System Analysis of Flow Blockage Phenomena in a Liquid Metal-cooled Small Marine Reactor

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1. Introduction

Liquid metal-cooled fast reactor is one of the 4th generation reactor technologies. It has some advantages such as atmospheric pressure operation, nuclear fuel reprocessing, safety and sustainability. So, it is being developed intensively in several countries such as Belgium, the UK, Russia, and China. The small lead-cooled fast reactor is a type of liquid metal-cooled fast reactor. It doesn't emit carbon compared with diesel engines and it can operate for several decades without refueling. So, it can be used as an energy source in various places such as ships.

Small lead-cooled reactors have several faults to overcome, and one of the most important is being corrosion of the reactor structure by lead-based high temperature coolant. Lead-based coolant has a high boiling point, so coolant boiling occurs rarely. But, since a high melting point (lead = 327℃, LBE = 125℃), it has a limitation in that coolant needs to be operated at a high temperature. When the lead-based coolant corrodes the reactor structure at high temperatures, debris may be generated, and the flow blockage can be occurred at fuel assembly. Thus, flow blockage due to major limitations is a phenomenon that must be considered essential in the design of small lead-cooled fast reactors.

LFRs (Lead-cooled Fast Reactor) being developed around the world are also considering the flow blockage phenomena caused by corrosion. ALFRED (Advanced Lead Fast Reactor European Demonstrator), one of the European LFR, analyzed the flow blockage phenomena in a single fuel assembly using the RELAP5 system code [1]. It assumed that the flow blockage has occurred at the beginning of the active region, and it was confirmed that the cladding is melted when the flow blockage rate over 97.5% SNCLFR-100, the natural circulation LFR of China, was calculated that the coolant, fuel, and cladding temperatures increased significantly as the fuel assembly inlet blockage rate increases. It was calculated that when the blockage ratio increased to 0.9, the coolant mass flow rate in the fuel assembly dropped under 12.6% [2].

Even in the 60MWth small-marine LFR developed by UNIST, the flow blockage phenomena by corrosion is one of the major limitations. It is important in terms of safety to calculate when the cladding melt occurs depending on the flow blockage rate increase in the fuel assembly.

2. Methods and Results

2.1 calculation model

The developed small-marine LFR has a 60MWth power and uses LBE (Lead-Bismuth Eutectic) as a coolant. It is a pool-type reactor with natural circulation performance due to the difference in the height of the heat center between the core and the steam generator. Forced circulation and natural circulation are used together.

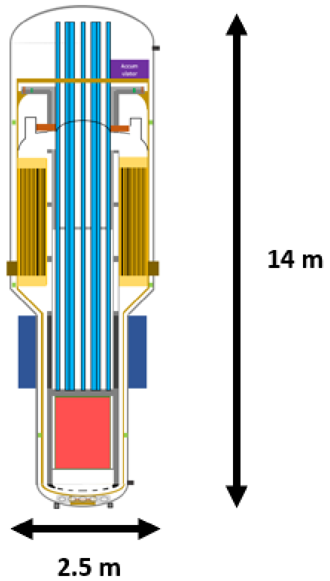

Fig. 1. Small-marine LFR primary system schematic diagram.

Table I: Small-marine LFR Primary System Design Parameters

Reactor power	60MWth
Reactor type	Pool-Type
Primary system coolant	LBE
Cladding material	15-15Ti
Primary system working pressure	1 atm
Core inlet temperature	250ºC
Core outlet temperature	350ºC

Mass flow rate	4196 kg/s

The hottest fuel assembly in the reactor core was modeled separately. Mass flow rate decreases and component temperature increases are analyzed as a ratio of flow blockage in the hottest fuel assembly. With reference to Shanghai Jiao Tong's flow blockage analysis [3], It was assumed that the flow blockage occurs with a thickness of 5 cm at the beginning of the active region of the fuel assembly and the material is stainless steel.

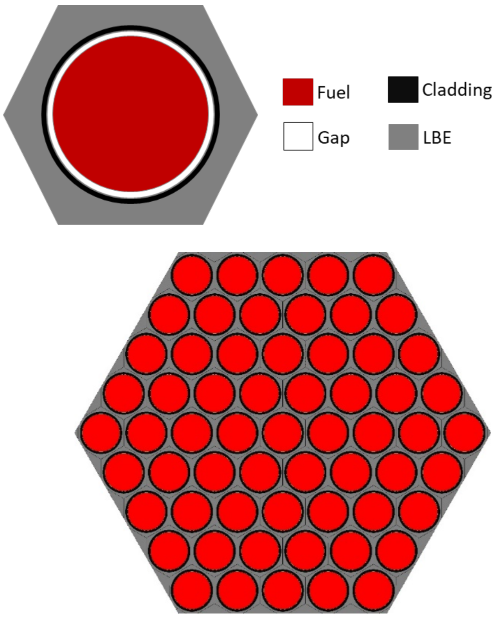

Fig. 2. Pin and fuel assembly schematic diagram.

Table II: Pin and Fuel Assembly Design Parameters

Pin diameter (cm)	2.00
Gap thickness (cm)	0.0015
Cladding thickness (cm)	0.0095
Pin pitch (cm)	2.16
Assembly pitch (cm)	17.15
# Pins	61
Active region height (cm)	155

The safety criteria for nuclear fuel, cladding, and coolant were established by referring to previous papers. The melting point of nuclear fuel was set at 2673℃ by referring to the safety criterion of SVBR 75/100 [4] using UO_2 fuel and M^{2}LFR-1000 [5] using MOX fuel. The melting point of the cladding material was selected as 1407℃ based on the characteristics of 15-15Ti [6]. In addition, referring to ALFRED, 700℃ was set as the temperature at which creep of the cladding material can occur. The freezing and boiling points of the LBE coolant were set as 127℃<LBE<1670℃ referring to the LBE handbook [7].

2.2 numerical result

While increasing the flow blockage ratio from 0% to 90% in the hottest fuel assembly, the rate of decrease in mass flow rate and the rate of increase in fuel, cladding and coolant temperature were analyzed. The mass flow rate slowly decreased as the blockage ratio increased in under 60%, and then decreased significantly above 60%. The heat transfer performance decreases because of a mass flow rate decrease, so the peak coolant, cladding temperature and maximum fuel temperature increase. However, it did not reach the coolant boiling point, cladding and fuel melting point even when the flow blockage by 90%, and did not reach 700℃, which is the cladding creep temperature.

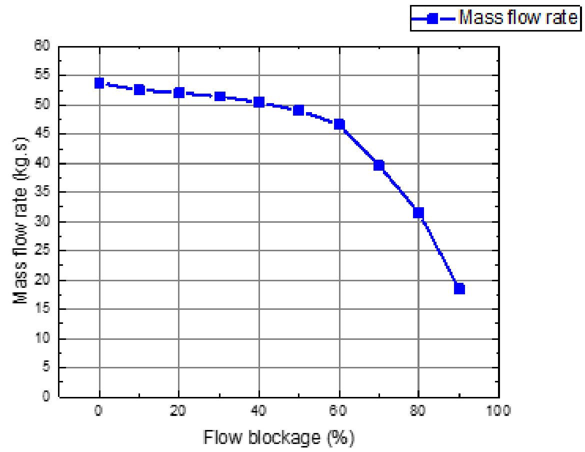

Fig. 3. Mass flow rate at 0% to 90% flow blockage.

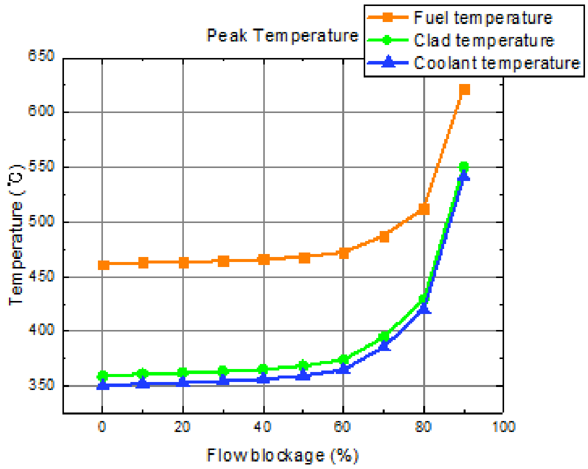

Fig. 4. Peak temperatures at 0% to 90% flow blockage.

Changes in mass flow rate, peak coolant temperature, peak clad temperature, and maximum fuel temperature were analyzed in case of blockage over 90%. In the case of flow blockage over 90%, the mass flow rate decreased significantly when the flow was blocked little by little. The peak cladding temperature increased significantly due to the low mass flow rate, and when the flow blockage ratio was over 97.5% to 98%, clad melting occurred at the outlet of the core. Before the clad melting, the clad creep temperature of 700°C was reached at 94% blockage. Therefore, clad creep may occur when operating for a long time in a 94% flow blockage condition.

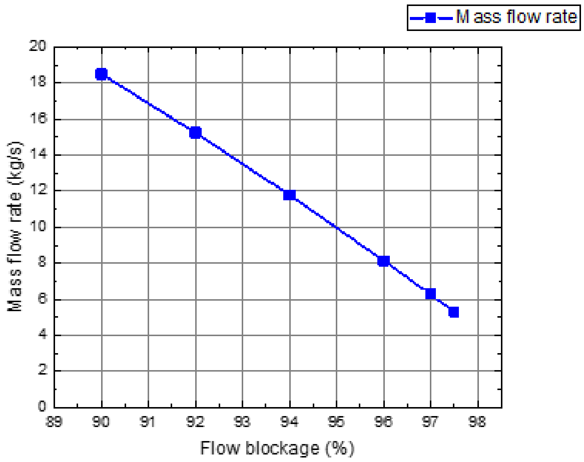

Fig. 5. Mass flow rate at 90% to 97.5% flow blockage.

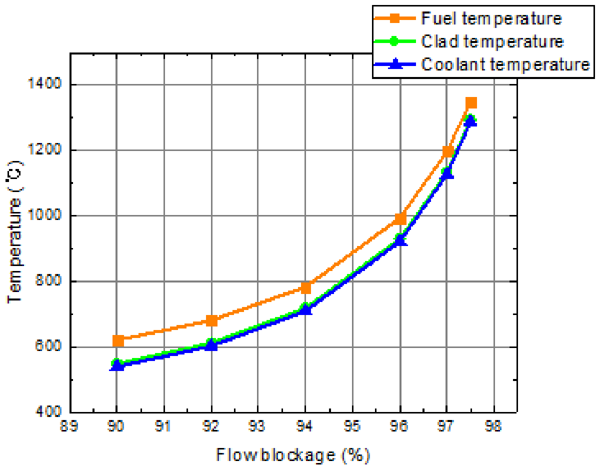

Fig. 6. Peak temperatures at 90% to 97.5% flow blockage.

Table III: Mass Flow Rate and Peak Temperature at 90% to 97.5% Flow Blockage

Flow blockage (%)	Mass flow rate (kg/s)	Fuel temp. (°C)	Clad temp. (°C)	Coolant temp. (°C)
90	18.49	622.0	550.2	540.9
92	15.23	682.4	613.3	604.3
94	11.78	784.6	719.3	710.6
96	8.13	994.7	931.0	923.0
97	6.27	1197.4	1134.7	1127.2
97.5	5.31	1348.1	1294.4	1287.5

3. Conclusions

In the hottest fuel assembly, the mass flow rate and the cladding, coolant temperature changes were calculated according to the flow blockage rate at the beginning of the active region. Changes from 0% blockage to 90% blockage and changes in blockage over than 90% were analyzed respectively. When the flow blockage ratio moves from 0% to 90%, the mass flow rate decreases and the peak temperature increases, but the peak temperatures are under the safety criterion. Clad creep was occurred at over 94% blockage, and clad melting occurred at over 97.5% blockage. For a more accurate flow blockage analysis, it is necessary to perform comparative verification through analysis using CFD in the future.

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