Development of Transient Fuel Performance Analysis System for Ultra Long-life Micro Lead-cooled Fast Reactor

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1. Introduction

During global efforts to reduce carbon to respond to climate change. According to the International Maritime Organization (IMO), the global shipping industry currently emits about 1 billion tons of CO_2 as of 2018, which is 2.89% of the world's total CO_2 emissions [1]. Therefore, ships registered with the IMO must reduce the sulfur content of diesel fuel to less than 0.5% from 2020 and reduce CO_2 by 40% and 50% compared to 2008 by 2030 and 2050, respectively [2]. Therefore, reactor-powered ships are a good alternative to conventional fossil fuel-powered marine ships because they have high energy density, no greenhouse gas emissions, and have already operated nuclear submarines and aircraft carriers around the world. Micro lead cooled fast reactor (LFR) called MicroURANUS which can be operated for 40 years without refueling is currently being studied for the reference system of the nuclear-propellant ships [3].

Accident analysis of a nuclear reactor is very important to evaluate whether the safety margin of the nuclear fuel is satisfied for possible accidents caused by the design of a nuclear reactor. In this study, a fuel transient performance code for LFR, FRAPTRAN-KAIST-1.0 has been developed based on FRAPTRAN-2.0. Because FRAPTRAN-2.0 is an LWR-based performance analysis code, the coolant and cladding modules were modified. The evaluation of the thermal and mechanical performance of nuclear fuel during the Loss-of-flow (LOF) scenario was conducted through the developed FARPTRAN-KAIST-1.0. The developed fuel transient analysis code was validated with 3D finite element analysis (FEA) solutions obtained by ANSYS thermal and mechanical.

2. Methods and Results

2.1 Simulation conditions and modified calculation module

Table I: Fuel rod design for the LFR core

Design Factor	*Design Value*
Fuel material	*UO_2*
Cladding material	*15-15Ti*
Fill gas material	*He*
Fuel rod outer diameter / Cladding thickness(mm)	*20.0/0.95*
Coolant Pb/Bi composition (wt%)	*44.5/55.5*

Table 2: Modified material properties in FRAPTRAN-KAIST-1,0

Module	*Material*	*Properties*
Cladding	*Zircaloy-4 → 15-15Ti*	*Thermal conductivity, Heat capacity, Thermal expansion, Transition temp., Modulus, Creep Irradiation swelling*
Coolant	*Water → LBE*	*Time & axial region dependent properties at Loss of Flow (LOF) of 1) Temperature 2) Heat transfer coefficient 3) Mass flux 4)Pressure*

Table 1 shows the nuclear fuel design and cladding material of the current reactor. Therefore, it is necessary to change the material of the cladding and coolant for FRAPTRAN-2.0, which was developed for the existing LWR, as shown in Table 2. In the cladding module, thermal conductivity, heat capacity, thermal expansion, transition temperature, and modulus were modified to 15-15Ti austenitic stainless steel. For the input of the coolant characteristics of FRAPTRAN-KAIST-1.0, MARS-LBE code evaluation results developed for the analysis of the transient thermal-hydraulic behavior of MicroURANUS in the previous study was used [4]. In this study, fuel performance was evaluated for loss of flow (LOF) accidents occurring at the beginning of life (BOL) among possible accident scenarios of MicroURANUS. Therefore, from the MARS-LBE calculation results, the temperature, heat transfer coefficient, mass flux, and pressure of LBE coolant according to the accident time and the axial region of the nuclear fuel were inputted to FRAPTRAN-KAIST-1.0 as shown in Figure 1. From Table 3, the event tree of BOL-LOF is specified. It is an accident assuming that the mass flux decreases assuming a pump stop of 10 seconds, and the passive heat exchanger system operates at 42.67 seconds after the reactor stop at 23.67 seconds. Also for the power input, it was assumed that constant power was just before the reactor shutdown. After the shutdown and control rod insertion, power was decreased as shown in Figure 2.

Table3: Event tree of the BOL-LOF accident

	Initiating event	Reactor protection signal	Reactor shut down	PRACS valve open
Event time	t =10s	t = 22.67s	t = 23.67s	t = 42.67s
Details	Emergency stop of primary coolant pump Coolant **Mass flow reduction**	High temperature signal at the coolant outlet region (420℃)	Linear **control rod insertion** after shut down	**Passive cooling** by natural circulation of super critical CO_2

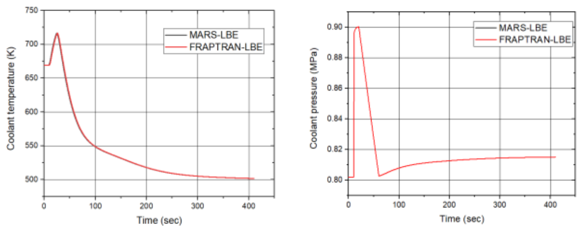

Fig. 1. (a) Coolant temperature and (b) coolant pressure input condition for BOL-LOF from MARS-LBE [4]

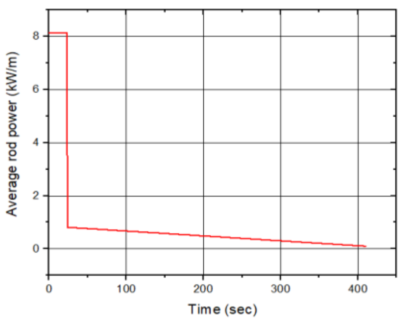

Fig. 2. Power input condition for BOL-LOF

2.2 Thermo-mechanical behavior of the fuel rod by FRAPTRAN-KAIST-1.0

The performance evaluation result of the outlet side with the highest temperature in the fuel rod is shown in Figure 3. After time at 10 s of primary pump shutdown, the heat transfer coefficient of the coolant rapidly decreases due to mass flux decrease and temperature of coolant increases. As a result, cladding temperature increased by 50K and reached the maximum temperature of 740K. To prevent damage to the cladding due to a high-temperature creep of 15-15Ti, the maximum temperature of the cladding is limited to less than 873K [5]. The cladding temperature was also low enough. Fuel temperature increment was negligible. It was found that enhancement in fission gas release did not occur this is due to the effect of increasing the fuel temperature being insignificant.

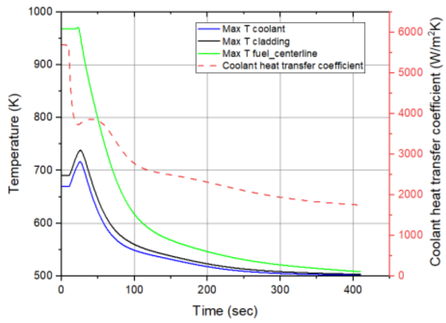

Fig. 3. Fuel and cladding temperature change profile in the hottest region

As fuel temperature increased, cladding temperature increased and reached to 740K. Thermal strain due to thermal expansion was observed during the temperature increase. Thereafter, due to natural circulation, the cladding temperature was lowered, resulting in shrinkage.

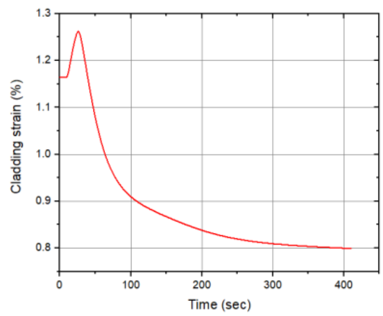

Fig. 4. Cladding strain change profile

2.3 Thermo-mechanical validation of the analysis results by 3D FEA

In this section, validation of thermo-mechanical analysis results from developed FRAPTRAN-KAIST-1.0 was discussed. Cladding only fuel rod models were adopted and two-steps calculations by ANSYS static-thermal and static-structural modules were performed. Steady-state thermal evaluation results which is temperature were transferred to the structural calculation. Boundary conditions are stated in Figure 5.

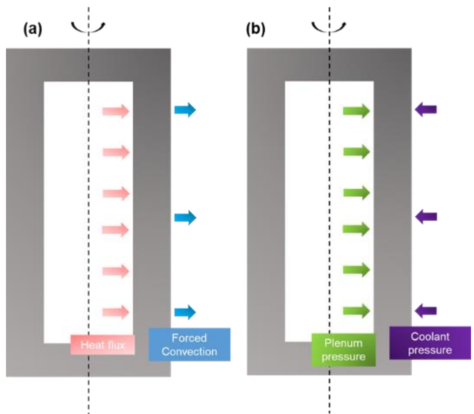

Fig. 5. Boundary conditions for (a) thermal and (b) structural validation using 3D FEA

The first part is the thermal validation result. By the inputted heat flux and cladding properties, cladding temperature shows good agreement. It was consistent with max 2 K error and it predicted almost the same maximum temperature and time at a maximum temperature which can be found in Table 4.

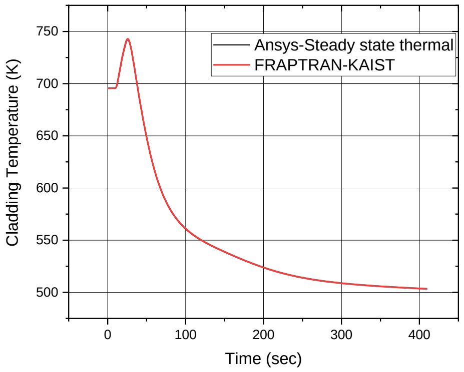

Fig. 6. Thermal validation results

Table 4: Maximum temperature and time validation results

	FRAPTRAN-KAIST-1.0	*3D FEA-Steady state thermal*
Maximum temperature[K]	*740.69*	*739.3*
Time at maximum temperature [sec]	*26*	*26.34*

For structural validation plenum pressure history due to fission gas release and coolant pressure boundary from thermal-hydraulics code was implemented as a boundary condition. Also, a fixed support constraint of the lower cladding surface was adopted. Temperature load calculated from the thermal module were transferred to the structural module.

Compared with the FRAPTRAN results, the overall pattern is the same, but an increase in the cladding hoop stress at the beginning of the accident was found in the 3D FEA structural calculations in Figure 7. Also for the hoop strain, both 3D FEA and FRAPTRAN-KAIST hoop strain results follow the plenum pressure trend. However, hoop strain changes were smaller in the 3D FEA case which means restricted deformation.

This difference originated from the bending of the cladding end region considered by the 3D FEA. In the FRAPTRAN calculations, however, loading is assumed to be uniform in the axial direction, and no bending is considered [6]. In real cases, the end region of the cladding cannot be axially uniform due to bending. Therefore, deformation was restricted due to the edge in the 3D FEA. Also, free expansion to axial direction due to axial stress constraint which is cladding edge part. Therefore, stress levels were slightly increased at the beginning in the 3D FEA case.

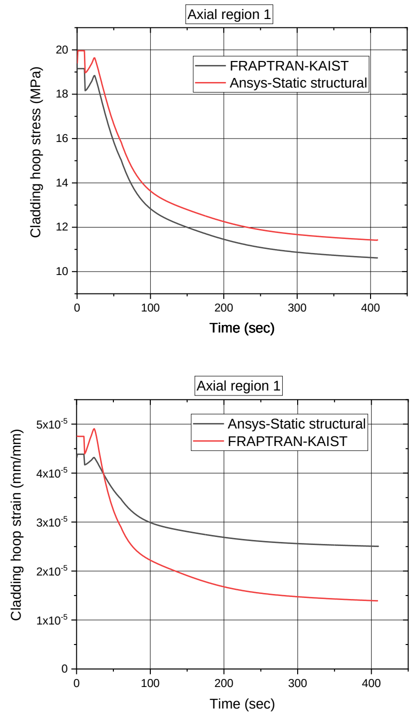

Fig. 7. *(a) Cladding hoop stress and (b) hoop strain validation results*

Table 5: Cladding structural validation results

	FRAPTRAN-KAIST-1.0	*3D FEA*
Max. cladding hoop stress [MPa]	*19.15*	*19.96*

3. Conclusion

In this study, the development of the transient fuel performance code FRAPTRAN-KAIST-1.0, which is for the austenitic stainless cladding, and LBE coolant fast reactor was conducted. Based on LWR normal operation fuel performance code FRAPTRAN-2.0, the material properties and models were modified to adopt the characteristics of the current reactor. Through the developed code, BOL-LOF transient operation analysis of MicroURANUS was conducted to evaluate fuel performance and safety in terms of thermal stability and mechanical integrity. All calculated results were validated by 3D FEA using ANSYS.

In the BOL-LOF accident scenario, the increase in fuel temperature was calculated to be negligible. Therefore low fuel temperature provides a large safety margin for fuel melting as well as low-pressure build-up fission gas release. The temperature of the cladding was evaluated with an increase of about 50 K, but it shows a sufficient margin from the creep rupture temperature of the cladding. As a result of thermal validation of the developed code, thermal calculation results were sufficiently consistent. In structural validation parts, there was a slight difference from the 3D FEA result since FRAPTRAN-KAIST-1.0 uses an axially uniform simplified model to analyze the mechanical response of the fuel rod.

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REFERENCES

[1] IMO, Greenhouse Gas Emissions, https://www.imo.org/en/OurWork/Environment/Pages/GHG-Emissions.aspx.

[2] IMO, MEPC.304(72) IMO Strategy on reduction of GHG emissions from shipsStrategy on reduction of GHG emissions from ships, Int. Marit. Organ. (2018).

[3] T.D.C. Nguyen, M.F. Khandaq, E. Jeong, J. Choe, D. Lee, D.A. Fynan, MicroURANUS: Core design for long-cycle lead-bismuth-cooled fast reactor for marine applications, Int. J. Energy Res. (2021). https://doi.org/10.1002/er.6661.

[4] S. Choi, J.H. Cho, M.H. Bae, J. Lim, D. Puspitarini, J.H. Jeun, H.G. Joo, I.S. Hwang, PASCAR: Long burning small modular reactor based on natural circulation, in: Nucl. Eng. Des., 2011. https://doi.org/10.1016/j.nucengdes.2011.03.005.

[5] G. Grasso, C. Petrovich, K. Mikityuk, D. Mattioli, F. Manni, D. Gugiu, F.C. Methods, N.T. Energy, Demonstrating the Effectiveness of the European Lfr Concept: the Alfred Core Design, IAEA Conf. FR13. (2013).

[6] K.J. Geelhood, W.G. Luscher, FRAPTRAN-2.0: Integral Assessment, 2 (2016) 158.