as follows:

Thermal effectiveness of process stream is

$$S = \frac{(T_{co} - T_{ci})}{(T_{hi} - T_{ci})} \tag{1}$$

Rewriting Eq. (1) in terms of heat transfer rate and heat capacity,

$$S = \frac{Q}{(mCp)_{cold}(T_{hi} - T_{ci})} \tag{2}$$

For fixed heat exchanger geometry, heat transfer rate may be expressed as the product of overall heat transfer coefficient, heat transfer area and driving force. Accordingly Eq. (2) becomes,

$$S = \frac{UA\Delta T}{(mCp)_{cold}(T_{hi} - T_{ci})} \tag{3}$$

Neglecting the heat transfer resistance in the tube wall, overall heat transfer coefficient may be related to shell side and tube side heat transfer coefficients, h_o and h_i respectively.

Therefore, Eq. (3) becomes

$$\frac{1}{U} = \frac{1}{h_o} + \frac{1}{h_i} \tag{4}$$

$$U = \frac{h_o h_i}{h_o + h_i} \tag{5}$$

Substituting Eq. (5) in Eq. (3)

$$S = \frac{h_o h_i \Delta T}{(h_o + h_i)(mCp)_{cold}(T_{hi} - T_{ci})} \tag{6}$$

If shell side and tube side velocities are 'v' and 'u' respectively, Eq. (6) may be written for the two-phase on the shell-side as follows, accounting heat transfer coefficient-velocity relationship in the power law form,

$$S = \frac{v^n u^m A\Delta T}{(v^n + u^m)(T_{hi} - T_{ci})(v\rho ACp)_{cold}} \tag{7}$$

In Eq. (7), m & n are exponents in $h_i = m_1 u^m \ and \ h_o = n_1 v^n$
Eq. (7) becomes

$$S = \frac{v^{n-1} u^m A\Delta T}{(v^n + u^m)(T_{hi} - T_{ci})(\rho AC_p)_{cold}} \tag{8}$$

For a constant tube side fluid velocity (u), Eq. (8) may be simplified as follows:

$$S \ \alpha \ \frac{1}{v\left[1 + k\left(\frac{v}{u}\right)^{-n}\right]} \tag{9}$$

where k is u^{m-n}, constant at constant tube velocity

From Eq. (9), it is evident that the thermal effectiveness decreases with 'v' or (v/u) ratio. The rate of decrease depends on 'n' in heat transfer coefficient-shell side velocity relationship.

Figures 9 to 15 show the influence of shell-side to tube-side velocity ratio on thermal effectiveness of process fluid when supplied in the tube side. It may be observed from Figure 9 to 15 that the thermal effectiveness of two-phase liquid mixture increases with increase in shell-side to tube-side velocity ratio, for all the two-phase systems when they are supplied inside the tubes. This observation may be explained as follows:

For constant shell side velocity, but varying tube-side velocities for two-phase mixture flowing inside the tubes, Eq. (6) may be modified as follows:

$$S = \frac{v^n u^m A\Delta T}{(v^n + u^m)(T_{hi} - T_{ci})(u\rho ACp)_{cold}} \tag{10}$$

$$S \ \alpha \ \frac{u^m}{\left[\frac{u^m}{v^n} + 1\right] u} \tag{11}$$

From Eq. (10), it is clear that the thermal effectiveness depends upon 'u' for a constant 'v'. Increase in tube side velocity (u) results in lower value of thermal effectiveness. In other words, with increase in (v/u) ratio, the thermal effectiveness increases when the two-phase mixture is supplied inside the tubes and when the shell side fluid velocity is constant. This is also evident from Figures 9 to 15.

The thermal effectiveness is a suitable means of assessing the thermal performance of the heat exchanger. The method of thermal effectiveness is based on the effectiveness of a heat exchanger in transferring a given amount of heat. Since the mass flow rate and specific heat of both fluids play major role in most industrial heat exchangers, thermal effectiveness is related to heat capacity ratio of cold fluid to hot water.

Thermal effectiveness may be considered to be a function of Reynolds number (Re), Prandtl number (Pr) and heat capacity ratio (F) as shown below:

$$E = k_o F^{k_1} \mathrm{Re}^{k_2} \mathrm{Pr}^{k_3} \tag{12}$$

Power law type function was assumed, following the conventional correlations for heat transfer coefficient and Nusselt number. Tube diameter and two-phase velocity were taken as characteristic dimension and characteristic velocity in Reynolds number. Heat capacity ratio is the ratio of heat capacity of the two-phase fluid to the heat capacity of single-phase fluid (hot fluid in this case).

The regression equation for thermal effectiveness (S) for the two-phase liquid mixture was obtained using Minitab-14 as follows:

$$S = 0.156\, F^{-0.257}\, \mathrm{Re}^{0.226}\, \mathrm{Pr}^{-0.163} \text{ for two-phase systems in tube side} \quad (13)$$

Figure 4 shows the comparison between the experimental values of thermal effectiveness and those calculated using Eqn. (13). It is evident from Figure 4 that the Eqn. (13) predicts the thermal effectiveness for the two-phase within ± 15% error for seven liquid-liquid systems for about 240 data points.

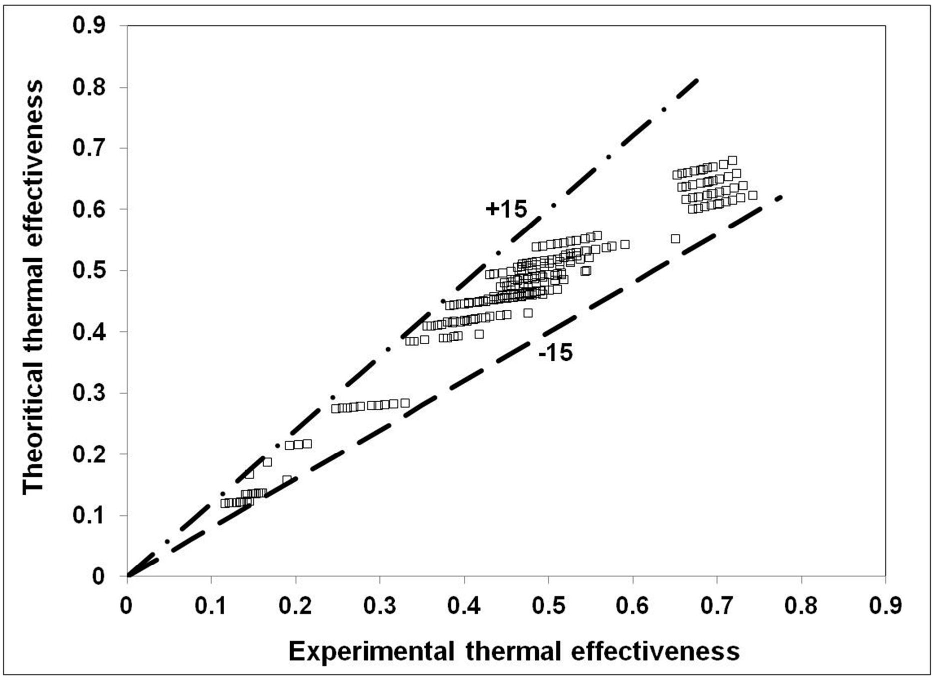

Figure 4: Variation between experimental and predicted values of thermal effectiveness for different compositions of liquid-liquid systems in tube side

CONCLUSION

Thermal effectiveness of two-phase liquid mixture decreases with velocity in a 1-2 shell and tube heat exchanger. However, the thermal effectiveness increases with Reynolds number in the laminar flow regime. The dependence of thermal effectiveness on Reynolds number follows power-law relationship, with higher exponent when the two-phase mixture is supplied on the tube-side. Similarly, the thermal effectiveness of two-phase mixture is more sensitive to heat capacity ratio while being supplied on the shell-side, compared to that supplied on the tube-side. The developed correlation predicts thermal effectiveness of two-phase liquid system with a maximum error of ± 15 % for wide range of data points covering 7 different two-phase liquid systems.

Nomenclature

A Heat transfer area, m^2

c_p Specific heat of process stream, J/kg K

D_i Inner diameter of the tube, m

D_o Outer diameter of the tube, m

D_s Inner diameter of shell, m

D_e Equivalent diameter, m

F Heat capacity ratio

v, u Shell-side and tube-side velocities, m/s

h_i, h_o Tube-side and shell-side heat transfer coefficients, W/m^2k

k Thermal conductivity of cold fluid, W/mK
m Mass flow rate of process stream, kg/s
N_{Nu} Nusselt number
N_{Pr} Prandtl number
N_{Re} Reynolds number
S Thermal effectiveness of process stream
T_{hi} Inlet temperature of hot water, K
T_{ho} Outlet temperature of hot water, K
T_{ci} Inlet temperature of cold fluid, K
T_{co} Outlet temperature of cold fluid, K
Q Volumetric flow rate of process stream, m^3/s
U Overall heat transfer coefficient, W/m^2K
Greek letters
ΔT Temperature difference in process side, K
μ Viscosity of cold fluid, kg/ms
ρ Density of cold fluid, kg/m^3

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