

Manufacturing and Experiments of Large-Scale Sodium Heat Pipe for Microreactor

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1. Introduction

Heat pipe-cooled microreactors are promising for distributed and off-grid power generation because they can remove core heat passively without pumps or complex coolant loops. In representative concepts such as eVinci, Aurora, and Megapower, high-temperature alkali-metal heat pipes are typically 2–4 m long with large aspect ratios [1–3]. Sodium is suitable for the expected operating range of 650–750 °C, and annular screen wicks are attractive for long heat pipes because of their relatively low liquid-return pressure drop. Scaling to several meters increases vapor-core pressure losses and sensitivity to non-condensable gas (NCG), wick wetting, sodium purity, and charge inventory. Recent studies have demonstrated the feasibility of 4 m-class sodium heat pipes through startup, heat-transfer-limit, and steady-state operating experiments, generally using actively controlled condenser cooling, and sodium inventories selected to ensure sufficient liquid return [4,5]. The present work develops an integrated fabrication route for a 4 m-class sodium heat pipe incorporating a segmented annular screen wick and an underfilled-wick charging. Horizontal tests were conducted over an input-power range of 1.5–5 kW to evaluate the wall-temperature distribution, condenser activation behavior, and liquid-return performance.

2. Manufacturing and Experiment

The heat pipe is a 316L stainless steel tube of 25.4 mm outer diameter and 1.65 mm wall thickness, giving a 19.05 mm vapor core. Condenser cooled by natural convection. For the present prototype, the 1.3/0.7/2.0 m partition is adopted as the test geometry based on the existing microreactor concepts; optimization of the individual section lengths is beyond the scope of this work. Fabrication follows three streams prepared in parallel and then merged, as summarized in Fig. 1. In the cladding stream the tube is cut to length, the evaporator end plug is laser welded, and the assembly is cleaned. The segmented annular wick uses two layers of 100 mesh and seven layers of 400 mesh screen. The segmented construction enables assembly of the long screen stack while maintaining an annular liquid-return path. The wick is fabricated by following the same procedure that described in the literature [6], and inserted into the cladding, leaving a 0.805 mm annular gap to the wall. The assembly is then cleaned, rinsed,

dried and baked, the fill stem is welded, and leak inspection, heat treatment and vacuuming are completed before charging.

Sodium is first trimmed of its surface oxide layer and chemically purified in an argon glove box, then transferred to the sodium facility. Sodium purification proceeds in three stages: chemical treatment, vacuum distillation and cold trapping. The dissolved oxygen concentration is inferred from the coldest isothermal region of the trap using the expression of Eichelberger [7]. During charging the residence time in the cold trap was 10–15 min, well above the 5 min minimum required by the RDT standard [8], and the isothermal region stabilized between 135 and 145 °C. Then the expression gives a dissolved oxygen concentration of 1.25–1.83 wppm, comfortably within the 5 wppm limit for reactor-grade sodium [8,9].

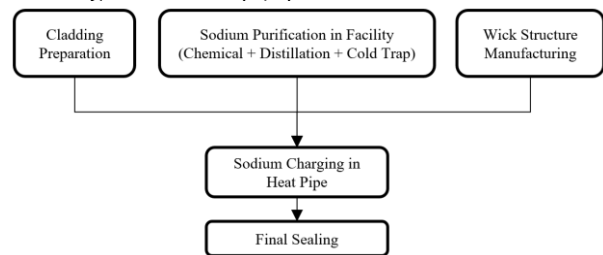


Fig. 1. Summary of manufacturing process.

The purified sodium was charged through the fill stem, which was crimped before the pipe was disconnected and weighed; the fill stem and condenser end plug were then welded closed. The measured charge was 196 g, so the device was sealed at a wick-based filling ratio of 77 % at 700 °C.

27 K-type thermocouples were distributed along the top of the wall over the full length with 15 cm spacing. The evaporator was heated stepwise from 1.5 to 5 kW, and each profile was recorded after the wall-temperature distribution stabilized for ~0.2 °C /min. The 5 kW level is the maximum tested heater input in this campaign and is not presented as a validated design heat-transport limit. The experimental setup is shown in Fig. 2.

3. Results and Discussion

Steady-state wall temperature profiles for the horizontal test are shown in Fig. 3. The evaporator and adiabatic sections are nearly isothermal up to an input

power of 4.5 kW, the operating temperature rising from 677 °C at 1.5 kW to 736 °C at 5 kW, confirming that the segmented wick returns liquid over their full 2 m. The condenser active front reaches only ~2.2 m at 1.5 kW and ~3.0 m at 5 kW, so no more than half of the 2 m condenser is activated. This behavior shows a signature for the NCG existence.

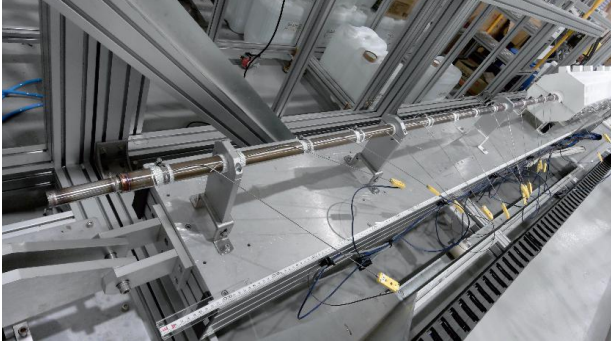


Fig. 2. Experimental setup.

The heat rejected by the condenser, estimated from radiative and natural-convective heat transfer, increases from 358 W at an input power of 1.5 kW to 3067 W at 5 kW. At 5 kW power, the heat pipe reaches the capillary limit as shown in Fig. 3. Two temperature profiles at 5 kW are presented to demonstrate the onset of the capillary limit. The temperature at the beginning of the evaporator increases at a rate of +1.5 °C/s, while the condenser section cools at a rate of -1.9 °C/s. The scenario show that the liquid starvation at the evaporator section was not sufficiently supported by the underfilled sodium amount. The calculated theoretical capillary limit is ~16 kW compared to ~3 kW experimental value. This indicates that the heat pipe was not optimally charged for prime performance.

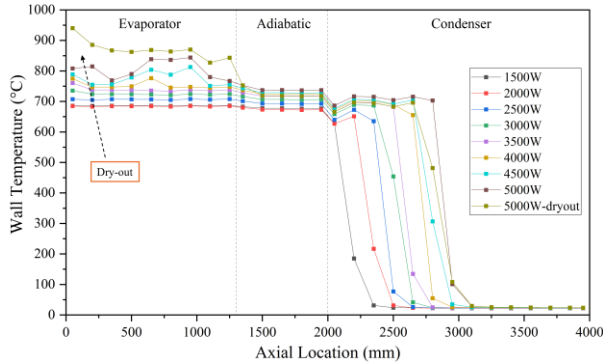


Fig. 3. Steady-state wall temperature profiles

4. Conclusions and Future Works

An underfilled 4 m-long sodium heat pipe with an annular screen wick was successfully manufactured and tested. The three-stage purification process produced sodium with an estimated dissolved oxygen concentration of 1.25–1.83 wppm, satisfying the 5 wppm reactor-grade limit. The evaporator and adiabatic regions remained nearly isothermal ($\Delta T \approx 32$ °C over the active region) during steady high-temperature operation, while only part of the 2 m condenser was

activated, and dry-out behavior appeared at approximately 4–5 kW, indicating that the 77% wick-based filling ratio limited liquid return and overall heat-transport performance. This work showed an experimental demonstration of an integrated manufacturing, sodium-purification, charging, and testing procedure for a full-scale 4 m-class sodium heat pipe. In addition to confirming that reactor-grade sodium purity and stable high-temperature operation can be achieved in a heat pipe of this scale, the experiments reveal practical performance limitations associated with condenser utilization and sodium inventory. These findings provide experimental information for improving the design and fabrication of long sodium heat pipes intended for microreactor applications and emphasize that appropriate sodium inventory and wick characterization are critical to achieving the required heat-transport capability in full scale devices. Future work will therefore focus on bubble-point characterization of the complete 4 m wick to evaluate its capillary characteristics more quantitatively and on recharging the heat pipe with an optimized sodium inventory. Subsequent testing will be used to determine whether the improved filling condition can extend condenser activation, delay dryout, and increase the maximum heat-transport capability of the heat pipe

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