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Design and evaluation of a hybrid cesium heat pipe shutdown rod as a passive safety system for microreactors

Dong Hun Lee, In Cheol Bang*
Department of Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST)
50 UNIST-gill, Ulju-gun, Ulsan, 44919, Republic of Korea
**Corresponding author: icbang@unist.ac.kr*

1. Introduction

A heat pipe-cooled microreactor is composed of a monolithic core, liquid metal heat pipes, a control drum, and a shutdown rod. Westinghouse's eVinci as shown in Fig.1. [1] is an example of this configuration. Fuel rods and heat pipes are inserted into the core, and reactivity is controlled by rotating the control drum. The heat pipes vaporize the working fluid, which is condensed and returned to the evaporator by capillary action. The microreactor has redundancy in terms of reactor safety and utilizes both active and passive shutdown mechanisms in accident conditions.

The structural health of the monolith core is a recent concern for microreactor safety. Stainless steel is generally used for the monolith core, which can be designed for negative reactive feedback with increased neutron leakage due to thermal expansion at high temperatures. However, effects such as thermal creep, fatigue, and gradient become significant at higher temperatures, which can lead to decreased allowable stress values of stainless steel. Therefore, it is important to lower the temperature of the monolith core to maintain its structural integrity. Various studies have been conducted to evaluate the structural safety of the monolith core in heat pipe-cooled microreactors. [2-3]. The consensus from previous studies is that it is necessary to prevent rapid temperature rise to maintain the structural safety of the solid core. Failures of liquid metal heat pipes may not cause large temperature gradients in the monolith core if adjacent heat pipes have enough margin to absorb the heat. However, if the heat exchanger loses or degrades its cooling capacity, the heat transfer performance of the liquid metal heat pipe may decrease, leading to an unexpectedly rapid rise in the temperature of the monolith core. This can increase the possibility of tear or fractionation of the monolith core due to temperature gradients as heat pipe performance degrades. The lack of a safety system to remove decay heat in case of an accident is also a concern.

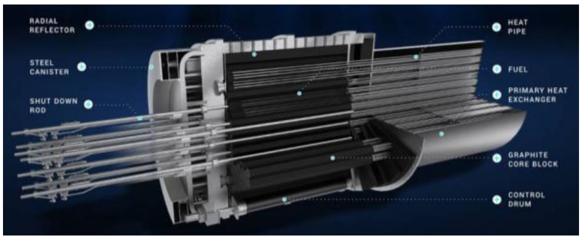

Fig. 1. Schematic of liquid metal heat pipe experiment [1]

This study proposes a passive safety system for microreactors, with the aim of minimizing increases in size, operating as a passive mechanism, and flattening the temperature of the monolith core quickly in the event of all heat pipe functions being degraded or lost. The hybrid heat pipe shutdown rod is proposed, which performs both the functions of a neutron absorber and a heat pipe. It uses liquid cesium as the working fluid due to its high vapor pressure and ability to quickly flatten the heat of the solid core. By validating this concept, we aim to contribute to the development of safer, smaller, and innovative microreactor designs.

2. Hybrid shutdown rod for passive safety

The hybrid heat pipe is a concept of a passive decay heat removal system that performs both the functions of the control rod and the heat pipe. The design and dimensions of the shutdown rod in the hybrid heat pipe for microreactors are different from those in conventional reactors. Unlike in pressurized water reactors (PWRs), there is no required grid for the shutdown rod in the microreactor, and the control drum can replace the function of the control rod. Therefore, the shutdown rod can be designed in various dimensions and shapes. The hybrid heat pipe can provide an additional heat transfer path to the microreactor in any accident scenario and replace the position of conventional shutdown rods, increasing the safety of microreactors. The heat sink of the hybrid heat pipes is air, allowing for infinite cooling in any situation. Compared to PWRs, the shutdown rod and control drum are separated in microreactors, allowing the heat loss by the hybrid heat pipe to be negligible in normal operating conditions because the shutdown rod is only inserted in unexpected conditions.

Heat pipes use working fluids to transfer heat over long distances through a phase change. Therefore, proper selection of working fluids is important for the heat pipe's operating environment. The liquid and vapor figure of merit (FOM) are commonly used indexes for selecting a working fluid. Liquid FOM is a quantification of the capillary operating limit of the heat pipe and compares how much heat the working fluid can transfer and how much fluid can circulate. Vapor FOM is a quantification of the sonic and viscous limits associated with heat pipe startup and should typically have a value above 1 to initiate a continuous flow of the heat pipe. Fig. 3 illustrates the liquid and vapor FOMs of common working fluids used in liquid metal heat pipes for microreactors. Liquid metal heat pipes are known for their high maximum heat transfer capacity but require a long startup time to produce sufficient vapor flow to the condenser due to their lower vapor pressure. For a hybrid shutdown rod in a microreactor, rapid operation of heat removal is crucial to prevent a sudden increase in the monolith core's temperature during an accident. Therefore, cesium was chosen as the working fluid since it allows for fast operation to quickly remove heat from the solid core in the event of an accident, even though its maximum heat transfer limit is lower than that of sodium and potassium.

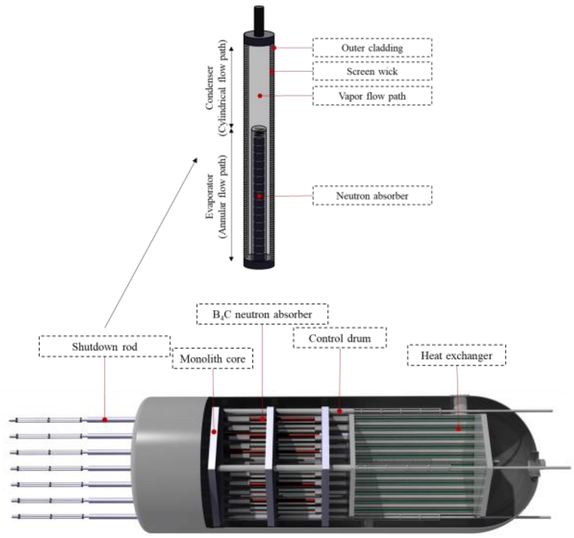

Fig. 2. Schematic of liquid metal heat pipe experiment

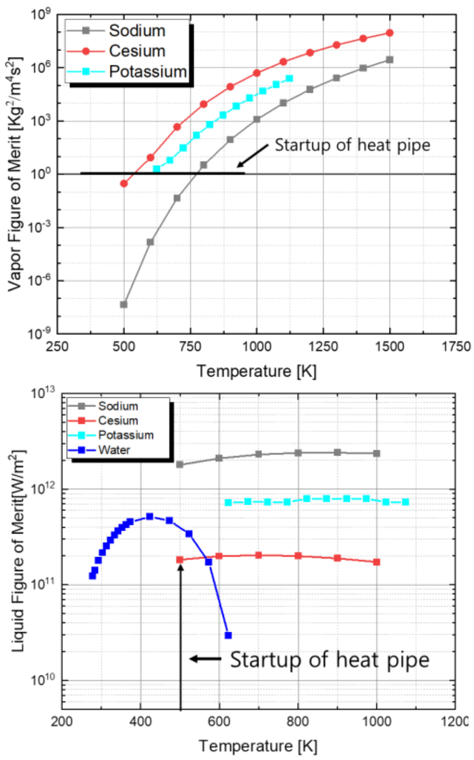

Fig. 3. FOM evaluation of different working fluid

3. Manufacturing of hybrid heat pipe

Heat pipe shutdown rods were fabricated and working fluids were charged to evaluate the designed passive safety system. The heat pipe had a length and dimension of L=900mm, the D_o=25.4mm, and D_i=15.875mm. The inner pipe contained B_4C pellets fixed with a spring and was sealed, and a screen wick with 6 layers of 120 mesh was inserted into the outer tube. Inner and outer pipes were connected by welding at the end cap, and a fill tube was installed. Table I provided more information on the manufactured heat pipe.

Table I: Information of Hybrid cesium heat pipe

Parameter	Value
Length	L_{HP}=900mm L_{BC}=300mm
Diameter	D_o=25.04mm D_i=15.875mm
Material	ASTM 316L
Porosity	0.634
Wick thickness	0.56mm
Working fluid	99.7% pure cesium
Filling amount	20.2g
Filling ratio	103%

4. Operating limitation of hybrid heat pipe

The purpose of hybrid heat pipes is to have quick and successful start-up in accident conditions and a large possible heat removal rate. The effect of diameter variation on the startup process of the liquid metal heat pipe is discussed, and it is noted that the effect on the capillary limit that causes dry-out can be neglected. The entrainment limit analysis method, which includes the critical Weber number (We=1), is used to evaluate the effect of vapor velocity that increases due to the narrowing of the flow path. Each expression (1)-(3) of heat transport limit is evaluated.

$$Q_{capillary} = \frac{\sigma\left(\frac{1}{r_{eff,i}} + \frac{1}{r_{eff,o}}\right) + \rho_l L g \sin\theta}{L_{eff}\left(2F_{v,av} + F_{l,av}\right)} \approx \frac{\frac{2\sigma}{r_{eff}} + \rho_l L g \sin\theta}{L_{eff} F_{l,av}} \quad (1)$$

$$Q_{ent,\text{Weber}} = A_v h_{fg} \sqrt{\frac{We \cdot \rho \cdot \sigma}{l}} \quad \text{Where } We = \frac{\rho V^2 l}{\sigma} \quad (2)$$

$$Q_{sonic} = 0.474 A_v h_{fg} \sqrt{\rho_v P_v} \quad (3)$$

Fig. 4 shows the maximum heat transfer rate of the hybrid cesium shutdown rod using the geometry summarized in Table I. The capillary limit is the most concerning phenomenon above 600K, but the effect of the entrainment limit is not significant. However, there is a lack of experimental validation regarding the operating limit evaluation of the diameter variation geometry of liquid metal heat pipes, and therefore, a comparison with experimental data is required. Additionally, a design optimization process is necessary to improve the capillary limit.

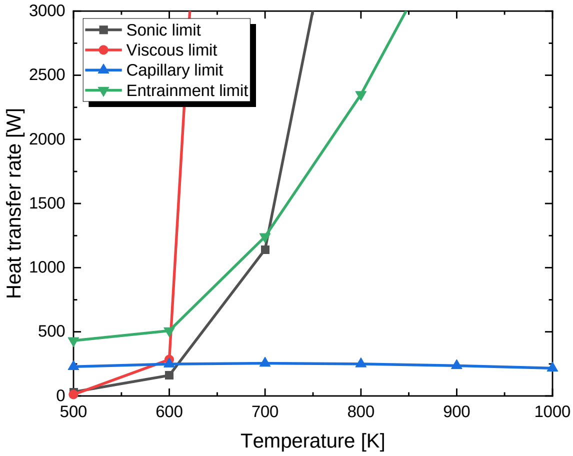

Fig. 4. Operating limitation of Hybrid Heat Pipe

5. Conclusion and future works

This paper proposes a novel passive safety system for microreactors, a hybrid cesium heat pipe shutdown rod, to prevent the tearing or rupturing of the monolith core due to excessive heat generation. Liquid cesium was chosen as the working fluid due to its high vapor pressure, allowing for faster operation than other liquid metals. Theoretical evaluations suggest that the capillary limit is the most concerning phenomenon above 600K, but the effect of entrainment limit is not significant. A rod with an outer diameter of 25.4 mm and a length of 900 mm was fabricated for future experiments to evaluate the thermal behavior and rapid operation of the heat pipe under decay heat conditions. This study aims to contribute to the development of safer, smaller, and more innovative microreactor designs.

ACKNOWLEDGEMENT

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