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Development of the Test Facilities for the Measurement of Core Flow and Pressure Distribution of SMART Reactor

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Abstract

A design of SMART reactor has been developed, of which the primary system is composed of four internal circulation pumps, a core of 57 fuel assemblies, eight cassettes of steam generators, flow mixing head assemblies, and other internal structures. Since primary design features are very different from conventional reactors, the characteristics of flow and pressure distribution are expected to be different accordingly. In order to analyze the thermal margin and hydraulic design characteristics of SMART reactor, design quantification tests for flow and pressure distribution with a preservation of flow geometry are necessary. In the present study, the design feature of the test facility in order to investigate flow and pressure distribution, named “SCOP” is described. In order to preserve the flow distribution characteristics, the SCOP is linearly reduced with a scaling ratio of 1/5. The core flow rate of each fuel assembly is measured by a venturi meter attached in the lower part of the core simulator having a similarity of pressure drop for nominally scaled flow conditions. All the 57 core simulators and 8 S/G simulators are precisely calibrated in advance of assembling in test facilities. The major parameters in tests are pressures, differential pressures, and core flow distribution.

Introduction

The design of a SMART reactor (System-integrated Modular Advanced ReacTor), which is a next-generation integral type reactor with enhanced safety, has been developed [1]. The SMART can be an energy source for electricity generation, seawater desalination, district heating, and etc. A single unit of SMART can provide 90 MWe of electricity and 40,000 tons of fresh water a day for a city with a population of 100,000. By eliminating large primary system pipes and penetrations, SMART is free from the possibility of LBLOCA, which greatly enhances reactor safety. The primary system of SMART is composed of four internal circulation pumps, a core with 57 fuel assemblies, eight steam generator cassettes, flow mixing head assemblies, and other internal structures. Figure 1 shows the features of the SMART design that is currently being developed.

The performance and safety of the system can be demonstrated based on the accurate thermal hydraulic information of the reactor system. The core thermal margin can be evaluated based on the reference of the boundary conditions of core, which is the core inlet flow and core outlet pressure at each of the fuel assemblies. The performance and safety analysis of the reactor's transient condition can be performed based on accurate information of pressure loss along the flow path in the primary system.

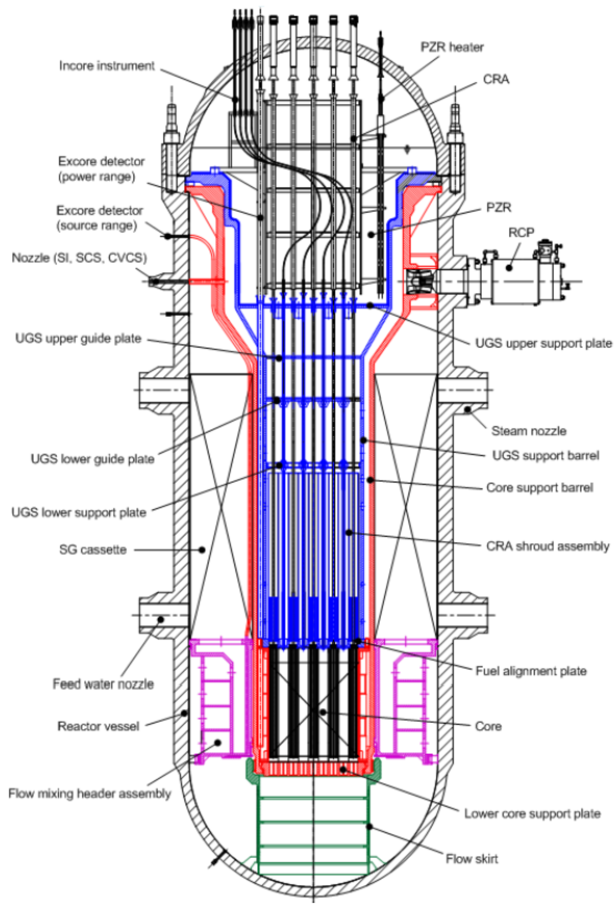

Figure 1 SMART Reactor

Since the primary design features are much different from conventional nuclear reactors, the SMART reactor is accordingly expected to have unique characteristics of flow and pressure distribution. The development of new and/or conventional nuclear system design should be strongly based on the reduced uncertainties of hydraulic characteristics. The hydraulic characteristics of a reactor system can be evaluated through the use of mathematical models, or an experimental investigation with the adaptation of a proper scaling theory. Although mathematical tools have been developed over the past several decades, they still need more improvement in order to guarantee their accuracy for the complex geometry of a system like a nuclear reactor.

Hetsroni (1967) proposed four principal parameters for a hydraulic model representing a nuclear reactor prototype, which are geometry, relative roughness, Reynolds number, and Euler number. He concluded that the Euler number should be similar in the prototype and model under preservation of the aspect ratio on the flow path. The effect of the Reynolds number at its higher values on the Euler number is rather small, since the dependency of the form and frictional loss coefficients on the Reynolds number is seen to be small.

ABB-CE has carried out several reactor flow model test programs, mostly for its prototype reactors. In the period of 1978-1980, when internal design of the prototype System 80 reactor was being developed, a series of tests were run using a 3/16 scale reactor model. Eventually, three test runs were completed for the final design [3].

Lee et al [2] performed experimental studies using a 1/5.03 scale reactor flow model of Yong-gwang nuclear units 3 and 4. They showed that the measured data met the acceptance criteria and were suitable for their intended use in terms of performance and safety analyses.

The design of SCOP(test facilities for SMART COre flow and Pressure) was performed on the basis of the conservation of Euler number, which corresponds to the hydraulic resistance based on the similitude of flow geometry. In order to preserve the flow distribution characteristics, SCOP is linearly reduced at a scaling ratio of 1/5. The Euler number has a good similitude between two systems for the sufficiently high Reynolds number of flow conditions. The test conditions adapted a similar velocity scale of the SMART reactor, which yields a 1/20 scaling ratio of Reynolds number when compared with the SMART reactor. The major parameters tested are static pressures, differential pressures at the segmented regions inside the reactor simulator, and the core flow distribution and loop flow rate.

The purposes of the present study are (1) to measure the boundary conditions for an analysis of the reactor's thermal margin, the major parameters of which are the distribution of core outlet pressures and core inlet flow rates, and (2) to measure the segmental and overall pressure losses along the main coolant flow paths in the model in order to verify the analytical hydraulic design method. The scaling method and design features of the SCOP facilities, including instrumentation, are introduced in this paper. Among the test matrixes predefined in the overall test program, the results for the first single test were performed in this study. The measured data will be utilized for the analysis of the SMART reactor's safety and system hydraulic performance.

1. Method for Scaling of SCOP

The primary system of the SMART reactor is composed of four internal circulation pumps, 57 fuel assemblies, eight steam generator cassettes, flow mixing head assemblies, and other internal structures. All the components inside the reactor vessel, which affect the primary side flow characteristics, were considered in the SCOP facility.

The model used to simulate the prototype flow system should be designed based on two types of similitude: geometric and dynamic similarities. Geometric similarity requires that the model and the reactor be the same shape, and that all linear dimensions of the reactor have a constant scale factor. Dynamic similarity between reactor and model is attained when the forces acting on similar volume elements have the same ratio [2]. While all these requirements must be met for strict dynamic similarity, some compromises are necessary in areas where previous experiments indicate that violation of the laws of similitude will not seriously impair the value of the test.

The design was based on the conservation of Euler number, which is a ratio of pressure drop to a dynamic pressure with a sufficiently turbulent region having a high Reynolds number. The Euler number has a low dependency on the Reynolds number when its high value is selected for the operating condition.

	SMART	Scaling Ratio	SCOP
Temperature, ^{o}C	310	-	60
Pressure, MPa	15	-	0.2
Length Ratio	1	l_R	1/5
Height Ratio	1	l_R	1/5
Diameter or Width Ratio	1	l_R	1/5
Area Ratio	1	$\boldsymbol{l_R^2}$	1/25
Volume Ratio	1	$\boldsymbol{l_R^3}$	1/125
Aspect Ratio	1	-	1.0
Velocity Ratio	1	$\boldsymbol{V_R}$	1.0
Mass Flow Ratio	1	$\boldsymbol{\rho_R V_R l_R^2}$	1/17.9
Density, kg/m^3	704	$\boldsymbol{\rho_R}$	983.2
Density Ratio	1	$\boldsymbol{\rho_R}$	1.40
Viscosity, Ns/m^2	8.43e-5	$\boldsymbol{\mu_R}$	4.66e-04
Viscosity Ratio	1	$\boldsymbol{\mu_R}$	5.53
Core Re Ratio	1	$\boldsymbol{\frac{\rho_R V_R D_R}{\mu_R}}$	1/1.12
Ex-Core Re Ratio	1	$\boldsymbol{\frac{\rho_R V_R D_R}{\mu_R}}$	1/19.8
DP Ratio	1	$\boldsymbol{\rho_R V_R^2}$	1.4

Table 1 Summary of Scaling of SCOP

The SMART design is linearly reduced to a 1/5 ratio while the geometrical similitude is conserved. To achieve a sufficiently large Reynolds number of the flow conditions, the test conditions of the SCOP are determined to have a similar velocity of scale as the prototype reactor, which yields a 1/20 Reynolds number scaling ratio. Table 1 shows a summary of the scaling relations adapted in the SCOP facilities with respect to the SMART reactor. The scaling ratio is based on 0.2 MPa and 60^{o}C. The viscosity, as an important property for the Reynolds number, significantly varies at the normal temperature range. For example, viscosity at 60^{o}C has a half value of that at 20^{o}C, which means that the Reynolds number at 60^{o}C is twice as large as at 20^{o}C. Therefore, one can partly control the Reynolds number by merely changing the operating temperature. In the current study, the system temperature was set at 60°C by considering the operationality with various resources applied to the test facilities. The flow geometry inside the core was not preserved since the core hydraulics were restructured using the simplified geometry of the core simulators. The importance of the Reynolds number at the core region is placed on its magnitude at the model. Normally, core flow has a lower Reynolds number than the other region since the hydraulic diameter is very small. Since the core simulator has a large diameter, the Reynolds number at the core region of SCOP is around 10% different from that at SMART reactor. It is remarkable that most of the sections where the flow geometry is conserved have 1/20 the Reynolds number of the flow condition.

2. Design Features of SCOP

The SCOP system is a linearly reduced copy of the SMART reactor, in which the number and configuration of the fuel assemblies, flow mixing head assemblies, and other internal structures were assembled and manufactured with almost the same shape, except for the details of each assembly and steam generator. In order to measure the pump flow accurately, the four reactor coolant pumps were setup outside the reactor simulator, although the reactor circulation pumps are working inside the reactor. The geometry of suction and discharge of the pump are preserved. An overall assembly of the test facility is demonstrated in figure 2. Each of the four external loops has a pump, heater, heat exchanger, and flow meter. Four mechanical seal-type centrifugal pumps with 2.167m^3/min of rated flow capacity, 40m of head, and 30kW of power were setup for the water circulation. The heaters preheat the system water at the start-up operation stage. Their specifications are 3P 440V and 20kWt. To control the system temperature, a heat exchanger is installed at each of the loops. To reduce the pressure drop across the heat exchangers, the primary sides are designed as once-through tube types.

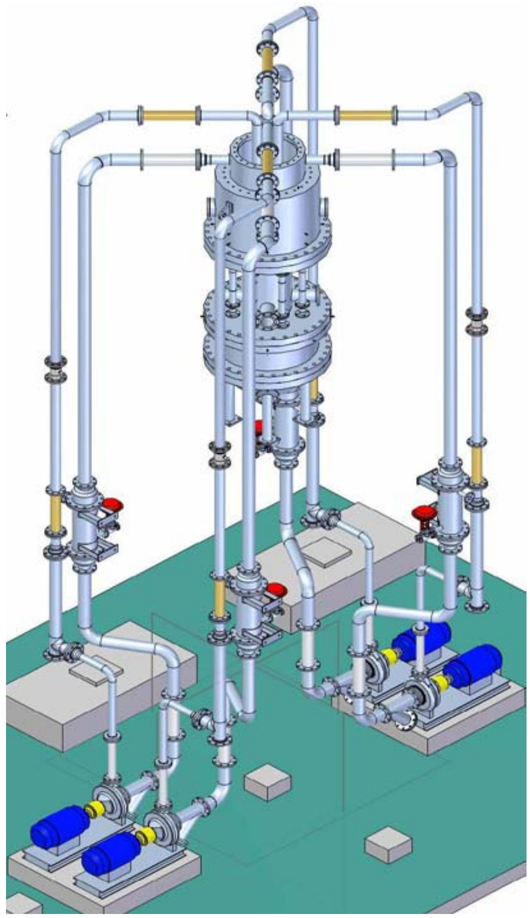

Figure 2 Bird's Eye View of SCOP Test Facility

Figure 3 shows a schematic of the SMART reactor simulator as a test section of the SCOP facility. Since the pump suction of SMART is simulated by an external loop, a discharge flow path was designed at the extruded upper side of the annulus section formed between the UGS (Upper Guide Structure) barrel and core support barrel.

The core region is simulated using the same number of fuel assembly simulators, the design of which is shown in figure 4. Core inlet flow distribution and outlet pressure distribution in order to supply boundary condition to estimate thermal margin of reactor will be simulated by 57 simulators which conserve the pressure drop of the fuel assemblies. The upstream region has a venturi shape to measure the inlet water flow rate. The total pressure drop of the fuel assemblies was adjusted using three orifices installed at the downstream region. Also, for the simulation of a cross flow effect between fuel assemblies, the cross flow holes were designed on both the sides of the fuel assembly simulators. SMART has upper guide structures at the upper side of the core. Some of those are for the control rods, and others are for instrumented rods. The shape, size, and configuration were preserved at the SCOP design. The test section includes hundreds of pressure convey tubes inside, which were drawn out and connected to the pressure transmitters.

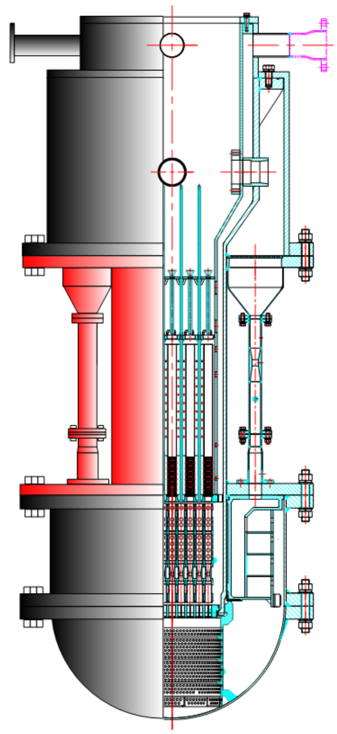

Figure 3 Schematic of SMART Reactor Simulator

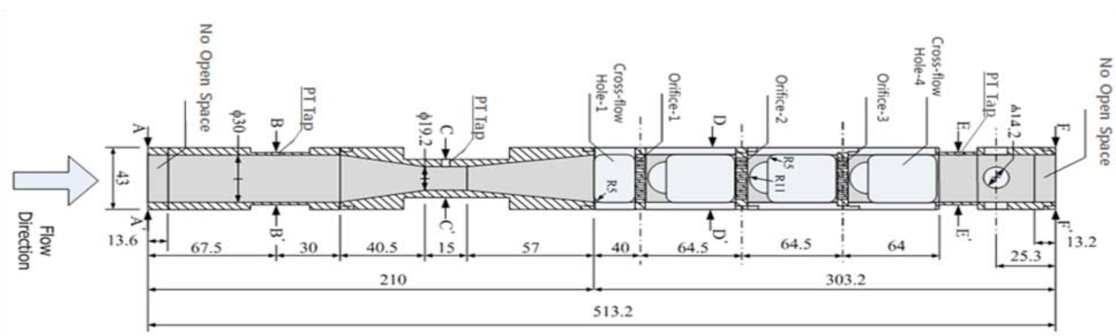

Figure 4 The Fuel Assembly Simulator of SCOP

The eight steam generators, which are supposed to be inside the reactor, are exposed to the outside of the pressure boundary in order to efficiently draw the instrumentation line. The shell type of the SG primary side was simplified into a cylindrical shaped simulator with a pressure drop adjustment and an inner orifice. The tube inside the secondary SG section was neglected in the SCOP facility, since the secondary SG is not a region of interest. The steam generator cassette is simplified as a hydraulic simulator preserving the flow resistance. Based on the venturi type design, the steam generator flow rate can be measured as shown in figure 5. The axial flow resistance was set at the scaled value of SMART by controlling the size of the orifices located at the three different downstream elevations. The flow resistance of fuel assembly simulator and steam generator simulator was controlled using a ring-type orifice. The suitable size of orifice was determined using an accurate calibration process at the CALIP loop, which was specially designed for SMART test facility.

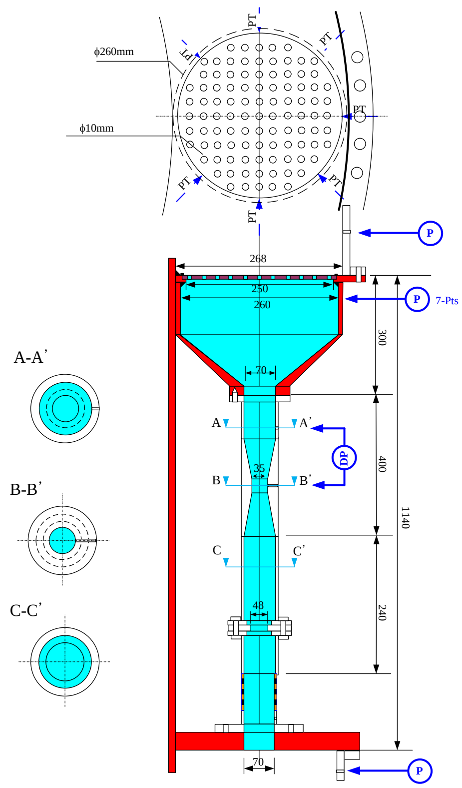

Figure 5 The Steam Generator Simulator

The FMHA (Flow Mixing Header Assembly) was designed to mix the primary coolant from 8 steam generators with the purpose that the primary coolant flows into the core uniform temperature. The FMHA was designed with the same shape as SMART. The FMHA has a size distribution along the azimuthal angle. The SCOP has a corresponding scaled design for the hole size. Figure 6 shows a shape of FMHA. Figure 7 shows hole elevation and development of FMHA.

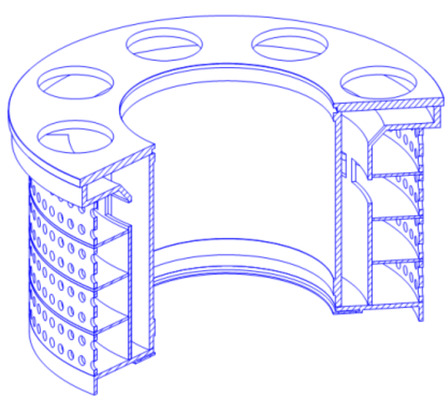

Figure 6 FMHA (Flow Mixing Header Assembly)

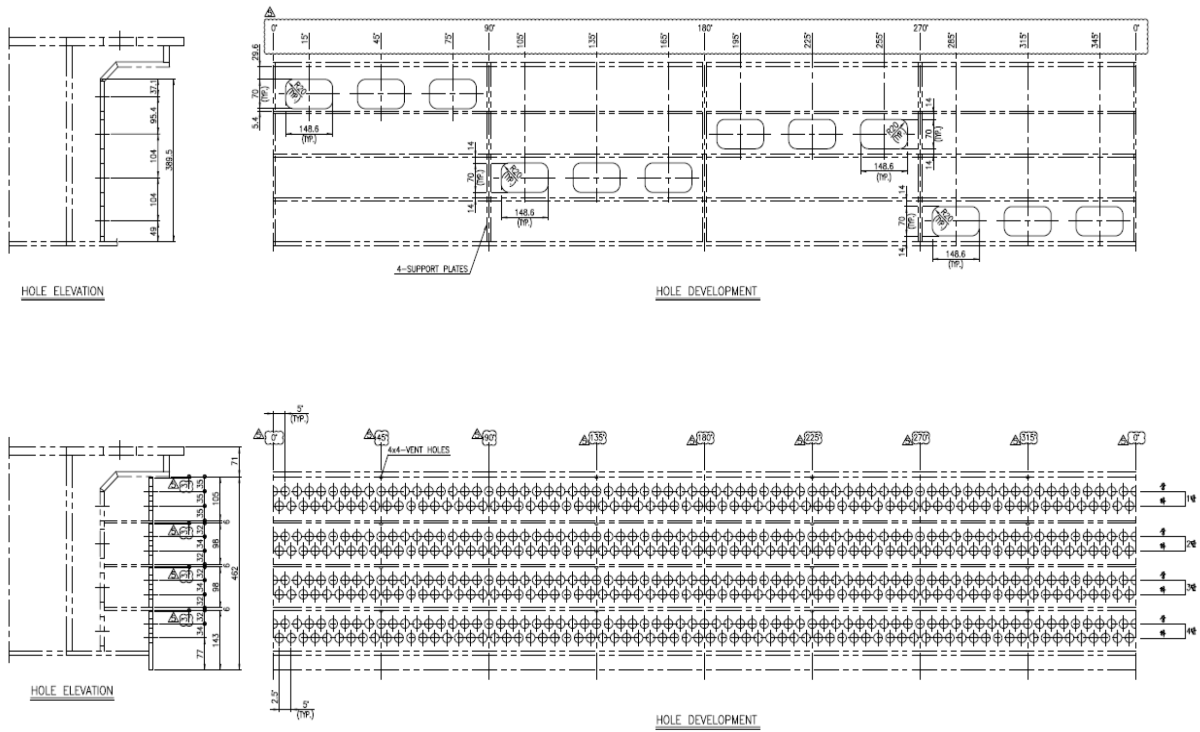

Figure 7 Holes elevation and development of FMHA

3. Control and measurement system of SCOP

Figure 8 shows a control diagram and instrumentation of the SCOP system. Each loop has a vortex flow meter, RTD and pressure tap for the measurement of mass flow rate, temperature, and pressure, respectively.

The temperature is controlled at each loop by controlling the heater power or heat exchanger's secondary flow rate by referring to the temperature measured by the RTD at the downstream of the heater. The flow rate is measured by a vortex flow meter. Since it measures the volumetric flow, the information of pressure and temperature is necessary in order to obtain the mass flow rate. At the discharge point of the flow meter, the pressure and temperature are measured by the PT transmitter and RTD, respectively. The flow rate is controlled through pump rotational speed by the inverter. The system is completely filled with water except for the makeup tank, which is installed at the top of the SCOP facility. The makeup tank has an air injection and a vent line with a flow control valve for each line. The system pressure is controlled by valves connected to the makeup tank.

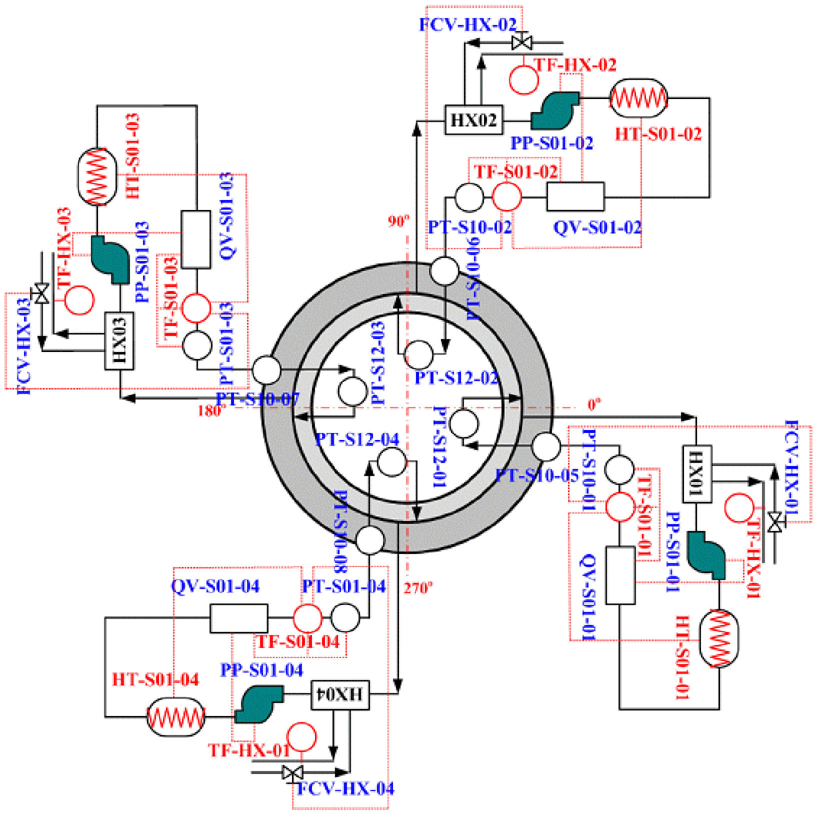

Figure 8 Instrumentation and Control of the SCOP

Figure 9 shows the instrumentation applied to the SCOP test section corresponding to the SMART reactor vessel. The core inlet flow distribution is made up of the flow rates measured at each inlet of the 57 core simulators, which were achieved at the venturi by measuring the differential pressure. The core outlet pressure distribution can be obtained by measuring the differential pressure between the core exit at each core simulator and core shroud, and static pressure at the core shroud. Steam generator flow distribution can be obtained by measuring the differential pressure between the neck and upstream of the venturi. By measuring the differential pressure drops between interesting intervals, the characteristics of the pressure drops could be obtained. Mostly, each sectional region has eight measurement intervals for differential pressure in the azimuth angle in order to check the symmetrical nature of the flow geometry. To get the pressure distribution above the core, differential pressures from the core shroud were measured, which could reduce the uncertainty of the measurements.

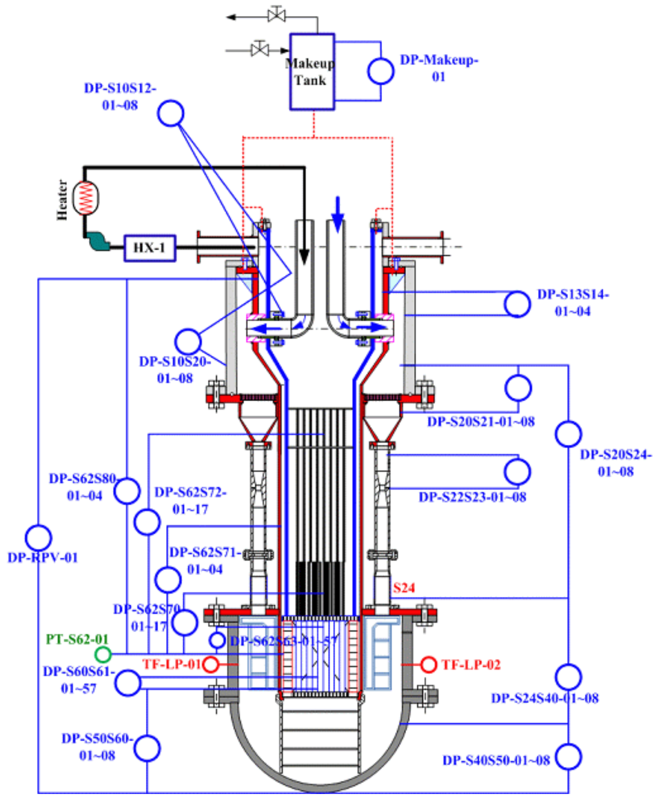

Figure 9 Instrumentation at the Test Section

In total, 13 points of static pressure and 226 points of differential pressure should be measured. The use of hundreds of pressure transmitters can be impractical in the sense of the setting space, setup effort, maintenance, and budget. To measure a huge amount of pressures with a limited number of pressure transmitters, a methodology for the application of distributed instrumentation using solenoid valves was developed. The pressure delivery lines from the same group with similar working intervals 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. By programming the sequential control logic for operating the solenoid valves, several numbers of pressure points could be measured with a sensor.

4. Conclusions

SCOP facility was designed based on the linear scaling law in order to preserve the flow characteristics of the prototype system, which are distributions of flow rate and pressure drop. The reduced scale was selected as a 1/5 of prototype length scale. The nominal flow condition was designed to be similar based on velocity as that of the SMART reactor, which can minimize the flow distortion in the reduced scale of test facility by maintaining high Re number flow. Test facility includes fluid system, control/instrumentation system, data acquisition system, power system, which were designed to meet the requirement for each system. This paper was described the details of the scaling and design features for the facility.

The measurement data using SCOP facility will be used for an analysis of the safety and system hydraulic performance, and also boundary conditions for the thermal margin analysis of SMART reactor.

Reference

[1] Choi S. et al, "SMART Design Description", 00-PL-403-001, KAERI, 2010

[2] Hetsroni G., "Use of Hydraulic Models in Nucleaer Reactor Design", Nucl. Sci. and Eng. Vol. 28, 1967, pp. 1-11

[3] Lee K, Im I, Lee B., and Goo J., "YGN 3&4 Reactor Flow Model Test", Journal of Korean Nuclear Society, Vol.23, 1991, p.340

[4] Lee B.J., Jang H.C., Cheong J.S., Baik S.J., Park Y.S., A Review on the Regionalization Methodology for Core Inlet Flow Distribution Map, Vol. 33, No. 4., 2001, pp. 441~456

[5] H. Bae, D.J. Euh, B.S. Shin, Y.J. Ko and T.S. Kwon, "Design Concept of a 1/5-Scale Core Simulator", Transactions of the Korean Nuclear Society Spring Meeting, 2010

[6] H. Bae, D.J. Euh, B.S. Shin, Y.J. Ko and T.S. Kwon, "Design Concept of a 1/5-ScaleSteam Generator Simulator", Transactions of the Korean Nuclear Society Spring Meeting, 2010

[7] Kim Y.I, Kim S.H., Jung Y.J., Lee W.J., "Reactor Flow Distribution (Model) Test Requirements for SMART", 100-TH454-007, KAERI, 2010

[8] D.J. Euh, Y. J, Youn, H. Bae, I. C. Chu , Y.J. Ko and T.S. Kwon, "Design Development of SCOP facilities for Core Flow and Pressure Distribution of SMART Reactor", Transactions of the Korean Nuclear Society Autumn Meeting, 2010

[9] Euh,D.J., Youn Y.J., Chu I.C., Lee J.W., Park J.C., Kim J.T., Ko Y.J., Bae H., Cho Y.I., Shin Y.C., Park C.K., Kwon T.S., Lee S.J., "Test Facility for SMART Reactor Flow Distribution", KAERI/TR-4239/2010, KAERI, 2010

[10] Youn Y.J., Euh,D.J., Chu I.C., Kwon T.S., "Performance Test of Solenoid Valves for Multi-Points Pressure Measurement", Transactions of the Korean Nuclear Society Autumn Meeting, 2010

[11] Youn Y.J., Ko Y.J., Chu I.C., Euh,D.J., "Performance Evaluation of Fuel Assembly Simulator for SMART" Transactions of the Korean Nuclear Society Autumn Meeting, 2010