Application of Looped Network Analysis Method to Core of Prismatic VHTR

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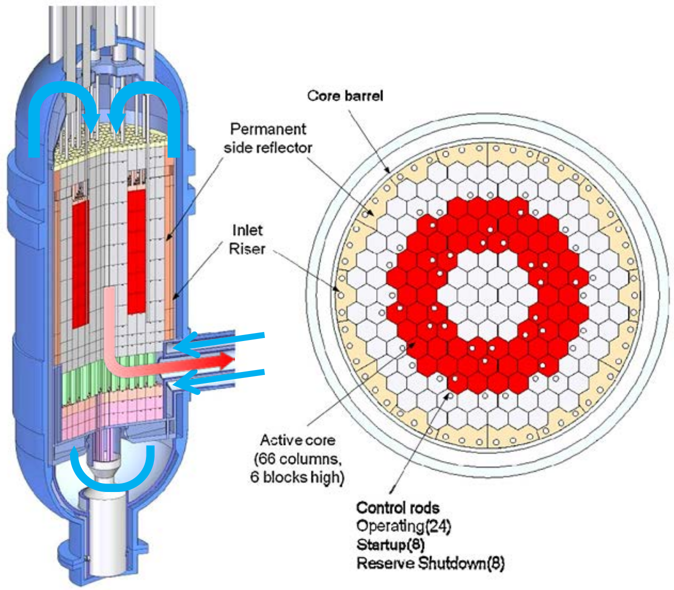
Contents

❖ Very High Temperature Reactor

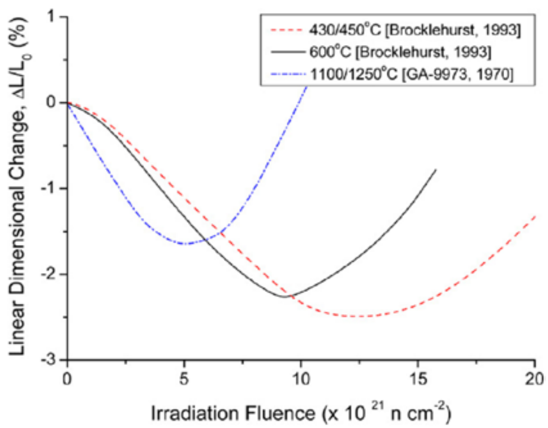
- Outlet temperature over 950 °C
- Working Fluid: He @7MPa

❖ Core of PMR200

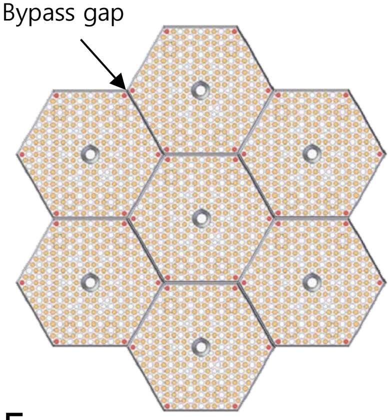
- Prismatic core (block type)
- Core element and moderator: Graphite
  - Capable of withstanding irradiation and high temperature
  - ✓ Shrinkage by irradiation fluence
  - ✓ Thermal expansion



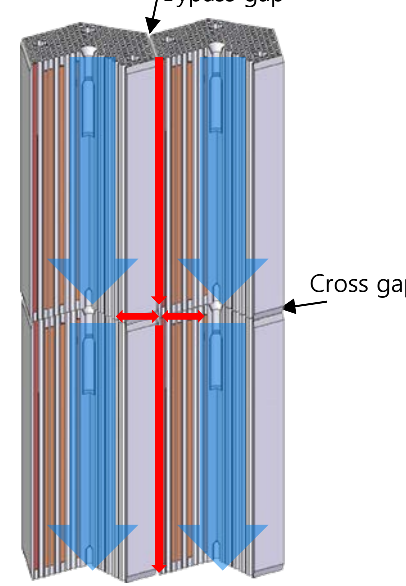
Core of PMR200



Dimensional change of graphite with irradiation fluence

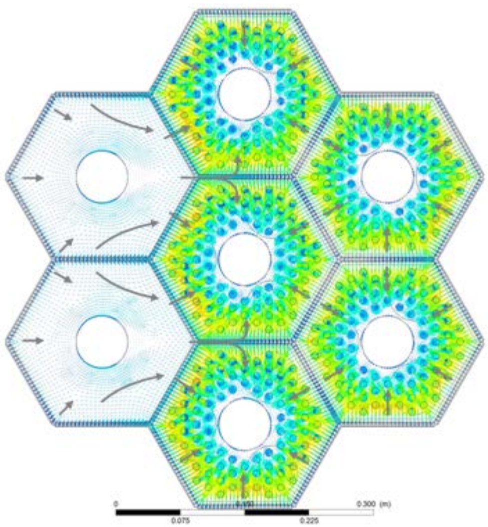


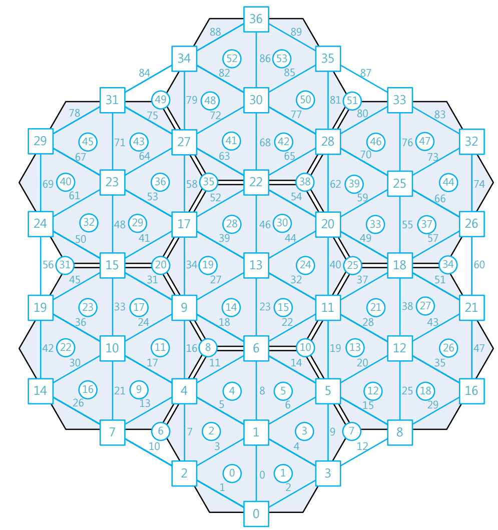
Top view



Side view

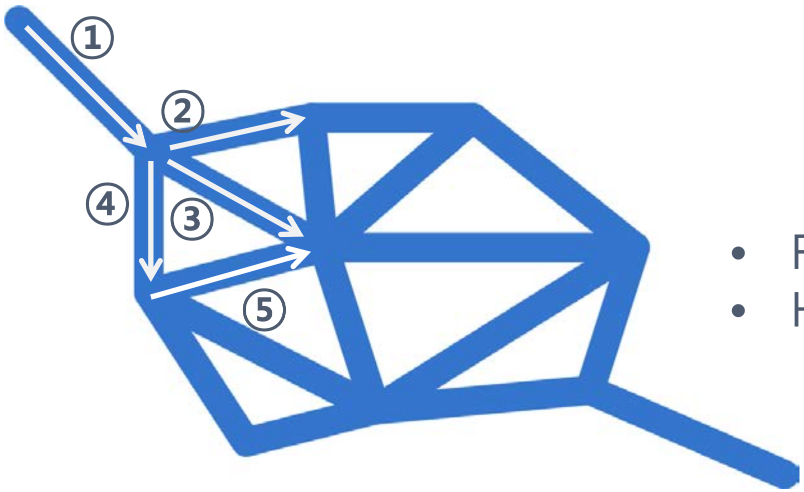
❖ Analysis of Flow Distribution in the VHTR Core





	CFD	Network code
Strengths	High accuracy Local information (Local flow field, flow separation)	**Fast calculation results** **Low computational cost** **Easy to change gap conditions**
Weaknesses	High computational cost and time Difficult to change gap conditions	Impossible to obtain local information

Looped Network Analysis Code



- Flow: ①=②+③+④
- Head loss: ③=④+⑤

❖ **The governing equations are based on Kirchhoff's circuit laws.**

1) The algebraic sum of inflow and out flow discharges at a node is zero.
2) The algebraic sum of the head loss around a loop is zero.

Looped Network Analysis Code

❖ Flow (Conservation of Mass)

$$F_j = \sum_{n=1}^{j_n} Q_{jn} = 0$$

"Linear Theory Method" →

$$F_j = \sum_{n=1}^{i_L} a_{jn} Q_{jn} = 0$$

Where a_{jn} is $+1$ for positive discharge flows in pipe n, -1 for negative discharge flows in pipe n, and 0 if pipe n is not connected to node j. The total pipes in the network are i_L.

❖ Head Loss (Conservation of Momentum)

$$F_k = \sum_{n=1}^{kn} R_{kn} |Q_{kn}| Q_{kn} = 0$$

"Linear Theory Method" →

$$F_k = \sum_{n=1}^{k_L} b_{kn} Q_{kn} = 0$$

Linearization coefficient

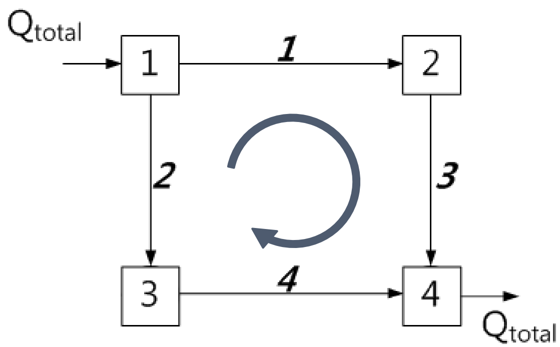
Where $b_{kn} = R_{kn}|Q_{kn}|$ if pipe n is in loop k or otherwise $b_{kn}=0$.
The coefficient b_{kn} is revised with current flow rates for the next iteration.

$$h_f = RQ^2 = f \frac{L}{D} \frac{V^2}{2g} \quad \Rightarrow \quad R = \frac{fL}{2gDA^2}$$

Darcy-Weisbach equation

Looped Network Analysis Code

❖ Example of Simple Looped Network using LTM



Node 1	$Q_{total} = Q_1 + Q_2$	
Node 2	$-Q_1 + Q_3 = 0$	
Node 3	$-Q_2 + Q_4 = 0$	
Node 4	~~$Q_3 + Q_4 = Q_{total}$~~	

Node equations
→ mass conservation

Loop $$R_1|Q_1|Q_1 + R_3|Q_3|Q_3 - R_2|Q_2|Q_2 - R_4|Q_4|Q_4 = 0$$

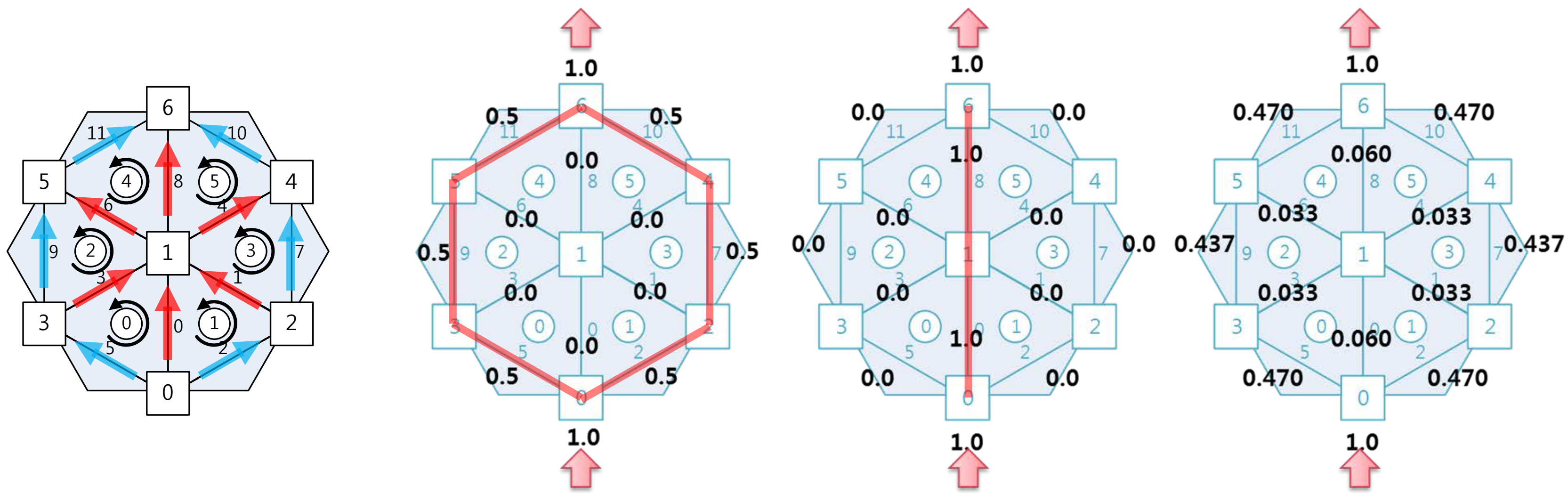
Loop equation
→ momentum conservation

$$\begin{pmatrix} +1 & +1 & 0 & 0 \\ -1 & 0 & +1 & 0 \\ 0 & -1 & 0 & +1 \\ b_1 & b_2 & -b_3 & -b_4 \end{pmatrix} \begin{pmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \end{pmatrix} = \begin{pmatrix} Q_{total} \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

where $b_n = R_n|Q_n|$

❖ Verification Case (2-D layer, one block)

- Cross flow and lateral flow (through bypass gap)



Flow Direction Determination

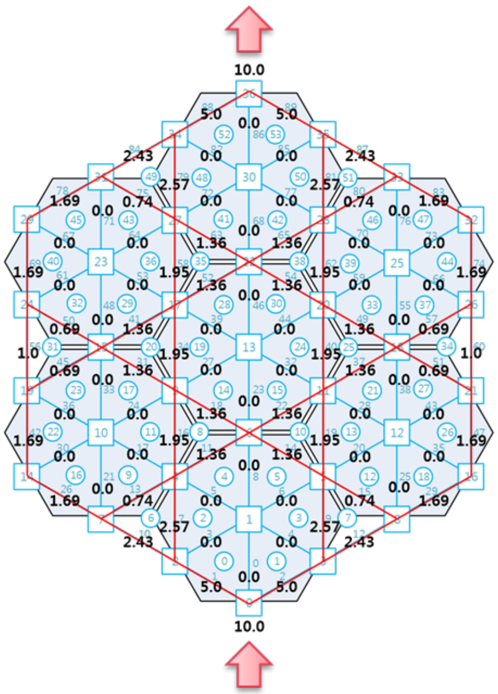
Bypass Gap 2 mm Cross Gap 0 mm

Bypass Gap 0 mm **Cross Gap 2 mm**

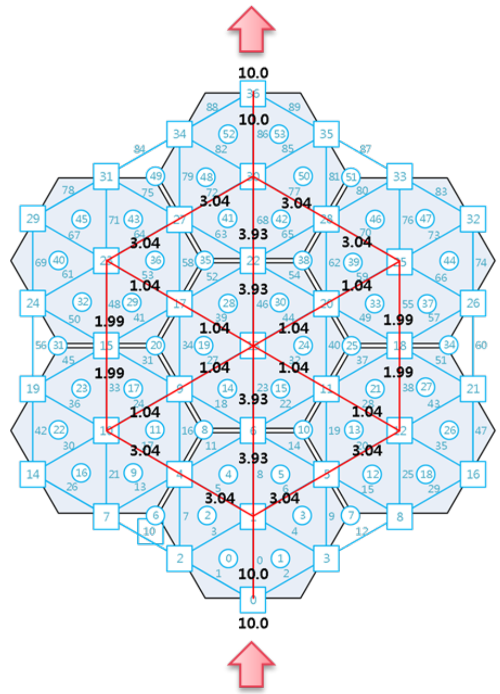
Bypass Gap 2 mm Cross Gap 2 mm

- 7 nodes, 6 loops, 12 flow paths (12 by 12 matrix)
- Flow direction has to be determined when the network is modeled.
- The calculation shows proper results.

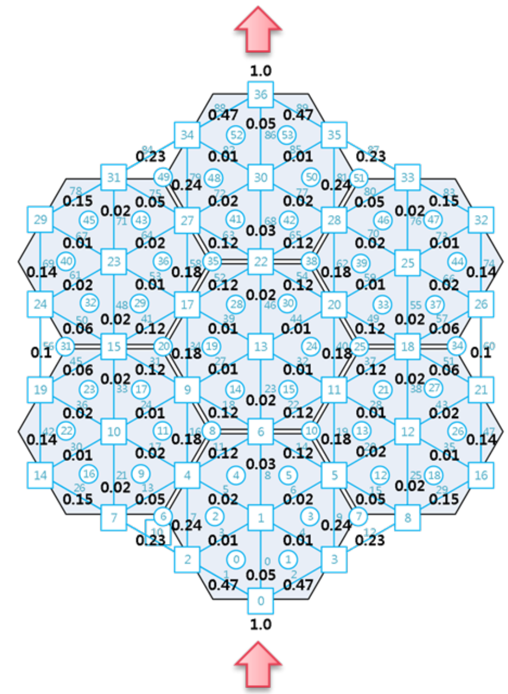
❖ Verification Case (2-D layer, 7 blocks)



Bypass Gap 2 mm
Cross Gap 0 mm



Bypass Gap 0 mm
Cross Gap 2 mm



Bypass Gap 2 mm
Cross Gap 2 mm

- 37 nodes, 54 loops, 90 flow paths (90 by 90 matrix)
- 7 block case also shows the proper results.
- Flow only pass through the open gap region.
- Flow distribution shows the bilateral symmetry.

Flow Resistance Model for Core of VHTR

❖ Determination of Flow Resistance (R)

- In the coolant channels (pipe flow)

$$R_{CH} = \frac{fL}{2gD_{CH}A_{CH}^2}$$

$$\frac{1}{f^{1/2}} \approx -1.8\log\left[\frac{6.9}{\mathrm{Re}_d} + \left(\frac{\varepsilon/d}{3.7}\right)^{1.11}\right]$$

Haaland (1983) equation

- In the bypass gap (parallel plate flow path)

$$R_{BG} = \frac{fL}{2gD_{BGh}A_{BG}^2}$$

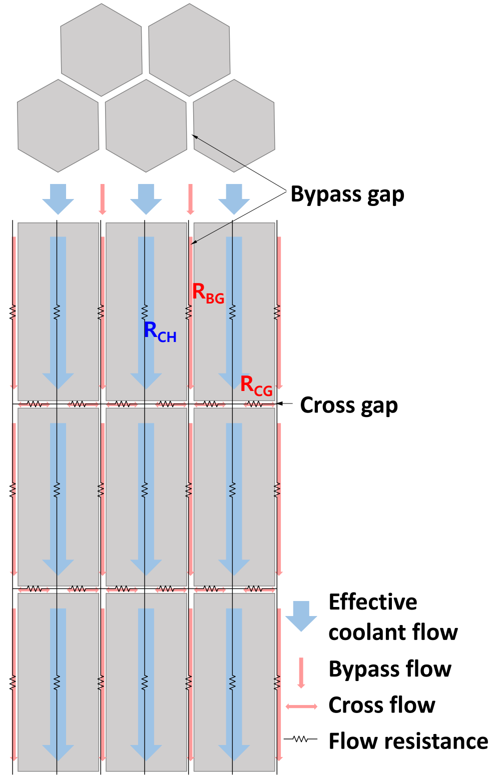
$$D_{BGh} = \frac{4\times Flow\ Area}{Wetted\ Perimeter} = 2\times\delta_{BG}$$

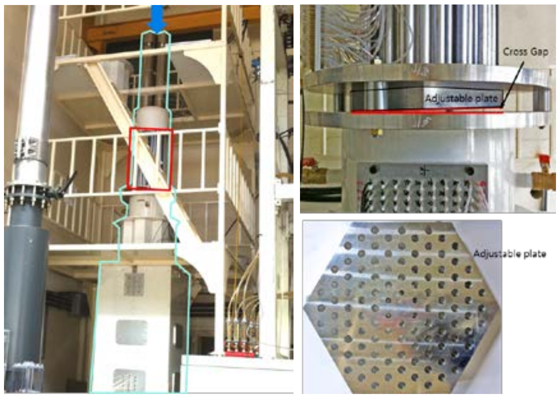
- In the cross gap (Lee et al., 2015)

$$R_{CG} = \rho\cdot\frac{C_1/(\delta_{CG}\,\mathrm{Re}_{CG}) + C_2}{2A_{CG}^2}$$

$$K = \frac{C_1}{\delta\,\mathrm{Re}} + C_2, \quad R = \frac{K\rho}{2A^2}$$

Wedge		Parallel	
C^*_1	C^*_2	C^*_1	C^*_2
0.61	3.5	0.65	3.5



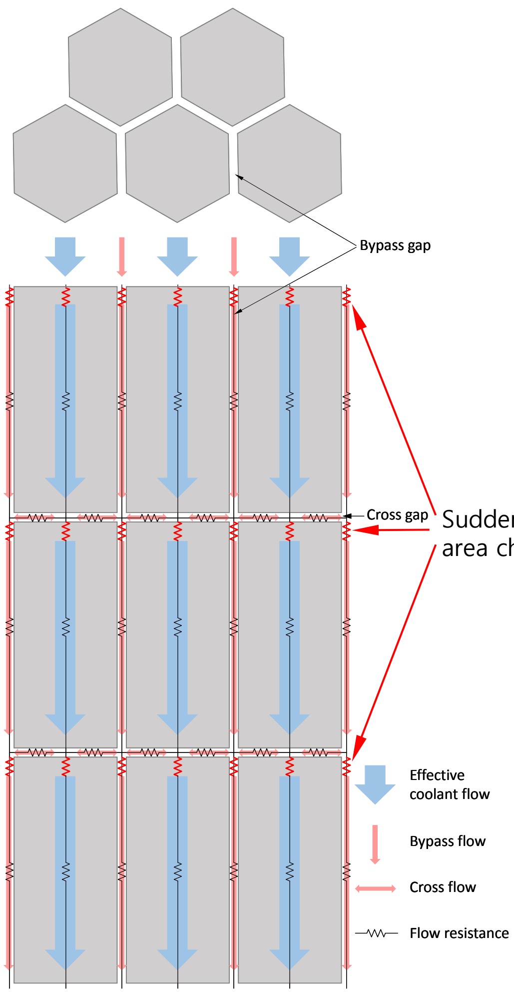


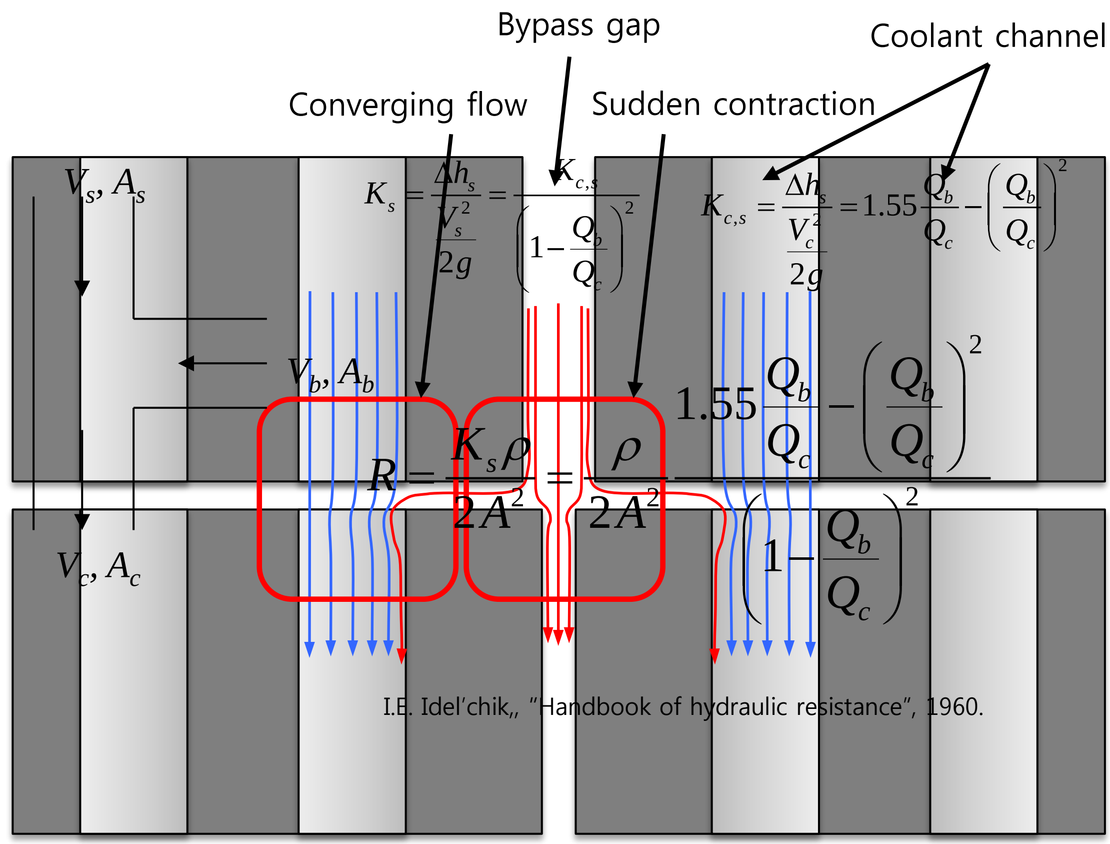
Cross flow experiment

Flow Resistance Model for Core of VHTR

Hydraulic Resistance between Layers

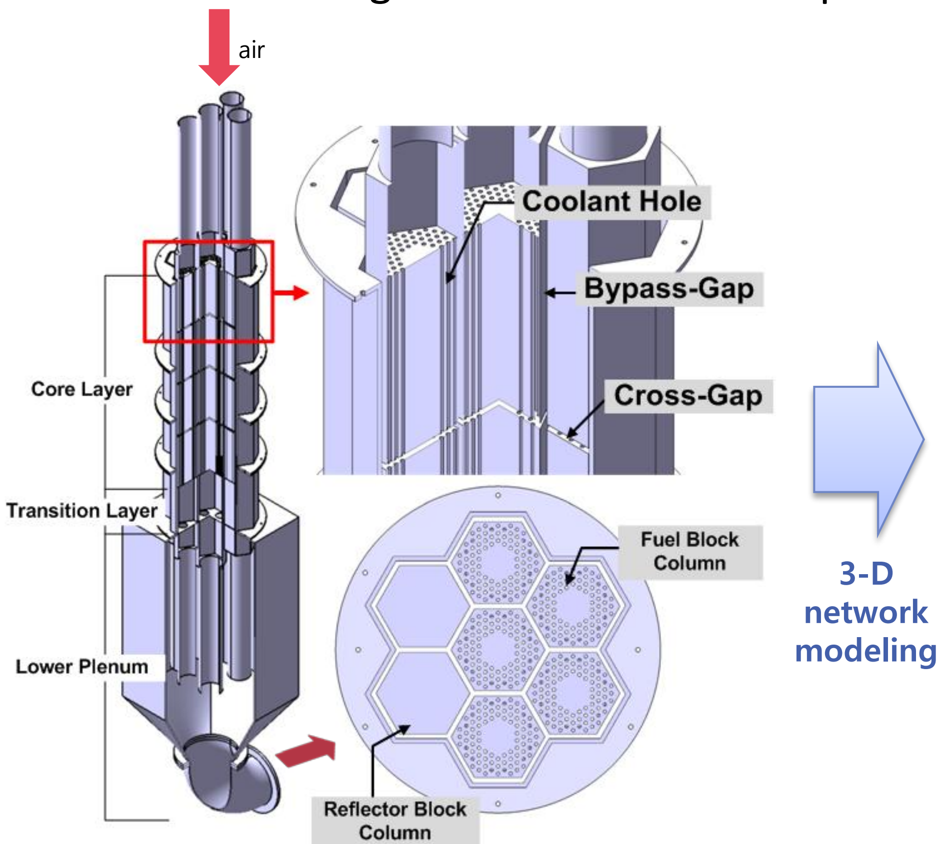
- Bypass gap – sudden contraction
- Coolant channel – converging flow



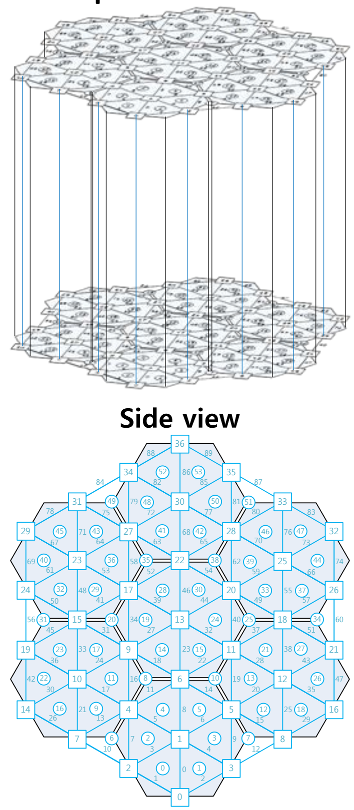


SNU Multi-Block Experiment (Yoon et al., 2011)

- 7 columns, 4 layers
- Working fluid: air at room temperature and pressure



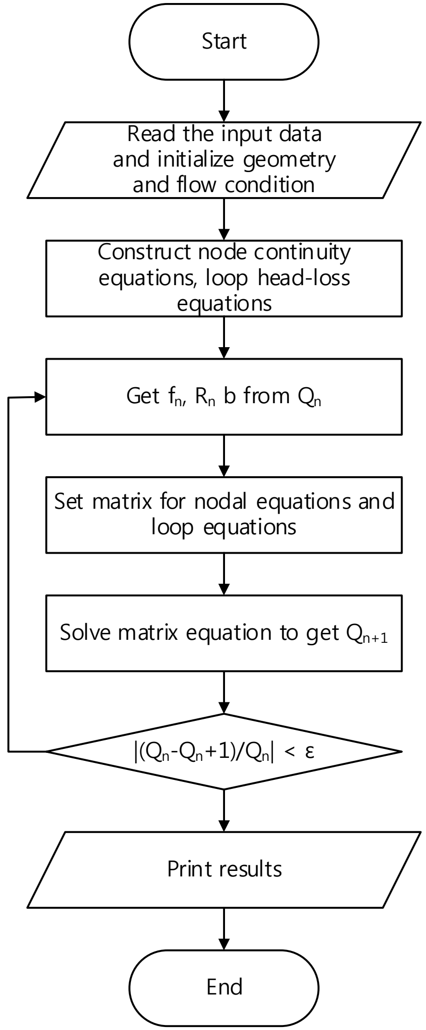
SNU Multi-Block Experimental Facility



Side view

Top view

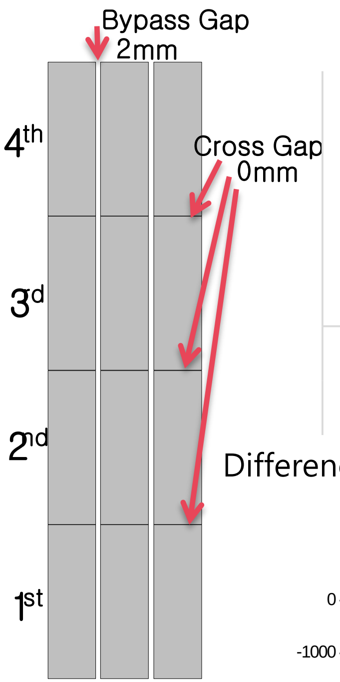
222 nodes, 774 loops, 725 flow paths
(725 by 725 matrix)



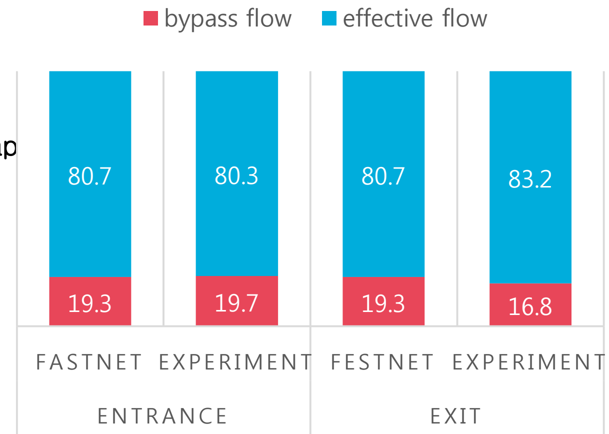
Flow chart

Validation Results

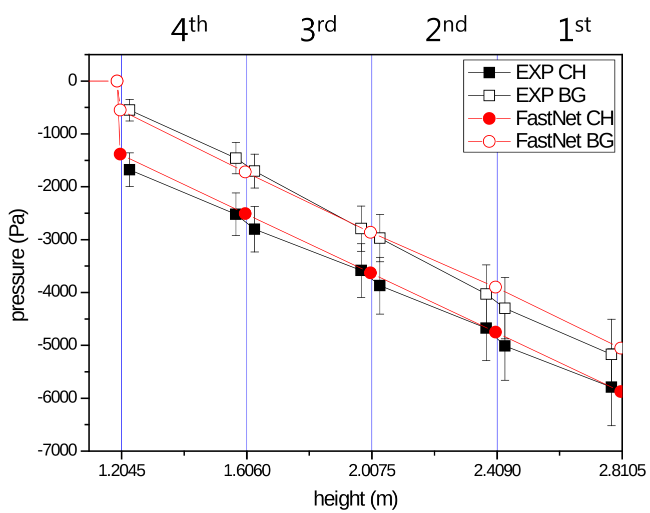
Bypass gap 2 mm, Cross gap 0 mm



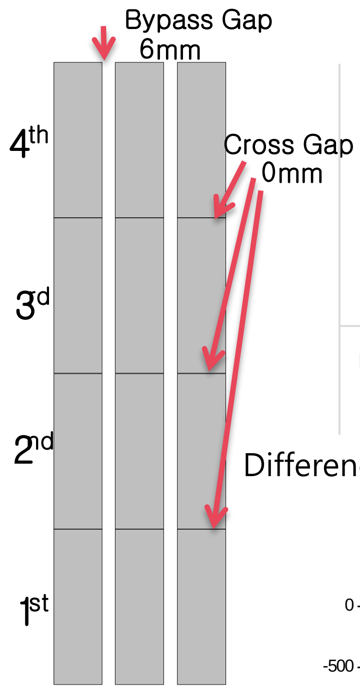
Graphite blocks



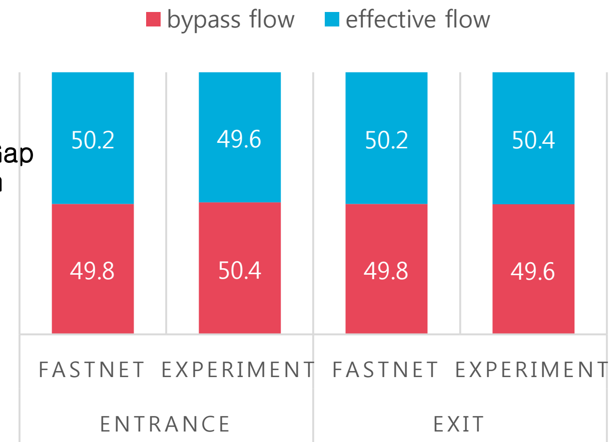
Difference: 0.4% 2.5%



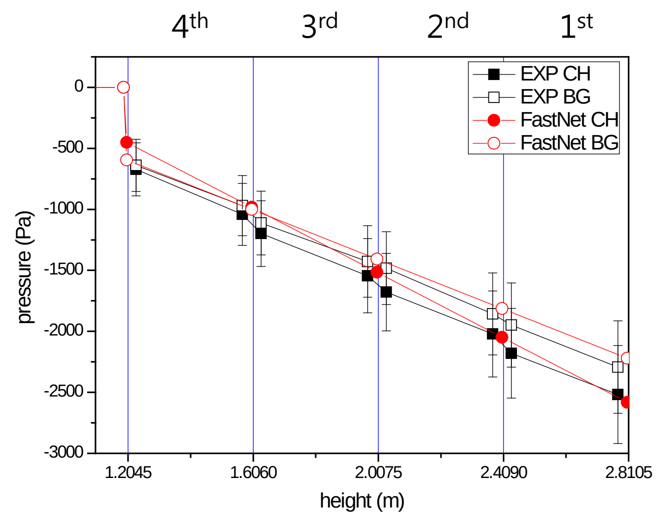
Bypass gap 6 mm, Cross gap 0 mm



Graphite blocks

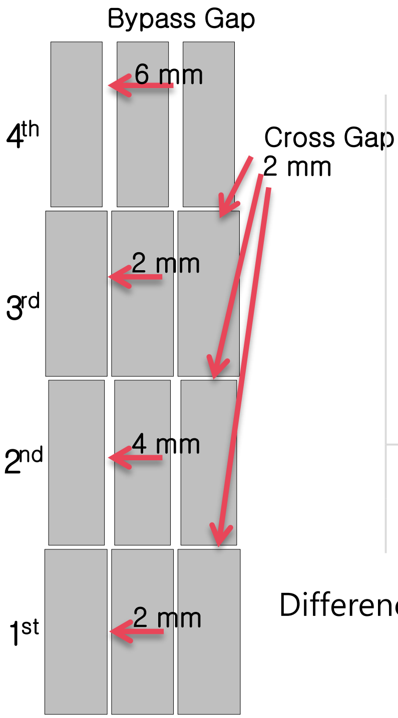


Difference: 0.6% 0.2%

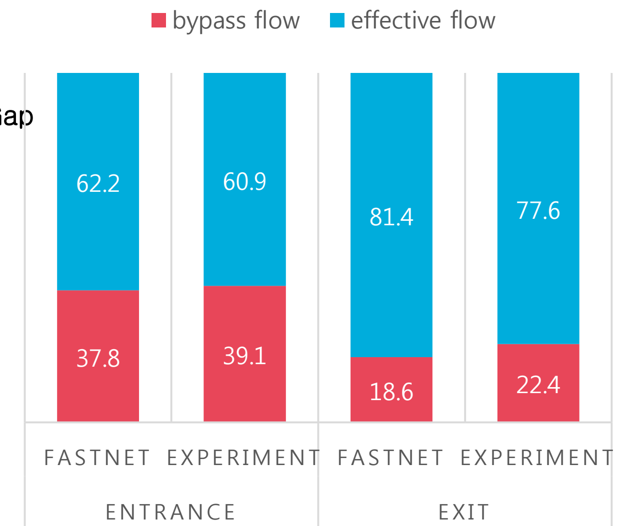


Validation Results

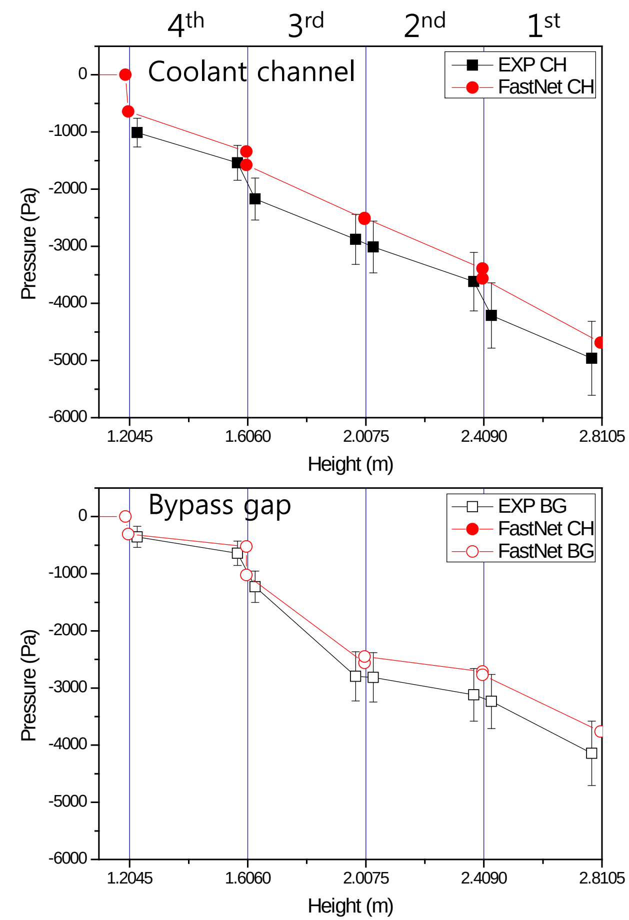
Bypass gap 6-2-4-2 mm, Cross gap 2 mm



Graphite bocks



Difference: 1.3% 3.8%



- The flow network analysis code slightly underestimates pressure drop.
- Considering the uncertainty of the experimental results, the flow network analysis code shows reasonable results.

Conclusions

- **A flow network analysis code was developed to evaluate the core bypass flow distribution by using looped network analysis method.**
- **The flow network analysis code was validated with SNU multi-block experiment.**
- **The flow network analysis code predicted the flow distribution and pressure drop of the SNU multi-block experiment.**
- **It can be expected that the developed network code can contribute to assure the core thermal margin by predicting the bypass flow in the whole core of VHTR.**

- **Further work**
  - Heat transfer module will be added on.

Thank You!

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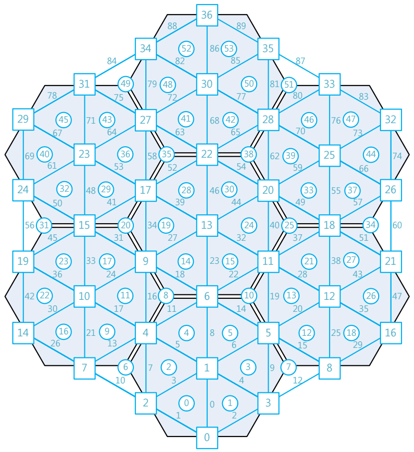
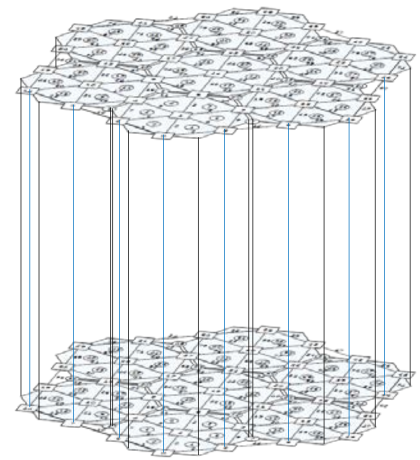
Number of Equations



Side view

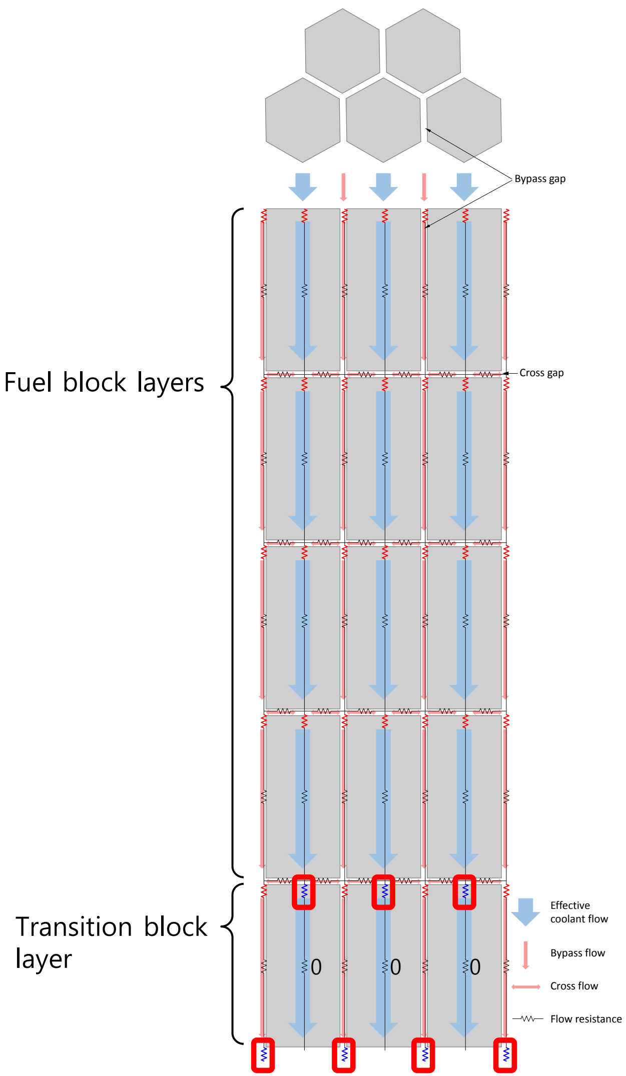


Top view

n layers	Lateral network	n+1
	Vertical network	n
Number of nodes		(number of base nodes)·(n+1)
Number of flow paths		(number of base sides)·(n+1)+(number of base nodes)·n
Number of loops		(number of base elements)·(n+1)+(number of base sides)·n

Layers	0	1	2	3	4	5
Pipes	90	217	344	471	598	725
Nodes	37	74	111	148	185	222
Loops	54	198	342	486	630	774
Equations	(37-1)+ (54)	(74-1)+ (198-54*1)	(111-1)+ (342-54*2)	(148-1)+ (486-54*3)	(185-1)+ (630-54*4)	(222-1)+ (774-54*5)

❖ Sudden expansion at the exit



$$A_1 v_1 = A_2 v_2$$

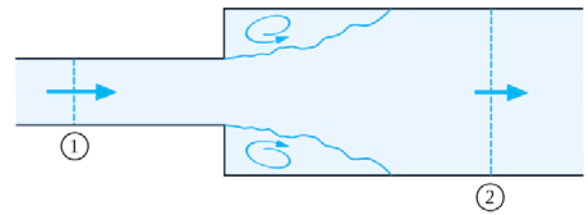
$$v_2 = \frac{A_1}{A_2} v_1$$

$$\Delta E = \frac{1}{2}\rho\left(1 - \frac{A_1}{A_2}\right)^2 v_1^2$$

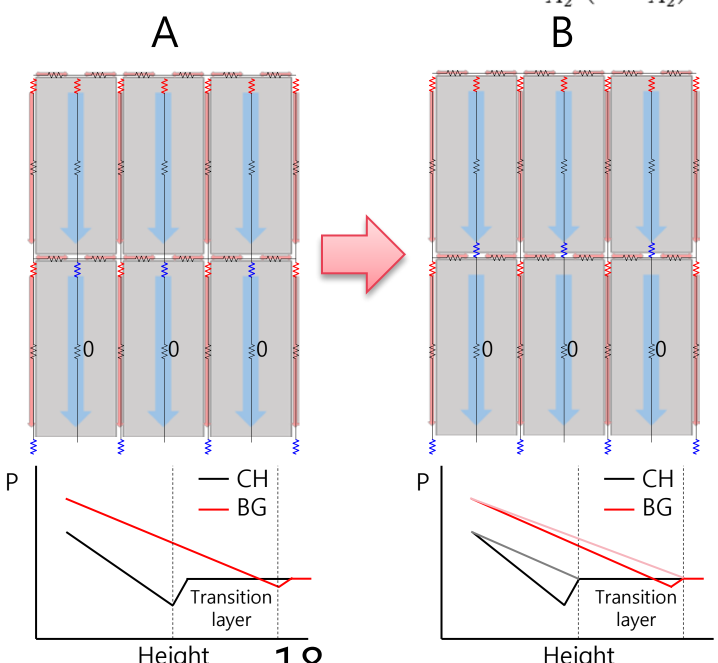
$$\Delta H = \frac{\Delta E}{\rho g} = \frac{1}{2g}\left(1 - \frac{A_1}{A_2}\right)^2 v_1^2$$

$$\Delta h = h_1 - h_2 = -\frac{1}{g}\frac{A_1}{A_2}\left(1 - \frac{A_1}{A_2}\right) v_1^2$$

$$\Delta p = p_1 - p_2 = -\rho\frac{A_1}{A_2}\left(1 - \frac{A_1}{A_2}\right) v_1^2$$



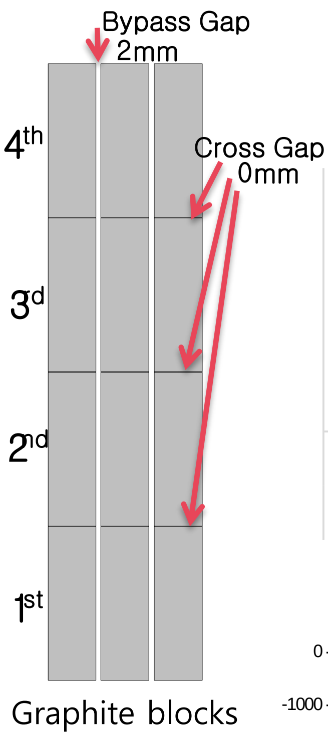
Boarda-Carnot Eq.

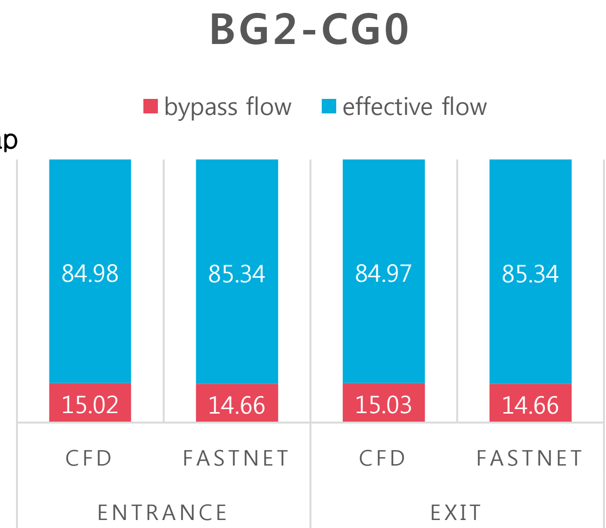


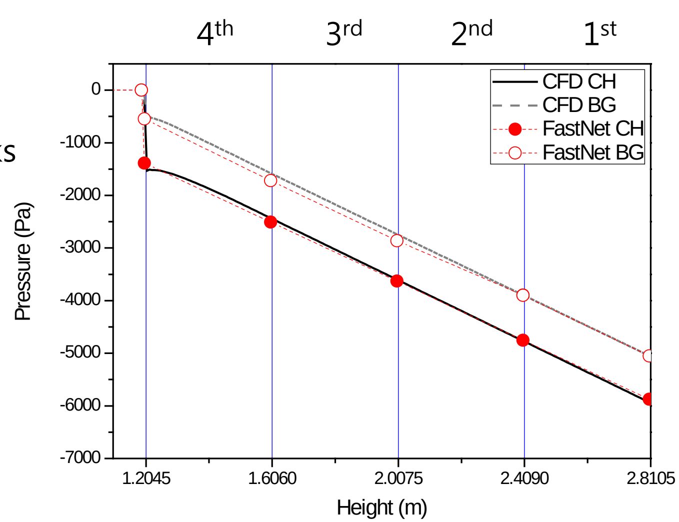
A – 유량의 역류가 발생하여 계산 불가능

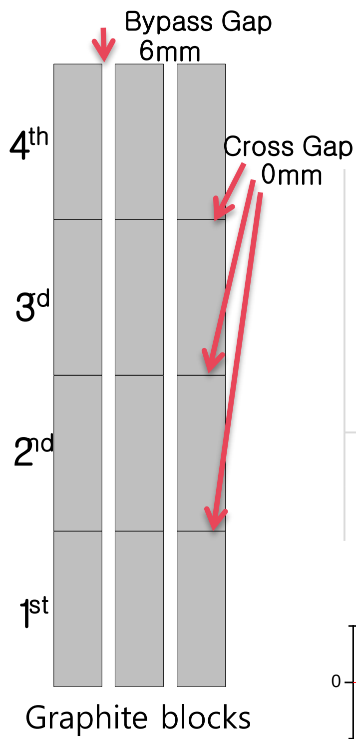
B – 압력회복, 수두회복을 위층의 저항과 함께 계산하면 이를 해결 가능

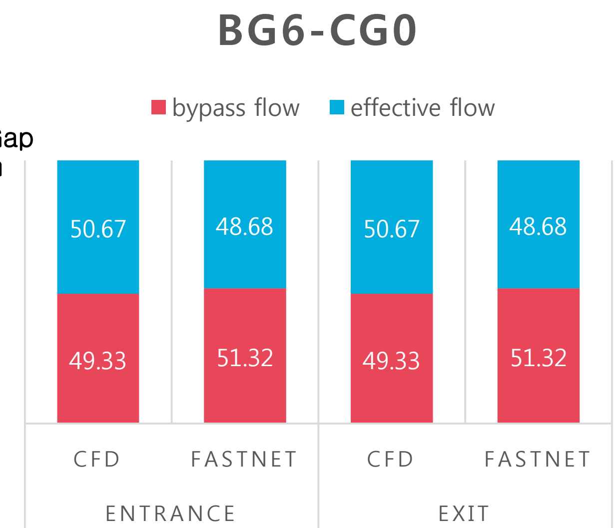
Bypass Gap 2 mm – Cross Gap 0 mm, Bypass Gap 6 mm – Cross Gap 0 mm

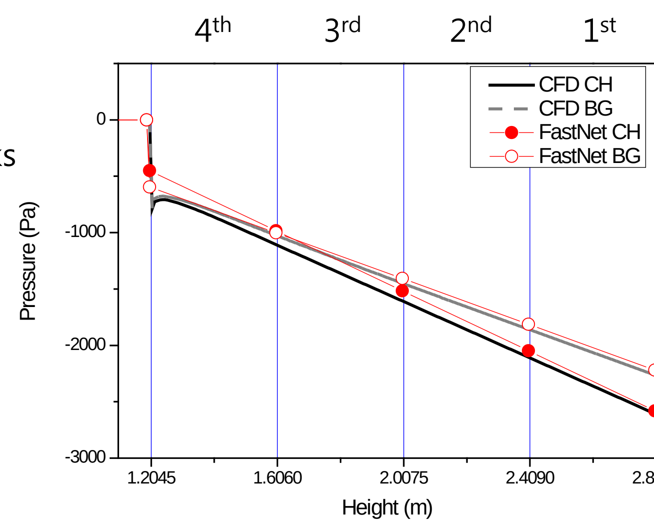




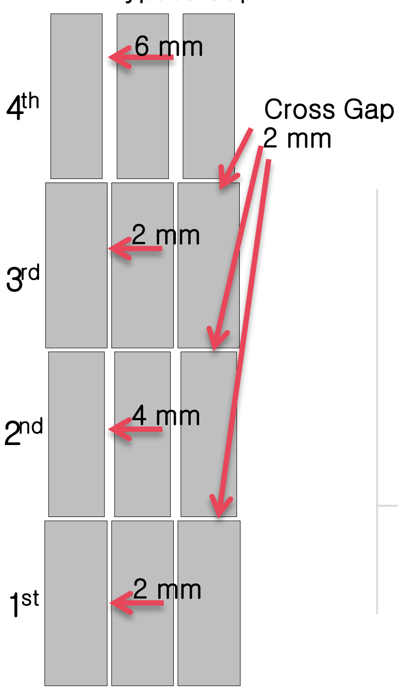








❖ Bypass Gap 6 – 2 – 4 – 2 mm – Cross Gap 2 mm

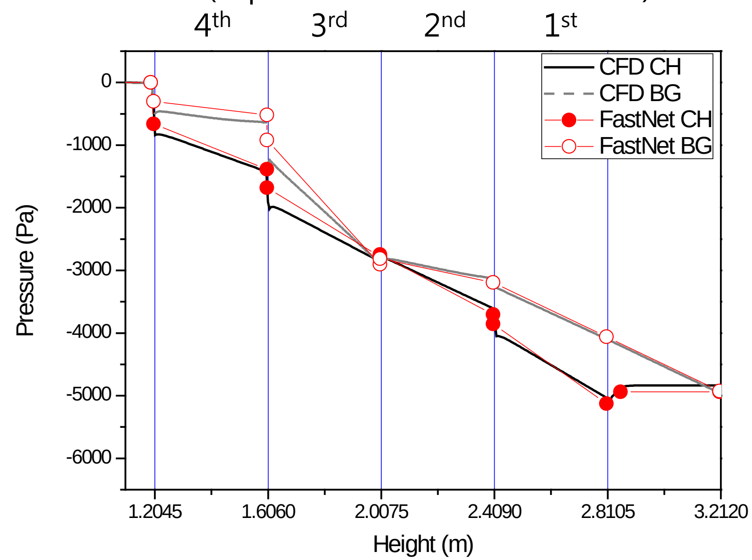


Graphite bocks

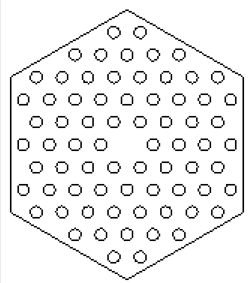
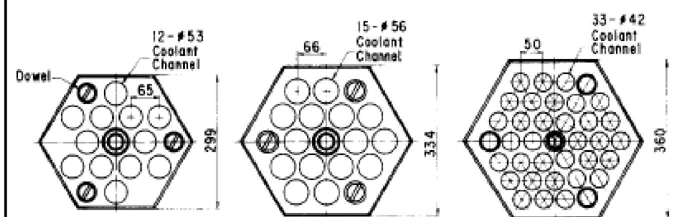
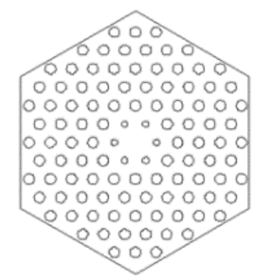
BG6242-CG2

	ENTRANCE CFD	ENTRANCE FASTNET	EXIT CFD	EXIT FASTNET
effective flow	62.82	64.15	85.77	86.17
bypass flow	37.18	35.85	14.23	13.83

Pressure drop (Experiment vs. Network code)



❖ Comparison of Fuel Block Type (Groehn 1981, Kaburaki 1990)

	German HTGR	Japanese HTTR	PMR200
Block type	Multi-hole type	Pin-in-block type (annular coolant hole)	Multi-hole type
Number of coolant channel	72	12, 15, 33	108
Channel diameter	18 mm	53 mm, 56 mm, 42 mm	16 mm
Cross section of fuel block			

⇒ different leakage perimeter

⇒ different cross flow loss coefficient

❖ Existing cross flow loss coefficient correlations

- H. G. Groehn (1981)

$$K = \left(\frac{A_{Gap}}{A_{CH}}\right)^2 \left[3.58\left(\frac{\delta}{D_{CH}}\right)^{-2.3} \cdot 6.33\left(\frac{A_{Gap}}{\delta \cdot l}\right)^{-1.68}\right]$$

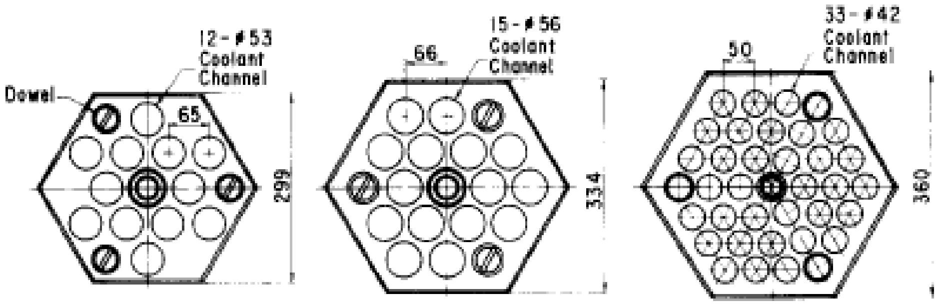
A_{Gap}: Area of the cross gap
A_{CH}: Area of the coolant channel
δ: Width of the cross gap
D_{CH}: Diameter of the coolant channel
l: Side length of the cross gap

  - Since Groehn's experiments is for turbulence (4200 < Re < 160000), the correlation includes only geometrical information but flow information.

- Hideo Kaburaki (1990)

$$K = \left(\frac{A_{Gap}}{\delta}\right)^2 \left(\frac{C_1}{\delta\, \mathrm{Re}_{Gap}} + C_2\right)$$

	C_1	C_2
Type I	0.67	3.13
Type II	0.90	2.0
Type III	0.78	1.7



Type I Type II Type III

❖ Comparison of loss coefficient correlations