A STUDY OF FLOW PATTERNS FOR GAS/ LIQUID FLOW IN SMALL DIAMETER TUBES

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Abstract: Time resolved void fraction data and flow pattern information have been obtained for two-phase air/water flows in a small diameter (5 mm) vertical pipe using conductance probes. The time averaged void fractions are seen to agree with values measured using a completely different approach.

Analysis of high speed videos reveals that the probability density function (PDF) technique is inadequate for accurately delineating the transition between slug and churn flows but performs better for the churn to annular flow transition. Instead a novel approach has been developed for transitions between flow patterns using the velocity of structures. This gives good agreement with the present experiments. Additionally, a modification to the bubble-to-slug flow transition of Taitel *et al.* (1980) gives improved predictions in narrow passages.

A flow pattern specific method for void fraction prediction has been applied and its predictions are in good agreement with the measured mean void fraction. The slug flow model gives better predictions of void fraction in churn flow that the annular flow model.

The velocities of disturbance waves on the wall film in annular flow are well predicted using the model of Pearce (1979). However, pipe diameter dependence of one of the constants is required.

Keywords: two-phase flow; flow pattern; void fraction; small diameter; vertical pipe; conductance probes; compact heat exchanger; nuclear fuel bundles.

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INTRODUCTION

Two-phase flow in one form or another exists in at least 60% of all process industry heat exchange equipment (Hewitt, 1981). However, most available data has been obtained for tube diameters typical of shell and tube exchangers. Two-phase flows in a small diameter tube have become important for compact heat exchanger applications and for nuclear reactors with tight passages. Compact heat exchangers are increasingly being applied to the chemical and process industries because of the significant benefits they offer. The national energy saving potential of this technology has been estimated to be worth 8 PJ year^{-1} (ETSU, 1994). They are used because of their greater effectiveness, smaller volume, improved safety and power savings when compared to most conventional heat exchanger types.

Much of the published information on two-phase flow characteristics have been confined to conduits with diameters greater than 20 mm. However, Oya (1971), Barnea *et al.* (1983), Wambsganss *et al.* (1992), Bao *et al.* (1994), Holt *et al.* (1999), Cheng and Lin (2001) and Okawa *et al.* (2004) are some of the researchers to have worked with tubes of smaller diameters. The recent review papers by Cheng and Mewes (2006) and Thome (2004) show that the challenges of exchanging heat with smaller surface areas such as those encountered in electronic devices are increasing research interest in fluid flow in small diameter channels. Barnea *et al.* (1983) found the pipe diameter effect to be minimal for upward air/water flow in vertical tubes with diameters ranging from 4 to 12.3 mm. Holt *et al.* (1999) used circular and non-circular channels with hydraulic diameters ranging from 3.9 to 10 mm to collect two-phase pressure drop and void fraction data in order to investigate typical conditions found in compact evaporators. The CISE (Premoli *et al.*, 1970) and Lockhart/Martinelli correlations were found to accurately predict the circular void fraction data only. Although the results obtained were compared with a novel flow pattern specific method, the flow patterns transitions were not studied. Cheng and Mewes (2006) conclude that any future research should include studies of two-phase flow pattern transitions in small and mini channels.

Workers including Hibi *et al.* (2000), Okubo *et al.* (2000) and Sakashita *et al.* (1999) report that several nuclear installations expect to attain high conversion ratios by reducing the moderation of neutrons. This results in the decrease of the core water volume and corresponds to a reduction in the cross-sectional area of flow channels. Okawa *et al.* (2004, 2005) working with a tube whose inside diameter is 5 mm, obtained experimental data of the deposition rate and entrainment fraction in annular flow to investigate the onset of critical heat flux condition, which is essential to the aforementioned nuclear power plants.

All heat exchanger design involves optimizing heat transfer and pressure drop characteristics, both of which are affected by the various two-phase flow patterns. Although the pressure drop characteristics are often overlooked, the mechanical pumping power expended to overcome friction and gravity is sometimes equal to that consumed in heat transfer when dealing with gases. It has been reported (Kays and London, 1998) that this mechanical energy is worth four to 10 times its heat equivalent in most thermal systems. In essence, mechanical energy can be transformed into heat with maximum efficiency (e.g., through friction) but when converting heat into mechanical energy (e.g., in a power station) some of the energy will be lost and 100% efficiency is never attainable. As a consequence, knowledge of the void fraction is useful because it is required for determining the acceleration and gravity components of pressure drop, from which the frictional component can be inferred.

In the present study, void fraction data and flow pattern information have been obtained from a small diameter (5 mm) pipe. High-speed video pictures, time-varying void fraction data and probability density functions (PDFs) have been used to discriminate between the various flow patterns. An empirical flow pattern map for the conditions of our experiment has been developed and compared with the most commonly used correlations for flow pattern transitions in two-phase vertical upflow. The velocities of the various structures present in the flow were determined and have been compared with the relationship proposed by Nicklin *et al.* (1962) and Pearce (1979) for slug velocity and the velocities of disturbance waves on wall film respectively. Some of our data has been taken in similar conditions to those of Holt *et al.* (1999), who used the method of quick closing valves for void fraction measurements. The results from the two sets have been compared. The mean void fraction values obtained have been tested against a flow pattern specific method to assess its predictive capability.

FLOW PATTERNS

Flow Pattern Classification

The classification of flow patterns in co-current vertical gas–liquid systems, by Hewitt and Hall-Taylor (1970), into four major groups: bubble, slug, churn and annular flow is now widely accepted. These flow patterns are depicted in Figure 1.

In bubble flow, the gas phase is approximately uniformly distributed in a continuous liquid phase in the form of discrete bubbles. Slug flow occurs at slightly higher gas flow rates. In this flow pattern, most of the gas phase is situated in large bullet shaped bubbles referred to as ‘Taylor bubbles’. Successive Taylor bubbles are separated by liquid slugs that bridge the pipe and usually contain small gas bubbles. Churn flow is a more chaotic, frothy and disordered version of slug flow which occurs at still higher gas flows. The shape of the Taylor bubbles is distorted resulting in narrower bubbles and the direction of the liquid phase in churn flow is oscillatory or alternating. Annular flow is characterized by continuity of the gas phase along the pipe in the core, occurring at the highest gas flow rates. Liquid flows in the upward direction, both as a thin wavy film and as entrained droplets in the gas core.

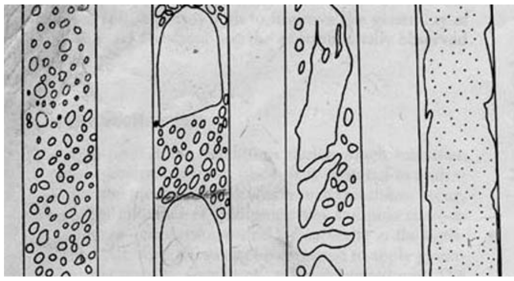

Figure 1. Bubble, slug, churn and annular flow patterns (Taitel *et al.*, 1980).

Flow Pattern Transitions

The widely applied models by Taitel *et al.* (1980), Jayanti and Hewitt (1992) and Barnea (1986) for the bubble-to-slug, slug-to-churn and churn-to-annular flow transitions respectively are to be tested to determine their suitability for small channels of similar size to those found in compact heat exchangers.

Taitel *et al.* (1980) postulated that discrete bubbles combine into larger vapour spaces whose diameter approximates to the tube by agglomeration. This is assumed to occur as the void fraction reaches 0.25 and results in a transition to slug flow.

Jayanti and Hewitt (1992) concurred that the flooding mechanism appears to be the most likely cause of the transition from slug to churn flow in vertical tubes and suggested an improvement to the modelling of the flooding mechanism given by McQuillan and Whalley (1985) which was capable of predicting the transition over the full range of liquid rates. Watson and Hewitt (1999) found that the model of Jayanti and Hewitt (1992) gives better predictions of the slug-to-churn flow transition than the methods by McQuillan and Whalley (1985), Mishima and Ishii (1984) and Brauner and Barnea (1986) in a 32 mm diameter tube.

The model for the transition from annular to intermittent flows (slug or churn) developed by Barnea (1986) is proposed to occur when the gas core is blocked at any location by the liquid. There are two mechanisms by which this blockage may occur. The first mechanism which predominates at low liquid flow rates is results from the instability of the annular configuration while the second mechanism is caused by spontaneous blockage of the gas core as a result of axial transfer of liquid in the film.

Flow Pattern Specific Model for Void Fraction

Published models in the literature for predicting void fraction in slug and annular flows have been applied to the present work. For churn flow, which is the least understood flow pattern intermediate between slug and annular flows, both models have been applied to determine the most appropriate.