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Air–water downscaled experiments and three-dimensional two-phase flow simulations of improved steam separator for boiling water reactor

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HIGHLIGHTS

- We design the improved steam separator for boiling water reactor (BWR).
- The improved steam separator comprises the swirler vanes in the first-barrel section.
- We evaluate separator performance by an air–water experiments and flow simulation.
- The improved separator can decrease the total pressure losses by about 30%.
- And the carryover performance is almost the same level as the conventional separator.

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ABSTRACT

Reducing the pressure losses in steam-separator systems in boiling water reactor (BWR) plants is useful for reducing the required pump head and enhancing the design margins to ensure core stability. We need to reduce the pressure losses while maintaining the gas–liquid separation performance. In this study, we improve a steam separator with air–water downscaled experiments and two-phase flow simulations.

First, we confirm the effectiveness for the separator performance prediction by adjusting the quality and the two-phase centrifugal force between the air–water downscaled experiments and the steam-water mockup tests, and we design the improved steam separator, which moves the swirl-vane section from diffuser section to the first-barrel section. From the air–water downscaled experiments, the improved separator can decrease pressure loss in the swirler more than 50% around the BWR normal operating conditions compared to the conventional separator, and the carryover of the improved separator is almost the same level as the conventional separator.

Next, we evaluate the improved steam separator performance under the BWR operating conditions by means of a two-phase flow simulation, and we have the prospects of the improved separator for reducing the total separator pressure losses by about 30% compared to the conventional separator, while maintaining carryover characteristics.

1. Introduction

Reducing the pressure losses in steam-separator systems in boiling water reactor (BWR) plants is useful for reducing the required pump head and enhancing the design margins to ensure core stability. Reducing the pressure losses generally leads to increased carryover. However, it is advantageous to reduce the pressure losses while retaining the characteristics of the gas–liquid separation performance and many studies have examined this issue (Wolf and Moen, 1973; Jensen et al., 1996; Nakao et al., 2001; Ikeda et al., 2003; Iwaki et al., 2010).

Fig. 1 outlines a conventional steam separator in a BWR. The steam separator of a BWR plant consists of a standpipe section, a swirl-vane section, and three barrel sections. A two-phase flow of steam and water enters the steam separator through the standpipe section and reaches the swirl-vane section. Centrifugal force is

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Nomenclature

A_D	interfacial area concentration (m^2/m^3)
C_D	inter-phase drag coefficient (–)
CO	carryover (–)
CO_a	carryover from the free surface separating region surrounding the separator (–)
D	mean diameter of dispersed phase (m)
F_c	two-phase centrifugal force (N/m^3)
F_d	inter-phase drag force (N/m^3)
F_l	lift force (N/m^3)
F_{vm}	virtual mass force (N/m^3)
g	gravitational constant (m/s^2)
J	volume flux (m/s)
k	turbulent kinetic energy (m^2/s^2)
M	inter-phase momentum transfer (N/m^3)
p	pressure (N/m^2)
R	radius of the standpipe (m)
Re	Reynolds number (–)
t	time (s)
u	velocity (m/s)
W_{air}	mass flow rate of the air (kg/s)
W_d	mass flow rate of the droplets (kg/s)
x	quality (–)

Greek letters

α	volume fraction (–)
ε	dissipation rate (m^2/s^3)
μ	viscosity (kg/ms)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ_α	turbulent Prandtl number (–)
τ	shear stress (N/m^3)

Superscript

t	turbulence

Subscripts

c	continuous phase
d	dispersed phase
G	gas phase
k	phase
L	liquid phase
m	two-phase mixture

applied to the two-phase flow in the swirl-vane section, and this is basically separated into steam and water. Therefore, investigating two-phase flow characteristics in the swirl-vane section is very important. The two-phase flow enters the barrel sections after it leaves the swirl-vane section. All three barrels have a pick-off ring (POR). The water in the barrel sections is mainly removed by these pick-off rings because it mainly flows upward as a liquid film in these areas due to the centrifugal force applied in the swirl-vane section.

This paper focuses on the improvements of the steam separator for a BWR. First, we examine how applicable the air–water downscaled experiments are for the steam separator performance prediction, and we design the improved steam separator with a lower pressure loss swirler, and confirm the separator performance. Next, we evaluate the improved steam separator performance under the BWR operating condition by means of a simulation method.

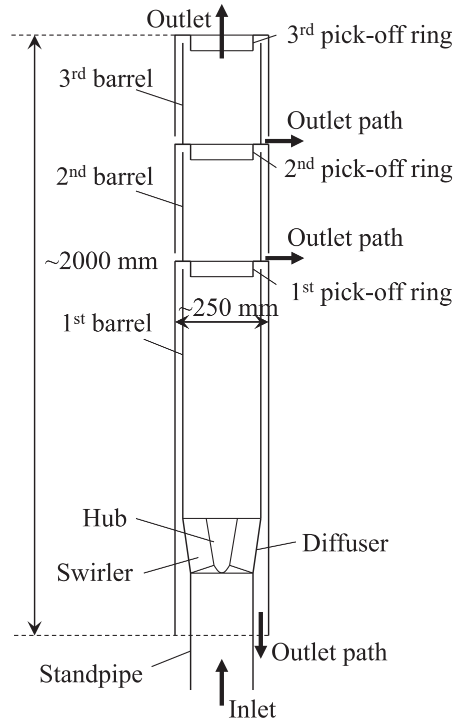

Fig. 1. Outline of steam separator for BWR.

2. Air–water downscaled experiments

2.1. Experiments setup

Fig. 2 shows the experimental apparatus. It consisted of the dryer, the plenum, the pick-off ring (POR), the barrel, the diffuser, the standpipe, the plenum, the air–water mixing section, the water supply system and the air supply system. The barrel, diffuser,

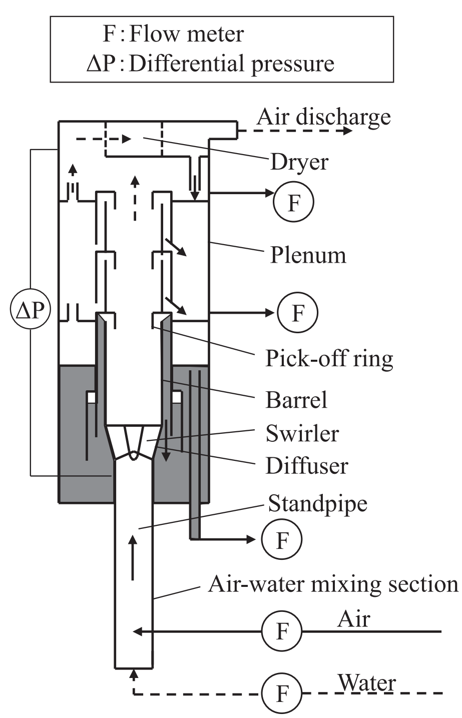

Fig. 2. Experimental apparatus (1/2 scaled air–water test loop).