Design and Analysis of a Tower-Type Thermoelectric Generation System for Heat Pipe Molten Salt Reactors

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Abstract

As one of the significant reactor types of fourth-generation advanced reactors, molten salt reactors utilize high-boiling-point molten salt as nuclear fuel and are characterized by high-temperature output and atmospheric pressure operation. Heat pipe molten salt reactors based on thermoelectric generation combine the advantages of molten salt reactors, heat pipes, and thermoelectric generation, possessing the advantages of high output temperature, high thermoelectric conversion efficiency, simple structure, and high safety and reliability. Therefore, this reactor type exhibits great potential in the field of energy systems and represents an ideal energy source for outer space and deep-sea exploration missions. However, the dense arrangement of heat pipes resulting from the low thermal conductivity of core molten salt presents challenges to the thermoelectric heat transfer design in the heat pipe condenser section. To address the design requirements of this reactor type, this paper proposes a heat pipe-thermoelectric coupling system structure suitable for molten salt reactors and performs heat transfer analysis. The heat pipe condenser section of the core adopts a tower-type thermoelectric generation system structure design, wherein the integrated hot-end seat interfaces with the heat pipe condenser ends of the core, forming hot-end sleeves from layer 1 to layer N from bottom to top; the cold-end seat is mounted outside the hot-end seat, containing cold-end heat pipe channels internally; thermoelectric modules are attached between the outer wall of the hot-end seat and the inner wall of the cold-end seat, and insulation cotton is employed in the gaps between modules to reduce heat leakage. Using Ansys Workbench, heat transfer simulations were conducted for a four-layer tower-type thermoelectric generation system suitable for heat pipe molten salt reactors. The analysis indicates that during system operation, the overall tower structure demonstrates uniform temperature distribution, the effective heat utilization efficiency exceeds 96%, system heat loss is less than 4%, and the temperature difference across the thermoelectric modules exceeds 490°C, which is favorable for enhancing thermoelectric conversion efficiency. The design demonstrates feasibility and facilitates the application of thermoelectric generation in heat pipe molten salt reactors.

Full Text

Preamble

Design and Analysis of a Heat Pipe Molten Salt Reactor Tower Thermoelectric Generation System

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Abstract

[Background] Molten salt reactors, as a key Generation IV advanced reactor type, utilize high-boiling-point molten salt as nuclear fuel, enabling high-temperature output and atmospheric pressure operation. Heat pipe molten salt reactors based on thermoelectric power generation combine the advantages of molten salt reactors, heat pipes, and thermoelectric conversion, offering high output temperature, high thermoelectric conversion efficiency, simple structure, and inherent safety. Consequently, this reactor type holds significant promise for energy systems and represents an ideal power source for outer space and deep-sea exploration missions. However, the dense arrangement of heat pipes necessitated by the low thermal conductivity of core molten salt presents challenges for the thermal design of thermoelectric generation systems at heat pipe condensing sections. [Purpose] To address these design requirements, this paper proposes a heat pipe-thermoelectric generation coupling system structure suitable for molten salt reactors and conducts comprehensive heat transfer analysis. [Methods] The condensing section of core heat pipes employs a tower-type thermoelectric generation system architecture. The integrated hot-end tower interfaces with the condensing ends of core heat pipes, forming hot-side sleeves from Layer 1 to Layer N in a bottom-to-top configuration. The cold-end tower encloses the hot-end tower and contains channels for cold-side heat pipes. Thermoelectric generator modules are mounted between the outer wall of the hot-end tower and the inner wall of the cold-end tower, with insulation cotton filling the gaps between modules to minimize heat leakage. Using Ansys Workbench, thermal simulation was performed on a four-layer tower thermoelectric generation system appropriate for heat pipe molten salt reactors. [Results] Analysis demonstrates that during system operation, the tower structure exhibits uniform temperature distribution, with effective heat utilization exceeding 96% and system heat loss below 4%. The temperature difference across generator modules surpasses 490°C, which benefits thermoelectric conversion efficiency. [Conclusion] The design proves feasible and promotes the application of thermoelectric generation in heat pipe molten salt reactors.

Keywords: Molten salt reactor; Heat pipe; Thermoelectric power generation; Heat transfer simulation; Energy

Introduction

Heat pipes are passive heat transfer elements that transport thermal energy through internal working fluid phase change and continuous circulation, offering high heat transfer efficiency, reversible heat flow direction, compact structure, and effective isolation between primary and secondary fluids [1]. In recent years, applying heat pipe technology to novel reactor designs has become a major research trend [2], with heat pipe reactor types primarily including liquid-fueled and solid-fueled configurations. Solid-fueled reactors include NASA's Kilopower space reactor [3], the Heat Pipe-Operated Mars Exploration Reactor (HOMER) [4], the Megapower nuclear reactor [5], and the Heat Pipe-Segmented Thermoelectric Module Converters (HP-STMCs) space reactor [6]. Liquid-fueled reactors encompass lead-cooled, sodium-cooled, and molten salt reactors. Among these, molten salt reactors represent a crucial Generation IV advanced reactor type that uses high-boiling-point molten salt as nuclear fuel, featuring high-temperature output, atmospheric pressure operation, and inherent safety characteristics. They demonstrate significant advancements and competitiveness in safety, resource sustainability, and environmental protection, making them a Generation IV reactor type prioritized for commercial deployment by various nations [7,8].

Heat pipe molten salt reactors based on thermoelectric power generation integrate the advantages of molten salt reactors, heat pipes, and thermoelectric conversion, offering simplified systems with moderate volume, excellent controllability, superior thermal transient feedback performance, high reliability, and minimal maintenance requirements [9,10]. These attributes enable flexible deployment in deep-sea and land-based nuclear power plant applications, providing substantial advantages in energy systems and holding profound significance for China's scientific and technological development. However, in heat pipe molten salt reactor designs where heat pipes are directly inserted into the core, the low thermal conductivity of molten salt necessitates relatively dense heat pipe arrangements to ensure effective core heat removal [11], which complicates the structural design of thermoelectric generation systems at heat pipe condensing sections. Due to the planar structure of thermoelectric modules, conventional designs typically employ metal plates to connect heat pipes with the hot side of generators, while water cooling circuits are embedded in metal plates at the cold side [12]. Wang et al. proposed a coaxial annular semiconductor thermoelectric generation system design for high-temperature heat pipes, where the evaporator section can be placed in the heat source to absorb heat and the condenser section is inserted into the annular thermoelectric generator, with the cold side of modules tightly contacting the inner wall of a cooling water sleeve [13]. Dense heat pipe arrangements and layout constraints increase system complexity when using single-pipe thermoelectric coupling designs, while integrated end-plate designs cannot ensure effective heat dissipation for central region heat pipes, thereby reducing thermoelectric generation efficiency and proving unsuitable for heat pipe molten salt reactor applications. Addressing these development needs, this paper proposes a tower-type thermoelectric generation system design and conducts simulation analysis.

System Design

1.1 Overall Architecture

As illustrated in [Figure 1: see original paper], the thermoelectric generation system comprises a hot-end tower, cold-end tower, high-temperature heat pipes, cold-side heat pipes, thermoelectric generator modules, and insulation cotton. The generator modules are positioned between the outer wall of the hot-end tower and the inner wall of the cold-end tower. The core of the molten salt reactor contains multiple high-temperature heat pipes forming a heat pipe bundle, with the upper portion serving as the condensing ends of core heat pipes. In the tower generation system design, the top heights of core heat pipe condensing ends increase progressively from the outer to inner regions of the bundle. Based on these varying heights, the heat pipe bundle is divided from outer to inner into Region 1 through Region N, resulting in N distinct height levels for the condensing ends. After the thermoelectric generation system is installed over the heat pipe condensing ends, Layer 1 of the hot-end sleeve primarily extracts heat from Region 1 of the core heat pipe condensing ends, Layer 2 from Region 2, and Layer N from Region N. The thermoelectric generator modules convert thermal energy from the core into electrical energy by exploiting the temperature difference between the hot-end and cold-end towers. Waste heat from the generation system can be removed through shaped moderate-temperature cooling heat pipes (constrained by available workspace).

1.2 Component Structural Design

Hot-End Tower: The hot-end tower ([FIGURE:2(a)]) interfaces with the condensing ends of core heat pipes in the molten salt reactor. Based on the varying top heights of core heat pipe condensing ends, which are divided from outer to inner into Regions 1 through N, the hot-end tower correspondingly comprises Layers 1 through N of hot-end sleeves from bottom to top. The central region of each sleeve accommodates heat pipes corresponding to upper layers, while the peripheral region contains heat pipe channels for the condensing ends associated with that specific layer. The hot-end tower can be fabricated from metal materials with good thermal conductivity and high-temperature resistance, with the outer wall shaped as a regular hexagonal prism or similar geometry to accommodate generator modules; the central region may be either solid or hollow.

High-temperature heat pipes typically employ alkali metal working fluids (operating temperature 450–1000°C), and for molten salt reactors, should utilize casing materials such as Hastelloy alloys that resist high-temperature corrosion and radiation.

Cold-End Tower: The cold-end tower ([FIGURE:2(b)]) encloses the hot-end tower and shares a similar structural configuration, featuring Layers 1 through N of cold-end sleeves from bottom to top with progressively decreasing outer diameters. Thermoelectric generator modules are mounted between the outer wall of the hot-end tower and the inner wall of the cold-end tower, with additional modules placed on the top of the hot-end tower to improve heat utilization. The cold-end tower incorporates channels for cold-side heat pipes. Due to space constraints and cooling requirements, the cold-side heat pipes feature a shaped design with evaporator sections wound within the cold-end tower to increase contact area. Cold-side heat pipes can employ moderate-temperature heat pipes such as copper-water types (operating temperature 0–250°C), with condenser sections dissipating heat through air or water cooling.

1.3 Tower Thermoelectric Generation System Parameters

[Figure 3: see original paper] presents a small heat pipe molten salt reactor design with 46 kW thermal power. The core contains 37 high-temperature sodium heat pipes (32 mm diameter) arranged in concentric circles. The evaporator sections (0.6 m length) are inserted into the core active region, with total lengths varying from 1 m to 1.6 m depending on position. The condenser sections are inserted into the tower thermoelectric generation system. The hot-end tower comprises four layers, each shaped as a regular hexagonal prism with solid construction and copper material. Heat pipe channels within the hot-end tower align with the core heat pipe layout to interface with condensing ends, with thermoelectric generator modules mounted on the copper tower's outer surfaces. The cold-end tower contains channels for moderate-temperature heat pipes, with its inner wall geometry matching the hot-end tower's outer wall where generator modules are mounted. The tower architecture increases surface area to meet the heat exchange requirements of thermoelectric modules. Generator modules are attached to the hot-end copper tower's outer surface on the high-temperature side and to the cold-end copper tower's inner surface on the low-temperature side, generating power from the temperature difference between towers. Moderate-temperature heat pipes inserted into the cold-end copper tower transfer waste heat to the reactor compartment's upper wall for final discharge into seawater.

[Figure 4: see original paper] illustrates the hot-end tower configuration and parameters. For the four-layer design, core high-temperature heat pipes are divided into four concentric circles with varying condenser lengths based on heat dissipation requirements and generator module arrangement. The first circle (outermost layer) contains 18 heat pipes with 14 cm condenser lengths inserted into peripheral channels of Layer 1. The second circle has 12 heat pipes with 29 cm condenser lengths, where the top 15 cm extends into Layer 2 after passing through Layer 1. The third circle (near-center) has 6 heat pipes with 39 cm condenser lengths, including 10 cm inserted into Layer 3. The fourth circle (center) has 1 heat pipe with a 44 cm condenser length, where 5 cm extends into Layer 4 after passing through previous layers.

Generator module arrangement and dimensions are shown in [Figure 5: see original paper], with rectangular blocks representing side-wall modules and square blocks representing top modules. Silicate-aluminum adhesive is applied between modules and tower surfaces. Insulation cotton fills gaps between modules to reduce heat loss. Each module row has 2 mm spacing for electrode wiring. Modules are connected in series within each tower layer and in parallel between layers.

The cold-end tower structure matches the hot-end tower to ensure proper contact with both sides of generator modules, as shown in [Figure 6: see original paper]. Due to layer height constraints and compartment space limitations, shaped moderate-temperature heat pipes are employed to increase evaporator length and enhance heat transfer while rationalizing pipe dimensions. Grouping adjacent sides together, the first, second, third, and fourth layers (from outer to inner) accommodate 4, 4, 3, and 1 heat pipe(s) per side group, respectively, totaling 36 shaped moderate-temperature heat pipes (2 cm diameter) within the tower.

Simulation Methodology

2.1 Physical Model

Ansys Workbench Fluent was employed for thermal simulation of the tower thermoelectric generation module. Effective heat utilization was determined from heat pipe and generator heat transfer rates, with electrical output calculated from generator heat transfer and thermoelectric conversion efficiency. A small heat pipe molten salt reactor tower thermoelectric generation model served as the research object. Due to model symmetry, only a one-third section was simulated. Generator modules can be selected or customized based on size requirements, so side-wall modules were modeled as continuous sheets to maximize effective heat transfer area. Considering module specifications and wiring area requirements, the modeled area represents effective heat transfer area. The model is shown in [Figure 7: see original paper].

2.2 Heat Pipe Model and Working Principle

The general heat pipe working principle is illustrated in [Figure 8: see original paper]. Heat from the source acts on the evaporator section through the pipe wall and wick structure, raising the working fluid temperature and causing evaporation. Since working fluids typically have large latent heats of vaporization, significant heat can be removed with minimal evaporation. Saturated vapor pressure in the evaporator increases with temperature, driving vapor through the adiabatic section to the condenser under thermal pressure difference. At the condenser, heat is released to the cold sink and the vapor condenses into liquid, which returns to the evaporator through capillary or gravitational forces. This continuous cycle efficiently transfers heat from the hot sink to the cold sink.

2.3 Governing Equations and Boundary Conditions

This study focuses on steady-state thermal analysis to obtain temperature fields, thermal gradients, and heat flux distributions. Solid conduction between high-temperature heat pipes, hot-end tower, generator modules, cold-end tower, moderate-temperature heat pipe evaporator sections, and insulation cotton follows Fourier's law:

$$dTqdx\lambda = -()$$

where λ is thermal conductivity (W/m · °C) and q is heat flux (W/m^2).

Heat transfer between moderate-temperature heat pipe condenser sections and the environment follows Newton's cooling law:

$$()wfqhATT = -$$

where h is convective heat transfer coefficient (W/m^2 · °C), Tw and Tf are pipe wall temperature and fluid temperature (°C), respectively, and q is heat flux (W/m^2).

Assuming uniform core power density, high-temperature heat pipe condenser sections are modeled with uniform heat flux boundary conditions. Heat flux values at different power levels are listed in . Moderate-temperature heat pipe condenser sections are assigned convective boundary conditions with h = 700 W/m^2 · °C and fluid temperature of 5°C based on Zheng's research [14]; other surfaces use default boundary conditions. Simulations were conducted at full power (46 kW) and reduced powers (44, 42, 40, 38, and 36 kW). Heat utilization efficiency is calculated as:

$$= 100\% effinQQ\eta\times$$

where Qeff and Qin represent heat transfer through generator modules and high-temperature heat pipe end faces (W), respectively.

2.4 Material Properties

Hot-end and cold-end towers are constructed from copper or tungsten-copper alloy with thermal conductivity of 394 W/m · °C. Generator modules are skutterudite-based single-stage devices, high-temperature resistant and suitable for large temperature differences, achieving thermoelectric conversion efficiency above 8% [15] with thermal conductivity of 2 W/m·°C. Heat pipes are modeled as good thermal conductors with effective thermal conductivity of 10^5 W/m·°C for high-temperature heat pipes [16] and 3$×10^{4}$ W/m·°C for moderate-temperature heat pipes based on experimental findings [17]. Insulation cotton uses aluminum silicate fiber with properties listed in .

2.5 Grid Independence Verification

To ensure numerical accuracy, grid independence was verified using models with 824,000, 1,157,000, 1,490,000, 1,874,000, 2,251,000, and 2,640,000 cells. Monitoring generator heat transfer showed minimal variation beyond 1,874,000 cells, as shown in [Figure 9: see original paper]. At this resolution, maximum grid skewness is below 0.86 with minimum orthogonal quality of 0.14, meeting computational requirements.

Results and Discussion

3.1 Simulation Results at 40 kW

[Figure 10: see original paper] presents the temperature distribution at 40 kW. The maximum temperature of high-temperature heat pipes exiting the core is 696°C. Significant temperature gradients appear across generator modules and insulation cotton, with an average temperature difference of 547°C across modules. As shown in [FIGURE:10(c)], side-wall modules exhibit smaller temperature differences at their lower portions due to heat conduction from lower hot-end towers, affecting generation efficiency. Insulation material of appropriate thickness should be filled below modules and at tower ends to increase temperature differences and improve efficiency. Besides heat transfer through modules, some core heat leakage occurs. Calculations indicate cold-end heat flux of 110,276.2 W/m^2 over 0.1166 m^2 area, yielding 12,858.2 W through generator modules. With 8% conversion efficiency [15], electrical output is 1,028.7 W per one-third section, or 3,086 W for the complete system. High-temperature heat pipe end face heat flux is 1,344,896 W/m^2 over 9.869$×10^{-3}$ m^2 area, delivering 13,272.8 W to the system. From Equation (3), effective heat utilization through modules is 96.9%, with heat leakage of approximately 3.1%.

[Figure 11: see original paper] shows average temperatures and temperature differences across side-wall and top modules for each layer. For side-wall modules, both hot-side and cold-side temperatures decrease from outer to inner layers, with cold-side temperature dropping more significantly, resulting in progressively larger temperature differences. Top modules exhibit similar trends. Hot-side temperature decreases with distance from the core, though the reduction is modest due to strong heat transfer capability of high-temperature heat pipes. Cold-side temperature decreases more markedly with proximity to the cold sink and cooling effect from heat pipes in outer layers.

Calculated power through side-wall modules from outer to inner layers is 5,220 W, 4,080 W, 1,978 W, and 413 W, respectively. Top module power is 529 W, 386 W, and 293 W from outer to inner layers. Although temperature differences and heat flux increase from outer to inner layers, the decreasing surface area of each layer results in declining power output per layer.

3.2 Temperature Distribution at Various Power Levels

Simulations were conducted at 36, 38, 40, 42, 44, and 46 kW with corresponding heat fluxes from . [Figure 12: see original paper] shows temperature fields at different power levels. Normalizing the temperature scale across all cases clearly illustrates the temperature variation trend from high to low power. Cold-side heat pipes effectively remove waste heat from the cold-end tower, maintaining reasonable temperature distribution throughout the system. Uniform temperature gradients across generator modules are observed at all power levels, with detailed temperature data and heat utilization discussed below.

3.3 Temperature Variation and Heat Utilization at Different Power Levels

With constant cooling conditions at moderate-temperature heat pipe condensers, hot-face temperatures of high-temperature heat pipes and generator modules increase nearly linearly with power, as shown in [Figure 13: see original paper]. Temperature differences across modules rise from 492.5°C to 627.2°C, which would increase thermoelectric conversion efficiency and power output. However, as system temperature increases, insulation cotton thermal conductivity increases and insulation performance degrades, causing effective heat utilization (ratio of heat through modules to total heat) to decrease slightly, as shown in [Figure 14: see original paper]. This limits overall power enhancement. Nevertheless, total heat leakage near generator modules remains below 4% across all power levels, maintaining heat utilization above 96% and demonstrating effective thermal insulation. This simulation represents ideal conditions; actual applications must consider additional heat losses from wiring and imperfect sealing.

For this design, comprehensive consideration of temperature distribution and heat utilization across power levels suggests an optimal operating power of 40 kW. At this condition, core temperature remains below 700°C, favorable for long-term system longevity, while high heat utilization yields maximum energy conversion. Since temperature variation trends are significant during power changes and may affect long-term stable operation, maintaining operation near the optimal power is recommended. If power adjustment is necessary, controlling the adjustment rate can mitigate temperature variation impacts.

Conclusions

This paper proposes a tower-type thermoelectric generation system design for heat pipe molten salt reactors, featuring progressively taller condensing sections of core heat pipes from outer to inner regions, with matching tower structures for hot-end and cold-end towers. Generator modules located between the towers generate power from the temperature difference between core heat in the hot-end tower and water cooling at the cold-end tower. Thermal simulation and analysis of a four-layer tower system for a small heat pipe molten salt reactor demonstrate that temperature differences across modules increase from 492.5°C to 627.2°C with power, while system heat leakage remains below 4%, confirming design feasibility. The proposed tower design simplifies the complex coupling structure required by dense heat pipe arrangements while ensuring effective heat dissipation for central region heat pipes, showing broad application potential for novel reactors with densely packed core heat pipes. However, this structure remains at the conceptual design stage, requiring more detailed analysis for practical implementation. Further research on thermal contact resistance at heat pipe-generator interfaces and optimization of series-parallel connections will significantly advance thermoelectric generation applications in heat pipe molten salt reactors.

Author Contributions: ZHANG Lei: conceptualization, data acquisition, formal analysis. CHEN Xingwei: critical review of intellectual content. DAI Ye: supervision. ZOU YANG: funding acquisition, supervision.

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