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Comparison of experimental and simulation results on interior subchannels of a 61-pin wire-wrapped hexagonal fuel bundle

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ABSTRACT

As part of a joint U.S. Department of Energy project, Framatome, Argonne National Laboratory, Terrapower, and Texas A&M University have collaborated to produce experimental data and computational results to characterize the flow behavior of a 61-pin wire-wrapped hexagonal fuel bundle. In this paper, comparisons are made between Texas A&M's experimental particle image velocimetry velocity field measurements and Argonne National Laboratory's large-eddy simulation results in an interior subchannel for a Reynolds number of 19,000. It can be concluded that the shape and magnitude of the mean vertical velocity component is in excellent agreement for the selected horizontal line plots. Maximum relative errors are less than 10% until the subchannel walls are approached. The shape and, to a lesser extent, magnitude of the mean horizontal velocity component is in satisfactory agreement between the particle image velocimetry and large-eddy simulation results.

1. Introduction

Liquid metal fast reactors using sodium as a coolant typically utilize a tightly packed triangular lattice of fuel pins enclosed in a hexagonal duct. The fuel pins may be wrapped with a helical wire spacer. The primary function of the wire spacer is to maintain a gap between adjacent fuel pins. They also mitigate vortex-induced vibration, increase the pressure drop, and enhance subchannel mixing to increase convective heat transfer to reduce the local maximum temperatures.

As part of a joint U.S. Department of Energy project, Framatome, Argonne National Laboratory (ANL), Terrapower, and Texas A&M University (TAMU) have collaborated on experimental measurements and numerical simulations for a 61-pin wire-wrapped hexagonal fuel bundle. The main objective of this joint project is to produce experimental data and computational results to support the research on advanced nuclear fuel development.

TAMU has conducted isothermal flow experiments on the wire-wrapped 61-pin hexagonal fuel bundle. The purpose of these tests was to perform high spatiotemporal resolution pressure and velocity measurements at different locations in the fuel bundle. The experimental activities provide a database of pressure and flowfield measurements for supporting the validation efforts of numerical modeling using Reynolds-averaged Navier-Stokes (RANS) and large-eddy simulation (LES) turbulence modeling techniques.

ANL obtained computational results using Nek5000, an open-source, high-fidelity, spectral element method computational fluid dynamics (CFD) code. As part of the validation efforts for Nek5000, ANL has computationally modeled the as-built 61-pin wire-wrapped hexagonal fuel bundle and performed CFD simulations utilizing LES.

Project deliverables can be found in the joint project final report (Mays and Jackson, 2017) and the following articles. Mays (2016) and Mathieu et al. (2016) performed pressure and temperature measurements on a 61-pin heated bundle. Vaghetto et al. (2018) obtained the 61-pin isothermal bundle pressure drop throughout laminar, transition, and turbulent flow regimes and also compared experimental bundle friction factors to existing correlations. Nguyen et al. (2017, 2018) performed axial plane particle image velocimetry (PIV) and transverse plane stereoscopic particle image velocimetry (SPIV) velocity measurements on a 61-pin isothermal bundle in subchannels near the hexagonal duct wall. Goth et al. (2018) performed axial plane PIV velocity measurement on the same bundle in multiple interior subchannels. Obabko et al. (2016) and Leonard et al. (2016) have performed LES and RANS simulations on both heated and isothermal fuel bundles.

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This paper compares TAMU's experimental PIV velocity field measurements to ANL's LES computational results at an interior subchannel for a Reynolds number of Re = 19,000. Comparisons in this paper include both the vertical and horizontal mean velocity vector fields.

2. Experimental facility

The experimental facility contained two loops. The primary loop included a centrifugal pump, variable frequency drive (VFD), inline surge volume, inline turbine flow meter, and resistance temperature detector, along with the hexagonal test section housing the fuel bundle. The secondary loop performed volume control, temperature control, and filtration via a centrifugal pump, VFD, storage tank, heat exchanger, and filter.

The test section contained a 61-pin hexagonal fuel bundle with helically wrapped wire spacers. The experimental fuel bundle was organized in a triangular lattice and was tightly packed with only the wire diameter defining the spacing between adjacent pins. The wire spacers were wrapped clockwise when visualized up from the bottom of the bundle. The pins were fixed to a bottom plate connected to the inlet plenum. Inlet and outlet plena were located below and above the test section, respectively. The test section contained 3.5 wire pitches to account for flow development and outflow effects, while allowing for velocity measurements along one full wire pitch.

The pins, wires, and test section were made of transparent poly (methyl methacrylate) to allow for flow visualization and laser diagnostic velocity measurements. The vertical and horizontal velocity fields in the edge, corner, and interior subchannels of the fuel bundle can be quantified using the matched-index-of-refraction (MIR) technique with the working fluid, p-Cymene. An overview of the experimental facility is shown in Fig. 1. A detailed description of the facility can be reviewed in Goth (2017).

3. Experimental methods

The PIV experimental setup consisted of two digital CMOS Phantom M310 cameras and a 10 W continuous laser at a wavelength of 527 nm. The laser beam was adjusted to form a 1.5 mm thick vertical laser sheet. For all experiments, the laser position was adjusted with motorized linear traversing systems. The seeding particles were silver-coated hollow glass spheres with a mean diameter and density of 16 μm and 1.6 g cm^{-3}. Fig. 2 shows a typical imaging hardware configuration to perform PIV measurements on the 61-pin bundle.

Vertical field PIV measurements presented in this paper were performed along the green line denoting the laser sheet in Fig. 3. In this configuration, cameras were positioned to look through an optical prism. In Fig. 3, the close-up view highlights two subchannels, named SC1 and SC2, of interest for this location. In the side view, the pins are dark grey and the subchannels are light grey. It can be seen that wires of neighboring pins cross into SC1 and SC2 at various axial locations. These wires are visible as dark grey sweeps across the light grey subchannels. The PIV measurement window for each camera is represented by a green rectangle. The optical prism was attached to the enclosure to achieve a perpendicular configuration between laser sheet and camera.

During each experimental run, two cameras recorded a sequence of 8,310 images of 12-bit color depth in a single-frame mode at a sampling rate of 2800 Hz. PIV measurements were repeated three times to increase the sample size to ensure the dataset would statistically represent the flow characteristics.

The applied PIV processing algorithms were advanced multi-pass, multi-grid PIV processing algorithms. These are based on robust phase correlations that have been implemented for the PRANA codes by Virginia Tech (Eckstein and Vlachos, 2009a,b). The initial and final interrogation windows were 64 × 64 pixels and 16 × 16 pixels. Velocity vectors were calculated from the correlation map with a Gaussian peak fit for sub-pixel accuracy (Raffel et al., 2007). Inside each pass, statistical validations were performed to identify and replace erroneous vectors. A

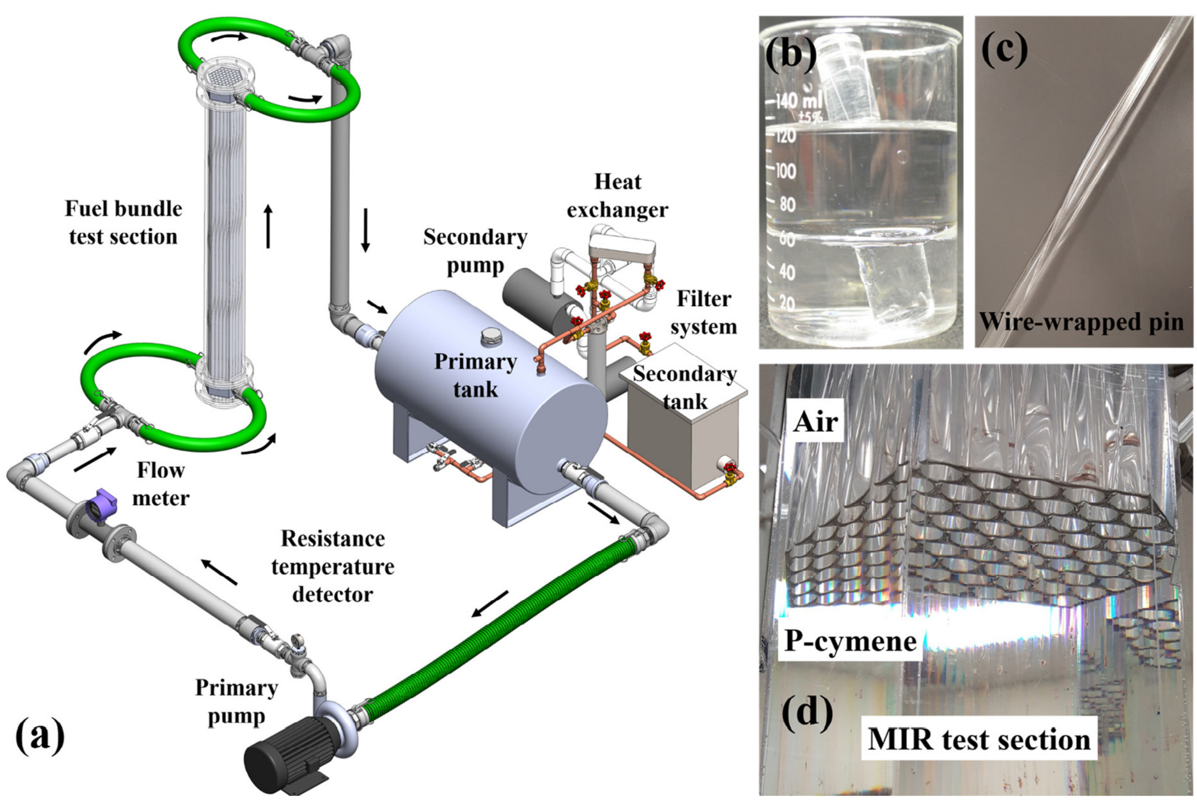

Fig. 1. (a) Overview of the experimental facility primary, (b) matched-index-of-refraction technique using p-Cymene and PMMA, (c) a wire-wrapped pin, and (d) fuel bundle half full of p-Cymene.