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Liquid film dynamics of two-phase annular flow in square and tight lattice subchannels

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HIGHLIGHTS

- A pair of liquid film sensors was applied to flow measurements in a double subchannel geometry.
- Film thickness distributions in square and tight lattice subchannels were measured.
- The characteristics of the water film flow were compared between each subchannel.
- Correlation feature of film thickness fluctuations in a subchannel gap were studied.

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ABSTRACT

The flow behavior of a liquid film on the wall in square-lattice and tight-lattice double subchannels was studied by using a pair of flexible liquid film sensors based on the electrical conductance method. The liquid film sensor has a network of electrodes on the surface and the electrical conductance between transmitter and receiver electrodes is detected by using a high-speed wire-mesh measurement system. The sensors were fixed on rod simulators with 20 mm diameter and the liquid film thickness distribution was estimated from the measured conductance data array. With this method, it is possible to observe the flow structure of the liquid film with a high sampling speed up to 10 kHz and a spatial resolution of 2 mm. In the present study, the spatial-temporal distributions of liquid film thickness in the annular flow in a square-lattice and a tight-lattice pair of adjacent subchannels were measured by using two liquid film sensors installed on the surface of opposing rods. The traveling of disturbance waves was observed in the time-series of two-dimensional film thickness distributions. The interaction of the liquid films on the opposing rods was investigated by correlating the signals of both sensors. As a result, the effect of the channel geometry on the averaged film thickness profiles and the correlation characteristics was analyzed for the first time.

1. Introduction

A stable energy source has to be ensured for a sustainable energy supply in the future. Nuclear energy has been considered as an option to cover the base load of the electricity supply. However, the management and effective utilization of plutonium is very important in terms of sustainability and issues of non-proliferation. High conversion boiling water reactors (HCBWR) are potential candidates for such an application as well as fast breeder reactors (Iwamura et al., 2006). The HCBWR can achieve a high conversion ratio by reducing the volume of water that is acting as coolant and moderator in the same time. For this purpose, a tight-lattice rod bundle with a narrow gap between the fuel rods is adopted. The main advantage of the HCBWR over Gen IV reactor concepts consists in the direct use of the well-established technology of light water reactors for the improvement of fuel sustainability.

In order to improve and assess the safety of the HCBWR, experimental data is needed to characterize the two-phase flow in the narrow subchannels of tight-lattice rod bundles. A number of studies on thermal-hydraulics in the tight-lattice rod bundle have been conducted by the Japan Atomic Energy Agency (JAEA). Kureta (2007) measured void fraction distributions in a rod bundle using neutron radiography. Tamai et al. (2004, 2006) studied the heat transfer characteristics in a 37-rod bundle. Furthermore, several

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numerical studies were also carried out to evaluate the two-phase flow phenomena in the tight-lattice configuration (Yoshida et al., 2008; Zhang et al., 2008). For the validation of high fidelity simulations using an interfacial tracking technique, an experimental database on the spatio-temporal characteristics of the flow structure is needed. Of particular interests are the bubble behavior at low void fraction conditions and the dynamics of the liquid film in the annular flow regime. Two-phase flow experiments with high-resolution instrumentation are not only interesting for tight-lattice geometries, but can contribute to a better understanding and modeling of traditional square-lattice rod bundles of the existing light water reactors. Recently, several measurement tools have been developed for such experiments in the rod bundle. There is considerable progress in the field of imaging by X-rays, gamma radiation and neutrons. The common main advantage is the non-intrusiveness of the measurement. Neutron radiography is an excellent tool for the visualization of a gas-liquid two-phase flow in metallic pipes (Mishima and Hibiki, 1998) because of the better contrast of low mass number nuclides (H_2) close to channel walls and fuel rod simulators than photons, which are much more strongly attenuated by the heavier elements in the metal wall. Kureta (2007) carried out neutron radiography experiments for a 3D visualization of the two-phase flow structure in a tight-lattice rod bundle. Kickhofel et al. (2011) and Zboray and Prasser (2013) have applied the technique of cold neutron imaging in a 3D tomography setup to measure the liquid film thickness profile along the walls of a tight-lattice subchannel model as well as in a square-lattice. However, cold neutron tomography requires large infrastructures, which is in case of the work of them the spallation neutron source facility SINQ of the Paul Scherrer Institute in Switzerland. Furthermore, the temporal resolution of the radiography is low. In the experiments of Zboray and Prasser (2013), a complete 3D scan took several hours and the obtained phase distributions are therefore time averaged, which requires keeping flow conditions constant over a long time. Individual interfacial structure, like wavy films or bubbles, cannot be resolved.

In order to study dynamic structures forming in the liquid film at the wall in the annular flow regime, Damsohn and Prasser (2009a, 2009b) developed a liquid film sensor which is based on a high speed electrical conductance measurement. They applied the sensor to time resolved measurements of the film thickness distribution in the square-lattice rod bundle (Damsohn and Prasser, 2010). Conductance measurements were used before in numerous other studies to characterize the liquid film thickness, however, the liquid film sensor has the advantage to acquire instantaneous two-dimensional distributions of the film thickness on a matrix of typically 16 × 64 individual measuring locations with a time resolution of 10 kHz. The lateral resolution is 2 mm and the film thickness range is about 0.8 mm. The resolution of the film thickness measurement is about 20 μm (Damsohn and Prasser, 2010).

The aim of this work is to clarify the difference of flow characteristics between a square-lattice and a triangular tight-lattice subchannel and to get a better understanding of the liquid film behavior in such subchannel geometry, which is important to improve the safety of the reactor core. Therefore, in the present study, a pair of the liquid film sensors is applied to measurements in an annular flow in the subchannel geometry of both the square-lattice and the tight-lattice configuration. The test channel consisted of a segment comprising a pair of adjacent subchannels (double subchannel geometry). Then, the liquid film dynamics are investigated by using the time-resolved film thickness distributions measured by the film sensor. Finally, the film thickness fluctuations on the opposing walls in the subchannels are correlated to study the dependence on the subchannel geometries and the inlet flow conditions.

2. Experiments

2.1. Experimental setup

The scheme of the experimental facility is given in Fig. 1. This setup was used for the experiments of Damsohn and Prasser (2010) (CALVIN test facility). The working fluids in the present study were air and water at room temperature. The compressor was used to send a high flow rate of air to the test channel. Water was injected upstream of the test section. The injection port is forming a slit spreading the water to the surface of the inner walls of the flow duct forming the subchannel geometry. The mixture at the exit of the vertical duct was sent to a separator. From there, both water and air were circulated back to the test section via storage tanks and a heat exchanger for keeping the temperature constant.

Two test channels with different subchannel geometries were used in the experiments (Fig. 2). The flow duct follows the walls and symmetry boundaries of a pair of adjacent subchannels of square fuel rod lattice (Fig. 2(a)) and a triangular tight-lattice (Fig. 2(b)) Both test sections were made of acrylic glass. They have the same length of 2.5 m. The square-lattice channel is confined by 6 adjacent rods. Two out of these 6 rods are in contact with the fluid of the simulated pair of subchannels over an angle of 180°. These rods form the subchannel gap. The outer 4 rods are only quarter rods covering 90° each. The pair of triangular tight-lattice subchannels is surrounded by 4 rods, two of them, forming the subchannels gap, cover an angle of 120°, the other two of 60° each. The rod simulators have a diameter of 20 mm. This means that the dimensions of the simulated subchannels are scaled up by a factor of 2–3 compared to realistic reactor cores. This makes it easier to reach higher Reynolds numbers in experiments at ambient temperature. It also better responds to the fact that the surface tension of water at room temperature and with it the capillary length scale is higher compared to reactor conditions. In the square-lattice subchannels, the rod pitch is 26.5 mm and the free cross-sectional area is 776 mm^2, the width of the subchannel gap is 6.5 mm. On the other hand, the tight-lattice channel has a gap width of 2 mm and the pitch is 22 mm. Its flow cross-section has an area of 34.9 mm^2. The hydraulic equivalent diameters of the square- and tight-lattice channels are 18.9 mm and 1.97 mm, respectively. A pair of film thickness sensors was installed on those two opposite fuel rod models, which form the subchannel gap, as shown in Fig. 2. The outer radius of these

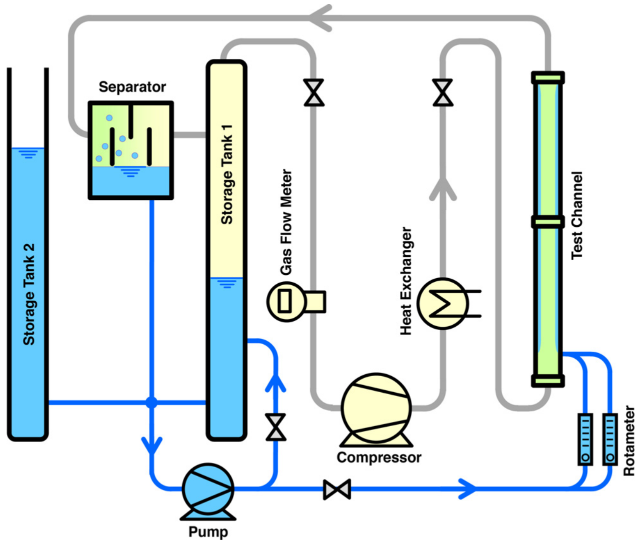

Fig. 1. Experimental test facility CALVIN (Damsohn and Prasser, 2010).