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Numerical simulation of two-phase flow behavior in Venturi scrubber by interface tracking method

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HIGHLIGHTS

- Self-priming occur because of pressure balance between inside and outside of throat is confirmed.
- VS has similar flow with a Venturi tube except of disturbance and burble flow is considered.
- Some of atomization simulated are validated qualitatively by comparison with previous studies.

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ABSTRACT

From the viewpoint of protecting a containment vessel of light water reactor and suppressing the diffusion of radioactive materials from a light water reactor, it is important to develop the device which allows a filtered venting of contaminated high pressure gas. In the filtered venting system that used in European reactors, so called Multi Venturi scrubbers System is used to realize filtered venting without any power supply. This system is able to define to be composed of Venturi scrubbers (VS) and a bubble column. In the VS, scrubbing of contaminated gas is promoted by both gas releases through the submerged VS and gas-liquid contact with splay flow formed by liquid suctioned through a hole provided by the pressure difference between inner and outer regions of a throat part of the VS. However, the scrubbing mechanism of the self-priming VS including effects of gas mass flow rate and shape of the VS are understood insufficiently in the previous studies. Therefore, we started numerical and experimental study to understand the detailed two-phase flow behavior in the VS. In this paper, to understand the VS operation characteristics for the filtered venting, we performed numerical simulations of two-phase flow behavior in the VS. In the first step of this study, we perform numerical simulations of supersonic flow by the TPFIT to validate the applicability of the TPFIT for high velocity flow like flow in the VS. In the second step, numerical simulation of two-phase flow behavior in the VS including self-priming phenomena. As the results, dispersed flow in the VS was reproduced in the numerical simulation, as same as the visualization experiments.

1. Introduction

In the wake of Fukushima Daiichi nuclear disaster, countermeasures against severe accidents in nuclear power plants are an urgent need. In particular, from the viewpoint of protecting the containment vessel of a light water reactor and suppressing diffusion of the radioactive materials from the light water reactor, it is important to install filtered venting devices to release high pressure pollutant gas to the atmosphere with elimination the radioactive materials in the gas.

Filtered venting systems with Venturi scrubbers and a pool, called as Multi Venturi Scrubber System (MVSS), Filtered Containment Venting System (FCVS) and so on, are used to realize filtered venting without any power supply in European and Japanese reactors (Lindau, 1988; Rust et al., 1995). These systems are composed of Venturi scrubbers part, in which there are several or hundreds of the Venturi scrubbers, and a pool part. In these systems, all of the Venturi scrubbers are branched off from a vent line, which connects the containment vessel to the systems. The Venturi scrubber is a venturi tube with holes for suction at the throat part. In these systems, there are a dispersed flow in each Venturi scrubber and a

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Nomenclature

e	energy	σ	acceleration by surface tension [m/s^2]
f	volume ratio of liquid	τ	shear stress [N/m^2]
g	acceleration of gravity [m/s^2]		
p	pressure [Pa]	*Greek letters*	
t	time [s]	g	represents gas phase
u	speed [m/s]	l	represents liquid phase
x	coordinate [m]	m	represents gas or liquid phase
λ	thermal conductivity [W/m^{2}K]	i	cell number
ρ	density [kg/m^3]		

bubbly flow in the pool part and the radioactive materials are eliminated through the gas-liquid interface from the pollutant gas to the liquid phase (Lindau, 1988). In the Venturi scrubber, the dispersed flow is formed from the suctioned liquid from the pool through the holes by the pressure difference between inside and outside of the throat part (called self-priming (Lehner, 1998)). The pressure difference caused hydraulic pressure from water surface of the pool to the holes and pressure drop by the convergent shape of the Venturi scrubber.

W. Luangdilok et al. simulated about decontamination performance of a MVSS among a severe accident. He reported a Venturi scrubber has ineffective time windows for scrubbing the contaminated gas. It is caused by the high pressure gas and the suctioned liquid with low velocity, especially when the beginning of the scrubbing the large amount of the gas (Luangdilok, 2009). N. Horiguchi observed the hydraulic behavior in a Venturi scrubber and confirmed that the high pressure and no suctioned liquid in it (he calls as self-priming suspension) under air-water conditions experimentally (Horiguchi et al., 2013).

H. Yoshida developed numerical simulation code TPFIT to simulate detailed two-phase flow behaviors in nuclear systems (Yoshida et al., 2004). H. Yoshida, et al. simulated rising bubble behavior under accelerating conditions by the code and validated it with the previous experimental date (Yoshida et al., 2014; Mizuno et al., 2012). T. Suzuki et al. simulated jet breakup phenomena in liquid-liquid contact in BWR lower plenum by the TPFIT and validated about the hydraulic behavior (Suzuki et al., 2014; Saito et al., 2014).

In existing study, evaluation methods for the scrubbing performance of the Venturi scrubber were developed. However, actual hydraulic behavior in it is too complicated, the previous evaluation was not validated the hydraulic behavior and studied the effect of differences between the simulated hydraulic behavior and an actual one on the performance of the Venturi scrubber. To develop a validated evaluation method for the scrubbing performance, it is important to develop detailed evaluation method for the hydraulic behavior in the Venturi scrubber. To simulate the complicated hydraulic behavior we consider to use analysis code TPFIT (Yoshida et al., 2004).

Then, an objective of this paper is to validate the hydraulic behavior simulated by TPFIT. As approaches, we conducted the analysis code by TPFIT under single-phase conditions in lab scale and validated its hydraulic behavior with previous studies. In addition, we perform a two-phase flow simulation for more realistic conditions.

2. Numerical simulation method

2.1. Outline of the TPFIT

This paragraph is written based on the report (Yoshida et al., 2004) to show you the outline of the TPFIT.

The TPFIT was developed by Japan Atomic Energy Agency to simulate detailed two-phase flow behaviors in nuclear systems (Yoshida et al., 2004). Governing equations used in the TPFIT consist of averaged (mixed) mass, momentum, and energy conservation equations for compressible fluid and transport equations for the mass of both phases as shown in the following.

Mass:

$$\frac{D\rho}{Dt} = -\rho\frac{\partial u_i}{\partial x_i}, \tag{1}$$

where u denotes the velocity component and x denotes the coordinate. Density ρ is calculated with the help of the following equation using the density and the volume fraction f of the gas and liquid phases:

$$\rho = \rho_l f_l + \rho_g f_g, \quad f_g = 1 - f_l. \tag{2}$$

Momentum:

$$\frac{Du_i}{Dt} = -\frac{1}{\rho}\cdot\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\cdot\frac{\partial \tau_{ij}}{\partial x_j} + g_i + \sigma_i, \tag{3}$$

where p denotes the static pressure, τ denotes the shear stress, and g and σ are the acceleration due to gravity and surface tension, respectively.

Energy:

$$\frac{De}{Dt} = -\frac{p}{\rho}\cdot\frac{\partial u_i}{\partial x_i} + \frac{1}{\rho}\cdot\frac{\partial}{\partial x_i}\left(\lambda\frac{\partial T}{\partial x_i}\right), \tag{4}$$

where e denotes the internal energy, λ denotes the thermal conductivity, and T denotes the temperature. In the evaluation of the volume fraction, in order to improve the precision of the analysis, the masses of both gas and liquid phases are evaluated.

Mass of both phases:

$$\frac{D\rho_m f_m}{Dt} = -\rho_m f_m\frac{\partial u_i}{\partial x_i}, \tag{5}$$

where subscript m denotes the gas or liquid phase. The mass and the volume fraction of liquid or gas are evaluated using the advanced interface tracking method developed by Yoshida et al. (2004). The two-phase capability, interface deformation and jet breakup, was validated (Yoshida et al., 2004; Suzuki et al., 2014).

2.2. Numerical conditions for single-phase flow simulation

In this paper, in order to validate the basic applicability of the TPFIT code for the flow in a Venturi scrubber, a numerical analysis of single-phase flow in the Venturi scrubber was performed. Fig. 1 shows the computational domain of the numerical simulation modeled the Venturi scrubber used by Horiguchi et al. (2013). Its width (x direction), depth (y direction), and height (z direction) were set to be 10.6, 8.0, and 160.2 mm, respectively. A ratio of the cross-section area between the inlet and the throat is 4.24.