International Journal of Multiphase Flow xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Experimental and modelling studies of gas–liquid vertical annular flow through a diverging section

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Gas–liquid flow
Vertical annular flow
Diverging pipe section
Abrupt expansion
Interfacial friction
Pressure drop

ABSTRACT

Gas–liquid annular flow through a vertical circular pipe is well-understood and detailed phenomenological models exist in the literature. In the present work, the case of flow through a diverging section is studied experimentally and theoretically. Experiments have been carried out in air–water flow through a vertical diverging pipe section with a diameter ratio of 1.5 and 2.0. Pressure profiles have been recorded upstream, across and downstream of the diverging section for the cases of sudden expansion and gradual expansion with included half-angles of 8° and 15° for the diverging section. These show that the pressure variation is characterized by a strong pressure recovery downstream of the expansion which is in turn influenced by the smoothness of the expansion and the interfacial friction. The non-dimensionalized pressure loss across the expansion, which has been determined by extrapolating the pressure variations upstream and downstream, is found to vary systematically with the diameter ratio, the angle of the expansion and the ratio of superficial liquid-to-gas Reynolds numbers. A method, which uses the equilibrium annular flow model and an empirically determined expansion pressure loss coefficient, has been developed for the prediction of the pressure variation across the diverging section.

1. Introduction

Two-phase gas–liquid flows occur widely in many industrial processes, such as steam generators, reboilers, gas–liquid contactors and oil and gas transport. Except in some very limited range of parameters, the structure of two-phase flow is quite complicated and is governed largely by the extent of inter-phase interaction. Depending on several factors, which include geometric orientation, flow rates and fluid properties, the two phases are distributed in distinct structures known as flow patterns (Collier, 1981). One of the most prevalent of these is the annular flow pattern in which the liquid flows partly as a thin film on the channel wall and partly as drops entrained in the gas core. Annular flow is characterized by a large convective heat transfer coefficient and is the desired flow pattern in many instances of gas–liquid transport. The end point of annular flow in a steam generating tube is associated with the important phenomenon of dry-out (Hewitt and Hall-Taylor, 1970) which occurs when the liquid flowing along the wall is completely evaporated. This leads to a sudden deterioration of the wall-to-fluid heat transfer mechanism leading to large and sudden changes in wall temperature (Hewitt et al., 1965). Its potentially deleterious consequences in a nuclear accident scenario have led to intense studies of annular flow with marked early contributions coming from Hewitt and co-workers (Hall-Taylor et al., 1963; Hewitt et al., 1964; Cousins et al., 1965). The two-phase, three-fluid nature of annular flow was established through measurements of the characteristics of the film and the droplet fields leading eventually to the establishment of the triangular relationship in annular flow (Wallis, 1969; Hewitt and Hall-Taylor, 1970; Collier, 1981). Measurements of drop sizes (Azzopardi, 1997), film thickness (Hewitt and Lovegrove, 1969) and phase velocities (Gill et al., 1964) along with pressure gradient enabled the development of rate laws for the dynamic processes of entrainment and redeposition of droplets which have led to the successful prediction of dry-out in tubes and rod bundles in nuclear reactors (Hewitt and Govan, 1990). These have later been used to develop a one-dimensional, two-phase, three-fluid model for annular flow which was used to predict dry-out and post-dryout heat transfer in tubes (Jayanti and Valette, 2004) and rod bundles (Jayanti and Valette, 2005) over a wide range of operating pressures and mass fluxes. Thus, it can be claimed that gas–liquid vertical annular flow in a straight tube is well-understood qualitatively and quantitatively. However, its detailed flow structure is still a subject of fascination, as evidenced by the use of more and more sophisticated techniques being used lately to understand the nature of interfacial waves (Zhao et al., 2013; Zadrazil et al., 2014).

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.05.009
0301-9322/© 2014 Published by Elsevier Ltd.

The present work is aimed at understanding the response of the fully developed vertical annular flow to a diverging section. Apart from its practical relevance, such flow situation is of academic interest as it provides a good test case for studying the different responses of the three constituent fields, namely, the gas field, the droplet field and the film field, to a change in the area of cross-section. A measure of the expected changes can be obtained from Table 1 which shows the predictions of annular flow model (see Section 3 below) for fully developed flow in vertical tubes of 0.025 and 0.050 m inner diameter with the same air and water flow rates going through each tube. The characteristic parameters of each field, namely, the film thickness and the liquid film velocity, the fraction of the liquid flow entrained in the form of droplets, the average velocity of the gas phase and the overall pressure gradient, are given in each tube; these parameters may therefore represent the upstream and the eventual downstream flow parameters following a pipe expansion from 0.025 m to 0.050 m. The values calculated for the case of gas and liquid superficial Reynolds numbers of 132,000 and 8500, respectively, are given. One can see that important features which represent the hydrodynamics of annular flow, namely, the entrainment fraction (and hence the film flow rate), the film thickness and the gas velocity, undergo large changes as the flow expands into the larger pipe. The substantial decrease in the entrained droplet fraction in the larger pipe implies significant redeposition after the expansion; a fourfold decrease, coupled to a twofold increase in the diameter, would lead to a 32-fold decrease in the pressure gradient in single phase flow. The liquid film velocity, which depends on the interfacial shear stress, would also be severely reduced despite the increased deposition. The liquid film thickness increases despite the twofold increase in the diameter (and hence the perimeter).

The possible response of the gas–liquid vertical annular flow across the expansion can thus be described with the help of Fig. 1 as follows. In the case of a sudden expansion (Fig. 1a), the flow expands and forms a jet at downstream in the larger pipe. The strong recirculation zone immediately downstream may cause significant deviations from the rates of entrainment and redeposition of drops in a straight pipe. Significant redeposition of the excess droplets in the larger pipe may occur in this region. The flow will gradually adjust to the fully developed annular flow status after the reattachment of the separated flow. In the case of a gradual expansion (Fig. 1b), both the liquid film and the droplet-laden gas have an opportunity to make a smoother transition to the fully developed status in the larger pipe with a thicker liquid film and lesser concentration of droplets in the gas core. Due to the large change in the gas velocity, there will be significant accelerational pressure variation within the diffuser section. The overall pressure variation across the diverging section would thus represent the net effect of interfacial friction-induced pressure loss and pressure recovery arising out of velocity reduction. When the former is low, as would be the case for low liquid flow rates, the pressure recovery component would dominate the pressure variation. At high liquid flow rates, the interfacial friction, though of decreasing magnitude, may still prevail over the pressure recovery.

Despite these interesting possibilities offered by the flow situation, the case of vertical annular flow through a diverging section does not appear to have received much attention in the literature. Early work on the flow through an abrupt expansion (Lottes, 1961; Jansen and Kervinen, 1964; Chisholm and Sutherland, 1969) focused on the prediction of pressure drop using homogeneous or separated flow models, the latter using a correlation for void fraction. Wadle (1989) included his own steam–water and air–water data for pressure drop in steep diffusers and proposed a correlation for the pressure drop using a separated flow model. Attou et al. (1997) presented a detailed analysis of bubbly flow through a sudden expansion using a slip-velocity based model and considered two limiting possibilities for the interaction of the two phases during the transition: the case of mechanical equilibrium corresponding to an infinite interfacial transfer coefficient and the case of mechanical frozen flow, in which it is assumed that no momentum transfer occurs between the phases. They proposed a new model which accounted for interfacial drag between the two phases and found that it compared favourably with their own and literature data. Flow pattern-specific models have not been reported for conventional pipe flows. There have been a number of studies in two-phase flow in small, mini- and micro-channels (Triplett et al., 1999; Ghiaasiaan and Abdel-Khalik, 2001; Cheng and Mewes, 2006; Omebere-Iyari and Azzopardi, 2007). The pressure loss in abrupt expansions and contractions in mini channels has been studied using homogeneous and separated flow models extensively by Abdelall et al. (2005) and Chalfi and Ghiaasiaan (2008), among others. Roul and Dash (2011) presented a computational model for gas–liquid flow through expansions and contractions in pipes of 1.6 and 0.84 mm pipes. Yang et al. (2001), Ahmed et al. (2008) and Kourakos et al. (2009) studied the flow development downstream of a horizontal sudden expansion.

The objective of the present work is to develop a model for the pressure variation specifically for the case of vertical annular gas–liquid flow through an area expansion focusing on the dynamic processes mentioned previously. To this end, experiments have been conducted to measure the pressure variation across an abrupt pipe expansion and for two gradual expansions over a range of air and water flow rates for expansion diameter ratios of 1.5 and 2.0. The results have been compared with the predictions of a phenomenological model of annular gas–liquid flow under two limiting cases (which are similar to those made by Attou et al. (1997) for horizontal bubbly flow through an expansion). Using these results, a model for the expansion pressure loss coefficient is proposed.

2. Experimental studies

The experimental set-up used for the pressure profile measurement is shown schematically in Fig. 2a. It consists of a vertical pipe section of 0.025 m inner diameter which is attached to another pipe section of 0.038 or 0.050 m inner diameter through a transition section of half included angle of 8° or 15°, both of which correspond to a gradual expansion, or without a transition section, which corresponds to the case of an abrupt enlargement of the cross-sectional area (Fig. 2b). Flow development lengths of 1.5 m have been provided on either side of the diverging section. Air is introduced axially from a compressor through an air filter and an orifice plate. Water is drawn from a tank through a water filter and is pumped through a bank of rotameters into the test section through a porous device used earlier by Vijayan et al. (2001) for their flooding studies. This ensures that water enters as a film all around the inside tube wall and is carried upwards by the air. In the experiments, the air flow rate is always kept well above that

Table 1
Comparison of predicted annular flow parameters upstream and downstream of the diverging section for air–water flow at ambient pressure.

	Upstream (0.025 m ID)	Downstream (0.05 m ID)
Re_{LS}	8500	4250
Re_{GS}	132,000	66,000
Entrainment fraction	0.57	0.12
Film thickness (mm)	0.088	0.44
U_{GS} (m/s)	85	21.5
Pressure gradient (N/m)	16,600	660
U_L (m/s)	6.80	1.38
Re_L	3650	3740

Please cite this article in press as: Anupriya, S., Jayanti, S. Experimental and modelling studies of gas–liquid vertical annular flow through a diverging section. Int. J. Multiphase Flow (2014), http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.05.009