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Inverted Core Flow Blockage Analysis in Micro-Marine Lead Cooled Fast Reactor

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1. Introduction

Lead-cooled fast reactors (LFRs) using lead or lead-bismuth eutectic (LBE) as a coolant can be used as a power source for marine ships such as icebreakers by taking advantage that it has atmospheric operating pressure and the small interaction between water and coolant. In Russia, research is underway to use the LFR as a power source for submarines using these advantages [1,2].

There are several disadvantages to using LFR as a power source for marine ships. The two main disadvantages are the large pressure drop due to the high density of the coolant and the corrosion of the structural material by the lead-based coolant. If a large pressure drop occurs due to the high density of the coolant, economic efficiency may be threatened due to an increase in pump pressure. And If corrosion of the structural material occurs, the flow is blocked by corrosion products, etc., and the structural material can be melted.

To reduce the pressure drop, Micro-Marine LFR which is being developed utilizes an inverted core. The inverted core has a lower pressure drop compared to the conventional core due to the larger hydraulic diameter of the coolant tube. And the inverted core has the advantage of a high fuel volume ratio due to its structure [3,4]. On the contrary, it is necessary to analyze the flow blockage caused by corrosion of structural materials even in an inverted core. The flow is blocked inside the fuel assembly may lead to serious accidents such as melting of the cladding material. In addition, in the inverted core, the coolant flow path is divided compared to the conventional core, so the analysis of flow blockage is more important.

Analysis of flow blockage is possible using the system code, but compared to global temperature change observation ability, the local temperature change is not well observed. To solve this problem, ALFRED (Advanced Lead Fast Reactor European Demonstrator) in Europe analyzed the flow blockage phenomenon using CFD code [5]. In CFD analysis, the peak temperature was shown at the outlet when less than 10% of the flow blocked ratio, but the peak temperature appeared in the flow disturbance region near the blockage in more than 10% of the flow blocked ratio. This indicates that the local temperature rise in the flow disturbance region near the blockage is more dominant than the global temperature rises at the outlet at a blocked ratio of 10% or more. Next, the flow blockage phenomena in the 19-pin bundled fuel assembly was analyzed using CFD code [6]. Like with the ALFRED flow blockage analysis, there was a region where the flow was disturbed near the blockage, and thus local temperature rise occurred. In addition, a comparison of the flow blockage analysis results using CFD codes and subchannels was performed [7]. Like the previous results, there was a region where the flow was disturbed near the blockage, and unlike the system code, it was confirmed that the analysis using the CFD code or subchannel code can simulate the local temperature rise according to the disturbed flow.

In this paper, temperature rise of the fuel and cladding after flow blockage were discussed with their safety limits. Since Micro-Marine LFR uses an inverted core, the temperature rises when one internal flow path is completely blocked in the inverted core was analyzed.

2. Numerical Methods

2.1. Calculation Model

The flow blockage phenomena were analyzed as a case in which one flow path was completely blocked in the inverted core. The core form adopted as the inverted core of Micro-Marine LFR is as follows.

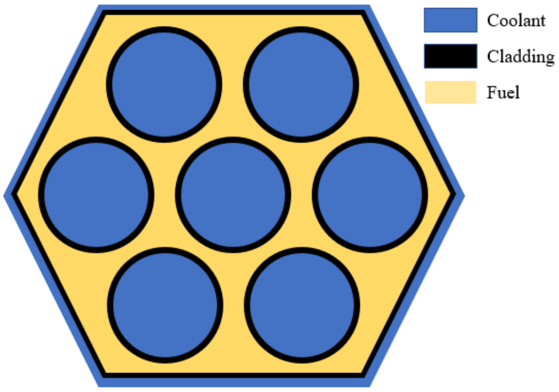


Fig. 1. Schematic diagram of inverted core fuel assembly.

Table I. Design Parameter of Inverted Core

Pitch-fuel	86mm
Pitch-fuel assembly	93.2mm
Diameter-flow path	16mm
Pitch-flow path	28mm

LBE was used as the coolant. There are 7 flow paths through which LBE coolant flows at the innermost part, and 15-15ti cladding surrounds the outside of the LBE flow path. UO_2 fuel exists outside the cladding. At the outermost of the fuel assembly, there is a coolant bypass flow. The diameter of each coolant flow path is 16mm, and the cladding surrounding each flow path has a thickness of 0.95mm. The pitch of the fuel assembly is 93.2mm.

In the fuel assembly, LBE coolant flows with a mass flow rate of 27 kg/s. The power density of the fuel is 34.09 W/cm^3. Fuel assembly inlet coolant temperature is 270℃, outlet coolant temperature is 370℃. It was assumed that the flow was blocked with a 15-15ti material to a height of 5 cm in the active region inlet of the introduced inverted core. When the central flow path is blocked, and one of the 6 edge flow paths is blocked was analyzed and compared as CFD codes respectively.

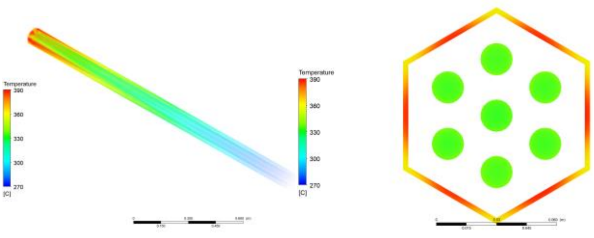
2.2. Safety Criterion

LBE coolant has a melting point of 127℃ and a boiling point of 1670℃ [8]. Since the LBE coolant must be maintained in a liquid state, the safety criteria were set to 127℃<LBE<1670℃. The 15-15ti cladding has a melting point of 1407℃, but it is known that the creep may occur above 700℃ [9]. Since the damage caused by creep also threatens the safety of the cladding, the safety criterion of the cladding was set to less than 700℃. UO_2 fuel has a melting point of 2740℃, so the safety criterion was set below 2740℃ to maintain a solid state [10].

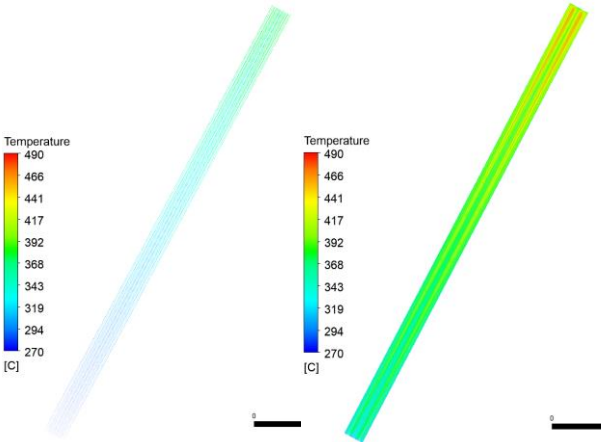
3. Numerical Results

3.1. Non-Blockage State Analysis

Prior to the flow blockage analysis, the temperature distribution in the case of no blockage was analyzed. It was confirmed that coolant is flowing from each of the 7 paths and the bypass, and the heat was removed well. A slightly higher outlet temperature in the bypass and a slightly lower outlet temperature in the 7 flow paths were observed, but the overall temperature was around 370℃. The cladding had a peak temperature of 399℃ near the outlet. The nuclear fuel had a maximum temperature of 486℃ near the outlet and it was the furthest place from the coolant flow. All peak temperatures satisfied the safety criterion. Based on this model, the flow blockage phenomenon was analyzed by adding blockage to the flow path.



(a). Coolant temperature distribution (left), Outlet coolant temperature distribution (right).



(b). Cladding temperature distribution (left), Fuel temperature distribution (right).

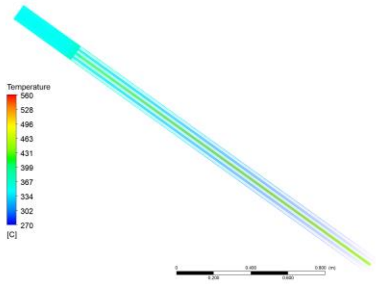
Fig. 2. Non-blockage state analysis results.

3.2. Central Flow Path Blockage Analysis

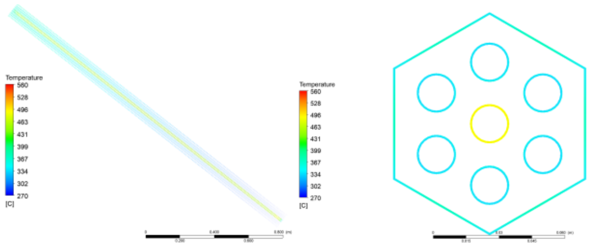
Among the 7 flow paths, the case where the central flow path was blocked was analyzed. In the inverted core, a temperature rise will appear until the outlet of the active region if one inlet of the core is blocked. Since the coolant does not flow in the blockage flow path, the coolant existing in the blocked path loses heat removal capability. Also, in Fig. 3, it is confirmed that the coolant temperature has risen to the outlet. As the heat removal capability is lost in the blocked flow path, the cladding temperature and fuel temperature rise overall not only near the blockage. Therefore, unlike the conventional core, which showed the peak temperature due to the local temperature rise, the peak temperature appears near the outlet. However, even when the central flow path is completely blocked, the peak coolant temperature is 490℃, the peak cladding temperature is 495℃, and the maximum fuel temperature is 516℃. All satisfy the safety criterion, proving that the inverted core is safe even when the central flow path is completely blocked.

3.3. Noncentral Flow Path Blockage Analysis

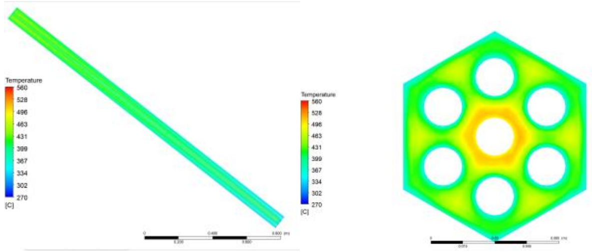
Like the analysis in which the central flow path is blocked, a case in which one noncentral flow path is completely blocked is analyzed. A case in which the location of the blocked flow path is not the central flow path among the 7 flow paths is analyzed. Same with the central flow path blockage analysis, the entire flow path is disturbed even if the active region inlet is blocked.



(a). Coolant temperature distribution.



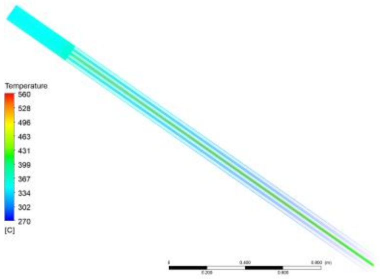
(b). Cladding temperature distribution (left), Outlet Cladding temperature distribution (right).



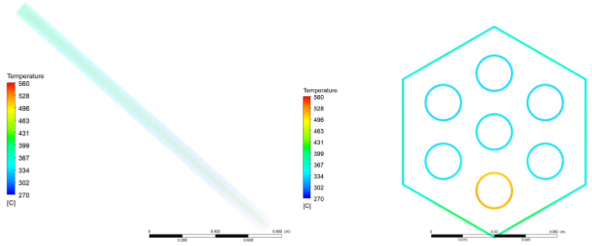
(c). Fuel temperature distribution (left), Outlet Fuel temperature distribution (right).

Fig. 3. Central flow path blockage analysis results.

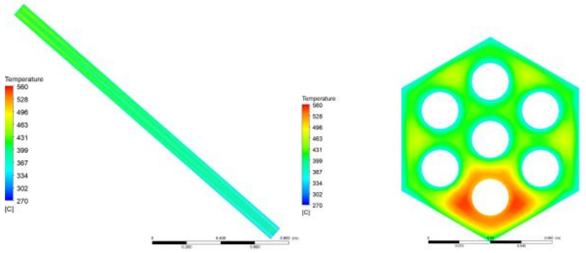
Accordingly, the coolant temperature from the inlet to the outlet all rises. Because the blocked flow path has no heat transfer capability, the fuel around the blockage path depends on the bypass to transfer heat. At the outlet cladding temperature, it appears that the temperature of the bypass cladding under the blocked flow path is slightly higher than that of other parts. The peak coolant temperature was 523℃, the peak cladding temperature was 528℃, and the maximum fuel temperature was 555℃, all satisfy the safety criterion. When one noncentral flow path was blocked, there was a part further away from the coolant than the case where the central flow path was blocked, resulting in a higher peak temperature. However, cladding creep, fuel melting, and coolant boiling did not occur even when the noncentral flow path was blocked.



(a). Coolant temperature distribution.



(b). Cladding temperature distribution (left), Outlet Cladding temperature distribution (right).



(c). Fuel temperature distribution (left), Outlet Fuel temperature distribution (right).

Fig. 4. Noncentral flow path blockage analysis results.

Table II. Comparison of Peak Temperatures of Two Blockage Cases

	Central flow path blockage	Noncentral flow path blockage
Peak coolant temperature	490℃	523℃
Peak cladding temperature	495℃	528℃
Maximum fuel temperature	516℃	555℃

4. Conclusions

The behavior of an accident in which one of seven flow paths was completely blocked is analyzed in an inverted core used in Micro-Marine LFR First, the temperature behavior in the state where blockage did not occur was analyzed, and based on the results, the case where the central flow path was blocked and the case where the noncentral flow path was blocked were analyzed and compared.

In the case where the central flow path was blocked, the peak coolant temperature was calculated as 490℃, the peak cladding temperature was 495℃, and the maximum fuel temperature was 516℃. When the noncentral flow path was blocked, the peak coolant temperature was 523℃, the peak cladding temperature was 528℃, and the maximum fuel temperature was 555℃. When the noncentral flow path was blocked, the fuel near the blocked flow path was far from other flow paths so it showed a tendency to remove heat depending on the bypass flow path, and accordingly, it has a higher peak temperature than the central flow path blockage. However, safety was maintained by satisfying the safety criterion in all cases where the flow blockage phenomena.

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