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Study on two-phase swirling flows in a gas–liquid separator with three pick-off rings

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HIGHLIGHTS

- Experiments on swirling flow in a separator with three PORs are carried out.
- Flow observation and measurement of liquid film thickness in the barrel are carried out.
- Liquid-separation rate and pressure drop at each POR are measured.
- Effects of total gas and liquid inflows on separator performance are investigated.

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ABSTRACT

Experiments on air-water two-phase swirling flows in a one-fifth scale model of a steam separator with three pick-off rings (PORs) are carried out to investigate characteristics of two-phase swirling flows and separator performance. In addition to flow observation, liquid film thickness, flow rates of separated liquid and pressure drops are measured. The ranges of the gas and liquid volume fluxes, J_G and J_L, tested are $12.0 \leqslant J_G \leqslant 17.8$ m/s and $0.05 \leqslant J_L \leqslant 0.11$ m/s, respectively. The main conclusions obtained are as follows: (1) the liquid film thicknesses at the PORs are smaller than the gap widths of the PORs under the nominal operating condition, which results in a high liquid-separation rate, (2) the increase in J_G decreases the flow rate of unseparated liquid, whereas the flow rate of unseparated liquid is independent of J_L except for low J_G conditions, under which the liquid film thicknesses at the 2nd and 3rd PORs tend to be larger than the gap widths of PORs, (3) the presence of the 2nd and 3rd PORs realizes high liquid-separation rates by capturing the liquid unseparated at the 1st POR and the pressure drops at the 2nd and 3rd PORs are much smaller than that at the 1st POR, and (4) the pressure drops at the swirler and the 1st POR, which are the main source of the pressure drop of the separator under the nominal operating condition, increase with J_G, whereas J_L increases only the latter.

1. Introduction

Steam separators of boiling water reactors (BWRs) separate steam–water two-phase flows flowing from the reactor core into steam and water by making use of centrifugal force. The separator consists of a standpipe, a diffuser with a swirler and a barrel with three pick-off rings (PORs). The stationary vanes of the swirler apply centrifugal force to the two-phase flow, causing water migration toward the barrel wall and formation of a liquid film flow on the barrel wall. A swirling annular flow is thus formed. The liquid film flow is discharged from the barrel through the PORs.

The performance of the separator has been evaluated by the carry-over, *CO*, the carry-under, *CU*, and the pressure drop, where *CO* is the ratio of the mass flow rate of unseparated water at the separator exit to the total mass flow rate of the two-phase mixture at the exit and *CU* is the ratio of the mass flow rate of vapor discharged through the 1st POR to the total mass flow rate at the POR. Wolf and Moen (1973) measured *CO* and *CU* for a wide range of vapor quality by mocking up the actual separator with three PORs. They pointed out that *CO* decreases with increasing the quality due to the increase in centrifugal force. Iwaki et al. (2010) measured not only *CO* and *CU* in a vapor-water system in a full-scale separator but also the pressure drops at the swirler and each POR. Their data showed that the swirler and the 1st POR were the main cause of pressure drop. However effects of the gas and liquid flow rates in the separator on the pressure drops at the swirler and the PORs have not been investigated. In addition, the

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contribution of each POR to the total flow rate of separated liquid (liquid-separation rate) has not been measured.

Since experiments using vapor–water systems simulating the actual BWR condition in full-scale separators are expensive and time-consuming, several studies on separator performance have been carried out using air–water systems at atmospheric pressure and room temperature (Jensen et al., 1996; Nakao et al., 2001a,b). Nakao et al. (2001a) measured liquid-separation rates at each POR using a half-scale separator. Their experiments confirmed that most of the liquid was separated at the 1st POR and the decrease in the quality decreased the liquid-separation rate at the POR. In addition, in spite of the reduction of the liquid-separation rate at the 1st POR, the total liquid-separation rates under high quality conditions were almost independent of the quality owing to the presence of the 2nd and 3rd PORs. Although knowledge of flow patterns in the barrel and liquid film thicknesses at the PORs would be of great importance in understanding relation between the flow pattern and the separation performance and in designing a separator, flow observation and liquid-film measurements for a separator with three PORs have not been carried out so far.

In this study, measurements of liquid-separation rates and liquid film thicknesses in a one-fifth scale separator with three PORs and observation of flows in the barrel were carried out using an air–water system at atmospheric pressure and room temperature to investigate the separation process at each POR and effects of the gas and liquid flow rates on them. Effects of the gas and liquid flow rates on the axial pressure distribution in the separator were also investigated.

2. Experimental

2.1. Experimental setup

Fig. 1 shows the experimental setup, which consists of the barrel of 40 mm inner diameter, the three pick-off rings, the swirler, the diffuser, the standpipe of 30 mm inner diameter, the plenum of 60 mm inner diameter, the gas–liquid mixing section, the water and air supply systems and the upper tank. The PORs are referred to as the 1st, 2nd and 3rd PORs from bottom to top. The segments of barrels between the swirler and the 1st POR, between the 1st and 2nd PORs and between the 2nd and 3rd PORs are referred to as the 1st, 2nd and 3rd barrels, respectively. The barrels were made of transparent acrylic resin for flow observation and optical measurement of film thickness.

Air was supplied from the oil-free compressor to the mixing section through the regulator and the flow meter. Water at 298 ± 2 K 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 swirler made of acrylonitrile butadiene styrene (ABS) resin was installed in the diffuser to form a swirling flow in the barrel. Its shape shown in Fig. 2 was based on the actual swirler for BWR (Ikeda et al., 2003), i.e. the swirler consists of eight vanes attached to the hub, whose diameter is 6 mm at the swirler inlet and 15 mm at the outlet.

2.2. Measurement methods

2.2.1. Mass flow rates

Fig. 3 shows the details of PORs. The distance between the barrel wall and the POR inner wall is referred to as the gap width. Following the current design of BWR separators, the gap widths of the 1st, 2nd and 3rd PORs were set at 3.4 mm, 1.9 mm and 1.15 mm, respectively, and the POR thickness was 0.6 mm. The mass flow rates, W_{LT}, W_{L1}, W_{L2}, W_{L3} and W_{LO}, of the total liquid inflow, the liquid separated at the 1st, 2nd and 3rd PORs and the unseparated liquid were measured using graduated cylinders. The measurement time for each flow rate was over 80 s. The ratio, W^*_{Si}, of the flow rate of liquid separated at the ith POR to the total liquid inflow is defined by

$$W^*_{Si} = \frac{W_{Li}}{W_{LT}} \qquad (i = 1-3) \tag{1}$$

and the ratio, W^*_{Si}, of the total flow rate of separated liquid to the total liquid inflow is defined by

$$W^*_{ST} = \sum_{i=1}^{3} W^*_{Si} = \frac{W_{L1} + W_{L2} + W_{L3}}{W_{LT}} \tag{2}$$

The uncertainties estimated at 95% confidence in W^*_{S1}, W^*_{S2}, W^*_{S3} and W^*_{ST} were 0.29%, 1.23%, 1.56% and 0.05%, respectively. The mass flow rate of the total gas inflow, the gas discharged at the 1st, 2nd and 3rd PORs, and the gas at the outlet of the separator are denoted by W_{GT}, W_{G1}, W_{G2}, W_{G3} and W_{GO}, respectively.

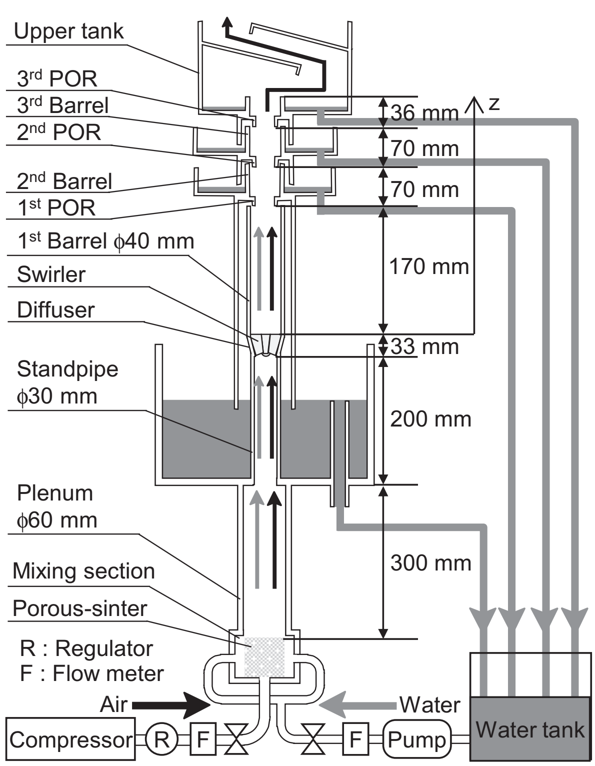

Fig. 1. Experimental apparatus.

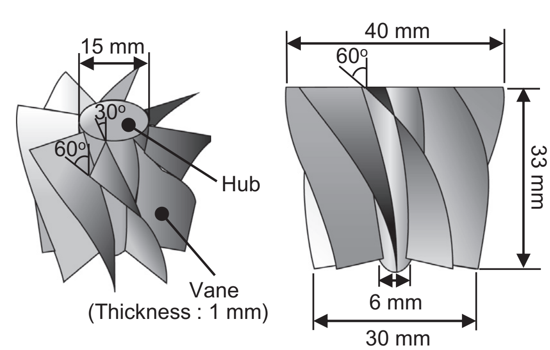

Fig. 2. Swirler.