Sub-channel Analysis of Ductless SFR Fuel Assemblies with Periodic Boundary Condition

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1. Introduction

The nuclear reactor core has design limitations due to its material properties and safety issues. In the Sodium cooled Fast Reactors (SFRs) the reactor coolant has very high boiling point, therefore the fuel centerline and the cladding temperatures are considered as the design limitations. The sub-channel analysis code is developed to estimate temperature distribution of the reactor coolant, and is able to evaluate whether the designed core is within the design limitations. Korea Atomic Energy Research Institute (KAERI) has been developing MATRA-LMR-FB code for the SFR core design and evaluation. The code is validated by many experimental data, therefore it shows reliable analysis results [1, 2].

The MATRA-LMR-FB is specialized for the duct SFR core design which is the general type in the SFR. The duct supports the fuel assembly structure and helps to control the coolant flow distribution by dividing coolant flow area. However the duct structure absorbs neutron and the neutron spectrum softens and the duct structure weakens. The duct structure causes friction loss and it leads to increase of pumping power in the reactor coolant system [3]. In safety issues, flow blockage accident gives critical damage to core.

The ductless SFR core design is one of the alternative to cope with the problems from the duct structure. The ductless SFR core has hardened neutron spectrum, reduced pressure drop in the reactor coolant system and mitigated flow blockage accident due to lateral flow between fuel assemblies. For the design and evaluation of the ductless SFR core, reliable thermal hydraulic analysis is required, however the ductless SFR core is not able to be analyzed by basic options of the MATRA-LMR-FB. The geometric input data of the MATRA-LMR-FB simulate duct structure and the code analyzes single fuel assembly, therefore the lateral flow between fuel assemblies is not analyzed. In this research, modification of the code input data for ductless core analysis and its results are introduced.

2. Methods and Results

2.1 Methodology of the ductless SFR core analysis

The MATRA-LMR-FB code simulates single fuel assembly, therefore analysis of the ductless SFR core requires modified methodology for calculating the lateral flow between fuel assemblies. For analysis of the lateral flow, Periodic Boundary Condition (PBC) is applied. When a specific appearance is repeated the system follows PBC, and a fuel assembly configuration is repeated in the ductless SFR core and the fuel rods generate similar heat due to characteristic of the SFR. Fig. 1 shows an example of ductless SFR core. In PBC, a side has same lateral flow rate with the opposite side due to the repetition.

The pressure drop at edge of the fuel assembly is analyzed by modified wetted perimeter. In the MATRA-LMR code the wetted perimeter of sub-channel is a major parameter for pressure drop calculation.

2.2 MATRA-LMR-FB input modification

In this research, 19 fuel pin assembly is simulated. The inlet mass flux, temperature and heat generation in the fuel rods are following the ORNL 19 pin experiment data, series 2 test 2 run 109 and the parameters are in the Table I [4].

The MATRA-LMR-FB code divides the fuel assembly into three types of sub-channel, which are interior, edge and corner channel. The wetted perimeter of the sub-channels are listed in Table II and the parameters used in the Table II are shown in Fig. 2. The duct doesn’t contribute to the wetted perimeter in the ductless SFR core. The pressure drop is calculated by Novendstern’s correlation, which is one of the pressure drop models in the MATRA-LMR-FB.

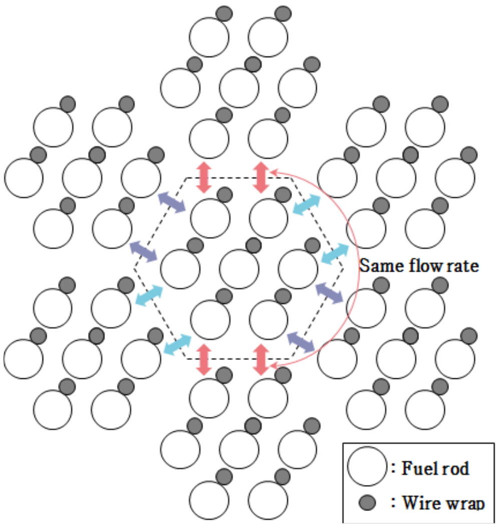

Fig. 1. Ductless SFR core in PBC (7 fuel pin)

Table I: ORNL 19 pin experiment, series 2 test 2 run 109

Parameter	Value
Mass flux	6476.8 kg/m^{2}s
Inlet temperature	315.6 ℃
Heat generation (per pin)	8.75 kW
Heat flux (average)	0.894 MW/m^2
Flow area	462.93 mm^2
Axial rod length	1,016 mm
Axial heated region	431.8 ~ 965.2 mm
Rod diameter	5.842 mm
Wire-wrap diameter	1.442 mm
Wire-wrap pitch	304.8 mm

Table II: Wetted perimeter of the sub-channels

Type	Duct core	Ductless core
Interior (1~24)	$\pi D/2 + \pi s/2$	$\pi D/2 + \pi s/2$
Edge (25~30)	$P + \pi D/2 + \pi s/2$	$\pi D/2 + \pi s/2$
Corner (31, 32)	$2/\sqrt{3}(D/2+g) + \pi D/6 + \pi s/6$	$\pi D/6 + \pi s/6$

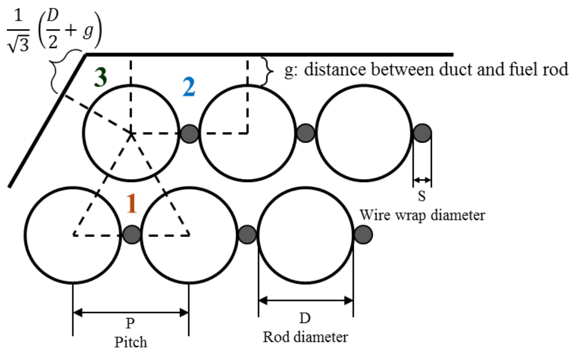

Fig. 2. Sub-channel types in the MATRA-LMR

The edge and corner channels are modified as Fig. 3. The edge and corner channels in one side and the sub-channels in the opposite side are merged due to PBC. Two edge sub-channels are merged and three corner sub-channels are merged, therefore the required number of sub-channels for analysis is reduced. For the geometry input data of the ductless core analysis, the edge channels have twice flow area of the channel of duct core and twice wetted perimeter calculated in Table II, and the corner channels have triple values. The interior channels are following configuration of the duct core analysis. The duct core requires 42 sub-channels, on the other hand the ductless core requires 32 sub-channels.

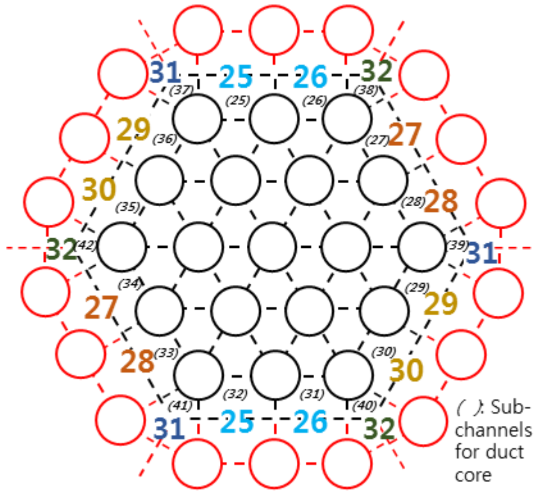

Fig. 3. Sub-channels configuration for ductless SFR core analysis

2.3 Analysis results

Both duct core and ductless core are simulated. Steady state condition and the implicit scheme are applied to this analysis, and the calculation variables which express the analysis condition are the default values of the code. The sub-channels have 12.7 mm of axial length and the simulation is conducted from 76.2 mm to 1,016 mm of the axial length, so there are 74 axial nodes in this simulation. The starting angle of the wire-wrap is given as zero. The heat generation in the rods are following the ORNL experimental data.

Pressure drop of the ductless SFR core is much smaller than the duct SFR core and the results are shown in Fig. 4. The ductless core has larger total hydraulic than the duct core, and it shows significant pressure drop difference between duct and ductless core. The major parameters in the analysis result are listed in Table III.

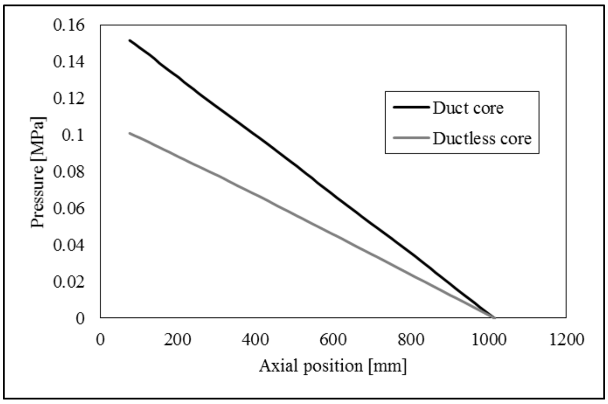

Fig. 4. Pressure drop of duct and ductless core

Table III: Parameters in pressure drop analysis

Parameter	**Duct core**	**Ductless core**
Total wetted perimeter (mm)	465.97	348.71
Total hydraulic diameter (mm)	4.23	5.66
Pressure drop (MPa) (76.2mm ~ 1,016 mm)	0.152	0.101

In the MATRA-LMR-FB, there are eight enthalpy mixing models and six models are used for this research. The enthalpy mixing models require the mixing parameter and this research uses the recommended mixing parameters. The analysis shows that the enthalpy mixing models have very similar results without the option 2. The enthalpy mixing models doesn't affect to the mass flux distribution, but the temperature and enthalpy distribution. The analysis results are shown in Fig. 5 and Fig. 6. The outlet temperature and mass flux are resulted and the comparison between duct and duct core is conducted.

The ductless core has large mass flux at the edge and corner channel due to reduced wetted perimeter of the channels, therefore the edge and corner have to show much lower temperature than the duct core analysis. However, the ductless core shows similar temperature distribution with the duct core due to the lateral flow between the fuel assemblies and the lateral flow and enthalpy mixing cause smooth temperature distribution in the core.

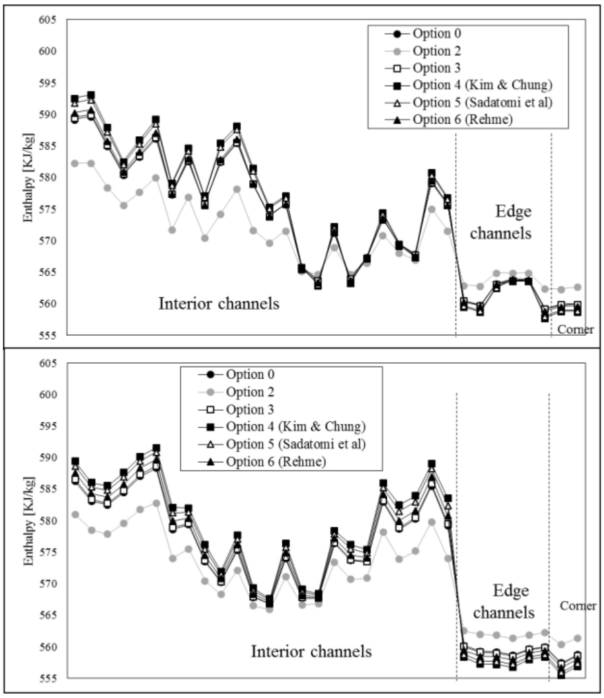

Fig. 5. Outlet enthalpy distribution (Upper: ductless, Lower: duct)

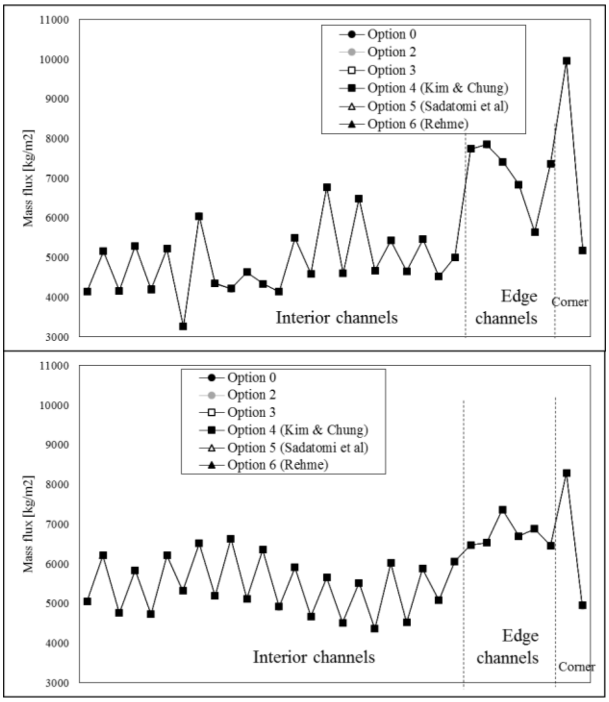

Fig. 6. Outlet mass flux distribution (Upper: ductless, Lower: duct)

2.4 Validation by CFD

For validation of the analysis by MATRA-LMR-FB, the CFD tool is used. Single fuel assembly is simulated and PBC is given at the side surfaces. There are total 80 million meshes, which are 1 prism layer on polyhedral meshes, and realizable k-epsilon model with high y+ wall is used. The minimum y+ is about 19 and the almost meshes' y+ are about 150. The solution is almost conversed.

Before the validation of ductless core analysis, duct core is analyzed first. The normalized temperature which is ratio between temperature rise of a sub-channel and all channels is explored at some sub-channels shown in Fig. 7 and the result is shown in Fig. 8. The CFD analysis result is obtained the average value of the sub-channel volume and the coverage means the minimum value and maximum value in the volume.

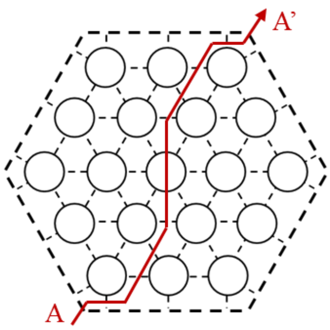

Fig. 7. Sub-channel plotting location

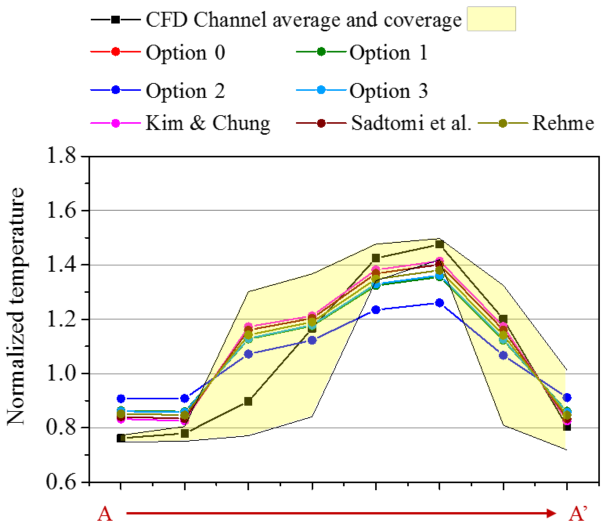

Fig. 8. CFD analysis for duct SFR core

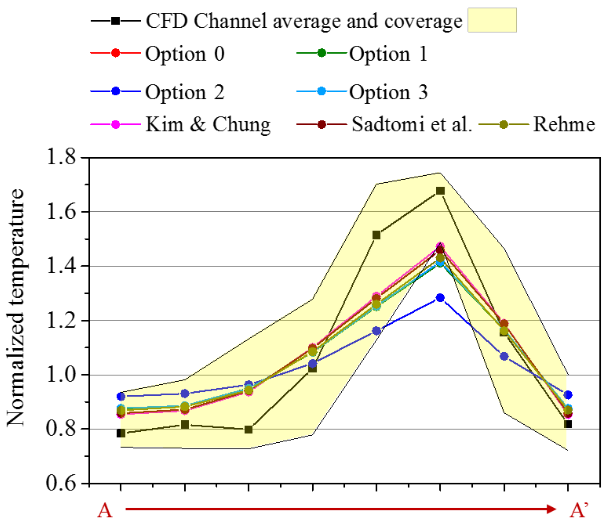

Fig. 9. CFD analysis for ductless SFR core

The duct core analysis shows that the CFD analysis has higher temperature at the center than the MATRA-LMR-FB. Among the enthalpy mixing models, Kim & Chung correlation shows the best estimation with the CFD analysis.

The ductless SFR core is also analyzed by CFD and the result is shown in Fig. 9 and the result shows that the CFD has much higher temperature at the center than the MATRA-LMR-FB. The pressure drop in the merged sub-channels seems to be overestimated, then the merged sub-channels have low mass flux and the temperature distribution becomes smooth.

3. Conclusions

The ductless SFR core is analyzed by the sub-channel analysis code MATRA-LMR-FB with PBC and its results are validated by the CFD tool. The analysis results show that the MATRA-LMR-FB code can be extended to analyze various type of SFR core such as ductless core. However, the reliable pressure drop model for the merged sub-channels at the edge and corner is required.

REFERENCES

[1] W. S. Kim, Y.G. Kim, Y.J. Kim, A subchannel analysis code MATRA-LMR for wire wrapped LMR subassembly, Annals of Nuclear Energy, Vol. 29, pp. 303-321, 2002.

[2] J. Moon, Y.H. Jeong, B.H. You, Validation of MATRA-LMR by ORNL 19-rods Fuel Assembly Experiment, Korean Nuclear Society Autumn Meeting, Oct.30-31, 2014, Pyeongchang, Korea

[3] A.A. Sedov et. al., A concept of Prospective Sodium Fast Reactor with Ductless Fuel Subassemblies in the Core, Proceedings of ICAPP 2007, May 13-18, 2007, Nice, France

[4] M. H. Fontana et. al., "Temperature distribution in a 19-rod simulated LMFBR fuel assembly in a hexagonal duct (fuel failure mockup bundle 2A) – record of experimental data," Oak Ridge National Laboratory, 1973