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Development of neutron and X-ray imaging techniques for nuclear fuel bundle optimization

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HIGHLIGHTS

- Experiments on adiabatic annular flows in fuel bundle mockups have been carried out.
- High-resolution, cold neutron imaging is used to measure film liquid thickness.
- Basic influence and working of functional spacers can be well studied.
- A heated fuel bundle mockup was built to study film dry out in convective boiling.
- First imaging data on the heated setup are presented.

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ABSTRACT

High-quality boiling crisis, i.e. dry out of the liquid film is an important operational safety issue for boiling water reactors. The phenomena involved in dry out are complicated and difficult to capture in full details in experiments. We follow a step-wise approach to the problem and utilize innovative, high-resolution measurement techniques. First extensive testing have been carried out on partial nuclear fuel bundle models containing typically a couple of neighboring subchannels. These first series featured adiabatic, air-water annular flows with and without the presence of prototypical functional spacers. Cold neutron imaging has been used to map the distribution of the liquid film thickness on the virtual fuel rods and on the spacer structures. As a next step a dedicated loop using a special working fluid has been designed enabling examining convective boiling two-phase flow in similar geometries as the adiabatic tests. Cold neutron and X-ray imaging can be used for the heated set-up to try to capture actual dry out phenomena. An overview of the result of the adiabatic test series and the first result with the heated experiments are given below.

1. Introduction

The high-quality boiling crisis, i.e. dry out of the liquid film, can occur typically in the upper part of a boiling water reactor (BWR) fuel assembly and is a severe safety concern in nuclear reactor technology endangering the integrity of the fuel (Lahey and Moody, 1993). The annular flow prevailing under such conditions exhibits a thin liquid film on the pin surfaces and a droplet laden gas core flow. The occurrence of dry out is strongly dependent on the local fluid conditions. Besides evaporation, two competing phenomena influence the liquid film thickness (LFT) in annular flow: the atomization of large disturbance waves on the dynamic gas-liquid interface resulting in droplet entrainment from the film into the gas core and the reverse process of droplet deposition onto the film (Hewitt and Hall-Taylor, 1970). Actually, a significant portion of the coolant flows in the form of droplets not contributing to the cooling of the fuel pins. Promoting droplet deposition onto the liquid film is therefore the preferred way in BWRs to enhance the LFT and the margin to dry out. This is done by using functional spacers having vanes. Spacer grids ensure the stability of the fuel pins while the vanes are used to control the flow to enhance droplet deposition on the liquid film and thus the margin to dry out. A vast number of patents and proprietary design exist for different types of spacer grids e.g. Gustafsson (1996), Smith and Maynard (2003), Nylund (2004), Helmersson et al. (2009). Functional spacers represent the common industrial practice to optimize the thermal-hydraulics performance of fuel bundles and to avoid the dry out. Earlier research has indeed confirmed the basic benefits

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of spacer vanes in enhancing the liquid films and the dry out margin (Kraemer et al., 1995; Feldhaus et al., 2002; Damsohn and Prasser, 2010). Nevertheless, the phenomena involved in dry out are complicated and difficult to capture in full details in experiments especially that appropriate, high-resolution measurement techniques are still scarce.

Regarding the latter issue we have tried utilizing innovative experimental techniques. Non-intrusive, high-resolution imaging methods have become increasingly popular in fuel bundle research but still count to be an exotic approach. Neutron radiography/tomography for fuel bundle investigations have been performed by Takenaka et al. in a number of studies (Takenaka et al., 1998, 1999; Takenaka & Asano, 2005). Lim et al. (2005) performed high-frame rate thermal neutron radiography on a model fuel bundle. Kureta has performed comprehensive investigations on tight-lattice fuel bundles of an advanced BWR design using thermal neutron tomography (Kureta, 2007a, 2007b; Kureta et al., 2008).

We have shown in earlier studies that cold neutron tomography is a promising tool for investigating annular flows and the basic functioning of spacers and optimized the technique to obtain accurate LFT measurements (Zboray et al., 2011; Zboray & Prasser 2013a, 2013b). We have investigated different conventional, rectangular (Zboray et al., 2011; Zboray and Prasser, 2013a) and triangular, tight lattice fuel bundle models with and without spacers (Zboray et al., 2011; Zboray and Prasser, 2013b).

Due to the complexity of the dry out phenomenon, all the aforementioned studies were carried out using adiabatic, air-water annular flows, representing the first stage of a step-wise approach with increasing complexity. The first half of the paper discusses these adiabatic tests illustrating their outcome by some representative result in details obtained for a model geometry consisting of five neighboring subchannels of a rectangular lattice.

As the next step of the research program, we have constructed a heated partial fuel bundle model to try to image dry out in convective boiling flows. This represents a major step forward towards prototypical reactor conditions compared to the first adiabatic tests. Note that neutron imaging investigations of heated channels are extremely rare. In one of them void fraction was measured in a heated pipe under oscillatory water flow conditions using neutron radiography at one of the port of the Kyoto University research Reactor (Umekawa et al., 2013). In another a single finned fuel pin simulator, heated internally with water, was studied using Freon 134a as working fluid flowing in an annulus around the pin with and without spacer by neutron radiography measuring the cross section-averaged void fraction (Lim et al., 2008). More studies can be found using gamma and X-ray methods for fuel bundle models in the literature. Just to mention a few: Kok et al. (2001) has performed low-resolution subchannel void-fraction measurements using the gamma transmission method in 6 × 6 rod bundle operated with Freon-12 at 12 bar. Windecker and Anglart (2001) have also performed low resolution gamma tomography on the FRIGG loop of Westinghouse Atom containing 24 heated rod bundle using water as fluid at prototypical pressures. Inoue et al. (1995) has performed X-ray tomography on a full-scale BWR bundle developed by the Nuclear Power Engineering Corporation (NUPEC) of Japan under prototypical conditions. None of the aforementioned studies concentrated on annular flows, liquid film thicknesses, spacer effects and dry out in a detailed manner. Our heated test geometry is very similar to the adiabatic one consisting of five neighboring subchannels. The design of the bundle model is optimized such to satisfy possibly all thermodynamic, thermal-hydraulic and imaging boundary conditions. As a result we use chloroform as working fluid, which in turn enables besides cold neutron also X-ray imaging of the process. Details of the design are given below. First cold-neutron and X-ray imaging results obtained on boiling annular flows will be shown and discussed.

2. Adiabatic annular flow imaging

2.1. Adiabatic fuel bundle models and two-phase flow loop

The different fuel bundle model geometries we have examined using adiabatic, air-water two-phase flows are shown in Fig. 1. All featured a two-phase flow loop a whit a closed water loop together with an open loop of dry air at near ambient temperatures and pressures. The scheme of the loop is illustrated in Fig. 2b. The two-phase mixture is created at the bottom of the fuel bundle model and it exits at the top of it into a tank, where the air is left to egress while the water is recycled by a pump. The air flow is measured by a rotameter (accuracy is about 2% o.r.), while the water flow is measured by a vortex flow meter (accuracy 0.75% o.r. specified by the manufacturer). The water is pumped back to the test section by a frequency controlled pump. The absolute pressure in the channel is measured at its base near the air inlet (accuracy ±0.05 bar). Flexible inlet and outlet hosing allows the entire channel to rotate 180 degrees around its vertical axis on a motor actuated turntable during the course of a tomographic measurement (see Fig. 2a).

The bundle model geometry we focus the discussion on here is shown in Fig. 1c featuring five neighboring subchannels at about 1:1 scale in a rectangular 8 × 8 BWR-6 fuel lattice, in such way that the middle subchannel is fully undisturbed from unrealistic boundaries (walls) unlike the others. The bundle model comprises a thin-wall (3 mm thickness) upper section and a thick-wall lower section. The channels are constructed entirely out of Anticorodal-110® (EN AW-6082). This aluminum alloy is chosen for its corrosion resistance and welding properties but most importantly it is nearly invisible to neutrons. The hydraulic diameter of the channel is D_h = 13.9 mm. The upper, thin-wall section, which is 45 cm tall, has always been used for imaging with neutrons. Below the thin-wall section, connected by a flange, is an 80.5 cm long segment with thick outer walls and the same subchannel geometry inside.

The base of the channel comprises a base plate adapter for connection to the turntable, four air inlets, a flow stratifier and four water inlets (one each side) above that (see Fig. 2), all this over 8 cm in height. The water inlet piece is designed specifically to inject the liquid at the walls using beveled edges such that the flow is already near-annular at the inlet (Zboray et al., 2011). The flow has about 90 cm (about 65 D_h) to develop before reaching the spacer vanes. The setup is modular; the two parts of the flow channel can be replaced by those featuring the geometry under study.

2.2. The imaging neutron beam line and detector setup

The imaging of the subchannels has been performed at the cold neutron beam line, ICON, at the SINQ spallation neutron source at the Paul Scherrer Institute, Switzerland (Kaestner et al., 2011). The beam line provides a neutron flux of about 4e6 $cm^{-2}\,s^{-1}$ and the majority of the neutrons has energies significantly below 0.025 eV, i.e. in the cold range. For details on the beam line see Kaestner et al. (2011).

The imaging optics consisted of a 1024 × 1024 pixels, cooled ANDOR CCD camera equipped with an f/2.0 100 mm Nikon macro lens focusing on a scintillator/converter screen through a mirror at 45 degree angle. The bit depth of the camera is 16 bits and the typical intensity (dynamic) range of the projection images in the experiments varies between 3000 and 8000 grey levels. A field of view (FOV) of about 9.2 cm∗9.2 cm has been achieved with a pixel size of the digitized images of 89.7 μm/pixel. The camera and mirror are placed in a light-tight box, whose only opening is covered by the scintillation screen (see Fig. 2a). A reasonably high L/D (L = collimator length, D = aperture diameter) ratio of about 604

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