Investigation of Coolant Flow Distribution and Inter-subchannel Mixing Characteristics on 37-pin Wire-wrapped Rod Bundle Using Magnetic Resonance Velocimetry

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1. Introduction

The sodium-cooled fast reactor (SFR) is one of the fourth-generation reactors that uses liquid sodium as a coolant to control the fission reaction of fast neutrons. It is expected to solve some of the storage problems by reusing spent nuclear fuel. A helical wire wrap has been introduced and studied for fuel rods in the SFR. It is very important to understand the influence and flow characteristics of the helical wire-type support on the flow inside the fuel assembly when designing the integrity of the reactor. The flow characteristics of wire-wrapped fuel rod bundle have been mainly studied through CFD analysis. [1] CFD analysis requires experimental results for validation, but it is difficult to experimentally confirm the internal flow structurally. Iso-kinetic sampling technique that measures the distribution of subchannel flow rate by placing a probe in the fuel rod bundle [2], and flow visualization studies using 2D particle image velocimetry (PIV) for more detailed velocity profile observation was performed for fuel assemblies with similar geometric characteristics. [3] However, in order to visualize the movement of particles in the inner passage of the rod bundle without distortion, there are difficulties in that the fuel rod bundle model must be made transparent and the refractive index of the object and the working fluid must be accurately matched.

Magnetic resonance velocimetry, one of the velocity field measurement techniques, is an electromagnetic signal-based velocity field measurement technique using an existing magnetic resonance imaging (MRI) scanner. It can measure three-dimensional (3D), three-component (3C) velocity and is a proven reliable technology. [4] It is non-invasive even for opaque and complex geometries and has the advantage of being able to conduct experiments without optical particles.[5] Recently, 3D velocity field was measured through MRV measurement for a CANDU fuel rod bundle [6]. This showed that the MRV technology can be effectively applied to fuel rod bundles. However, there is still no research on experimentally obtaining 3D 3C velocity field data for wire-wrapped rod bundles, and this MRV technology can solve this problem.

In this study, a 37-pin wire-wrapped rod bundle designed based on a Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) at the Korea Atomic Energy Research Institute (KAERI) was used [1,2] and the 3D 3C velocity was measured using MRV. We aim to measure and analyze the flow distribution and mixing performance. First, the measured velocity field is validated, and the flow distribution characteristics and flow structure are examined using the 3D 3C velocity field. Also, we examined the mixing characteristics using inter-subchannel mean velocity data for some cross-sections.

2. Experimental Setup and Methods

2.1 Description of Experimental Conditions

For the MRV experiment, a closed-loop flow circuit system was constructed as shown in Fig. 1. A flow conditioner was installed upstream of the fuel rod bundle so that a uniform flow could flow through the fuel rod bundle, and the fuel rod bundle was manufactured in a flange type using a stereolithography (SLA) 3D printer and combined. All of them are made of plastic material to prevent magnetic field distortion in the MRI room. It was confirmed that the test section produced by 3D printing had a deviation of 0.02mm and 0.01mm compared to the design dimension, respectively, with an output error of about 1%.

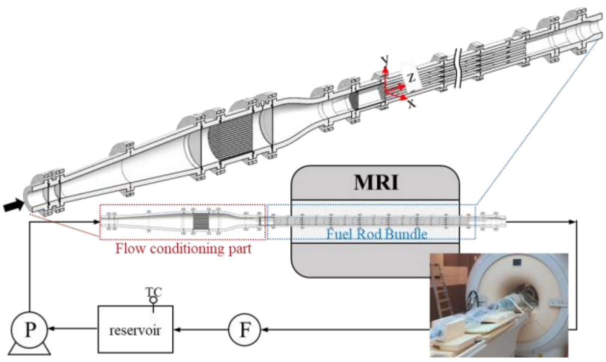

Fig. 1. Schematic diagram of closed-loop flow circuit and test section.

2.2 Flow conditions

Experimental conditions must be set to enable MRV experiments, not actual SFR operating conditions. The working fluid was changed from liquid sodium to water, and it was necessary to change the temperature and flow conditions to facilitate MRV measurement. In addition, the direction of the nuclear fuel rod bundle in the vertical direction was changed to a horizontal direction. If the flow is incompressible and geometric similarity is satisfied, it can be similarized using the reynolds number. Therefore, the flow conditions of this experiment are shown in Table 1.

Table I: Flow conditions

Flow parameters	**Values**
Fluid material	20 mM $CuSO_4$ aqueous solution
Reynolds number	9,800
Volumetric flow rate [L/min]	160.1
Hydraulic diameter [mm]	3.057
Temperature [℃]	25.4
Hydrostatic pressure [atm]	1

3. Results and Discussion

3.1 Validation

The MRV measurement results for the 37-pin wire-wrapped rod bundle coolant flow can be confirmed as the streamline results in Fig. 2. It is possible to check not only the flow along the narrow flow path and wire in the rod bundle, but also the vortex structures appearing in the wake of the wire.

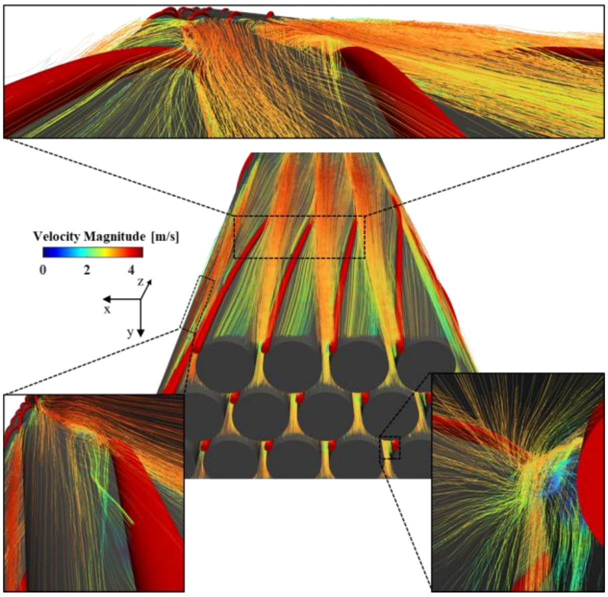

Fig. 2. 3D Streamlines of velocity magnitude measured by MRV.

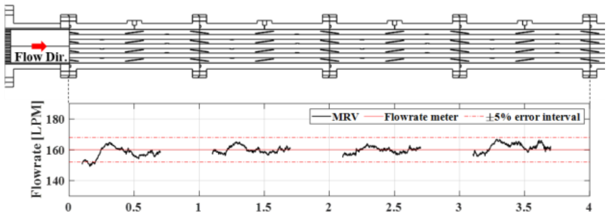

Fig. 3. Comparison between flowrate measured by MRV and flowrate meter.

To verify the MRV measurement, the flow rate inside the fuel rod bundle measured by MRV was compared with the flow rate value of the flow meter installed in the closed-loop system. Flow rate of MRV was calculated using the axial velocity of the cross-section perpendicular to the flow direction in the fuel rod bundle area. The flow rate measured by the MRV for each section compared with the flow rate measured by the electromagnetic flowmeter in Fig. 3. The flow rate per section measured by MRV is almost similar to the electromagnetic flow meter measurement value (160.1 ± 0.4 LPM) with a difference within ±5%, it was confirmed that the velocity field was measured accurately.

3.2 Flow split factor and inter-subchannel mean velocity

In order to quantitatively analyze the overall flow velocity distribution and inter-subchannel mixing characteristics, the flow split factor for each subchannel and the inter-subchannel mean velocity at the subchannel boundary were confirmed in a specific section in Fig 4. The flow split factor was 0.89 on average in the area of interior subchannels, 1.26 on average on edge subchannels, and 0.88 on average on corner subchannels. Looking at the normalized inter-subchannel mean velocity vectors, the swirling characteristic of rotating in the direction of wire rotation along the hexagonal wall was confirmed. In the interior subchannel region, the flow rotated along the hexagonal wall flowed from the right corner to the interior region due to the wire blockage effect. The flow was formed in the same direction as the wire direction at all the boundaries between the interior regions, and the flow could not flow at the boundary where the wire was located. It was confirmed that the flow moved from the interior region to the edge region at the left boundary between the interior subchannels and the edge subchannels.

As a quantitative comparison, the average value at the interior-interior boundary was 0.43, and the average value at the edge-edge-corner was 0.99, indicating that the degree of circumferential mixing was about 2.3 times higher than that of interior mixing. At the boundary between the interior subchannels and the edge subchannels, the averaged flow velocity from the is 0.05.

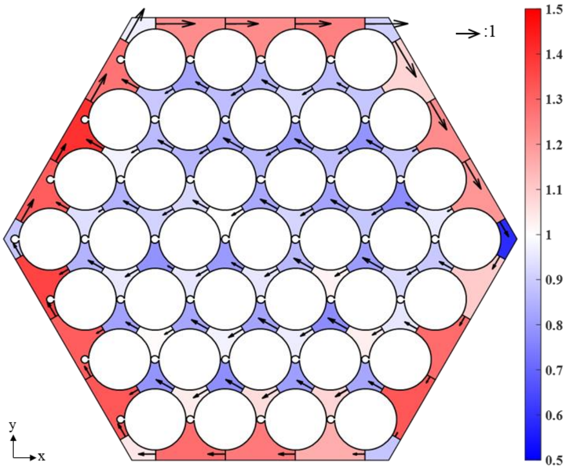

Fig. 4. Flow split factor distribution (color contours) and normalized inter-subchannel velocity (vectors).

4. Conclusions

In this study, the 3D 3C velocity field inside 37-pin wire-wrapped rod bundle was measured by MRV, and reliability was verified through comparison with existing data. From the 3D 3C velocity field, it was possible to confirm the flow distribution of each subchannels, and the mixing characteristics between subchannels. In addition, this experimental data can be used as benchmarks experimental data for CFD analysis and safety analysis code developments.

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