Development of Flow Identification Technology for the PGSFR Thermal Fluidic Design Validation

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Abstract. Various experimental programs were selected for the validation of the thermal fluidic design of the PGSFR reactor system and design codes as the results of the PIRT. Among them, this study includes a core subchannel flow experiment, a reactor flow distribution test and an IHX flow characteristic test. For the assessment of the thermal margin of the core design, several essential physical parameters were identified as a result of PIRT, which are a friction coefficient, mixing factor, and pressure drop. These were considered as important parameters having significant uncertainties in the model and correlations of the core thermal design code. To identify the core subchannel flow rate and mixing characteristic, an iso-kinetic method, a wire mesh and a LIF technique were developed and optimized for the purpose of our experiment. The experimental database for the core inlet flow and outlet pressure distribution are also important for the evaluation of the core thermal margin especially for an evaluation of the clad thermal stress related to the creep. The pool side flow distribution including the pressure drop of the major flow path of the PHTS is important for the validation of the fluidic design of the reactor. The PHTS of the prototype plant was reduced to a 1/5 length scale at our test facilities with a preservation of the internal structures affecting the flow characteristics. Experimental techniques for the identification of the flow including the fuel assembly-wise inlet flow rate and outlet pressure were developed. To validate the pressure drop correlations used in the computational code for the IHX design, a test facility was designed for the flow characteristics of the shell side of the IHX with a proper scaling approach. In this paper, a brief experimental technology and facilities design for each experiment were described. The experimental database constructed in the current work will contribute to acquiring the license of the core thermal and reactor fluidic design of the PGSFR.

Key Words: Sodium-cooled Fast Reactor, flow distribution, Intermediate heat exchanger, Inlet Plenum

1. Introduction

The Korea Atomic Energy Research Institute (KAERI) has performed a conceptual design of the 4th generation SFR and is now further carrying out experimental works for the T/H design verification. The next generation SFR is planned to be realized according to a milestone of the final goal of constructing a prototype plant by 2028 under the program of the mid and long term project of the Korean atomic authority.

It is important to understand the flow characteristics in subchannels through the experimental investigations and to estimate the calculation uncertainties for insuring the confidence of the correlations or subchannel analysis code. (Choi et al., 2013) The most influencing parameters on uncertainties of the subchannel analyses were selected as a friction coefficient and a mixing coefficient. The friction coefficient is related to the flow distribution in the reactor sub-channels. The mixing coefficient is defined by the cross flow between neighbour sub-channels. The eventual purpose of the thermal fluidic design considering these parameters is to guarantee the fuel cladding integrity as a design limit parameter. This study developed an instrumentation for the flow characteristics of an open channel such as a subchannel and performed experiments for a wire wrapped 37- and 61-rod assembly and its hexagonal test rig based on the similarity of the reference reactor.

PGSFR is a pool type reactor in which the major components are installed inside the reactor vessel including four IHXs, four DHXs, and two PHTS pumps. The flow distribution will show multi-dimensional phenomena, which depend on the geometrical configuration of the components. The pool side flow distribution including the pressure drop of the major flow path of the PHTS is important for the validation of the fluidic design of the reactor. The experimental database for core inlet flow and outlet pressure distribution is also important for the evaluation of the core thermal margin especially for the evaluation of the clad thermal stress related to the creep. In order to identify the overall flow behaviour of the PHTS (Primary Heat Transfer System), the prototype plant was reduced to a 1/5 length scale in our test facilities with a preservation of the internal structures affecting the flow characteristics. The core and IHX part having the rod bundle geometry were simplified by simulators having the same pressure loss characteristics and the capability to measure the flow rate. In this paper, the experimental methodology for the identification of the reactor flow characteristics including fuel assembly-wise inlet flow rate and outlet pressure is described.

The prototype SFR reactor has 4 IHXs(Intermediate Heat Exchanger) located at the boundary between the high temperature pool and the low temperature pool. The IHX transports primary heat to the secondary system through shell-and-tube type heat exchanges with a counter-current flow, and significantly affects the SFR system performance. The SHAXA code is used for the IHX design and performance verification under the transient and normal operation conditions. Pressure drop correlations in the SHAXA code were developed based on the single-phase and ideal flow geometry condition. However, under a complex geometry and spatial developing flow condition, as well as a low flow condition, the uncertainties of the pressure drop correlations may significantly increase. Therefore, a series of experimental verification works for the correlations under various operating conditions is essentially required. The annulus shell type of the IHX primary side was scaled to a slab geometry having a volume ratio of 1/29. The detailed design approach to preserve the prototype pressure drop and the measuring techniques are described in this paper.

2. Experiment for the Core Subchannel Flow Distribution

2.1. Scaling and Test Condition

The major parameters characterizing the subchannel flow are the pitch and lead length to rod diameter ratios as for the geometrical similarity and Reynolds number for the fluid-dynamic similarity. The 37- and 61- rod test rigs were considered separately, of which the prototype thermal hydraulic conditions are quite different according to the reactor design status. Since the current experiment is focused on the fluidic dynamics, the operation was performed at low temperature. By considering the property and pump characteristic as well as previous studies, the temperature was selected to be 60^{o}C.

2.2. Design of Fluid System

Figs. 1 and 2 show a schematic of a test loop called FIFFA and a test rig having a 37-pin wire wrapped fuel assembly. The test section has a housing having a hexagonal internal shape. At the top part, measuring structures are installed, such as an iso-kinetic sampling device, transparent pipe for laser optics and a wire mesh sensor.

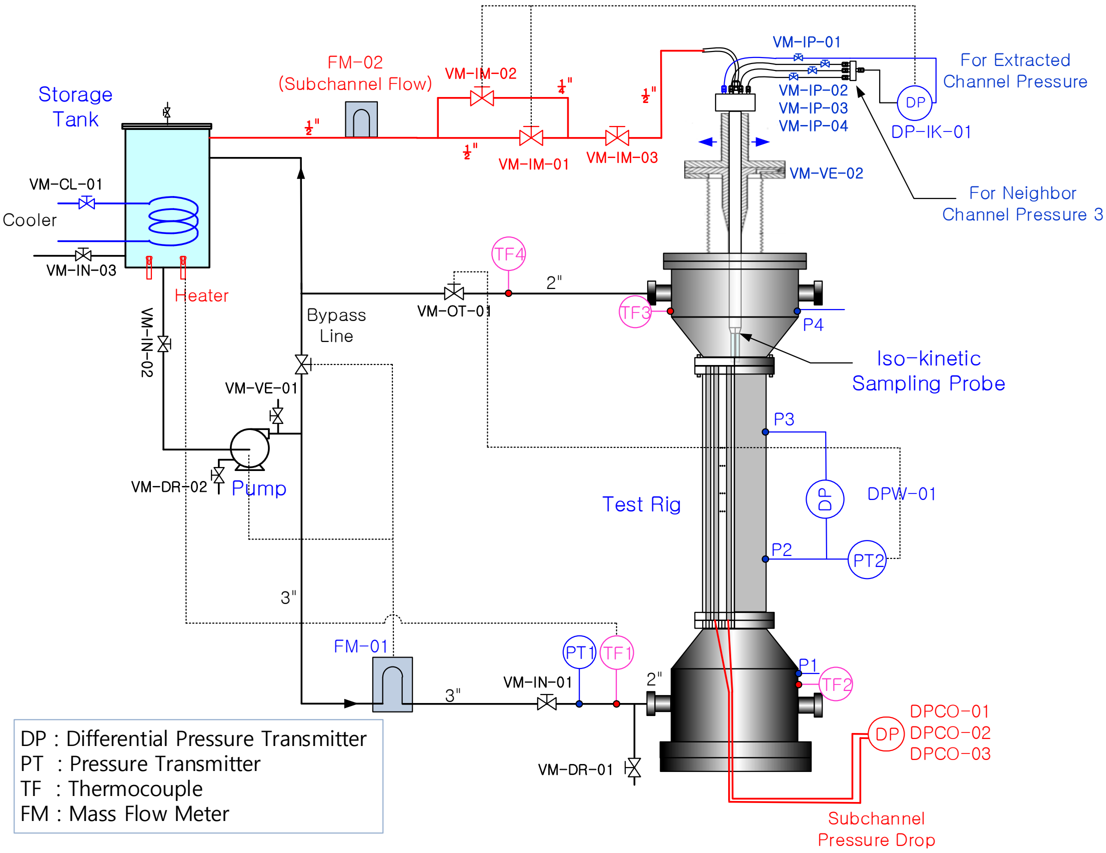

FIG. 1. Test Apparatus (FIFFA)

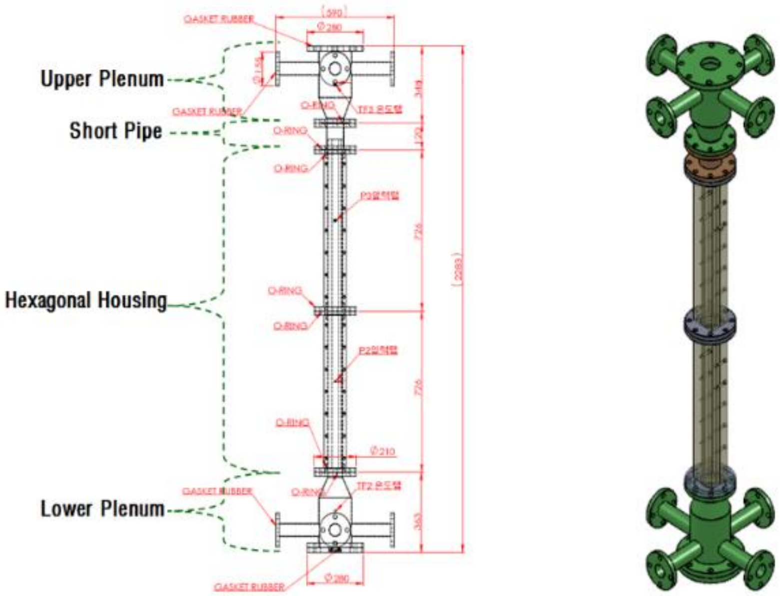

FIG. 2. Design of Test Section for 37 rod assembly

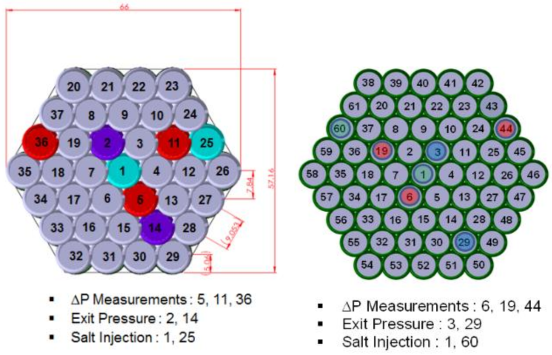

FIG. 3. Configuration of Rods

The assembly includes three tubes for the internal pressure drop and two tubes for electrolyte injection, as shown in Fig. 3. The tubes were utilized for the instrumentation by inserting a 1/16” tube inside the rod simulator tube and penetrating through the measuring hole and laser welded at the measuring point.

2.3. Measurement Method

2.3.1 Iso-Kinetic Method for Subchannel Flow Distribution

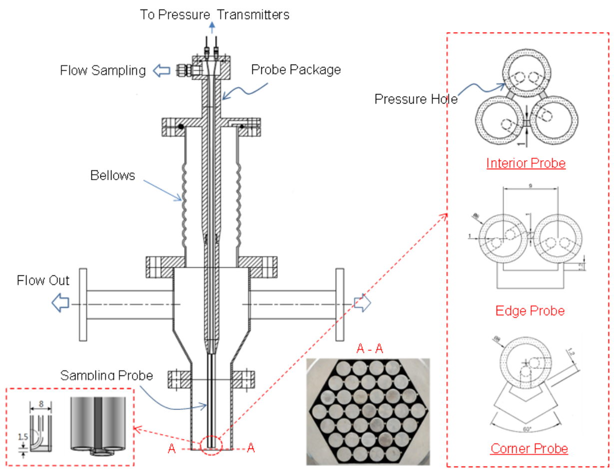

FIG. 4. Iso-kinetic sampling probe and installation

Figure 4 shows an iso-kinetic sampling probe design and driving mechanism, of which the sampling part geometry preserves the cross-sectional flow area at every type of subchannel. Thus, the cross-sectional shape of the probe tip, which is enclosed by thin plates, is identical with the peripheral structure of the sampling subchannel as well as the subchannel itself. Three kinds of sampling probe have the pressure sensing holes at 1.5 mm upward from the probe end. For all kinds of probe, one inward directed sensing hole is for the static pressure measurement at the sampling subchannel, and three sensing holes are opened for the neighbour subchannels. The iso-kinetic condition is considered to be established from the same static pressure between the sampling subchannel and the neighbour subchannels by controlling the sampling flow rate.

The sampling probe is installed vertically on top of the rod bundle and can be moved laterally to any specified subchannels. The flexible bellows has been adopted to give flexibility to move the sampling probe in the lateral and axial directions. The pressure impulse lines of the sampling probe are guided outside and connected to the pressure transmitters for the judgment of the iso-kinetic condition. The sampling line is connected to a mass flow meter to measure the flow rate of the sampling subchannel.

2.3.2 Wire Mesh Method for Mixing Characteristic

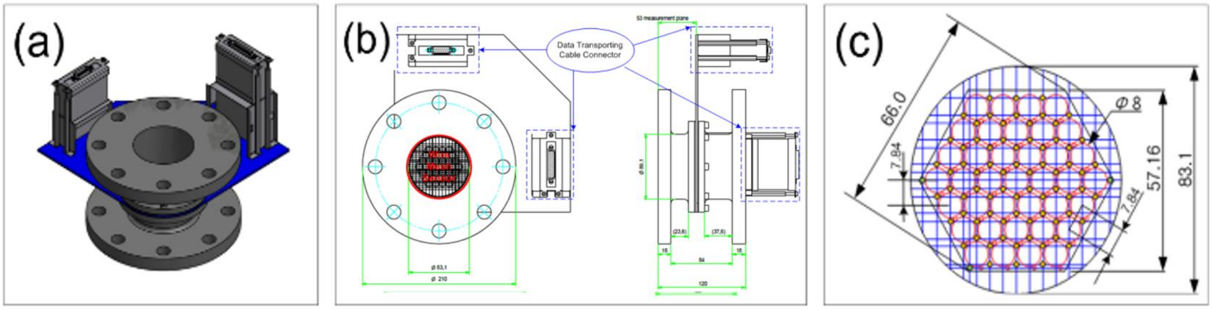

FIG. 5. Design of a wire mesh sensor for 37-rod assembly

To obtain the mixing data of the assembly, a wire mesh sensor (WMS) was applied. A wire mesh sensor has a transmitting and a receiving electrode layer with a short distance and a cross angle of 90°. The property of each subchannel flow was represented by the value measured at the cross point of two layers. The wires were aligned that each cross point are positioned at the center of the subchannels. To match the location between the cross points of WMS and the subchannels of the bundle, the WMS was fabricated having irregular rectangular cells. Fig. 5 shows this for a 37 rod bundle in which (a) the bird's eye view, (b) design drawing of the sensor and (c) the wire mesh structure were shown.

The main loop was filled with deionized (DI) water as the background liquid, and tap water was used as the tracing liquid. The tracing liquid was injected using a rod consisting of a rod bundle, inside which a tracing tube was connected exquisitely. Two rods were selected for the injection at two different elevations of the rod, which are shown in Fig. 3. Therefore, there are four different points for the injection: upper (1L) and lower (1S) holes for an interior subchannel, and upper (25L) and lower (25S) holes for an edge subchannel. The intake of the test rig includes a flow regulator to make the flow uniform, and the experimental hydraulic conditions are fully turbulent. The WMS was installed at the exit of the subchannels of the wire-wrapped 37-pin bundle with a 5-mm gap from the end of the rods.

2.3.3 LIF Method for Mixing Characteristic

To identify the mixing characteristics among the rod bundles, the optical measurement technique was also adopted. To visualize and quantify the mixing characteristics between each rod bundle, the laser induced fluorescence (LIF) technique is a suitable measurement technique. The LIF technique is an optical measuring technique used to measure the instant whole-field concentration or temperature field in a flow. Figure 6 shows a schematic diagram of the experimental setup for the LIF measurement.

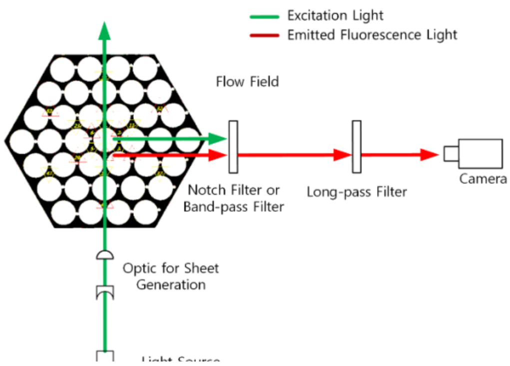

FIG. 6. Schematic diagram for LIF experiment

It consists of a 5 W Nd:YAG continuous laser, a 2K×2K CCD camera, and a few optics. The laser light sheet illuminates the test flow section through the left side of the tempered glass. The working fluid used for the LIF measurements is de-ionized water with 60^{o}C. Rhodamine B is used as a fluorescent dye. A long pass filter (λ>550 nm) and a notch filter are used to eliminate the scattered light except the fluorescence light and block the 532 nm wavelength, which are installed in front of a digital recording device. The LIF technique has the following disadvantages: (a) uniformity of the laser sheet, (b) laser power changes between the calibration test and experiment, and (c) an absorption effect of the fluorescent dye. In this study, a dimensionless method is adopted to resolve the disadavantage of the LIF technique, and dimensionless LIF results are compared with the wire mesh measurement data and the CFD analysis results. In this study, Rodamine B (fluorescent dye) is injected into the same rods used for WMS. An experiment was also carried out for the different injection locations at the rated flow rate and temperature conditions.

3. Experiment for the SFR Flow Distribution

3.1 Design of pool side of the test section

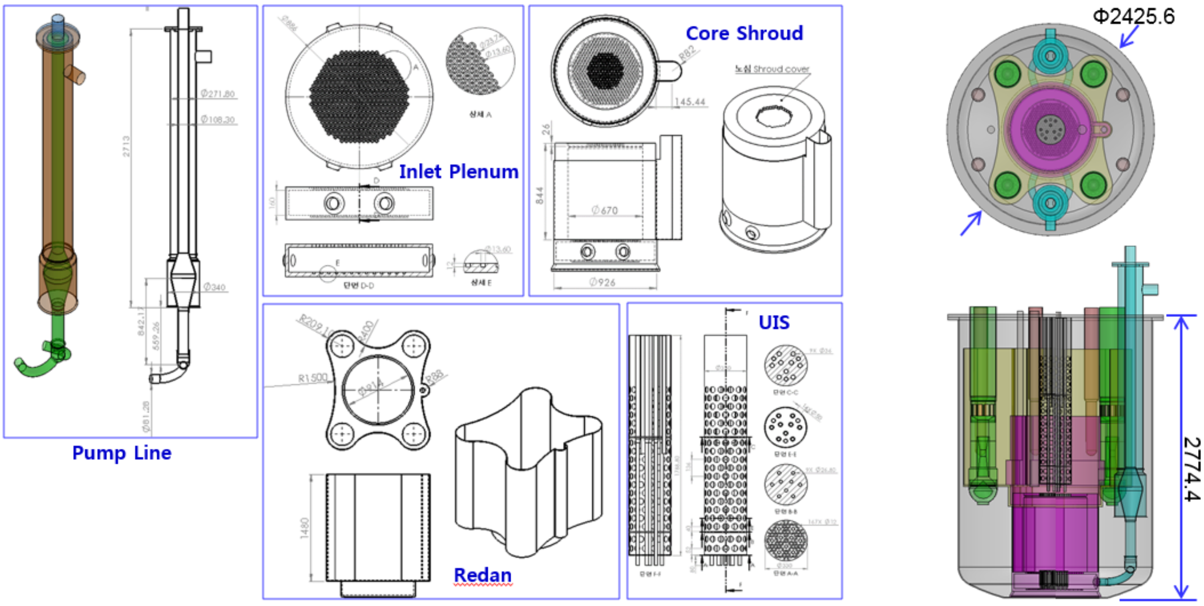

FIG.7 Reactor vessel for reactor flow distribution test

The PGSFR flow distribution is supposed to be preserved in the test facility using a geometrical and dynamic similarity scale method. The prototype geometry was linearly scaled down to a ratio of 1/5. The geometry of the major flow path facing the fluid is strictly preserved with the prototype design except for the core and IHX having a rod bundle geometry. Figure 7 shows the design feature of the important components. The Reynolds number has an order of 10^7 at the overall points of the flow path in the test facilities, which can be considered as a sufficiently high turbulent flow condition. Therefore, the Euler number is preserved, which corresponds to dynamic similarity. Since the current test is focused on the flow characteristics, the experiment was performed at low pressure and low temperature.

3.2 Quantification Method of Core Flow and IHX Flow

PGSFR has 112 fuel assemblies and 4 IHXs which have a rod bundle geometry. Each fuel assembly consists of a large number of wire wrapped fuel rods. Since the fine geometry of the subchannel flow does not affect the reactor scale of the flow distribution, the fuel assembly is simplified by a simulator which preserves the core pressure drop and is capable to measure the flow rate. The bypass flow is neglected in the current test because the flow rate through the non-fuel assemblies is estimated to be a few percentages of the total core flow, which is the uncertainty level of the flow measurement and does not significantly affect the dimensionless core flow distribution.

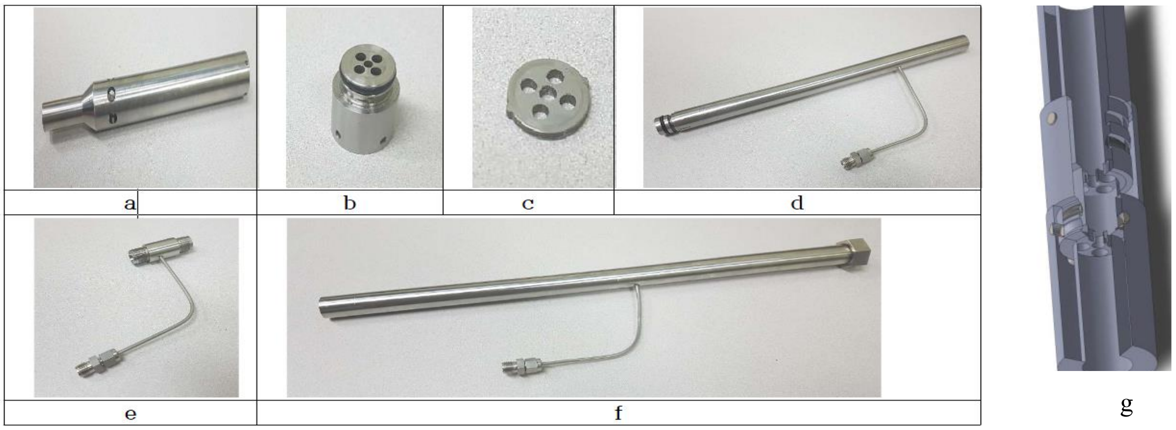

FIG. 8. Core simulator and VRROS

The figure 8 shows a core simulator, which consists of (a) a receptacle, (b)(c)orifices, (d) a flow tube, (e) a venturi and (f) a flow tube. To achieve the desired pressure loss easily by rotating an orifice, an innovative design of a variable resistance rotating orifice spool (VRROS) was developed in this study. Figure 8(g) shows the design of VRROS. By adjusting the rotation angle of VRROS, the flow resistance of the core simulator can be finely tuned without changing the orifice plate. To assemble the core simulators in the reactor vessel, three pressure impulse lines per core simulator should be drawn out and connected to the pressure transmitters without significant interference of the reactor flow. To minimize the perturbation due to instrumentation, 336 pressure impulse lines were guided through the CRDM guide tubes where the flow is stagnant and does not affect the reactor flow. The assembling of the pressure impulse lines was investigated at a separated mock-up in advance as shown in figure 9.

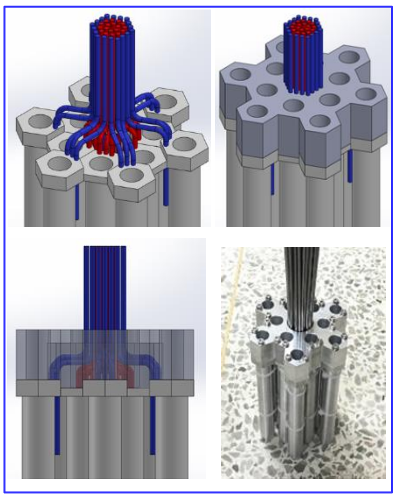

FIG. 9. Assembling of pressure impulse line

Each IHX was also designed by using a simulator to have the desired pressure drop and a venturi geometry inside it for the flow measurement, like the core simulator design concept. Figure 10 shows a photograph and the design features of the IHX simulator.

The performance of each simulator is evaluated at a flow and pressure drop calibration facility named CALIP (CAlibration Loop for Internal Pressure Drop) which was first constructed for the performance verification of the SMART reactor fuel assembly simulators, and was modified for the PGSRF fuel assembly simulators and IHX simulators. It is equipped with two test channels each for the fuel assembly and IHX simulators, two pumps with different capacity that control the flow rate by VVVF inverters, four high accuracy Coriolis mass flow meters, two high accuracy pressure transmitters and twelve high accuracy differential pressure transmitters for precise measurements of the flow rate and pressure drops across the simulators. Figure 11 shows a CALIP loop for the calibration experiment.

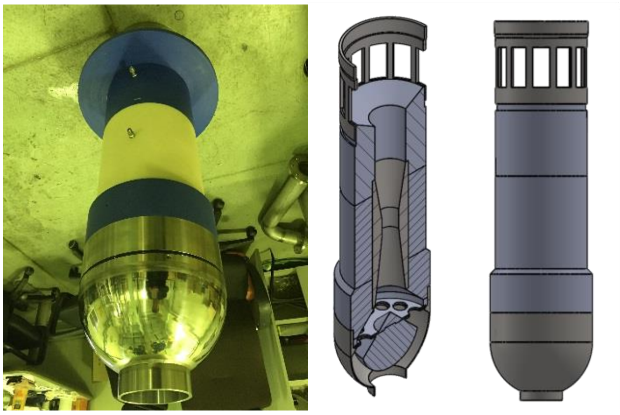

FIG. 10. IHX simulator

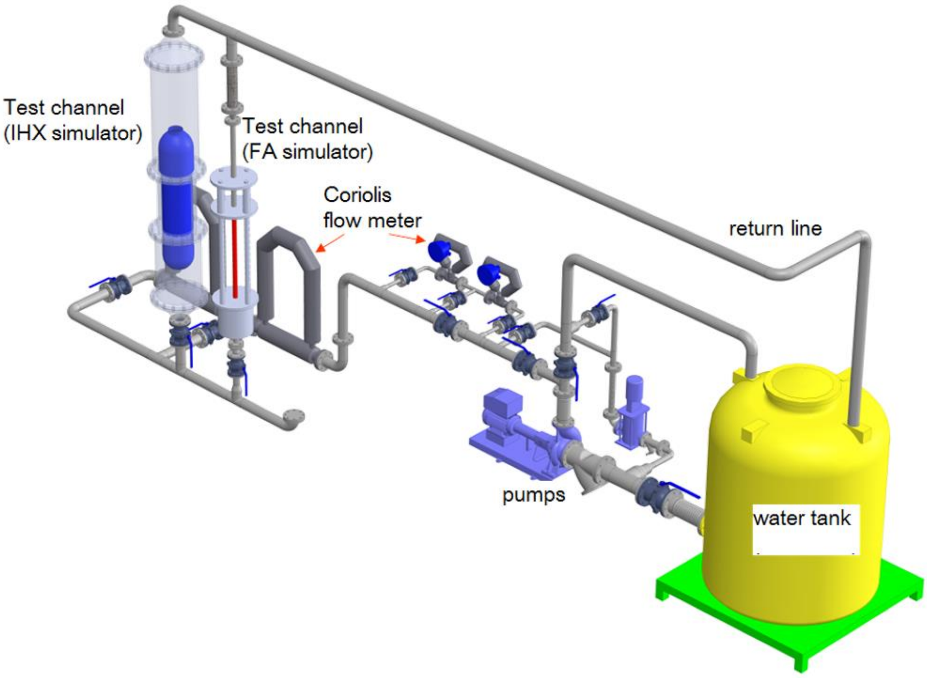

FIG. 11. CALIP loop for calibration

3.3 Instrumentation System

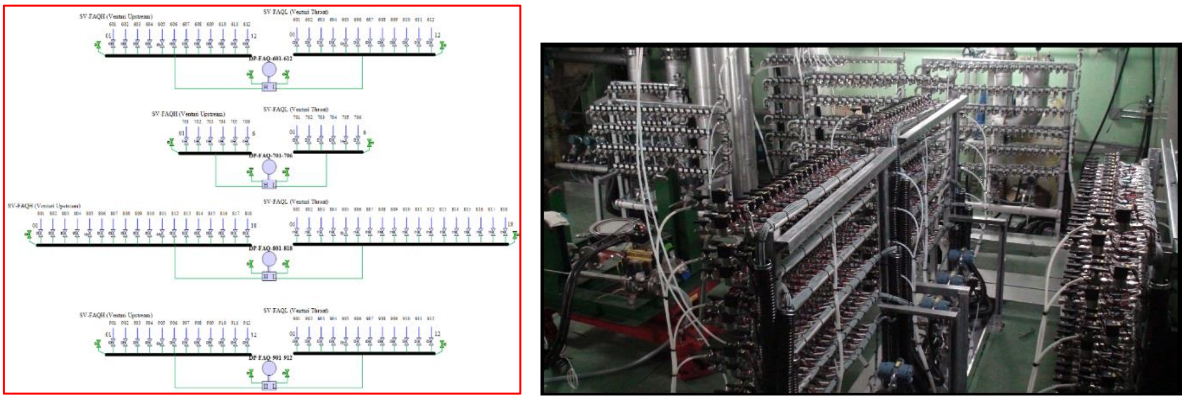

FIG. 12. (a) Schematics and (b) photograph of solenoid valve network

The reactor flow distribution is supposed to be quantified by measuring the pressures at large numbers of points, i.e., 292 points based on the current design. A methodology for the application of the distributed instrumentation using solenoid valves was developed to measure a large amount of pressures with a limited number of pressure transmitters. (Youn et al., 2010, Euh et al., 2012b) The pressure impulse lines from the same group having a similar region and working ranges were combined into a common header with solenoid valves at each line. From the common header, only one pressure delivery tube is connected to a pressure transmitter, as shown in Fig. 12(a). By programming the sequential control logic for operating the solenoid valves, several numbers of pressure points can be measured with a single sensor automatically. Fig. 12(b) shows a photograph in which sequential valve networks were installed for the multi-point pressure measurements.

4. Experiment for the IHX Flow Characteristics

4.1 Scaling Method and Design of Test Section

To validate the pressure drop correlations used for the IHX design, the IHX flow characteristics test facility was constructed based on a proper scaling approach. The annulus geometry of the IHX shell side is sectionalized to slab geometry preserving the Reynolds number and hydraulic diameter of the tube bundle of the prototype SFR. The flow area ratio in the grid plate region is maintained as a ratio of 1:1. The height scale is at a ratio of 1:1 and has a volume scale ratio of 1/29. At the upper region of the test section, a flow distributer is installed to simulate a uniform flow distribution at the inlet of the prototype SFR. The number of heat exchanger tubes is reduced based on the volume ratio and the shape of the triangular arrangement should be preserved. The shapes of the inlet and outlet sections of the prototype IHX should be as similar as possible. Five grid plates are installed in a test section as the prototype plant. The flow hole diameter, pitch, and gap should be preserved. The design features were depicted in Fig.13.

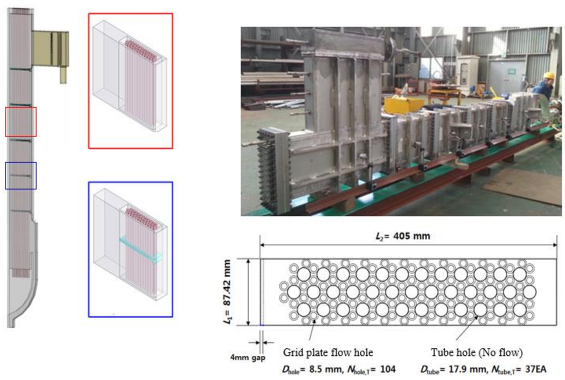

FIG. 13. IHX Test Facility Design

4.2 Flow Distributor

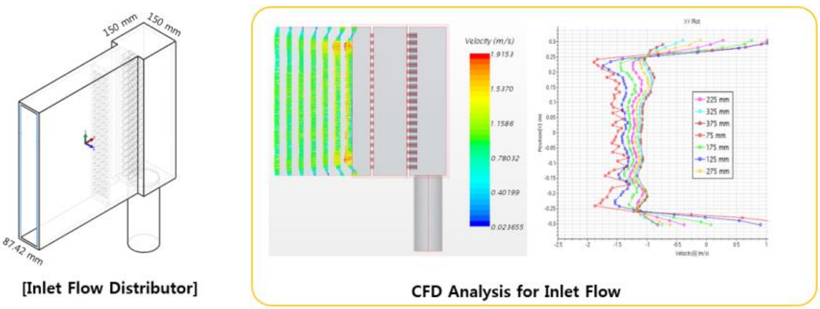

FIG. 14. IHX inlet flow distributor design and CFD validation

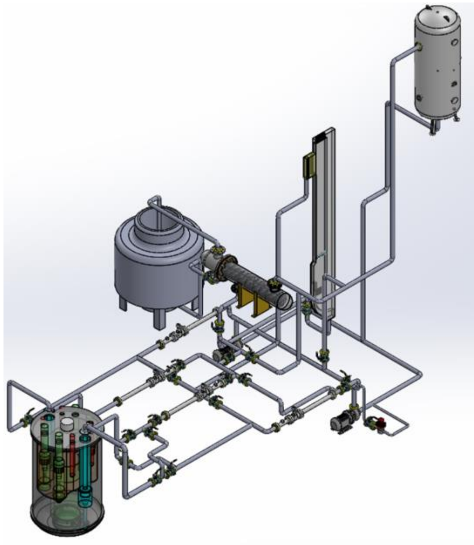

FIG 15 Schematic of reactor flow and IHX flow characteristics test loop

At the upper region of the test section, a flow distributer is installed to simulate a uniform flow distribution at the inlet of the prototype SFR. The basic design concept of the distributor is originated from the header geometry of the header-channel heat exchangers. The direction of the flow from the pipe of the test loop is perpendicular to the direction of the flow to the inlet window. By applying this configuration, a primary reduction of the dynamic pressure could be achieved. Inside the flow distribution device, a primary perforated plate and a secondary perforated plate are installed. At the primary perforated plate, short tubes are intruded to the upstream for an effective reduction of the dynamic pressure. The flow is further distributed before the inlet window by passing the secondary perforated plate. The performance of the flow distributor was evaluated through a CFD analysis, which was very successful as shown in Fig. 14. The facilities for the IHX flow characteristic test consist of a test section, cooling tower, circulation pump, flow control valves, flow meters and related piping. Two separate trains of piping systems were designed for the low and high flow conditions. The proper instrumentation was designed, of which the type and ranges were decided based on the test requirements and scaling analysis, for the pressure, pressure drop, and temperature, flow rate. The IHX test loop is shared with the reactor flow distribution test in order to efficiently use the budget and infrastructure. Figure 15 shows a schematic of the reactor flow and IHX flow characteristics test loop.

5. Conclusions

Three topics for the PGSFR flow characteristics were defined and a fluidic design and special measurement technique were developed in this study. For the core thermal margin analysis, the core subchannel flow rate, mixing factor, and pressure drop were quantified using the iso-kinetic method, wire-mesh, and LIF method, which were uniquely developed. To identify the overall PGSFR flow characteristics, a linear scaled test facility was designed and best estimated experimental methodology was developed for the pressure and flow distribution. The IHX pressure drop is a measured slab type geometry preserving the tube and flow hole geometry as well as the height and hydraulic diameter. The design and measuring method developed in this study will contribute to an experimental database construction for each subject, and can be used for validation of the model accuracy and uncertainty of the models used in the design code.

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