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Flow patterns and volume fractions of phases during liquid–liquid two-phase flow in pipe bends

Marcin Pietrzak *

Opole University of Technology, Department of Chemical and Process Engineering, Mikolajczyka 5, 45-758 Opole, Poland

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ABSTRACT

This paper presents the results of research into hydrodynamics of horizontal two-phase liquid–liquid flow in pipe bends. The conducted research involved the observation of flow pattern formation and determination of volume fraction of the specific phases which were identified in the flow. On the basis of the results of experimental flow map was created for such flow and a method of calculating volume fractions of the phases was established. The testing was conducted in 180° pipe bends with the internal diameters of 0.016, 0.022, 0.030 m and the respective radius of curvature equal to 0.110, 0.154 and 0.210 m. The media applied in the measurements were machine oils Iterm 12 and LAN 15 as well as water.

1. Introduction

Chemical, petrochemical, food and pharmaceutical industries frequently apply flow of liquid–liquid mixtures. Pipe bends form elements of armature which are used to separate the flow of two-phase mixture by changing its flow direction. This, in turn, leads to the origin of secondary flows resulting in vortices of the flow which passes through a channel and results in disturbance to the structures of multi-phase flow. Moreover, the values of the volume fractions of the particular phases are also affected. Ultimately, such disturbance can adversely affect the operation and exploitation of a variety of apparatus, for instance heat exchangers, in which flow disturbance manifested by liquid film break on a wall can negatively influence the course of processes and even lead to failure in high-temperature energy apparatuses.

Two-phase flow of non-mixing liquids is a very complex phenomenon by its nature due to the occurrence of components of the mixture that are distinct in terms of their physical properties, their mutual effect on the interfacial surface and turbulence that is inherent in it. All phenomena which are specific to two-phase flow rate, including occurrence of many variable structures in the flow, effect of the reduction of pressure losses, various values of interfacial slippage, liquid phase inversion which accompany the appearance of liquid emulsions in two-phase mixture have not been comprehensively explored and described. Liquid–liquid two-phase flow in straight pipes has been well investigated both experimentally and theoretically. These topics are confined to the hydrodynamics of liquid–liquid flow through straight conduits namely vertical pipes (Govier et al. [1], Hamad et al. [2], Parda and Bannwart [3], Simmons and Azzopardi [4], Jin et al. [5], Jana et al. [6], Liu et al. [7], Rodriguez et al. [8]) and horizontal pipes (Lovick and Angeli [9], Chakrabarti et al. [10], Mandal et al. [11], Sotgia et al. [12]). These studies have explored flow regimes as well as pressure drop characteristics. Different measurement techniques have also been proposed to identify flow patterns for low viscous oil–water flow (Simmons and Azzopardi [4], Jin et al. [5], Jana et al. [6], Liu et al. [7], Rodriguez et al. [8]).

To the best of the author's knowledge no literature is available on oil–water flow through pipe bends despite the fact that pipe bends are common in process industries. Recently Sharma et al. [13,14] conducted a study of low viscosity oil–water flow through return bends. Extensive experiments were performed on three flow directions (up, down and horizontal flow). They applied kerosene oil (ρ_o = 787 kg m^{-3}, η_o = 0.0012 Pa s) and lubricating oil (ρ_o = 960 kg m^{-3}, η_o = 0.22 Pa s) as the oil phase and observed type of flow patterns and pressure drop. They were found to be independent of flow patterns for all cases. The correlation has been proposed for liquid–liquid pressure drop in a bend.

On the contrary, a number of investigations were performed on gas–liquid two-phase flow through pipe bends. Usui et al. [15] reported the phase distribution of air–water upflow through a U-bend of circular cross-section made of arylic resin, with 0.024 m inner diameter. Ulbrich and Witczak [16] investigated flow patterns during the flow of air–water across pipe bend of 0.025 m. Wang et al. [17,18,24] observed the influence of return bend on the flow patterns during air–water flow in pipes with a small diameter (0.0030, 0.0049 and 0.0069 m). They found that

* Tel.: +48 774498374; fax: +48 774498366.
E-mail address: m.pietrzak@po.opole.pl

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Nomenclature

d	internal diameter of pipe bend (m)
g	gravitational acceleration (m s^{-2})
t	temperature (°C)
u	superficial velocity (m s^{-1})
De	Dean number (–)
MAE	mean absolute error (%)
R	curvature radius (m)
Re	Reynolds number (–)
S	slip ratio (–)
Q	volumetric flow rate (m^3 s^{-1})
α	in situ mean volume fraction (–)
β	input volume fraction (–)
η	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
X	non-dimensional parameter (–)
x	mass flow rate ratio (–)

Subscripts

2P	two-phase mixture
o	oil
w	water
cal	calculated value
exp	measured value
W/O	dominant oil phase (water in oil)
O/W	dominant water phase (oil in water)

annular flow formation was more likely for tube diameters greater than 0.003 m. For a gas–liquid two-phase flow studies conducted by Chen et al. [19], Domanski et al. [22], Padilla et al. [25] considered different refrigerants and their vapor as the test fluids and attempted to predict the pressure drop which could be noted in a pipe bend. Kirpalani et al. [21] conducted visualizations for air–water mixtures in curved channels (0.001 and 0.003 m). Spedding and Benard [20] and Benbella et al. [23] investigated the air–water pressure drop in vertical 90° bend. Pietrzak and Witczak [26,27] investigated pressure drops and void fraction during horizontal flow of air–water and air–water–oil mixture through 180° pipe bends of 0.016, 0.022 and 0.030 m in diameter. They proposed a new method for determination of their values.

In the light of the above considerations, the present work is based on extensive experiments whose aim was to understand the hydrodynamics of oil–water flow through pipe bends installed in horizontal pipe. Three diameters of pipe bends bend were used and, consequently, three different flow directions, i.e. up-flow, down-flow and horizontal flow through these geometries are considered. The volume fractions of liquid–liquid two-phase flow in pipe bends are described in the paper for the first time.

2. Description of experiments

Figs. 1a and 1b show a diagram of the installation. The installation for the testing of hydrodynamics of flow in pipe bends consisted of gear oil pump type PZ 25 (9) and centrifugal water pump type Grundfos CR 10 (7), oil tank (10), water tank (8), mixing chamber (4), test section (2), separator (11) and a battery of rotameters type Rotameter and Kobold (6). The main element of the test stand was a test channel which was made of two straight plexiglas pipes (2), with the respective diameters d = 0.016, 0.022, 0.030 m and lengths L = 1.5; 3.5; 3.5 m, connected by bends. The radius of curvature was selected to ensure the radius of curvature equal to R/d = 7 while the bend angle φ is 180°. The measurement channel was mounted on a carrying plate (1). The plate could be rotated (1), as a result, it was possible to conduct testing for both horizontal flow conditions, both upward and downward. This study was focused only on horizontal flow. The oil tank was equipped with a mixer and a system of heaters. The heating apparatus ensured that the temperature of the oil was raised to the required level, which ensured that the assumed densities and viscosities were maintained. The volume flow rates were regulated by means of control valves type Zetkama (14) and both float and electronic rotameters. Pumps were used to circulate the media from the tanks into the mixer. The formed multi-phase mixture passed through a measurement channel and was subsequently drained into the separator, where the separation of the phases took place. The separated oil returned into the tank and was applied for further circulation, while water was disposed of into the drains.

Testing was conducted for oil–water mixtures in pipe bends with the internal diameters of: 0.016 m, 0.022 m, 0.030 m. The bend angles were equal to 180° with the curvature radius of 0.110, 0.154, 0.210 m. The oils applied were machine oil Iterm 12 and LAN 15 with the following range of physical properties: ρ_o = (875.5–884.5) kg m^{-3}, η_o = (0.02–0.528) Pa s. Table 1 contains a summary of the conditions in which testing was performed.

The regulation and measurement of the specific media applied a battery of rotameters. The applied devices were included both manual and electronic ones. For the case when rotameters were applied, the flow rate was measured directly, and the resulting values were recorded in measurement sheets. In contrast, for the use of electronic rotameters the specific signals were registered by a computer system designed for data acquisition and registration. The values of absolute and differential pressures were registered by means of measurement cards installed with Sitrans P DS III Siemens electronic pressure transducers (5). Beside the measurements of pressure drops and absolute pressures in various points in the channel, other measurements were made as well regarding the temperatures of the circulating media (temperatures were measured through a system of thermosteams) in order to register the properties of the components of the multi-phase mixture on the basis of measurements.

The registration of the parameters of two-phase liquid–liquid flow, including the flow rates of the specific components of the mixture applied a central computer based system (12) for acquisition and processing of the measurement data.

Observations regarding the development of the flow structures were undertaken along with the measurements of pressure drops. As a result, it was possible to directly compare the relations between these two values. The registration of the observed flow structures was performed by means of a digital apparatus type Canon 300 D (shutter speed of 1/4000 s) and a high resolution VDS Vosskühler HCC-1000 digital camera (resolution of 1024 × 1024 pixels, frequency of 1800 Hz). This made it possible to precisely analyze the flow patterns. The observation and registration of the structures was performed both in pipe bends and axial sections of the pipe upward and downward a local element in pipe sections in which steady hydraulic flow was observed.

The measurement of volume fractions of the phases was undertaken by means of quick closing valves. For this purpose the research applied pinch valves type Homatic (3). These valves operate by feeding compressed air through them. Compressed air is supplied into a valve and leads to the clamping of a flexible membrane inside the