

Preliminary Experimental Evaluation of Cascading Failure in Multi Heat Pipe Test Facility

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1. Introduction

Heat pipe-based cooling technology can be incorporated into microreactor designs. Heat pipe reactors maintain stable operation under harsh environmental conditions where conventional power systems exhibit limited operational capability [1]. The low gravity dependence and passive heat transport characteristics of heat pipes allow operation under vertically varying gravitational conditions, including maritime applications and microgravity space environments. However, fuel enrichment level, coolant selection, economic feasibility, and licensing frameworks remain key factors influencing commercialization. Comparative evaluations of alternative design concepts are therefore actively conducted to identify optimal deployment strategies [2].

Yilgor et al. provided a comprehensive review of recent experimental studies on heat pipes for microreactor applications and systematically summarized experimental configurations, measurement techniques, and accident scenario testing performed by major research institutions [3]. They emphasized that high-resolution experimental data obtained under transient and accident conditions are essential for model validation and regulatory framework development. Tian et al. experimentally investigated the thermal transport limits of sodium heat pipes incorporating screen mesh wicks, including capillary, sonic, and entrainment limits [4]. Quantitative comparison of temperature rise behavior and model prediction errors under each limiting condition identified the applicability range and limitations of existing theoretical correlations.

Experimental studies on heat load redistribution and limit behavior in multi-heat-pipe systems under cascading failure remain limited. In this study, a multi-heat pipe experimental facility was designed and constructed, and cascading failure scenarios were simulated in real time to assess the potential for sequential limit attainment. The results establish an experimental foundation for heat pipe design strategies and safety evaluation frameworks that incorporate cascading failure resistance.

2. Experimental Setup

A multi-heat pipe experimental facility was constructed to assess transition potential toward cascading failure in a heat pipe reactor. A schematic of the facility is shown in Figure 1. The facility accommodates simultaneous operation of seven heat

pipes. The evaporator section comprises a heating block containing 21 cartridge heaters. The heater block and the external surface of the evaporator are enclosed within an insulated to suppress heat loss. K-type thermocouples are mounted on the evaporator wall, condenser wall, and heater surface to record temperature response. The internal configuration of cartridge heaters and heat pipes within the heater block is illustrated in Figure 2.

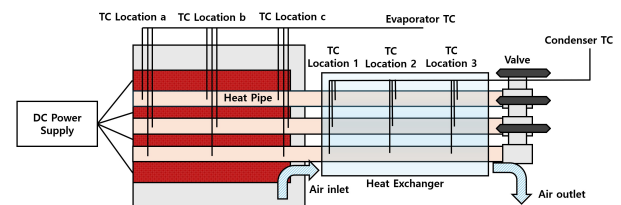


Fig. 1. Schematic of the multi heat pipe experimental setup

The configuration of the experimental facility is shown in Figure 3. The condenser section is air-cooled for heat removal. Multi failure accident conditions were imposed through control of externally operable valves. After steady-state conditions were established, the valve of the heat pipe was opened to raise the internal pressure to atmospheric level, inducing failure. This procedure enables transient evaluation of thermal load escalation in adjacent heat pipes and captures the progression of cascading failure following steady-state operation.

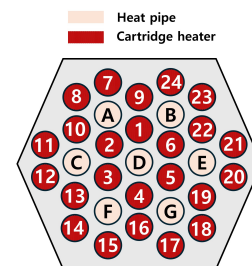


Fig. 2. Schematic of cartridge heater installation and heat pipe locations

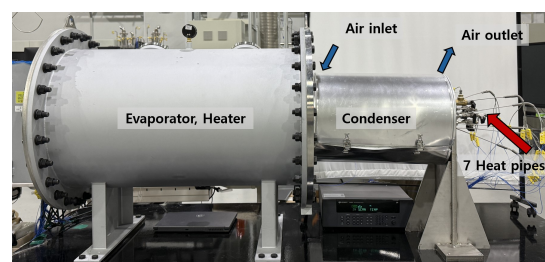


Fig. 3. Photograph of the experimental facility

3. Results and Discussion

The experiment was initiated under steady-state conditions. Failures of A and B were imposed first, and after the system stabilized at a new steady-state, failures of C, D, and E were subsequently introduced. Wall temperatures measured at the evaporator-b location of each heat pipe are presented in Figure 4. After failure, A and B lost heat removal capability and exhibited a rapid temperature increase. The remaining operational heat pipes reached elevated steady-state temperatures under increased thermal loading. Following failure of A, B, C, D, and E, both heater wall and evaporator temperatures increased significantly. The temperatures of heat pipes F and G continued to rise despite no valve actuation. This response is attributed to redistribution of thermal load to the remaining two heat pipes, resulting in capillary limit onset.

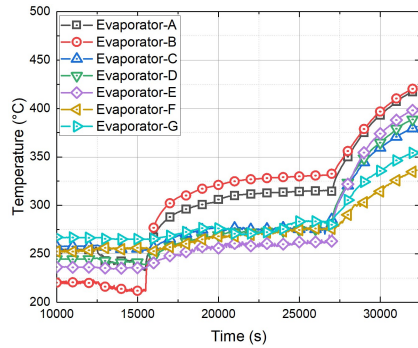


Fig. 4. Experimental results of evaporator temperature

Condenser surface temperatures of the seven heat pipes are shown in Figure 7. When A and B failed, the failed heat pipes exhibited a rapid temperature decrease that was subsequently maintained. Upon failure of A and B, condensation of the working fluid within the heat pipe increased heat removal, leading to a temporary temperature reduction in the remaining five heat pipes. As the number of operational heat pipes decreased, a new steady-state was reached at a higher temperature. In contrast, when five heat pipes failed, condenser temperatures of all seven heat pipes decreased sharply. This behavior indicates that evaporator dryout occurred in heat pipes F and G despite no valve actuation, preventing effective heat removal.

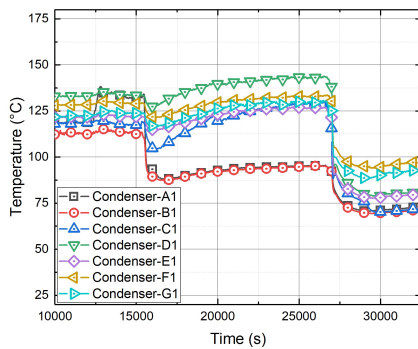


Fig. 6. Experimental results of condenser wall temperature

4. Conclusions

A seven-heat pipe experimental facility was designed and constructed to evaluate the influence of multiple heat pipe failures on adjacent heat pipe thermal loading. After steady state operation was established, failure was induced by opening externally actuated valves to raise the internal pressure of selected heat pipes to atmospheric level. Failure of two heat pipes increased the thermal load on the remaining five, which stabilized at a new steady-state. At the same applied power, failure of five heat pipes imposed excessive thermal loading on the remaining two heat pipes, leading to evaporator dryout and a rapid decrease in condenser temperature. This response indicates capillary limit attainment and loss of heat removal capability under cascading failure conditions.

The facility enables real-time assessment of thermal load redistribution during partial failure and captures the progression of cascading failure under multiple-failure scenarios. It provides a platform for assessment of accident-resistant wick designs applicable to heat pipe reactors and for evaluation of cascading failure resistance in newly developed configurations. Future work will focus on the development of wick and structural designs resistant to cascading failure and will quantitatively evaluate their accident resistance using the present facility.

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