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Simulations and measurements of adiabatic annular flows in triangular, tight lattice nuclear fuel bundle model

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ABSTRACT

High conversion light water reactors (HCLWR) having triangular, tight-lattice fuels bundles could enable improved fuel utilization compared to present day LWRs. However, the efficient cooling of a tight lattice bundle has to be still proven. Major concern is the avoidance of high-quality boiling crisis (film dry-out) by the use of efficient functional spacers. For this reason, we have carried out experiments on adiabatic, air-water annular two-phase flows in a tight-lattice, triangular fuel bundle model using generic spacers. A high-spatial-resolution, non-intrusive measurement technology, cold neutron tomography, has been utilized to resolve the distribution of the liquid film thickness on the virtual fuel pin surfaces. Unsteady CFD simulations have also been performed to replicate and compare with the experiments using the commercial code STAR-CCM+. Large eddies have been resolved on the grid level to capture the dominant unsteady flow features expected to drive the liquid film thickness distribution downstream of a spacer while the subgrid scales have been modeled using the Wall Adapting Local Eddy (WALE) subgrid model. A Volume of Fluid (VOF) method, which directly tracks the interface and does away with closure relationship models for interfacial exchange terms, has also been employed. The present paper shows first comparison of the measurement with the simulation results.

1. Introduction

To improve the long-term sustainability of nuclear power generation and to achieve better fuel utilization, different innovative reactor concepts have emerged in the last decade with significantly increased conversion ratios nevertheless still relying on well-established light water reactor (LWR) technology. High conversion ratios are obtained by hardening the neutron spectrum via reducing the water fraction in the core adopting usually a triangular, tight-lattice fuel bundle geometry, featuring narrow gaps combined with relatively large diameter rods. The boiling-type, high conversion light water reactor (HCLWR) is a promising concept to achieve the aforementioned goals. Intensive research focusing on this type of HCLWR has been carried out in Japan in the past decades. Iwamura et al. (1999) describe already the research efforts toward a Reduced-Moderation Water Reactor (RMWR), which aims at breeding, high burn-up, long operation cycles and plutonium recycling. By a more step-wise approach on the evolutionary way toward cores with a triangular lattice, it is proposed to start with increasing the density of the rectangular lattice (Kondo et al., 2004). In the second step, triangular fuel rod lattice would lead to hexagonal fuel element cross-sections, which would be combined with Y-shaped control rods (Yamashita et al., 2004). Uchikawa et al. (2007) describe the next evolutionary step toward a light water reactor with flexible fuel cycle (FLWR) for minor actinide (MA) recycling.

The FLWR core concept is envisioned in two stages, the first would be a continuation of current LWR technology, where the fuel rod gap is the same as current LWR's. When loaded with 9% Plutonium containing mixed oxide (MOX) fuel, a conversion ratio of approximately 0.9 can be achieved. The fuel assemblies in the second phase of the FLWR concept have the exact same configuration (rod number, pitch) as before, but with increased Pu content and a larger fuel rod diameter. With 18% plutonium containing fuel, conversion ratios over 1.0 can be realized (Uchikawa et al., 2007), enabling breeding in an LWR. While power output of the first and second phases of the FLWR project are the same, the increased rod diameter decreases interstitial coolant volume. This poses a challenge on cooling the bundle properly, as the same amount of power has to be removed with less coolant. To ensure the thermal-hydraulic feasibility of the concept, and to ensure continuity between the first and second FLWR phases in the same core,

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Nomenclature

k	turbulent kinetic energy
ε	dissipation rate
D_h	hydraulic diameter
u_τ	shear velocity
τ_w	wall shear
ρ	density
y	distance from wall
ν	kinematic viscosity
φ	void fraction
u^+	dimensionless velocity
y^+	dimensionless wall distance
u'	fluctuating velocity field
U	mean velocity field

significant experimental and modeling R&D still has to be done. The use of computational fluid dynamics (CFD) modeling is planned and being done (Ohnuki et al., 2008; Takase et al., 2004; Yoshida et al., 2006). This is accompanied by significant experimental activity to check the accuracy of CFD simulations, and to validate the models for certain phenomena in the numerical approach (Ohnuki et al., 2008). The latter involves mainly critical power, critical heat flux (CHF), pressure drop and spacer tests on different sized fuel bundle models (Yamamoto et al., 2004, 2006; Kureta et al., 2006). Also the 3D void distribution has been studied in great detail using neutron tomography, a non-intrusive technique, by Kureta (2007a, 2007b) and the prediction of a range of codes have been validated against these experimental results (Kureta et al., 2008).

Clearly, the influence of geometry and scale in tight lattices should be carefully evaluated for phenomena such as the boiling transition (crises) in the annular flow regime caused by the dry-out of the liquid film. It is a severe safety issue for the tight lattice fuel bundles just as it is in conventional rectangular BWR lattices (Lahey and Moody, 1993). Therefore, a thorough understanding of the behavior of annular flows and liquid films is crucial for the HCLWRs. Related to this, the development and use of functional spacers in tight lattice geometries for enhancing the margin to dry out should also be examined in detail.

To attack this problem, at first in a simplified manner, we have carried out experiments on adiabatic, air-water annular two-phase flows in a tight-lattice, triangular fuel bundle model. A high-spatial-resolution, non-intrusive measurement technology, cold-neutron tomography, has been utilized (Zboray and Prasser, 2013a). The influence of functional spacers on the annular flow has been also studied to better understand the basic functioning of the mixing-vane spacer. The main measured quantity is the distribution of the liquid film thickness on the virtual fuel pin surfaces downstream of the spacer (Zboray and Prasser, 2013b).

Unsteady CFD simulations have also been performed to replicate and compare with the experiments using the commercial code STAR-CCM+. Large eddies have been resolved on the grid level to capture the dominant unsteady flow features expected to drive the liquid film thickness distribution downstream of a spacer while the subgrid scales have been modeled using the Wall Adapting Local Eddy (WALE) subgrid model. A Volume of Fluid (VOF) method, which directly tracks the interface and does away with closure relationship models for interfacial exchange terms, has been employed.

Below the experimental set up and measurement technology is introduced first. Then the computational models and methods are explained in detail. Finally, the first comparison of the measurement results with those of the simulations is shown. Time-averaged film thickness results are compared while liquid film velocity profiles are also obtained with the simulation results.

2. Experimental setup and conditions

2.1. The fuel bundle model

The setup comprises of a flow channel featuring the tight lattice geometry complemented by a recirculation auxiliary system closing the two-phase flow loop operated at near ambient temperature and pressure. The scheme of the loop and the subchannel is illustrated in Fig. 1. The channel geometry models four neighboring subchannels (quadruple subchannel test section) of a conceptual FLWR fuel rod bundle at a scale approximately twice that of the actual bundle (see Fig. 2a). The investigation focuses on the middle subchannel (subch2 in Fig. 2a) as it is not limited by the presence of walls, which pose unrealistic no-slip boundary conditions that are not present in a full fuel bundle, whereas such unrealistic boundaries are present in the other three subchannels.

The channel is constructed entirely out of Anticorodal-110® (EN AW-6082). For details on the test section see Zboray and Prasser (2013b).

We have investigated here a simple, generic spacer geometry shown in Fig. 2c. It comprises split vanes that have been developed in the context of low-quality CHF problems to promote crossflow between subchannels (Shin and Chang, 2009) and resembles in geometry to the ULTRAFLOW™ spacer developed for the ATRIUM™ fuel assemblies by AREVA (Kraemer et al., 1995). The spacer grid is placed just above of the start of the thin-wall section (see Fig. 1a). The spacer is constructed out of 0.6 mm thick aluminum sheets welded together. Note that as the vanes are quite tiny the uncertainty in the actual inclination angle could be around 3°.

2.2. The neutron imaging method

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. 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 Li^6-doped scintillator/converter screen through a mirror at 45° angle. A field of view (FOV) of about 6 × 6 cm^2 has been achieved with a pixel resolution of the digitized images of 59.5 μm/pixel. The camera and mirror are placed in a light-tight box, whose only opening is covered by the scintillation screen.

The image pre-processing and tomographic reconstruction is performed as described in Zboray and Prasser (2013a, 2013b). Projections of the empty channel (no flow) are used as references for reconstruction and the raw projection data are corrected for spectral (beam hardening) and scattering effects based on Monte Carlo (MC) simulations as described in Zboray and Prasser (2013a). The liquid film thickness (LFT) is determined by integrating the liquid hold-up profile over the liquid film obtained from the reconstructed gray-scale image. As is shown by Zboray and Prasser (2013a) the LFT obtained in such a way has a minimal bias (around −2% or less) and its statistical uncertainty is typically 7–9% for the present measurements. Artifacts occurring in the reconstructed image, their significance as well their suppression or compensation are thoroughly discussed in Zboray and Prasser (2013a). Experimental results are shown in details in Section 4.

2.3. Test conditions

We have investigated three flow combinations, summarized in Table 1, with and without the spacer shown in Fig. 2. The experiments with spacer have been carried out using two field-of-views (FOVs), one focusing at the spacer and one above the spacer. All