Effect of Mass Transfer Phenomenon on the Operating Characteristics of Sodium Heat Pipes

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Abstract

Liquid metal heat pipes are important thermal conductive components for space exploration vehicles, exhibiting excellent heat transfer capabilities and isothermal performance. However, during space exploration missions, sodium heat pipes may operate under conditions below or even far below the design specifications, causing the liquid metal working fluid to freeze and deposit in the condenser section, which results in migration of the working fluid within the pipe toward the condenser. This study employs both experimental and numerical simulation methods to investigate the influence of mass migration phenomena on the operating characteristics of sodium heat pipes. The results demonstrate that the restart process following mass migration exhibits a heat transfer lag effect, leading to untimely heat dissipation and compromising the stability and reliability of overall system operation. The wick structure at freeze-deposition sites becomes blocked by solidified working fluid, preventing participation in the condensation heat dissipation process, which significantly reduces the effective heat dissipation length of the sodium heat pipe and ultimately leads to complete failure. The mass migration phenomenon degrades the heat transfer capability and isothermal characteristics of the heat pipe, consequently affecting the overall thermal stability of the system.

Full Text

Effect of Mass Migration on the Working Characteristics of Sodium Heat Pipes

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Abstract

Liquid metal heat pipes are critical thermal conductive components in spacecraft, offering excellent heat transfer capability and isothermal performance. However, during space exploration missions, sodium heat pipes may operate under conditions significantly below their design specifications, causing the liquid metal working fluid to freeze and deposit in the condenser section and resulting in mass migration of the working fluid toward the condenser. This study investigates the effects of mass migration on the working characteristics of sodium heat pipes through experimental and numerical simulation methods. The results demonstrate that during mass migration, the temperature difference across the heat pipe can reach 430°C, causing it to lose its isothermal characteristics. The restart process after mass migration exhibits a heat transfer hysteresis effect, leading to delayed heat dissipation and compromising the stability and reliability of the overall system operation. The wick structure at the frozen deposition sites becomes blocked by solidified working fluid, preventing participation in the condensation and heat dissipation process and significantly reducing the effective heat dissipation length of the sodium heat pipe, ultimately leading to complete failure. The mass migration phenomenon thus degrades both the heat transfer capability and isothermal characteristics of the heat pipe, consequently affecting the overall thermal stability of the system.

Keywords: Sodium heat pipes; Phase change flow; Frozen deposition; Mass migration; Heat pipe failure

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Liquid metal heat pipes (LMHP) feature a simple structure that leverages the phase change latent heat of liquid metal working fluids, providing excellent isothermal characteristics and heat transfer capability that can exceptionally match the thermal management requirements of spacecraft systems and ensure their thermal stability. Sodium heat pipes, in particular, have broad application prospects in heat transfer for space nuclear power systems and thermal management of spacecraft systems. In recent years, researchers have designed various sodium heat pipe-cooled reactor systems for space applications, such as the HOMER program [1], Kilopower program [2], MegaPower reactor [3], LEGO-LRC [4], and Martian surface reactors [5].

The basic structure of a liquid metal heat pipe is illustrated in Figure 1a [Figure 1: see original paper], consisting primarily of a pipe shell and a wick structure attached to the inner surface. Both ends are sealed, forming an enclosed cavity for vapor flow, resulting in a completely sealed structure after fabrication. Under design conditions, liquid in the evaporator section absorbs heat and vaporizes into high-temperature steam, which flows through the adiabatic section to the condenser section. In the condenser, the vapor releases heat and condenses, transferring heat out of the system. Simultaneously, the condensed liquid returns to the evaporator section along the wick structure driven by capillary force, completing the working cycle. However, in actual space exploration missions, spacecraft require long-duration, long-distance flight to reach their targets, during which most equipment remains dormant while only a few systems operate. This causes the heat absorption power of the heat pipe to be significantly lower than its heat dissipation power. As shown in Figure 1b, when the heat absorption in the evaporator section is far below the heat dissipation in the condenser section, the condenser temperature decreases until it falls below the melting point of the working fluid, causing the working fluid to freeze and deposit in the condenser section. This prevents the fluid from returning to the evaporator section, ultimately leading to complete working fluid freeze-out in the condenser section and heat pipe failure. This phenomenon is termed mass migration [6], which causes wick blockage, disrupts the flow cycle, leads to evaporator dry-out, completely eliminates heat transfer capability, compromises spacecraft system thermal stability, and can result in mission failure.

In recent years, research on liquid metal heat pipes has primarily focused on startup characteristics and heat transfer performance, with limited investigation of mass migration phenomena. Ma et al. [7] demonstrated that the installation inclination angle of sodium heat pipes affects startup time, operating temperature difference, and minimum startup power. Liu et al. [8] confirmed the influence of inclination angle on heat pipe performance and improved startup efficiency by heating the condenser section. Huang et al. [9] investigated the startup characteristics and operational performance of sodium heat pipes with 67%, 102%, and 172% fill ratios, finding that heater power and condenser cooling conditions significantly affect operating temperature within the achievable heat transfer rate range. Lee et al. [10] examined the performance of overfilled sodium heat pipes with 260% fill ratio under high heat flux conditions, observing that excess liquid moved toward the condenser end and formed a liquid pool, reducing effective heat dissipation length and heat transfer capability. Teng et al. [11] studied the effects of low-frequency oscillation on startup and thermal performance, finding that oscillatory motion had minimal impact on startup but caused periodic temperature fluctuations, particularly in the evaporator section. Heat transfer limits are essential aspects of heat pipe research, and in-depth investigation contributes to improved thermal design. Tian et al. [12] evaluated various heat pipe heat transfer limit models, finding that the Chi model predicted capillary limits for horizontal operation with 19.0% error but was unsuitable for inclined conditions, the Levy model overpredicted sonic limits, and the wave-induced model estimated entrainment limits with 45.3% error. Liu et al. [13] demonstrated that sodium heat pipes exhibit different phase change flow characteristics under various heat transfer limits, with vapor-liquid distributions in the evaporator section corresponding to specific heat transfer limits and evaporator wall temperatures showing fluctuations. The vapor-liquid phase change flow phenomena during transitions between different heat transfer limits are closely related to the transition limits. In the early 1990s, researchers at Los Alamos National Laboratory [6,14-15] conducted preliminary studies on mass migration phenomena, investigating frozen deposition distribution by sectioning heat pipes, though temperature variations during cutting affected results. This research failed to explain the mechanism of mass migration and internal phase change flow processes, nor did it determine whether heat pipes could restart after mass migration.

Based on the current research status, this study investigates the effects of mass migration on the working characteristics of typical screen mesh wick sodium heat pipes. The research first experimentally reproduces the mass migration phenomenon, then conducts restart experiments after frozen deposition, and finally reveals the frozen deposition process through numerical simulation. The findings provide scientific reference for ensuring long-term stable operation of heat pipes and their integrated systems.

1.1 Research Object

This study focuses on screen mesh wick sodium heat pipes for space applications, investigating their working characteristics under mass migration conditions. Table 1 presents the characteristic parameters of the sodium heat pipe.

Table 1 Sodium Heat Pipe Characteristic Parameters

Parameter	Value
Shell size (diameter × thickness), mm	30 × 1.5
Structural material	Stainless steel
Wick type	Wire mesh wick
Mesh count	-
Wick thickness, mm	-
Total length, mm	-
Evaporator length, mm	-
Adiabatic length, mm	-
Condenser length, mm	-
Working medium	Sodium

1.2 Experimental Setup

The experimental platform is illustrated in Figure 2a [Figure 2: see original paper], employing a 1:1 full-scale sodium heat pipe. The experiments consist of three parts: (1) heat pipe startup testing, (2) mass migration reproduction through enhanced condenser heat dissipation, and (3) mass migration reproduction through reduced evaporator heating power. The heat pipe is heated using a high-frequency electromagnetic coil, with quartz glass insulation between the evaporator section and coil to prevent electrical arcing from induction contact. The adiabatic section is insulated with thermal insulation cotton. The condenser section uses a water-cooled jacket for cooling, with a gas gap between the jacket and heat pipe that can be evacuated or filled with argon-helium mixtures. Adjusting the argon-helium ratio and cooling water flow rate controls condenser heat dissipation power. Maximum heat dissipation occurs when the gas gap is completely filled with helium at maximum cooling water flow. Cooling water flow rate is measured by a flowmeter, and water temperature at inlet and outlet is measured by thermocouples to calculate heat dissipation power. Wall temperatures are measured by high-precision thermocouples arranged axially and circumferentially, enabling real-time monitoring through a data acquisition system. The thermocouple arrangement is shown in Figure 2b [Figure 2: see original paper].

1.3 Numerical Simulation Method

Computational fluid dynamics (CFD) methods simulate the internal flow field and phase change processes in sodium heat pipes. Reference [16] successfully simulated frozen deposition in water heat pipes under low-power conditions. This numerical simulation of sodium heat pipe mass migration follows a similar approach. The Realizable k- model solves the flow field, the Volume of Fluid (VOF) model predicts multiphase flow, the Lee model simulates liquid-vapor phase change, and the solidification-melting model solves liquid-solid phase transition. User-defined functions (UDF) introduce capillary forces in the wick to simulate the phase change flow cycle in sodium heat pipes.

Working fluid thermophysical properties are crucial for flow field simulation. Since temperatures vary under different conditions, the physical properties of liquid and vapor sodium are temperature-dependent. Density, viscosity, latent heat, thermal conductivity, and surface tension coefficient are provided as temperature-correlated functions in the simulation based on the parameter database from reference [17].

2.1 Experimental Conditions

Sodium heat pipes primarily function in reactor core heat conduction and waste heat removal for space nuclear power systems, particularly in heat pipe radiators where the condenser end is integrated with fins to significantly enhance heat dissipation efficiency [18]. When spacecraft equipment transitions from operational to dormant states, the evaporator input power becomes low while the condenser end and radiating fins remain in the space environment with unchanged external temperature, maintaining normal heat dissipation power. This causes the heat pipe to operate under low-power conditions where input power (P__in) is far below output power (P__out), making mass migration highly probable. In the experimental platform described in Section 1.2, adjusting the high-frequency coil power changes the evaporator input power, while adjusting the Ar/He ratio in the cooling jacket gas gap changes the condenser heat dissipation power. This study reproduces low-power operating conditions of sodium heat pipes using both methods: enhanced condenser heat dissipation for rapid mass migration reproduction and reduced evaporator power to approximate actual spacecraft operating conditions. Detailed experimental conditions are listed in Table 2 .

Table 2 Experimental Conditions of Sodium Heat Pipe

Stage	Electrical Power (W)	Heating Power (W)	Gas Gap
Frozen startup	-	-	-
Enhancing heat dissipation with Ar gap	-	-	Ar
Enhancing heat dissipation with Ar/He gap	-	-	Ar/He 1:1
The second start	-	-	-
Enhancing heat dissipation with He gap	-	-	He
The 3rd start	-	-	-
Reducing heating power	-	332.1	-

2.2 Experimental Results

The complete temperature curves for all measurement points are shown in Figure 3 [Figure 3: see original paper], with cooling water flow rate maintained at 0.0551 m/s throughout the experiment. Three frozen deposition events were observed. At 2400 s, the cooling jacket gas gap was changed to Ar/He 1:1 mixture, resulting in frozen deposition at the 900 mm measurement point in the condenser section at 2730 s. Beginning around 2570 s, the evaporator section temperature increased due to the decreasing temperature at the condenser end approaching the frozen deposition region. The large axial temperature difference indicated that the internal phase change flow cycle had deviated far from normal operation, preventing effective heat conduction and causing heat accumulation and temperature rise in the evaporator section. During frozen deposition, the temperature difference across the heat pipe reached nearly 430 K, significantly affecting isothermal performance. At 3828 s, the gas gap was changed to pure He, causing rapid temperature decrease in the condenser section. Frozen deposition first occurred at the 800 mm measurement point, then spread to 700 mm and 900 mm points. Unlike the Ar/He mixture experiment where freezing began at 900 mm, this demonstrates that the freezing front position is not fixed and does not necessarily initiate from the condenser end.

In the reduced evaporator power experiment, when evaporator power decreased to 332.1 W, the temperatures at 800 mm and 900 mm measurement points in the condenser section dropped below sodium’ s melting point, initiating frozen deposition. Further power reduction to 172.2 W expanded the frozen region to the 700 mm point, and reduction to 134.5 W expanded it to the 600 mm point. When all condenser measurement points showed frozen deposition, the condenser section was deemed completely frozen and unable to perform condensation and heat dissipation.

The sodium heat pipe underwent three startup processes: frozen startup, second startup after mass migration induced by Ar/He gap enhanced cooling, and third startup after mass migration induced by He gap enhanced cooling. During frozen startup at 613.3 W heating power, successful startup required 1760 s, reaching an operating temperature of 612°C with an overall temperature difference of 9.3°C. At 850 s, a high-temperature fluctuation appeared at the evaporator end, likely due to encountering a heat transfer limit during startup before transitioning to normal operation, or insufficient heat conduction causing heat accumulation at the evaporator outlet.

After mass migration reproduction via Ar/He gap, the sodium heat pipe no longer maintained normal operation, necessitating a second startup process to melt the frozen deposition region and restore normal operation. For the second startup, the Ar/He mixture was evacuated and replaced with air, with heating power adjusted to 720.0 W. Startup required approximately 990 s, reaching an operating temperature of 580°C with a temperature difference of 7.5°C. During this period, waste heat could not be effectively removed. In space exploration missions, a 940 s period represents a significant duration during which the system may complete its detection cycle before entering the next dormant period, subjecting the sodium heat pipe to another mass migration process. This cyclical process poses severe challenges to overall system thermal stability due to accumulated heat from each hysteresis event.

The third startup required melting frozen deposition caused by He gap enhanced cooling, with heating power of approximately 1069.4 W. Startup required about 940 s, reaching a final operating temperature of 587°C with a temperature difference of 8.2°C.

3 Numerical Simulation Study of Sodium Heat Pipe Mass Migration

Boundary condition settings and mesh configuration for the numerical simulation are shown in Figure 4 [Figure 4: see original paper]. All walls are set as heat flux walls, with axisymmetric mesh distribution along the center and boundary layer refinement near the heat pipe wall and wick surface. After mesh independence verification, the mesh count is 400,000 with quality above 0.9. In Fluent solver settings, the SIMPLE algorithm solves pressure-velocity coupling with PRESTO! interpolation. Considering space applications, gravity is set to zero and operating pressure to 101325 Pa.

3.1 Numerical Simulation Conditions In actual space environments, low-power operating conditions primarily result from reduced input power. Therefore, numerical simulation conditions select two cases from the reduced input power experiments, detailed in Table 3 .

Table 3 Numerical Simulation Case Conditions

Input Power (W)	Output Power (W)	P_out/P_in	Experimental Stage
-	-	6.21	Reducing heating power
-	-	7.95	Reducing heating power

3.2 Numerical Simulation Results Low-power conditions more closely approximate actual space environments. Figures 5 [Figure 5: see original paper] and 6 [Figure 6: see original paper] show axial wall temperature distributions and phase distributions for two simulation cases, with blue phases in Figure 6 representing solid phases.

For Case 1 (Figures 5a and 6a) with P_out/P_in = 6.21, working fluid freezing began at the condenser end at 588 s. The frozen region gradually developed axially leftward, extending into the vapor cavity. The frozen regions near upper and lower walls merged at 660 s, with frozen working fluid developing toward the condenser inlet along the wick. A new freezing point appeared at 745 s, demonstrating multi-point initiation. Multiple frozen regions continued developing and eventually merged at 760 s, forming finger-like frozen distributions. The condenser end became completely frozen with expanding frozen regions, completely blocking the condenser wick and preventing liquid return. The overall working fluid migrated to and frozen in the condenser section, disrupting the phase change flow cycle.

For Case 2 at 134.5 W heating power with P_out/P_in = 7.95, wall temperature and phase distributions are shown in Figures 5b and 6b. The frozen deposition process differs significantly from Case 1. The freezing front position is not fixed but depends on operating conditions, specifically the P_out/P_in ratio. As shown in Figures 5b and 6b, the first frozen region appeared near the condenser inlet at 667 s, then gradually developed and expanded. A second frozen region appeared near the upper wall at 680 s, followed by third and fourth regions at 698 s and 725 s. These frozen regions developed and spread along the wick (740 s) and gradually merged (760 s and 802 s), eventually completely blocking the condenser wick. The frozen region at the condenser end diffused into the vapor cavity and developed toward the condenser inlet, finally forming finger-like frozen distributions with overall working fluid migration toward the condenser section.

4 Effects of Mass Migration on Sodium Heat Pipe Working Characteristics

The primary performance parameters during liquid metal heat pipe operation include: (1) response time—faster startup enables earlier participation in heat conduction, avoiding hazards from system heat accumulation; (2) heat conduction capability—effective condenser working length is crucial for heat transfer performance; and (3) isothermal characteristics—based on saturated vapor-liquid phase change flow cycles, providing small internal temperature differences and excellent isothermal performance critical for aerospace systems requiring high thermal stability. Mass migration significantly impacts these three key performance aspects, which are analyzed below based on experimental and numerical simulation results.

4.1 Heat Transfer Hysteresis Heat transfer hysteresis in sodium heat pipes refers to the situation where, when the system requires instantaneous heat conduction capability, the heat pipe cannot respond immediately due to non-normal operating status, requiring startup time and causing heat accumulation in the system. This hysteresis effect prevents timely heat removal, causing overall system temperature rise and potentially compromising stability and reliability.

The sodium heat pipe underwent three startup processes: frozen startup from room temperature, second startup after mass migration induced by Ar/He gap enhanced cooling, and third startup after mass migration induced by He gap enhanced cooling. Frozen startup at 613.3 W required 1760 s to reach 612°C operating temperature with 9.3°C temperature difference. In actual engineering applications, after spacecraft launch, all systems activate with high heat generation, enabling complete startup and effective waste heat removal. Subsequently, partial equipment shutdown places heat pipes in low-power operation where mass migration occurs. When equipment reactivates, sodium heat pipes must undergo second startup. At 720 W, second startup required 940 s, during which waste heat could not be effectively removed. In space exploration missions, 940 s represents a significant duration during which the system may complete its detection cycle before entering the next dormant period, subjecting sodium heat pipes to another mass migration cycle. This periodic process throughout space missions subjects overall system thermal stability to severe challenges from accumulated heat during each hysteresis event.

4.2 Effective Heat Dissipation Length Reduction As enclosed heat transfer components, heat pipes rely entirely on condenser heat transfer, making effective condenser working length critical for performance. When frozen deposition occurs, the wick and even vapor cavity become blocked by solid sodium, reducing evaporator working fluid quantity. The frozen deposition sections cannot return, significantly shortening effective heat dissipation length and compromising heat removal capability. For multi-region frozen deposition, evaluation should reference the first frozen region near the condenser inlet, as subsequent unfrozen condenser sections cannot participate in phase change cycles due to wick blockage. Numerical simulation results in Figure 6 [Figure 6: see original paper] show mass migration deposition blocking the condenser wick, with frozen length gradually increasing and even completely blocking the vapor cavity end. This severely reduces effective condenser heat dissipation length and significantly impacts heat pipe heat transfer performance. Complete condenser freezing eliminates heat dissipation capability, causing complete heat pipe failure and adversely affecting system operation.

4.3 Impact on Isothermal Performance Sodium heat pipes achieve heat transfer through vapor-liquid phase change flow cycles, with internal saturated vapor flow maintaining small temperature differences and excellent isothermal performance, making them highly suitable for aerospace systems requiring high thermal stability. However, operation under off-design conditions alters internal flow characteristics, directly affecting temperature distribution and causing isothermal performance fluctuations. Mass migration causes destructive impacts on isothermal characteristics, consequently affecting overall system thermal stability.

Figure 7 [Figure 7: see original paper] shows temperature difference variations during mass migration experiments. In Ar/He gap enhanced cooling experiments, frozen deposition began at 2570 s with a 415°C temperature difference that continued increasing. In He gap enhanced cooling experiments, frozen deposition began at 3920 s with a 420°C temperature difference that also increased continuously. In reduced input power experiments, frozen deposition occurred at 6890 s with a 360°C temperature difference. Under all conditions, mass migration caused temperature differences of hundreds of degrees Celsius, completely losing isothermal characteristics. In reduced input power cases, the temperature difference first increased then decreased not because isothermal performance was recovering, but because the experiment terminated and overall heat pipe temperature decreased.

Conclusions

This study investigated mass migration phenomena in sodium heat pipes using experimental and numerical simulation methods. Experiments employed 1:1 full-scale sodium heat pipes for frozen startup and frozen deposition testing. Numerical simulations based on Ansys-Fluent used UDF to introduce wick capillary forces combined with VOF-Lee-solidification-melting models to study mass migration processes under low-power conditions. The main conclusions are:

1) Mass migration experiments were conducted through enhanced cooling and reduced heating power methods. The freezing front position is not fixed but depends on the output/input power ratio. Frozen deposition occurs when any condenser region temperature drops below the working fluid melting point. During sodium freezing, heat pipe temperature differences can reach hundreds of degrees Celsius, causing complete loss of isothermal characteristics.

2) A gas-liquid-solid three-phase phase change flow simulation method incorporating capillary forces was established in Ansys-Fluent to simulate mass migration processes, with results showing good agreement with experiments. Frozen deposition exhibits multi-point initiation, with frozen regions eventually developing into finger-like distributions that completely block the wick and even the vapor cavity end. Working fluid migrates overall toward the condenser, preventing completion of phase change flow cycles and severely degrading heat transfer performance.

3) After mass migration, sodium heat pipes must undergo restart processes to resume operation. During startup, effective heat transfer is unavailable, causing heat transfer hysteresis and preventing timely heat removal from

the system. Deposited working fluid blocks the wick, significantly reducing effective condenser heat dissipation length and severely impacting heat transfer performance. Mass migration causes heat pipes to lose isothermal characteristics, adversely affecting overall system thermal stability.

Author Contributions

LIU Jianshu: Methodology research, experimental and simulation design, data analysis, and manuscript writing. MOU Yupeng: Assisted with simulation and data processing. ZHANG Hongna: Guided simulation methodology. LI Xiaobin: Assisted with experimental design. WANG Zeming: Helped construct the experimental platform. CHAI Baohua: Guided experimental work. LI Fengchen: Provided guidance and revisions for manuscript writing. SUN Jiaye: Assisted with application background writing and practical engineering application analysis.

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Note: Figure translations are in progress. See original paper for figures.