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Time-resolved fast neutron radiography of air-water two-phase flows

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Abstract

Neutron imaging, in general, is a useful technique for visualizing low-Z materials (such as water or plastics) obscured by high-Z materials. However, when significant amounts of both materials are present and full-bodied samples have to be examined, cold and thermal neutrons rapidly reach their applicability limit as the samples become opaque. In such cases one can benefit from the high penetrating power of fast neutrons. In this work we demonstrate the feasibility of time-resolved, fast neutron radiography of generic air-water two-phase flows in a 1.5 cm thick flow channel with Aluminum walls and rectangular cross section. The experiments have been carried out at the high-intensity, white-beam facility of the Physikalisch-Technische Bundesanstalt, Germany. Exposure times down to 3.33 ms have been achieved at reasonable image quality and acceptable motion artifacts. Different two-phase flow regimes such as bubbly slug and churn flows have been examined. Two-phase flow parameters like the volumetric gas fraction, bubble size and bubble velocities have been measured.

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1. Introduction

Application of neutron imaging as a non-intrusive, high resolution technique is increasingly popular in many engineering and applied science disciplines. For two-phase flows, thermal and cold neutron imaging have also found increasing application in the last three decades, mainly because they provide a better contrast for aqueous two-phase flows in a metallic piping in comparison to other techniques such as X- or gamma-rays. This makes neutron imaging appealing for general two-phase flow research [1], especially for high-pressure, high-temperature two-phase flows in thick metal casings, e.g. in nuclear fuel bundle models. These studies aim to determine two-phase flow parameters with high spatial and/or temporal resolution in bundle geometries, which could then be used for fuel bundle optimization. A multitude of different flow regimes are encountered in a fuel bundle with convective boiling flows, ranging from low-gas fraction (bubbly flow) to very high gas-fractions (annular flow). For the latter flow regime in limited

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geometries (partial bundle), cold- and thermal-neutron imaging have been shown to be very useful (e.g. [2]). However for other flow patterns with a higher water content and/or for larger (full) bundle geometries, cold and thermal neutrons are not penetrating enough to be applicable. This has been demonstrated in [3] comparing the performance of fast and thermal neutron imaging for the steady state measurement of gas distribution in a fuel bundle. The significantly higher penetrating power of fast neutrons is a clear advantage for such cases enabling higher-contrast imaging. A fast neutron imaging system is proposed and is under development at the Paul Scherer Institute [4] for fuel bundle studies and beyond.

Two-phase flow, in general, is a very rapidly changing process, requiring high-frame-rate imaging to capture its dynamics. In a first attempt, we have already examined and demonstrated the feasibility of high-frame-rate, fast neutron radiography for generic two-phase flows of relevance for fuel bundle studies [5]. However the detector setup used for the study turned out to be suboptimal for this purpose. Therefore it has been optimized and a second attempt has been made, which is reported here together with some comparison of the results from the first run. The experiments have been carried out at the high-intensity, fast-neutron beam line of the accelerator facilities of the Physikalisch-Technische Bundesanstalt (PTB), in Braunschweig, Germany. For demonstration purposes, we have examined adiabatic, air-water two-phase flows at atmospheric pressures in a rectangular channel at different flow regimes, including bubbly, slug and churn flows. The instantaneous volumetric gas fraction, bubble sizes and bubble velocities have been determined. The next section presents a short description of the experimental setup consisting of the fast neutron beam, the imaging detector system and the two-phase flow channel.

2. Measurement setup

The experiments have been carried out at the high intensity, white-spectrum, fast neutron beam line at PTB. The neutrons are produced by the d+Be reaction at an average energy of 5.5 MeV with a flux at the sample position of about 1.3×10^7 $\mathrm{cm^{-2}s^{-1}}$. The experimental setup including the beam line and the two-phase flow channel is described in details in [5]. We will only focus here on the original and the optimized detector. The imaging detector used in the first experimental run by a third generation, multiple-frame Time-Resolved Integrative Optical Neutron (TRION) detector developed at PTB in the context of high resolution, energy-selective fast neutron resonance radiography [6]. It is based on a plastic-fiber scintillator screen and a two stage intensified CCD camera system. The components and layout of the detector are shown in Figure 1a. The fiber scintillator screen (BCF-12, produced by Crytur, fiber size 0.7 mm) has an active surface area of 200×200 $\mathrm{mm^2}$ and is 50 mm thick, enabling a detection efficiency of 25.7 % at 6 MeV. Behind the bending mirror, a 120 mm lens focuses the light on a position sensitive optical preamplifier (OPA), featuring a 40-mm Photek image intensifier (IMI), which intensifies the image from the scintillator screen and preserves the few-nanosecond fast timing property of the scintillator by using an E36 phosphor screen, which was important in the original neutron Time-of-Flight (TOF) applications. The intensified image from the OPA is splitted by a kaleidoscopic image splitter to a field of 3x3 sub-images. This image splitter is coupled through a lens to a 9-fold segmented IMI of which 8 segments can be gated independently. Each of the segments on the IMI photocathode views the scintillator screen and can acquire an image for an independently selectable time window with exposure times ranging down to 5 ns. The purpose of the 8-fold image splitting is to enable quasi-simultaneous recording of multiple images at different time slices, originally for TOF-sensitive imaging applications, in our case, for observation of a fast dynamic process. A CCD camera records all segments simultaneously on a large area CCD chip with 16 megapixels. Further details of the TRION detector can be found in [6].

Unfortunately, some adverse effects have been encountered using the TRION detector in the first experimental run. The two most severe are circular vignetting and intensity saturation in the images. Both are influenced by several factors, two important ones being the use of a low-intensity, fast phosphor in the IMIs and the presence of the image splitter (for details see [5]) and both have been found only tolerable for relatively long exposure times of 30-40 ms, due to the lower gains applied on the IMIs. Therefore the detector has been modified and optimized for the second experimental run. Compared to Figure 1a, in the modified detector the OPA has been equipped with regular P43 phosphor, which is slower than the E36 but provides a much higher light yield than the latter. The image splitter and the segmented IMI have been eliminated, and the CCD camera has been replaced by a high-speed CMOS (made by Edgertronic) camera looking through a 50 mm lens directly on the OPA.