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Design of New Facility for Bypass Flow Experiment

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Abstract

Bypass flow in prismatic core of very high temperature gas-cooled reactor (VHTR) is an important feature in the reactor core design of Generation IV reactor. Although many researchers have investigated about flows in VHTR for a long time, details of thermal/hydraulic characteristics of flows in this reactor core type still are not fully understood. As starting of bypass flow project, old facility was designed to assess the methods of flow measurement including PIV technique to enhance the understanding about bypass flow.

In preliminary study, basic characteristics of air flow in the model of prismatic core of VHTR were studied experimentally and numerically based on old facility. All results were matched successfully but flow similarities between experiment and actual operation of reactor core could not be attained. In the first step of new facility design, the concept of multiple-path flow is employed by matching pressure drop of each flow passage. Because the results of this design show some unfavorable features, another concept starting from specifying mass flow rate based on flow area ratio is applied and examined by numerical simulations. The compromised design of new facility is met after performing few simulations.

Keywords*:* Bypass Flow, Prismatic Core, VHTR, Generation IV Reactor.

1. Introduction

The Generation IV Forum (GIF) was initiated in 2000 and formally chartered in July 2001. Late of 2002, GIF announced the selection of six reactor technologies which were believed to represent the future shape of nuclear energy. These reactor types were selected on the basis of being clean, safe and cost-effective, resistant to diversion of materials for weapons proliferation and secure from terrorist attacks [1]. The Generation IV systems are expected to become available for commercial introduction in the period between 2015 and 2030 or beyond [2]. The evolution of nuclear systems is shown in Fig. 1.

Six reactor technologies selected by GIF are gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), molten salt reactor (MSR), sodium-cooled fast reactor (SFR), supercritical water-cooled reactor (SCWR), and very high-temperature gas-cooled reactor (VHTR).

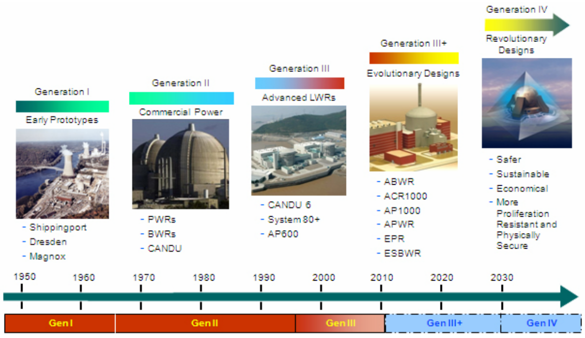

Fig. 1 Generations of nuclear power plants [3].

VHTR is a graphite-moderated, helium-cooled, thermal neutron spectrum reactor [4]. The reactor core can be either a “prismatic block” or a “pebble-bed” core. The VHTR system is designed to be continuously operated with average core outlet temperature between 900°C and 950°C [5] which enable high temperature applications. The schematic concept of VHTR is shown in Fig. 2.

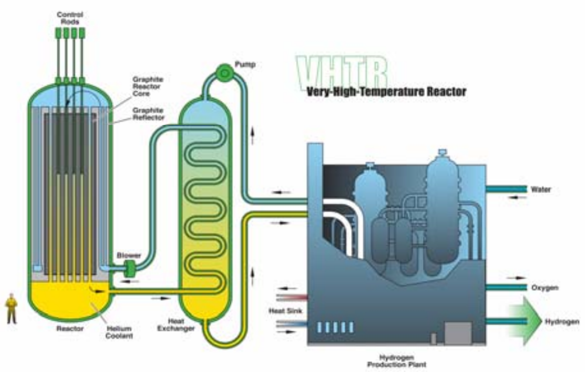

Fig. 2 Schematic representation of VHTR [6].

The earlier version of VHTR design was known as a high-temperature gas-cooled reactor (HTGR). The HTGR design was first proposed by the Staff of the Power Pile Division of the Clinton Laboratories (known now as Oak Ridge National Laboratory) in 1947. The Peach Bottom reactor in the United States was the first HTGR to produce electricity with operation from 1966 through 1974 as a technology demonstrator. Fort St. Vrain was one example of the design that was operated as an HTGR from 1979 to 1989 [7]. The modular high temperature gas reactor (MHTGR) was conceived in the 1980’s to overcome the causes for the dearth of new nuclear plant orders [8].

HTGRs have also existed in the United Kingdom (the Dragon reactor) and Germany (AVR and THTR-300), and currently exist in Japan (the HTTR using prismatic fuel with 30 MW_{th} of capacity) and China (the HTR-10, a pebble-bed design with 10 MW_e of generation) [7]. Two full-scale pebble-bed HTGRs, each with 100-195 MW_e of electrical production capacity are under construction as the demonstration plants in China with the date of completion around 2013 [9].

Because the prismatic block type VHTR is focused in this paper, the core of VHTR of this type and flow sketch are shown in Fig. 3 followed by the core arrangement in Fig. 4 [10].

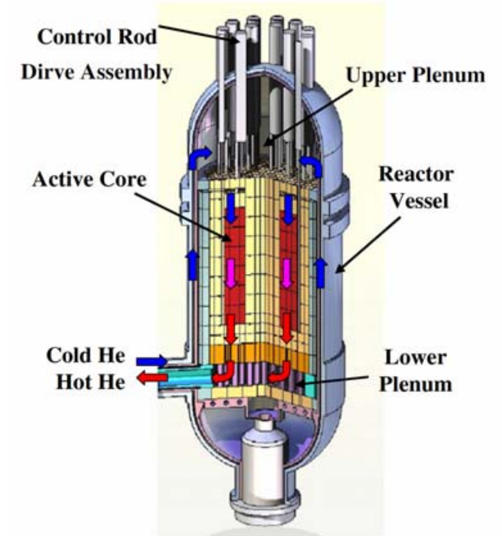

Fig. 3 Core of VHTR and flow sketch [10].

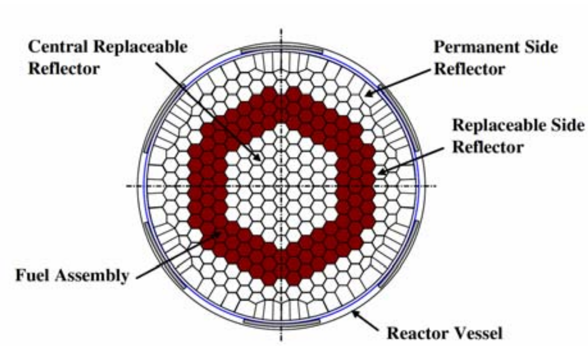

Fig. 4 Prismatic block core arrangement [10].

The bypass flow in prismatic block core of very high temperature reactor (VHTR) is an important feature in the reactor core design of Generation IV reactor. It is the flow that does not pass through the fuel element coolant channels consists of crossflow through the gaps located between two blocks contained in same column, flow through bypass gaps, and flow through side gaps. Although bypass flow can provide cooling to other components of reactor core, it should be minimized because cooling of fuel element is more important.

Many researchers have investigated on bypass flow in the core of VHTR experimentally and numerically but details of thermal/hydraulic characteristics of flows in this core type are not fully understood because of its complex geometry. Reviews of research works related to bypass flow are introduced in the following paragraphs.

Olson, et al. [11] reported that one cause of temperature fluctuations of Fort St. Vrain high temperature gas-cooled reactor was small movements of core components accompanied by periodic changes in bypass flow and crossflow of primary coolant helium. After installing constraint devices on the top of the core in October 1979, testing above 70% power was performed in spring of 1981 and 100% power was reached in November 1981 without fluctuations and with performance close to design values [12].

Effects of crossflow on flow distribution through the coolant channels were investigated by Groehn [13], [14]. Crossflow rate through gaps between contacting cylindrical graphite blocks was measured to predict interface equivalent gap width and permeability of graphite material was determined by Kaburaki and Takizuka [15]. Kaburaki and Takizuka [16] analyzed the coolant flow distribution in the core by a one-dimensional flow network model based on experiments, and more accurate prediction of pressure drop characteristics were determined experimentally and estimated numerically based on finite element model both parallel and wedge-shaped gaps [17].

Flat-shaped seal mechanism was devised and characteristics of bypass flow under this seal mechanism were studied by Kaburaki and Takizuka [18]. Because the flat-shaped seal mechanism was vulnerable to wedge-shaped block configurations, a seal mechanism which consists of graphite seal element with triangular cross section and V-shaped seal seat had been proposed by Kaburaki and Takizuka [19].

Study of thermal/hydraulic characteristics of the flows in VHTR was started by construction of the Helium Engineering Demonstration Loop (HENDEL). Thermal and hydraulic tests using the single-channel rig of the fuel stack test section had been conducted by Maruyama, et al. [20]. Experimental and analytical investigations on thermal and hydraulic performance of the fuel stack of the VHTR with the multi-channel test rig of the fuel stack test section were performed by Maruyama, et al. [21].

The hot spot factors selected in the thermal/hydraulic designs and their estimated values, and evaluation results of the thermal and hydraulic characteristics of the High Temperature Test Reactor (HTTR) were reported by Maruyama, et al. [22].

The core thermal and hydraulic design procedure of HTTR which employed pin-in-block type fuel was described by Maruyama, et al. [23].

The maximum fuel temperature was revised by using of operational data of HTTR by Takada, et al. [24].

The preliminary study of prism-type very high temperature reactor (VHTR) had been studied by Nakano, et al. [25] by using ANSYS v.10 code. Tak, et al. [26] carried out 3-D CFD analyses by using commercial code CFX 11. Recently, Sato, et al. [27] conducted 3-D CFD calculations of a prismatic VHTR to better understand bypass flow phenomena and establish an evaluation method for the reactor core using commercial CFD code FLUENT.

In preliminary study, basic characteristics of air flow in the model of prismatic core of VHTR (percentage of bypass flow, pressure drop, and Reynolds number of flow in coolant channels) were studied experimentally and numerically based on the old facility. All results were matched successfully but flow similarities between experiment and actual operation of reactor core could not be attained due to very high percentage of bypass flow caused by sudden area reduction in flow passages [28]. Therefore, the objective of present paper is to demonstrate the concept design of new facility for bypass flow experiment that can meet requirements in actual operation of reactor core. And this new facility will be used in the experiment with PIV technique in the future.

2. Design by Matching Pressure Drops

Standard fuel element of Gas Turbine-Modular Helium Reactor (GT-MHR) is shown in Fig. 5. Two opposite flat sides of fuel element are 360 mm apart. This yields side length (l) of 207.85 mm (rounded to 208 mm) and cross-sectional area of 112237 mm^2. Coolant channels consist of 102 holes of 15.9-mm diameter and 6 holes of 12.7-mm diameter. These yield total area of coolant channel flow (A_C) of 21013 mm^2, hydraulic diameter (d_h) of 15.756 mm, and porosity of fuel element (ε) of 0.18722.

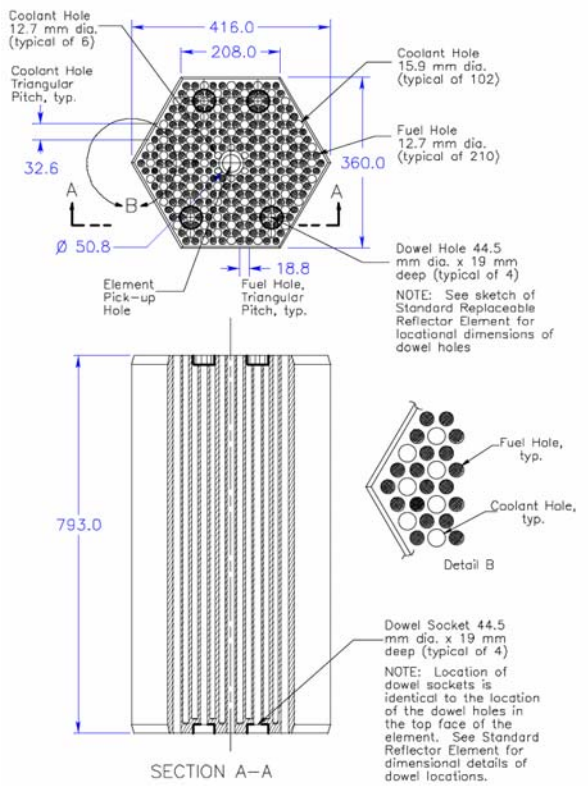

Fig. 5 Standard fuel element of GT-MHR.

The first try of new facility design is based on multiple-path flow analysis. Data from actual operation provided as input in calculation consists of porosity of fuel block model (ε) and Reynolds number of flow through coolant channel (Re_C) and bypass gap (Re_B). Block side length (l) of 50 mm is used as starting point based on the dimension of old facility. Then, coolant channel diameter (d) for small-scaled model is calculated after specifying block side length (l) and number of coolant channels (n).

For block side length (l) of 50 mm, cross-sectional area of 6495 mm^2 should have coolant channel flow area of 1216 mm^2 to keep the porosity (ε) at 0.18722. The diameter (d) of 9.274 mm is required for 18 holes (n) of coolant channel.

The height of prismatic block (h) should be 185.5 mm for block height to coolant channel diameter ratio (h/d) of 20.

The geometry of the block specified by these dimensions is sketched in Fig. 6. The assembly of fuel block models is shown in Fig. 7. Symmetric planes of fuel block model assembly expected to be useful in the simulation are shown in Fig. 8 with other two parameters, bypass gap width (b) and side gap width (s).

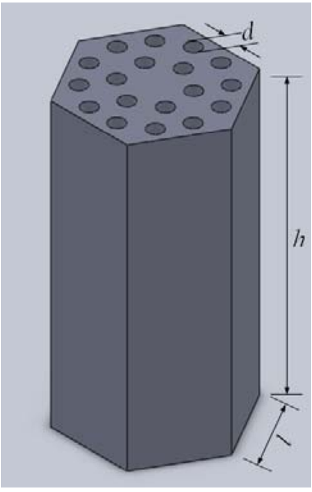

Fig. 6 Geometry of fuel block model.

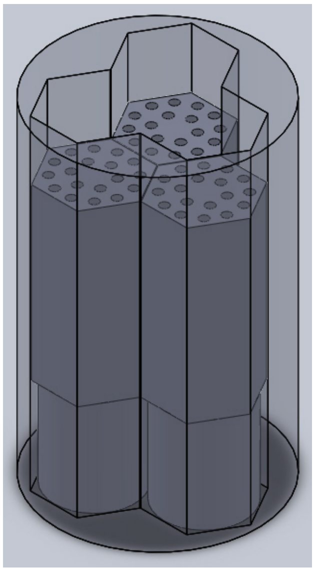

Fig. 7 Assembly of fuel block models.

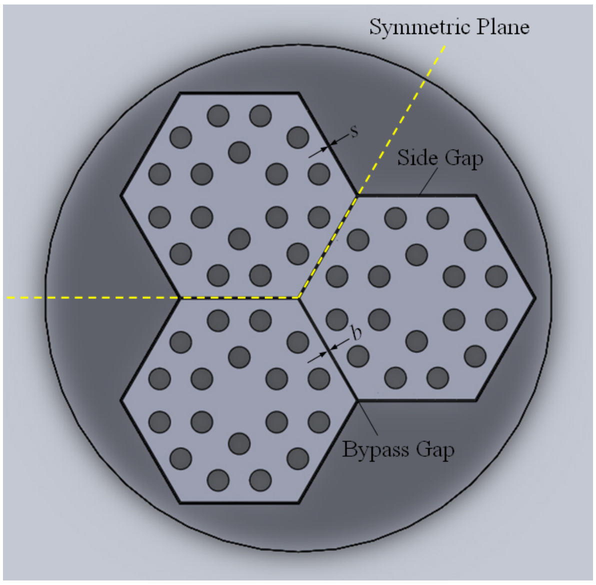

Fig. 8 Symmetric planes of fuel block assembly.

Average velocity of the flow in coolant channel is computed from Reynolds number of flow through coolant channel and pressure drop is estimated. Then, bypass gap width can be found from Reynolds number of flow through bypass of actual operation and estimated pressure drop. Finally, the volume flow rate is obtained by summing volume flow rate of flow through coolant channels, bypass gaps and side gaps which their widths are equal to bypass gap width.

Properties of p-cymene which will be used as matched-index-of-refraction (MIR) fluid are density of 853 kg/m^3 and dynamic viscosity of 1.153x10^{-3} Pa-s. Parameters specified in the first design are:- coolant channel Reynolds number (Re_C) at 35000, bypass gap Reynolds number (Re_B) at 2500, porosity of fuel block model (ε) at 0.18722, block height to coolant channel diameter ratio (h/d) at 20 (this ratio is about 50 for most of coolant channels in standard fuel element), and side length (l) at 50 mm. Parameters estimated from the procedures mentioned above are summarized in Table 1.

Although the first design can fulfill the desired values of Reynolds number of coolant channel and bypass gap under actual operation, the estimated bypass gap width is difficult to be manufactured and makes the PIV technique to be impossible because it is thinner than laser sheet thickness. So the second design is performed to obtain wider bypass gap by increasing side length (l) to 120 mm. Parameters obtained from the second design are summarized in Table 2 and the configuration of this design is shown in Fig. 9.

Table 1 Summary of the 1st design.

Estimated Parameters	*Value*
Number of Coolant Channels (n)	18
Coolant Channel Diameter (d)	9.274 mm
Block Height (h)	185.5 mm
Coolant Channel Velocity (V_C)[1]	5.27 m/s
Pressure Drop (Δp)[2]	23630 Pa
Bypass Gap Width (b)	0.771 mm
Average Velocity in Bypass Gap (V_B)	2.27 m/s
Volume Flow Rate (Q)	317 gpm
Percentage of Bypass Flow	3.938%

[1] Average velocity.

[2] Two blocks stacked in one column estimation.

Table 2 Summary of the 2nd design.

Estimated Parameters	*Value*
Number of Coolant Channels (n)	18
Coolant Channel Diameter (d)	22.26 mm
Block Height (h)	445.2 mm
Coolant Channel Velocity (V_C)	2.196 m/s
Pressure Drop (Δp)	4102 Pa
Bypass Gap Width (b)	1.85 mm
Average Velocity in Bypass Gap (V_B)	0.947 m/s
Volume Flow Rate (Q)	761 gpm
Percentage of Bypass Flow	3.938%

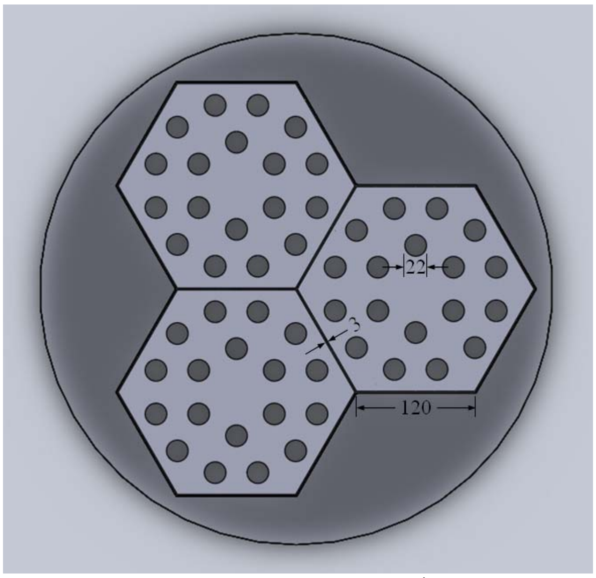

Fig. 9 Configuration of the 2nd design.

Bypass flow simulation is performed for the case with one block stacked in column as shown in Fig. 7 by using STAR-CCM+ software. Because bypass gap width of 1.85 mm caused the problem on specifying base size used in meshing process, bypass gap width (b) was increased to 3 mm to construct the mesh easier. Meshes of one-third model on few plane sections are shown in Fig. 10.

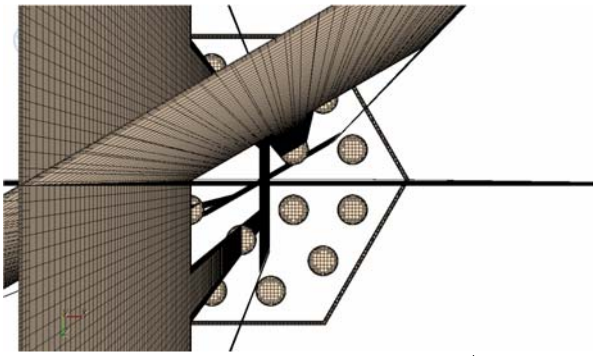
Fig. 10 Mesh representation of the 2nd design.

Base size of 0.65 mm is the largest base size that can capture the smallest portion of computational domain. The mesh used in the simulation has 34,115,810 cells in total and mass flow rate of 13.5 kg/s is set in one-third model simulation corresponded to total mass flow rate of 40.5 kg/s (753 gpm) for full model simulation.

The implicit unsteady scheme is selected with time step size of 1 second. The maximum inner iteration is set as default at 20 iterations. The physical time to stop the simulation is set at 250 seconds which yield 5000 iterations in total to attain steady state of the flow as shown in Fig. 11.

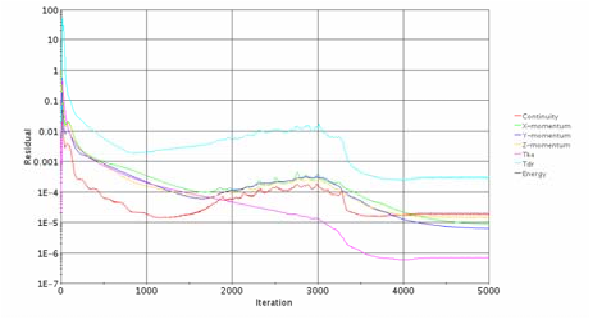

Fig. 11 Residual curves of the 2nd design after physical time of 250 seconds.

The simulation yields bypass flow fraction of 12.92%, pressure drop of 2720 Pa as shown in Fig. 12, Reynolds number of coolant channel (Re_C) at 30425 estimated from velocity profile in coolant channel in Fig. 13, and Reynolds number of bypass gap (Re_B) at 4716 estimated from velocity profile in Fig. 14.

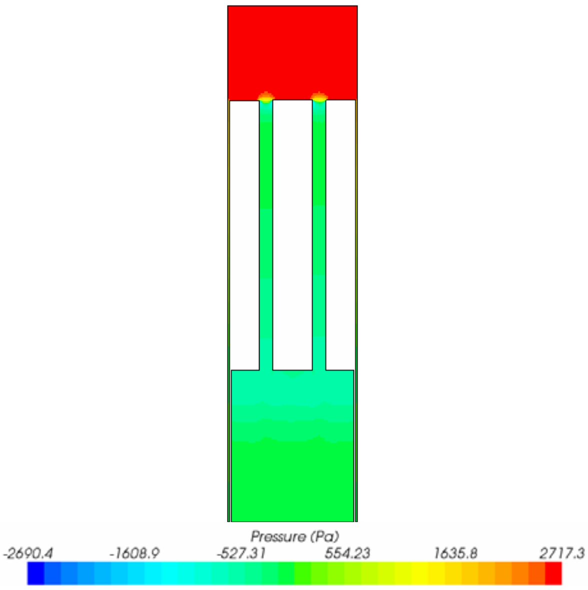

Fig. 12 Pressure distribution of the 2nd design after physical time of 250 seconds.

The second design shows that concept design by matching pressure drops suffers from several unsatisfied features:- volume flow rate at 760 gpm is very high and the size of pump is prohibited, size length of the block at 120 mm is moderately large, and all loss coefficients used in this design are based on standard configuration while the model configuration is non-standard; so another concept design is needed.

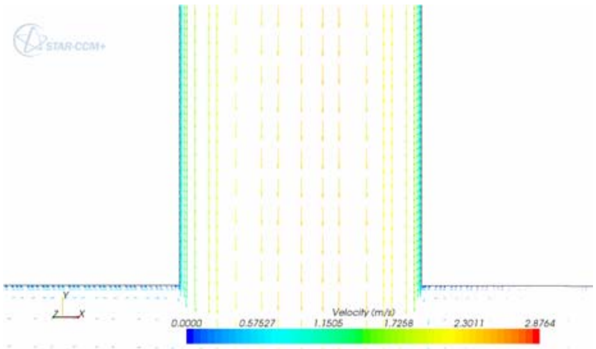

Fig. 13 Velocity distribution in coolant channel of the 2nd design after physical time of 250 seconds.

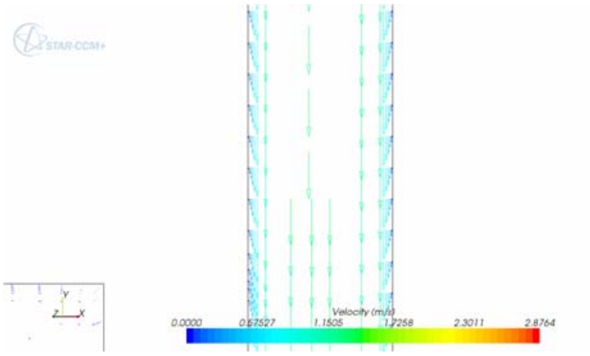

Fig. 14 Velocity distribution in bypass gap of the 2nd design after physical time of 250 seconds.

3. Design Based on Flow Area Ratio

This concept design is demonstrated by estimating percentage of bypass flow from area ratio from the configuration used in the second design. Then, three parameters are calculated:- percentage of bypass flow is 20.74%, Re_C is 28582, and Re_B is 7710. After comparing with the existing simulation results, it can be seen that Re_C is roughly predicted by this concept design.

The first modification based on the new concept design will be made to get shorter block side length (l) in the third design. Because the capacity of pump can be a constraint as mentioned in the previous section, mass flow rate at 10 kg/s (186 gpm) is fixed at the beginning of the calculations. Another constraint is bypass gap width should not be lower than the thickness of laser sheet at about 1.5 mm. So it is set at 3 mm in the third design to examine this concept design before refining it to fulfill other requirements of new facility. Parameters of the third design are summarized in Table 3 and the configuration of this design is shown in Fig. 15.

Table 3 Summary of the 3rd design.

Specified Parameters	*Value*
Volume Flow Rate (Q)	186 gpm
Side Length (l)	40 mm
Coolant Channel Diameter (d)	10 mm
Block Height (h)	200 mm
Number of Coolant Channels (n)	6
Porosity of Fuel Block Model (ε)	0.11336
Bypass Gap Width (b)	3 mm
Estimated Parameters (Based on Flow Area Ratio)	*Value*
Percentage of Bypass Flow[1]	56.96%
Coolant Channel Re (Re_C)	25476
Bypass Gap Re (Re_B)	15286
Estimated Parameters (Simulation)[2]	*Value*
Percentage of Bypass Flow	53.53%
Coolant Channel Re (Re_C)	26989
Bypass Gap Re (Re_B)	14033
Pressure Drop (Δp)	11622 Pa

[1] Based on all areas beside coolant channels i.e. cross-sectional area of bypass and side gaps.

[2] The simulation is stopped at 100 seconds.

From the results, it is clear that Reynolds number of coolant channel (Re_C) can be predicted as expected. Additionally, the percentage of bypass flow is predicted accurately based on flow area ratio but is very high compare with the condition in the actual operation. All side gaps should be removed to reduce the percentage of bypass flow in the fourth design.

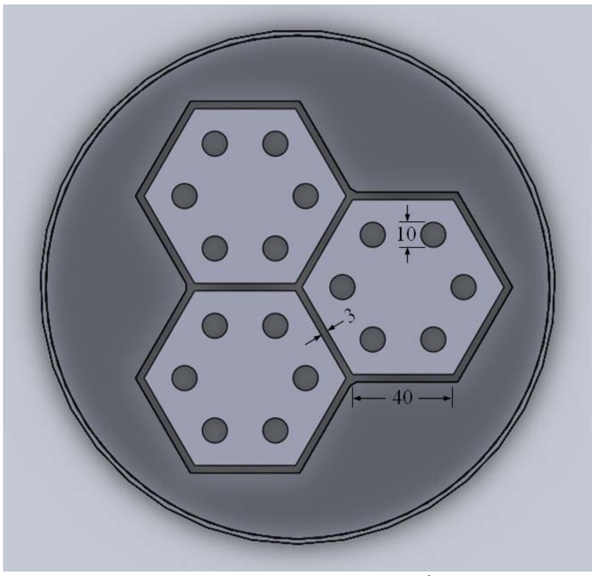

Fig. 15 Configuration of the 3rd design.

Table 4 Summary of the 4th design.

Specified Parameters	*Value*
Volume Flow Rate (Q)	186 gpm
Side Length (l)	50 mm
Coolant Channel Diameter (d)	15 mm
Block Height (h)	300 mm
Number of Coolant Channels (n)	6
Porosity of Fuel Block Model (ε)	0.16324
Bypass Gap Width (b)	3 mm
Estimated Parameters (Based on Flow Area Ratio)	*Value*
Percentage of Bypass Flow	12.49%
Coolant Channel Re (Re_C)	34534
Bypass Gap Re (Re_B)	13814
Estimated Parameters (Simulation)[1]	*Value*
Percentage of Bypass Flow	9.278%
Coolant Channel Re (Re_C)	34802
Bypass Gap Re (Re_B)	10050
Pressure Drop (Δp)	7979 Pa

[1] The simulation is stopped at 100 seconds.

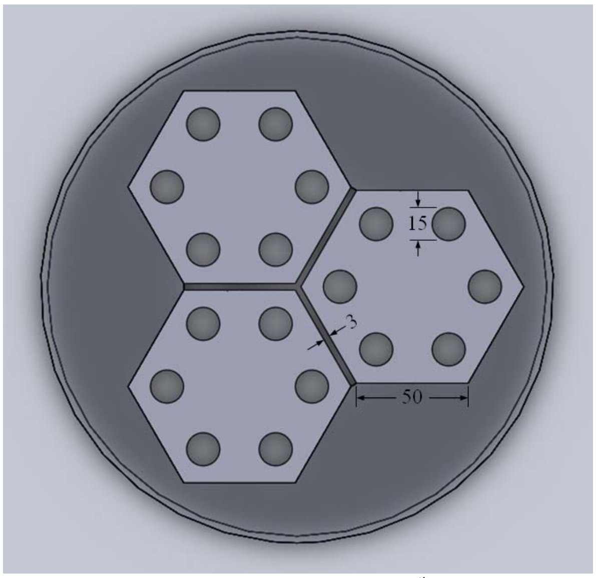

Fig. 16 Configuration of the 4th design.

The fourth design yields Re_C at 34802 (from simulation) which is almost equal to the desired value at 35000. The porosity of fuel block model at 0.16324 is closed to that of 0.18722 of standard fuel element. The percentage of bypass flow estimated from flow area ratio is higher than that obtained from the simulation because flow resistance is higher than expected from linear relationship based on flow area ratio. However, smaller percentage of bypass flow is preferred because it is lower than 10% which occur in actual operations.

The final design is performed to find the limitation of the new facility by setting the bypass gap width to be 1.5 mm which is the minimum width that the laser sheet may be used. The results in Table 5 show that the final design meet almost all requirements of the new facility:- Re_C (from simulation) is very close to 35000, porosity is almost equal to that of standard fuel element, bypass flow fraction is less than 10%, except Re_B (from simulation) is at 3226 which is quite higher than the desired value at 2500.

Table 5 Summary of the final design.

Specified Parameters	*Value*
Volume Flow Rate (Q)	186 gpm
Side Length (l)	50 mm
Coolant Channel Diameter (d)	16 mm
Block Height (h)	320 mm
Number of Coolant Channels (n)	6
Porosity of Fuel Block Model (ε)	0.18573
Bypass Gap Width (b)	1.5 mm
Estimated Parameters (Based on Flow Area Ratio)	*Value*
Percentage of Bypass Flow	5.948%
Coolant Channel Re (Re_C)	34795
Bypass Gap Re (Re_B)	6524
Estimated Parameters (Simulation)[1]	*Value*
Percentage of Bypass Flow	2.740%
Coolant Channel Re (Re_C)	35234
Bypass Gap Re (Re_B)	3226
Pressure Drop (Δp)	6784 Pa

[1] The simulation is stopped at 100 seconds.

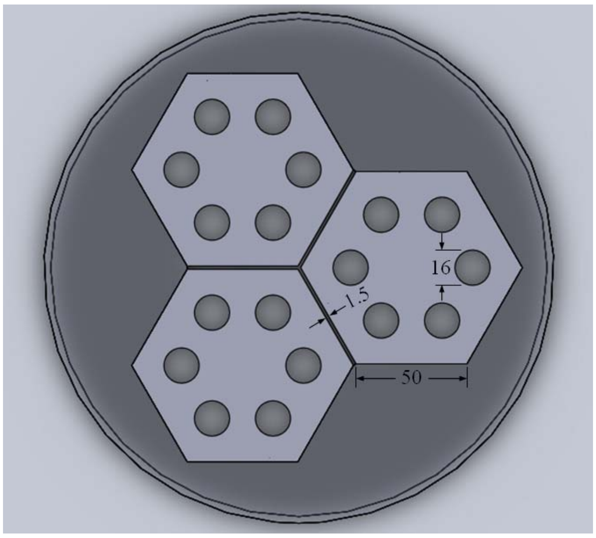

Fig. 17 Configuration of the final design.

4. Conclusions

New facility for bypass flow experiment was designed to attain the required values of Re_C, Re_B, porosity of fuel block model, and percentage of bypass flow. Firstly, the concept of matching pressure drops was employed and flow simulation was performed but this concept was suffered from various unfavorable conditions because too many constraints were specified. Another concept based on flow area ratio was demonstrated with simulation result and it was concluded that Re_C could be predicted accurately. By adjusting some parameters to make the estimated Re_C close to desired value at 35000, desired values of all remaining parameters could be met in few simulations except the condition of Re_B at 2500.

5. Acknowledgements

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Equation Chapter 1 Section 7

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