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EXPERIMENTAL STUDY OF FLOODING AND FLOW REVERSAL IN AN AIR–WATER ANNULAR FLOW

Šefko Šikalo, Ifet Ajanović
Faculty of Mechanical Engineering, University of Sarajevo,
Vilsonovo šetalište 9, 71000 Sarajevo, Bosnia-Herzegovina

ABSTRACT
An annular flow regime is associated with known critical situations in industrial application: flooding or flow reversal during condensation and dry-out of liquid film during evaporation. The transition between these two extreme cases is studied experimentally. A special test section was designed for an annular flow investigation. Water and air are used to simulate the water–vapor flow and investigate the flooding and the flow reversal. Experiments were carried out under adiabatic flow conditions for a range of air and water flow rates in a test section made of Plexiglas pipe. The transition between the flooding and the reversal flow are presented by a map. Both the gas Reynolds number and the liquid Reynolds number could be used as a criterion to predict the flow regime: the flooding and the reversal flow. To utilize this map, the following parameters are required: liquid and gas velocities, tube internal diameter, liquid and gas densities, liquid dynamic viscosity and gas dynamic viscosity, and these parameter are grouped in both the gas and the liquid Reynolds numbers.

Keywords: annular two-phase flow, liquid film, flooding, flow reversal

1. INTRODUCTION
Typical experiments with gas-liquid flows through pipes involve steam and water or air and water. It is observed that there are several different flow régimes, depending on the gas and liquid mass fluxes. The particular régime considered in the present work is annular flow in a vertical pipe, in which the liquid phase flows next to the pipe wall, while the gas phase streams upward in a central core. Annular flow occurs naturally in two-phase flows through vertical heated tubes where, following the inception of boiling, the régime changes successively from bubbly flow, slug flow, churn flow and, finally, to annular flow. These various régimes have been described by Jones and Zuber [1]. To attain an annular flow régime in an unheated flow, it is common to admit the gas flow at the base of a tube but to force the liquid into the pipe through a porous segment in the tube wall at some distance above the inlet. Because of the way the annular flow is created, it is evident that, if the gas flux is low enough, the liquid will simply fall under the gravity as a film, so that a countercurrent flow is obtained. On the other hand, as the gas flux is increased, the transition from the falling to the upward film flow is termed flooding. When the gas flux is reduced in a concurrent flow, the transition to the countercurrent flow is termed flow reversal. The process is illustrated in Fig. 1.
Although a great deal of work has been carried out in the past few decades, there is still considerable uncertainty concerning the mechanisms causing flooding and associated phenomena as well as the most appropriate correlations for practical applications. Review papers [2,3,4] provide a good account of this research, which deals mainly with experiments in vertical tubes with inner diameter (ID) much larger than those considered here. Hewitt [5] reported data on flooding in vertical and inclined tubes of 32 mm ID and pointed out the significance of the conditions at the entrance. Barnea et al. [6] studied air–water countercurrent flow in a 51 mm ID tube for a wide range of inclination angles (1–90° from horizontal). Celata et al. [7] conducted their experiments in 20 mm inner diameter tubes and for steep inclinations (75–90° from horizontal). Zapke and Kroeger [8] investigated flooding mainly in a vertical 30 mm ID tube for various liquids and gases.

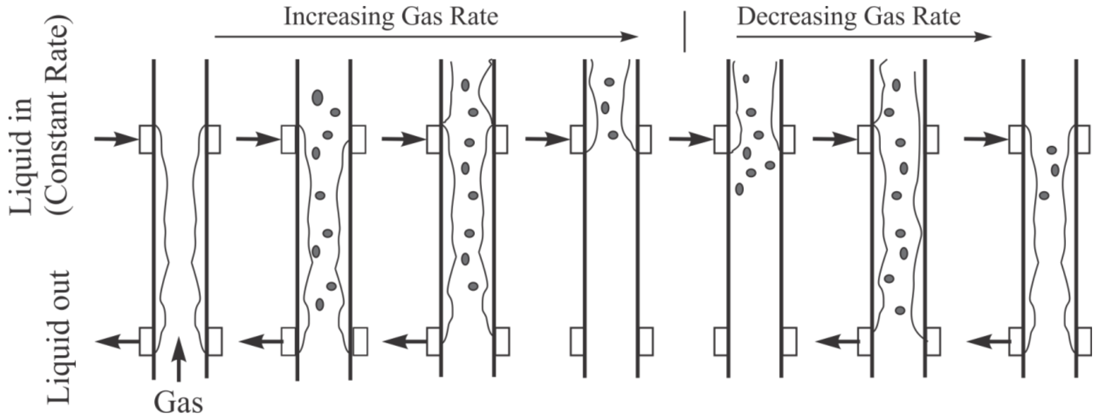

Figure 1 The processes of flooding (left) and flow reversal (right) in a vertical pipe in which liquid injection takes place via a porous segment of the pipe (adapted from [2]).

In general, the factors that tend to influence the onset of flooding are the conduit dimensions, the type of the liquid and the gas entry, the liquid properties and the inclination angle [3,8].
The region of the tube downstream of the locus of flooding of the gas can be described as a churn-annular flow [9]. Mouza et al. [10] conducted flooding experiment with four relatively small ID tubes (6, 7, 8 and 9 mm) in the range of inclination angles 30–60°. The growth of interfacial waves is likely to contribute to the flow reversal, and the resulting co-current flow may be driven by the interfacial shear force [10].

2. EXPERIMENTAL SET-UP

The experimental setup used in the present study is illustrated by a line diagram in Figure 2a. A photograph view of the test set-up is shown in Figure 2b. In more details the set-up is described in [11].
Air from a compressor (1) passes first through a refrigerated air dryer to remove the moisture and then through an oil filter (2) to eliminate the oil content. The air flow is measured by means of calibrated variable-area rotameters (3). Pressure and temperature corrections are made in calculating the air flow at the operating conditions. Distilled water from a water tank (4) is circulated by a variable speed pump (5), and is measured through a calibrated rotameter (6). Compressed air flows into a chamber (7) of an inner diameter of 47 mm and height of 140 mm. A converging section has length of 50 mm is used to connect the chamber to the porous segment (8a) and the flow development section (9). Following porous segment (8b) is connected to the test section (10) which has another porous segment (8c) at the upper side. These two porous segments (8a,c) are connected to the cyclone gas–liquid separator (11a,b). The middle porous segment (8b) is used to inject the water into the test section and form a liquid film in it. As shown in Fig. 2a, the flow section (9) having diameter of 14 mm ID (inner diameter) al L/D of 60 is employed to ensure that the flow is fully developed at the inlet of the test section. The test section (10) is a smooth Plexiglas tube of 14 mm ID and 924 mm long. The pressure is measured at the inlet of the test section and the pressure drop across the test section is measured using a water manometer (U-tube).
The porous segments are employed to inject the liquid into the test section to form the liquid film and to remove the liquid film at the other end of the test section. The porous section is 41.4 mm long, and consists of 23 stainless steel washers with inner diameter equal to that of the test section. The washers are separated by thin (0.1 mm) copper rings placed between the washers. The washer assembly is enclosed in a Plexiglas cylinder shutter, and is provided with a drain that is connected to a pump (second porous section to inject water) while other two porous sections are connected to the cyclone gas–liquid separators.

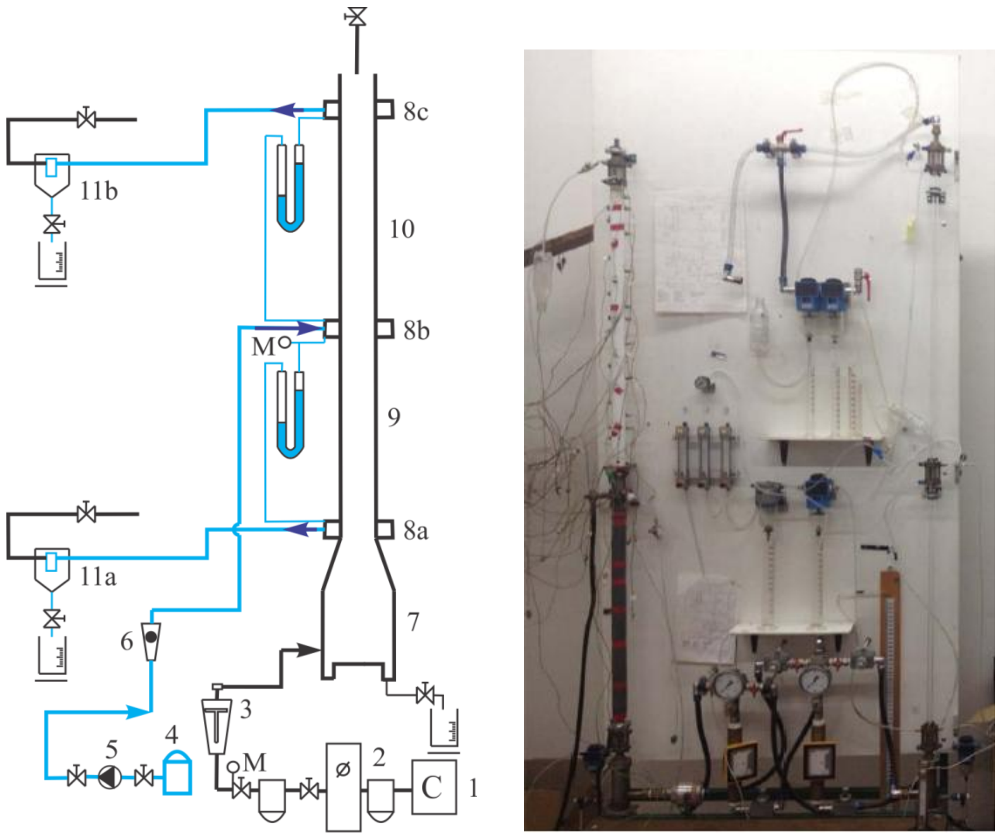

Figure 2 Experimental set-up: a) line diagram and b) a photograph view.

3. EXPERIMENTAL PROCEDURE

Distilled water is pumped through the porous section at the inlet of the test section (middle porous section). The initial flow of the water is 1 dm^3/h and at this point we have a liquid film on the wall of the acrylic tube in the upper part of the test section. The air flow has a constant value and the water flow rate is changed in order to form an annular flow and then to investigate transition to flooding and the flow reversal.

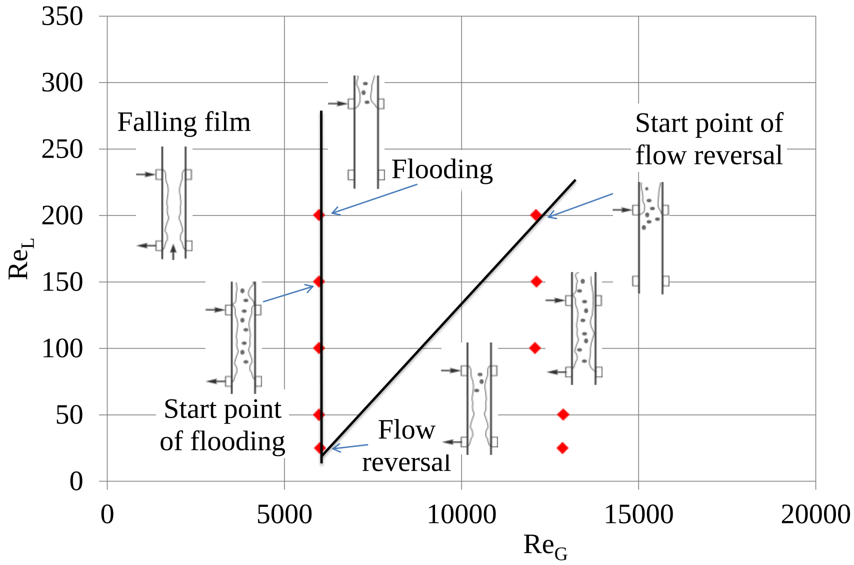

Figure 3 Ratio of Reynolds numbers for the air and the water at a constant flow of air.

At the beginning of the experiment, the liquid phase flows along the pipe wall and the air flows through the core. When the gas velocity was high, and due to the interfacial shear stress the liquid flows upwards, this represents the vertical co-current flow. At a higher air flow the system passes from falling film regime through the flooding transition at which liquid begins to travel upwards, followed by simultaneous upward and downward flows and then by a climbing film flow. When the gas flow was reduced, the liquid begins to creep below the injection point, and the flow reversal is observed. A map of the transition between the falling film, flooding and the flow reversal are proposed as shown in Figure 3.

4. CONCLUSION

The present paper shows results of a large number of experimental data for flooding and the flow reversal in an annular two-phase flow in vertical tubes. Measurements were carried out at the air flow rate in a range from 0.5 to 6 m^3/h and the water flow rate in a range from 1 to 12 dm^3/h. The transition between the falling film, flooding and the reversal flow is presented by a map. The gas Reynolds number and the liquid Reynolds number could be used as a criterion to predict the flow regime: the flooding and reversal flow. The flow parameters: liquid and gas velocities, tube internal diameter, and fluid properties: densities of the liquid and the gas, and viscosities combined in the liquid and gas Reynolds numbers can be used to predict characteristic flow regimes and its transitions in an annular flow.

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