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Preliminary Scale-down Standard Fuel Block Tests to Validate CORONA Code

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) has developed CORONA (Core Reliable Optimization and thermo-fluid Network Analysis) code for core thermo-fluid analysis of prismatic High Temperature Gas-cooled Reactor (HTGR) [1]. The CORONA code is aimed to the whole-core thermo-fluid analysis of a prismatic HTGR with fast computation and reasonable accuracy. The key idea for the fast computation is to solve three-dimensional conduction equation combined with one-dimensional fluid flow network equations.

The active core of the prismatic gas-cooled reactor consists of the vertically-stacked hexagonal graphite blocks. The gaps between the graphite blocks result in the bypass and the cross flow between core gaps and coolant channels. The bypass and the cross flows are the important factors to estimate the thermal margin in the core thermo-fluid design of the prismatic gas-cooled reactor.

The code validation experiments for the prismatic HTGR core are categorized into the isothermal test for the computational fluid dynamics validation [2, 3], the isothermal test for the loss coefficient of the cross gap [4, 5, 6], the isothermal test to validate the fluid models of the design analysis code [7, 8], and the thermal test to validate the heat transfer models of the design analysis code [9]. Inagaki et al. [9] performed thermo-fluid tests on the core of the high temperature using the helium engineering demonstration loop (HENDEL) at the reactor operating condition, but the data cannot be used for CORONA validation because of the annulus channel with the heated rod.

KAERI prepared the heated tests for scale-down standard fuel block test using a high pressure Helium Experimental LooP (HELP) to validate the CORONA code [10]. This paper presents the experimental setup, and the comparison with isothermal test results and CORONA analysis results. The test results include the outlet flow velocity of each coolant hole, the bypass flow fraction at the outlet, and the pressure drop.

2. Methods and Results

2.1 Experimental Setup

Scale-down standard fuel block was designed on Cho et al.[11]'s preliminary core thermo-fluid design for 350MWth VHTR. The test section was installed at a Helium Experimental LooP (HELP) at KAERI. The reference test condition was selected to maintain the Re similarity of the coolant channels and the bypass gaps. The test section has 7 coolant holes and 12 fuel holes as shown in Fig. 1. The number of the coolant channels was selected with considering HELP circulator design specification. The diameters are of the central coolant hole and the peripheral coolant holes are 12.7 mm and 15.9 mm, respectively.

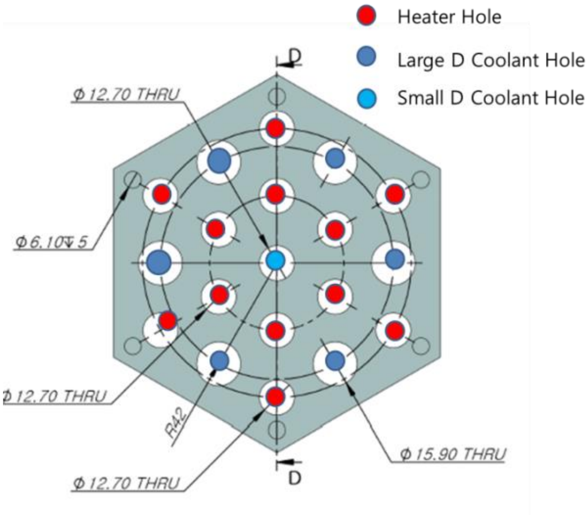

Fig. 1. Crossectional View of Scale-down Standard Fuel Block

Fig. 2 shows the vertical-direction schematic diagram. The heated block with 800 mm height was stacked on two stages. A 200mm-height unheated block at the inlet is installed to minimize the axial-direction heat loss of the heated block and obtain the fully-developed velocity distribution in the coolant holes. A 600mm-height unheated block at the outlet is installed to obtain the thermal mixing length at the helium outlet flow. The total height of the test section is 2400mm. The height of the unit block is 100 mm, which is the maximum machining height of Al_2O_3. The average pitch of the hexagonal block is 72.29mm. The standard deviation of the pitch is ±0.436%. The average bypass gap size is 2.64 mm. The standard deviation of 24 bypass gap sizes was ±2.71%. The deviation of the gap size resulted from the surface polishing process. The blocks can be categorized into the temperature-measurement block, the interface block for the cross gap and the basic block. The internal insulator at the vessel was installed to minimize the heat loss at the test condition.

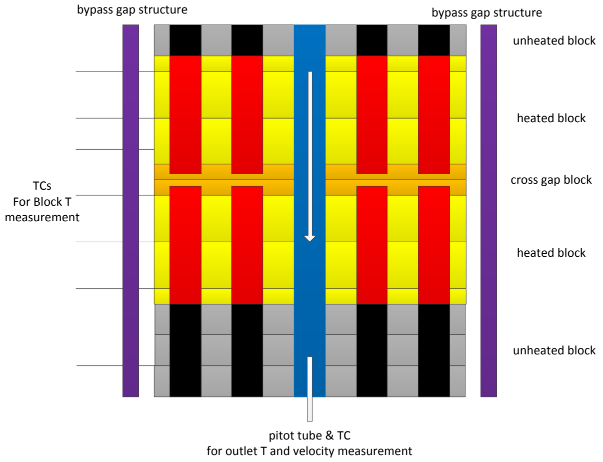

Fig. 2. Vertically Directional Schematic Diagram of Test Section

24 heated rods in the test section are divided into four groups of six, each of which is controlled by a AC transformer. 6 heaters are parallel-connected in three phases. The bypass flow rate can be calculated based on the difference between the total mass flow rate measured by the coriolis mass flow meter at the test section inlet and the sum of the flow rates measured by the pitot tubes at the coolant channel outlets. The test parameters are the bypass gap (0, 2.64 mm), the flow velocity (3.6 kg/min~6.0 kg/min), the power distribution, the double coolant holes blockage, and the cross gap (0, 2mm). The diameter of the inlet and outlet pipe is 3 inch, so the flow area of the pipe is larger than the total flow area of the fuel block. The differential pressure between the inlet and the outlet of the bypass gap is measured to estimate the friction factor for the CORONA analysis. Each thermocouple attached to the pitot tubes are used to measure the outlet temperature of each coolant hole. Figure 3 shows the picture of the installed pitot tubes, fuel block, gap structure, heating rods in the vessel of the test section.

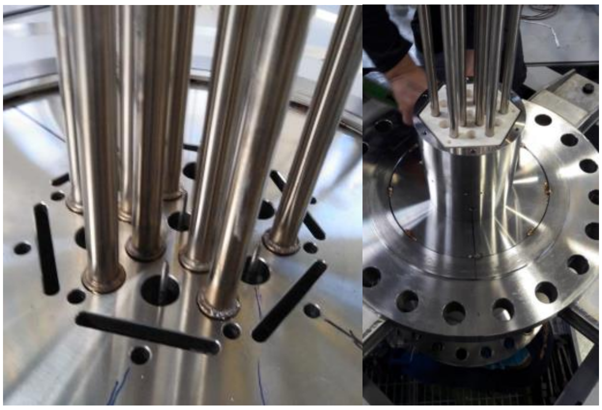

Fig. 3 Pitot Tubes at the Outlet, Fuel Block, Bypass Gap Structure, Heating Rods

2.2 Test Results

Figure 3 shows the bypass flow fractions from CORONA analysis and the isothermal tests. CORONA showed the good predictability of the bypass flow fraction except for the low Reynolds number case. It means that the Reynolds number of the bypass gap is not enough large to use the friction factor correlation for the turbulent flow in the case of 3.4 kg/min. The non-uniform axial bypass gap distribution makes that CORONA with uniform gap distribution over-predicts the bypass fraction at the experimental conditions.

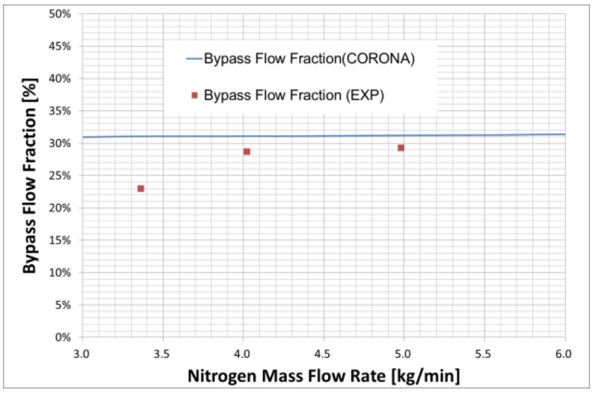

Fig. 3. Bypass Flow Fraction from CORONA Analysis and Tests

Figure 4 shows the measured flow rates of the each channel from the isothermal test and the calculated flow rates of the central and the peripheral channels from CORONA. The uncertainty of the differential pressure at pitot tubes was ±1%. The peripheral flow rates could be calculated from the differential pressure of the pitot tube. The standard deviation of the calculated peripheral flow rates was ±1.46 %. The deviation is enough small to assume the uniform mass flow rate distribution of the peripheral channels. As in Figure 3, Figure 4 shows that CORONA can predict the flow rates of each channel except for the case of 3.4 kg/min.

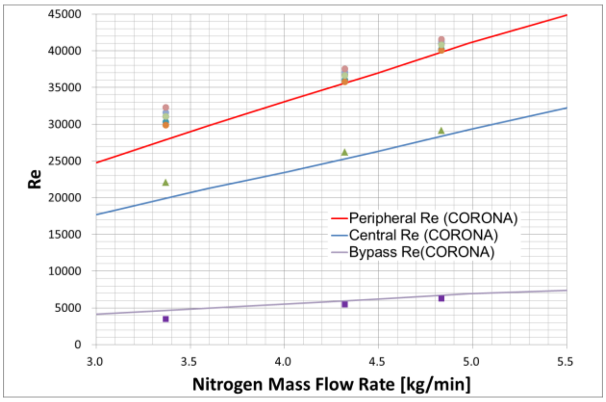

Fig. 4. Re of Channels & Bypass Gap from CORONA and Tests

Since Figures 3 and 4 show that CORONA can simulate the large mass flow rate condition, the measured pressure drop in the test section was compared with the calculated pressure drop from CORONA at the case of 5.7 kg/min. The measured pressure drop of the test section was 1.02 kPa, and the calculated pressure drop from CORONA was 0.78 kPa. The measured pressure drop and the calculated pressure drop didn't include the gravity head from the height difference and the pressure loss in the inlet and outlet pipe, respectively. If the gravity head and the pressure losses in the plenums are considered to compare the measured and calculated pressure drops as the following equation, it becomes close to the measured pressure drop of the test section.

$$\Delta p_{exp} = \Delta p_{code} + \rho g h + \frac{1.5 \rho u_{pipe}^2}{2} \tag{1}$$

Table I shows the outlet temperatures of each channel from test results and CORONA analysis. Standard deviation of peripheral outlet temperatures is ±1.3~2.6℃. With considering the uncertainty of the thermocouple, the difference among the measured peripheral outlet temperatures is negligible. The calculated outlet temperature by CORONA is slightly higher than the measured outlet temperatures. If the differences between CORONA analysis and test result from the heat loss, the heat losses of the central and the peripheral flow were 3.1~4.3% and 5.2~6.8%, respectively. After the shakedown test, the external insulator was installed on the pressurized vessel to minimize the heat loss during the test. Additionally, the bended pipe heater was added on the outlet plenum to shorten the test time.

Table I: Outlet Temperatures from Heated Tests

Inlet P&T	6.0bar /31.7℃		6.2/32.8	
Flowrate	5.9 kg/min		5.8 kg/min	
Heated Power	6.69 kW		12.2kW	
Outlet T[℃]	Test	Analysis	Test	Analysis
Central Ch.	97.7	100.6	151.4	155.2
Peripheral Ch.	88.7 (±1.3)	92.3	133.6 (±2.6)	140.0

3. Conclusions

The shakedown test results showed that there is no problem to perform the code validation tests. Especially, isothermal test results show that CORONA shows the good predictability to simulate test results at the large Reynolds number at bypass gap. The friction factor should be improved to simulate test results at the low Reynolds number at bypass gap. Test parameters are the bypass gap (0, 2.64 mm), the flow velocity (3.4 kg/min ~6.0 kg/min), the power distribution, the double coolant holes blockage, and the cross gap (0, 2mm). In the future, these experiments will produce the following CORONA code validation data.

- outlet flow velocity and temperature of each coolant hole
- fuel block temperature distribution
- bypass flow fraction at the outlet
- pressure distribution of the bypass gap
- heater rod temperature

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