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Interfacial and wall friction factors of swirling annular flow in a vertical pipe

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ABSTRACT

Experiments on air–water two-phase swirling annular flows in a vertical pipe of 40 mm diameter were carried out at atmospheric pressure and room temperature to investigate interfacial and wall friction factors, f_i and f_w. The friction factors were evaluated using measured pressure drops and void fractions. Measurements of liquid film thickness and flow observation were also conducted. The ranges of the gas and liquid volume fluxes, J_G and J_L, were $12.5 \leq J_G \leq 20.0$ m/s and $0.03 \leq J_L \leq 0.11$ m/s, respectively. The main conclusions obtained are as follows: (1) f_i and f_w in swirling annular flows are several times larger than those in non-swirling flows, (2) f_i is well correlated in terms of the liquid volume fraction and the gas Reynolds number, Re_G, (3) Re_G and the liquid Reynolds number, Re_L, are required for correlating f_w, and (4) the liquid film thicknesses in two-phase swirling flows in a one-fifth model of a BWR separator are well predicted using the two-fluid model and the correlations of f_i and f_w developed based on the experimental data.

1. Introduction

Steam separators in a boiling water reactor, BWR (Wolf and Moen, 1973), utilize swirling annular flow to separate steam-water two-phase flows flowing from the reactor core into steam and water. Stationary vanes of a swirler in the separator apply a centrifugal force to the two-phase flow, causing water migration toward the pipe wall and formation of a liquid film flow on the wall. A swirling annular flow is thus formed. When uprating the power density of the BWR core, the pressure drop in the steam separator of BWR may increase, which results in deterioration of the stability of the flow, i.e. the increase in the possibility of density-wave oscillation, and the increase in the load, 20% of which is due to the separator (Nakao, 2007), of the re-circulation system. We (Funahashi et al., 2017) recently showed that reducing the gap between the liquid separation component of a pick-off ring (POR) and the liquid film is effective in decreasing the pressure drop in the separator. It is therefore important to accurately predict the pressure drop and the liquid film thickness in the two-phase swirling flow.

A one-dimensional form of a multi-fluid model has often been used to predict the annular flow (Hewitt and Hall-Taylor, 1970). The two-fluid model can be used when we can assume that drops in the gas flow are negligible. Since the flow rate of droplets in the swirling flow is much smaller than that in the non-swirling flow due to the centrifugal force (Kataoka et al., 2008), the two-fluid model may be more suitable for the swirling annular flow. The accuracy of the two-fluid model prediction however strongly depends on the accuracy of interfacial and wall friction factors, f_i and f_w.

The well-known correlation of f_i proposed by Wallis (1969) was developed from the experimental data of non-swirling annular flows. Since then several correlations of f_i have been proposed. A review and comparisons between available f_i correlations can be found in literature e.g. Aliyu et al. (2017). Most of available f_i correlations were obtained for a fully-developed non-swirling annular flow. The pressure drop in a single-phase swirling flow is known to be larger than that in a non-swirling flow due to the increase in the frictional pressure drop (Hatazawa, 1998, Kitoh, 1991). Kataoka et al. (2009) showed that the pressure drop and liquid film thickness in a swirling annular flow are well evaluated by using the two-fluid model if the values of f_i and f_w in the non-swirling annular flow are increased by a factor of about five. However f_i and f_w in the swirling annular flow have not been experimentally investigated so far, and therefore, our knowledge required for modeling the friction factors in the swirling annular flow is insufficient.

In this study, experiments on air-water two-phase swirling flows in a vertical pipe at atmospheric pressure and room temperature were conducted to investigate f_i and f_w for a wide range of gas and liquid volume fluxes. The void fraction and the pressure drop were measured for this purpose. The measurement of liquid film thickness and flow observation were carried out to understand the relation between the friction factors and the flow structure.

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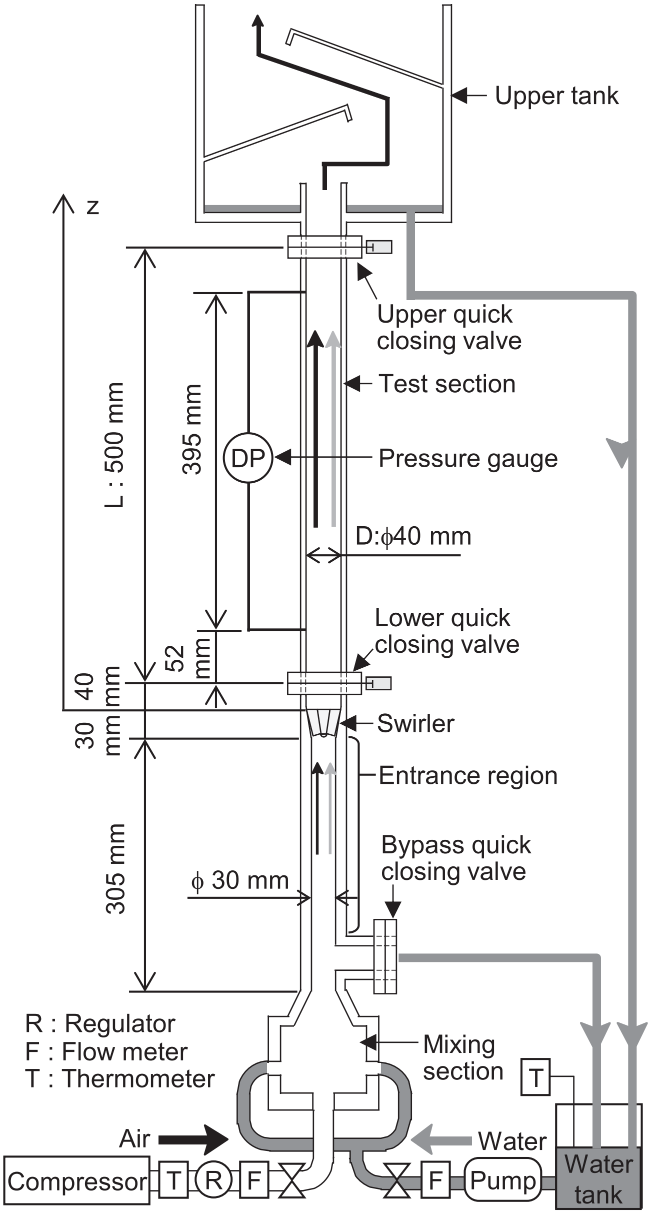

Fig. 1. Experimental setup.

2. Experiment

2.1. Experimental setup

Fig. 1 shows the experimental setup, which consists of the upper tank, the test pipe, the swirler, the entrance region, the bypass section, the gas-liquid mixing section, the water tank, and the water and air supply systems. The inner diameters, D, of the entrance region and the test pipe were 30 mm and 40 mm, respectively. The test pipe was made of transparent acrylic resin for flow observation and optical measurement of liquid film thickness. The void fraction and the pressure drop in the test pipe were measured to obtain f_i and f_w, which will be described in Section 3.

Air was supplied from the oil-free compressor to the mixing section through the thermometer, the regulator and the flow meter. Water was supplied using the magnet pump to the mixing section through the wall made of the porous-sinter. The liquid flow rate was measured using the flow meter. The temperature of air and water was 298 ± 2 K. The air-water two-phase flow, which was formed at the mixing section, passed through the entrance region. The swirler applied the centrifugal force to the two-phase flow, and then, the two-phase swirling flow entered the test pipe. After air and water passed through the test pipe, air discharged into the atmosphere, whereas water was captured and returned to the water tank.

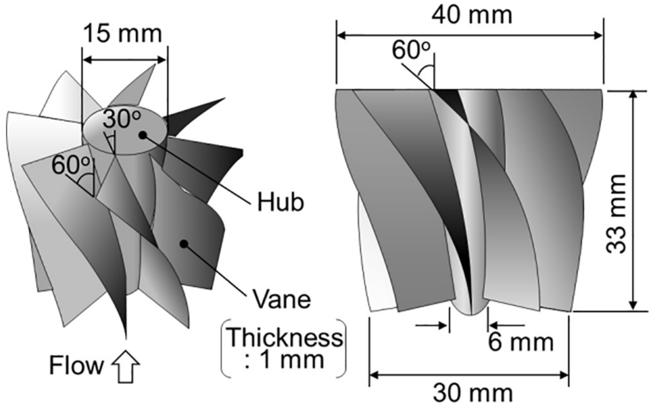

Fig. 2. Swirler.

The swirler made of acrylonitrile butadiene styrene (ABS) resin was located in the diffuser-shape segment between the entrance region and the test pipe. The swirler is shown in Fig. 2, which consists of the eight vanes attached to the hub, whose diameter was 6 mm at the swirler inlet and 15 mm at the outlet, i.e. its structure was based on the actual swirler in a BWR (Katono et al., 2015).

The inner diameter of the test pipe was 1/5 times smaller than that of the steam separator in the BWR. The pipe length was 500 mm. The ranges of the gas and liquid volume fluxes in the test pipe, J_G and J_L, tested in the present experiment were $12.5 \leq J_G \leq 20.0$ m/s and $0.03 \leq J_L \leq 0.11$ m/s, respectively. Note that the liquid-separation performance of a downscaled air-water separator can be the same as that of a steam-water separator in a BWR by setting the quality and the two-phase centrifugal force per unit volume of the two separators same (Katono et al., 2014). Applying this scaling law to the present experimental system, the experimental condition corresponding to the nominal operating condition of the Hyper ABWR (Mishima et al., 2006) is $J_G = 14.6$ m/s and $J_L = 0.08$ m/s. The above ranges of J_G and J_L therefore include this nominal operating condition.

2.2. Measurement methods

The pressure drop in the pipe between $z = 92$ mm and $z = 487$ mm was measured by using differential pressure transducers. The sampling frequency was 1000 Hz and the measurement was carried out for 50 s. The measurements were repeated five times. The uncertainty estimated at 95% confidence in time-averaged pressure drop was 1.5%.

The volume fraction was measured by three quick-closing valves (QCVs). Three QCVs were installed in the test pipe at $z = 40$ and 540 mm and the bypass section. The QCV consists of the slide plate with 40 mm hole and the pneumatic cylinder as shown in Fig. 3. Motions of the three cylinders were electrically synchronized. The QCV can open and close within 40 ms. When the QCVs in the test pipe were closed, the QCV in the bypass was opened to prevent a sharp increase of the pressure in the pipe.

The instantaneous void fraction of the ith measurement, α_{Gi}, was obtained by measuring the height of accumulated liquid within the measurement section between the two QCVs as

$$\alpha_{Gi} = 1 - H_i/L \tag{1}$$

where H_i is the height of the liquid column of the ith measurement (see Fig. 3(d)) and L the distance between the two QCVs (500 mm). Using α_{Gi}, the ensemble-averaged void fraction, $\overline{\alpha}_G$, defined by