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Visualization of Direct Contact Condensation of Steam-Air Mixtures at Chugging Mode

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1. Introduction

SMART is a small-medium-sized reactor under development by the Korea Atomic Energy Research Institute and has an 100MWe power, about one tenth of the conventional pressurized light-water reactor of 1000MWe [1]. Structure of the Containment Pressure and Radioacticity Suppression Syetem (CPRSS) shown in Fig.1 has been added as part of the reinforcement of safety design after the 2011 Fukushima accident. This passive cooling system is a device that reduces the in-containment pressure and temperature by directly sparging steam generated by the accident into the In-containment Refueling Water Storage Tank (IRWST). At this time, steam and subcooled water come into contact and direct contact condensation occurs. The direct contact condensation phenomenon has been carried out a lot of experimental studies to apply to BWR or conventional PWR, but most of them correspond to jet condensation mode not chugging mode, and the effects of non-condensing gases, including air in the plant, have not been considered.

This study performed visualization of direct contact condensation phenomena of steam-air mixture in pure steam chugging area [2]. The change in behavior was identified by converting the visualization results into 3D reconstruction and the variation in visualization results was presented according to the steam mass flux, the temperature of water tanks, and the mass fraction of air.

2. Research methodology

2.1 Image reprocessing

Whether external chugging occurs in this study is determined based on changes in the volume of condensation bubbles filmed through the high-speed camera. At this time, condensation bubble images are used to calculate quantitative volume changes, and the existing 2D reconstruction techniques are used by rotating images from one side, but 3D reconstruction techniques using front and side images used by Han [3], Kim [4] and others to obtain more accurate geometrical information were also used in this study.

3. Direct Contact Condensation Visualization Experiment

3.1 Experimental facility

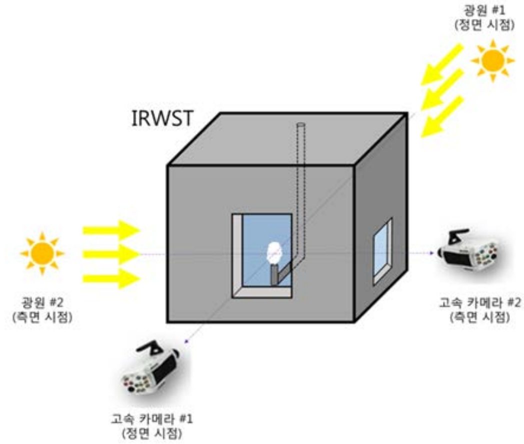

Fig.1. Schematic of visualization device setup

Steam generator for supplying steam and a subcooled water tank where condensation occurs, and an air tank for supplying non-condensable gas exists. The water tank has a size of 1 m X 1 m X 1.2 m (W X D X H) with a water level of 1 m. The flow rate of steam is controlled by the heater of the steam generator and the flow rate control valve, and measured by a corioli-type mass flow meter of Rheonik. The spager emitting steam is a horizontal acrylic spager with an internal diameter of 19mm, as shown in Fig.1. The flow rate of the air was measured using Nuritech's TSF air flow meter.

The high-speed camera of Phantom was installed on the visible window of the water tank and the light source was installed on the other side to reveal the inside of the tank. In addition, an additional high-speed camera and light source were installed at an angle of 90° to take images of the front and the side for the 3D reconstruction method. The two high-speed cameras were controlled to take pictures simultaneously through a function generator. The resolution of the filming was 1280×720PPI and the filming speed was 1,000 fps for 8 seconds.

The first step of the experiment is steam generator, water tank, and pipe preheating. When the pipe wall temperature is equal to the steam temperature, FCV is controlled to continuously flow the desired flow rate and the temperature of the water tank is checked. Filming was carried out after checking the flow rate, temperature, air flow rate, and water tank temperature and level.

3.2 Experiment results and analysis

3.2.1 Effect of Non-condensable gas existence

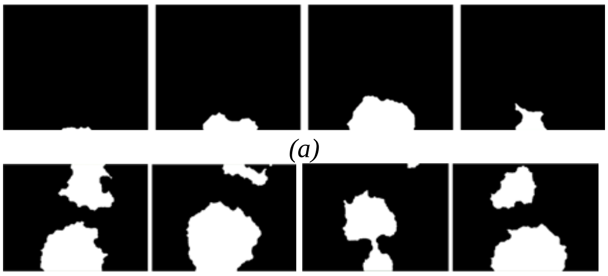

Fig.2. Condensation bubble shape change (water temperature: 40°C, steam mass flux: 60kg/m^{2}s): (a): pure steam, (b): mixed steam with air mass fraction 0.5%

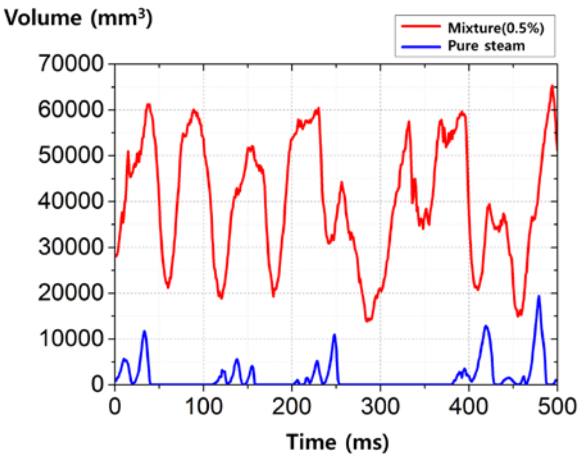

Fig.3. Condensation bubble volume of pure steam and mixed steam

To see the effects of non-condensable gases, the water tank temperature and steam flow were kept common at 40°C and 60kg/m^{2}s for each case, and the pure steam and mixed steam which contain air within 0.5% mass fraction were compared. Fig.2 is final image that converts from raw image of a pure and mixed vapor and Fig.3 is a volume with time. As a result of the experiment, the pure vapor periodically maintains a volume in 0 mm^3, but if air is mixed, the volume value is always greater than 0 mm^3. This means that the interface always exists outside the nozzle, and it can be confirmed that no chugging occurs if non-condensable gas is included in the experimental conditions.

3.2.2 Effect of steam mass flux

The conditions of water tank temperature(40°C) and air flow rate (0.005 kg/min) were applied in common to see the effects of steam mass flux and the two cases of steam flow rate 30 kg/m^{2}s and 60 kg/m^{2}s were compared. The experiment confirmed that both cases always maintain a volume greater than zero and that no chugging occurred. In addition, the maximum bubble volume was found to be approximately 30% greater at a steam mass flux of 30kg/m^{2}s than 60kg/m^{2}s.

3.2.3 Effect of subcooled water temperature

The conditions of steam mass flux(60kg/m^{2}s) and air mass fraction (0.5%) were applied in common to see the effects of subcooled water temperature and the three cases of water temperature 40°C, 50°C and 60°C were compared. The experiment confirmed that all three cases always maintain a volume greater than zero and that no chugging occurred. Also, the higher the water tank temperature, the greater the maximum volume of the bubbles. A rise in the temperature of the water tank means a decrease in the subcooling and soon becomes a relatively difficult environment for condensation. Therefore, even with the same amount of supply, it was interpreted as being larger because the amount of loss was small.

4. Conclusion

This study visualized the phenomenon of direct contact condensation of mixed vapor containing air and calculated the volume of condensed bubbles with irregular features using 3D reconstruction techniques. The experiment was conducted in the external chucking area for conservative verification based on the results of the safety analysis of CPRSS and observed that the frequency and volume of condensation bubbles were affected by the air existence, the steam mass flux and the temperature of the water tank. The volume of condensed air bubbles tended to be greater, the slower the steam mass flux, the higher the water tank temperature, and the higher the air mass fraction. In particular, it was confirmed that the condensation interface is maintained outside the nozzle even if the air contains only a 0.5% mass fraction at 60kg/m^{2}s of steam mass flux.

ACKNOLEDGEMENT

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