# Improved Numerical Model of Variable Conductance Heat Pipe Based on Network Method: Application in Residual Heat Removal System for Marine Heat Pipe Reactor

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## Abstract

The Variable Conductance Heat Pipe (VCHP), which incorporates non-condensable gas (NCG) to regulate heat transfer capability, finds extensive application in reactor systems, enabling simultaneous heat transfer, control, and related functions. However, complex phenomena such as two-phase boiling flow and the coupling of NCG cavity compression and release present significant challenges for numerical simulation. This study proposes a numerical method for the efficient simulation of VCHP, specifically tailored to the computational requirements of emergency residual heat removal systems employing VCHP. The methodology integrates a network model, vapor space flow pressure drop calculations, and a VCHP plane interface theory. Heat conduction within the heat pipe is treated as highly efficient, with transient behavior resolved through iterative updates of node temperatures and NCG length. The model's accuracy is validated through comparison with conventional VCHP models, demonstrating a balanced enhancement in computational speed and precision without compromising either aspect. The effects of heating power, gas charge quantity, and non-uniform heating conditions on heat pipe temperature and NCG behavior are systematically analyzed. When applied to residual heat removal systems, the model reveals the dynamic response characteristics of temperature and NCG behavior following reactor shutdown, thereby confirming the feasibility of utilizing VCHP as switching elements in such systems.

## Full Text

## Abstract

The Variable Conductance Heat Pipe (VCHP), which contains non-condensable gas (NCG) to regulate heat transfer capability, is widely used in reactor applications to enable simultaneous heat transfer and thermal control functions. However, complex phenomena such as two-phase boiling flow and the coupling of NCG cavity compression and release pose significant challenges for numerical simulation. This study proposes an efficient numerical method for simulating VCHP, specifically tailored to the computational demands of residual heat removal systems that utilize these devices. The approach integrates the network method, vapor space flow pressure drop calculations, and VCHP plane interface theory. Heat conduction within the heat pipe is treated as highly efficient, with transient behavior resolved through iterative updates of node temperatures and NCG length. The model' s accuracy is validated against experimental data and compared with traditional VCHP models, demonstrating a balanced improvement in computational speed without compromising precision. The effects of heating power, gas charge quantity, and non-uniform heating conditions on heat pipe temperature and NCG behavior are systematically analyzed. When applied to a residual heat removal system, the model reveals the dynamic response of temperature and NCG behavior following reactor shutdown, confirming the feasibility of using VCHP as switches in such safety-critical systems.

**Keywords:** variable conductance heat pipe, heat transfer performance, residual heat removal, network method

## Introduction

The heat pipe reactor represents an innovative reactor concept whose core advantage lies in using high-temperature heat pipes (HTHP) as heat transfer elements to efficiently remove heat generated by nuclear fission [?, ?, ?]. This reactor type is characterized by passive safety features, high reliability, simple system structure, and compact design [?, ?, ?]. Heat pipes transfer fission power from the reactor core to the evaporator section, where absorbed heat causes the working fluid to vaporize [?, ?, ?]. [Figure 1: see original paper] presents the thermophysical model of the VCHP, illustrating its key components and heat transfer processes. After passing through the adiabatic section, the vapor is cooled and condensed in the condenser section, with the condensed working fluid returning to the evaporator section via capillary forces or gravity [?, ?, ?, ?], thereby completing the thermal cycle.

HTHP serves as the primary heat transfer component in the reactor, and VCHP [?, ?], as a specialized type of HTHP, not only provides heat transfer functionality but also enables active thermal control [?, ?, ?, ?, ?]. In this work, VCHP is designed to function as the primary heat transfer path during normal reactor operation and as a control mechanism for the residual heat removal system under accident conditions [?]. Given these dual requirements, developing a numerical model capable of rapidly and accurately calculating VCHP performance is essential. Although VCHP are relatively simple to manufacture, they involve complex physical processes including phase-change heat transfer, working fluid circulation, and NCG movement [?].

For HTHP simulation, Zuo et al. [?] proposed a simplified network method that neglected vapor flow pressure drop and working fluid energy transport, providing only approximate overall temperatures for different heat pipe sections. However, this method cannot calculate actual temperature distributions and is limited to uniform heating conditions, making it unsuitable for non-uniform heating scenarios. Guo et al. [?, ?, ?] developed a fast-computation model for HTHP by simplifying vapor space heat transfer to thermal conduction and integrating the network method to calculate evaporation and condensation rates and working fluid reflux. Harley and Faghri (1994) [?] proposed a two-dimensional transient mathematical model that successfully predicted experimental data for HTHP with and without NCG. Sameh et al. [?] extended the network method for VCHP, developing a transient network method for capillary-driven heat pipes that accounts for axial heat conduction and NCG effects. Wang et al. [?] developed an analysis code for HTHP incorporating NCG effects, considering both rarefied and continuum zones, and used an external iteration method to obtain steady-state temperatures and NCG fractions. The shortcomings of these existing methods lie in their complexity, which consumes substantial computational resources, or their oversimplification, which compromises accuracy. Experimental studies on VCHP have also been conducted; Ponnappan et al. (1994) [?] experimentally investigated wall temperature, startup, and condensation processes in heat pipes containing NCG under steady-state conditions, while Guo et al. [?] systematically analyzed and compared the steady-state temperature, thermal resistance, and self-regulation characteristics of four different VCHP designs, examining design principles from structural, thermophysical, and working fluid charge perspectives.

Considering the large number of heat pipes typically arranged within a reactor core, the model must be sufficiently simple to enable overall reactor modeling and simulation with minimal computational resources. Traditional models struggle to meet these competing requirements simultaneously. Therefore, the objective of this paper is to develop a simplified model capable of performing efficient and accurate calculations for VCHP. The model is based on the concept of a superconducting vapor space, simplifying the entire VCHP process to solid heat conduction, with NCG length determined through iterative calculations of node temperatures. Experimental studies provide reference data for model validation, and comparison with these studies demonstrates the model' s accuracy. Finally, the dynamic response characteristics of the VCHP model and the dynamic variation of NCG are analyzed, showing that the model can be effectively coupled with reactor simulation programs.

[Figure 1: see original paper] Thermophysical Process of VCHP

## 2. Numerical Model Establishment

The model proposed in this work does not directly simulate two-phase flow in the vapor space or capillary phenomena in the wick. Instead, it simplifies passive heat transfer to equivalent thermal conduction. Network nodes are introduced to solve for node temperatures and iteratively calculate NCG length based on plane interface theory, where high-temperature VCHP form a distinct interface between vapor and NCG [?]. Based on these concepts, the model makes the following assumptions: (1) heat conduction through the pipe wall is simplified to two-dimensional conduction; (2) steam within the vapor space is treated as a compressible ideal fluid; (3) working fluid return in the wick is incompressible with constant flow channel volume; (4) temperature at the vapor-wick interface always equals the saturation temperature corresponding to the local pressure; (5) sparse steam in the NCG non-active zone is neglected; and (6) a distinct interface exists between the vapor space and NCG. The model simplifies heat pipe heat transfer to multi-region, multi-boundary thermal conduction, thus requiring only the numerical solution of the conduction differential equation:

$$= \nabla\nabla($$

[Figure 2: see original paper] Single Thermal Resistance Physical Model [Figure 3: see original paper] Overall VCHP Model

The VCHP consists of the metallic containment wall, porous wick, vapor space, and NCG. The success of model development depends on accurately determining the thermal properties and volumetric heat sources for each region.

### 2.1 Wall Modeling

The wall is typically a cylindrical closed shell made of metal. Heat exchange between the heat pipe and external environment can be described by appropriate boundary conditions, with three types available: Dirichlet boundary condition, Neumann boundary condition ($= -\nabla$), and Robin boundary condition.

### 2.2 Wick Model

The wick consists of a porous metal structure saturated with liquid working fluid. This region is typically treated as a composite material, with its thermal properties determined by both the porous metal and the liquid working fluid. For instance, in the case of a wire mesh wick, the density, specific heat capacity, and thermal conductivity of this region can be approximated using the following equations:

$$= +1 - +1-$$

During heat pipe operation, the working fluid continuously flows from the condenser section back to the evaporator section within the wick. This return flow contributes to heat transfer, which is represented by a heat source term in the conduction differential equation.

[Figure 4: see original paper] The heat transfer process of Wick

Based on the calculated temperature field at the current time step, temperature values at each node can be determined. By combining these with the thermal resistance, the evaporation and condensation rates of the working fluid at the gas-liquid interface can be determined [?]. The heat transfer is calculated through vapor condensation:

$$) - ($$

$$) \, h$$

### 2.3 Vapor Space Model

For thermal conduction calculations in the vapor space, the method proposed by Guo [?] is referenced, with the key being determination of the equivalent thermal conductivity for this region. First, the pressure drop of steam flow within the vapor space is calculated, including contributions from the evaporation, adiabatic, and condensation sections [?]:

$$\Delta = \Delta \; + \Delta + \Delta$$

The pressure drop calculation for steam flow in the evaporation section proceeds as follows:

$$\Delta \;\; \times 1+$$

Frictional pressure drop calculation is divided into two flow regimes: laminar and turbulent. For laminar flow:

$$=$$

For turbulent flow:

$$= 0.079 \times \;^{-0.25}$$

The axial Reynolds number in the equation can be expressed as:

$$= 0.61 \;^{3.6} +$$

For the pressure drop of steam flow in the adiabatic section:

$$\Delta 18 + 5 \ {}^{1+0.106\ 1-} \ - 30$$

Similarly, the pressure drop in the condensation section can be calculated:

$$\Delta \ > -2.25(17) - 1.23\ \Delta$$

Using equations (11) to (18), the overall pressure drop within the vapor space can be calculated. Assuming that steam inside the pipe and liquid working fluid in the wick are in thermodynamic equilibrium, the Clausius-Clapeyron equation describes the relationship between temperature and pressure:

$$= +3.3835-$$

Using Fourier' s law, the equivalent thermal conductivity of the vapor space can be calculated:

$$=$$

**2.4 NCG Region**

$$Q = -Av\lambda\nabla T \approx Av\lambda$$

Once NCG is charged into the heat pipe, a distinct interface forms between the vapor in the vapor space and the NCG, as described by the plane interface theory. Therefore, the key to determining thermal conduction in the NCG region is calculating the length of the NCG, which is determined solely by the initial gas charge and the pressure within the vapor space. The pressure in the vapor space is described by Equation [?]:

$$= +3.3835-$$

In this equation, parameters A and B are empirically correlated and depend solely on the medium type within the vapor space. Using this formula, the vapor space pressure can be obtained. By equating this pressure to that of the NCG, the NCG pressure can be determined, which satisfies Equation [?]:

$$= \ m_{NGC} R_{gT_{NGC}} P_{NGC,a} Av$$

The thermal conductivity of the NCG region cannot be simply regarded as the thermal conductivity of the NCG itself. In the study by Hoang et al. [?], the vapor space is divided into an active vapor region and an inactive NCG region, with axial heat transfer between the two regions represented by the ratio of their axial heat transfer coefficients, denoted as . This treatment is applied only to thermal resistance, and diffusion effects at the interface are not considered in the model. Therefore, in the network method, the axial heat conduction thermal conductivity of the NCG region can be defined as the thermal resistance of the vapor region multiplied by the ratio of the heat transfer coefficients of the two regions, :

$$\lambda^* =$$

### 2.5 Numerical Calculation

hvapor The essence of the calculation for this model can be simplified to the following form:

Various algorithms, such as linear multistep methods and Runge-Kutta methods, can be used to solve such a system of differential equations. However, due to the ultrahigh equivalent thermal conductivity of the heat pipe vapor space —theoretically reaching $10^5$ W/(m·K) or higher—stiffness issues are likely to arise during the calculation process. Therefore, it is essential to employ methods specifically designed for solving stiff systems of equations. In this work, a multistep method with a delayed scaling prediction-correction approach is applied. The computational logic of the program is illustrated in [Figure 5: see original paper].

[Figure 5: see original paper] VCHP Program Calculation Flow Chart

## 3. Numerical Model Validation

In experimental studies of VCHP, Ponnappan et al. [?] investigated the performance of stainless steel-sodium heat pipes with NCG in both vacuum and gas-loaded environments. By inputting parameters consistent with the experimental conditions into the established heat pipe model and comparing results with literature data, the model parameters are presented in . As shown in [Figure 6: see original paper], the wall temperature distribution agrees well with experimental data, with corresponding errors listed in . The relative errors in steady-state wall temperature calculations are all less than 2.5%, satisfying computational accuracy requirements. The model is capable of accurately and efficiently calculating VCHP performance. When compared with Wang C' s VCHP model [?] against Ponnappan' s experimental results, that model exhibits relative errors ranging from 2.0% to 3.1%. In contrast, the model demonstrated in this work achieves a minimum relative error of 0.87% and a maximum of 2.21%, with an average relative error approximately 1% lower.

Parameters Related to VCHP Parameter | Value –|–Evaporation section length (mm) | Adiabatic section length (mm) | Initial condensation section length (mm)

| Initial NCG section length (mm) | Outer diameter (mm) | Wall thickness (mm) | Porosity | 67.5% Wall emissivity |

[Figure 6: see original paper] Steady-State Wall Temperature Distribution of VCHP

Errors between Calculated and Experimental Values of VCHP Heating Power (W) | Maximum Absolute Error (K) | Maximum Relative Error –|–|–| | 1.26% | | 1.26% | | 0.87% | | 2.21%

## 4. Performance Analysis

### 4.1 Analytical Object

The method addresses computational requirements for VCHP in the residual heat removal system of a 3.12 MW novel inherently safe oceanic HTHP [**?**, **?**, **?**, **?**]. As shown in [Figure 7: see original paper] and [Figure 8: see original paper], the reactor system consists of the reactor core, cooling system, and shielding body. The cooling system employs a shell-and-tube heat exchanger configuration. During normal operation, supercritical $CO_2$ flows over the heat transfer tube bundle on the shell side of the main heat exchanger, removing heat transferred from the reactor core via heat pipes. lists the main parameters of the inherently safe HTHP. The core utilizes annular uranium nitride as nuclear fuel, with heat conducted to the secondary circuit through heat pipes. To save axial space, a gas reservoir measuring 30 mm in length (twice the pipe diameter) is placed at the end of each heat pipe. Under accident conditions, when the cooling system fails and heat pipe temperatures increase, the NCG compresses, causing the working section of the heat pipe to extend. This extended section then connects to the shell via conductive materials, transferring residual heat from the reactor core to the ocean and preventing core meltdown.

[Figure 7: see original paper] Unmanned Underwater Vehicle Plant [Figure 8: see original paper] Schematic of VCHP in Unmanned Underwater Vehicle

Reactor-Related Parameters Feature | Parameters | Value –|–|–Power | | 3.12 MWt Height | | 755 mm Weight | | 1800 mm Passive heat transfer redundancy | | 550 mm Number of Fuel-Heat Pipe Assemblies | | Number of VCHP | | Length of VCHP | | Length of core | |

The heat pipe wall is made of Inconel 617 alloy, with evaporation, adiabatic, and condensation sections measuring 550 mm, 350 mm, and 600 mm, respectively. An appropriate amount of helium is charged to maintain an NCG length of 300 mm during normal operation. A cylindrical wire mesh core design is adopted with a wick porosity of 67.5%. In subsequent sensitivity analyses, unless specifically targeting a particular boundary condition, the boundary conditions are as shown in . The temperatures of various VCHP parts at this stage are shown in [Figure 9: see original paper], where the NCG section length is 302.1 mm.

[Figure 9: see original paper] Temperature Contour of Heat Pipe under Normal

Operating Conditions

Boundary condition Boundary condition | Measure –|–Convective heat transfer coefficient/(W/m$^2$/K) | Heating power/kW | Emissivity of radiative heat transfer |

### 4.2.1 Heating Power

As depicted in [Figure 10: see original paper] and [Figure 11: see original paper], the impact of heating power on both wall temperature and NCG section length becomes more pronounced once the initial NCG charge is determined. When heating power is gradually increased from 8 kW to 11 kW, the maximum heat pipe temperature rises from 1008 K to 1078 K. Simultaneously, as heating power increases, the NCG section length decreases while the working section of the heat pipe extends. In a reactor accident scenario following shutdown and loss of secondary loop cooling capacity, both core and heat pipe temperatures inevitably rise, causing the heat pipe working section to elongate. While the original working section loses its heat dissipation function, the extended section can be passively activated due to the residual heat removal system design. This extended section, connected to the UUV housing via thermally conductive materials, enables natural heat exchange with surrounding seawater, thereby effectively dissipating core residual heat. Under high heating power conditions, both pressure and temperature within the vapor space increase, demonstrating that VCHP can function as an effective switch for the residual heat removal system.

[Figure 10: see original paper] Heat Pipe Wall Temperature under Different Heating Powers [Figure 11: see original paper] Temperature Contour of Heat Pipe under Different Heating Powers

### 4.2.2 NCG Charge

As illustrated in [Figure 12: see original paper] and [Figure 13: see original paper], the initial NCG charge significantly affects the NCG section length during heat pipe operation. When the initial NCG charge increases from 5.56% to 27.8%, the NCG section length under normal conditions increases from 157.3 mm to 338.1 mm. Consequently, the initial NCG charge can be adjusted to position the switch at a critical point, enabling passive activation following an accident. Meanwhile, as NCG charge increases, the average NCG temperature first decreases and then increases. This non-monotonic behavior results from the combined effects of NCG thermal conductivity and length variation, as both parameters change with different charging amounts. Under normal conditions, the initial charge can be set to achieve an NCG length of 300 mm. This 300 mm section is connected to the UUV housing via thermally conductive materials. In an accident scenario, as core and heat pipe temperatures rise, the extended working section automatically initiates operation, effectively exporting residual heat from the core.

[Figure 12: see original paper] Temperature Contour of Heat Pipe under Different NCG Charges [Figure 13: see original paper] Wall Temperature under Different NCG Charges

### 4.2.3 Case with Non-Uniform Heating

In HTHP applications, heat pipe cooling is often non-uniform, making it essential to investigate effects of non-uniform heating on temperature distribution and NCG behavior in VCHP. Various heating power distributions are listed in . [Figure 14: see original paper] illustrates the temperature distribution under different heating powers. Non-uniform heating affects only the temperature distribution in the evaporator section, with minimal effects on overall performance, suggesting that VCHP possesses inherent resistance to non-uniform heating. This attribute arises because heat transfer between evaporator and condenser sections is facilitated by high-speed steam flow, which effectively mitigates the impact of non-uniform heating on heat pipe performance.

[Figure 14: see original paper] Wall Temperature of Heat Pipe under Non-uniform Heating

Different Heating Powers (W) Case1 | Case2 | Case3 | Case4 | Case5 –|–|–|–|–

### 4.3 Dynamic Response

The maximum heat rejection requirement is determined in conjunction with the UUV system. If the heat sink is lost, the reactor shuts down immediately. The core decay power is:

$$P(t) = 3.12 \times 0.1 \times 7^{-0.2} 7^{-0.2} t + 10^{-t+\tau} + 10^{-0.87t+2\times -t+\tau+2\times}$$

As shown in [Figure 15: see original paper], decay power decreases with time after shutdown and depends on operating time $\tau$. The longer the operating time $\tau$, the greater the decay power. For conservative estimation, the reactor operating time is taken as 500 days for calculations. The decay power after shutdown is:

Following loss of the heat sink, the core temperature changes with time:

$$P(t) = 3.12 \times 0.1 \times e^{-0.1t}$$

During steady-state operation, the initial temperature is 1008 K. In an accident scenario, the temperature rises. To meet safety requirements, the core temperature should not exceed 1273 K.

[Figure 15: see original paper] Chart of Decay Heat Power Versus Shutdown Time

Under accident conditions characterized by complete loss of secondary loop cooling capacity, heat pipes rely exclusively on compression of the NCG reservoir interfaced with the containment structure to enable passive heat dissipation. Numerical simulations of this postulated accident scenario demonstrate the resultant thermal resistance distribution pattern, as illustrated in [Figure 16: see original paper]. For heat transfer between the outer housing and seawater, typical large-space natural convection heat transfer occurs, described by the Miheyev formula:

$$(Pr_f/Pr_w)Nu = C(GrPr)$$

[Figure 16: see original paper] Residual Heat Removal Thermal Resistance Model

As depicted in [Figure 17: see original paper] and [Figure 18: see original paper], with complete loss of cooling capacity in the secondary loop, heat pipe temperature increases over time following shutdown, progressively compressing the NCG. The NCG section length is compressed from 302.1 mm to 83.4 mm, effectively extending the heat pipe working section by 218.7 mm. This extended section is connected to the UUV housing via thermally conductive materials. The shell facilitates timely export of residual heat through large-scale natural convection with seawater, thereby dissipating core residual heat and preventing core meltdown or heat pipe burnout.

[Figure 19: see original paper] shows the variation of maximum heat pipe temperature over time after the accident. The heat pipe temperature gradually increases, reaching 1197 K at 60 seconds. The heat pipe wall is made of high-temperature nickel-based alloy, and at this point, the heat pipe remains within its safe operating range.

[Figure 17: see original paper] Temperature of Heat Pipe after a Certain Time following Accident Shutdown [Figure 18: see original paper] VCHP Wall Temperature after a Certain Time following Accident Shutdown [Figure 19: see original paper] Time-dependent variation of peak wall temperature

## 5. Conclusions

This paper develops a numerical model for rapidly predicting NCG behavior and temperature distribution within a VCHP. By simplifying the entire VCHP as solid heat conduction and assigning equivalent thermal conductivities to both the vapor space and NCG region, the model significantly streamlines traditional approaches. Validation results confirm the model's high accuracy, and sensitivity analysis reveals that heating power, non-uniform heating, and initial gas charge all affect VCHP behavior. Specifically: (1) increased heating power results in shorter NCG length and higher heat pipe temperature under steady-state conditions; (2) higher initial NCG charge leads to higher heat pipe temperatures, reduced heat transfer efficiency, and increased final NCG section length; and

(3) non-uniform heating has negligible impact on overall heat transfer capacity, affecting only evaporator section temperature distribution.

Using this model, a preliminary analysis of VCHP as a critical component in the residual heat removal system of a novel marine HTHP is conducted. The model predicts the dynamic response of NCG in the system post-accident. It is found that at a peak temperature of 1182 K, the NCG section length can be compressed to 48.4 mm while the working section extends by 253.7 mm. These findings suggest that employing VCHP as switches in residual heat removal systems is both rational and reliable.

## Nomenclature

| Symbol | Description | Units |
|---|---|---|
| | Material density | kg/m$^3$ |
| T | Calculated temperature | K |
| c_p | Specific heat capacity | J/(kg · K) |
| ΔP | Pressure drop | Pa |
| $\lambda$ | Thermal conductivity | W/(m · K) |
| L_{eff} | Effective length of a heat pipe | mm |
| L_{NCG} | Length of NCG | mm |
| h | Heat transfer coefficient | W/(m$^2$ · K) |
| Q | Heating power | W |
| ṁ | Mass flow rate | kg/s |
| v | Velocity | m/s |
| $\tau$ | Core full-power operation time | d |
| m | Total mass | t |

## References


1. C. Mueller, P.J.A.o.N.E. Tsvetkov, Novel design integration for advanced nuclear heat-pipe systems, 141 (2020) 107324. https://doi.org/10.1016/j.anucene.2020.107324.
2. C. Wang, D. Zhang, S. Qiu, W. Tian, Y. Wu, G.J.N.E. Su, Design, Study on the characteristics of the sodium heat pipe in passive residual heat removal system of molten salt reactor, 265 (2013) 691-700. https://doi.org/10.1016/j.nucengdes.2013.09.023.
3. H. Buchberg, I. Catton, D. Edwards, Natural convection in enclosed spaces—a review of application to solar energy collection, (1976). https://doi.org/10.1115/1.3450516.
4. G. Hu, R. Hu, L. Zou, Development of heat pipe reactor modeling in sam. 2019, Argonne National Lab.(ANL), Argonne, IL (United States).
5. B. Yan, C. Wang, L.J.A.o.N.E. Li, The technology of micro heat pipe cooled reactor: A review, 135 (2020) 106948. https://doi.org/10.1016/j.anucene.2019.106948.
6. S. Guo, X. Guo, G. Wang, Y. Guo, Z. Wang, J. Leng, W. Yang, B. Tang, Y. Liu, D.J.I.J.o.A.N.R.D. Qian, Technology, Conceptual Design

of a Novel Megawatt Portable Nuclear Power System by Supercritical Carbon Dioxide Brayton Cycle Coupled with Heat Pipe Cooled Reactor, (2024). https://doi.org/10.1016/j.jandt.2024.04.003.

7. A. Faghri, Heat pipe science and technology, Global Digital Press, A. Bushman, D. Carpenter, T. Ellis, S. Gallagher, M. Hershcovitch, M. Hine, E. Johnson, S. Kane, M. Presley, A.J.M.-N.-T.-. Roach, The Martian surface reactor: An advanced nuclear power station for manned extraterrestrial exploration, (2004).
8. C.J.I.J.o.H. Busse, M. Transfer, Theory of the ultimate heat transfer limit of cylindrical heat pipes, 16 (1973) 169-186. https://doi.org/10.1016/0017-9310(73)90260-3.
9. J. Gu, M. Kawaji, R.J.J.o.T. Futamata, H. Transfer, Effects of gravity on the performance of pulsating heat pipes, 18 (2004) 370-378.
10. M. Mameli, L. Araneo, S. Filippeschi, L. Marelli, R. Testa, M.J.I.J.o.T.S. Marengo, Thermal response of a closed loop pulsating heat pipe under a varying gravity force, 80 (2014) 11-22.
11. A. Data Not, Effects of Gravity on Gas-Loaded Variable Conductance Heat Pipes, (1974).
12. C.L. Wang, H. Qin, D.L. Zhang, W.X. Tian, G.H. Su, S.Z. Qiu, Numerical investigation of natural convection characteristics of a heat pipe-cooled passive residual heat removal system for molten reactors, Nuclear Science Techniques. (2020). https://doi.org/10.1007/s41365-020-00780-z.
13. B.D. Marcus, Theory and design of variable conductance heat pipes, (1972).
14. P.R. Mock, D.B. Marcus, E.A. Edelman, Communications technology satellite: A variable conductance heat pipe application, Journal of Spacecraft and Rockets. 12 (1975) 750-3. https://doi.org/10.2514/3.57044.
15. W. Anderson, M. Ellis, J. Hartenstine, C. Peters, C. Tarau, K. Walker, Variable conductance heat pipes for variable thermal links. in 42nd International Conference on Environmental Systems. 2012.
16. C.-Y. Xie, H.-Z. Tao, W. Li, J.-J.J.A.o.N.E. Cheng, Numerical simulation and experimental investigation of heat pipe heat exchanger applied in residual heat removal system, 133 (2019) 568-579. https://doi.org/10.1016/j.anucene.2019.07.009.
17. W.N. Crowson, Temperature control of variable conductance heat pipe receivers in concentrating solar collectors, 1983. https://192.227.237.16.
18. K. Goncharov, Y. Panin, A. Kochetkov, Application of variable conductance arterial heat pipes for storage battery cooling system, 2013. https://10.2514/6.2013-3305.
19. D. Mishkinis, J. Corrochano, A. Torres, Development of miniature heat switch-temperature controller based on a variable conductance loop heat pipe, Heat Pipe Science and Technology. 6 (2015) 111-20. https://doi.org/10.1615/HeatPipeScieTech.v6.i1-2.80.
20. G.Y. Wang Z, Guo X, Guo S, Conceptual Design of a Passive Residual Heat Removal System for Megawatt-Class Nuclear Power Units in Unmanned Underwater Vehicles, International Conference on Nuclear Engi-

neering. (2025).
21. R.J.J.o.t. Bobco, h. transfer, Variable conductance heat pipes-A first-order model, 1 (1987) 35-42. https://doi.org/10.2514/3.5.
22. Z. Zuo, A.J.I.J.o.H. Faghri, M. Transfer, A network thermodynamic analysis of the heat pipe, 41 (1998) 1473-1484. https://doi.org/10.1016/S0017-9310(97)00220-2.
23. Y. Guo, Z. Su, Z. Li, K. Wang, X.J.F.i.E.R. Liu, An improved model of the heat pipe based on the network method applied on a heat pipe cooled reactor, 10 (2022) 848799. https://doi.org/10.3389/fenrg.2022.848799.
24. Y. Guo, Z. Li, K. Wang, Z. Su, A transient multiphysics coupling method based on OpenFOAM for heat pipe cooled reactors, Science China Technological Sciences. 65 (2022) 102-114. https://doi.org/10.1007/s11431-021-1874-0.
25. Y.C. Guo, Z.L. Su, Z.G. Li, K. Wang, Numerical investigation on the startup performance of high-temperature heat pipes for heat pipe cooled reactor application, Nuclear Science and Techniques. 32 (2021). https://doi.org/10.1007/s41365-021-00947-2.
26. C. Harley, A. Faghri, Transient two-dimensional gas-loaded heat pipe analysis, (1994). https://doi.org/10.1115/1.2910927.
27. S.M. Saad, C.Y. Ching, D.J.A.T.E. Ewing, The transient response of wicked heat pipes with non-condensable gas, (2012) https://doi.org/10.1016/j.applthermaleng.2011.11.058.
28. C. Wang, Z. Zhang, M. Zhang, P. Li, Z. Tian, W. Tian, S. Qiu, G.J.A.o.N.E. Su, Numerical evaluation of non-condensable gas influence on the heat transfer characteristics of high-temperature lithium heat pipe during reactor operation, 173 (2022) 109077. https://doi.org/10.1016/j.anucene.2022.109077.
29. R. Ponnappan, W.J.J.o.t. Chang, h. transfer, Startup performance of a liquid-metal heat pipe in near-vacuum and gas-loaded modes, 8 (1994) 164-171. https://doi.org/10.2514/3.516.
30. Y. Guo, C. Liu, H. Pan, W. Lyu, H. Zhang, G. Lin, J.J.A.T.E. Miao, Experimental investigation and multiparameter analysis of variable conductance heat pipes, 202 (2022) 117589. https://doi.org/10.1016/j.applthermaleng.2021.117589.
31. C. Ferrandi, F. Iorizzo, M. Mameli, S. Zinna, M.J.A.T.E. Marengo, Lumped parameter model of sintered heat pipe: Transient numerical analysis and validation, 50 (2013) 1280-1290. https://doi.org/10.1016/j.applthermaleng.2012.07.022.
32. R.S. Reid, Heat pipe transient response approximation. in AIP Conference Proceedings. 2002; : American Institute of Physics.
33. K. Sun, C.J.I.J.o.H. Tien, M. Transfer, Thermal performance characteristics of heat pipes, 18 (1975) 363-380. https://doi.org/10.1016/0017-9310(75)90026-5.
34. T. Hoang, R. Baldauff, D. Mahony, Mathematical modeling of variable conductance heat pipes for steady state and transient operation. in 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. 2011.
35. Z. Wang, J. Gou, Z. Wang, H. Wu, D. Jiang, J.J.A.T.E. Shan, Research

on start-up strategy optimization for a compact megawatt nuclear power system based on surrogate model construction genetic algorithm, (2025) https://doi.org/10.1016/j.applthermaleng.2024.125127.

36. Q. Jiang, P.J.E. Wang, NSGA-II algorithm based control parameters optimization strategy for megawatt novel nuclear power systems, (2025) https://doi.org/10.1016/j.energy.2025.134444.

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