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Optimizing the performance of cold-neutron tomography for investigating annular flows and functional spacers in fuel rod bundles

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HIGHLIGHTS

- Annular flows w/wo functional spacers are investigated by cold-neutron imaging.
- Performance of liquid film thickness measurement under different imaging modalities is evaluated and optimized.
- MC simulations of the cold neutron imaging are performed to help quantifying the measurement accuracy.
- Spectral, scatter corrections and minimizing the blur are necessary to avoid bias in film thickness estimate.
- Empty channel referencing offers in general the highest accuracy and quality.

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ABSTRACT

In a previous study we used cold-neutron imaging to examine annular flows and the influence of functional spacers on such flows in a fuel bundle model. Investigating adiabatic, air–water annular flows in a scaled-up model of two neighboring subchannels of a BWR fuel assembly, we have shown that cold-neutron tomography is a promising tool to study such flows in nuclear fuel bundles. Here we try to optimize the performance of the method and examine the influence of certain parameters and modalities of the imaging on the quality and accuracy of the results.

1. Introduction

Dryout of the coolant liquid film at the upper part of the fuel pins of a boiling water reactor (BWR) core is the type of boiling crisis occurring at high void fraction conditions (Lahey and Moody, 1993). The annular flow occurring under such conditions features a mostly thin water film present on the surfaces of the fuel pins and a droplet laden gas core. Dryout is clearly a safety concern and it also limits the thermal power output of a BWR. The behavior and occurrence of dryout is strongly dependent on the local fluid conditions. Therefore a thorough understanding of the behavior of annular flows and liquid films is crucial for the safety and economy of BWRs.

The gas–liquid interface in annular flows is very dynamic with waves traveling on it. The atomization of large disturbance waves by the turbulent gas core is believed to be the main source of droplet entrainment from the film into the core of the annular flow (Hewitt and Hall-Taylor, 1970). Actually, a huge portion of the coolant travels in the form of droplets in the annular regime carried by the vapor 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 liquid film thickness (LFT) and dryout margins. This is done by using functional spacers equipped with vanes in the fuel bundle. Spacer grids enhance the stability of the fuel pins while the vanes are used to control the flow. The main requirement for BWR spacers is that they provide a maximal efficiency in phase separation to transfer the droplets from the gas core onto the fuel rods (droplet deposition) while causing a minimal pressure drop. A vast number of patents and proprietary designs exist for different types of spacer grids, e.g. Gustafsson (1996), Smith and Maynard (2003), Nylund (2004), and Helmersson et al. (2009). BWR fuel vendors have put great efforts into improving spacers in order to obtain better performance from their fuel assemblies. A volume of research has confirmed the basic benefits of spacer

Abbreviations: AC-110, Anticorodal 110; BWR, boiling water reactor; CCD, charge coupled device; CHF, critical heat flux; ESF, edge spread function; FBP, filtered back projection; FWHM, full width at half maximum; FOV, field of view; ICON, imaging with cold neutrons; LFT, liquid film thickness; LSF, line spread function; MC, Monte Carlo; QNI, quantitative neutron imaging; PSI, Paul Scherrer Institute; ROI, region of interest.

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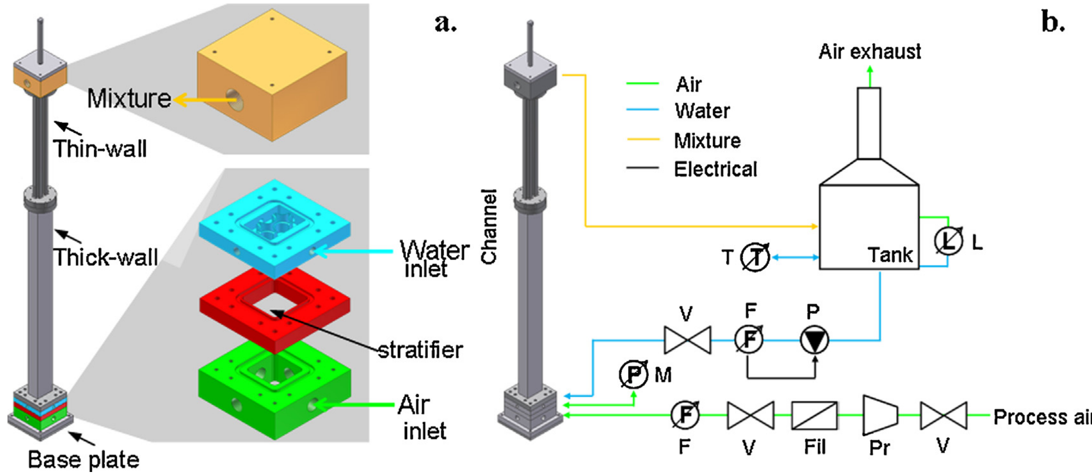

Fig. 1. (a and b) Scheme of the double subchannel test section and the two-phase flow loop.

vanes in enhancing the liquid films and thus the dryout margin (Kraemer et al., 1995; Feldhaus et al., 2002; Damsohn & Prasser, 2010).

Nonetheless, the mechanisms by which the spacers affect the annular flow and film thickness are still subject to debate and might depend strongly on the actual spacer and vane geometry. Therefore there is a need for high-resolution methods to quantify spacer performance to support fuel bundle development. In a previous study, we have shown that cold neutron tomography is a promising tool for such purposes (Zboray et al., 2011; Kickhofel et al., 2011). This non-intrusive, contactless method is still exotic in this field though it started to be increasingly applied in the last decade. Neutrons provide better contrast for aqueous two-phase flows in a metallic casing like a fuel bundle in comparison to X- or gamma-rays. Using neutron radiography/tomography for fuel bundle research, Takenaka et al. have performed a number of studies (Takenaka et al., 1998, 1999; Takenaka and Asano, 2005) and compared the performance of fast and thermal neutron imaging (Takenaka et al., 1999). Lim et al. (2005) performed high-frame rate thermal neutron radiography on a model fuel bundle. Mishima et al. (1999) have examined a model of two adjacent subchannels of a high conversion light water reactor (HCLWR) tight lattice fuel bundle using neutrons. Along this line, the research by Kureta (2007a,b) and Kureta et al. (2008) must be also mentioned who have performed comprehensive investigations on tight-lattice fuel bundles of an advanced BWR design using thermal neutron tomography.

We have investigated in previously (Zboray et al., 2011; Kickhofel et al., 2011) air–water annular flows in a test section modeling two neighboring subchannels of a BWR fuel bundle using cold neutron imaging. Here we present the continuation of those investigations. We examine the influence of different parameters and modalities of the imaging on the quality and accuracy of the results in more detail. This is done, on one hand, based on new experimental series performed at the ICON beam line of the Spallation Neutron Source (SINQ) at the Paul Scherrer Institute, Switzerland. On the other hand, we also compare and validate the experimental results against Monte Carlo simulations.

The same two-phase flow loop with a double subchannel has been used for these tests as in our previous study (Zboray et al., 2011), therefore only the most important features and eventual modifications of the setup are described here for brevity. The description of the cold-neutron tomography station at the ICON beam line is treated in the same fashion.

2. Experimental setup

2.1. The two-phase flow loop with a double subchannel

The setup comprises a closed water loop met by an open loop of dry air at near ambient temperature and pressures. The scheme of the loop and the double subchannel is illustrated in Fig. 1. The two-phase mixture is created at the bottom of the double subchannel 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, whose speed is controlled based on the reading of the vortex flow meter. 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° around its vertical axis on a motor actuated turntable during the course of a tomographic measurement.

The channel geometry models two neighboring subchannels in a BWR fuel rod bundle at a scale approximately twice that of a true commercial fuel element (see Fig. 2a and b). For details on the choice of this scaling see Zboray et al. (2011) and Damsohn and Prasser (2010).

The double subchannel model as is shown in Fig. 1 comprises a thin-wall (3 mm thickness) upper section and a thick-wall lower section. The channel is 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 (see Fig. 4b), ensuring the majority of neutron flux is attenuated by the water film inside the test section and not by the channel walls. 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 thicker, rectangular outer walls and the same double 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. 1a), 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 (Damsohn and Prasser, 2010). The flow is provided approximately 90 cm upstream to develop before reaching the spacer vanes.