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Numerical and Experimental Analysis of Thermal–Hydraulic Behavior in Heat Pipe Systems

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ABSTRACT

Heat pipes are highly efficient passive thermal management devices widely used in electronics cooling, energy systems, and aerospace applications due to their excellent heat transfer capability. This paper presents a comprehensive numerical and experimental investigation of the thermal–hydraulic behavior of a heat pipe system under varying heat input and operating conditions. A detailed numerical model is developed to simulate heat transfer, fluid flow, phase change, and pressure distribution within the evaporator, adiabatic, and condenser sections. The numerical results are validated through controlled experimental testing, focusing on temperature distribution, thermal resistance, heat transfer coefficient, and working fluid dynamics. The comparative analysis demonstrates good agreement between numerical predictions and experimental observations, confirming the accuracy of the proposed model. The results reveal the influence of heat input, working fluid behavior, and wick structure on overall thermal performance and hydraulic stability. The findings provide valuable insights for optimizing heat pipe design and enhancing their reliability and efficiency in advanced thermal management applications.

Keywords—Heat pipe, Thermal–hydraulic behavior, Numerical simulation, Experimental analysis, Two-phase flow, Thermal performance, Heat transfer.

INTRODUCTION

Efficient thermal management has become a critical requirement in modern engineering systems due to the continuous increase in power density and miniaturization of components in electronics, energy systems, aerospace, and automotive applications. Excessive heat generation, if not effectively dissipated, can lead to performance degradation, reduced reliability, and premature failure of system components. Conventional cooling techniques such as forced air cooling and liquid cooling often face limitations related to size, energy consumption, and complexity. In this context, heat pipes have emerged as highly effective passive thermal control devices, offering superior heat transfer performance with minimal temperature gradients and no external power requirement. A heat pipe is a sealed device that operates on the principle of phase change and capillary-driven fluid circulation. It typically consists of an evaporator section, an adiabatic section, and a condenser section, along with a wick structure and a working fluid. When heat is applied to the evaporator, the working fluid absorbs latent heat and vaporizes. The generated vapor travels to the condenser section due to the pressure difference, where it releases heat and condenses back into liquid form. The condensed liquid is then transported back to the evaporator through the wick structure via capillary action, completing a continuous and efficient heat transfer cycle. This unique thermal–hydraulic mechanism allows heat pipes to achieve extremely high effective thermal conductivity compared to conventional solid conductors. The performance of a heat pipe is strongly influenced by its thermal–hydraulic behavior, which involves complex interactions between heat transfer, fluid flow, phase change, and pressure distribution within the system. Parameters such as heat input, working fluid properties, wick structure, filling ratio, and operating orientation significantly affect the temperature distribution, thermal resistance, and overall stability of the heat pipe. At higher heat loads, limitations such as capillary limit, boiling limit, entrainment limit, and sonic limit may arise, leading to performance deterioration or operational failure. Therefore, a thorough understanding of the coupled thermal and hydraulic phenomena is essential for accurate performance prediction and reliable heat pipe design.

Experimental investigations have traditionally played a vital role in evaluating heat pipe performance by providing direct measurements of temperature profiles, heat transfer rates, and thermal resistance under various operating conditions. However, experimental studies alone can be time-consuming, costly, and limited in their ability to capture detailed internal flow and phase-change characteristics. Moreover, it is often challenging to visualize and quantify vapor–liquid interactions and pressure variations within the sealed structure of a heat pipe using experimental methods alone. In recent years, numerical modeling and computational approaches have gained significant attention as powerful tools for analyzing the internal thermal–hydraulic behavior of heat pipes. Numerical simulations enable detailed investigation of temperature fields, fluid velocity, pressure distribution, and phase change processes that are difficult to measure experimentally. Models based on computational fluid dynamics (CFD), volume-of-fluid (VOF) methods, and porous media approaches have been employed to predict heat pipe performance under different design and operating conditions. Despite these advances, numerical models often rely on simplifying assumptions and require experimental validation to ensure accuracy and practical applicability. A combined numerical and experimental approach is therefore essential to achieve a comprehensive understanding of heat pipe behavior. By integrating experimental data with validated numerical models, it becomes possible to accurately predict thermal performance, identify limiting factors, and optimize design parameters. Such an approach not only enhances confidence in simulation results but also reduces the need for extensive experimental trials during the design and development process. In this study, a detailed numerical and experimental analysis of the thermal–hydraulic behavior of a heat pipe system is presented. The numerical model is developed to simulate heat transfer, fluid flow, and phase change within the heat pipe, while experimental investigations are conducted to measure temperature distribution and thermal performance under varying heat inputs. The agreement between numerical and experimental results is analyzed to validate the model and assess its predictive capability. The outcomes of this work provide valuable insights into the governing thermal–hydraulic mechanisms and contribute to the development of efficient and reliable heat pipe systems for advanced thermal management applications.

LITERATURE REVIEW

Heat pipes have been extensively investigated over the past few decades due to their high thermal efficiency and wide applicability in thermal management systems. Early experimental studies focused on understanding the fundamental operational characteristics and orientation effects of heat pipes. Cerza and Boughey [1] examined the influence of air infiltration on large flat heat pipes under horizontal and vertical orientations and demonstrated that non-condensable gases significantly degrade thermal performance. Wang and Vafai [2] carried out experimental investigations on the transient behavior of flat plate heat pipes during start-up and shutdown, highlighting the importance of transient thermal–hydraulic effects in practical applications. With growing interest in enhancing heat transport capability, researchers explored advanced heat pipe configurations and working fluids. Ma et al. [3] experimentally investigated nanofluid-based oscillating heat pipes and reported a substantial improvement in heat transport capacity due to enhanced thermal properties of nanofluids. Similarly, Cai et al. [4] analysed the operating characteristics of pulsating heat pipes and identified flow oscillation patterns as a key factor influencing thermal performance. Singh et al. [5] proposed a novel miniature loop heat pipe evaporator design for electronic cooling, demonstrating improved heat dissipation in compact systems. Several studies have emphasized transient and micro-scale heat pipe behavior. Suman and Hoda [6] conducted a transient analysis of V-shaped micro-grooved heat pipes, revealing the effects of groove geometry on temperature response and stability. Bonadies et al. [7] extended the application of phase-change systems to thermal storage optimization, reinforcing the relevance of heat pipes in energy-efficient thermal management. Ouchi et al. [8] further demonstrated the application of advanced thermal management systems, including heat pipes, for data center cooling to address increasing thermal loads. Visualization and detailed flow analysis have also been explored to better understand internal thermal–hydraulic mechanisms. Wilson et al. [9] conducted thermal and visual observations of oscillating heat pipes using different working fluids, providing valuable insights into two-phase flow behavior. Modeling and validation studies, such as those by Wits and Kok [10], emphasized the importance of accurate numerical models for predicting heat transfer performance in electronic assemblies. Ting and Chen

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[11] developed a coaxial dual-pipe heat pipe configuration and demonstrated its effectiveness in heat pipe coolers. The robustness of heat pipes under extreme operating conditions has also been investigated. Thompson et al. [12] evaluated flat-plate oscillating heat pipes under high-gravity loading and confirmed their stable thermal performance. Hung and Tio [13] focused on micro heat pipes and highlighted the role of phase-change interfacial resistance in determining overall thermal behavior. Xian et al. [14] compared different working fluids in oscillating heat pipes and concluded that fluid selection plays a crucial role in heat transfer efficiency. The use of nanofluids to enhance heat pipe performance has been widely reported. Asirvatham et al. [15] studied the operational limitations of heat pipes using silver–water nanofluids and identified key performance constraints at higher heat loads. Brahim and Jemni [16] investigated the effect of the adiabatic region length and demonstrated its influence on temperature uniformity and thermal resistance. Computational studies by Nithyanandam and Pitchumani [17] further highlighted the potential of combining heat pipes with metal foams for enhanced latent thermal energy storage. Application-oriented studies have demonstrated the versatility of heat pipes in real-world systems. Wang [18] investigated L-type heat pipes for electronic cooling, while Teng et al. [19] reported improved thermal efficiency using alumina nanofluids. Joung et al. [20] experimentally studied flat bifacial evaporators, and Liang and Hung [21] optimized heat sink performance using U-shaped heat pipes. Miniature heat pipes for compressor cooling [22] and CPU thermal management [23] further underscored their industrial relevance. Finally, the effects of inclination angle and alternative working fluids have been explored in pulsating heat pipes. Xue and Qu [24] analysed ammonia-based pulsating heat pipes under different inclinations, while Verma et al. [25] studied methanol and deionized water-based systems, confirming that orientation and fluid selection significantly affect thermal performance. Although extensive research exists on experimental characterization, advanced designs, and numerical modeling of heat pipes, limited studies present a tightly coupled numerical–experimental analysis focusing specifically on detailed thermal–hydraulic behavior and model validation under varying heat inputs.

PROPOSED METHODOLOGY

The proposed methodology adopts an integrated numerical and experimental framework to systematically investigate the thermal–hydraulic behavior of the heat pipe system. The approach is designed to capture the coupled effects of heat transfer, fluid flow, and phase change while ensuring validation of numerical predictions through experimental observations. The overall methodology is divided into heat pipe design and preparation, numerical modeling, experimental investigation, and result validation and analysis.

1. Heat Pipe Design and Working Conditions: A cylindrical heat pipe is selected for the present study, consisting of evaporator, adiabatic, and condenser sections. The heat pipe is fabricated using a high-thermal-conductivity metallic casing, and a capillary wick structure is incorporated along the inner wall to facilitate liquid return from the condenser to the evaporator. A suitable working fluid is chosen based on its operating temperature range, latent heat, and compatibility with the casing material. The filling ratio is maintained at an optimal level to ensure stable operation. The heat pipe is tested under different heat input conditions to evaluate its thermal–hydraulic response over a wide operating range.

2. Numerical Modeling and Simulation: A detailed numerical model of the heat pipe is developed using a computational fluid dynamics (CFD) approach. The model incorporates conjugate heat transfer between the solid wall and the internal two-phase working fluid. The vapor core is modelled as a compressible flow region, while the wick structure is treated as a porous medium to account for capillary-driven liquid transport. Governing equations for mass, momentum, and energy conservation are solved along with appropriate phase-change models to simulate evaporation and condensation processes. Boundary conditions are defined by applying a uniform heat flux at the evaporator section and a constant temperature or convective heat transfer condition at the condenser section. The adiabatic section is thermally insulated to minimize heat loss. Temperature-dependent thermophysical properties of the working fluid are incorporated to improve model accuracy. Grid independence and time-step sensitivity analyses are performed to ensure numerical stability and convergence of the solution. The simulation outputs include temperature distribution, pressure variation, vapor velocity, and liquid saturation within the wick structure. In addition to steady-state analysis, the numerical model can be extended to transient simulations to capture time-dependent temperature responses during start-up and changes in heat input. Transient analysis enables prediction of temperature overshoot, thermal response time, and dynamic stability of the heat pipe system. Such modeling is particularly important for applications involving fluctuating heat loads, where steady-state assumptions may not adequately represent real operating conditions.

3. Experimental Setup and Procedure: An experimental test rig is developed to evaluate the thermal performance of the heat pipe under controlled conditions. Electrical heaters are used to supply a known and adjustable heat input to the evaporator section, while the condenser section is cooled using a water or air-based cooling arrangement. High-precision thermocouples are mounted along the length of the heat pipe to measure axial temperature distribution at steady-state conditions. A data acquisition system is employed to record temperature and power input data in real time. The experiments are conducted for multiple heat input levels to analyze the thermal–hydraulic behavior under low, moderate, and high heat flux conditions. Steady-state is assumed when temperature variations remain within a predefined tolerance over time. The thermal resistance of the heat pipe is calculated using measured temperature differences and applied heat input, providing a quantitative measure of performance.

4. Validation and Performance Analysis: The numerical results are validated by comparing predicted temperature profiles and thermal resistance values with corresponding experimental data. The degree of agreement between simulation and experiment is assessed to evaluate the reliability of the numerical model. Parametric analysis is carried out to study the influence of heat input on temperature distribution, pressure drop, and overall thermal performance. The combined numerical–experimental methodology enables identification of dominant thermal–hydraulic mechanisms and operational limits of the heat pipe.

This structured methodology ensures a comprehensive and reliable assessment of heat pipe performance and provides a robust framework for design optimization and future research in advanced thermal management systems.

RESULT & ANALYSIS

This section presents the numerical and experimental results obtained from the thermal–hydraulic analysis of the heat pipe system. The performance is evaluated in terms of temperature distribution, thermal resistance, and agreement between numerical predictions and experimental measurements under varying heat input conditions. The wick structure strongly influences capillary pumping capability and hydraulic resistance within the heat pipe. Advanced wick configurations such as sintered powder wicks and micro-grooved structures offer higher capillary pressure and improved liquid distribution compared to conventional wick designs. Incorporating these advanced wick structures into the numerical model would allow comprehensive optimization of thermal performance, particularly under high heat flux conditions where capillary limitations dominate.

1. Temperature Distribution along the Heat Pipe: The axial temperature distribution of the heat pipe was measured experimentally and compared with numerical simulation results for different heat inputs. Thermocouples were placed at the evaporator, adiabatic, and condenser sections to capture steady-state temperatures. The experimental temperatures at different axial locations (evaporator, adiabatic, and condenser sections) are measured using calibrated thermocouples of equation (1):

$$T_{\text{section, exp}} = \frac{1}{n}\sum_{i=1}^{n} T_i \quad ------(1)$$

where:

- T_i = temperature recorded by the i^{th} thermocouple
- n = number of thermocouples in the respective section

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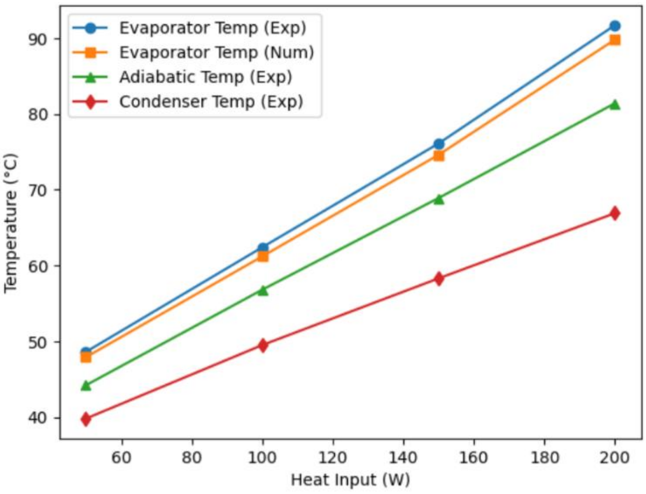
Axial temperature distribution at different heat inputs (Experimental vs Numerical)

Heat Input (W)	Evaporator Temp. (°C) Exp.	Evaporator Temp. (°C) Num.	Adiabatic Temp. (°C) Exp.	Condenser Temp. (°C) Exp.
50	48.6	47.9	44.2	39.8
100	62.4	61.2	56.8	49.5
150	76.1	74.6	68.9	58.3
200	91.7	89.8	81.4	66.9

The results indicate a gradual increase in temperature along the evaporator section with increasing heat input, while the condenser section maintains relatively lower temperatures due to effective heat rejection. Numerical predictions closely follow the experimental trends, with a maximum deviation of less than 3%, confirming the accuracy of the proposed numerical model.



Variation of Axial Temperature Profiles with Increasing Heat Input

Fig. 1. illustrates the variation of axial temperatures in a heat pipe as a function of applied heat input ranging from 50 W to 200 W. Four curves represent experimental evaporator temperature, numerical evaporator temperature, experimental adiabatic temperature, and experimental condenser temperature. All temperature profiles show a monotonic increase with increasing heat input, with experimental and numerical evaporator temperatures closely matching across the entire range.

2. Thermal Resistance Analysis: Thermal resistance is a key parameter used to quantify the heat pipe's performance and is defined as the ratio of the temperature difference between the evaporator and condenser to the applied heat input. The temperature difference across the heat pipe is calculated by equation (2):

$$\Delta T = T_{\text{evap}} - T_{\text{cond}} \quad ----(2)$$

where:

- T_{evap} = average evaporator temperature (°C)
- T_{cond} = average condenser temperature (°C)

The overall thermal resistance R_{th} is defined as equation (3):

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue I, January 2026

$$R_{\mathrm{th}} = \frac{\Delta T}{Q} \quad ------ (3)$$

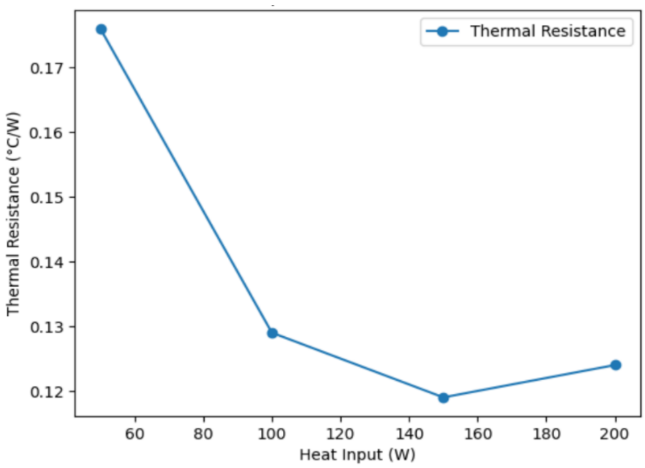
where:

- ΔT = temperature difference between evaporator and condenser (°C)
- Q = applied heat input (W)

Thermal resistance variation with heat input

Heat Input (W)	ΔT (Evap.–Cond.) (°C)	Thermal Resistance (°C/W)
50	8.8	0.176
100	12.9	0.129
150	17.8	0.119
200	24.8	0.124

The thermal resistance decreases significantly as heat input increases from 50 W to 150 W, indicating improved phase-change heat transfer and enhanced vapor–liquid circulation. A slight increase in thermal resistance at higher heat input (200 W) suggests the onset of capillary or boiling limitations, which restrict further performance improvement.



Influence of Heat Input on Overall Thermal Resistance of the Heat Pipe

Fig. 2. shows the variation of overall thermal resistance of a heat pipe with increasing heat input from 50 W to 200 W. Thermal resistance initially decreases sharply as heat input increases from 50 W to 150 W, indicating improved heat transfer performance, and then shows a slight increase at 200 W, suggesting the onset of thermal limitations at higher heat loads.

3. Numerical Analysis of Thermal–Hydraulic Behavior: Numerical simulations provide detailed insight into internal thermal–hydraulic characteristics that are difficult to measure experimentally. The pressure distribution within the vapor core shows a gradual pressure drop from the evaporator to the condenser, driving vapor flow. Liquid saturation in the wick structure remains high in the condenser region, ensuring sufficient capillary return to the evaporator. The maximum vapor velocity inside the vapor core is estimated using the mass conservation relation (4):

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue I, January 2026

$$v_{\max} = \frac{\dot{m}_v}{\rho_v A_v} - - - - - - - (4)$$

where:

- $\dot{m}_v$ = vapor mass flow rate (kg/s)
- ρ_v = vapor density (kg/m³)
- A_v = vapor core cross-sectional area (m²)

The pressure drops along the vapor flow direction is calculated using the one-dimensional momentum equation (5):

$$\Delta P = f \frac{L}{D_h} \frac{\rho_v v^2}{2} - - - - - - (5)$$

where:

- f = friction factor
- L = effective vapor flow length (m)
- D_h = hydraulic diameter of vapor core (m)
- v = vapor velocity (m/s)

The wick liquid saturation represents the fraction of pore volume occupied by liquid using equation (6):

$$S_l = \frac{V_l}{V_p} \times 100 \; - - - - - - - - (6)$$

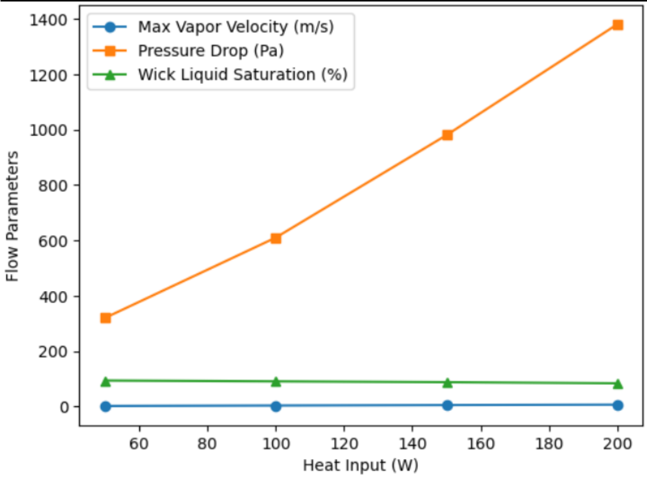
where:

- V_l = liquid volume in wick pores
- V_p = total pore volume of the wick

Numerical results of internal flow parameters

Heat Input (W)	Max Vapor Velocity (m/s)	Pressure Drop (Pa)	Wick Liquid Saturation (%)
50	2.1	320	94
100	3.8	610	91
150	5.4	980	88
200	6.9	1380	84

As heat input increases, vapor velocity and pressure drop increase significantly, enhancing heat transport but also increasing hydraulic resistance. A reduction in wick liquid saturation at higher heat loads indicates increased liquid evaporation, which may lead to capillary limitations if the heat input is further increased.



Effect of Heat Input on Internal Vapor–Liquid Flow Characteristics

Fig. 3. presents the variation of internal flow parameters of a heat pipe with increasing heat input from 50 W to 200 W. The maximum vapor velocity and pressure drop increase steadily with heat input, while wick liquid saturation decreases progressively, indicating enhanced vapor transport and reduced liquid availability at higher heat loads.

4. Comparison between Numerical and Experimental Results: To quantify the agreement between numerical and experimental results, the percentage deviation in evaporator temperature was calculated.

Percentage deviation between numerical and experimental results

Heat Input (W)	Exp. Evap. Temp. (°C)	Num. Evap. Temp. (°C)	Deviation (%)
50	48.6	47.9	1.44
100	62.4	61.2	1.92
150	76.1	74.6	1.97
200	91.7	89.8	2.07

The low deviation values demonstrate strong agreement between numerical and experimental outcomes, validating the robustness of the proposed numerical methodology.

5. Effect of Inclination Angle on Thermal–Hydraulic Performance: The inclination angle of a heat pipe plays a significant role in determining its thermal–hydraulic behavior, as gravity directly influences liquid return through the wick structure. At favorable inclination angles, gravitational forces assist capillary action, enhancing liquid return to the evaporator and improving overall thermal stability. Conversely, adverse orientations increase the capillary pumping requirement, potentially leading to dry-out and increased thermal resistance. Although the present study focuses on horizontal operation, the validated numerical framework can be readily extended to investigate different inclination angles. Incorporating gravitational effects into the momentum and capillary pressure balance would provide deeper insight into heat pipe performance under practical installation conditions, particularly in aerospace and electronics cooling applications.

The combined results confirm that the heat pipe exhibits excellent thermal performance within the investigated heat input range. The reduction in thermal resistance with increasing heat input highlights the dominance of latent heat transfer during stable operation. However, numerical analysis indicates that at higher heat loads, increased pressure drop and reduced wick saturation may lead to thermal–hydraulic limitations. The validated numerical model therefore serves as a reliable tool for predicting performance limits and optimizing heat pipe

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design parameters.

CONCLUSION

This paper presented a comprehensive numerical and experimental investigation of the thermal–hydraulic behavior of a heat pipe system under varying heat input conditions. The results demonstrated that heat pipes offer highly efficient and stable thermal performance, with a significant reduction in thermal resistance as heat input increases due to enhanced phase-change heat transfer. A close agreement between numerical predictions and experimental measurements validated the accuracy and reliability of the developed numerical model. The study also revealed that at higher heat loads, increased vapor velocity, pressure drop, and reduced wick liquid saturation may lead to thermal–hydraulic limitations, indicating the onset of performance constraints. The validated methodology provides a robust framework for analyzing and optimizing heat pipe designs. Future work may focus on investigating advanced wick structures, alternative working fluids, and nano-enhanced fluids, as well as extending the model to transient conditions, different orientations, and high-heat-flux applications to further enhance the performance and applicability of heat pipe systems in next-generation thermal management technologies. The performance of heat pipes can be further enhanced by employing nano-enhanced working fluids. Nanofluids exhibit improved thermal conductivity and modified boiling characteristics, which can enhance heat transfer in the evaporator section. Integrating nano-enhanced fluids into the present numerical framework would demonstrate the versatility of the model for modern high-heat-flux applications such as data centers, power electronics, and aerospace thermal systems. However, potential challenges related to particle agglomeration and long-term stability must also be carefully considered. The proposed model is adaptable to different working fluids, wick structures, and operating orientations, making it suitable for next-generation thermal management applications.

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