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# HYDRAULIC CHARACTERISTICS OF SMART REACTOR FOR A NOMINAL CONDITION

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## ABSTRACT

SMART (**S**ystem-integrated **M**odular **A**dvanced **R**eac**T**or) is an integral-type reactor being developed, which has major components including core, pumps, steam generators and a pressurizer inside the reactor vessel. In order to analyze the various safety features of the reactor, the quantification for the flow and pressure distributions are very important. A test facility, named "SCOP", was designed based on the conservation of Euler number which is a ratio of pressure drop to dynamic pressure with a sufficiently high Reynolds number. In order to preserve the flow distribution characteristics, the SCOP is linearly reduced with a scaling ratio of 1/5. For the present work, a total of 9 tests were performed for a nominal SMART flow condition. By using the test results, a statistical final flow distribution for the SMART reactor were presented. The current data could be applied for the validation of a CFD analysis method as well as reactor safety and system performance analyses.

## INTRODUCTION

The design of a SMART reactor, which is a next-generation integral type reactor with enhanced safety, has been being developed [1]. The SMART can be an energy source for electricity generation, seawater desalination, district heating, etc. A single unit of SMART can provide 90 MWe of electricity and 40,000 tons of fresh water a day, which is enough for a city with a population of 100,000. By eliminating large primary system pipes and penetrations, SMART is free from the possibility of "Large Break Loss of Coolant Accident"(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 a schematic drawing of the SMART reactor.

The performance and safety of the system can be demonstrated based on thermal hydraulic information of the reactor systen. The core thermal margin can be evaluated based on core boundary conditions, which are 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 the information of pressure loss along the flow path in the primary system.

Since the SMART design features are significantly different from conventional pressurized water reactors, it is expected to have unique flow and pressure distribution. The development of new and/or conventional nuclear system design should be strongly based on the reduced uncertainties in hydraulic characteristics. The hydraulic characteristics of a reactor system can be evaluated by using mathematical models, or an experimental apparatus with a adaptation of a proper scaling theory. Although mathematical tools have been developed for the complex geometry of systems like nuclear reactors, over the past several decades, they still need to be improved to verify their accuracy.

The author of reference [2] proposed four principal parameters for a hydraulic model representing hydraulics of prototype nuclear reactor, 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 the preservation of the aspect ratio on the flow path. The effect of the Reynolds number at a sufficient turbulent region on the Euler number is rather small, since the dependency of the form and frictional loss coefficients on the Reynolds number is considered to be small.

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

Lee et al (1991) 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. [4]

To simulate the hydraulic performance of SMART, a test facility, named SCOP (test facilities for SMART COre flow and Pressure), has been established. Since the present study focuses on the hydraulic features of the reactor, the operating conditions were set to low pressure and temperature. The design was performed on the basis of the conservation of the 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 adopted a similar velocity scale for 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. [5][6]

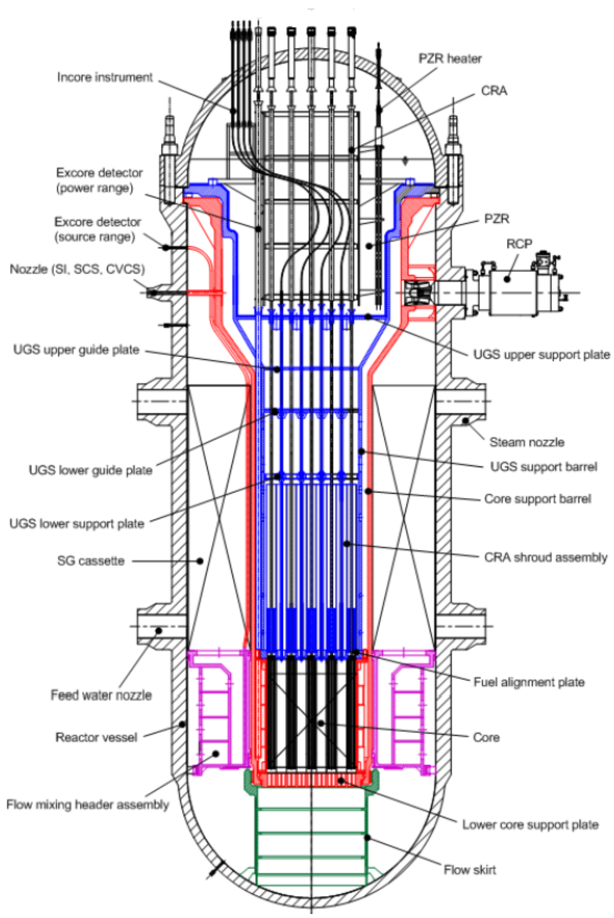


**Figure 1** Schematic Drawing of SMART Reactor

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 distributions of core outlet pressures and core inlet flow rates, respectively, and (2) to measure the segmental and overall pressure losses along the main coolant flow paths in the model in order to analyze the steady and transient behaviors of the reactor and verify the analytical hydraulic design method. The scaling method and design features of the SCOP facilities, including instrumentation, are introduced in this paper. This paper includes statistical results of a total of 9 tests for the nominal flow conditions of SMART reactor. The statisitical process was performed in order to characterize the hydraulic characteristics of the reactor.

## TEST FACILITY (SCOP)

To preserve the flow characteristics of SMART reactor, the test facility, named SCOP, was designed based on the Euler number conservation. The Euler number is a ratio of pressure drop to the dynamic force, which can be considered as a pressure drop coefficient. Two types of similarities were important: geometric and dynamic similarities. Geometric similarity requires that all linear dimensions of reactor and the model are scaled by a constrant. . Dynamic similarity between reactor and model is attained when the forces acting on similar volume elements have the same ratio (Lee et al., 1991). 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.

Table 1 summarises the scaling ratio of major design parameters applied to the SCOP facilities.

The SMART design is linearly scaled to a 1/5 ratio while the geometrical simility is conserved. To achieve a sufficiently large Renolds number of the flow conditions, the test conditions of the SCOP are determined to have a velocity of scale as the prototype reactor, which yields a Reynolds number scaling ratio of 1/20. Table 1 also 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 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 regions 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 noted that most of the sections where the flow geometry is conserved have 1/20 ratio of the Reynolds number of prototype system.

The SCOP system is a linearly scaled 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. To measure the pump flow efficiently, the four reactor coolant pumps were setup outside the reactor simulator, which is different from the SMART design where the reactor circulation pumps are working inside the reactor. Neverthelss, the geomery of suction and discharge of the pump are preserved. An overall assembly of the test facility is demonstrated in Fig. 2.

**Table 1** Summary of Scaling of SCOP

| | SMART | Scaling Ratio | SCOP |
|---|---|---|---|
| Temperature, °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 | $l_R^2$ | 1/25 |
| Volume Ratio, - | 1 | $l_R^3$ | 1/125 |
| Aspect Ratio, - | 1 | - | 1.0 |
| Velocity Ratio, - | 1 | $V_R$ | 1.0 |
| Mass Flow Ratio, - | 1 | $\rho_R V_R l_R^2$ | 1/17.9 |
| Density, kg/m$^3$ | 704 | $\rho_R$ | 983.2 |
| Density Ratio | 1 | $\rho_R$ | 1.40 |
| Viscosity, Ns/m$^2$ | 8.43e-5 | $\mu_R$ | 4.66e-04 |
| Viscosity Ratio, - | 1 | $\mu_R$ | 5.53 |
| Core Re Ratio, - | 1 | $\frac{\rho_R V_R D_R}{\mu_R}$ | 1/1.12 |
| Ex-Core Re Ratio, - | 1 | $\frac{\rho_R V_R D_R}{\mu_R}$ | 1/19.8 |
| DP Ratio, - | 1 | $\rho_R V_R^2$ | 1.4 |

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 20kW. 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.

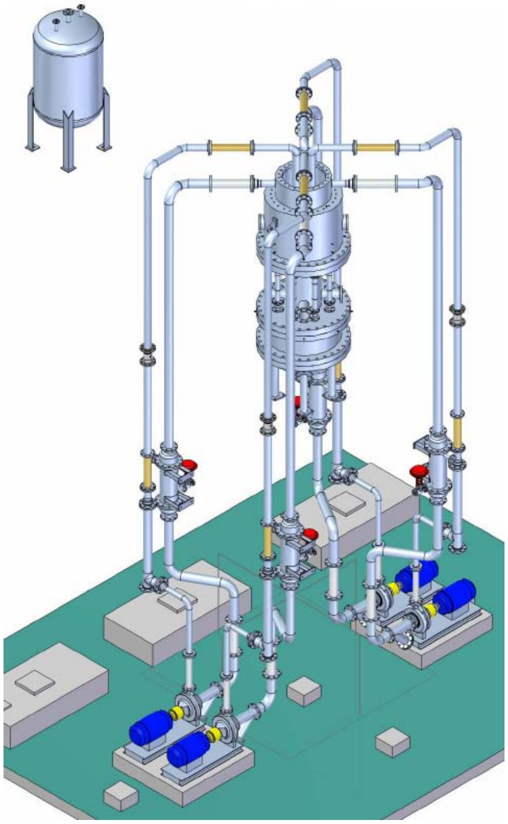

**Figure 2.** Isometric Drawing of SCOP Test Facilities.

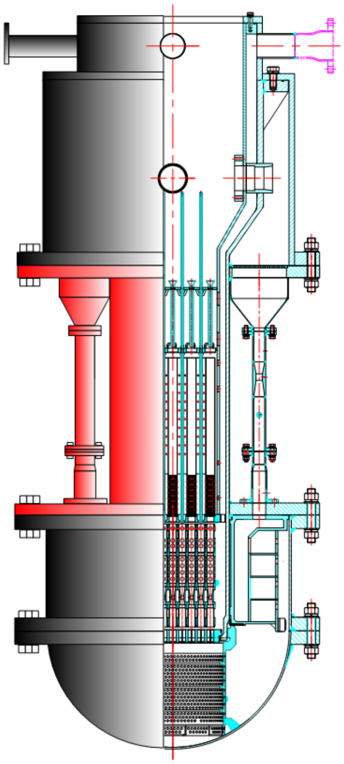

**Figure 3** Schematic Representaton of SMART Reactor Simulator

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 Upper Guide Structure(UGS) barrel and core support barrel. The eight steam generators, which are supposed to be inside the reactor, are exposed to the outside of the reactor vessel 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 facilities, since the secondary SG is not a region of interest. The steam generator cassette is simplified as a hydraulic simulator preserving the flow resistence. Based on the venturi type design, the steam generator flow rate can be measured. The flow resistance was controlled using a ring-type orifice of which the suitable size was determined using an accurate calibration process at the separate loop. The Flow Mixing Header Assembly (FMHA) was designed with the same shape as SMART. The FMHA has a lot of holes having a size distribution along the azimuth angle. The SCOP has a corresponding scaled design for the hole sizes. The core region has 57 fuel assembly simulators, of which the upstream region has a venturi shape to measure the inlet water flow rate. The axial flow resistence was set at the scaled value of SMART by controlling the size of the orifices located at the three different downsteam elevations. 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 delivery tubes inside, which were drawn out and connected to the pressure transmitters.

Figure 4 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 downstream of the heater. The flow rate is measured by a vortex flow meter. The measured volumetric flow, pressure and temperature are used to calculate a 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 by controlling pump rotational speed using an inverter. The system is completely filled with water except for the makeup tank, which is installed at the top of the SCOP facilities. 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 5 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 flow resistence of each core simulator was precisely calibrated in advance of the test facility assembly. 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. A table of the flow coefficients for various flow rates was prepared at the CALIP loop. By measuring the differential pressure drops between interesting intervals, the characteristics of the pressure drops could be obtained. 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.

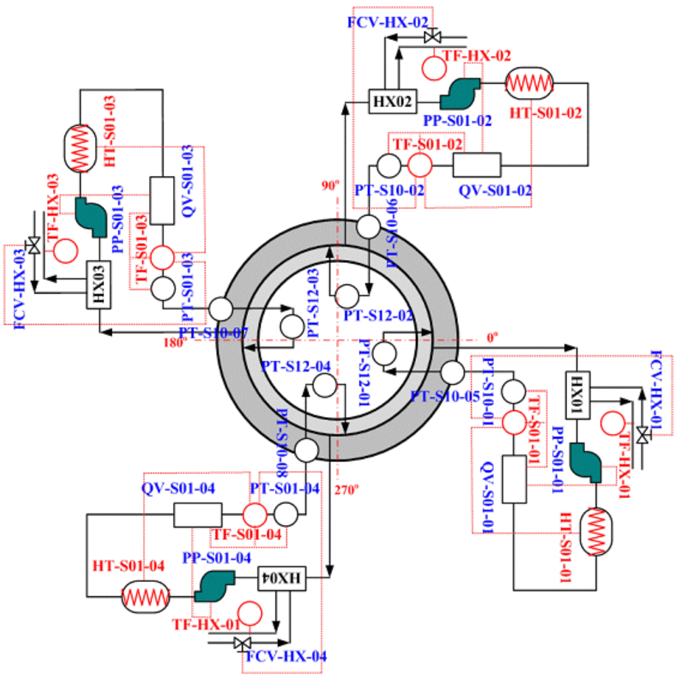


**Figure 4** Instrumentation and Control of the SCOP

In total, 13 points of static pressure and 226 points of differential pressures are measured. The use of hundreds of pressure transmitters can be impractical when considering the space, setup effort, maintenance, and budget. A methodology for the application of distributed instrumentation using solenoid valves was developed to measure a large amount of pressurs with a limited number of pressure transmitters. 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 can be measured with a single sensor.

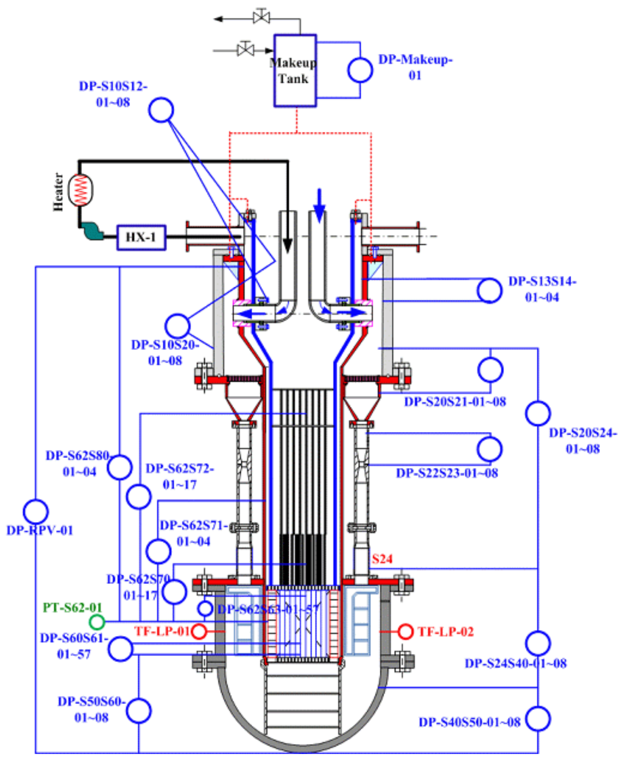


**Figure 5** Instrumentation at the Test Section

## RESULTS

**Table 2** Test Condition

| Parameter | Values | S.D.(%) | Comment |
|---|---|---|---|
| Pressure, kPa | 200.8 | 0.8 | Core Shroud |
| Temperature, °C | 59.9 | 0.18 | At Lower Downcomer |
| Loop-01, % | 100 | | |
| Loop-02, % | 100 | | |
| Loop-03, % | 100 | | |
| Loop-04, % | 100 | | |

The SCOP program has 9 steady state flow conditions in order to get the nominal flow characteristics of SMART reactor. The major flow parameters which are ensembly averaged for all test matrixes were list at Table 2. Although the absolute values are not critical to the distribution, the tests were very accurately controlled to get the almost same thermal hydraulic conditions. Even the pressure is controlled within 1% standard deviation. The flow is less than 0.001% of fluctuation of averaged values.

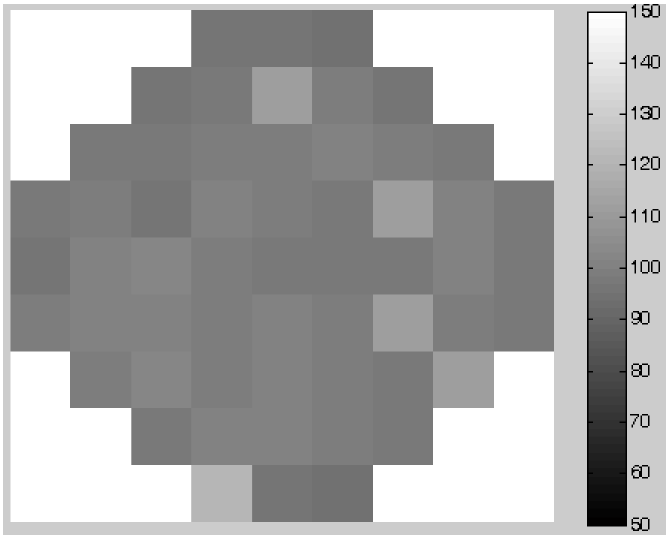


**Figure 6** Ensemble Average of Normalized Core Inlet Flow (%)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 0.038 | 0.019 | 0.041 | | | |
| | | 0.023 | 0.011 | 0.018 | 0.018 | 0.019 | | |
| | 0.080 | 0.016 | 0.018 | 0.020 | 0.018 | 0.053 | 0.033 | |
| 0.023 | 0.018 | 0.009 | 0.023 | 0.029 | 0.027 | 0.008 | 0.015 | 0.020 |
| 0.021 | 0.022 | 0.023 | 0.032 | 0.024 | 0.023 | 0.042 | 0.036 | 0.029 |
| 0.023 | 0.024 | 0.021 | 0.017 | 0.015 | 0.037 | 0.019 | 0.038 | 0.050 |
| | 0.024 | 0.017 | 0.017 | 0.048 | 0.023 | 0.030 | 0.032 | |
| | | 0.032 | 0.022 | 0.027 | 0.017 | 0.036 | | |
| | | | 0.051 | 0.019 | 0.025 | | | |

**Figure 7** Standary Deviation of Ensenble Averaged Core Inlet Flow (%)

Figure 6 shows the ensembled average of core inlet flow distribution, the distribution covers 95.0% to 121% of the average fuel assembly flow rate. The core flow distribution is an important boundary condition. An even flow distribution is more desirable for the possibility of DNB (Departure of Nucleate Boiling) occurrence. In other words, if the normalized flow rate at the minimum flow channel is higher, the system has a large thermal margin. Although more than 10% larger flow rates were measured at the five fuel assemblies, no particularly lower flow channels were detected. The 95.2% of minimum channel flow is a relatively higher value when compared with previous work performed on conventional pressurized water reactors. Figure 7 shows the standary deviation of the flow distribution. Maximum deviation was 0.08%.

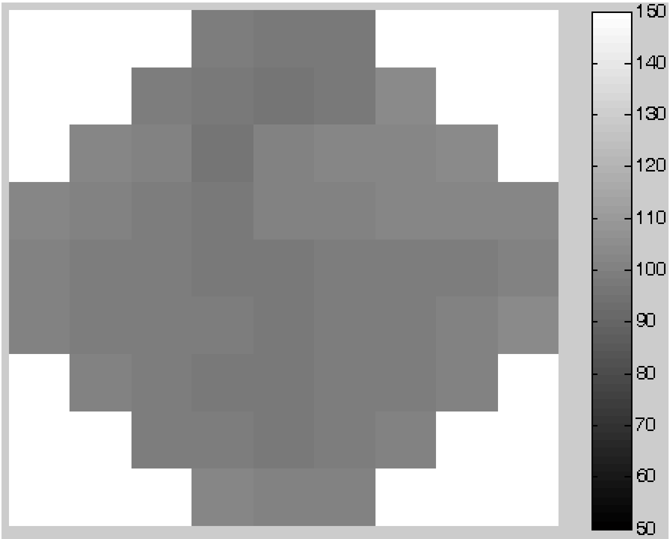


**Figure 8** Ensemble Average of Core Outlet Pressure Distribution Referred to the Core-DP (%)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 0.031 | 0.022 | 0.008 | | | |
| | | 0.039 | 0.035 | 0.027 | 0.028 | 0.027 | | |
| | 0.036 | 0.038 | 0.036 | 0.029 | 0.025 | 0.023 | 0.027 | |
| 0.033 | 0.039 | 0.040 | 0.043 | 0.048 | 0.025 | 0.017 | 0.035 | 0.032 |
| 0.030 | 0.021 | 0.052 | 0.033 | 0.048 | 0.049 | 0.049 | 0.018 | 0.019 |
| 0.029 | 0.050 | 0.029 | 0.029 | 0.029 | 0.031 | 0.027 | 0.015 | 0.046 |
| | 0.022 | 0.033 | 0.017 | 0.018 | 0.037 | 0.041 | 0.023 | |
| | | 0.054 | 0.036 | 0.052 | 0.030 | 0.030 | | |
| | | | 0.047 | 0.031 | 0.075 | | | |

**Figure 9** Standard Deviation of Ensemble Average of Core Outlet Pressure Distribution Referred to the Core-DP (%)

Another important boundary condition for the analysis of thermal margin is the core exit pressure distribution. Figure 8 shows the distribution of the pressure drop between the core exit and core shroud. The values in the figure have the definition of equation (1).

$$E_{out,i} = 1 - \frac{\Delta P_{out,i} - \Delta P_{out,ovg}}{\Delta P_{referencce}} \quad (1)$$

where

$E_{out,i}$ dimensionless pressure distribution,
$\Delta P_{out,i}$ the pressure difference between the core shroud and exit of fuel assembly I,
$\Delta P_{out,avg}$ the average of $\Delta P_{out,i}$
$\Delta P_{reference}$ the average pressure drop of the core simulator.

The normalized pressure drop has a range of 96.4% to 104.3%, which shows a fairly even distribution. Maximum deviation of the pressure distribution was also 0.08%.

## CONCLUSION

In order to identify the flow and pressure distribution of the SMART reactor, a 1/5 linearly reduced scale of the test facility, SCOP, was designed. The overall design features including scaling, assembling, component design, and instrumentation were described in the current paper. In order to get the flow distribution representing the nominal flow condition of SMART reactor, 9 cases on the same flow condition for each case were performed. The test results were analyzed with a proper statistical process.

The results show that the data set shows good consistency at the measurement of the mass flow rate and pressure drops. The inlet flow distribution showed a high minimum channel flow when compared with previous work performed for OPR1000 or APR1400. The core exit pressure was found to have a fairly even distribution.

The data will be utilized for an analysis of the safety and system hydraulic performance of the SMART reactor.

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