Design of Scale-down Standard Fuel Block Test Section to Validate Core Thermo-fluid Analysis Code for Prismatic Gas-Cooled Reactor

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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 thermo-fluid analysis of prismatic High Temperature Gas-cooled Reactor (HTGR) core [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 hexagonal graphite blocks stacks stacked vertically in the core. 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 flow are the important factor to estimate the thermal margin in the core thermo-fluid design of the prismatic gas-cooled reactor.

Most of the code validation data for the prismatic HTGR core are the iso-thermal test results [2-6] using the room temperature air. Inagaki et al. [7] 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 type with the heated rod.

This paper presents the experimental design for the CORONA and the pre-test analysis for the design.

2. Design of Scale-down Standard Fuel Block

Scale-down standard fuel block was designed based on Cho et al.'s [8] preliminary core thermo-fluid design for 350MWth VHTR. Table 1 shows the CORONA analysis results on the hot spot standard fuel block for 350MWth VHTR.

Table 1 CORONA analysis results on the hot spot standard fuel block for 350MWth VHTR

Design Parameter	Calculation Results
Column Power	6.193 MW
Maximum Block Power	788.9 kW
Column Flow Rate	117.24 kg/min
Hot Spot Channel Flow Rate	1.098 kg/min
Bypass Flow Rate	5.694 kg/min
Coolant Hole Re (Large Channel)	27,100 ~ 39,600
Bypass Gap Re	3,010 ~ 4,250
Fission Power per Fuel Hole	3.76 kW (210 holes)

The test section was installed at a Helium Experimental LooP (HELP) [9] at KAERI. The reference test condition was selected to maintain the Re similarity of the coolant channels and the bypass gaps. Fig. 1 shows the cross-sectional view of the test section. The test section has 7 coolant holes and 12 fuel holes. The number of the coolant channels was selected with considering the HELP circulator design specification. The diameter of the electrical heater rod is 12.6 mm, same as that of the fuel compact in Cho et al.'s preliminary design. The diameters of the central coolant hole and the peripheral coolant holes are 12.7 mm and 15.9 mm, respectively. The pitch of the hexagonal block is 74 mm, the minimum size required for CORONA analysis. The material of the fuel block is Al_2O_3 to simulate the low thermal conductivity of the irradiated graphite. The bypass gap structure was made of stainless steel 304 because the gap size deformation is minimized at the heated condition.

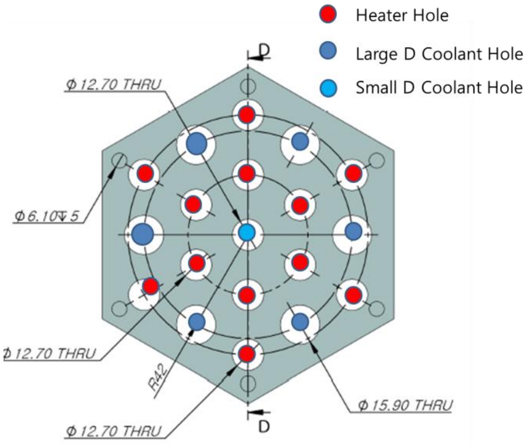

Fig. 1 Cross-sectional view of scale-down standard fuel block

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 blocks can be categorized into the temperature-measurement block, the interface block for the cross gap and the basic block. 7 pitot tubes with K-type thermocouple are installed at of the outlets of 7 coolant holes to measure the gas flow velocity and temperature at the outlets.

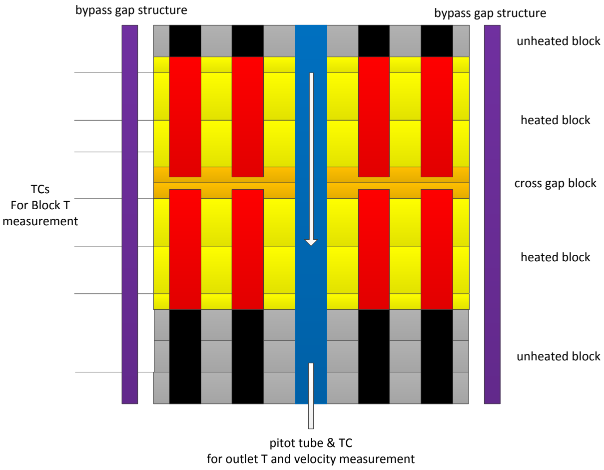

Fig. 2 Vertically directional schematic diagram of test section

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 size (0, 2, 4 mm), the flow velocity (3.6 kg/min ~6.0 kg/min), the power distribution, the double coolant holes blockage, and the cross gap. The diameter of the inlet and outlet pipe is 3inch, 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. Fig. 3 shows the picture of the installed fuel block, gap structure, heating rods in the vessel of the test section.

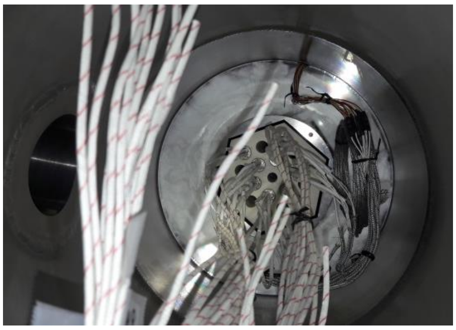

Fig. 3 Fuel block, bypass gap structure, and heater rods at the inlet of the test section

3. Pre-test Analysis

The thermal mixing at the outlet was simulated with ANSYS FLUENT. The gas flow temperature measurement at the outlet of the coolant hole is necessary to validate the CORONA model. It is impossible to measure the outlet temperature of the coolant hole without the unheated channel due to the large gas temperature gradient at the heated channel. Fig. 4 shows the inlet a schematic of the calculation domain and mesh profiles. The selected turbulence model was standard k-ε model with the standard wall function, because the Reynolds number is larger than 25,000. The inlet mass flow rate was 0.64284 kg/min (inlet Re=43,100), and the heat flux on the heated rod was 75.6 kW/m^2 (inlet & outlet T = 300 & 466 K).

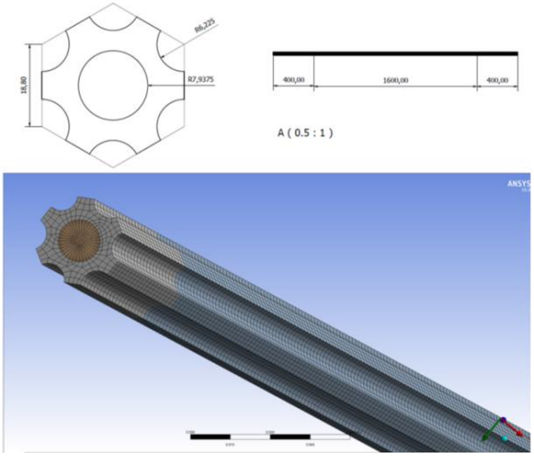

Fig. 4 A Schematic of Calculation Domain & Mesh Profiles

Figure 5 shows the thermal mixing at the outlet of the radial temperature distributions. The large temperature gradient gradually decreases as it passes through the unheated flow channel. The unheated channel with 600 mm at the outlet is long enough to flatten the gas temperature distribution at the outlet of the coolant hole.

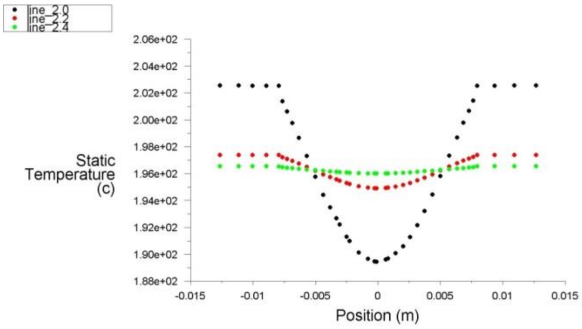

Fig. 5 Radial temperature distribution at the unheated channel

The pre-test analysis using CORONA was performed to maintain the similarity of Reynolds numbers in the coolant holes and the bypass gaps. Fig. 6 shows the input model for this pre-test analysis. The model has a scale-down standard fuel block and a bypass gap structures. A scale-down standard fuel block consists of 12 Fuel/BP basic unit cells, 6 standard coolant channel basic unit cells, 1 small coolant channel basic unit cell, 12 edge basic unit cells, and 6 corner basic unit cells. A bypass gap structure consists of 3 pentagonal special unit cells. The geometrical size is the same as the design of the test section.

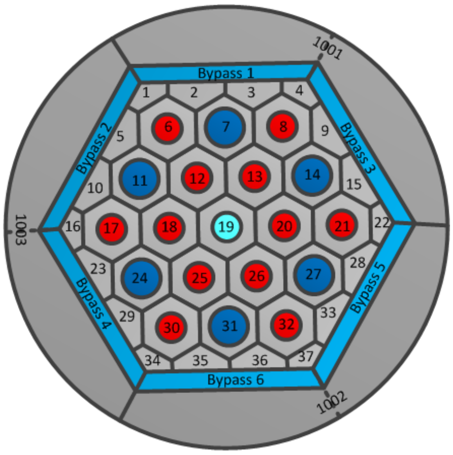

Fig. 6 CORONA input Model

The helium mass flow in the test section is 5.1 kg/min. The inlet temperature and pressure are set to 25℃ and 4 MPa, respectively. The total heater power is 56.7 kW. The outer surface of the bypass gap structure is adiabatic. The used friction factor correlation in this analysis was developed by Blausis and McAdam. The used heat transfer correlation is McEligot correlation. Fig. 7 shows the heater temperature and helium flow temperature axial profiles. The outlet temperature difference between center channel and peripheral channel are large enough to neglect the uncertainty of the thermocouples. The heater temperature is low enough to avoid the damage of a stainless steel case and inner nichrome heated elements.

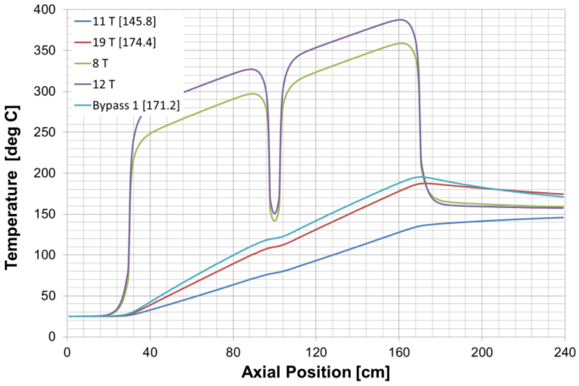

Fig. 7 Heater & He Flow Temperature Profiles

Table 2 Summary of CORONA Results

Parameter	11 Channel	19 Channel	Bypass 1
Inlet Re	39,986	27,305	4,326
Inlet T	25℃	25℃	25℃
Outlet Re	32,069	20,982	3,339
Outlet T	145.8℃	174.4℃	171.2℃
Bypass Fraction	Flow Fraction	22.64 %	
	Cooling Fraction	25.81 %	

Table 2 summarizes CORONA analysis results including the temperature and Reynolds number of the inlet and outlet in the coolant holes and the bypass gap. Table 2 shows that the Reynolds number of the scale-down test section is in the range of the hot spot standard fuel block operation condition in Table 1.

4. Conclusions

Pre-test analysis of FLUENT and CORONA showed that the test section design is adequate to maintain the Reynolds number similarities of the coolant holes and the bypass gaps for core thermo-fluid design of the prismatic gas-cooled reactor. The pre-operation is in-progress of the test section using HELP. In the future, this experiment 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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