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Utilization of a Liquid Metal as Thermal Media in the Irradiation Capsule

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1. Introduction

Some materials to be used in the reactors like VHTR and SFR of the Gen-IV program are required to be irradiated at a relatively high temperature. To meet the requirement, a new type of capsule is being developed at HANARO. The irradiation tests of the materials at HANARO up to the present have been performed usually at temperatures below 300℃ under which the RPV (Reactor Pressure Vessel) materials of PWR are being operated [1]. The standard material capsule has a simple shape containing the specimen holders in a sealed tube. The external tube is made of stainless steel to have enough strength to withstand an external impact when it is installed in the irradiation holes in the reactor, but the specimen holders are usually made of aluminum to process the specimen holes and instrument grooves easily on the surface. However, the aluminum specimen holder cannot be used at the high-temperature irradiation capsule owing to the low melting point, and thus another material is being sought out. Liquid metal has been accepted as an alternative way for use in an application of high temperature irradiation for Gen IV reactor material development [2]. And thus, liquid metal such as NaK (Sodium Potassium) and LBE (Lead Bismuth Eutectic) is reviewed for use as a material to replace aluminum in capsule.

2. Capsule design

As an alternative material of aluminum, solid metals like Ti, Ni, Mo, and W, and liquid metals such as NaK and LBE are being reviewed at HANARO. In this paper, liquid metals are reviewed for use as the thermal media of a high-temperature irradiation capsule. NaK is a cooling medium of SFR, and thus it is desirable to conduct an irradiation test in the environment of the NaK in order to study the irradiation features of SFR materials. However, it is highly reactive with water and may catch fire when exposed to air, and thus it must be handled with special precautions. It is not very desirable to use NaK at the irradiation test of a capsule.

LBE is a eutectic alloy of lead and bismuth used as a coolant in some nuclear reactors, and is a proposed coolant for a lead-cooled fast reactor, as part of the Gen-IV reactor initiative. LBE has significantly higher boiling points as compared to NaK, and thus it can be operated without risk of coolant boiling at higher temperature and improves thermal efficiency. In addition, it does not react easily with water or air, and has an excellent radiation shield blocking the gamma radiation. Even though LBE is more corrosive to steel than NaK, it is very advantageous to use LBE rather than NaK as the liquid thermal media in a capsule. Therefore, LBE is strongly recommended as a liquid thermal media for a high-temperature irradiation capsule instead of aluminum. To use LBE as a thermal media instead of NaK in the capsule, the effects of both materials exerted at the temperature of the specimens would be evaluated before use at the irradiation test. The overall shape of the capsule with the liquid metal thermal media is quite similar to the present standard material capsule except for use of liquid metal instead of aluminum as the thermal media. The cross sections of the capsules with solid and liquid thermal media are shown in Figure 1.

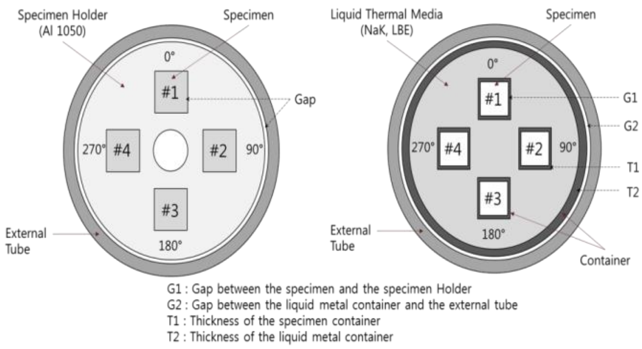


Figure 1. Cross sections of capsules with solid and liquid thermal media

The capsule is 56mm in diameter and 870mm long, and consists of a specimen container, a liquid metal container, and an external tube. The 4 columns of the specimen holders are placed at 90 degrees to maximize the space. Helium gas is filled into the gap between the container and the external tube, and between the specimen and the specimen holder. There are walls and gaps that block the heat transfer out from the specimen to the outside cooling water. They are the wall of the external tube, the specimen container (the thickness T1), and the liquid metal container (the thickness T2) and the gap (the thickness G1) between the specimen and the specimen container, and the gap (the thickness G2) between the liquid metal container and the external tube.

3. Results

3.1 Thermal characteristics

The results of thermal analyses for capsules with solid and liquid thermal media, in which the solid thermal media is aluminum and the liquids are NaK and LBE, are shown in Figure 2. This was aimed at analyzing the characteristics of temperature for a capsule conducting an irradiation test of high-temperature materials to be used in a VHTR in which the coolant is flowing at 950℃.

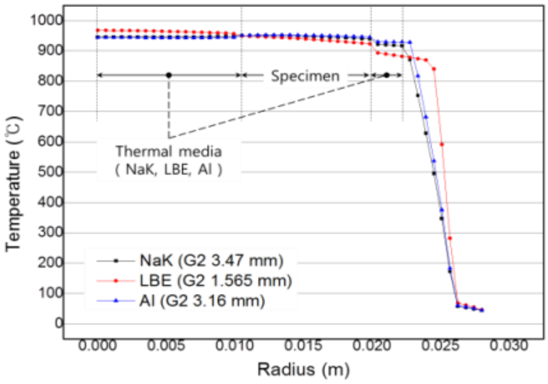


Figure 2. Temperature distribution of the capsules with three kinds of thermal media

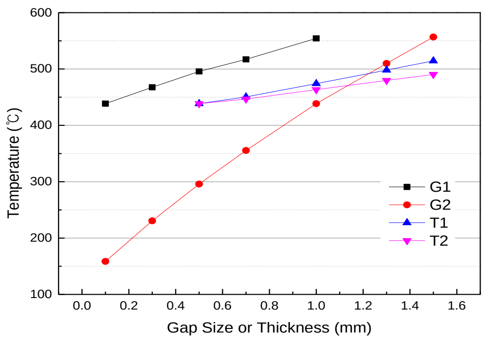
When the gap G2 in the capsule using LBE thermal media (LBE capsule) is 1.565 mm, the specimen reaches the target temperature of 950℃, where the values of other variables such as G1, T1, and T2 are fixed. On the other hand, the specimen temperature reaches 950℃ when gap G2 in the capsule using NaK thermal media (NaK capsule) becomes 3.47 mm, and the specimen reaches 950℃ when gap G2 in the capsule using aluminum thermal media (Al capsule) is 3.16 mm.

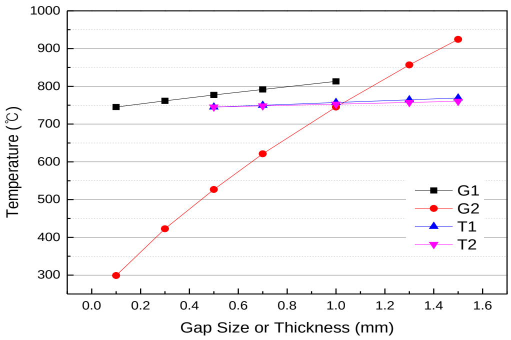
In the aluminum capsule, when the specimen temperature reaches 950℃, aluminum thermal media would reach a similar temperature. This temperature exceeds the melting point of aluminum, and therefore aluminum cannot be used as the thermal media in a high-temperature irradiation capsule. In the case of a NaK capsule, to raise the temperature of the specimen to 950℃, gap G2 of the NaK capsule should be 3.48 mm, which is greater than the 1.575 mm gap in the LBE capsule. The capsule will be loaded into the irradiation hole of the reactor for testing. In HANARO, the capsule will be placed in the cooling water flowing upward with high pressure and high speed, and thus it will tremble with vibration. The vibration becomes larger as the gap between the parts in the capsule grows more. Because the gap between the parts in the NaK capsule is greater than that in the LBE capsule, the vibration increases more. It will be difficult to hold the parts in the capsule at a constant position, and keep the temperature constant during the irradiation test.

3.2 Effect of the gap G1, G2, the thickness T1, T2 on the specimen temperature

Figure 3 shows the effects of the gap size G1 and G2, and thickness T1 and T2, on the specimen's temperature in the capsule with NaK, LBE, and aluminum thermal media. Among the 4 variables, the G2 effect is the most significant, and the effects of the others are very small. The steep gradients of the G2 curves indicate that heat is well transferred through thermal media in all cases, and the temperature change by G2 is bigger than those by other variables. While the gap G2 varies from 0.1 to 1.5 mm, the temperature of the specimen changes from 150 to 550℃ in NaK, 300 to 935℃ in LBE and 140 to 595℃ in aluminum. Other variables such as G1, T1, and T2 do not have a great impact on the change in specimen temperature.

The effect of the thickness of the liquid container on the specimen's temperature is also analyzed and shown in the figure. The thickness of the liquid container, T1 and T2, change from 0.5 to 1.5 mm in both cases. The temperature changes from 438 to 514℃ in the NaK capsule, and 745 to 769℃ in the LBE capsule. The variation rate in the NaK capsule is much bigger than in the LBE capsule. It indicates that the LBE is more stable than NaK on the specimen temperature according to the variation of the container thickness. This analysis showed that G2 plays an important role in determining the temperature of the capsule.





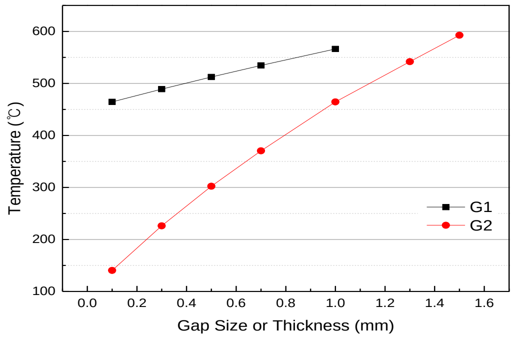


Figure 3. Effects of gap and thickness on the specimen temperature
(From the top ; Capsule with NaK/LBE/Al thermal media)

4. Conclusion

For irradiation of high-temperature materials to be used in a future nuclear system like a VHTR and SFR, a new type of capsule using liquid metal was reviewed for application to high-temperature irradiation tests. As an alternative to aluminum which has been used as the thermal media in a standard material capsule, the characteristics of liquid metals such as NaK and LBE are reviewed. The temperatures of the capsule are affected by the variation of parameters such as the gap and wall thickness of the container. In particular, the external gap G2 has the greatest influence on the temperature of the specimen, and thus G2 is the most important in determining the target temperature. The LBE capsule can lessen the gap of the parts to reduce the vibration for a long-term stable test in the reactor. In addition, LBE has a higher boiling point and is convenient to treat in comparison with NaK.

Acknowledgements

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