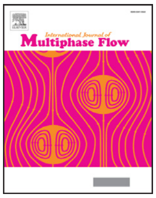
International Journal of Multiphase Flow 81 (2016) 1–14

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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



Effect of pipe rotation on downward co-current air–water flow in a vertical pipe

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ARTICLE INFO

Article history:
Received 22 July 2015
Revised 3 January 2016
Accepted 5 January 2016
Available online 12 January 2016

Keywords:
Two-phase flow
Image processing
Vertical pipe
Flow regime
Downward flow

ABSTRACT

The present research experimentally studied the effect of pipe rotation on the flow patterns of downward gasliquid two-phase flow. Two-phase flow patterns and their transition boundaries were observed and analyzed at different pipe revolutions. The experimental setup was fabricated to show flow patterns in a downward direction. The setup includes a transparent vertical pipe with a diameter of 50 mm and an aspect ratio (L/d) of 80 that can rotate at different speeds. Eight flow maps were obtained at revolutions of 0, 60, 120, 180, 240, 300, 400 and 500 rpm by changing the air and water velocities at any revolution (a total of 2205 points). The gasliquid downward two-phase flow regimes were analyzed using image processing. The experimental results were compared with published flow maps for vertical flow. It was found that pipe rotation has major effect on flow patterns map and their transitions boundaries. Increasing pipe rotation cause slug and annular flow start at lower V_{SG}.

Introduction

Gas–liquid two-phase flow is common in the petroleum industry, chemical engineering and other production processes. Prediction of the flow pattern of two-phase flow is essential for precise calculation of pressure drop, pumping power, convective heat and mass transfer, and other design parameters (Narinder, 1982). Most research has focused on analysis of horizontal and upward vertical flow and less attention has been made on downward vertical flow. Downward vertical flow plays an important role in drilling, the petroleum industry, in heat exchangers with U-type tubes, reactors, and boilers (Ozbayoglu and Ozbayoglu, 2007).

Correct calculation of important quantities depends on the type of two-phase flow regime. For example, under-balanced drilling of oil and gas wells requires prediction of two-phase flow patterns for precise calculation of bottom-hole pressure to prevent damage to the walls or well rupture (Tellez, 2003). Although some studies have investigated gas–liquid downward two phase flow, but no study has examined the effect of pipe rotation on downward two-phase flow. A few studies have examined flow patterns in annular space with a rotating inner tube.

Sadatomi et al. (1982) developed flow pattern maps for air–water vertical flow in noncircular channels. He developed flow pattern boundaries and compared their channel geometry. Hasan and Kabir (1992) investigated inclined annular space and estimated the void fraction during upward concurrent two-phase flow in annuli. They adopted a drift-flux approach to model the slip between phases and the transition between regimes. Caetano et al. (1992a) investigated the model developed by Taitel and Dukler for two-phase flow for concentric and eccentric annuli.

Flow patterns and frictional pressure loss in two-phase flow through a horizontal annulus with a rotating inner pipe were studied by Ozbayoglu and Ozbayoglu (2007). They used an artificial neural network (ANN), developed a mechanistic model, and compared it with experimental data. Ettehadi et al. (2013) studied three-phase flow in inclined eccentric annuli. They studied the characteristics of two-phase drilling fluid using cuttings as the third phase of inner pipe rotation. They showed that flow patterns are influenced by geometry and the presence of cuttings. Shiomi et al. (1993) studied two-phase flow in a concentric annulus with a rotating inner cylinder. They showed that increasing the rotating inner cylinder caused the bubbles to agglomerate and form a spiral flow. Flow visualization of a cross-section of the annulus showed

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.01.002

that spirals or rings of bubbles formed very close to the rotating inner cylinder.

Most studies examining the effect of pipe rotation on flow inside the pipe studied single-phase flow. Numerical study of viscous flow in rotating rectangular ducts was conducted by Speziale (1982). Reich and Beer (1989) examined the effects of tube rotation on the characteristics of turbulent flow. They found that rotation has a marked influence on suppression of turbulent motion from radially-increasing centrifugal force. Imao et al. (1996) examined the effects of tube rotation on the turbulent flow experimentally by using single-component laser-Doppler velocimetry. They showed that the intensity of turbulence in the rotating pipe decreased gradually as pipe rotation increased from the stabilizing effect of centrifugal force and that momentum transfer caused by turbulence is strongly suppressed in a rotating pipe.

Different methods have been used for flow pattern prediction in downward two-phase flow, although direct observation is common. Golan and Stenning (1969) predicted flow pattern maps of annular-mist, annular oscillatory, bubbly and slug flow. They stated that U-bends cause oscillatory flow and, without this section, the flow should not be considered downward. Oshinowo and Charles (1974) observed downward two-phase flow patterns using high-speed motion camera high speed motion photography. They studied the effect of fluid properties such as viscosity, density and surface tension on flow pattern. Their flow map classified six regimes: coring-bubble, bubbly-slug, falling film, falling bubbly-film, froth and annular flow.

Yamazaki and Yamaguchi (1979) observed and photographed flow patterns that were bubbly, slug, wispy, annular, and annular. They focused on annular flow with a smooth gas–liquid interface at low to medium air flow rates and called it "wetted wall flow". Recent studies, including the present research, have referred to this as "falling film" flow. Barnea et al. (1982) proposed a model for the prediction of flow pattern in downward gas–liquid two-phase flow based on mechanistic modeling and direct observation. They produced maps for a 2.5 cm ID pipe and a 5.1 cm ID pipe that depict only annular, slug, and dispersed bubbly flow regimes. The natural and dominant flow was annular and took the form of falling film flow at low gas flow rates and typical normal annular flow at high gas flow rates.

Kendoush and Alkhatab (1994) studied flow regimes in downward two-phase flow made with an isothermal air–water system and showed that they resulted in three distinct flow regimes: bubbly, slug, and annular, and that flow pattern transitions were observed to be fairly gradual instead of sharp. Lopez et al. (2010) examined gas entrainment by liquid falling film around a stationary Taylor bubble in vertical downward flow using videometry, image processing, and a wire mesh sensor. They measured the gas void fraction and bubble size distribution using a high speed camera perpendicular to the wire-mesh sensor measuring plane. Bhagwat (2011) experimentally investigated flow patterns and void fractions in vertical downward two-phase flow. Flow visualization confirmed the existence of the bubbly, slug, falling film, froth and annular flow patterns in the downward two-phase flow.

Usui (1989) experimentally studied downward two-phase flow. His previous research examined void distribution and average void fraction using a conductance needle probe for downward two-phase flow. He presented equations for each flow regime transition for bubbly, slug, falling film, and annular drop flow. Ishii et al. (2004) identified flow regimes for vertical downward concurrent air–water two-phase flow using an impedance void meter coupled with a self-organized neural network. The experimental test sections were round pipes with internal diameters of 25.4 and 50.8 mm. Jha et al. (2012) presented a new ultrasonic method for flow pattern classification that can be implemented in a variety of industrial applications.

Lee et al. (2008) developed an instantaneous and objective flow regime identification method for vertical upward and downward concurrent two-phase flow. Their design used preprocessed impedance signals of the cross-sectional void fraction to satisfy the requirements of both objective and an instantaneous identification. The experimental data for concurrent upward and downward two-phase flow in a two-phase flow loop of 25.4 mm ID and 50.8 mm ID was used to develop a flow regime map.

Almabrok (2013) studied gas–liquid two-phase flow in upward and downward vertical pipes experimentally. He examined the effect of 180° bends on flow in the straight part of the pipe and the liquid film behavior close to the bends on the characteristics and development of gas–liquid downward and upward two-phase flows in large diameter pipes. Julia et al. (2013) identified both global and local flow regimes in two-phase downward flow in a 50.8 mm internal diameter pipe under adiabatic conditions. They measured the bubble chord length distributions simultaneously using three double-sensor conductivity probes with a self-organized neural network for classification.

The present paper examined the effect of pipe rotation on flow pattern maps of downward vertical two-phase flow using high speed videometry and image processing. Flow patterns can be discovered by direct observation high-speed photography, X-ray and similar image processing techniques without the use of complicated methods requiring many sensors and instrumentation. These methods are less expensive than complicated methods and implementation is easy and more accessible.

Experimental setup

An experimental setup was constructed to show the behavior of downward two-phase flow. The experimental loop and apparatus is shown schematically in Fig. 1. Air and water were used as the gas and liquid phases in all experiments. The water was pumped from the main tank by a centrifugal pump. To prevent vibration in the system, six shock absorbers were mounted at the inlet and outlet of the pump (Hanafizadeh et al., 2011). The water flow rates were regulated by four valves and measured by two calibrated rotameters.

The compressed air at 8 bar of pressure was fed continuously from a large tank connected to the compressor. The air flow rates are measured by four calibrated rotameters. One valve was used to fine control air flow rate, especially at the low flow rate. Air and water were mixed in the mixing section. The mixer is a cylindrical porous stone connected to the inlet air pipe and inserted inside the water pipe as shown in Fig. 2.

The main pipe was 4 m in height with an internal diameter of 50 mm. The main pipe was composed of Plexiglas to allow observation of the two-phase flow patterns in whole pipe but the test section for taking the pictures was located close to the pipe end to make sure fully developed and stable flow. Actually, the test section was located around 3.5 m downstream of the mixer and 3 m downstream of the final bend in the setup as can be seen in Fig. 1. Therefore, the flow has enough distance to reach fully developed regime. Based on the turbulent flow correlation, the entrance length is around 0.5 m which is much less than the available length in the experiment. The visual observation, also, confirmed that the entrance effect was important only in the initial 0.5 m of the pipe and after that the flow was fully developed and stable.

The air and water mixture was drained into the main tank to be separated. The water storage tank was divided by a baffle to prevent turbulence in the suction side of the pipe. The temperature of the water was held constant under ambient conditions. The setup had the ability to rotate the pipe about its axis at different speeds. An electric gearbox, a shaft and two gears were used for rotation. The electromotor produced 1400 rpm and the gearbox converted