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Measurements of liquid film and droplets of annular two-phase flow on a rod-bundle geometry with spacer

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ABSTRACT

Measurements have been conducted to simultaneously consider both liquid films and droplets of the annular flow on a 3×3 simulating BWR fuel rod-bundle test-section with spacers. The optical system of a high speed camera and a tele-microscope was used to record the backlight images at the gap between a corner rod and a side rod of the bundle at high time and space resolutions. The data obtained from the liquid film showed that the mean film thickness, wave height, power spectral density, and wave velocity at the corner rod are larger than those at the side rod, and that the influences of the spacer are different in the cases of low and high gas superficial velocities. Simultaneously, the data containing size and spatial distributions as well as the axial velocity distribution of liquid droplets were obtained. In the case of lower gas flow rates, the spacer generates not only a large number of small droplets but also big droplets whose size exceeds the maximum droplet diameter at upstream. At further downstream, the spatial distribution of the droplets indicates an asymmetry characteristic, which emphasizes the contribution of the droplet impingement mechanism to the entrainment phenomena. Moreover, a close-up observation at right up- and downstreams of the spacer was conducted to describe the interactions between the two-phase flow and this structure. By using these new experimental arrangements, the interaction mechanisms among the wavy liquid film, droplets and spacer were discussed.

Introduction

Being the last flow regime that occurs before a possible dryout situation, the characteristics of the annular two-phase flow affect not only the efficiency of the mass and energy transfers but also the safety of many heat exchange systems. This is particularly important in the case of the boiling water reactor (BWR) in which the annular flow does occur near the top of the fuel core. Therefore, all the components of this two-phase flow (such as the liquid film flowing on the rod surface and the liquid droplets flying in the steam core between the rods) as well as the spacer's influences on the flow need to be considered carefully. The annular two-phase flow, however, has caused many difficulties for existing experimental studies because of its highly turbulent characteristics and unstable gas–liquid interfaces.

Many experimental techniques have been conducted to acquire the liquid film's thickness and wavy characteristics. Existing optical methods, including the planar laser-induced fluorescent (Alekseenko et al., 2009; Schubring et al., 2010a; Farias et al., 2012) and the laser focus displacement (Hazuku et al., 2008), have mostly been applied to circular pipe test-sections. Kamei and Serizawa (1998) used the ultrasonic transmission technique with a rotating reflector for single-rod geometry but this method faced difficulty in detecting large-curvature wavy surfaces. While the X-ray and neutron tomography methods are generally considered complex and expensive, electric conductivity based techniques have become much more popular (Azzopardi, 1986; Feldhaus et al., 2002; Damsohn, 2011; Zhao et al., 2013) because the conductance probes can be applied to a complicated geometry (such as rod bundles) and achieve a very high sampling frequency. However, due to machinery limitations, this method produces very low spatial resolution.

The total volume of liquid droplets of the annular flow can be determined by using suction probes (Barbosa et al., 2002; Kraemer et al., 1995) but details such as the droplet's size and velocity should be obtained by an optical based techniques (Azzopardi, 1997). These optical methods include the laser-diffraction technique (Azzopardi, 1985); the laser anemometry technique (Fore and Dukler, 1995; Yano et al., 2000); and the photography technique (Hay et al., 1998; Cho et al., 2011). Apart from the studies of Yano and Cho (which were conducted with mist flow) the

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others considered the annular flow in a circular pipe, thus their measuring devices required the removal of the liquid film to detect the droplets flying in the gas core. In other words, the droplet' diameter and velocity could be determined but the wavy characteristics of the liquid film were out of the consideration.

Several studies mentioned above were conducted to investigate the influences of different spacer designs. Both Feldhaus et al. (2002) and Damsohn (2011) considered the effects of spacers on the liquid film flow in a subchannel test-section. Among the few studies considering the annular flow with a mockup rod-bundle test-section, Nishida et al. (1994) and Kraemer et al. (1995) used circular electrodes and an extraction device, respectively, to measure the liquid film thickness. By treating the entrained droplets with a suction probe as mentioned above, Kraemer's group could consider both liquid film and droplet, but only per the total volume of corresponding liquid.

Most of the previous annular flow experiments have been designed to study only one component of the annular flow: either liquid film or droplet, despite the fact that there is a continuous interchange between the liquid distributed in each of them. Moreover, in the case of rod-bundle geometry, there has been little information on the wavy liquid film's characteristics, especially the interaction between the spacer's structure and the liquid waves. These limitations have restricted a comprehensive understanding of the annular flow phenomena on the rod-bundle geometry with the spacer.

As an attempt to fill in these gaps, the current study is aimed at the following targets:

- To confirm that the high speed camera technique using back light source can be applied to measure both the liquid film and droplets of the annular flow on rod-bundle geometry simultaneously.
- To grasp the characteristics of the wavy liquid film as well as the liquid droplets.
- To improve the understanding of the phenomena happening at the spacer regions.

The visualization arrangement established by Pham et al. (2014) is applied to measure both the liquid film and droplets of the annular flow in a 3 × 3 simulating BWR fuel rod-bundle test-section. The results obtained at high time and space resolutions not only describe the characteristics of the liquid film and droplets in the interactive relationships between them but also indicate the influences of the spacer on the two-phase flow. Furthermore, a close-up observation was conducted at right up- and downstreams of the spacer to describe the interactions between the wavy liquid film and the spacer, as well as the generation of droplets and their behaviors in these regions.

Experimental methodology

This section describes the experimental apparatus and an attempt to avoid the distortions that can occur in the image-data of the liquid film and droplets' measurements. After that, the experimental settings used to obtain the close-up qualitative images of phenomena happening at right up- and downstreams of the spacer are presented.

Annular two-phase flow loop

The annular two-phase flow loop (Fig. 1) is similar to the one used in the previous work (Pham et al., 2014). From the water tank, the purified water is pumped to the inlet of the test-section where it meets the gas (normal air) coming from the gas compressor to form the annular flow in the 3 × 3 simulating BWR fuel rod-bundle test-section. After that, the two-phase flow moves to the separator where the gas is released into the environment and the water is returned to the water tank.

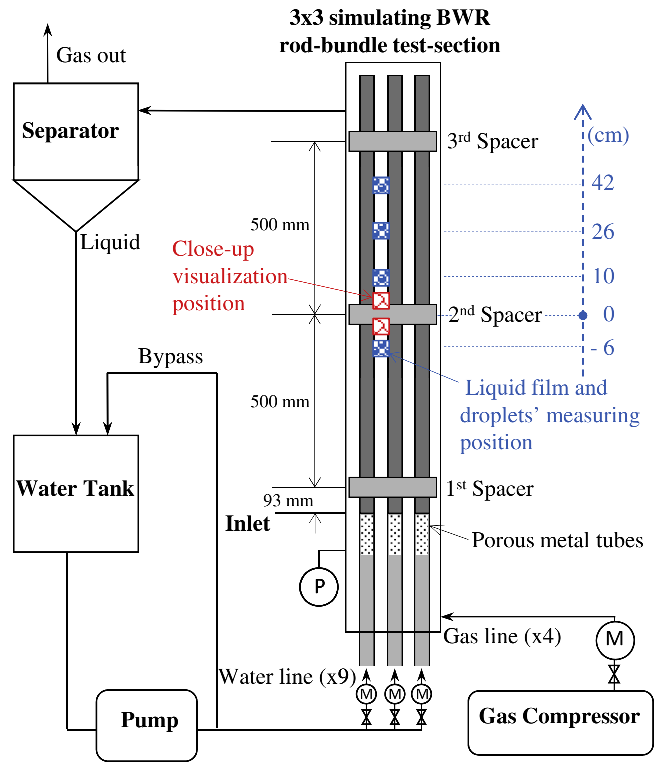

Fig. 1. Schematic diagram of experimental apparatus.

The test-section consists of a rectangular duct made of transparent acrylic resin and nine steel rods of OD 12 mm fixed by three circular ferrule-type spacers. A change compared to the system in previous work is that the first spacer is located after the inlet section to increase the rod-fixing capacity of the three spacers. This is necessary to minimize the moving of the rods during the measurement performed at the micro-scale resolutions.

The image data of the liquid film and droplets' measurements are taken by the system of the high speed camera Phantom V7.1 (Vision Research Inc.) and the Cassegrain tele-microscope (Seika Corporation) at four axial positions located before and after the second spacer (Fig. 1). The cross-sections of the test-section, the porous inlet structure, and the specification of the circular ferrule-type spacer are provided in Fig. 2. The image focus plane of the optical system is located at the gap between corner rod #1 and side rod #4 as shown in Fig. 2a. All image data of the liquid film and droplets' measurements are taken at this gap only, due to the fact that if the image focus plane of the optical system (DOF ~ 0.5 mm) is located further inside the test-section, the existence of the liquid films between the camera and the focal plane (such as the films on rod #1 and #4) will cause image distortions. It can be seen in Fig. 2c that the dimples and springs of the spacer are located beyond this gap (three spacers are installed in the same orientation) and therefore they are expected to not cause a local effect on the portions of liquid film located at the gap. Instead, their influences on the measuring data are considered to be embedded in an average effect of the whole spacer structure. The camera system is used to verify the smooth introduction of water to the test-section through the porous inlet structure (Fig. 2b).

While the location of a rod's surface in the image data is calibrated by turning off the valve of corresponding water line,