Experimental investigation of hybrid cesium heat pipe for microreactor applications

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1. Introduction

A heat pipe-cooled microreactor as shown in Fig. 1. is constructed with several components, including a solid core, liquid metal heat pipes, a control drum, and a shutdown rod. The monolith core contains fuel rods and heat pipes, and the reactivity is managed by manipulating the control drum. The heat pipes play a role in the main heat transfer system that vaporizes a working fluid which is then condensed and returned to the evaporator through capillary action. In terms of safety, this microreactor incorporates both active and passive shutdown mechanisms to ensure redundancy during accident scenarios.

Recent safety concerns regarding microreactors are focused on the structural health of the monolithic core. Microreactors rely on a robust monolith core to house both heat-generating fuel rods and heat-removing liquid metal heat pipes. It's crucial to prevent any tears or fractures in the core to avoid releasing fission products. Stainless steel is commonly chosen due to its manufacturability, compatibility, and safety features. However, thermal creep and fatigue can occur when temperature gradients become more significant. Graphite is being considered as an alternative core material. Graphite's mechanical integrity in radiation-exposed environments relies on avoiding substantial temperature increases. Graphite degradation depends on radiation dose and temperature, particularly at higher temperatures. Therefore, careful operating conditions are necessary for successful graphite use. Recent research explores composite moderators for microreactors with higher temperature capabilities. However, using YH_x as a moderator may encounter issues related to hydrogen redistribution due to thermal gradients. [2] Lowering the temperature gradient in the monolith core is vital for maintaining its structural integrity in all conditions. As a result, the potential for tears or fractures in the monolith core due to temperature gradients arising from the deterioration of heat pipe performance can become a significant concern. In response to these challenges, this research introduces and conducts an experiment for an innovative concept for a passive safety system for application in microreactors.

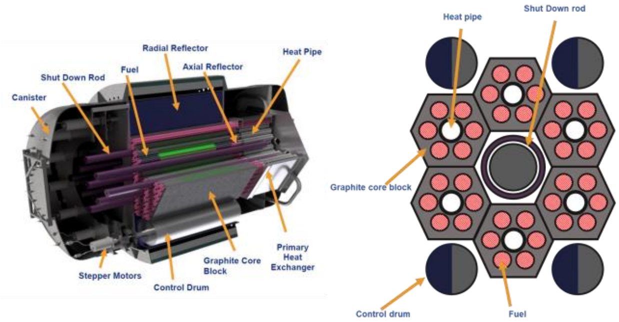

Fig. 1. Schematic of microreactor system. [1]

2. Manufacturing of hybrid heat pipe

The hybrid heat pipe for microreactors is an innovative idea for a passive system that combines the functions of a shutdown rod and heat pipe. It uses a setup shown in Fig. 2, where the inner cladding has B_4C neutron absorbers, while the outer cladding contains wick structures and a working fluid for passive heat transfer. To maintain good heat transfer performance, the vapor flow area is crucial. To avoid reducing this area, a B_4C absorber cladding is placed only in the evaporator section, allowing vapor to flow in an annular shape in the evaporator and then transition to a cylindrical shape in the condenser area.

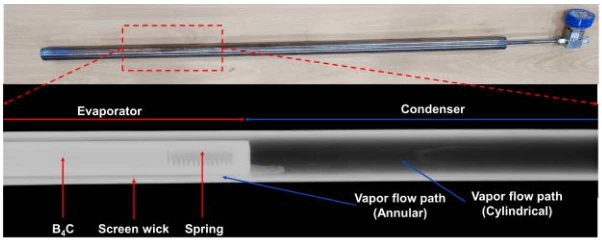

Fig. 2. X-ray and optical image of hybrid heat pipe concept

Scaled-down hybrid heat pipe shutdown rods were created to test the passive safety system design. Table 1 outlines details of the manufactured heat pipes, including length (900 mm), outer pipe dimensions (25.4 mm diameter), and inner pipe dimensions (15.875 mm diameter). The inner pipe held B_4C pellets secured by a spring and was sealed, while the outer tube contained a screen wick with six layers of 120 mesh. Table I. summarize the information of hybrid cesium heat pipe that used in this paper.

Table. 1. Geometry information of hybrid cesium heat pipe

Index	Parameter	Unit	Value
Envelop	Outer/Inner Pipe Length	mm	900/300
	Outer/Inner Pipe diameter	mm	25.04/15.875
	Outer/Inner Pipe Wall thickness	mm	1.24/0.89
Wick	Material		ASTM 316L
	Type		Screen (#120)
	Porosity		0.634
	Wick thickness	mm	0.56
Working Fluid	Material		cesium
	Filling amount	g	50

3. Experiment setup

The experimental arrangement for testing the thermal performance of the cesium heat pipe is shown in Figure 3. The evaporator conditions were created using RF induction heating, allowing for different boundary conditions like rapid heat transfer and decay heat. Air was used as the heat sink for the heat pipe, mimicking the conditions found in a microreactor application.

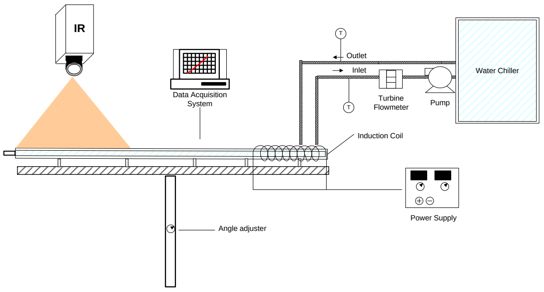

Fig. 3. Experiment setup for hybrid cesium heat pipe test

To monitor the heat pipe wall temperature, 12 K-type thermocouples and 3 IR pyrometers were placed at specific intervals, as illustrated in Fig. 4. The thermocouples were situated along the heat pipe side with 50mm gaps, starting from the condenser section. To prevent errors from induction heating, IR pyrometers were used at three points (50mm, 150mm, and 250mm along the evaporator). Data was collected using an Agilent 34980A data acquisition system, recording measurements every second. Additionally, an IR camera with 640×480 pixel resolution and 125 frames per second was utilized to visually capture the heat pipe temperature distribution.

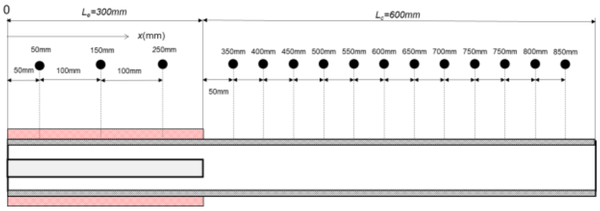

Fig. 4. Temperature measurement points for heat pipe tests

4. Pressure distribution numerical analysis

A heat pipe is a device that transfers heat from a heating section to a cooling section through the natural circulation of vapor and liquid flow. In the case of a hybrid heat pipe, where the internal geometry varies between the evaporator and condenser, the effects of these geometrical variations are significant due to their influence on the internal flow patterns. To understand the impact of these internal flow variations on the heat pipe's thermal behavior, an evaluation was conducted concerning the 1D steady-state pressure distribution and operational limits. For each configuration, relevant factors related to flow effects, such as entrainment limit, sonic limit, and capillary limit, were computed. Additionally, the maximum heat removal rate at various temperatures was calculated, along with the corresponding pressure distribution. The results depicted in Fig. 5. confirm that the hybrid cesium heat pipe can operate in low-temperature ranges as well. Particularly when compared to cases where sodium is used as the working fluid, it is evident that sufficient heat removal is achievable even in the low-temperature regime. This suggests that the design's objective of rapidly flattening the monolith core temperature during shutdown.

The hybrid heat pipe has an annular flow path in the heating section and transitions to a cylindrical flow path from the condenser onwards. Due to these distinct characteristics, vapor velocity is approximately 4 to 5 times higher in the evaporator compared to a cylindrical-type heat pipe. Consequently, this leads to a greater pressure drop, indicating a lower operational limit compared to a Conventional Heat Pipe (CHP).

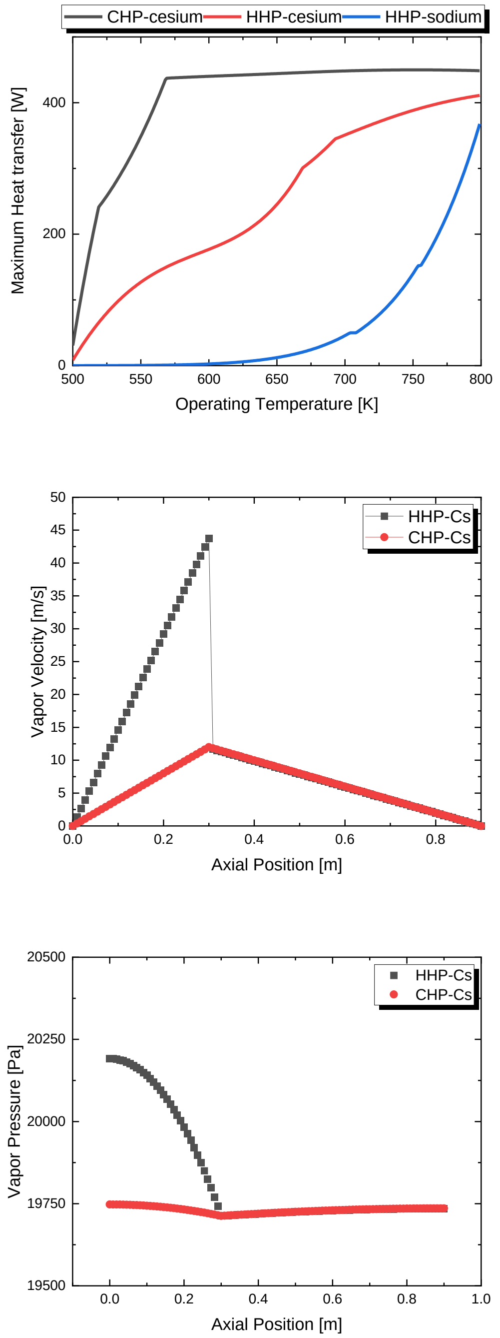

Fig. 5. Pressure distribution analysis of hybrid cesium heat pipe, hybrid sodium heat pipe and cylindrical cesium heat pipe

5. Future works

This study introduces an innovative passive safety mechanism for microreactors, termed the hybrid cesium heat pipe shutdown rod. Its purpose is to avert potential damage to the monolith core. The selection of liquid cesium as the working fluid stems from its elevated vapor pressure, enabling quicker response times compared to other liquid metals. The research includes theoretical assessments and experimental setup. From the pressure distribution analysis, it is evident that effective heat removal is achievable even within this low-temperature range. This reinforces the potential for the design to rapidly heat remove the monolith core temperature even in accident. However, due to the annular path in evaporator, hybrid heat pipe has lower operational limit as compared to a Conventional Heat Pipe (CHP). In the future, experiments to evaluate the thermal behavior and rapid operation of the heat pipe under decay heat conditions will be conducted for validation the analysis code and verification the performance of hybrid heat pipe as a passive safety system.

REFERENCES

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[2] Cutler, T., Trellue, H., Blood, M., Grove, T., Luther, E., Thompson, N., & Wynne, N. (2023). The Hypatia experiment: Yttrium hydride and highly enriched uranium critical experiment. Nuclear Technology, 209(sup1), S92-S108.