FLOW MIXING CHARACTERISTICS IN SUBCHANNELS OF A WIRE-WRAPPED 61-PIN ROD ASSEMBLY FOR A SODIUM-COOLED FAST REACTOR

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ABSTRACT

Flow mixing characteristics inside a wire-wrapped 61-pin bundle were measured using a wire-mesh sensor with a customized design for a sodium-cooled fast reactor (SFR). An SFR, one of the fourth-generation nuclear power plant types, can be the most promising solution for effective utilization of uranium resources, a minimization of the waste, enhanced safety, and nuclear proliferation resistance. To verify the flow mixing behaviors inside an SFR fuel bundle, a hexagonally arrayed 61-pin wire-wrapped rod bundle has been fabricated. The obtained experimental data will be used for validating the capability of subchannel analysis codes for the SFR core thermal hydraulic design. A wire-mesh sensing system was successfully developed including tracing liquid injection system, and a post-processing method was also developed for our experiments. Experimental tests have been performed at the conditions which are corresponding to 20 to 115 % flow of the prototype reactor nominal flow based on the Reynolds number. A preliminary CFD analysis under pre-determined boundary conditions was also conducted to verify the design parameters and range of various operating value of the current flow mixing experiments. The experimentally identified flow mixing behaviors were compared with the CFD results, which show good agreements with each other. The uncertainty including error propagation based on flow rates and temperatures has been evaluated to validate the experimental results.

KEYWORDS
Sodium-cooled fast reactor, core thermal design, flow mixing, a wire-mesh sensor, electro-tomography

1. INTRODUCTION

Fourth-generation nuclear power plants have been being developed for a minimal waste and effective utilization of uranium resources [1]. A sodium-cooled fast reactor (SFR) is one of the most promising options to pursue these purposes, and the Korea Atomic Energy Research Institute (KAERI) is currently developing a prototype SFR [2]. Among the many component designs in an SFR, a core thermal design is very important to assess the safety issue as a temperature limitation in a fuel assembly in spite of the heat flux limitation in a pressurized water reactor (PWR). In particular, the subchannels in an SFR core consisting of many hexagonally arrayed fuel assemblies have smaller hydraulic diameters than those in a PWR. For this reason, a wire is periodically wrapped on a rod to generate a swirl flow around the rod for an enhancement of the subchannel flow mixing, and the mixing characteristics including a diffusion

constant and a cross-flow coefficient should be assessed in a core thermal/hydraulic design through subchannel flow mixing experiments [3, 4].
A wire mesh sensing technique can be a useful method for measuring the flow mixing characteristics. A wire mesh sensor has been traditionally used to measure the void fraction of a two-phase flow field, i.e., gas and liquid [5, 6]. However, recent reports have shown that a wire mesh sensor can be used successfully to recognize the flow field in a liquid phase by injecting a tracing liquid with a different level of electric conductivity [5, 6]. This can be powerfully adapted to recognize the flow mixing characteristics by wrapped wires in an SFR core thermal design. In this work, we conducted flow mixing experiments using a custom designed wire mesh sensor.

2. EXPERIMENTAL METHOD

2.1. Test loop for measurements

All experiments were conducted at the FIFFA (Flow Identification test loop for Fast reactor Fuel Assembly) test facility at Korea Atomic Energy Research Institute (KAERI). The test loop consists of a tracing water tank, a fuel rod with an inner tube for water injection, and a wire mesh sensor at the end of the test rig. Fig. 1 shows a schematic drawing of our test loop and the 61-pin assembly.

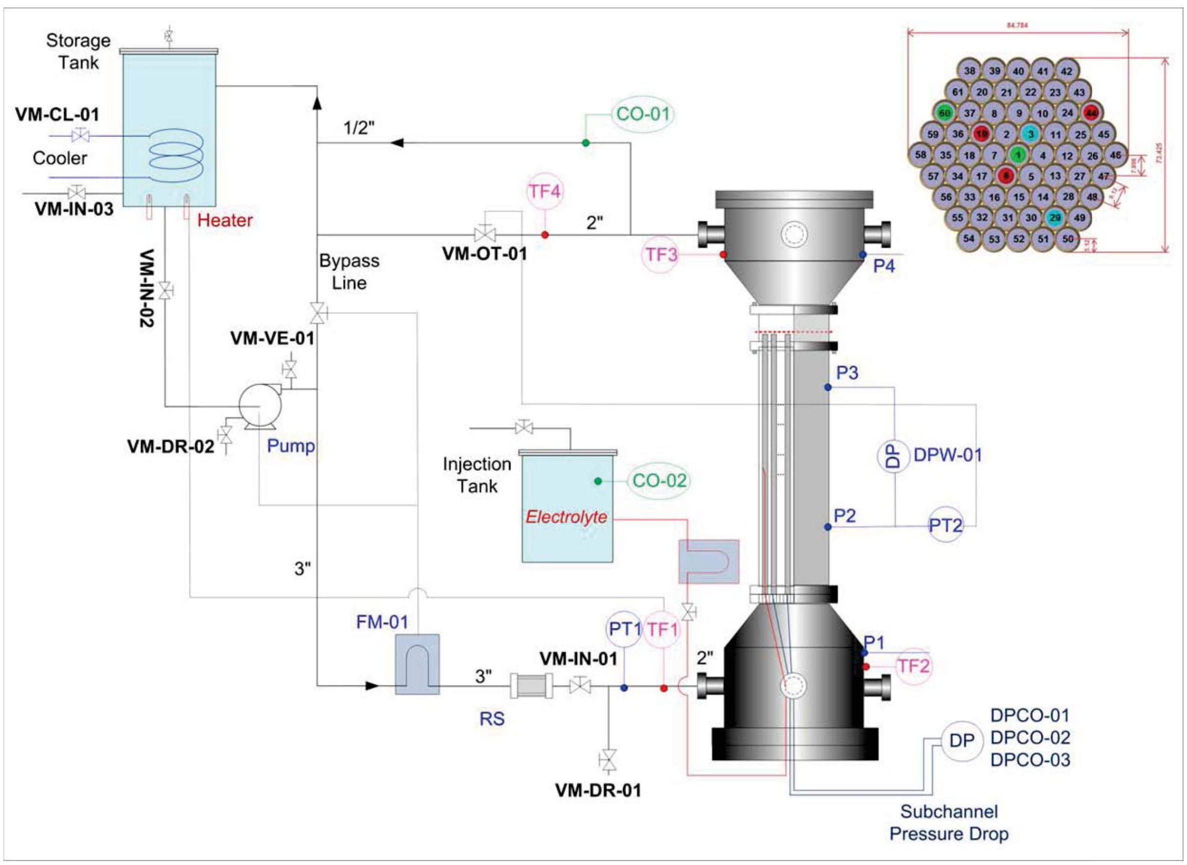

Figure 1. Schematic of the test loop for measurements of flow mixing.

The test section of 1.5-m in height was fabricated including 61 rods with wrapped wires in a hexagonal arrangement. The pitch to rod diameter ratio (P/D) and wire lead length to rod diameter ratio (H/D) were preserved with our prototype SFR design (i.e., P/D of 1.14, H/D of 29.9). The diameters of the rod and the wrapped wire are 8.0 and 1.0 mm, respectively and the lead length of the wrapped wire is 238.9 mm.

2.2. Wire-mesh sensor description

A wire-mesh sensor (WMS) has both a transmitting electrode layer and a receiving electrode layer with a short distance and an angle of 90°. As a driving voltage is supplied to the transmitting electrode layer, a current is derived in the receiving electrode layer (Fig. 2). According to the electric conductivity level of the liquid between two layers, the derived currents are varied. Using this principle, a difference in the electric conductivity of the liquid across the cross points can be measured.

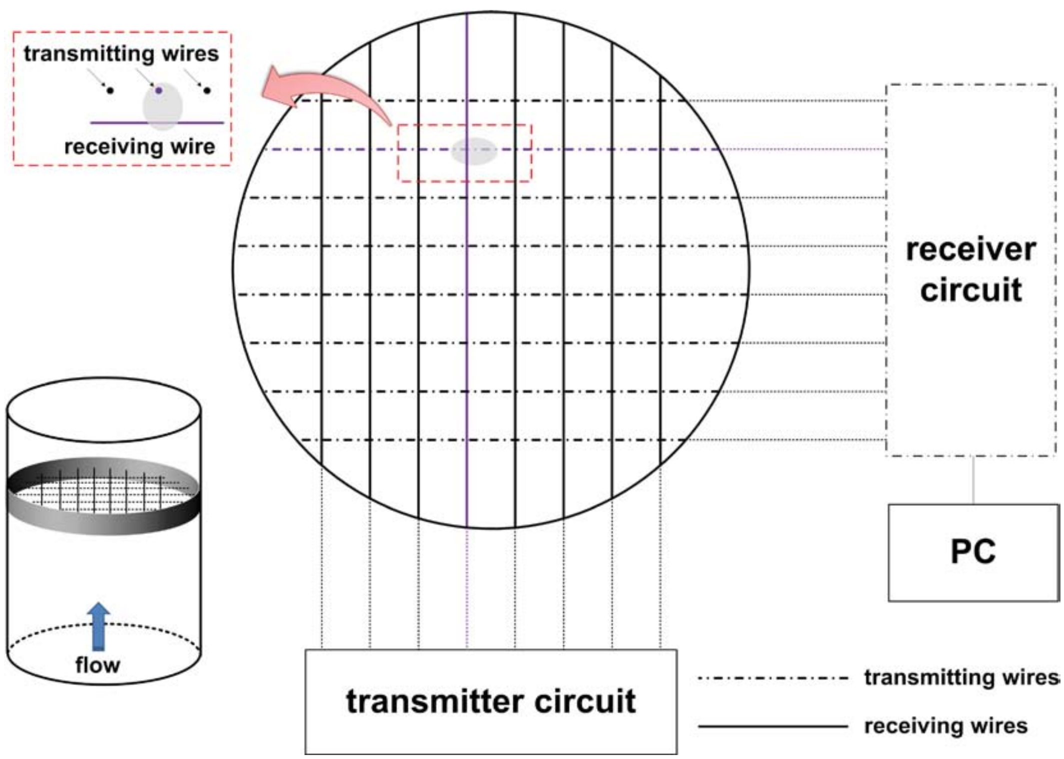

Figure 2. Principle of a wire-mesh sensor.

Our wire mesh sensor was installed 5 mm above the upper end of wire-wrapped 61-pin fuel assembly. A cross point of the wires was fabricated to be located at the center or beside each subchannel. The active transmitting and receiving electrode wires consist of 19 × 19 channels, respectively. According to the geometry parameters such as a P/D, a WMS had been designed for the flow experiments. The cross points were set at the center of each subchannel. To match the location between the cross points of WMS and the subchannels of a 61-pin bundle, the WMS has been fabricated having irregular rectangular cells. A schematic drawing and assembled pictures of the wire mesh sensor are shown in Fig. 3.

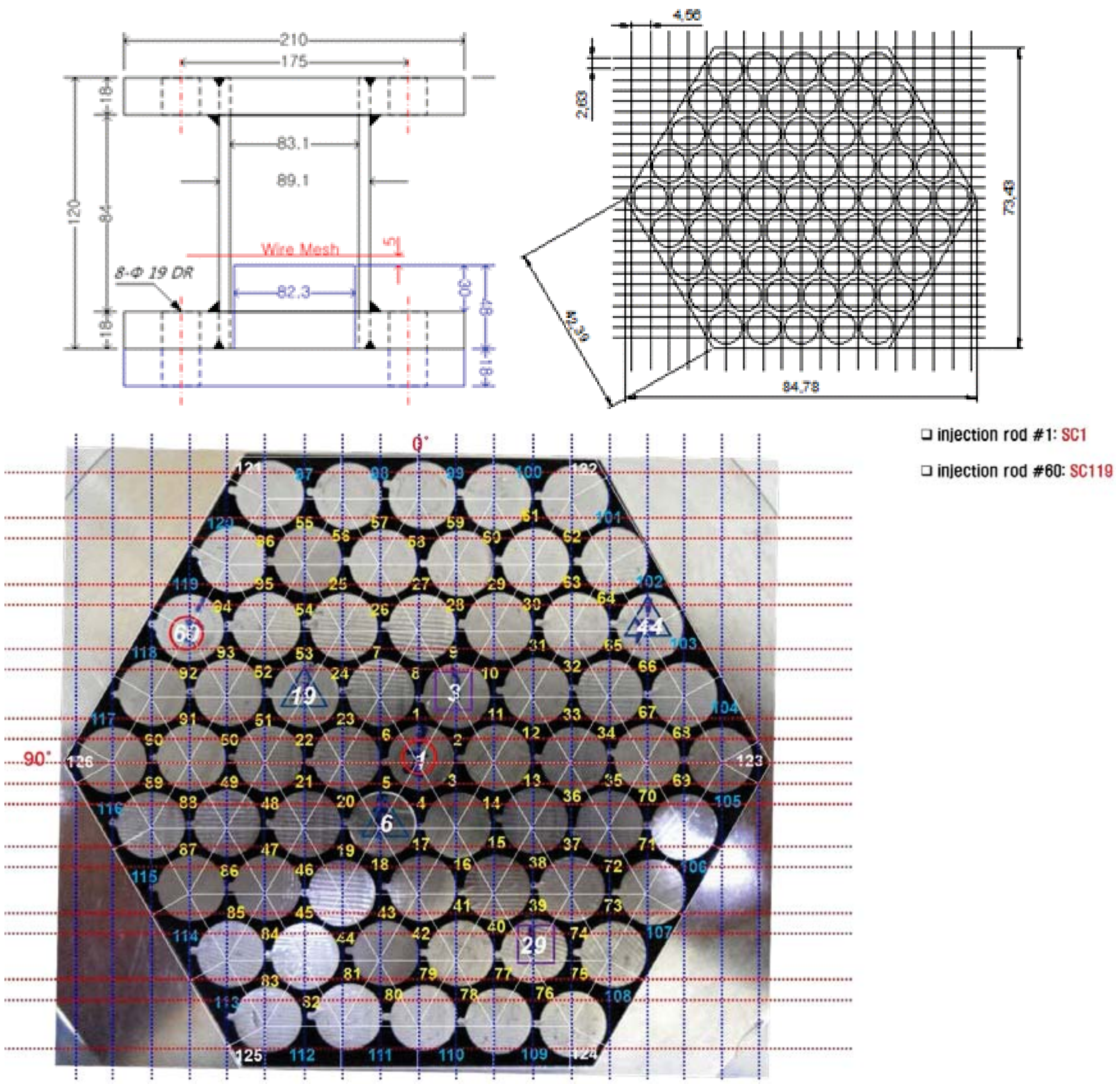

Figure 3. Design of our wire mesh sensor and matching with our 61-pin assembly.

2.3. Test procedure

A wire mesh sensor can receive an electric conductivity level as integer values from 0 to 4079 (12 bits). We used deionized (DI) water as a background liquid, and tap water was injected as a tracing liquid. Because the conductivity of the tap water is much higher than DI water, it is a useful tracing liquid. The sensor gain was fixed as 150, and the sampling frequency was also selected as 100 Hz. Every measurement was conducted continuously at every 30 seconds including both the homogeneous (>10 s) and injecting stages (>10), as shown in Fig. 4. Operating conditions in a test fuel assembly are 15.02 kg/s at 60 ^{o}C which is equivalent to Re ~ 60,749.

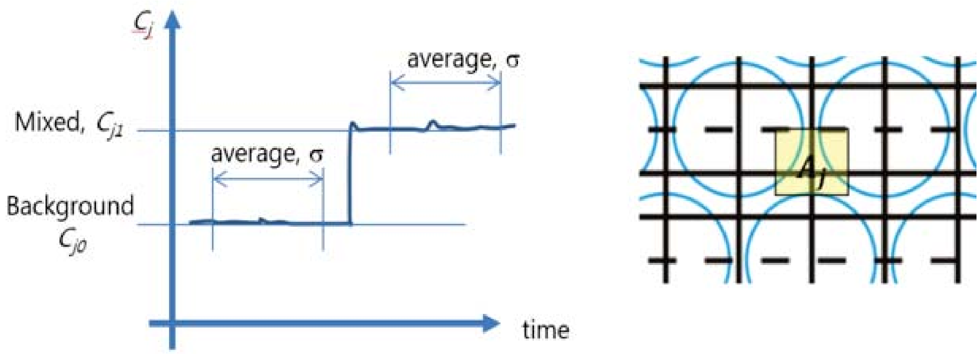

Figure 4. Test procedure and definition of area factor (A_j).

Eq. (1) shows the present post-processing method considering both the unit cell area and the local value differences in a homogeneous liquid. In particular, because our wire mesh sensor was designed as an irregular type, the weighting value is essentially represented in Eq. (1). From this process, we had two major benefits. First, the uniformity in a homogeneous state is extremely increased. Second, we can normalize the data in spite of a conductivity increase in the background liquid as repeating experiments (Fig. 5).

$$C_{j,n} = \frac{C_{j1} - C_{j0}}{\sum_j A_j \left(C_{j1} - C_{j0}\right) / \left(\sum_j A_j\right)} \quad (1)$$

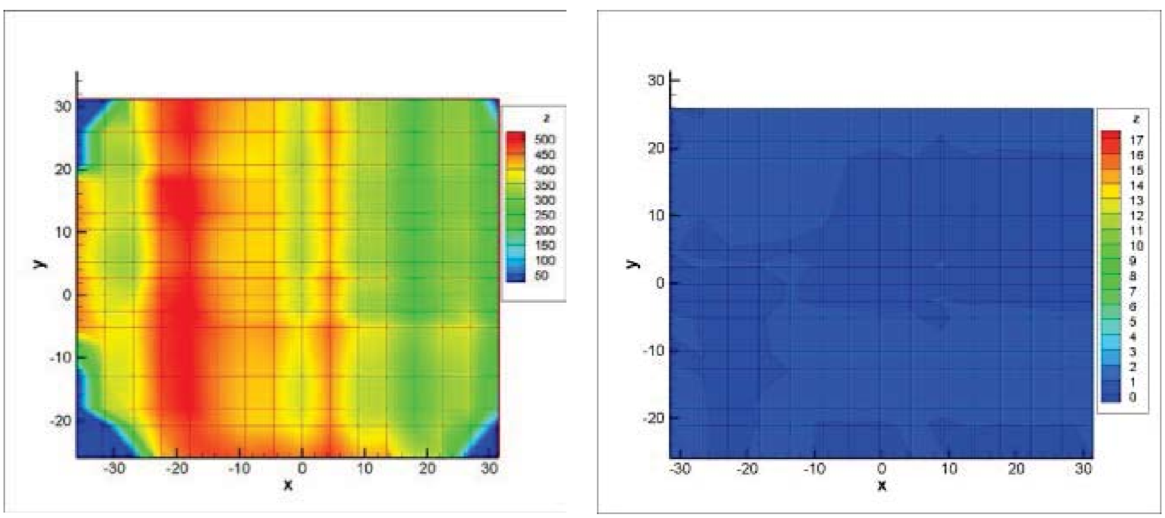

Figure 5. Homogeneous stage example:
without post-process (left) and after post-processing result (right) in a homogeneous state.

3. RESULTS AND DISCUSSION

3.1. Preliminary results by CFD analysis

A computational fluid dynamics (CFD) analysis was preliminary conducted for a cross check of our experimental results. Fig. 6 shows the overall contour graphs of the CFD calculations. The STAR-CCM+ as computing tool was used with the anisotropic standard k-epsilon turbulent model (cubic) and high y+

wall treatment condition with 45 million computational cells decided by preliminary mesh quality tests. All calculation was done in steady state, and mass flow rate and *Re* number were matched with the experimental cases (15.02 kg/s and 60,749, respectively). The results of CFD show a good agreement with our experimental results. Fig. 6 shows the overall contour graphs of the CFD calculations for comparison between the CFD and experiments. A quantitative comparison between the CFD and experiments is ongoing. Case 1 is the mixing when the tracer was injected through lower hole inside rod #1 (1H), and case 2 is the result at the upper hole inside rod #1 (1L). Case 3 and 4 are the results of 60H and 60L, respectively.

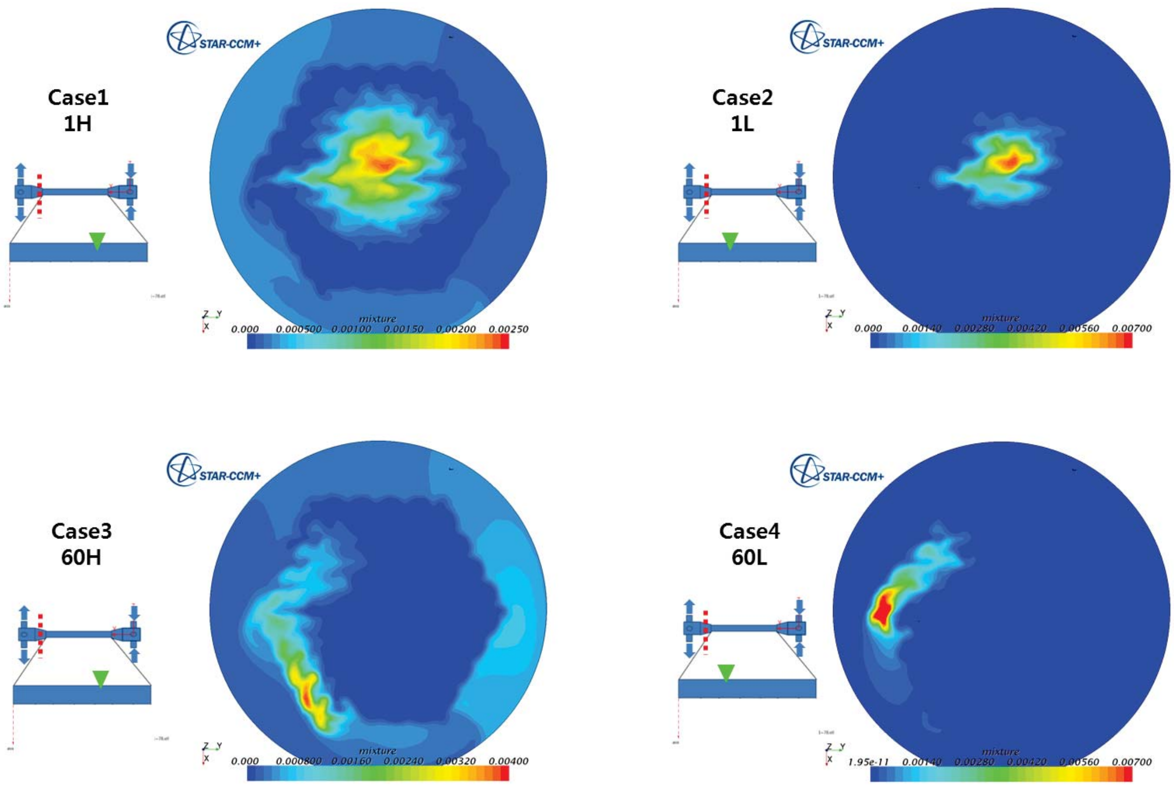

Figure 6. CFD analysis results.

3.2. Flow mixing measurement results

Fig. 7 shows the flow fields from the flow mixing experiments using a wire mesh sensor and our post-processing method. In the case of an interior subchannel injection, the injected liquid gradually diffused, as shown in the upper results (1H and 1L) of Fig. 7, because the cross flow by the wrapped wires is almost eliminated for the opposite direction cross flow collision. However, in the case of an edge subchannel, all cross flows by wrapped wires should have the same direction: a clockwise direction without collisions. Thus, the peak point of the flow field should move around as edge walls of the fuel assembly, as shown in the lower results (60H and 60L) of Fig. 7. These results show very good agreements with the two-region model used in the design code for the SFR. This model considers only enhanced eddy diffusivity by wire-wraps in the interior subchannel region, and oscillatory lateral flows by wire-wraps in the edge subchannel region.

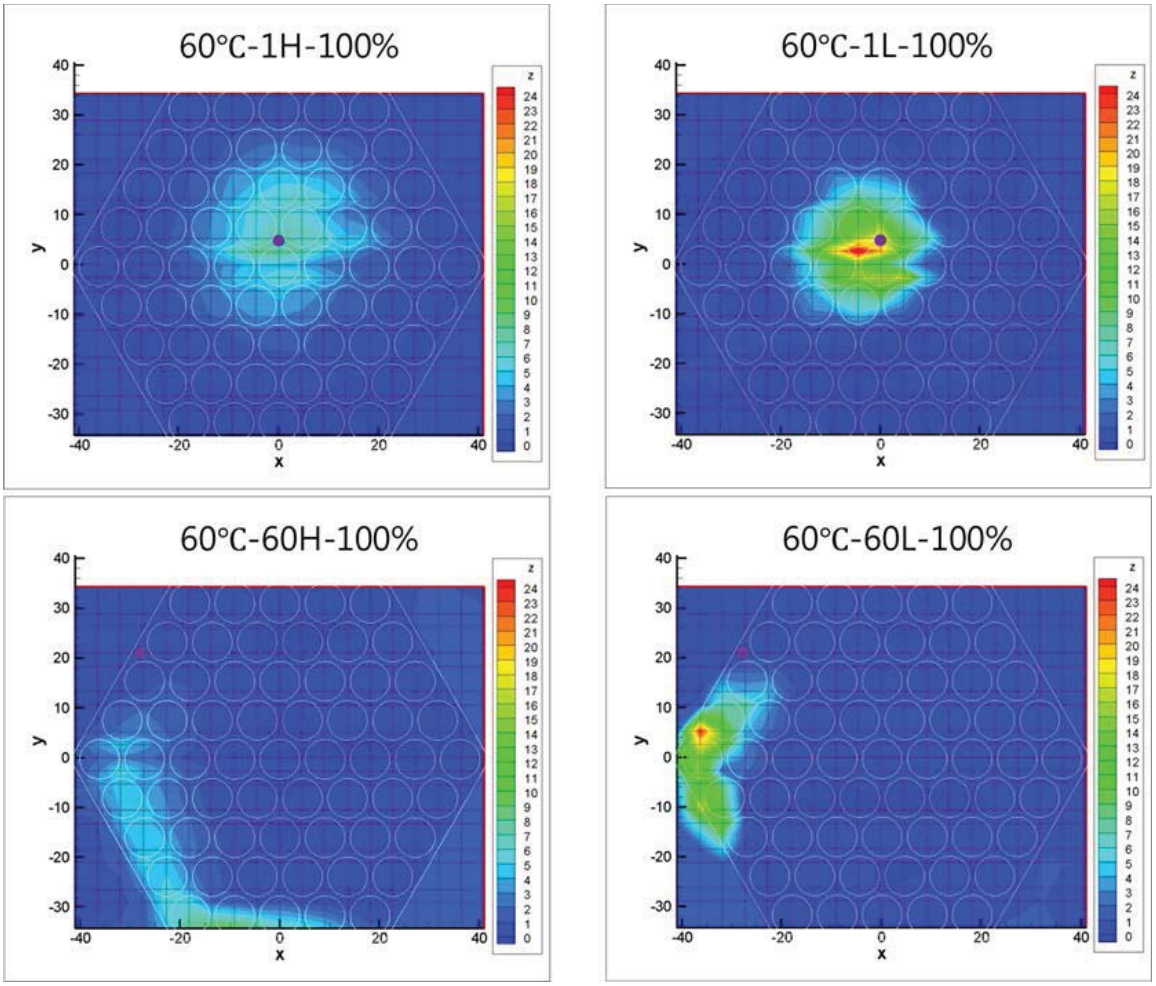

Figure 7. Flow mixing contour graphs.

3.3. Uncertainty analysis

An uncertainty analysis including the error propagation was also conducted. The temperature (T) and flow rate (M) variations were considered as the system error components in the experiments. The methodology of the system error calculations is shown in Eq. (2).

$$(\delta C_{j,n})^2 = \left(\frac{\delta C_{j,n}}{\delta C_{j1}}\right)^2 (\delta C_{j1})^2 + \left(\frac{\delta C_{j,n}}{\delta C_{j0}}\right)^2 (\delta C_{j0})^2$$

$$\left(\frac{\partial C_{j,n}}{\partial B}\right)(\delta B) = \frac{(\sum_j A_j - C_{j,n} A_j)}{\sum_j \{A_j (C_{j1} - C_{j0})\}} \sqrt{\left(\frac{\partial C_{j1}}{\partial B}\right)^2 + \left(\frac{\partial C_{j0}}{\partial B}\right)^2} (\delta B) \tag{2}$$

where B is a known error component (eg. T and M).

A random error was obtained from Eq. (3).

$$\partial C_{j,n} = \frac{(\sum_j A_j - C_{j,n} A_j)}{\sum_j \{A_j (C_{j1} - C_{j0})\}} \sqrt{\left(\delta C_{j1}\right)^2 + \left(\delta C_{j0}\right)^2} \tag{3}$$

Table I shows the estimated results of the system errors (from T, and M) and random errors. Though the order of magnitude of the peak values is about 10, the estimated errors were very small values.

Table I. The maximum estimated errors: system and random errors

	Max. error from δT (95%)	**Max. error from δM (95%)**	**Max. random error (95%)**
1H	5.523×10^{-3}	6.245×10^{-3}	2.923×10^{-1}
1L	4.629×10^{-3}	8.586×10^{-3}	3.448×10^{-1}
60H	5.320×10^{-3}	1.179×10^{-2}	2.744×10^{-1}
60L	3.902×10^{-3}	5.838×10^{-3}	2.693×10^{-1}

4. CONCLUSIONS

To verify and validate the computer codes for the SFR core thermal design, mixing experiments were conducted at a hexagonally arrayed 61-pin wire-wrapped fuel rod bundle test section. A well-designed wire mesh sensor was used to measure the flow mixing characteristics. The developed post-processing method has its own merits, and the flow mixing results were reasonable. In addition, through an uncertainty analysis, the system errors and random errors were estimated in our experiments. Therefore, the present results and methods can be used for design code verification and validation.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP). (No. 2012M2A8A2025635)

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