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Summary: Study on wavy interface behavior and droplet entrainment of annular two-phase flow in rod bundle geometry with spacers

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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 at high time and space resolutions provided the detailed descriptions of the gas-liquid interface behaviors at the region close to the inlet as well as further downstream. The formation of the "singlet disturbance-crest" near the inlet which is suggested to be the first form of the disturbance wave was observed. An explanation on the mechanism of this formation process was proposed. Obtained images of three types of the entrainment process (bag break-up, ligament break-up, and droplet impingement) not only agreed with the previously proposed mechanisms but also included the information about wavy behavior right before and after these events and the created droplets. In addition, the side-view images of the disturbance waves at different stages of development were presented. These data can be used to evaluate other measuring techniques applied to the study of this type of waves. Moreover, a close-up observation at right up- and downstream 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 are discussed.

1. Introduction

The annular liquid-film flow on rod bundle geometry plays a very important role for momentum and heat transfers, especially 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. The two-phase flow is characterized by the thin liquid films distributed on the rod's surface, the high velocity of the core of gas (or vapor) flowing through the gaps between these rods, and the liquid droplets flying with the gas core. Therefore, all the components of this two-phase flow (such as the liquid film flowing on the rod's 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.

One of the most difficult challenges in applying an observation technique to investigate the annular flow comes from the very unstable gas–liquid interfaces. They do not only require the high time and space resolutions of the image data acquisition systems but also cause the light scatter and reflection which lead to significant distortions in the image data. Therefore, the wavy surfaces of the liquid film flowing on the wall of the test-section strongly affect the observation of the waves themselves, as well as further inside the flow. To avoid these optical distortions, a popular method named as axial viewing technique (Hewitt and Whalley, 1980; Badie et al., 2001; Lecoeur et al., 2010) was used. The image series showed the cross section of the pipe with some bubble-like and ligament shapes corresponding to the two entrainment mechanisms proposed (Azzopardi, 1983): bag break-up and ligament break-up. These two processes were also recalled in a review (Azzopardi, 1997) on the droplets involved in annular two-phase flow phenomena. Although axial viewing technique offered good evidences for two proposed mechanisms, it has faced difficulties to provide the important information about the wavy interfaces'

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behaviors right before and after the event and the droplets' characteristics. The missing comes from the fact that the flow is generally high velocity in the axial direction, while the obtained image is a radial cross section.

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,b; Farias et al., 2012) and the laser focus displacement (Hazuku et al., 2008), have mostly been applied to circular pipe test-sections. The ultrasonic transmission technique with a rotating reflector for single-rod geometry (Kamei and Serizawa, 1998) 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 and Prasser, 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 et al. (2000), Cho et al. (2011) (which were conducted with mist flow) the 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. The effects of spacers on the liquid film flow in a subchannel test-section were considered in Feldhaus et al. (2002), Damsohn and Prasser (2011). Among the few studies considering the annular flow with a mockup rod-bundle test-section, circular electrodes were used in Nishida et al. (1994) and an extraction device was used in Kraemer et al. (1995) 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.

We discussed on a more comprehensive understanding of the interface behaviors related to the entrainment processes and the wave structures (Pham et al., 2014). In the following study (Pham et al., 2015a), we achieved the clear side-view images of the phenomena at the micro-scale by using a high speed camera and a tele-microscope to take the images of the vertical upward annular flow on a 3 × 3 simulating BWR rod-bundle test-section. The formation of a singlet wave crest near the inlet, the disturbance waves downstream, and three types of entrainment mechanisms: bag break-up, ligament break-up, and droplet-impingement, were discussed.

2. Experimental setup

In this section the experimental apparatus is firstly described, and to avoid the distortions that can occur in the image-data of the liquid film and droplets' measurements is attempted. The experimental settings used to obtain the close-up qualitative images of phenomena happening at right up- and downstream of the spacer are presented.

2.1. Annular two-phase flow loop

The annular two-phase flow loop as shown in Fig. 1 was used in Pham et al. (2014, 2015a). 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. 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

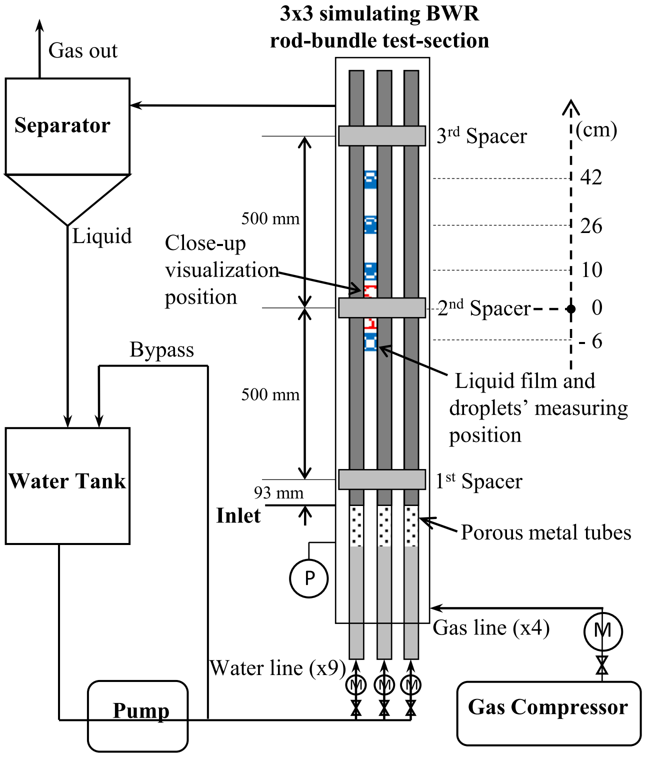

Fig. 1. Schematic diagram of experimental apparatus.

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