Measurements of Enhanced Mixing with U-pattern Wire Wrap Spacer in 19-pin Rod Bundle Using Particle Image Velocimetry

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1. Introduction

Korea has developed 150 MWe capacity of prototype gen-IV SFR (PGSFR), which is pool-type fast reactor using metallic fuel and liquid sodium as coolant [1]. In fuel assembly, wire wrap spacer is helically wound on each fuel pin to prevent collisions of adjacent pins, as well as to promote swirl flow in subchannel. Conventional wire wrap spacer has regular pattern which has same configurations for all pins, such as wrapping direction, lead, and so on. To promote coolant mixing flow by wire wrap design, UNIST thermal-hydraulics and nuclear safety laboratory suggested new pattern of wire wrap spacer, called U-pattern, which consists of 7 pin unit having no wire wrap on center pin and opposite wrapping direction with adjacent pins. With U-pattern wire wrap spacer, enhanced mixing characteristics were analyzed by CFD simulation in 7 pin and 19-pin bundle [2-3]. Fig. 1 shows the schematics of U-pattern wire wrap spacer.

With aims of velocity measurement techniques such as particle image velocimetry (PIV), laser induced fluorescence (LIF) or advanced sensors, velocity field has been analyzed in non-intrusive way. For flow visualization, matching-index of refraction (MIR) technique has been widely used combined with PIV, a state-of-art for complex flow channel such as fuel bundle. Detailed velocity distribution in subchannel of 7-pin rod bundle was measured [4]. 61-pin fuel bundle has been tried to measure the velocity field in subchannel in recent [5]. They performed flow distribution along assembly with conventional wire wrap spacer. In this study, flow visualization experiment of 19-pin rod bundle with U-pattern wire wrap spacer was performed and compared with conventional ones in terms of mixing effect using PIV and MIR technique.

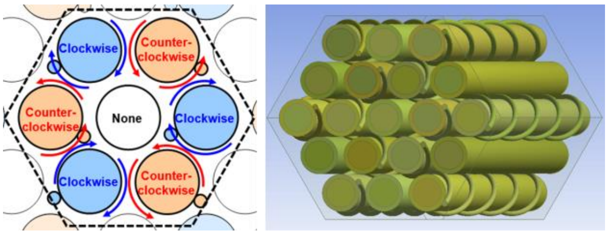

Fig. 1. Configurations and 19-pin rod bundle with U-pattern wire wrap spacer.

2. Experimental Method

In this study, 19-pin rod bundle was selected to have representatives of normal fast reactor fuel assembly having 217 or 271 pin bundle. For test section, pitch to diameter ratio (P/D) and wire wrap lead to diameter ratio (L/D) were matched with those of PGSFR's fuel assembly. Each rod and wire wrap was made of transparent fluorinated ethylene propylene (FEP) tube to match refractive index with water (n=1.333). Hexagonal duct was made of transparent acrylic. To minimize inlet and outlet channel effect, two ends of test section channel was divided into 4 channels.

Test loop consists of test section, liquid reservoir tank, pump and flowmeter. Pressure drop across rod bundle was measured by DP transmitter at each flow rate. For 2D PIV observation, Nd-YAG double cavity laser beam having 532 nm wavelength, CCD camera of 2048×2048 pixels with 1GB onboard memory were used. For PIV particle, glass hollow sphere with 9-13 μm diameter was utilized. Fig. 2 shows the 19-pin rod bundle test loop.

3. Results and Discussions

At flow rate of 87 lpm, where corresponding Reynolds number is 16,500 for 19-pin rod bundle test section, flow visualization experiment was performed in isothermal condition. Fig. 3 shows the measured velocity field in axial direction for the sections covering all types of subchannels with conventional wire wrap spacer.

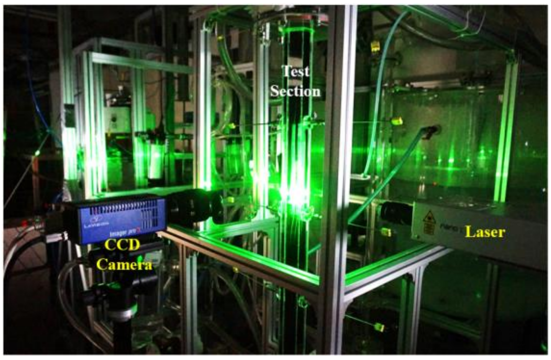

Fig. 2. Flow visualization experiment facility and 19-pin rod bundle test section.

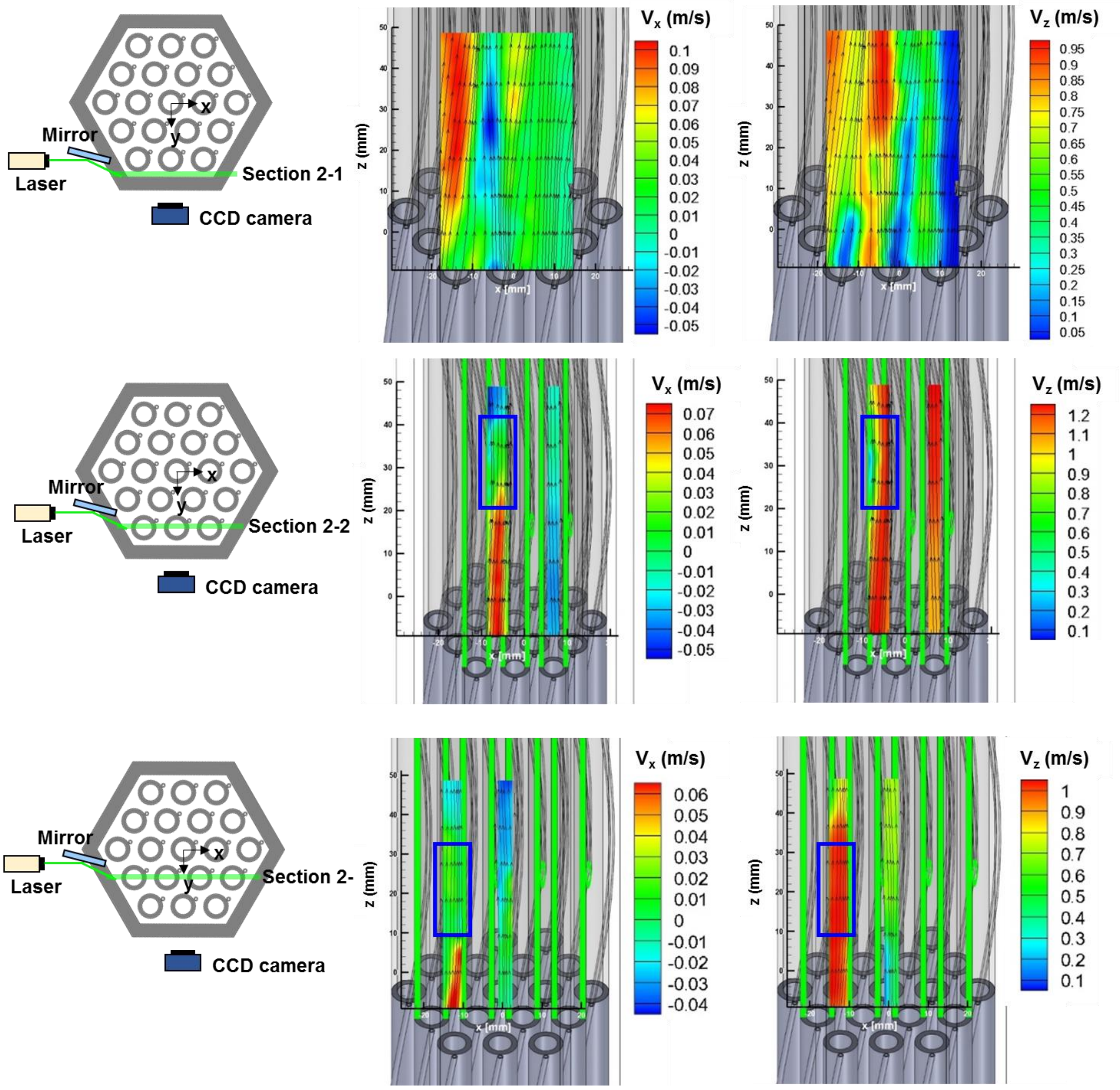

Fig. 3. Measured velocity field at 87 lpm with conventional wire wrap spacer.

Section 2-1 covers corner and edge subchannel, and Section 2-2 and 2-3 do center subchannel. Streamline velocity, V_z showed constant value, almost 1.0 m/s under 87 lpm flow rate. for the center subchannel. As shown in blue box in Fig. 3 for section 2-2 and 2-3, there was little cross flow in gap between pins. Most of cross flow component, V_x indicated in Fig. 3 becomes large near wire wrap spacer, and swirl flow was generated according to wrapping direction of wire. For the center subchannel, interactions of these swirl flows induced by each pin can cancelled out of cross sectional flow components due to regular pattern of conventional wire wrap spacer, where possibility of recirculation zone near wire wrap was pointed out by CFD analysis. It shows that swirl flow in narrow gap can be much influenced by adjacent structures and change of channel shape, especially by wire wrap spacer for hexagonal fuel assembly. However, For the edge subchannel, it is less interactions of swirl flow due to slightly larger channel area compared to that of center subchannel.

Velocity fields under same condition obtained by CFD analysis using ANSYS-CFX were good agreement with experimental results, as shown in Fig. 4, where CFD model was validated by ORNL 19-pin rod bundle experiment [3].

To quantify mixing effect for evaluation of thermal-hydraulic performance of U-pattern wire wrap spacer, turbulent kinetic energy (TKE) was chosen as a representative parameter. TKE is defined as magnitude of turbulence in eqn. (1).

$$TKE = \frac{1}{2}\left|V_{rms}\right|^2 \quad \text{(for 2D case)} \qquad (1)$$

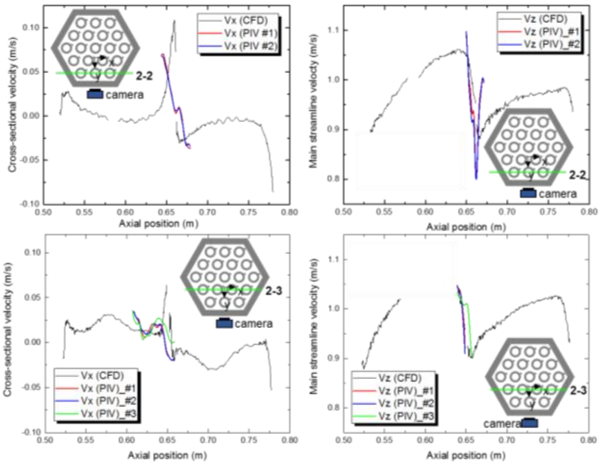

Fig. 4. Comparison of velocity distribution with PIV and CFD results at 87 lpm

Fig. 5 shows a coutour of TKE for each measurement section at 87 lpm flow rate with conventional wire wrap spacer. For section 2-2 and 2-3, same region having little cross flow indicated as blue box in Fig. 3 showed almost zero TKE, which means less effective zone for turbulent flow. At high flow rate, strength of turbulence takes a major role of enhancement of heat transfer near heater. In case of hexagonal pin bundle having narrow channel, it determines heat transfer coefficient to coolant, resulted from coolant mixing. To be compared with magnitude of TKE, mixing in subchannel can be configured.

For U-pattern wire wrap spacer, maximized lateral velocity promotes thermal mixing resulting increasing heat transfer and flatten temperature gradient in radial direction inside hexagonal duct. Lateral flow components from each pin having opposite winding direction of U-pattern wire merge together to have enhanced cross flow. Center pin having no wire wrap is also influenced by strong cross flow from swirl flow merge effect from circumferential pins. These features can contribute to increase thermal margin of SFR for avoiding sodium boiling, as well as economics with evenly distributed temperature field.

4. Conclusions

Velocity field in SFR fuel assembly was measured for conventional and U-pattern wire wrap spacer using PIV and MIR technique. For 19-pin rod bundle with conventional wire wrap spacer, velocity field was compared with data predicted by CFD analysis for validation of PIV measurement results. From designated pattern of wire wrap spacer, U-pattern has stronger swirl flow in subchannel, determined by comparing the magnitude of turbulence kinetic energy with conventional one. Since U-pattern has no wire wrap at the center rod in 7-unit pins, pressure drop for 19-pin rod bundle with U-pattern wire wrap spacer is less than that with conventional ones in same flow rate. Thus, U-pattern wire wrap spacer can improve economics of SFR as well as safety by enhancing efficiencies and increasing thermal margin from sodium boiling from possible generation of local hot spot due to recirculation flow.

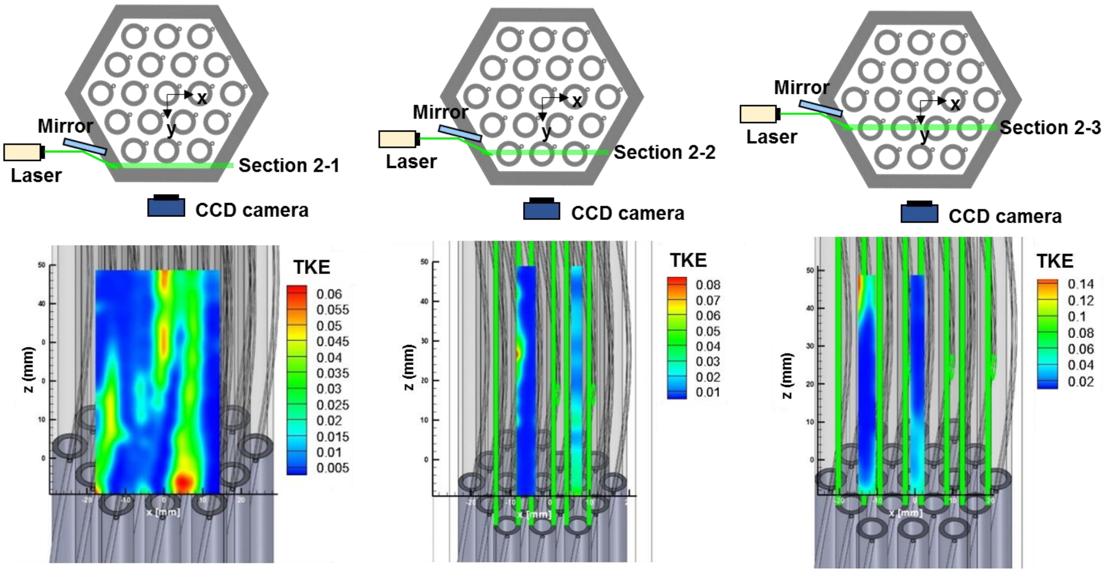

Fig. 5. Turbulent kinetic energy (TKE) for PIV measurement on section 2-1 to 2-3.

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