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Preliminary Thermal Hydraulic Design of SMR Core with 13 x 13 Annular Fuel Assemblies

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1. Introduction

Accident tolerant fuel (ATF) has been highlighted as one of inherent safety features to reduce the risk on the severe accident. It has been known that main capability of ATF is the reduction of hydrogen generation and protection of fuel melting under severe accident. The capability of ATF can be realized as combination of various materials of cladding and fuel rod to enhance the property of original material. Fully ceramic micro-encapsulated (FCM) fuel which is one of ATF concept has been developed around KAERI [1]. Kyung-Hee university (KHU) has conducted to apply the ATF fuel of FCM type to SMR core like SMART. Different from the previous design concept with solid type of FCM fuel, KHU suggested an advanced 13x13 fuel assembly concept which is comprised of FCM annular fuel and UO_2 annular fuel rods. In particular, the FCM annular fuel rods are considered to effectively consume TRU nuclides of PWR spent fuel stocks [2, 3].

Generally, it is well known that the annular fuels have the high performance aspects of DNBR and fuel temperature resulted from the double cooling on both of inner and outer surface of fuel [4]. FCM annular fuel combined with ATF and annular fuel concept is devised as one of alternatives satisfying both requirements of safety and performance. Recently KHU has performed neutronic design and analysis on a SMR core using 13x13 fuel assemblies with FCM and UO_2 annular fuel rods.

The objective of this work is to perform thermal-hydraulic analysis on the whole core of the small modular reactor (SMR) core using the axial and radial pin power distributions provided by KHU. MDNBR and fuel temperature are assessed on the hot pin which is evaluated in the result of whole core analysis. Thermal-hydraulic performance analysis on FCM annular fuel is compared with the typical UO_2 solid fuel.

2. Methods and Results

Whole core analysis system based on MATRA code to conduct the thermal-hydraulic analysis on SMR core consisted of FCM annular fuel is described. In order to estimate the performance of FCM annular fuel assembly, whole core analysis is conducted at BOC and EOC condition. Detail calculation in hot pin is conducted to evaluate MDNBR and available overpower margin (AOPM) in which these parameters are directly related on the core thermal margin. Fuel temperature of the hot pin is calculated and compared with temperature of solid fuel.

2.1 Method of Thermal-Hydraulic Analysis

Subchannel analysis code, MATRA developed by KAERI, is applied to perform the thermal-hydraulic analysis of SMR core with FCM fuel assembly. MATRA-GUI system to generate input file and output results for whole analysis is used as shown in Fig. 1. MATRA code applied to whole core analysis is a parallel computing version using hybrid MPI and OPEN-MP [5]. The performance of parallel version of MATRA code is estimated on the whole core TH calculation of SMR core with 57 assemblies. In this calculation, calculation speed is estimated with about 100 seconds with 40 CPUs.

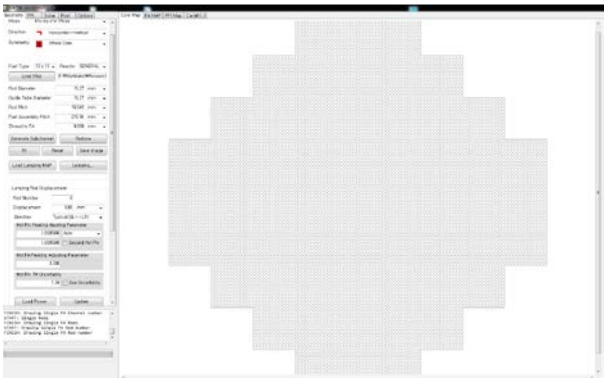


Fig. 1. Example of input processing using MATRA-GUI System

FCM annular fuel analysis using MATRA code is conducted using 2-stage calculation. Firstly, flow split factor determined of the mass flow rate of inner and outer channel is calculated based on the assembly-wise lumped channel analysis. The flow split factor is used to evaluate heat split factor which was determined of the partitioning ratio of heat flux of inner and outer rod surface. Calculated heat and flow split factors are used as an input parameter in the whole core analysis. In a second step, whole core calculation is performed on the inner and outer channel separately. An iterative calculation is continued until the difference between these two flow rates reaches a convergence criteria by comparing the initial input flow rates with the calculated flow rates. Fuel temperature of hot pin is evaluated using surface heat transfer coefficients on both sides which is calculated based on converged mass flow rates. The calculation procedure of MATRA analysis is summarized as shown in Fig. 2.

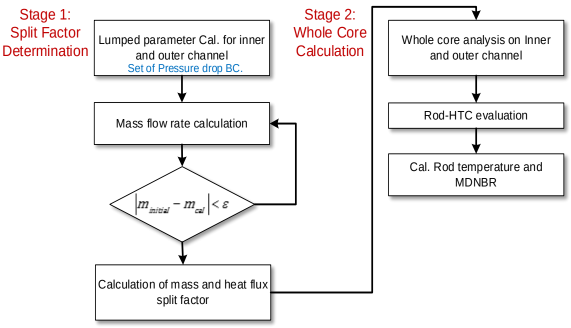


Fig. 2. Schematic flow charts for calculation of annular fuel assembly using MATRA-Annular

Table I: Geometry of FCM annular fuel

	Inner	Outer
Fuel pellet diameter (cm)	0.945	1.363
Inside cladding diameter(cm)	0.82	0.934
Outside cladding diameter(cm)	1.379	1.527
Guide tube diameter(cm)	1.379	1.527

Table I shows the general descriptions of FCM annular fuel applied to the calculation. The material property of FCM fuel was described in reference 1.

2.2 Design Requirement of FCM Annular Fuel Assembly Core

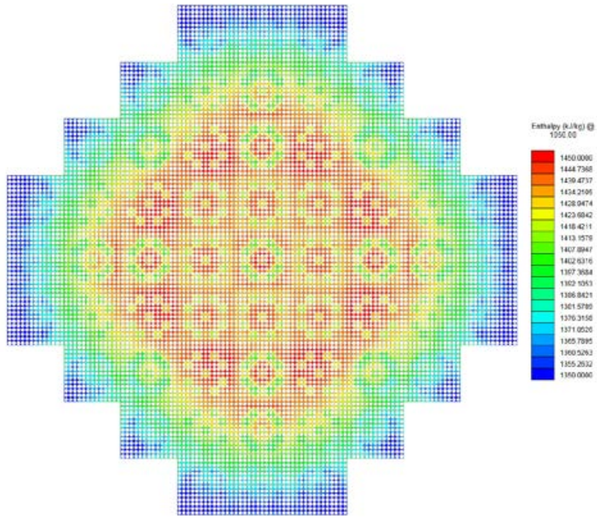
The important parameters of thermal-hydraulic design are peak fuel temperature, core pressure drop and MDNBR. Low fuel temperature was ensured compared with reference assembly to protect the fuel integrity. Core pressure drop of new fuel assembly shall not be exceeded with the value of reference core pressure drop because of pump capacity and integrity of upper core plate. MDNBR of new fuel assembly shall not be deteriorated with comparison of reference fuel assembly if new fuel assembly is loaded in reference core with reference fuel assembly. These design requirements for FCM annular fuel assembly are summarized in Table II

Table II: Thermal-Hydraulic design requirements for FCM annular fuel assembly

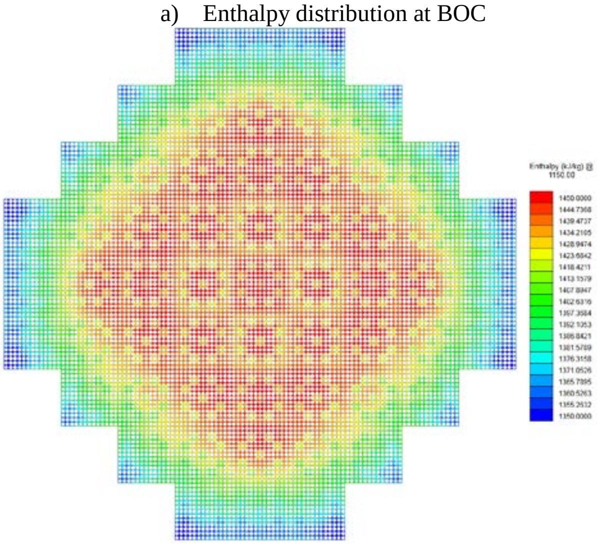
Parameter	Criteria
Fuel temperature	$T_{fuel\_AF} < T_{fuel\_ref}$
Core pressure drop	$\triangle P_{fuel\ AF} \sim \triangle P_{fuel\_ref}$
MDNBR	$MDNBR_{fuel\_AF} > MDNBR_{fuel\_ref}$

2.3 Whole Core Analysis Results

Whole core analysis of SMR core consisted of 57 FCM annular fuel assembly are conducted. Fig. 3 shows the enthalpy distributions at BOC and EOC on the outer channel of whole core. Coolant enthalpy distribution is proportional to the radial power distribution. In a whole burn-up, hot assembly which has the maximum enthalpy occurred at assembly at center position in which alphabet represent column and Arabic number means row number.



a) Enthalpy distribution at BOC



b) Enthalpy distribution at EOC

Fig. 3. Results of whole core analysis at location of MDNBR occurrence

2.4 Hot Rod Results

Based on the results of whole core analysis, hot assembly and hot channel are identified and evaluated on the aspect of MDNBR. The critical heat flux (CHF) correlation, W-3, is applied to the calculation. It is available to the various operating condition and geometry type such as fuel assembly and tube [6].
MDNBR distribution on the outer and the inner fuel surface of hot rod is shown in Fig. 4. In this figure,

MDNBR of FCM annular fuel is compared with the typical MDNBR of solid fuel to estimate the thermal margin aspects of the MDNBR.

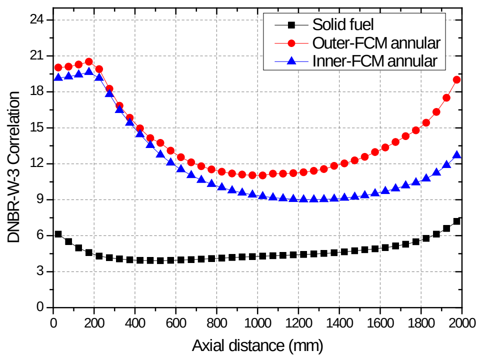


Fig. 4. Axial distributions of MDNBR compared with that of solid fuel.

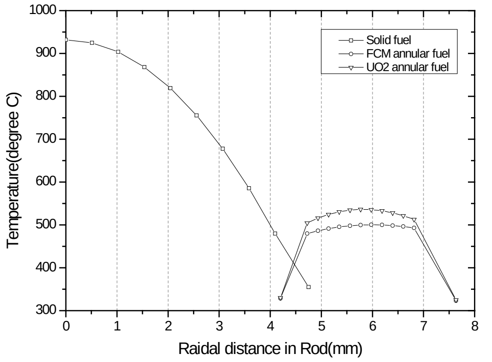


Fig. 5. Comparison of annular fuel temperature with solid fuel

Thermal margin of SMR core is estimated on the AOPM defined as equation (1). When the Limit DNBR with 1.3 is applied, AOPM of FCM annular fuel is evaluated as a 240 % at the inner channel in which the minimum DNBR occurred. The AOPM of FCM annular fuel was estimated on the 30% improved in comparison of solid fuel.

$$AOPM = \frac{Power_{at\ LimitDNBR}}{Power_{at\ \mathrm{nominal}}} \quad (1)$$

From a view point of surface heat flux, FCM annular fuel has advantage on the solid fuel owing to the dual cooling of both sides. Figure 5 shows the comparison of fuel temperature distribution of solid fuel. Centerline temperature of annular fuel is assessed apparently as low as about 50 % compared with the solid fuel. In comparison of FCM annular fuel and UO_2 annular fuel, centerline temperature of FCM annular fuel is assessed to be about 40℃ lower because the thermal conductivity of the FCM fuel is slightly higher than that of UO_2.

3. Conclusions

The system of thermal-hydraulic analysis for whole core was developed to evaluate the performance of FCM annular fuel. The analysis based on the power distribution provided by KHU was conducted on MDNBR, fuel temperature and AOPM of the SMR core with FCM annular fuel.

FCM annular fuel was estimated with improvement of thermal margin with 30% as well as fuel centerline temperature with 50% in comparison of conventional PWR.

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