Experimental Thermal and Fluid Science 81 (2017) 175–186

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Upward flow of air-oil-water mixture in vertical pipe

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ARTICLE INFO

Article history:
Received 18 January 2016
Received in revised form 13 October 2016
Accepted 17 October 2016
Available online 18 October 2016

Keywords:
Three-phase upward flow
Flow patterns
Void fraction
Pressure drop
Vertical pipe

ABSTRACT

The results of an experimental study into three-phase air-oil-water flow carried out in a vertical pipe with 0.03 m diameter are reported. The experiments were conducted with the input superficial phase velocity: water from 0.02 to 1.07 m/s, oil from 0.001 to 0.63 m/s and gas from 0.01 to 16.40 m/s. In order to investigate the influence of gas injection on an oil-water two-phase flow, the mean in situ phase fraction and pressure drop were measured. This was accompanied by performing flow pattern observations. Consequently, new methods were obtained with a practical potential for application in phase fraction and pressure drop predictions of gas-liquid-liquid three-phase flow through a vertical pipe. A good conformity between calculated and measured data in this work was obtained.

1. Introduction

Systems involving two or more phases which are often transported over long distances are commonly found in industrial applications. The simultaneous flow of mixture, which consists of two immiscible liquids and gas, occurs in many apparatuses of chemical and petrochemical industry, in installations for food industry as well as plastics industry. Flow like this takes place for example in condensers and evaporators of cooling devices, distillation and extractive columns, tubular reactors as well as in pipelines connecting the equipment used in petrochemical processing.

The reduction of pressure drop in liquid-liquid systems in a horizontal pipe resulting from a decrease in flow rates of fluid or resulting from adapting the diameter of pipe is in a majority of cases impossible due to technology related problems. This is opposite in contrast to the case of gas and liquid mixture flow where reduction of pressure drop without the decrease in a conveyed volume can be undertaken [1,35].

An important aspect of hydrodynamics of flows is connected with an adequate identification of the flow regime, and the ability to accurately predict void fraction and pressure drop offers an improvement of safety and overall performance in multiphase flow systems. The prediction of the pressure drop in such systems is very complex because of the large number of variables involved [2–8]. It can be expected that in order to establish appropriate relations between the flow rates, pressure drop and geometrical parameters of tubing in pipelines for upward three-phase flow can play a significant practical role in the industries in which we have to do with a vertical pipe layout.

Even though we are aware of the conditions occurring during the simultaneous flow of oil, water and gas in pipes, the conditions in pipelines and other production facilities have not been completely researched to this data. Most of the studies to date have focused on horizontal flows [9–11], only little attention has been paid to gas-liquid-liquid three-phase flow in vertical pipes.

Early works on the vertical gas-liquid-liquid three-phase flow for operating oil wells resulted in the description of correlations for pressure drop and undertaken by Poettmann and Carpenter [4] as well as Tek [7]. In other works, air, water and kerosene with a density of 810 kg/m3 and dynamic viscosity of 1.5 mPa·s were used as the liquid phases (e.g. Foreman and Woods [8]). In this paper, the study of the three-phase flow provided results for 0.019 m i.d. pipe. Authors considered separately the flow of gas and liquids mixture, on the basis on Zuber-Findlay [12] drift-flux model and described the void fraction of gas phase in kerosene-water-air three-phase flow.

The experiment reported by Shean [5] and Pleshko and Sharma [3] was performed in a 0.019 m i.d. and 0.051 m i.d. vertical pipe, respectively. Shean [5] studied the upward flow of both water-oil and air-water-oil mixtures and recognized flow patterns, void fractions and pressure drops for mixture velocities from 1.22 to 6.1 m/s and for oil in liquid volumetric ratio from 0 to 1. Shean [5] attempted to extend two-phase water-oil flow pattern map and frictional pressure drop prediction model elaborated by Govier et al. [13] to handle three-phase flow conditions. Pleshko and Sharma [3] tested the flow pattern transition models established for two-phase gas-liquid flow by Taitel et al. [14], Hagedorn and

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http://dx.doi.org/10.1016/j.expthermflusci.2016.10.021
0894-1777/

Nomenclature

A	cross section area of pipe (m^2)
d	internal diameter of pipe (m
G	mass flux density ($kg/(m^2s)$)
g	acceleration of gravity (m/s^2)
H	height of the three-phase mixture column (m)
p	pressure (Pa)
Re	Reynolds number (–)
V	volume (m^3)
Q	volumetric flow rate (m^3/s)
j	superficial velocity (m/s)
ΔP	pressure drop (Pa)
$\Delta P/H$	unit pressure drop (Pa/m)

Greek symbols

α	in situ average void/volume fraction (–)
β	input void fraction (–)
β^*	input volume fraction of liquid in three-phase flow (–)
η	dynamic viscosity (Pa s)
λ	friction factor (–)
θ	angle of pipeline (°)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

A	acceleration
$3P$	three-phase flow
cr	critical values
exp	measured value
g	gas
$g\text{-}3P$	relation between gas and three-phase mixture
H	hydrostatic
i	i-phase
inv	inversion phenomena
l	liquid
o	oil
p	predicted
R	frictional
w	water
$w\text{-}o$	relation between water and oil

Brown [15] and Duns and Ross [16] by contrasting them against the data for vertical air-water-oil three-phase. The research applied Exxon Isopar-V oil with a density of 814 kg/m^3, and a viscosity of 7.48 mPa s. Prior to entering a vertical pipe, the liquid phases were mixed to homogeneous conditions in a tank, which enabled the authors to classify three-phase flow patterns into gas-liquid two-phase flow patterns as bubble, slug and churn flows. The results were reported as a series of flow patterns map of average superficial liquid velocities against superficial gas velocities for different values of oil concentration in the liquid mixture.

Both studies by Shean [5] and Pleshko and Sharma [3] were concerned with the limitations and uses of two-phase flow models (for predicting flow pattern transitions, phase void fraction, frictional and total pressure drops) in predicting three-phase flow behavior. These authors concluded that two-phase conditions cannot be readily extended to the three-phase vertical flow and quantifies the limitations of using two-phase flow models and discussed the reasons for these discrepancies.

A more detailed study was undertaken by Woods et al. [8] and Spedding et al. [6] in a 0.026 m i.d. vertical pipe, which gave more details regarding the occurrence of specific flow patterns and how they affected the measured pressure drops and void fractions. Woods et al. [8] presented an equation for determining the transitional boundary between oil and water dominant flow patterns and change in total and separate void fractions in the form of series of complex curves showing the influence of input liquid flow rates, gas rates and flow patterns. They stated that the maximum liquid volume fraction existed at the phase inversion point.

Oddie et al. [17] and Shi et al. [18] performed steady-state and transient experiments with regard to water-gas, oil-water and oil-water-gas multiphase flows in a transparent pipe with a length of 11 m and a diameter of 0.152 m using kerosene, tap water and nitrogen. The experiments were performed at different flow rates and at eight deviations of a pipe in the range from vertical layout (0°) to 2 degrees downward (92°). The paper by Oddie et al. [17] reports extensive results for void fraction as a function of the flow rates, flow pattern and pipe inclination. The observed flow patterns and void fraction data compared with predictions from the Petalas and Aziz [19] in a mechanistic model. The authors stated that although the analyzed model was mostly based on data from small diameter pipes, flow patterns are predicted accurately. Void fraction predictions were less accurate but they were still at a reasonable level. Shi et al. [18] continued experimental investigations of Oddie et al. [17] and three-phase flow data for large-diameter inclined pipes used to determine drift-flux modeling parameters. The developed and applied two- and three-phase flow models include the impact of gas phase on oil and water volume fractions in three-phase flow inversion point. According to Shi et al. [18], this new model provides much more accurate predictions for oil and water void fractions in three-phase systems than were achieved by application of the previous models.

Descamps et al. [2,20] investigated the influence of gas injection and different types of injectors on phase inversion between oil and water flowing through a vertical pipe and on the pressure drop increase over the pipe during a phase inversion. Tests were performed in stainless steel pipe with a length of 15.5 m and an internal diameter of 0.0828 m. The salted water (brine) and oil (Vitrea 10) with a density of 830 kg/m^3 and a viscosity of 7.5 mPa s were used as the components of the liquid mixture. For different mixture velocities, only dispersed flows was observed (oil drops in water or water drops in oil). The results provided examples of phase inversion without gas injection as a source of results for reference. It was found that gas injection did not significantly change the critical concentration of oil in liquid but the influence on the pressure drop was considerable.

Fundamental difficulties in the elaboration of comprehensive three-phase flow models result in a necessity of properly defining the properties of the three-phase mixture. One of the possible considerations of three-phase flow is to combine oil and water into a single liquid phase; consequently, the flow model can be considered as a two-phase liquid-gas flow. In such a study, the slip between oil and water is ignored and the liquid phase is assumed to form a homogeneous mixture. The reports in some papers indicate; however, that a simple treatment of the problem can lead to significant errors in phase void fractions prediction [10], while other observations suggest that this approach is valid [21]. An alternative technique was proposed to model three-phase flow in wellbores [22]. This approach uses gas-liquid and liquid-liquid two-phase flow models. In the first stage of this model, gas-liquid-liquid three-phase flow is considered as a gas-liquid flow