ELSEVIER

Chemical Engineering Science 62 (2007) 3032–3042

Chemical Engineering Science

www.elsevier.com/locate/ces

Effect of inclination on circumferential film thickness variation in annular gas/liquid flow

G. Geraci[a,1], B.J. Azzopardi[a,*], H.R.E. van Maanen[b]

[a]School of Chemical, Environmental and Mining Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK
[b]Shell Global Solution International, Upstream Sector, Advanced Production Management Team, P.O. Box 60, 2280 AB Rijswijk, Netherlands

Received 8 January 2007; received in revised form 22 February 2007; accepted 27 February 2007
Available online 12 March 2007

Abstract

Time-varying, circumferentially local liquid film thickness data have been collected on a 38 mm internal diameter pipe at inclinations of 0°, 30°, 45°, 60° and 85° from the horizontal using flush-mounted and parallel wire conductance probes. Analysis of these data permits time-averaged thicknesses, probability density functions, and power spectral densities to be determined. Results show that the distribution of the liquid film is not symmetrical with thicker films on the lower part of the pipe, which are dominated by large disturbance waves. Moreover, as the inclination angle deviates from horizontal, the film thickness distribution becomes systematically less asymmetric. The probability density functions show a strong narrow peak where the liquid film is less disturbed by the presence of waves. The power spectra show that a large portion of wave energy at the bottom is carried by waves of frequency $\leqslant 12$ Hz. There is no influence of liquid velocity on the shape of the spectra. However, the dominant frequency appears to decrease with increasing liquid flow rate. The frequency of the disturbance waves at the bottom decreases with increasing inclination. Moreover, the spectra tend to flatten out with increasing inclination, due to the more uniform distribution of energy among waves of a broad frequency range.

Keywords: Gas–liquid flow; Annular flow; Film properties; Disturbance waves; Pipe inclination

1. Introduction

Annular flow is one of the most common flow patterns encountered in natural gas well-bores and pipelines. It occurs at high gas and low to medium liquid flowrate and at all pipe orientations. In this configuration, some of the liquid travels as a film on the channel walls and the remainder is carried as drops by the gas. The fraction of liquid travelling as drops can vary from zero to close to one. The interface between the gas core and the liquid film is usually very wavy, and atomization and deposition of liquid droplets occur through this interface. In the literature, information on circumferential variations of liquid film thicknesses in two-phase flows is almost exclusively for horizontal or near horizontal pipes. Only Paz and Shoham (1994) provide such data for steeply inclined pipes. They found that significant changes in the thickness variation occur as the inclination angle varies from vertical through inclined to horizontal flow conditions. As the pipe is inclined from the vertical to off vertical, the film thickness distribution becomes systematically circumferentially non-uniform. In contrast, Azzopardi and Zaidi (1997), Azzopardi et al. (1997) found that inclination had only a small effect on the fraction of liquid travelling as drops and on the drop size. However, the film thickness variation might be expected to have a significant effect on the liquid hold-up and pressure drop in the system and must be allowed for in the design of pipelines, wellbores, and separation facilities. There is still a question unanswered regarding the dominant mechanism for the maintaining of a film at the top of the pipe. Gravity will cause any film to drain. Obviously, droplet entrainment, especially from the lower part of the pipe, and their subsequent redeposition at the top contribute to the maintenance of that liquid film. Butterworth (1972) argued that the magnitude of droplet deposition rate is insufficient to sustain the film

* Corresponding author. Tel.: +44 115 951 4167; fax: +44 115 951 4181.
E-mail address: Barry.Azzopardi@nottingham.ac.uk (B.J. Azzopardi).

[1] Present address: University of Tulsa, TUHFP, 2450 E. Marshall, Tulsa, Oklahoma 74110.

0009-2509/$ - see front matter
doi:10.1016/j.ces.2007.02.044

at the upper part of the pipe and suggested a wave spreading mechanism to interpret his observation. Waves at lower part of the pipe are considered to be deformed, with the front (right at the bottom) moving faster. The impact pressure of the gas on such waves gives rise to forces acting in the circumferential direction, which can then transfer liquid in that direction against gravity. Other proposed mechanisms are attributed to the complicated gas–liquid wave interactions. Laurinat et al. (1985) and Lin et al. (1985) took the occurrence of a secondary flow in the gas and the related circumferential interfacial stresses into account. Laurinat et al. (1985) concluded that these stresses (due to circumferential fluctuations in the film) are primarily responsible for moving liquid to the upper part of the pipe. Lin et al. (1985) proposed that both the secondary flow and the entrainment/deposition mechanisms are important. By adjusting various parameters in these models, good agreement was obtained between predicted and measured film thickness distributions. Fukano and Ousaka (1989) modified the model of Laurinat et al. (1985) to include the effect of the waves on the liquid surface. Their model is based upon a disturbance wave flow model, which consists of disturbance waves and a base film. The liquid is transferred in the circumferential direction by the pumping action of disturbance waves, which counteracts the drainage due to gravity. Fukano and Ousaka (1989) assumed the interfacial shear due to secondary flows and the surface tension force to be negligible. Azzopardi (2006) has drawn together the information on the diverse models and shows that models with very different assumptions can all give good predictions of experimental data.

2. Experimental facilities

The annular two-phase flow experiments were carried out on an inclinable rig in the Chemical Engineering laboratory of the School of Chemical, Environmental and Mining Engineering, University of Nottingham. The pipe was mounted on an inclinable beam so that it could be positioned at any angle between vertical and horizontal. The distance between the injection point of the liquid, introduced as a film, and the test section was 132 pipe diameters long, which, over the range of flow rates studied, provided well-developed annular flow, Fig. 1. The experiments concentrated on a small range of gas mass flowrates, motivated by the rest of the wider project on wet-gas metering of which this was a part. The gas and liquid mass flowrates ranged, respectively, from 0.03 to 0.04 kg/s and 0.0079 to 0.0899 kg/s. The pressure in the test section ranged from 1.3 to 1.5 bars absolute. Air was supplied from the laboratory compressed air mains (pressure = 6 bar) and its flow rate was measured by an orifice plate and controlled by valve V1, Fig. 1. Water was taken by a centrifugal pump from a 300 l supply tank and its flow was metered by one of the three calibrated rotameters. After passing down the length of the inclinable beam, the water entered into the main pipe through a porous wall located 0.5 m from the start of it. Valve V2 on the two-phase exit line upstream of a disengagement tank allowed a constant pressure to be set at the end of the pipe. The air/water mixture was separated in a large vessel. Air was released to the atmosphere and water was returned to the supply tank.

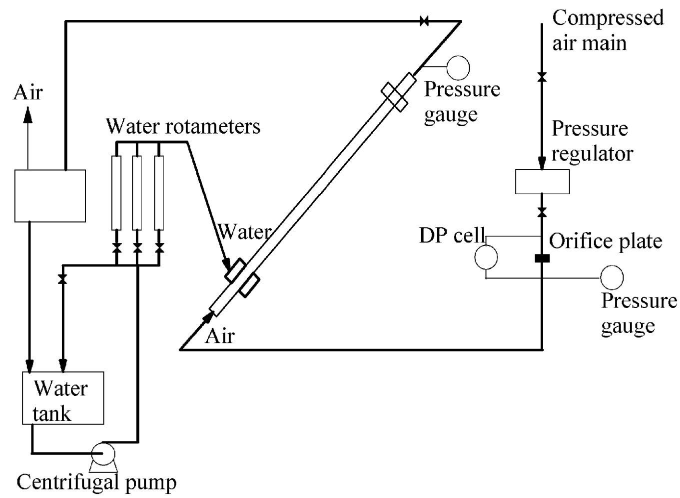

Fig. 1. Schematic arrangement of the inclinable flow facility.

3. Measurement methods

The types of probe employed in this study were chosen on the basis of their range of operability and previous visual observations of flow patterns in pipes. The liquid film in annular flow was observed to be asymmetrical with a thick pool at the pipe bottom and a thin film at the top. Film thickness measurements were carried out using a conductance technique, which employed either flush-mounted probes or wire-pair probes. The first type was used for the entire section of the pipe. The second type, suitable for higher film thickness, was used only for the bottom side.

3.1. Flush-mounted probes

The test section containing the flush-mounted probes used for the liquid film thickness measurement was a 17 mm long pipe of 38 mm internal diameter, Fig. 2. The pins were positioned at one extremity of the pipe, 3 mm from the flange. The linear distance between the pins was 5 mm around the circumference. The pins (1.5 mm diameter) were made of stainless steel to avoid problems of corrosion. They were glued in precision machined holes and mounted flush to the internal surface of the pipe. However, the electrodes were not perfectly flush and further machining was needed. Pairs 3(2) and 5(1) were used by switching the connections so that the intermediate pin could be coupled with two different probes. The sequences of pairs of the test section are shown in Fig. 2.

The resistance between pairs of flush mounted was measured. Obviously, this depends on the film thickness and the conductivity of the liquid. The measurements were converted to film thicknesses using calibration curves obtained as described below. Liquid conductivity was monitored and the appropriate calibration curve was used. The arrangement employed an