Effects of Swirler Shape on Two-Phase Swirling Flow in a Steam Separator*

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Abstract
Experiments on two-phase swirling flow in a separator are carried out using several swirlers having different vane angles, different hub diameters and different number of vanes to seek a way for improving steam separators of uprated boiling water reactors. Ratios of the separated liquid flow rate to the total liquid flow rate, flow patterns, liquid film thicknesses and pressure drops are measured to examine the effects of swirler shape on air-water two-phase swirling annular flows in a one-fifth scale model of the separator. As a result, the following conclusions are obtained for the tested swirlers: (1) swirler shape scarcely affects the pressure drop in the barrel of the separator, (2) decreasing the vane angle is an effective way for reducing the pressure drop in the diffuser of the separator, and (3) the film thickness at the inlet of the pick-off-ring of the separator is not sensitive to swirler shape, which explains the reason why the separator performance does not depend on swirler shape.

Key words: Swirler, Steam Separator, Film Thickness, Deposition, Pressure Drop

1. Introduction

Boiling water reactors (BWR) are equipped with steam separators for splitting a two-phase mixture into steam and water. The steam separator consists of a standpipe, a diffuser with a swirler, and a barrel with several pick-off-rings (POR). The swirler consists of eight stationary vanes and a hub for holding the vanes. The vanes apply a large centrifugal force to the steam-water two-phase flow, and thereby, most of water in the barrel rapidly migrates toward the barrel wall. A swirling annular flow with few droplets in the gas core is thus formed in the barrel. The liquid film flow and the gas core flow are to be separated by POR.

When uprating the power density of BWR core, one of the technical issues we have to deal with is the improvement of the steam separators. Since the uprating causes the increase in the steam quality and flow velocity at the entrance of the steam separator, pressure drops in two-phase flow regions may increase, which, in turn, results in the deterioration of flow stability, i.e., the increase in the possibility of density-wave oscillation. We, therefore, need to improve the steam separator so as to decrease the pressure drop at high steam qualities without degrading the separator performance. One way for improving the steam separator may be the modification of swirler shape.

Nakao et al. measured pressure drop and separator performance for a swirler with lowered vane angle and a swirler with lowered hub diameter. They confirmed that the reduction of vane angle and hub diameter is effective in reducing pressure drop. Ikeda et al. proposed a swirler having an almost uniform cross-sectional area in the flow direction, by which they decreased the pressure drop by about 20%. However these experiments were not conducted under the high steam-quality conditions of the uprated BWR, but under...
normal quality conditions of the standard BWR. In addition, the effects of swirler shape on flow pattern and film thickness have not been examined yet. In our previous study\(^3\),\(^4\),\(^5\), we therefore measured ratios of the separated liquid flow rate to the total liquid flow rate, flow patterns, liquid film thicknesses and pressure drops using a 1/5-scale model of the actual separator to understand characteristics of a two-phase swirling flow and to establish an experimental database applicable to the modeling and validation of numerical methods for predicting two-phase swirling flows in steam separators for the uprated BWR.

In the present study, the effects of swirler shape on two-phase swirling annular flows in the separator are examined by carrying out experiments using several swirlers. The ratios of the separated liquid flow rate to the total liquid flow rate, flow patterns, liquid film thicknesses and pressure drops are measured for a wide range of gas and liquid volume fluxes to understand the effects of swirler shape.

![Figure 1 Experimental apparatus](image1)

**2. Experimental Setup**

**Figure 1** shows the experimental apparatus. It consisted of the upper tank, the barrel, the diffuser, the standpipe, the plenum, the gas-liquid mixing section, the water supply system and the air supply system. The barrel, diffuser and standpipe were made of transparent acrylic resin for observation and optical measurements of two-phase flows. The size was one-fifth of the actual steam separator for BWR. Air was supplied from the oil-free compressor (Oil-free Scroll 11, Hitachi Ltd.) to the regulator (R600-20, CKD, Ltd.), the flowmeter (FLT-N, Flowcell, Ltd.) and the mixing section. Tap water at room temperature (20 °C) was supplied from the magnet pump (MD-40RX Iwaki, Ltd.) to the flowmeter and the mixing section. The two-phase flow formed in the mixing section flowed up through the plenum of 60 mm in inner diameter \(D\) and 300 mm in length \(L\), the standpipe of \(D = 30\) mm and \(L = 200\) mm, the diffuser of \(L = 33\) mm and the barrel of \(D = 40\) mm and \(L = 270\) mm.

The swirler shown in **Fig. 2**, which was made of ABS (Acrylonitrile Butadiene Styrene) resin, was installed in the diffuser to form a swirling flow in the barrel. Swirlers tested are summarized in **Table 1**. The swirler based on an actual swirler is called type 1. The vane...
angle θ of type 2 is a half of that of type 1. The hub diameter $D_{hub}$ of type 3 is a half of that of type 1. The number of vanes $N_{vane}$ of type 4 is six. The type 2 - 4 swirlers were designed so as to realize lower pressure drops than type 1, while keeping the separator performance, i.e. the same separation rate as type 1.

Figure 3 shows the upper part of the barrel, the upper tank and the device for separating the liquid film flow from the gas core flow, i.e. the mixture of gas and droplet flows. Note that the flow in the barrel is annular flow. In the actual steam separator, the pick-off-ring, POR, is utilized for the separation. The inner pipe was inserted in the barrel to simulate POR. For measuring liquid film thicknesses at the inlet of POR, the lower end of the inner pipe was located at $z = 220$ mm, where $z$ is the axial distance from the bottom of the barrel. This location was by 50 mm higher than that of the actual POR, i.e., the actual position of the inlet of the first POR corresponds to $z = 170$ mm. Note that we had confirmed in preliminary experiments that there were no difference in separation performance between the two positions, $z = 170$ mm and 220 mm. The gap $b_{gap}$ between the barrel wall and the outer wall of the inner pipe, the thickness $t$, and the inner diameter $D_1$ of the inner pipe were 2, 2 and 32 mm, respectively. Most of the liquid film flowed through the gap, while most of air and droplets flowed through the inner pipe. The separated liquid and the droplets carried over returned to the water reservoir through independent pipelines.

Kataoka et al.\(^{(4)}\) confirmed that steam-water annular swirling flow in a separator can be simulated with air-water flow if the gas and liquid volume fluxes are adjusted so as to make the flow quality and the two-phase centrifugal force in the two systems the same. Experimental conditions were, therefore, determined by adjusting the values of the flow quality and the two-phase centrifugal force to cover those in the nominal operating condition of the separator for the uprated BWR. The values of the flow quality $x$, the gas and liquid volume fluxes in the barrel, $J_G$ and $J_L$, corresponding to the nominal operating condition were 0.18, 14.6 m/s, and 0.08 m/s, respectively\(^{(3)}\). Hence the present experiments were carried out for a wide range of volume fluxes including the nominal condition, i.e., $J_G = 12.0 – 24.1$ m/s and $J_L = 0.05 – 0.11$ m/s, to cover possible operating conditions of the uprated BWR.

**Table 1 Specifications of swirlers**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>type 1</th>
<th>type 2</th>
<th>type 3</th>
<th>type 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$ [deg]</td>
<td>60</td>
<td>30</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$D_{hub}$ [mm]</td>
<td>15</td>
<td>15</td>
<td>7.5</td>
<td>15</td>
</tr>
<tr>
<td>$N_{vane}$</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

![Fig. 3 Pick-Off-Ring (POR)]
The mass flow rates, $W_{Ls}$ and $W_{Lus}$, of the separated liquid and the unseparated liquid returning to the reservoir were measured using timers and graduated cylinders. Each measurement was conducted for 50 seconds to make the uncertainty estimated at 95% confidence in measured $W$ less than 3%. The ratio $W_s^*$ of the separated flow rate to the total liquid flow rate defined by

$$W_s^* = \frac{W_{Ls}}{W_{Ls} + W_{Lus}}$$  \hspace{1cm} (1)

was used as an index of the separator performance.

Flow patterns in the barrel, diffuser, and standpipe were recorded using a high-speed video camera (Dantec Dynamics, Nano sence Mk3, frame rate = 2000 – 4000 fps, exposure time = 100 µs). The film thickness $\delta$ was measured using a laser focus displacement meter (LFD, LT-9030, Keyence, Ltd.) at $z = 170$ mm, i.e. at the location corresponding to the inlet of the actual POR. The sampling period was 0.64 ms and the measurement time was 30 seconds, which was long enough to obtain accurate time-averaged film thicknesses. The uncertainty in measured $\delta_{\text{mean}}$ was 0.65 %. Pressure drops in the diffuser and the barrel were measured using differential pressure transducers (DP45, Valydyne, Ltd.). As shown in Fig. 4, seven holes of 1 mm diameter were made at seven elevations to measure a pressure distribution in the flow direction. The sampling period was 1.0 ms and the measurement time was 50 seconds, which was long enough to obtain accurate time-averaged pressures. The uncertainty in measured pressures was less than 0.3%.

3. Results and Discussion

3.1 Separator performance and film thickness

Figure 5 shows $W_s^*$ at the nominal liquid volume flux, $j_L = 0.08$ m/s. The ratio $W_s^*$ does not depend on swirler types, i.e., the separator performance is not sensitive to swirler
shape. Recorded images of flow patterns in the four swirlers are shown in Figs. 6 and 7. As shown in Fig. 6, spiral streaks are formed from each vane. Most of the liquid in the streak is supplied from liquid droplets deposited on the swirler vanes, that is, the liquid transfer from droplets to the film is caused not only by the direct droplet deposition but also by the collection of droplets on the vanes\(^{(3,7)}\). The type 2 swirler has the smallest streak angle \(\theta_{st}\) because its vane angle is the smallest. The region of droplet deposition is also shown in Fig. 7. The range of droplet deposition is longer in types 2 and 3 than in types 1 and 4. This must be because the centrifugal force induced by the former are weaker than by the latter due to the lowered vane angle and hub diameters. It is somewhat interesting that the reduction of the number of vanes (type 4) from 8 to 6 does not cause a significant decrease of deposition. In any case, droplet deposition comes to an end before reaching POR for all the swirlers.
The mean film thickness $\delta_{\text{mean}}$ was obtained as the arithmetic average of measured instantaneous film thickness. Figure 8 shows the effects of swirler shape on $\delta_{\text{mean}}$ at $J_L = 0.08$ m/s. The film thickness decreases with increasing $J_G$. This is obviously due to the increase in the interfacial friction. The difference in swirler shape, however, does not cause any difference in $\delta_{\text{mean}}$. This is the main reason why the separation performance $W_s^*$ does not depend on swirler shape. Figure 9 shows the effect of $J_L$ on $\delta_{\text{mean}}$. The film thickness increases with $J_L$ because the film flow rate in the swirling annular flow is nearly equal to the total liquid flow rate.
3.2 Pressure drop

Figure 10 shows axial distributions of the dimensionless pressure $P^*$ defined by

$$P^* = \frac{P}{P_1}$$

where $P_1$ is the pressure at the uppermost gauge station shown in Fig. 4. There is no difference in $P^*$ for $z > 0$, that is, swirler shape scarcely affects the pressure drop in the barrel. On the contrary, the pressure in the diffuser strongly depends on swirler shape.

Figure 11 shows the ratio $R_{\Delta P_i}$ of the dimensionless pressure drop for type $i$ swirler to that for type 1 swirler defined by

$$R_{\Delta P_i} = \frac{(\Delta P_i^*)_{\text{type}i}}{(\Delta P_1^*)_{\text{type1}}} = \frac{(P_i^* - P_1^*)_{\text{type}i}}{(P_1^* - P_1^*)_{\text{type1}}} \quad (i = 2, 3, 4)$$

This figure clearly shows that the decrease in vane angle (type 2), hub diameter (type 3), and the number of vanes (type 4) is effective for the reduction of pressure drop. The reduction rates of types 2, 3, 4 at the nominal liquid volume flux, $J_L = 0.08 \text{ m/s}$, are about 36, 13 and 21 %, respectively. The decrease in vane angle is, therefore, the most effective way for the pressure drop reduction among the swirlers tested. It should be also noted that the gas volume flux $J_G$ scarcely affects $R_{\Delta P_i}$. 

![Fig. 9  Effects of $J_L$ on $\delta_{\text{mean}}$](image)
Figure 10  Effects of swirler on $P^*$

Figure 11  Effects of swirler on $R_{\Delta P}$
5. Conclusion

The effects of swirler shape on ratios of the separated liquid flow rate to the total liquid flow rate, flow patterns, liquid film thicknesses and pressure drops in the one-fifth scale model of a steam separator for an uprated boiling water reactor were investigated using four types of swirlers. Pressure drops in the barrel and diffuser of the separator were measured using differential pressure transducers. Film thicknesses at the inlet of the pick-off-ring were measured using a laser focus displacement meter. Experiments were carried out in an air-water system at atmospheric pressure and room temperature. The air and liquid volumetric fluxes ranged from 12-24.1 m/s and 0.05-0.11 m/s. As a result, the following conclusions were obtained for the examined swirlers.

1. Swirler shape does not affect the pressure drop in the barrel.
2. Reduction of vane angle is an effective way for decreasing the pressure drop in the diffuser.
3. The film thickness at the inlet of the pick-off-ring is not sensitive to swirler shape, because most of the droplets deposit on the liquid film before reaching the pick-off-ring, and therefore, the separator performance does not strongly depend on vane angle, hub diameter and the number of vanes.

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