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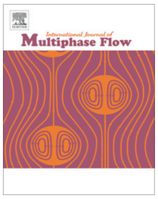

A new type of flow structure in cocurrent adiabatic vertically downward air–water flow: Membrane flow

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ABSTRACT

A new type of flow structure has been observed in cocurrent adiabatic vertically downward air–water flow and is described here. Membranes, in the form of thin liquid films spanning the channel cross-section and horizontally dividing the gas core were visualised over a wide range of air and water flow rates. Videos recorded with a high-speed digital camera showed that these membranes formed by the coalescence of dispersed bubbles, from the interaction between large entrained bubbles and the annular liquid film, or from the shrinkage of the liquid slugs. The objectives of this paper are to describe the characteristics of these membranes, to present how they interact with other two-phase flow structures, and to investigate how they form and develop as they are convected along the annular liquid film by the air core. The influence of the air–water mixer, the test section geometry, and the operating conditions on the formation of these thin liquid membranes are also assessed.

1. Introduction

Past research on two-phase flows in cocurrent adiabatic vertically downward channels has highlighted the existence of a rich variety of flow structures such as annular flow, slug plus bubbly flow, and bubbly flow (Golan and Stenning, 1970; Oshinowo and Charles, 1974; Spedding and Nguyen, 1980; Barnea et al., 1982; Yamaguchi and Yamazaki, 1984; Crawford et al., 1985; Usui and Sato, 1989; Usui, 1989; Kim et al., 2004; Ishii et al., 2004; Lee et al., 2008). In the present study, we present a new type of two-phase flow structure identified as *membrane flow*. This flow phenomenon was found to exist over a range of air–water flow rates within the annular and the slug plus bubbly flow regimes of the system. They comprised very thin liquid films that spanned the entire tube cross-section thus axially dividing the gas core into compartments. These liquid lamella were attached to the liquid annular film by meniscus like Plateau borders, and were convected downstream by the air core.

Previous studies on two-phase flows of relevance to this study include Serizawa et al. (2002) who observed a liquid ring flow structure in their microchannels. They suggested that these liquid rings formed due to shrinkage of the liquid slugs existing between consecutive gas bubbles, until they formed an unstable liquid bridge that collapsed to form a liquid ring which then dispersed slowly into the annular liquid film. Such liquid ring flows have not been observed in mini or macrochannels under normal gravity conditions. However, Rezkallah (1998) observed a frothy slug-annular flow structure that is similar to liquid ring flow under microgravity conditions.

Due to its physical characteristics, membrane flow has similarities with the flow of soap films through narrow channels. In particular, a recent study by Dollet and Cantat (2010) observed the dynamics of isolated soap films pushed through wetted inclined narrow tubes at velocities up to 2.47 ms^{-1}. Their soap films were produced by injecting nitrogen through a stationary reservoir of sodium dodecyl sulphate (SDS), glycerol and water; therefore their liquid flow rate was negligible. The surface tension of this aqueous soap solution was approximately half that of the clean filtered deionized water used in the present study, with a dynamic viscosity approximately 20% greater. Furthermore, other studies have shown that channel materials, channel geometries, inlet devices and fluid properties have a strong influence on foam formation and characteristics in micro-fluidic devices. In particular, a membrane flow like foam pattern has been observed in microchannels and defined as the *bamboo/hex-one* foam regime (Raven et al., 2006; Raven and Marmottan, 2009).

The objectives of this paper are to describe the characteristics of the observed membrane flow, to show how it interacts with other two-phase flow structures, and to describe how it develops as it is convected downstream from the test section inlet.

2. Experimental apparatus

Schematics and photographs of the cocurrent adiabatic vertically downward air–water experimental facility used in this study are shown in Fig. 1; for further details see Milan et al. (2013). The test section was made from a round Plexiglas tube with an internal

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diameter of $D = 8.8$ mm. The total length of the test section was 2000 mm; equivalent to approximately 227 tube diameters. Two different inlet devices were implemented in this study: Firstly, we used a 'ball mixer' made from an 80 mm long copper tube with an 18 mm internal diameter filled with 3 mm diameter Plexiglas balls, as shown in Fig. 1(c). Water entered the mixer axially from the top whilst air was introduced by three 2 mm diameter holes positioned equidistantly around the perimeter of the mixer. This mixer generated a randomised dispersed bubble flow which then developed as it flowed downstream. Secondly, we implemented a coaxial injector comprising a water reservoir in which the water entered from the top and flowed through flow straighteners before entering the test section, as shown in Fig. 1(d). Air was then injected axially into the core of the test section from a concentric co-axial tube. This annular mixer was specifically designed to obtain a clean annular flow at the inlet. The system was fully automated to control and regulate the air and the water flow rates, respectively denoted as Q_G and Q_L. Superficial air and water velocities were respectively defined as $U_{GS} = 4Q_G/\pi D^2$ and $U_{LS} = 4Q_L/\pi D^2$. Due to the nature of the observed flow phenomena and their sensitivity to surface tension forces, clean filtered deionized water was used during the tests. Furthermore, the system was flushed beforehand for long periods of time to remove contaminants and to avoid the presence of surfactants. Throughout the experiment, the air was maintained at atmospheric pressure at the outlet of the test section by an open reservoir, and the air and water temperatures were maintained at 25°C. A high-speed PHOTRON Fastcam SA3 digital camera was used to record the flow at various locations z along the test section that was uniformly backlit with a LED panel light, see Fig. 1(b). The optical resolution of the visualisation system was between 25 and 140 μm/pixel, depending on the magnification used.

3. Results and discussion

3.1. Membrane flow characteristics

Membranes appeared as thin liquid films that spanned across the entire tube cross-section, thus separating the air core flow into compartments, see Fig. 2. From investigation of the recorded

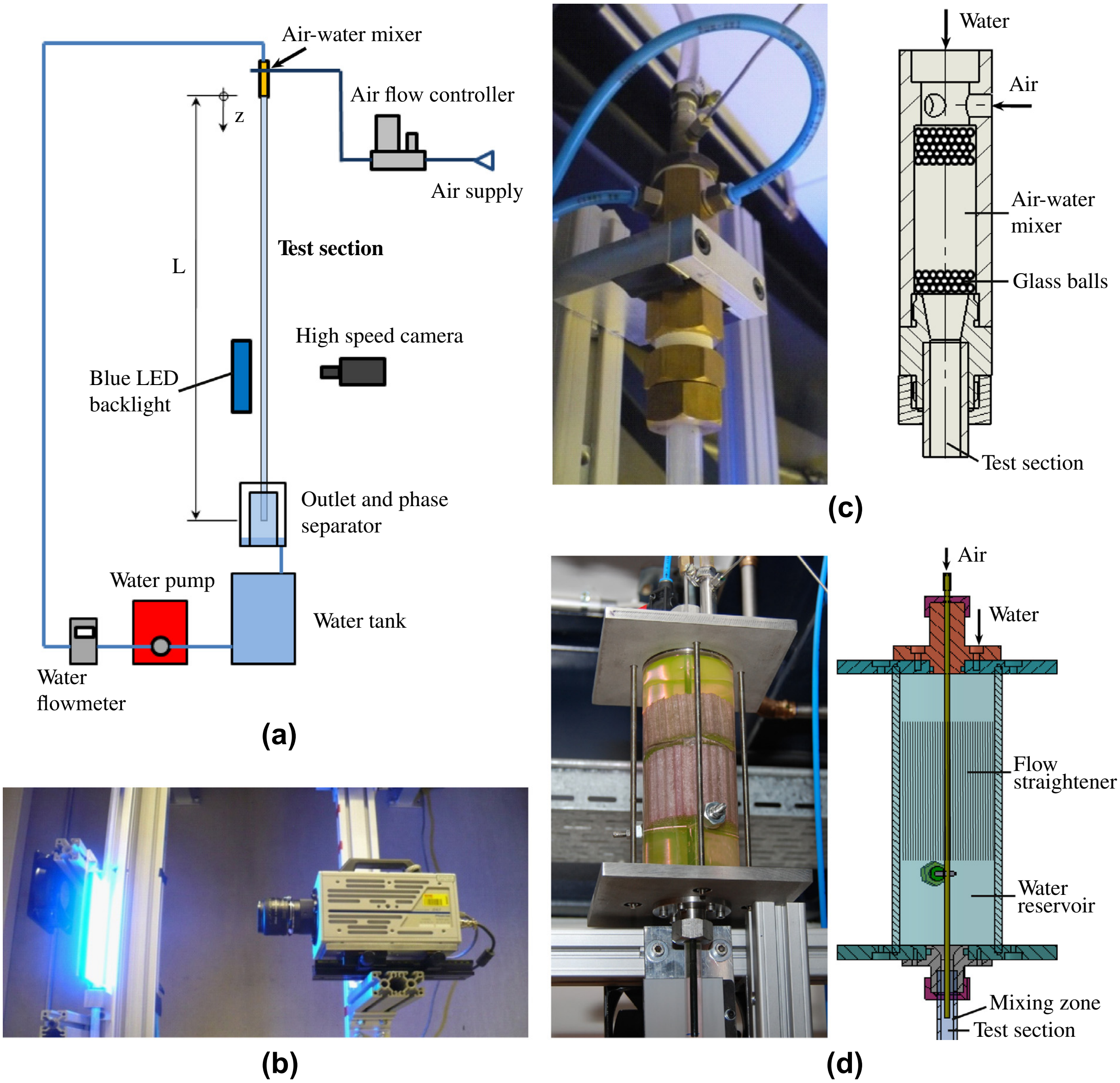

Fig. 1. Schematics and images of the (a) air–water flow facility, the (b) test section with LED backlight illumination and high speed camera, the (c) ball mixer, and the (d) coaxial injector.