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Heat transfer measurements for oil–water flow of different flow patterns in a horizontal pipe

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ABSTRACT

Flow patterns and local heat transfer coefficients were measured for oil–water flow in a horizontal pipe. The test section was an 11 mm ID copper pipe with L/D ratio of 164. In this study, water and diesel fuel (2.49 mPa s viscosity and 798 kg/m^3 density) were selected as immiscible liquids and high speed photography technique was used for the flow pattern identification. Measurements were made for superficial Reynolds numbers in the range of 1350–13700 for water and 300–3700 for oil. Experimental results demonstrated that the heat transfer to flowing immiscible mixtures is strongly flow pattern dependent. In addition, a heat transfer correlation was developed for two flow patterns: stratified flow with mixing at the interface (STMI) and dispersion of water in oil and oil in water (Dw/o & o/w). The proposed correlation predicted the data with an average deviation of −2.768% and a standard deviation of 12.84%.

1. Introduction

The knowledge of heat transfer in immiscible liquid–liquid flow is important for many industries, such as petroleum industry, petrochemical processes, extraction processes and biotechnology processes. Heat transfer to flowing immiscible liquid–liquid mixtures is often encountered in some equipment of these industries: transportation of oil–water mixtures, process pipelines, tubular reactors, heat exchangers, etc. In some of these industries, the change in flow patterns can be affect the flow behavior.

Some authors [1–5] stated that heat transfer to oil–water two-phase flow is more complex than single-phase flow because heat transfer in the two-phase flows depends not only on flow rate, fluid properties and geometry, but also on the flow patterns. Lang and Auracher [1] measured the phase distribution and the heat transfer coefficient for n-heptane-water flow in a vertical pipe. The results clearly showed that the two-phase heat transfer is controlled by the properties of the continuous phase. This means that the heat transfer to oil–water flow is dependent on the phase distribution.

In past few decades, heat transfer to liquid–liquid mixtures has been attempted only for some special flow patterns. Some studies resulted in recommendation of correlations for two-phase heat transfer coefficient in liquid dispersion systems. Wright [6] measured the overall heat transfer coefficient for liquid–liquid dispersions in a pipe. A petroleum solvent was used as the dispersed phase and the experimental data were correlated with the use of a Colburn type equation. Legan and Knudsen [7] investigated heat transfer of unstable liquid–liquid dispersions in a circular pipe. Two different oils (light and heavy oils) were used as the dispersed phase. They suggested an empirical equation to predict the heat transfer coefficient in turbulent flow ($Re > 60{,}000$). Somer et al. [8] studied heat transfer to a mixture of two immiscible liquids in co-current flow (with and without phase change). They concluded that the rate of heat transfer is dependent on volume percent of liquids. They also correlated their data with an equation which employs to prediction of the heat transfer coefficient in turbulent regime ($Re > 200{,}000$) for oil in water dispersions up to 50% oil.

There are some correlations for single-phase flow in literature which are applicable to predict the heat transfer coefficient of oil in water dispersions (o/w systems) and one of water in oil dispersions (w/o systems). Hapanowicz and Polaczek [2] and Dybek [3] compared the correlations against their experimental data for dispersion flow patterns and concluded that there is no method to predict accurately heat transfer of two-phase liquid dispersions for horizontal pipes.

There have been some attempts to try to model the heat transfer of oil–water flow in horizontal and vertical pipes [9–11].

This work is focused on forced convection heat transfer in horizontal pipe flow for different flow patterns experimentally. A correlation is also developed to predict the oil–water heat transfer rate for STMI and Dw/o & o/w flow regimes.

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Nomenclature

A_c	cross-sectional area of the element
C	Input fraction of each phase
c_p	specific heat (J kg^{-1} K^{-1})
D	pipe diameter (m)
F	friction factor
H	heat transfer coefficient (W m^{-2} K^{-1})
H	holdup (dimensionless)
I	current
K	thermal conductivity (W m^{-1} K^{-1})
L	length of test section (m)
l_i	element length of each station
N	sensor station number
Nu	Nusselt number ($h\ D\ k^{-1}$)
Pr	Prandtl number ($\mu\ c_p\ k^{-1}$)
$\bar{q}''$	local mean heat flux (W m^{-2})
q_{tot}	produced heat by the element
R	tube radius
Re	Reynolds number ($\rho\ U\ D\ \mu^{-1}$)
Re_s	superficial Reynolds number ($\rho\ U_s\ D\ \mu^{-1}$)
T	temperature (K)
U	actual velocity (m s^{-1})
U_s	superficial velocity (m s^{-1})
X	axial coordinate (m)

Greek symbols

Δ	difference
μ	viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
γ_i	electric resistivity of the element
σ	oil–water interfacial tension (N m^{-1})

Subscripts

b	bulk
E	wall
Exp	experimental
i	sensor station index
In	inlet or inside
Mix	mixture
O	oil
Out	outlet or outside
Pre	prediction
TP	two phase
W	water

Acronyms

Do/w & w/o	dispersion of oil-in-water and water-in-oil
o/w	oil in water dispersion
QCVs	quick-closing-valves
STMI	stratified flow with mixing at the interface
w/o	water in oil dispersion

Superscript

–	average

2. Experimental setup

Fig. 1 presents a schematic diagram of the experimental setup for heat transfer measurements and flow pattern visualizations in two-phase liquid–liquid flow in a horizontal pipe.

The average properties of processing fluids diesel fuel (as oil) and water are shown in Table 1. The two-phase oil–water flow system consists of a flow loop, data recording and acquisition system.

Each fluid was transferred from its storage tank with a pump to into the experimental liquid line, where two flow meters one with a maximum capacity of 1 l/min and the other with a maximum capacity of 10 l/min, attached to each flow line which was regulated through pin valves to control the flow rate of the fluid. The flow meters were calibrated with the fluids with accuracy of 1% full scale. Oil and water are moved into the heating test section after entered in the Y like-junction (Fig. 2). The water phase was allowed to enter from the bottom while the oil joined from the top to reduce the effect of mixing. In the heating test, flow enters the transparent section with 11 mm ID, 12.7 mm OD and 50 cm length to allow visualization of the flow pattern. The two-phase flow is heated in a copper pipe with a length of 1.8 m, under uniform heat flux provided by nickel-chrome wire an electric heater placed around the outer pipe wall. The heating test section was insulated by glass wool with the thickness of about 5 cm.

Fig. 3 indicates that the test section is 180 cm in length; the internal diameter is 11 mm and the thickness is 1.7 mm. fourteen thermocouples by PT 100 type (with accuracy of ±0.1 °C) are located on the outer surface of the test section at uniform interval of 25 cm tube. The inlet and outlet flow temperatures are measured separately using two thermocouples.

The data acquisition system used to record and store the temperature measurements was an ECD model 7200 data logger with 50 input channels in which connected to a PC.

Flow then passes through a second transparent section with 1 m length to ensure continuation of the same flow pattern before entering the heating section. The in situ water holdup also measured via quick closing valves (QCVs) technique that is placed at second observation section.

Finally the flow passing through the heat exchanger returns to the storage tank after being separated from the separator. At each run the fluid was flowed through the heated pipe for 10–15 min to ensure that a steady state had been reached.

High-speed camera (Panasonic, DMC-FT1) and visual observations were used to identify the flow patterns at various conditions. The camera used has shutter-speed of 60–1/1500 s. The camera was located 50 cm from the observation section.

In the experiments the water and oil superficial Reynolds numbers ranged from $Re_{sw} = 1350–13700$ and $Re_{so} = 300–3700$, respectively. In all runs, first oil wets the test section. Some researchers have reported that prewetting can affect oil–water flow behavior [12].

The experimental heat transfer coefficient is defined as:

$$\bar{h} = \frac{q''}{(T_w - T_b)} \tag{1}$$

where $\bar{h}, q''\ T_w$ and T_b denotes the local mean heat transfer coefficient, the local mean heat flux, the local mean temperature and the mean bulk temperature at the thermocouple station respectively. The q'' at the inner surface of station i can be calculated by:

$$q'' = \frac{q_{tot_i}}{\pi D \Delta x_i} \tag{2}$$

where Δx_i is desistance between two station i and $i-1$. The heat generated at each station is given by:

$$q_{tot_i} = \frac{I^2 \gamma_i l_i}{A_c} \tag{3}$$