Study on the Characteristics of Cross Flow in the Prismatic VHTR Core

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ABSTRACT

Very High Temperature Reactor (VHTR) is currently envisioned as a promising future reactor concept because of its high-efficiency and capability of generating hydrogen, a future energy carrier. Prismatic Modular Reactor (PMR) is one of the main VHTR concepts, which consists of hexagonal prismatic fuel blocks and reflector blocks made of nuclear grade graphite. The graphite blocks have lots of advantages for neutron economy and high temperature structural integrity. However, their shape could be easily changed by neutron damage during the reactor operation and the shape change can makes the gaps between the blocks inducing bypass flow. Most of reactor coolant flows through the coolant channel within the fuel blocks, but some portion of that bypasses to the interstitial gaps. The vertical gap and horizontal are called bypass gap and cross gap, respectively. The cross gap complicates flow field in reactor core by connecting coolant channel and bypass gap and it could lead to loss of effective coolant flow in fuel block. Hence, the cross flow phenomena should be investigated. In this paper, two stacked fuel block experimental facility was constructed to represent the cross flow phenomena in core of VHTR and the results of the experiments were compared with CFD analysis results. Good agreement between experimental results and CFD predictions was observed and the characteristics of cross flow was discussed.

INTRODUCTION

Very High Temperature Reactor (VHTR), one of the Generation-IV (Gen-IV) reactors, is uranium-fueled, graphite-moderated and helium-cooled reactor. It has several advantages over the previous generation reactor. These include fuel integrity, proliferation resistance, relatively simple fuel cycle and modularity to supply electricity (Gauthier, 2006). Prismatic modular reactor (PMR) is one of the prospective VHTR core type candidates. PMR200 is considered as a candidate for the Nuclear Hydrogen Development and Demonstration plant (Jo, 2008). The core of the PMR type reactor consists of assemblies of hexagonal graphite blocks. The graphite blocks have lots of advantages for neutron economy and high temperature structural integrity. The height and flat-to-flat width of fuel bock are 793 mm and 360 mm, respectively. Each block has 108 coolant channels that are 16 mm in diameter. And there are gaps between blocks not only vertically but also horizontally for reloading of the fuel elements. The flow which passes through the vertical gap is called the bypass flow and the flow which passes through the horizontal gap is called the cross flow. In principle, it would be easy to predict the flow characteristics and the pressure distribution in the core of PMR type reactor since it can be simplified ideally as a pipe flow. However, it cannot be treated as a pipe flow in actual situation, because the complicated flow distribution occurs by the bypass flow and cross flow. The effective reactor core consists of multiple layers of fuel blocks. The shape change of the fuel blocks could be caused by the thermal expansion and fast-neutron induced shrinkage. It could make different axial shrinkage of fuel block and this leads to wedge-shaped gaps between two stacked fuel blocks. The cross flow is often considered as a leakage flow through the horizontal gap between stacked fuel blocks and it complicated the flow distribution in the reactor core by connecting the coolant channel and the bypass gap. Moreover, the cross flow could lead to uneven coolant distribution and consequently cause superheating of individual fuel element zones with increased fission product release. Since the core cross flow has a negative impact on safety and efficiency of VHTR, core cross flow phenomena have to be investigated to improve the core thermal margin of VHTR (INEEL, 2003). For this reason, studies on cross flow were conducted by Groehn (1982) in German and Kaburaki (1990) in Japan. However, the shape of fuel blocks in previous study differs from that of NHDD PMR-200 fuel block and the cross flow loss coefficient for PMR-200 core has not been studied yet. To develop the cross flow loss coefficient model, study on cross flow for PMR-200 core is essential. In particular, to predict the amount of flow through the cross flow gap, obtaining accurate flow loss coefficient is important.

In this paper, the full-scale cross flow experimental facility was constructed to represent the cross flow phenomena of two stacked fuel blocks and the wedge-shaped gap is introduced between fuel blocks. Cross flow was evaluated from the difference between measured outlet flow and inlet flow. From the experimental results, ANSYS CFX 13 which is commercial computational fluid dynamics code was validated. The characteristics of flow distribution which could not be observed in detail in experiment were also examined with CFD analysis. Experimental results and that of CFD analysis are in good agreement. Furthermore, characteristics of cross flow is discussed in this paper.

CROSS FLOW EXPERIMENT FOR CORE OF PMR-200

In order to understand cross flow phenomena, cross flow experiment was designed and the full scale experimental facility was constructed. Wedge-shaped gap was formed between two fuel elements. Figure 1 shows schematic view of experimental apparatus. Air at ambient conditions was used as working fluid. The air flows through the test section from upstream block to downstream block. Inlet flow rate of upstream block, outlet flow rate of downstream block, pressure drops in coolant channels and pressure distribution in cross gap can be measured in this experimental facility. Cross flow rate can be evaluated from the difference between measured outlet flow rate and inlet flow rate. Test section was designed to be able to change the shape of the cross gap.

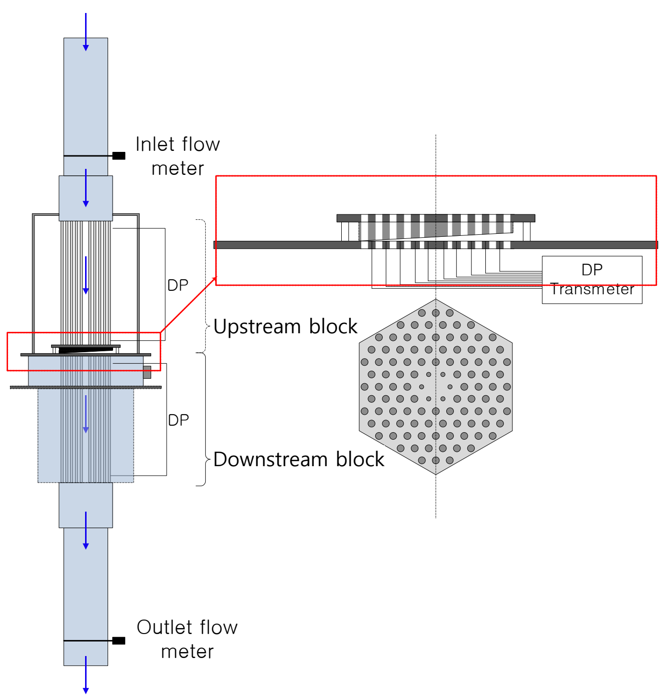

Figure 1. Schematic view of experimental apparatus

The 3D design of the experimental apparatus which was modeled by CATIA is shown in Figure 2. The materials of experimental apparatus was selected mainly metal. By assembling metal parts, manufacturing errors could be reduced. Blower, connected to the bottom of the test section, suck up the air. Figure 3 is the actual experimental apparatus. Wedge-shaped gap is simulated and the size of the gap was selected 1, 2, 4 and 6 mm. Outlet flow rates were selected to be 0.3 ~ 1.35 kg/s which are evaluated to be ranged between 12,000 and 54,000 in Reynolds numbers.

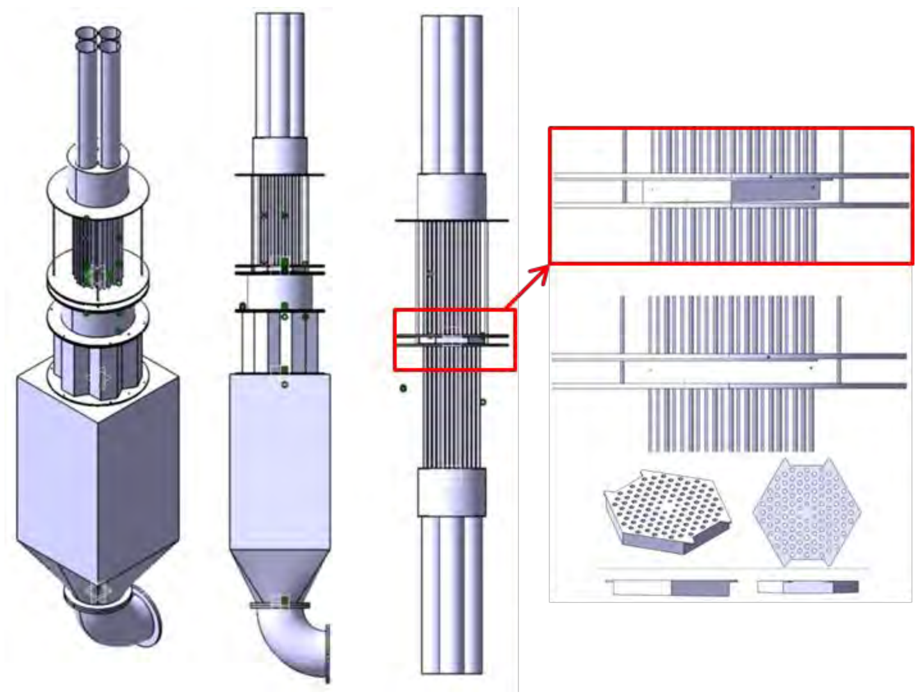

Figure 2. Design of the experimental apparatus and cross gap

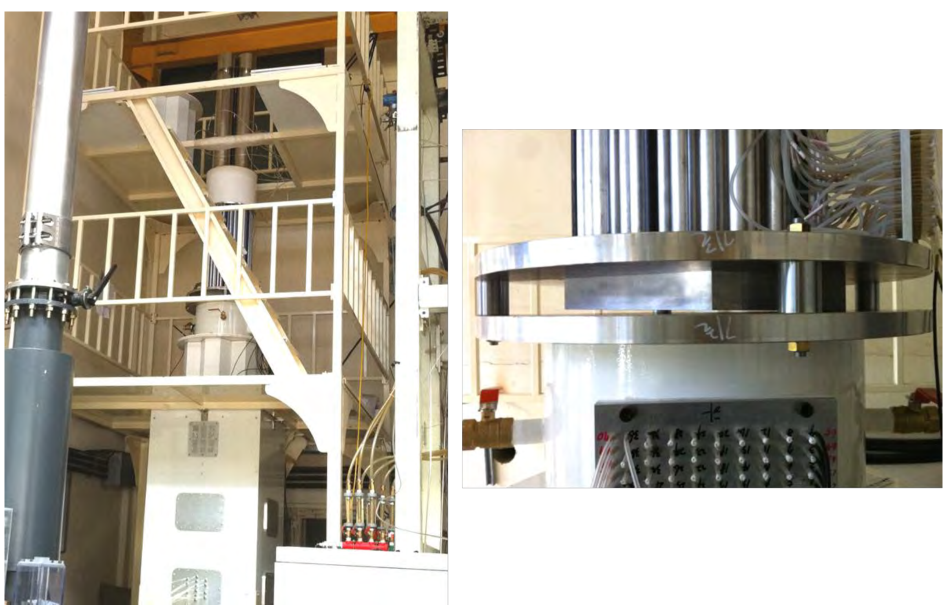

Figure 3. Experimental apparatus and cross gap

CFD ANALYSIS

Due to the complexity of core geometry, it is hard to investigate every detail in the experimental study. On the other hand, Computational Fluid Dynamics (CFD) analysis could be used as great tools for understanding the cross flow phenomena. To apply the CFD code on the cross flow phenomena, the ability of the CFD code, CFX 13, was verified by comparing the predictions with the experimental data. In Figure 4 shows computational domain and mesh structure for the case of gap width 0.6 mm. In present simulation, GAMBIT 2.2.30 was used for generating geometry and mesh grid. Approximately 8.76 million nodes of hexahedra mesh were used. Grid near the cross gap has higher mesh density. Wall y+ value is approximately 20. The working fluid used is air at ambient temperature and pressure as it is in the cross flow experiment. The properties of fluid were kept constant. The Shear Stress Transport (SST) model of Menter (1994) with an automatic wall treatment based on the Reynolds Averaged Navier-Stokes (RANS) equation was adopted for turbulence modeling. The basic foundation of the SST-k-ω model was first proposed by Wilcox (1986). Since the k-ω model has the sensitivity problem in free-stream turbulence, SST model switches to the k-ε model in the free-stream (Menter, 1994). SST-k-ω shows good results for the flow with separation. In addition, the better results can be obtained by using the transitional Gamma-Theta option (Langtry and Menter, 2005). In this study, the 2nd order upwind scheme was implemented for the convective terms. Residual for convergence criteria of iteration was set under 10^{-5}. The calculation conditions were set according to experimental conditions. The opening boundary condition was adopted to the upstream block and the cross gap between blocks, and the outlet of the downstream block is defined by the mass-flow-rate boundary condition. No slip wall and smooth wall were adopted as wall boundary conditions. Widths of the cross gaps were selected to be 1, 2, 4 and 6 and outlet flow rates were determined to be 0.3 ~1.35 kg/s as in the experiment.

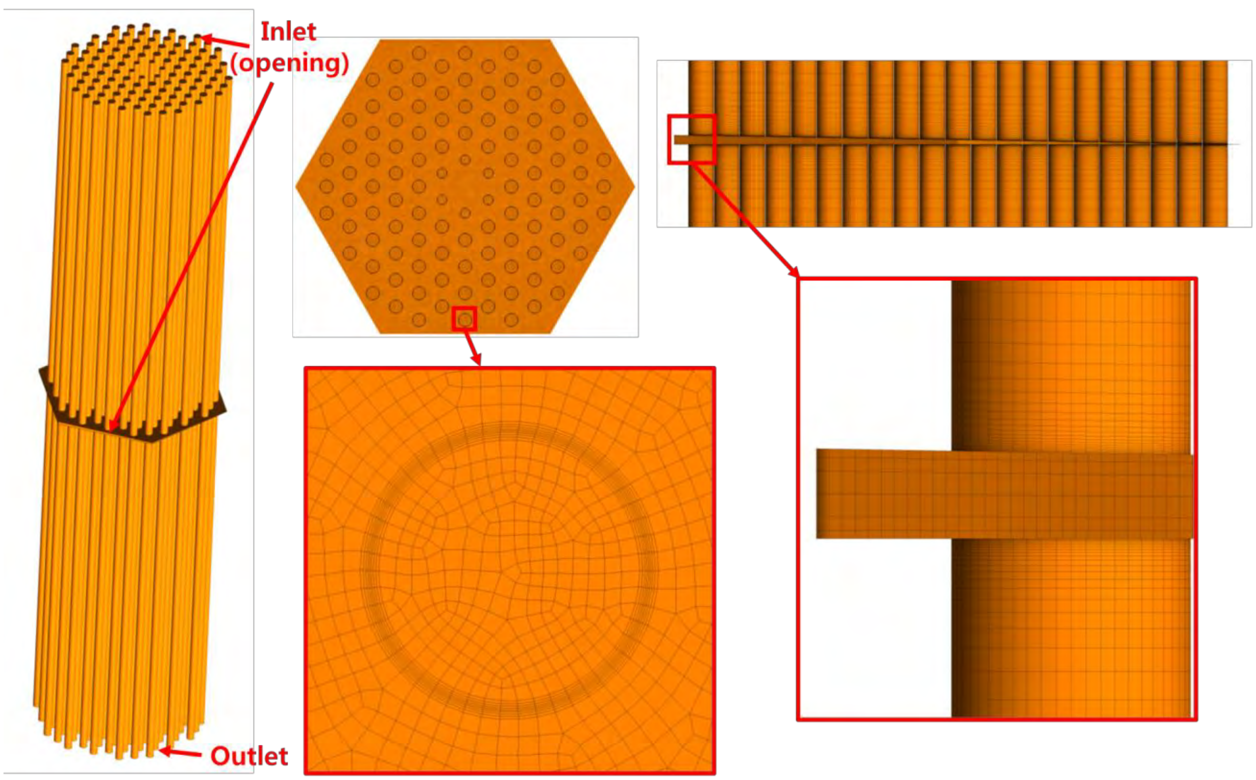

Figure 4. Computational domain and mesh structure

RESULTS AND DISCUSSION

The CFD results were compared with the experimental data in Figure 5. The graphs of cross flow to the total flow were plotted for each case. For the case of gap width 2.0 mm, discrepancy is observed in low velocity. The reason for this difference might be that the effects of laminar flow. This tendency can be seen in the case of gap width 1.0 mm. On the other hand, another reason could be the uncertainty of experiment. Since the flow rate is very low, the error effect can increase in these low cross flow velocity cases. In low velocity range, more sophisticated experiment and should be required and CFD verification should be conducted.

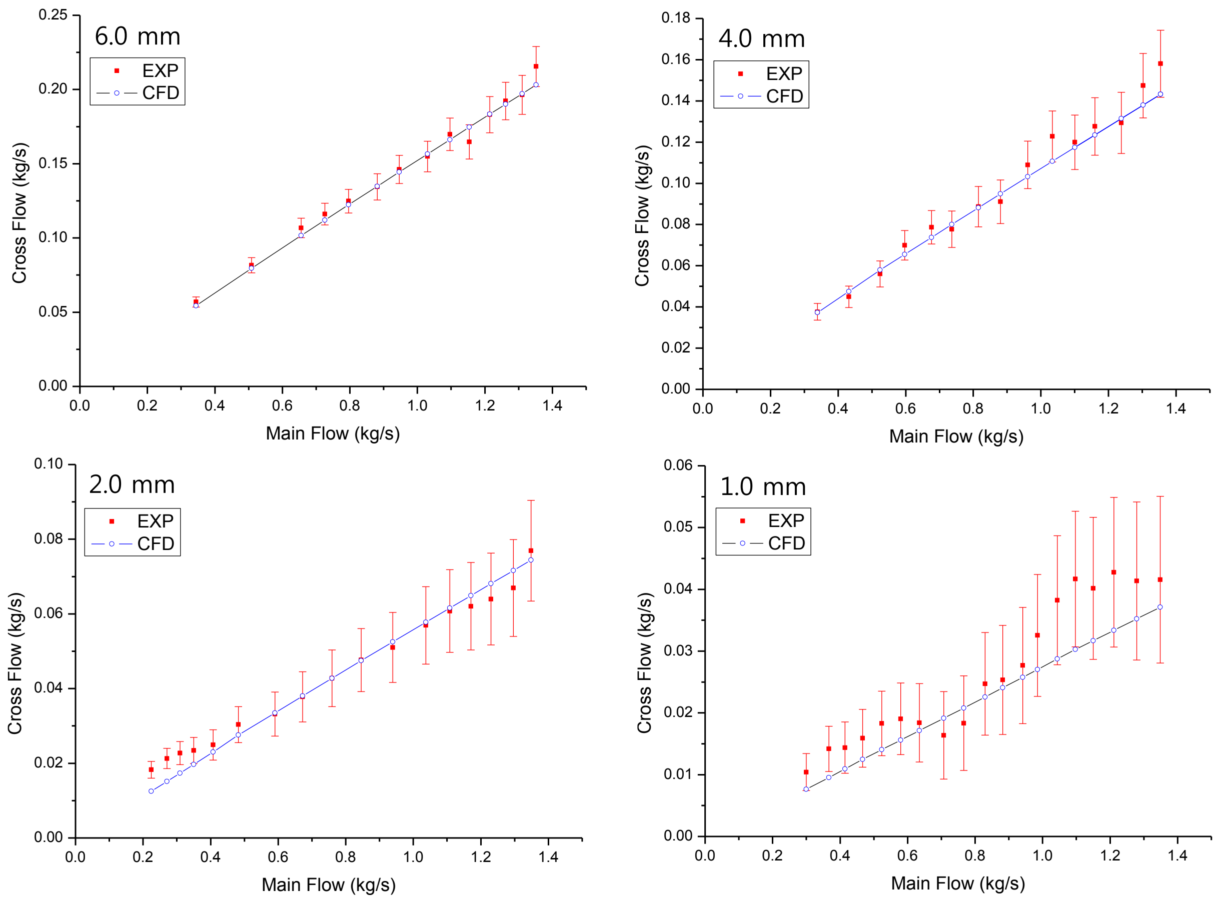

Figure 5. The cross flow rate to the total flow rate

Cross flow rate ratio was defined as the ratio of the cross flow rate and main flow rate. The cross flow ratio, obtained from CFD calculation, was tabled in Table 1. As shown in Table 1, in the same cross gap width case, significant cross flow ratio difference was not observed. It means that the ratio of the cross flow rate was affected by cross gap size rather than the amount of the main flow rate. Though it may seem cross flow has linear relation with main flow rate, cross flow ratio shows not simple tendency. For the case of gap width 6 mm, cross flow ratio in low main flow rate is larger than that in high main flow rate. However, for the case of gap width 1 mm, the opposite tendency is observed. This results can be interpreted with difference of flow regime. Even though it could not be observed in this experiment because of its uncertainty of experimental data, if more sophisticated experiment is conducted, this phenomena can be detected.

Table 1: The ratio of the cross flow rate and main flow rate

Case		Cross flow ratio [%]
Cross gap width [mm]	Main flow rate [kg/s]	
6	0.344	15.8
	1.35	15
4	0.339	11
	1.35	10.6
2	0.224	5.56
	1.39	5.67
1	0.3	3.34
	1.35	3.9

CONCLUSION

In the present paper, in order to understand the cross flow phenomena in the core of PMR-200, full-scale cross flow experimental facility was constructed. Wedge-shaped cross gap experiment was conducted and it was investigated in 6 difference cross gap width cases and the range of 0.3 ~ 1.35 kg/s main flow rate. In addition, CFD analysis was performed to validate the capability of CFD prediction and to observe the unmeasured data in experiment. 8.76 million nodes of hexahedra mesh was used and SST and Gamma-Theta model was adopted to solve turbulence flow. Results of the CFD analysis and experimental data are in good agreement. The cross flow ratio is affected by the cross gap size than the main flow rate. Nevertheless, the cases of gap width 6 mm and 1 mm show opposite tendency. To confirm this phenomena more clear, more sophisticated experiment should be conducted.

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