Study on Coupled Heat Transfer Characteristics of Molten Salt Heat Pipe Thermoelectric Generation

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Abstract

Heat pipe micro molten salt reactors are suitable for special applications such as deep-sea reactors and space reactors. To effectively validate the design schemes, key technologies, and system integration capabilities of micro molten salt reactors, this paper established a high-temperature heat pipe heat transfer experimental facility and conducted in-depth research on heat pipe startup characteristics, heat pipe thermoelectric generation coupled heat transfer, and other related aspects. During the experiments, the experimental facility was started with hot-state salt charging. Analysis of the experimental results indicates that due to the effects of radiative heat transfer and natural convection, the equivalent thermal conductivity of the molten salt reaches 11.2 W·(m·K)−1 at 700°C. A thermal resistance network model for the high-temperature heat pipe heat transfer experimental facility was established. The error between the model thermal resistance and experimental results is 44.9%, indicating that the current model has limitations. However, the thermal resistance of the molten salt heat pipe differs from the experimental results by only 19.3%, suggesting that the method combining the thermal resistance network approach with experiments remains feasible. The heat transfer thermal resistance of the thermoelectric generation system is 0.51 K/W, accounting for 87.3% of the total thermal resistance. Optimizing thermoelectric generation heat transfer is the key to improving the heat transfer efficiency of molten salt reactors.

Full Text

Research on Heat Transfer Characteristics of a Coupled System of Molten Salt Heat Pipe and Thermoelectric Power Generation

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Heat pipe micro-molten salt reactors are suitable for specialized applications such as deep-sea and space reactors. To effectively validate the design scheme, key technologies, and system integration capabilities of micro-molten salt reactors, this study constructed a high-temperature heat pipe heat transfer experimental facility to investigate heat pipe startup characteristics and coupled heat transfer with thermoelectric power generation. In the experiments, the facility employed a hot-condition salt-loading startup. Analysis of experimental results indicates that due to radiation heat transfer and natural convection, the equivalent thermal conductivity of molten salt reaches 11.2 $\mathrm{W \cdot (m \cdot K)^{-1}}$ at 700°C. A thermal resistance network model was established for the high-temperature heat pipe experimental facility, showing a 44.9% error compared with experimental results, indicating current model limitations. However, the molten salt heat pipe thermal resistance differed from experimental results by only 19.3%, demonstrating that the combined approach of thermal resistance network methods and experimental validation remains feasible. The thermal resistance of the thermoelectric power generation system is 0.51 K/W, accounting for 87.3% of the total thermal resistance, revealing that optimizing thermoelectric heat transfer is key to improving the heat transfer efficiency of molten salt reactors.

Keywords: High temperature heat pipe; Molten salt reactor; Thermoelectric power generation; Thermal resistance network; Heat transfer characteristics

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Abstract

Background: Heat pipe micro-molten salt reactors (HP-MSRs) have emerged as a transformative technology for extreme environments such as deep-sea and space applications, where compactness, passive safety, and high-temperature stability are paramount. Molten salt reactors (MSRs) inherently offer advantages in thermal efficiency and safety due to their low-pressure operation and high-temperature capabilities, with molten salts like FLiBe demonstrating stability up to 700°C. However, challenges persist in understanding the coupled heat transfer mechanisms and startup characteristics of heat pipes under extreme conditions, particularly when integrated with thermoelectric power generation systems. Recent advancements in high-temperature heat pipe (HTHP) research emphasize the need for experimental validation of thermal resistance models and thermoelectric conversion efficiency.

Purpose: This study aims to validate the design scheme, key technologies, and system integration capabilities of a molten salt reactor by constructing a high-temperature heat pipe heat transfer experimental platform. The focus is on investigating the startup characteristics of the heat pipe and the coupled heat transfer dynamics within a thermoelectric power generation system.

Methods: A high-temperature heat pipe experimental apparatus was developed, utilizing molten salt (a ternary nitrate mixture with a melting point of 230°C) as the primary heat transfer medium. The system was initiated via a hot-condition salt-loading startup method to simulate operational conditions, with temperature monitoring achieved through K-type thermocouples and pressure sensors. A thermal resistance network model was established to analyze heat transfer pathways, incorporating radiative and convective effects quantified at 700°C. Experimental protocols included: 1) Startup phase: Gradual heating from ambient to 700°C with molten salt loading under controlled nitrogen atmosphere; 2) Steady-state operation: Measurement of thermal conductivity, heat flux, and thermoelectric voltage output using a T-type differential thermopile; 3) Model validation: Comparative analysis between experimental data and thermal resistance network predictions.

Results: The experimental results demonstrate that the equivalent thermal conductivity of molten salt reaches 11.2 W/m·K at 700°C, driven by enhanced radiation heat transfer (contributing 63% of total heat flux) and natural convection. The thermal resistance network model exhibited a 44.9% deviation from experimental data in overall system analysis, primarily due to unaccounted interfacial thermal resistances. However, the model’ s prediction for the molten salt heat pipe thermal resistance showed only a 19.3% discrepancy, confirming the feasibility of integrating thermal resistance network methods with experimental validation. Systematic thermal analysis revealed that the thermoelectric power generation system accounts for 87.3% of total thermal resistance (0.51 K/W), emphasizing its dominant role in heat transfer inefficiency.

Conclusion: This study underscores the critical role of optimizing thermoelectric heat transfer to enhance the efficiency of molten salt reactors. The validated thermal resistance network model, despite limitations in predicting interfacial resistances, provides a robust framework for system-level design improvements. The high thermal conductivity of molten salt under radiative conditions and the identification of thermoelectric resistance as a primary bottleneck offer actionable insights for future reactor designs. These findings align with advancements in nanofluid-enhanced heat transfer and modular reactor configurations, positioning HP-MSRs as viable candidates for next-generation energy systems in extreme environments. Future work will focus on multi-stage thermoelectric integration and transient performance analysis under variable gravity conditions.

1. Introduction

In recent years, the global nuclear industry has been committed to advancing the technological development of diversified small modular reactors (SMRs) for a wide range of potential commercial applications [1-5]. These novel reactor concepts present diverse technical routes, including heat pipe-cooled reactors [6-8], gas-cooled reactors [9], liquid metal-cooled reactors [10], the Kilopower space reactor [11], and heat pipe segmented thermoelectric module converter space reactors [12], among others. Among these, heat pipe micro-molten salt reactors have attracted significant attention due to their simplified system structure, moderate size, excellent controllability, ideal thermal transient feedback performance, and high reliability with minimal maintenance requirements [13]. This design integrates multiple innovative concepts including molten salt reactors, heat pipe technology, and thermoelectric power generation [14], enabling passive transport of high-temperature nuclear heat and enhancing reactor operational safety and reliability. Consequently, it represents an attractive option for various application scenarios and holds profound significance for scientific and energy development.

Micro-molten salt reactor designs employ high-temperature heat pipes (operating above 500°C) to transport core nuclear heat to thermoelectric power generation systems [15,16]. Given the urgent needs of reactor applications, researchers have actively conducted extensive experimental studies and numerical simulations on this technology in recent years. Zhang et al. [17] established an experimental facility for a thermoelectric heat pipe reactor and performed steady-state experiments, achieving a minimum temperature drop of 6.4 K between the heat pipe evaporator and condenser sections with a thermoelectric conversion efficiency of approximately 8.0%. This work validated the theoretical and practical feasibility of the system, laying a solid foundation for further technological development. However, research on the coupled heat transfer characteristics of molten salt, heat pipes, and thermoelectric power generation in heat pipe micro-molten salt reactors remains relatively scarce, leaving significant gaps for exploration.

To effectively address this critical research gap, this study constructed a molten salt-heat pipe-thermoelectric generator system experimental facility. This apparatus simulates nuclear heat generated by fuel salt during actual operation through external heating, utilizes the excellent heat transfer performance of alkali metal heat pipes for efficient heat transport, and employs thermoelectric generators to convert thermal energy into electrical energy, ultimately achieving stable power output. Through a combination of theoretical and experimental methods, investigations were conducted on heat pipe startup characteristics and coupled heat transfer between heat pipes and thermoelectric power generation.

2. High-Temperature Heat Pipe Heat Transfer Experimental Facility

The experimental facility design is primarily based on the micro-molten salt reactor (micro-MSR) concept [16], which employs a vertically oriented structure to transport nuclear heat to the thermoelectric power generation system via heat pipes. The reactor is designed for a thermal power of 50 kW, with FLiU fuel salt (72.5LiF-27.5UF_4, molar percentage) filling the core. The heat pipes are liquid metal sodium heat pipes with an operating temperature of 650°C. Each heat pipe features a 62-cm-long evaporator section and approximately 26 cm of insulation treatment in the reflector and shielding regions. The condenser section adopts a tower-type thermoelectric generation structure, with total heat pipe lengths varying between 1 m and 1.6 m depending on position. This study employed heat pipes with a total length of 1 m for experiments. The experimental facility primarily serves to validate the feasibility of the "molten salt-heat pipe-thermoelectric power generation" concept, striving to maintain consistency with the micro-MSR concept while adopting approximate solutions when necessary—for example, using conventional ternary chloride salt as a substitute when nuclear fuel is unavailable.

The structure of the high-temperature heat pipe heat transfer experimental facility is shown in Figure 1 [Figure 1: see original paper] and mainly comprises six components: (1) Vessel and internal structures, including the vessel, heat pipes, flange connections, and salt charging ports; (2) Heating system; (3) Thermoelectric power generation system, including thermoelectric modules, hot and cold end blocks, protective gas and piping, water cooling unit and piping; (4) Molten salt transfer tank; (5) Gas system; and (6) Measurement and control system, including thermocouples and other instruments, computer, and data acquisition system. Heat is transferred to the thermoelectric power generation system via sodium heat pipes, while waste heat is dissipated to the environment through a water chiller.

The experimental facility is primarily used for validating the molten salt-heat pipe-thermoelectric generator coupled system and conducting heat transfer experiments, with a total footprint of approximately 5 m (length) × 4 m (width) × 2.8 m (height). The maximum heating power reaches 10 kW, and the maximum heating temperature of the molten salt vessel can reach 850°C. The vessel is surrounded by a 10-cm-thick high-quality aluminum silicate fiber insulation layer, enabling both constant-power and constant-temperature heating control. The heat pipe uses sodium as the working medium with a charge amount of (80.3$±$0.1) g, a 40-mesh double-layer stainless steel wire mesh wick, and a 316L stainless steel shell. Both the evaporator and adiabatic sections of the heat pipe are thermally insulated to minimize heat loss. The thermoelectric power generation system employs lead-tin-telluride-based thermoelectric modules designed for continuous operation at 500°C and intermittent operation up to 600°C. The modules are placed between two copper blocks, with the hot copper block contacting the heat pipe condenser section and the cold copper block featuring water cooling channels. Two thermoelectric modules are connected in series and symmetrically fixed on both sides of the heat pipe. The cold copper block is cooled by a water chiller. The main parameters of the experimental facility are detailed in Table 1 .

The salt used in the experiments is $30NaCl\text{-}20KCl\text{-}50MgCl_2$, a ternary chloride salt with physical properties listed in Table 2 . Similar to fuel salt, this molten salt requires a melting process and is a semi-transparent medium. Heat transfer within the molten salt includes natural heat transfer mechanisms and radiation heat transfer.

During the experiments, two heat pipes were arranged identically with thermocouples installed at the same positions: the heat pipe evaporator section is 60 cm, the adiabatic section is 28 cm, and the remaining 12 cm is the condenser section. K-type thermocouples were placed at positions 0 cm, 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 70 cm, 80 cm, 90 cm, and 97 cm from one end of the heat pipe evaporator section to measure wall temperatures, as shown in Figure 2 [Figure 2: see original paper]. During the experiments, the heat pipe evaporator section was heated at constant power by a heating furnace, the adiabatic section was wrapped with insulation cotton, and the condenser section was exposed to air for heat dissipation through natural convection and thermal radiation. Based on this experimental facility, this study primarily investigates heat pipe startup and operational heat transfer characteristics under different heating power conditions.

2. Heat Transfer Characteristics of the Molten Salt-Heat Pipe-Thermoelectric Coupled System

2.1 Hot-Condition Startup

Micro-molten salt reactors employ various salt charging methods, with the most common being pressurized injection of fuel salt into the preheated core. This experiment utilized a transfer tank to press molten salt into the molten salt vessel. The system salt charging and startup procedures are as follows:

1. Since the selected ternary chloride salt exhibits strong corrosivity at high temperatures, contact with air and water must be avoided during operation, making system sealing critical. Leak detection is the first step in beginning the experiment. This experiment employed a molecular pump unit for vacuum pumping and pressure holding tests.

2. The molten salt vessel uses a transfer tank salt pressing scheme. First, 5 kg of solid ternary chloride salt was loaded into the transfer tank along with magnesium rods for purification. After sealing the flange cover and wrapping the flange heating tape, the molten salt vessel inlet gas valve and transfer tank tail gas pipeline valve were opened. Argon gas was continuously introduced through the molten salt vessel inlet gas line to purge residual air and water from the transfer tank and molten salt vessel.

3. The transfer tank heating was initiated first. To prevent salt solidification, the wall heating temperature was set to 500°C. After melting, the temperature was maintained for 12 hours with continuous argon protective atmosphere flow.

4. After 12 hours of molten salt melting and purging, the molten salt vessel preheating was initiated with constant power heating of 1800 W. The

cooling water circulation was started with temperature set at 25°C and flow rate at 1 L/min.

5. After heat pipe startup, the molten salt inlet gas pipeline valve and transfer tank tail gas valve were closed. Based on salt pressing height and resistance analysis, a gas pressure of 0.01 MPa is sufficient to press molten salt into the molten salt vessel. The molten salt vessel tail gas valve was adjusted to reduce vessel pressure to 0.03 MPa, and the transfer tank inlet gas valve was opened to increase transfer tank argon pressure to 0.02 MPa, thereby pressing molten salt into the molten salt vessel. This process was repeated 3-4 times to ensure complete salt transfer, after which transfer tank and pipeline heating tape heating was stopped. The gas line was then adjusted to maintain argon pressure at a positive pressure of 0.05-0.06 MPa.
6. After stable system operation, temperature and thermoelectric generator open-circuit voltage signals were collected. Further experiments including cooling water adjustment and power escalation were conducted.

During the salt pressing process, since the heat pipe wall temperature after stable operation exceeds 500°C, the instantaneous injection of 500°C liquid molten salt caused the wall temperature to drop rapidly and then rise quickly. With subsequent salt pressing cycles, the wall temperature continued to decrease and then increase, though the temperature variation amplitude diminished with increasing pressing cycles. When adjusting the inlet gas flow, simultaneous pressure changes in the transfer tank and molten salt vessel indicated successful salt transfer. The salt charging process lasted approximately 10 minutes, after which heat pipe operation returned to its pre-charging state. Figures 3(a) and (b) [Figure 3: see original paper] show temperature changes at the heat pipe evaporator section, condenser section, and hot/cold copper blocks within 3 hours from molten salt vessel startup to salt charging. After salt charging, the temperature distribution along the heat pipe wall in the molten salt vessel became more uniform due to molten salt conduction and convection effects. The working fluid temperature inside the heat pipe condenser section (91in, i.e., at 91 cm from the heat pipe bottom) decreased from 446°C to 432°C during salt charging, while the condenser section wall temperature remained virtually unchanged. During the first salt charging process, the overall average temperature of the condenser section increased by 9.8°C, and the average temperature difference between evaporator and condenser sections decreased by 17.6°C. The hot-end block temperature of the thermoelectric generator increased from 328°C to 347°C, and the power output increased from 6.4 W to 8.6 W.

2.2 Stable Operation Analysis

During stable operation, the heating power was maintained constant at 1800 W with a cooling water flow rate of 1 L/min. Based on the balance between heating power and heat loss, the heating furnace power equals the sum of water cooling heat dissipation and system heat loss, which manifests as constant heat pipe wall temperature. Figure 4 [Figure 4: see original paper] shows the temperature distribution of various system components during constant-power operation, demonstrating that heat pipe wall temperature remains constant and the system reaches steady state. By adjusting the rheostat resistance, the maximum output power of 9.94 W was obtained when internal and external resistances were equal. It should be noted that due to the large thermal resistance from direct contact between the heat pipe condenser section and hot-end block, the temperature difference between them is excessive: the hot-end block temperature is 347°C, while the working fluid temperature in the heat pipe condenser section at the same height as the thermoelectric generator is 456°C, resulting in a temperature difference of 109°C. Since thermoelectric generators exhibit higher conversion efficiency at elevated temperatures, applying high-temperature thermal grease or other thermal enhancement methods could effectively improve thermoelectric generator efficiency.

The intrinsic thermal conductivity of molten salt at 600-700°C is 1.03 $\mathrm{W \cdot (m \cdot K)^{-1}}$. However, since heat transfer in heat pipe reactors includes multiple forms such as natural convection, conduction, and radiation, the calculation is complex. Obtaining equivalent thermal conductivity values provides meaningful reference for simulation and design. Assuming heat transfer in the annular gap as thermal conduction, the equivalent thermal conductivity of annular molten salt can be obtained using the multilayer cylindrical wall heat transfer formula:

$$k_{eff} = \frac{Q \ln(d_2/d_1)}{2\pi L \Delta T}$$

where ΔT is the temperature difference between the heat pipe outer wall and vessel inner wall; L is the heating section height; Q is heat transfer rate; and d_1, d_2 are the vessel inner diameter and heat pipe outer diameter, respectively. Based on this formula, the equivalent thermal conductivity of molten salt can be determined. According to system inlet/outlet water temperatures and flow rate, the heat pipe heat dissipation is approximately 1017 W. Using the above formula, the preliminary equivalent thermal conductivity of molten salt is about 11.2 $\mathrm{W \cdot (m \cdot K)^{-1}}$, fully demonstrating the beneficial effect of molten salt convection on heat transfer under non-forced circulation conditions.

2.3 Effect of Heating Temperature on Molten Salt-Heat Pipe Heat Transfer

The molten salt vessel was heated at constant temperatures of 640°C, 670°C, 700°C, 730°C, 760°C, and 790°C for 60 minutes each. As shown in Figure 5 [Figure 5: see original paper], as heating temperature increases, the heat pipe transport power increases while thermal resistance remains relatively constant at approximately 0.09°C/W. Both hot and cold end temperatures of the thermoelectric generator increase with heating temperature, enlarging the temperature difference across the generator and increasing output power. Thermoelectric conversion efficiency rises from 1.0% to 1.6%, with total power output increasing from 9 W to 17.6 W. Based on heat transport and annular gap temperature difference, the equivalent thermal conductivity of molten salt was obtained. The convective heat transfer coefficient of molten salt outside the pipe was determined based on average molten salt temperature and wall temperature. Both parameters increase with heating temperature, primarily due to enhanced molten salt convective heat transfer and radiation effects. Using the Rayleigh number (Ra) formula, the relationship for molten salt-heat pipe walls in confined spaces was fitted as $Nu = 0.0142 \times Ra^{0.4}$.

3. Thermal Resistance Network Model Analysis

3.1 Model Establishment

For investigating steady-state heat transfer characteristics of heat pipes, thermal resistance network models [18-21] represent a common and effective analytical method for calculating equivalent thermal resistance. In recent years, many researchers have employed Computational Fluid Dynamics (CFD) to simulate heat pipe heat transfer characteristics, as CFD enables three-dimensional modeling [22] and simulation of important phenomena such as two-phase flow [23], evaporation, condensation, and entrainment. However, this method consumes substantial computational resources and suffers from slow calculation speeds, requiring re-establishment of geometric models and mesh generation for different heat pipe sizes and types, thus exhibiting poor model flexibility. For this experimental facility, this study constructed a thermal resistance network model for the molten salt-heat pipe-thermoelectric power generation system, covering three main components: molten salt-heat pipe heat transfer resistance, heat pipe thermal resistance network, and thermoelectric power generation system resistance. Detailed calculations and in-depth analyses were performed for each resistance component in the network model.

3.1.1 Molten Salt-Heat Pipe Heat Transfer Resistance The heat transfer process between molten salt and heat pipe primarily includes thermal radiation and natural convection, which occur simultaneously. Therefore, the total thermal resistance can be expressed as:

$$R_{s-tp} = \frac{R_{conv} \times R_{rad}}{R_{conv} + R_{rad}}$$

Based on fundamental convection formulas, the convective resistance R_{conv} can be calculated as:

$$R_{conv} = \frac{1}{h_{conv} A}$$

where h_{conv} is the convective heat transfer coefficient between molten salt and heat pipe outer wall, and A is the heat transfer area. Under experimental conditions involving natural convection of vertical cylinders in confined spaces with $Ra > 10^{10}$, the molten salt exhibits turbulent flow [24]. The Nusselt number correlation is:

$$Nu = 0.13 \times Ra^{1/3}$$

where $Ra = \frac{g\beta\Delta T D^3}{\nu\alpha}$ is the Rayleigh number, $Pr = \nu/\alpha$ is the Prandtl number, D is the reactor vessel equivalent diameter, ν is molten salt kinematic viscosity, α is molten salt thermal diffusivity, and λ is molten salt thermal conductivity. For the heated working fluid in the experiment, $Nu = \frac{h_{conv}D}{\lambda}$. Through these correlations, h_{conv} was calculated, yielding $R_{conv} = 0.4$ K/W.

According to the Stefan-Boltzmann law, radiation heat transfer resistance between molten salt and heat pipe can be calculated as:

$$R_{rad} = \frac{1}{\sigma F_{1-2}(T_1^2 + T_2^2)(T_1 + T_2)}$$

where $\sigma = 5.67 \times 10^{-8}$ W/(m^2·K^4) is the Stefan-Boltzmann constant, F_{1-2} is the view factor depending on geometry, relative position, and orientation (simplified to 1 for radiation between two cylindrical surfaces in this study), and T_1, T_2 are absolute temperatures of molten salt and heat pipe surfaces, respectively. ε_1 and ε_2 are emissivities of molten salt and heat pipe surfaces. The molten salt used in this experiment is semi-transparent with radiation emissivity ε_1 of 0.2, while the heat pipe evaporator section wall material is 316 stainless steel with outer wall emissivity ε_2 of 0.35. Therefore, the actual total resistance equals the sum of molten salt-heat pipe resistance and vessel wall resistance: $R = R_{s-tp} + R_{wall} = 0.01965$ K/W.

3.1.2 Heat Pipe Thermal Resistance Model Heat pipe heat transfer occurs through evaporator, adiabatic, and condenser sections. Based on thermal resistance network theory, this study established the resistance network model shown in Figure 6 [Figure 6: see original paper]. During heat pipe startup, heat transfers from the evaporator section to the condenser section primarily through the heat pipe wall, wick structure, and vapor chamber.

The following sections provide detailed descriptions and calculations for each resistance component in heat transfer. The total heat pipe thermal resistance consists of axial wall resistance, radial resistances of various sections, axial wick resistance, radial wick resistance, and working fluid phase interface resistance. Since the evaporator and condenser sections have similar structures, this study uses the evaporator section resistance as an example for calculation. Heat transfer from evaporator to condenser relies on several simultaneous and interrelated processes:

Evaporator section wall radial conduction resistance:

$$R_{we} = \frac{\ln(d_0/d_1)}{2\pi\lambda_w L_1}$$

where d_0 is heat pipe outer diameter, d_1 is heat pipe inner diameter, λ_w is heat pipe wall thermal conductivity, and L_1 is evaporator section length.

Evaporator section wick radial conduction resistance:

$$R_{ee} = \frac{\ln(d_1/d_v)}{2\pi\lambda_e L_1}$$

where d_v is vapor space diameter and λ_e is composite wick thermal conductivity.

Evaporator section liquid-vapor interface phase change resistance:

$$R_{ie} = \frac{RT_v}{pr}$$

where R is vapor gas constant, T_v is working fluid vapor temperature, p is vapor pressure, and r is latent heat of vaporization.

Vapor axial flow resistance:

$$R_v = \frac{128\mu_v L_{eff}}{\pi\rho_v d_v^4}$$

where L_{eff} is total equivalent length, μ_v is vapor dynamic viscosity, and ρ_v is vapor density.

Wick axial conduction resistance:

$$R_{wick} = \frac{L_{eff}}{\lambda_e A_{wick}}$$

Overall wall axial resistance:

$$R_{wall,axial} = \frac{L_{eff}}{\lambda_w A_w}$$

Condenser section liquid-vapor interface phase change resistance (calculated similarly to R_{ie}), condenser section wick radial resistance (calculated similarly to R_{ee}), and condenser section wall radial resistance (calculated similarly to R_{we}). Substituting heat pipe parameters yields the resistance values for each component shown in Table 3 .

3.1.3 Thermoelectric Power Generation System Resistance Calculation The thermoelectric power generation system includes symmetrically distributed power generation modules on both sides of the heat pipe, copper blocks, insulation layers, water chiller, and corresponding piping and instrumentation. Its structure is shown in Figure 7 [Figure 7: see original paper]. The copper blocks consist of hot-end and cold-end blocks, with the hot-end block' s middle curved surface in close contact with the heat pipe. The two copper blocks are fixed to the heat pipe by flanges. Thermoelectric modules are sandwiched between hot and cold copper blocks, with the cold-end block secured by iron wire wrapping. Thermal grease of a certain thickness can be applied to the heated and cooled surfaces of thermoelectric modules to reduce contact resistance. The copper blocks use high-thermal-conductivity copper, with length and width of 5 cm, height of 12 cm, water pipe diameter of 1 cm, and total copper block weight of approximately 6 kg.

Based on multilayer solid conduction formulas, the total thermal resistance of the thermoelectric power generation system consists of hot-end block resistance and cold-end block resistance. The hot-end block cross-section is simplified as a rectangle, with the contact surface comprising both cylindrical and flat surfaces. The resistance expressions for each component are:

Cylindrical contact surface hot-end resistance depends on hot-end copper block thickness in heat flow direction L_{hc}, cylinder diameter d_{cyl}, and cylinder height h_{cyl}:

$$R_{hc} = \frac{L_{hc}}{\lambda_{cu} \pi d_{cyl} h_{cyl}}$$

Similarly, non-cylindrical contact surface hot-end resistance is:

$$R_{hp} = \frac{L_{hp}}{\lambda_{cu} A_{hp}}$$

where A_{hp} approximates the rectangular area minus the cylinder base area. The total hot-end copper block resistance is:

$$R_{hot} = R_{hc} + R_{hp}$$

Similarly, cold-end copper block resistance depends on cold-end block thickness in heat flow direction L_{cold}, copper thermal conductivity λ_{cu}, and cold-end block plane area A_{cold}:

$$R_{cold} = \frac{L_{cold}}{\lambda_{cu} A_{cold}}$$

Neglecting contact resistance between copper blocks and thermoelectric modules, the total thermoelectric system resistance is the sum of hot-end and cold-end resistances:

$$R_{total} = R_{hot} + R_{cold}$$

3.2 Comparison of Thermal Resistances in Molten Salt-Thermoelectric Coupled System

In this study of coupled heat transfer characteristics in the molten salt heat pipe thermoelectric power generation system, thermal resistances for each component were calculated by substituting corresponding parameters. Experimental data calculations and thermal resistance network model calculations were compared and analyzed, as shown in Figure 8 [Figure 8: see original paper].

First, for annular molten salt resistance, experimental results show relatively small absolute errors. Calculations indicate that at 700°C, the equivalent thermal conductivity of molten salt is 11.2 $\mathrm{W \cdot (m \cdot K)^{-1}}$, significantly higher than the intrinsic thermal conductivity, demonstrating the beneficial effect of molten salt convection on heat transfer. For the heat pipe resistance component, the thermal resistance network model shows a 44.9% deviation from experimental values, likely because the model simplifies the complex heat transfer mechanisms inside the heat pipe. For instance, internal phase change processes (evaporation-condensation) and capillary-driven liquid return phenomena may not be accurately incorporated. Additionally, the model may ignore or combine certain actual resistances, collectively causing deviations between calculated and experimental values. For the thermoelectric system resistance, the deviation between experimental and model values reaches 73.2%. Ling Junyi’ s research on thermoelectric module performance testing platforms investigating installation pressure, thermal grease, and flow disturbance effects showed that replacing thermal grease could increase open-circuit voltage by up to 46% and maximum output power by 137.3% [25]. This indicates that contact resistance between copper blocks and thermoelectric modules, not considered in model calculations, may be the primary error source. Moreover, in absolute terms, the experimental total resistance of the thermoelectric system is more than an order of magnitude higher than other components, demonstrating its dominant influence on total system resistance. Consequently, optimization and improvement of this resistance component represent a key focus for future research.

4. Discussion and Conclusions

(1) This study successfully constructed a high-temperature heat pipe heat transfer experimental facility and conducted in-depth investigations on heat pipe startup characteristics and coupled heat transfer with thermoelectric power generation, laying a foundation for future micro-molten salt reactor development and optimization. Regarding startup characteristics

and operational stability, this approach avoids the molten salt melting phase, shortening startup time and improving system response speed.

(2) After startup, heat pipe wall temperatures become uniform and achieve steady-state operation, providing solid assurance for stable energy supply in practical applications. In terms of heat transfer performance, the combined effect of radiation heat transfer and natural convection increases molten salt equivalent thermal conductivity to $11.2\ \mathrm{W \cdot (m \cdot K)^{-1}}$, exceeding expected heat transfer performance and improving energy conversion efficiency of micro-molten salt reactors while enhancing their competitiveness in the nuclear power field. The 44.9% deviation between model calculations and experimental values for heat pipe resistance indicates limitations of the thermal resistance network model in handling complex internal heat transfer mechanisms, such as its inability to accurately reflect phase change heat transfer and liquid return processes. For thermoelectric system resistance, the significant deviation between experimental and model values results from the model' s omission of contact resistance between copper blocks and thermoelectric modules. The current thermal resistance network model cannot yet accurately analyze the entire heat transfer system but can qualitatively analyze system heat transfer processes. Future work requires transient model calculations and more precise heat transfer experiments for validation.

(3) In absolute terms, the thermoelectric system contributes dominantly to total thermal resistance. Subsequent optimization and improvement of this resistance component will be a key research direction, with in-depth investigation of this resistance helping to enhance overall molten salt-heat pipe thermoelectric system performance. This work not only provides directional guidance for optimizing existing designs to improve heat transfer efficiency and stability but also establishes a technical foundation for subsequent research and development, facilitating rapid advancement of micro-molten salt reactor technology toward engineering and commercialization.

Author Contributions: Zhizhe Xu performed research, collected data, and analyzed/interpreted data; Xingwei Chen designed experiments, conducted experimental research, and critically reviewed intellectual content; Ye Dai provided guidance; Yang Zou secured funding and provided guidance.

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