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Experimental Visualization of Flow Structure inside Subchannels of Rod Bundle

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1. Introduction

The analysis of Large Break-Loss of Coolant Accidents (LB-LOCAs) required specific experimental programs to investigate large scale 3D effects particularly during downcomer refill, and core reflooding. The 2D-3D program included UPTF, SCTF and CCTF facilities which provided precious information on phenomena and quantitative data for system code validation. However, due to the difficulty to implement instrumentation in high pressure and temperature steam water flow in a very complex geometry, the validation remained global and could not validate separately each sensitive model of the code in presence of 3D effects. SB-LOCAs (Small Break) and IB-LOCAs (Intermediate Break) also encounter significant 3D effects in core due to the radial power profile, with crossflows and diffusion-dispersion. Similar situations exist at lower pressure for loss of RHR (Residual Heat Removal) accidents. Other transients such as steam line break and boron dilution are sensitive to all mixing phenomena in the core. Then a need exists of a more precise validation of each of the mixing processes. The subchannel analysis is one of the key thermal–hydraulic calculations in the safety analysis of the nuclear reactor core. At present, subchannel computer codes are employed to simulate fuel elements of nuclear reactor cores and predict the performance of cores under normal operating and hypothetical accident conditions. The ability of these subchannels codes to predict both the flow and enthalpy distribution in fuel assemblies is very important in the design of nuclear reactors. Recently, according to the modern tend of the safety analysis for the nuclear reactor, a new component scale analysis code, named CUPID, and has been developed in KAERI. The CUPID code is based on a two-fluid and three-field model, and both the open and porous media approaches are incorporated. In a view point of porous media approach, the momentum and energy equation is rearranged by using time- and volume-averaging method (double decomposition technique). To evaluate the performance of macroscopic transport equation in CUPID code, many experimental data should be utilized for developing new model for subchannel analysis. From this motivation, the PRIUS (in-PWR Rod-bundle Investigation of Undeveloped mixing flow across Sub-channel) test facility is being designed and constructed to generate an experimental database in a rod-bundle geometry addressing the modeling and validation of sub-channel analysis. It can also be useful for CFD in open medium validation. Various combinations with a selection of inlet flow condition in test section are set for the test matrix. In the present work, PIV-MIR technique is adopted to measure the velocity field of multi-dimensional flow structure inside the subchannels of rod bundle.

2. Test Facility

Figure 1 shows a schematic of the test facility, called PRIUS. The fluid system consists of a test section, a storage tank, and 2” piping system for the water supply to the test section and return back to the storage tank. The storage tank is installed at the top part of the facility. The water temperature in the system is controlled using a cooler and heater imbedded in the storage tank. The water flow is supplied using a centrifugal pump with a 40 m head and 48 m^3/hr capacity, which is controlled by adjusting the impeller speed using an inverter. A bypass line is established at the upstream of the test section for an efficient control of the water flow. In the water injection line of which is divided to two branch lines, instrumentations for the flow rate, temperature, and pressure are installed. To maintain a straight flow at the inlet, a multi-hole plate and honeycomb is installed inside the inlet chamber.

The test section of PRIUS has rectangular geometry with a dimension of 84 mm × 58 mm × 1.5 m which is made of acryl of 15 mm thickness. The typical configuration for the rod bundle examined in this study consists of a 4 × 6 array of parallel rods as shown in Figure 2. The rods are almost the same size as those commonly used in pressurized water reactors, which have an outer diameter, D, of 10.0 mm and are separated on a pitch, P, of 13 mm.

To remove the image distortion induced by different refraction index of water and acryl rods, the matching index of refraction (MIR) technique is adopted. Transparent acrylic rod is chosen in combination with a solution of 62.5% sodium iodine (NaI) in 37.5% deionized water of 30 °C. The viscosity of the solution is low enough to enable Reynolds-number identity with a feasible mass flow. However, the NaI-solution, it is highly corrosive to ferrous metals, even to stainless steels, and then piping with Teflon coating for preventing corrosion is installed. The internals of circular pump are made of FRP (Fibre-reinforced plastic). Valves and storage tank are also made of PVC (Polyvinyl chloride) or PE (Polyethylene).

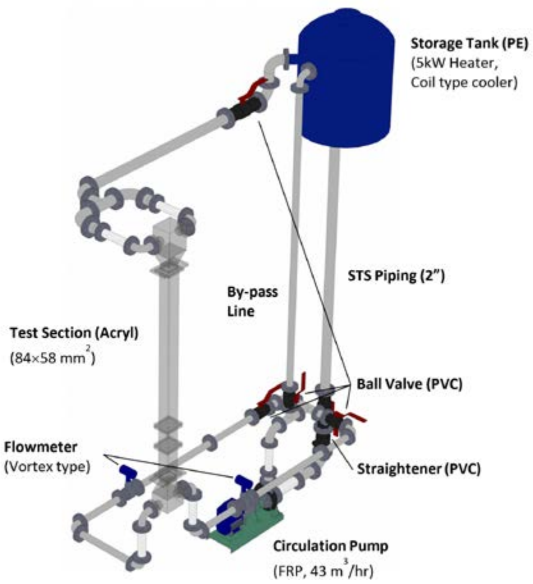


Fig. 1. Schematic of the test facility (PRIUS).

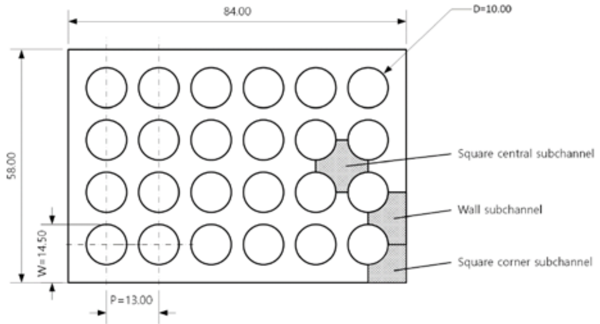


Fig. 2. Geometry of 4 × 6 rod bundles.

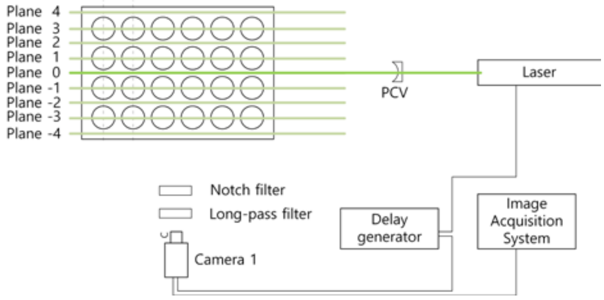


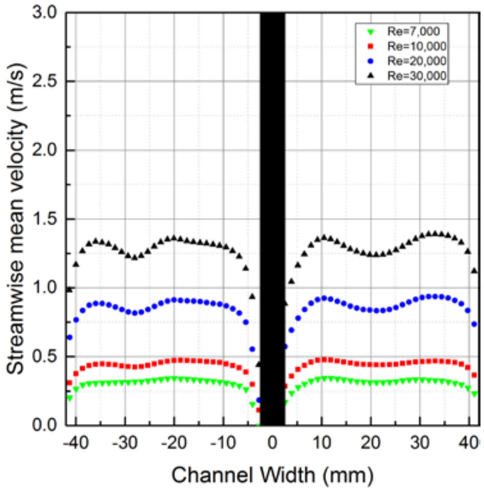
Fig. 3. Experimental setup of PIV measurement system.

3. Experimental Set-up

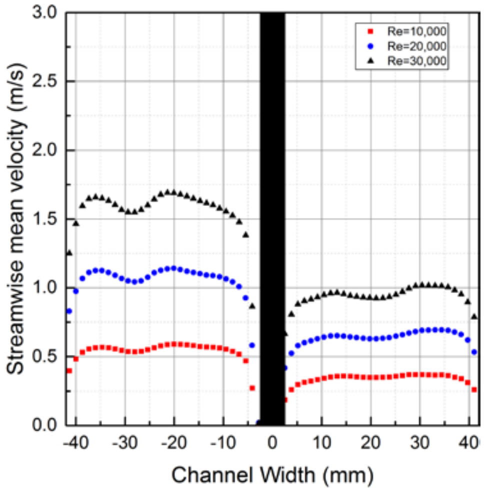
Several types of commercially available instruments are installed to measure the boundary conditions. The volumetric flow rate of the water is measured using a 2" vortex flow meter installed at each inlet water line. The estimated uncertainty for the measured mass flow was 0.80% of its read value. The system pressure is measured at the top of the test section and each inlet water line using two SMART-type PTs (pressure transmitter). The estimated uncertainty of each PT reading was 0.08% of the full scale, including the DAS uncertainty. To measure the temperature of the fluid, four TCs are installed at the piping system. The system temperature was maintained at 30 °C by considering the heat generation from the pump at the maximum flow condition and the cooling capability of the loop. By referring to the temperature at the water supply line, the applied power of the heater inside the storage tank was controlled by an SCR. Figure 3 shows a schematic diagram of the optical setup for PIV velocity field measurements, which consists of a 65-mJ Nd:YAG laser with an emission wavelength of 532 nm, a 2K×2K CCD camera and a delay generator. The acquisition rate of the raw image is controlled by a delay generator, and in this study, 5 frames per second is used. The laser light sheet illuminated the test flow through the right side as shown in Figure.3.

Table 1: Test matrix of PRIUS.

V_{left}/V_{total}	Re(total)		
	10000	20000	30000
0.5	⊕	⊕	⊕
0.7	⊕	⊕	⊕



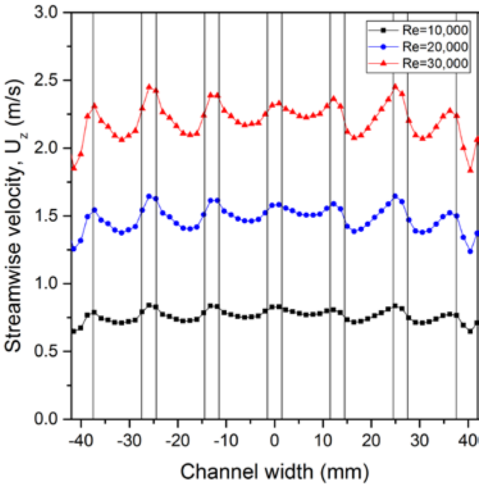
(a) Uniform inlet condition



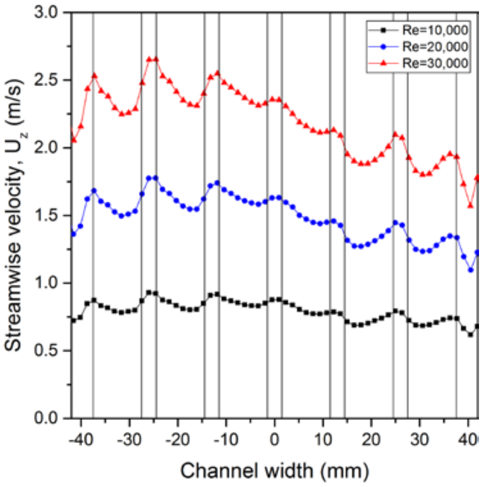
(b) Non-uniform inlet condition

Fig. 4. Streamwise mean velocity profiles at the inlet.

Fluorescent (Rhodamine B) polymer beads with an average diameter of 20 μm and a specific gravity of 1.02 were used as the tracer particles. A long pass filter ($\lambda > 550$ nm) and a notch filter were used to eliminate the scattered light, except the fluorescence light, and block the 532 nm wavelength light, which were installed in front of the CCD camera. Using the ensemble average of 1,000 instantaneous velocity vector fields, statistical results are obtained, such as the mean velocity vector fields and turbulence intensity and so on. The velocity fields for interrogation window size of 64 × 64 pixel^2 was calculated with 50% overlap was used for the final interrogation window size of 32 × 32 pixel^2. This results in an effective spatial resolution of 16 × 16 pixel^2. After calibration of the images, a resolution of 41 × 41 μm^2/pixel was achieved. This corresponds to an effective spatial resolution of 0.66 × 0.66 mm^2 for the final velocity field. The measurement location is about 460 mm (40 D_h) from the inlet. Table 1 shows a test matrix for visualization experiment. For the PIV measurement, 3 tests are planned, in which 2 sets of combinations of the flow conditions are selected.

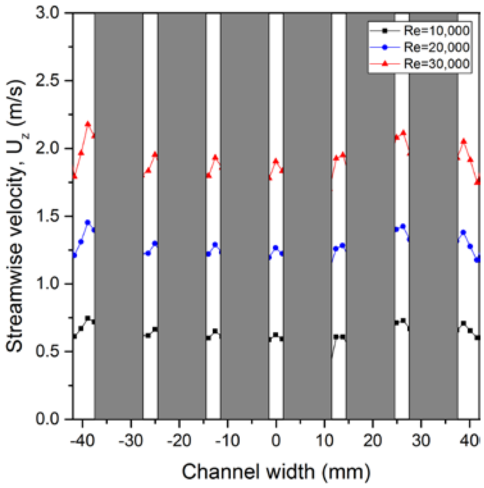


(a) Uniform inlet condition

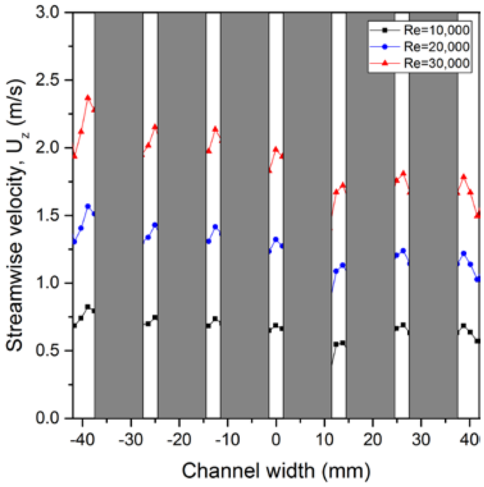


(b) Non-uniform inlet condition

Fig. 5. Streamwise mean velocity profiles at center section (plane 0).



(a) Uniform inlet condition

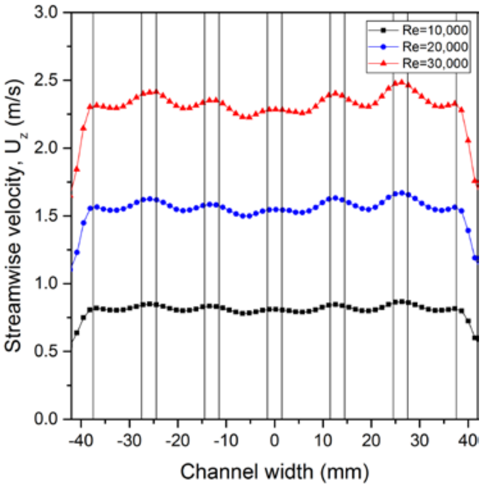


(b) Non-uniform inlet condition

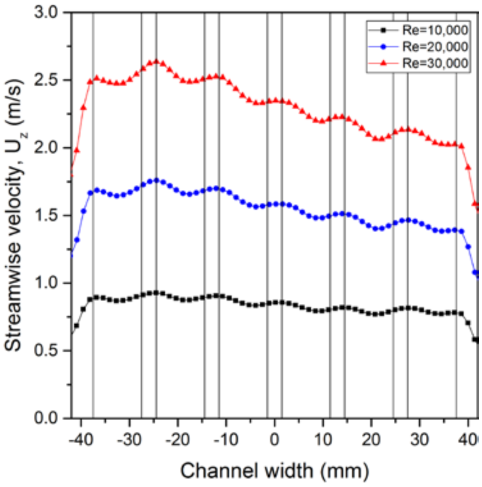
Fig. 6. Streamwise mean velocity profiles at plane -3.

4. Results and Discussions

PIV-MIR technique makes it possible to acquire optically clear images. As a preliminary test, the inlet velocity profile acquisition experiment was conducted on the uniform and non-uniform flow condition at the entrance region. A tranquillisation chamber has been designed in two separated parts in order to be able create an asymmetry of the flow entering the vertical structure. Each part of the tranquilisation chamber is composed of a straight larger pipe, a honeycomb and a grid. The velocity field distribution was measured with the flow rate change at the center section (plane 0) as shown in Figure 4. In this study, the window offset and recursive scheme was used to calculate the velocity field and enhance the subpixel accuracy. Figure 5 shows the streamwise mean velocity at the center section according to the flow conditions from Re=10,000 to 30,000. Figure 6 and Figure 7 also show the streamwise mean velocity at plane -3 and plane -4 according to the flow conditions from Re=10,000 to 30,000. In case of the asymmetric inlet flow condition, the velocity distribution becomes uniform due to the lateral turbulent



(a) Uniform inlet condition



(b) Non-uniform inlet condition

Fig. 7. Streamwise mean velocity profiles at plane -4.

mixing as the flow goes to downstream. In this test condition, it was confirmed that the asymmetric inlet velocity distribution disappeared at about 100 D_h downstream. The experimental results are expected to be used in the verification of the subchannel analysis codes because it includes the information on the lateral flow velocity distributions between the adjacent subchannels.

5. Conclusions

The PRIUS experiment has addressed many key topics related to flow behavior in a rod bundle. These issues are related to the flow conditions inside a nuclear fuel element during normal operation of the plant or in accident scenarios. Flow visualization has been performed by using a PIV-MIR technique, from which detailed information for the two-dimensional movement of single phase flow is quantified. The experimental database in a rod-bundle geometry will be addressed the modeling and validation of sub-channel analysis. It can also be useful for CFD in open medium validation.

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