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Experimental Study on Flow Visualization inside Subchannels of PWR Rod Bundle

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1. Introduction

The fuel element geometry frequently used in nuclear reactors is the rod bundle. The coolant is flowing axially through the subchannels formed between the rods. The mixing of cooling fluid in a rod bundle reduces the temperature differences in the coolant and along the perimeter of the rods. Flow inside rod bundles has a similarity with flow in porous media. To ensure thermal performance of a nuclear reactor, detailed information of the heat transfer and turbulent mixing flow phenomena taking place within the subchannels is required. 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, a test facility, called PRIUS (in-PWR Rod-bundle Investigation of Undeveloped mixing flow across Sub-channel), was newly designed and constructed to generate an experimental database for a multi-dimensional flow distribution in a rod-bundle geometry. Various combinations with a selection of inlet flow condition and flow area sudden change in test section are set for the test matrix. In the present work, PIV-MIR technique is used to measure the velocity field of multi-dimensional flow driven by various combinations with inlet flow condition and flow area change.

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 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

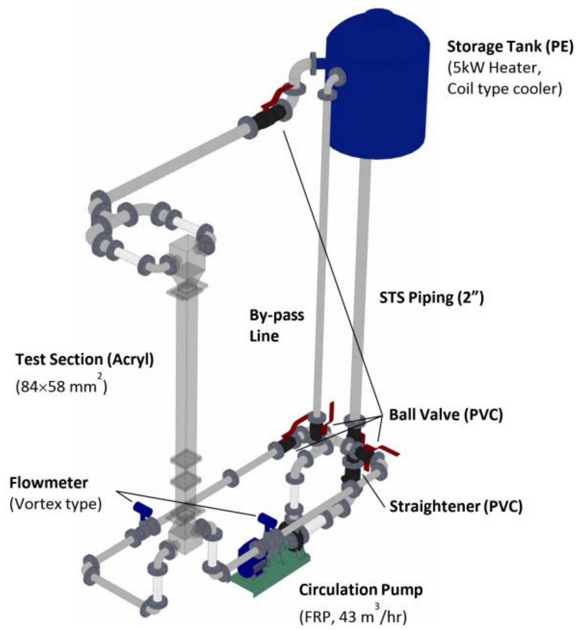

Fig. 1. Schematic of the test facility (PRIUS).

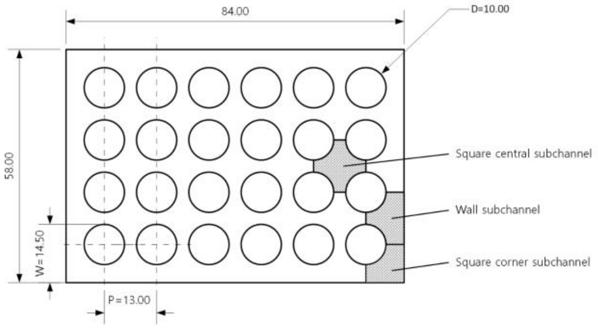

Fig. 2. Geometry of 4 × 6 rod bundles.

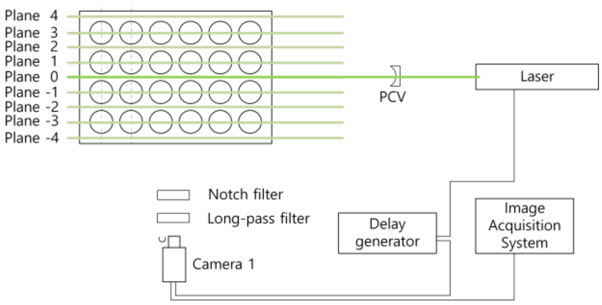

Fig. 3. Experimental setup of PIV measurement system.

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 is made of FRP (Fibre-reinforced plastic). Valves and storage tank are also made of PVC (Polyvinyl chloride) or PE (Polyethylene).

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 I: Test matrix of PRIUS.

No.	**Flow condition**			**Blockage**	**Thermal Mixing**
	Uniform flow	Non-uniform (2:8)	Non-uniform (4:6)		
1	•				
2		•			
3			•		
4	•			•	
5	•			•	
6	•			•	
7		•		•	
8	•				•
9	•				

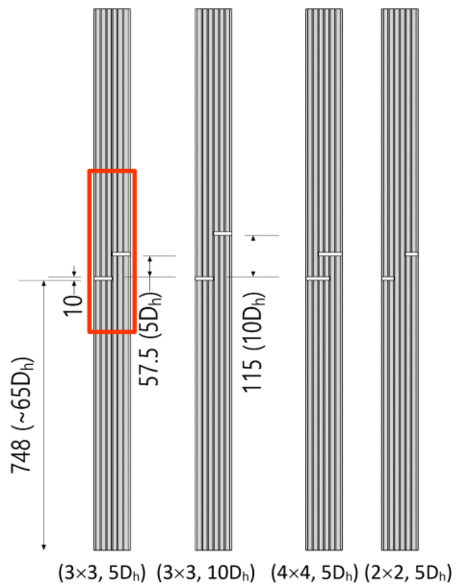

Fig. 4. Blockage arrangement with different size and distance.

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 (λ > 550 nm) and a notch filter were used to eliminate the scattered light, except the fluorescence light, and

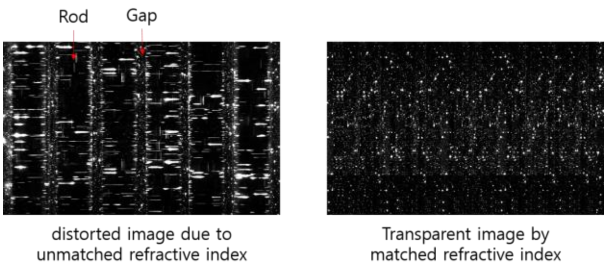

Fig. 5. Raw particle image before and after applying MIR technique (Re=10,000 at plane 0).

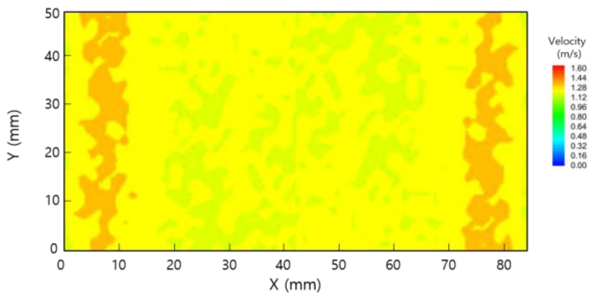

Fig. 6. Instantaneous velocity contour map for Re=20,000 at plane 0.

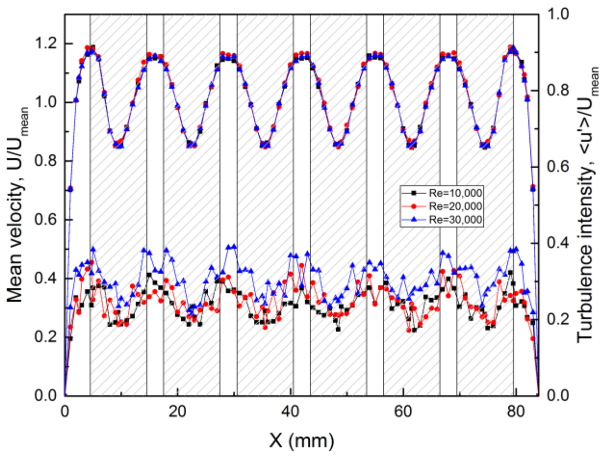

Fig. 7. Streamwise mean velocity and turbulence intensity profiles with different flowrates at plane 0.

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.

Table 1 shows a test matrix for visualization experiment. For the PIV measurement, 9 tests are planned, in which 7 sets of combinations of the flow condition and blockage are selected. For the flow blockage effect test, four different blockage arrangement are prepared as shown in Figure 4.

4. Results and Discussions

Figure 5 shows the raw particle image disappeared due to matching the refractive index by applying the MIR technique. PIV-MIR technique makes it possible to acquire optically clear images. As a preliminary test, test ID-1 experiment was conducted on the uniform flow condition. The velocity field distribution was measured with the flow rate change at the center section (plane 0). Figure 6 shows the instantaneous velocity contour map at Re = 20,000 conditions in the center section. In this study, the window offset and recursive scheme was used to calculate the velocity field and enhance the subpixel accuracy. 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. Figure 7 shows the streamwise mean velocity and the turbulent intensity profiles at the center section according to the flow conditions from Re=10,000 to 30,000.

Experiments that are simulating non-uniform flow and subchannel partial clogging conditions will be conducted in the future.

5. Conclusions

The PRIUS experiment has addressed many key topics related to flow behaviour 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.

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