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The Evaporation Process in a Heat Pipe: A Review Study

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Abstract

The heat pipe is one of the efficient devices applied in industries for thermal management and energy conservation. This review outlines the evaporation process of the heat pipes, the most critical stage that will determine their thermal efficiency and operational performance. The review covers trends in the development of heat pipes regarding new materials, wick structures, and working fluids, together with the latest developments in their applications related to electronic cooling, renewable energy systems, and aerospace. It highlights the integration of CFD simulations in order to optimize heat transfer efficiency and design configurations. Experimental studies and simulations provide insight into phase-change phenomena, temperature distribution, and the impact of working fluids on evaporation dynamics. Despite significant advances, some challenges include thermal resistance, operational constraints, and inefficiencies due to nanofluids. It gives an overview of specific urgent issues that need immediate resolution to unlock the high-performance capabilities of heat pipe technology applied in sustainable and advanced thermal systems.

Keyword: *Heat pipe; Evaporation process; Thermal efficiency; Working fluids; CFD simulation*

1. Introduction

Heating and air conditioning are needed for both residential and commercial purposes. For the building of sustainability, two techniques which have to be taken into consideration are energy transfer and energy conservation. Humans in the Kurdistan Region are in search of other alternate energy-saving strategies as well as ways to come closer to developed nations by entering the world of sustainability. One method that can give a way to sustainability is the heat pipe [1]. The heat pipe's schematic diagram is displayed in figure 1 [2]

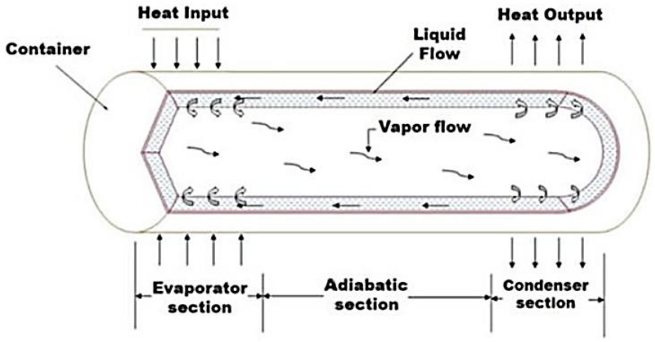


Fig. 1. Schematic diagram of the heat pipe [2]

The heat pipe can be utilized as a mechanism for serving user needs and saving energy. To achieve optimum performance of the heat pipe system, its thermodynamic processes need further improvement. [3, 4]. Evaporation is the process of one of the thermodynamic processes in a heat pipe system, an essential step that gives heat pipes optimum performance with high efficiency in several applications. [5, 6]. Furthermore, the design element of this study is quite significant. It includes material selection, geometric optimization of the heat pipe structure for improved evaporation rates, and the integration of sophisticated coatings or wick structures for overall thermal performance enhancement. [7, 8]. The researchers use computational modeling and iterative experimentation to better understand the fundamental processes controlling evaporation dynamics, thus opening the door for creative developments in heat pipe technology. In the final analysis, design and experimental study of the heat pipe evaporation process represent a multidisciplinary undertaking that links basic scientific concepts with useful engineering solutions [9, 10]. In addition, other than perfection in the current systems of thermal management, this project opens up avenues for next-generation heat pipe applications pertaining to fields such as electronics cooling, renewable energy systems, and aerospace Recently, much research has been directed toward the optimization of the evaporation process in heat pipes for increased thermal efficiency and to reach ideal operating conditions.

Table 1. Summary of Research Contributions on Heat Pipe Technologies and Thermal Management

Author	Study Focus	Key Finding
Chen et al. [11]	Experimental study on a miniature stainless-steel-ammonia loop heat pipe with a biporous wick	Demonstrated reliable startup at 2.5 W, maximum heat load of 130 W, high isothermality (temperature differences within 3 °C), and thermal resistance varying from 1.42 to 0.33 °C/W.
Mahdavi et al. [7]	Experimental analysis of a cylindrical copper heat pipe with a mesh wick	Investigated the impact of fluid fill volume, inclination angle, and heat input. Found gravity-opposed orientations increased thermal resistance, while under- and over-filling degraded performance. Validated a numerical model.
Chan et al. [10]	Review of heat pipe types, mechanisms, and advancements	Explored latent heat transfer, wick designs, nanotechnology applications, hybrid systems, and future research on lightweight materials, advanced geometries, and nanotechnology to enhance heat pipe performance.
He et al. [12]	New flat evaporator loop heat pipe (FELHP) design	Achieved consistent temperature uniformity and stable operation across 10–160 W with R245fa working fluid, maintaining heating

	for high vapor pressure handling	block temperature below 80 °C in horizontal orientation.
Xie et al. [13]	CFD and experimental analysis of heat transfer in a rotating heat pipe	Rotating heat pipe showed efficient heat transfer with minimal temperature differential (4 °C) compared to non-fluid pipes with poor heat transfer (27 °C differential).
Alizadehdakhel et al. [14]	CFD modeling and experiments on thermosyphon phase change phenomena	Revealed optimal fill ratios for performance. Increasing heat flow improved performance up to a point, but excessive energy reduced it. Validated CFD predictions against experimental results.
De Schepper et al. [15]	Flow boiling in hydrocarbon feedstock inside convection heat exchangers using a 3D evaporation model	Simulated two-phase flow regimes and phase changes using CFD. Identified areas for improvement in modeling temperature-dependent properties and heat flux profiles, requiring greater computational resources for enhanced accuracy.

2. Heat pipe application

Heat pipes are very effective devices that transfer heat with the principle of phase change. Heat pipes have become widespread in applications related to efficient heat management, including electronics cooling, aerospace, and solar technologies. Being able to handle high heat fluxes with compact and lightweight designs, they have become irreplaceable in modern industries. Recent developments also involve new wick structures, working fluids, and some very new applications: heat pipe-integrated solar collectors, turbines, and flexible designs for space and micro-scale technologies. These are in attempts to try to overcome design challenges and extend the applicability of heat pipes to more fields. [16]. Mochizuki et al. [17] have reviewed heat pipe applications, putting emphasis on their evolution and their critical role in modern thermal management. Heat pipes and vapor chambers revolutionized electronics cooling by extending air cooling limits, minimizing thermal resistance, and enhancing heat dissipation for high-performance processors. Figures 2 and 3 illustrate the success of heat pipes. Figure 2 presents the three major types-grooved, sintered, and composited wick-already in widespread use in electronics, with about 15 million units being manufactured every month. Figure 3 shows the effectiveness of heat pipes transferring heat from small sources to larger dissipation areas that has enabled processors to move from 10–15 W/cm² in 2000 to over 100 W/cm² in 2010. Other topics investigated by Mochizuki et al. are more innovative applications such as heat-pipe-based cold water storage for energy-efficient cooling of data centers, the utilization of natural cold and hot energy for agricultural storage, snow melting, and geothermal energy extraction. They recommended further development in the field of micro-scale heat pipes for compact electronics and large-scale systems for terrestrial and space applications, showing the ability of the technology to further enhance energy efficiency and alleviate global warming.

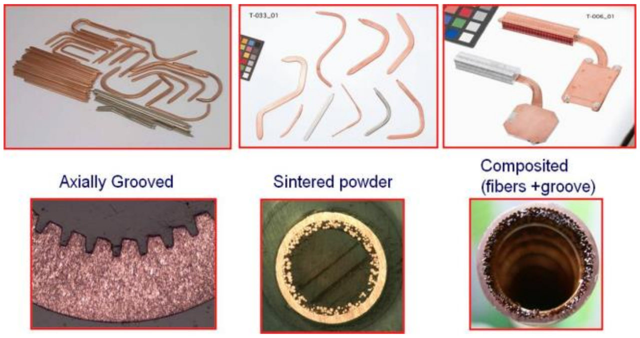


Fig. 2. Types of heat pipes [17]

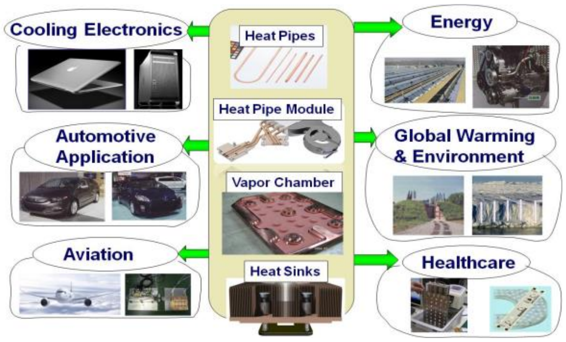


Fig.3. Types of heat pipes [17]

Abdali et al. [16] analyzed the performance of heat pipes by studying the properties of various materials, wick structures, and working fluids. Conventional working fluids such as water, ethanol, and ammonia were experimented with alongside new nanofluids with nanoparticles including graphene, SiO_2, and Al_2O_3 to improve thermal conductivity and capillary action. Grooves, mesh screens, and sintered material wick designs have been studied for their effectiveness. The phase change phenomena in the evaporator and condenser sections were studied using temperature distribution and moving boundary conditions to predict the phase change zones and interface velocities. Experimental setups included thermocouple measurements along the length of the heat pipe and simulations for modeling heat transfer behavior. Khairnasov & Naumova, [18] analyzed the integration and application of various types of heat pipes in solar energy systems, including photovoltaic-thermal collectors, solar thermal collectors, concentrating photovoltaic systems, and solar power plants. They investigated the suitability of various HP types, namely thermosyphons, wicking HPs, flat plate HPs, loop HPs, pulsating HPs, and high-temperature HPs, considering their advantages and limitations, and the necessity of optimizing their design for minimum thermal resistance. Figure 4 compares conventional FPCs with heat pipe FPCs, showing that hydraulic resistance is reduced by more than two times when heat pipes are used. It may also present the modular nature of HP systems, touting their robustness since a single failure of an HP does not significantly reduce efficiency, unlike the complete circuit failure in traditional liquid-based FPCs. They stressed that systems must be designed to compensate for thermal resistance arising from HPs through an increase in the surface area, efficient heat removal strategies, and thermosyphon operation to maximize heat transfer efficiency.

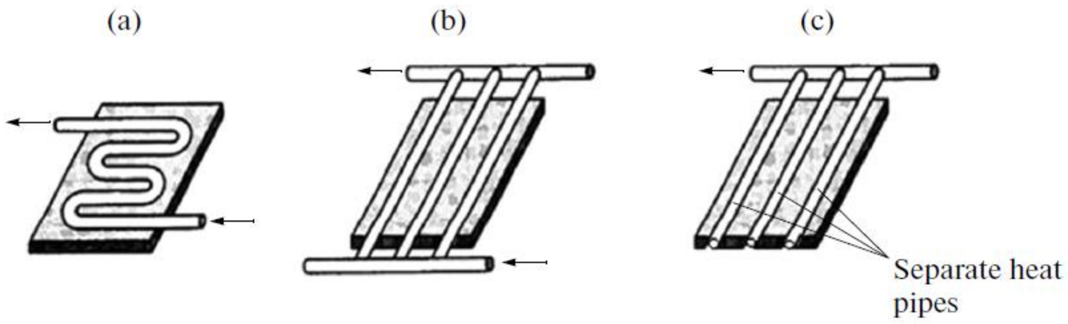


Fig. 4. The design and flow circuit in FPC: a—serpentine circuit; b—collector circuit; c—circuit with the heat pipes. [18]

Jouhara et al. [3] have provides a comprehensive analysis of heat pipe technology, focusing on its applications across various temperature ranges. Correspondingly, in low-temperature heat pipes, there exist systems such as oscillating heat pipes given by figure 5, and loop heat pipes shown in figure 6. OHPs rely on creating an oscillating motion of liquid slugs and vapor bubbles without needing a wick structure in order to operate while the latter represents LHPs, designed originally with separate liquid and vapor channels, becoming ideal in dissipating heat from a number of sources. Cryogenic thermosyphons shown in figure 7, sorption heat pipe shows in figure 8 that depend on gravity for the return of liquid rely on gravity for the return of liquid also have been investigated. Vertical orientation is essential for optimum performance. Heat pipes have found application in waste heat recovery and solar power systems at high temperatures. Difficulties arise when nanofluids are introduced into such systems. The resulting nanofluids have improved thermal performance but, in operation over time, particles tend to stick to the pipe walls and increase thermal resistance. Also, these systems are difficult to model. Thermal modeling techniques including non-Newtonian fluids and nanofluids will also be reviewed for simulation within geothermal and automotive systems, among others. Besides such promising advantages in the bettering of thermal efficiency and reduction of emission, operational constraints, cost aspects, and further research studies along with validation of models were needed to be performed, as especially under high-temperature applications and nanofluid, the paper points to crucial limitations in the use of heat pipes. He concludes that even though the heat pipe technologies have been expanding to a number of industries, some gaps exist in the research and modeling for fully optimizing the systems before the implementation of such systems into all their potential applications.

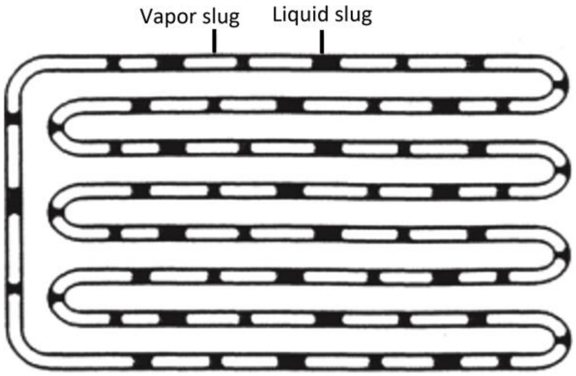


Fig. 5. Oscillating heat pipe[3]

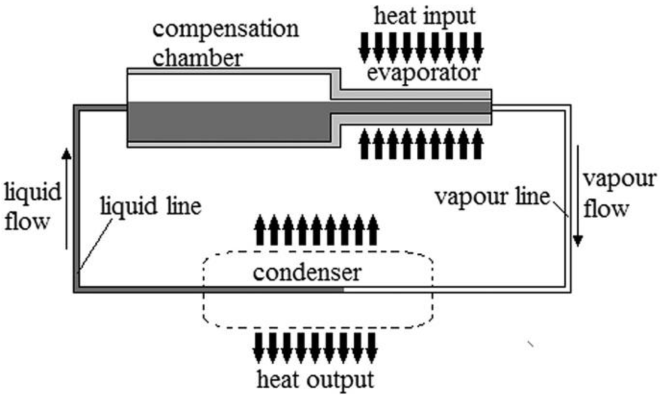


Fig. 4. Loop heat pipe [3]

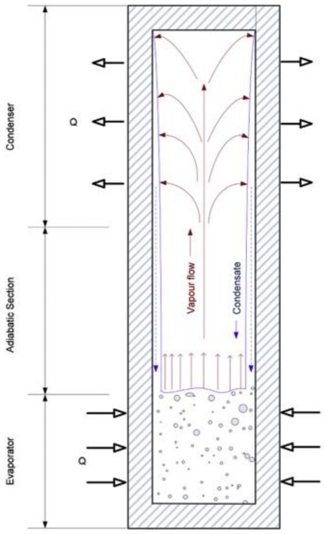


Fig. 7. Schematic of a thermosyphon [3]

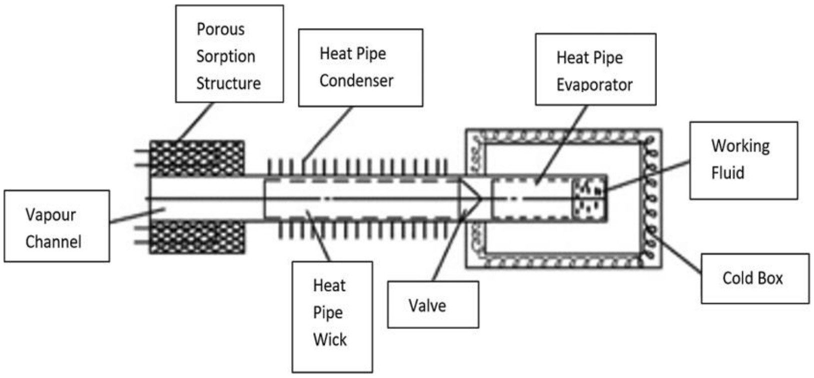


Fig. 8. sorption heat pipe [3]

Wang & Vafai [19] have carried out an experimental investigation to analyze the thermal performance of a flat plate heat pipe as shown in the figure 9. They identified that the temperature along the heat pipe surfaces, especially in the condenser section, was quite uniform and of a small temperature difference across the heat pipe. The dominant thermal resistance was found within the porous wick in the evaporator section, which provided the highest temperature drop and consequently the performance of the heat pipe. They also calculated the heat transfer coefficient in the condenser section and introduced the concept of a heat pipe time constant to describe transient behavior. Empirical correlations were developed for time constant, maximum temperature change, and temperature difference with respect to input heat flux. Experimental results were compared with analytical results, and good agreement was observed that validated the experimental setup.

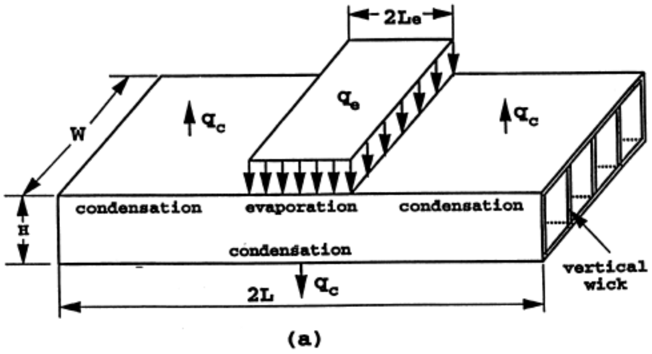


Fig. 9. Schematic of the flat plate heat pipe [19]

Abd El-Baky & Mohamed, [20] investigated the overall efficiency of employing heat pipe heat exchangers to recover heat through buildings' external air conditioning systems to reduce cooling demand. The thermal performance of the system was considered for different fresh air inlet mass flow rates and stream temperatures. Based on the experimental setup, a mathematical model was developed that included two air ducts of 0.3 m × 0.22 m in cross-sectional area, and the heat pipe configuration was composed of 25 copper tubes with 0.2 m for the evaporator and condenser and 0.1 m for the adiabatic section. The working fluid R-11 had a saturation temperature of 303 K. The conclusions of the study were that, with the increase in temperature of the fresh air inlet, the effectiveness and heat transfer rate also increases. The studies also revealed that the mass flow rate ratio affects the fresh air temperature change highly and the heat recovery rate rises about 85% by increase in fresh air inlet temperature. Figure 10 shows the heat exchanger's schematic.

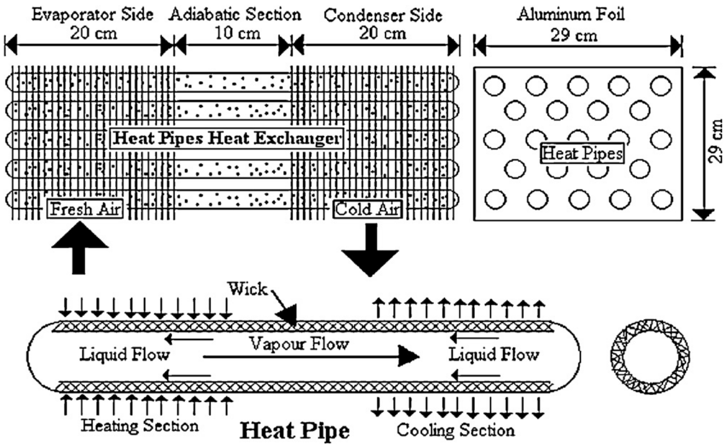


Fig. 10. Heat pipe heat exchanger and heat pipe design.[20]

3. Impact of Working Fluid on Heat Pipe

The selection of working fluid in the heat pipe is very crucial because the nature of the working fluid will directly influence the heat transfer performance and efficiency of the heat pipe in its operating range. A working fluid should possess proper thermophysical properties, such as a low boiling point, high latent heat of vaporization, and good thermal conductivity, to ensure effective heat transfer between the evaporator and condenser sections. Common working fluids are water, ammonia, and acetone. The fluid should be compatible with the heat pipe materials, besides being able to withstand the operating temperature range without degradation. Further, the fluid needs to be tested on different pressure and temperature conditions to achieve optimum efficiency and reliability of the\ heat pipe for space applications. [21, 22]. Various experiments have been analyzed to review the influence of working fluids on the heat transfer performance of heat pipes, including comparison studies between different fluids with regard to thermal resistance, boiling and condensation characteristics, and heat transfer coefficients at various operating conditions.

Table 2. Summary of Working Fluids in Heat Pipe Studies.

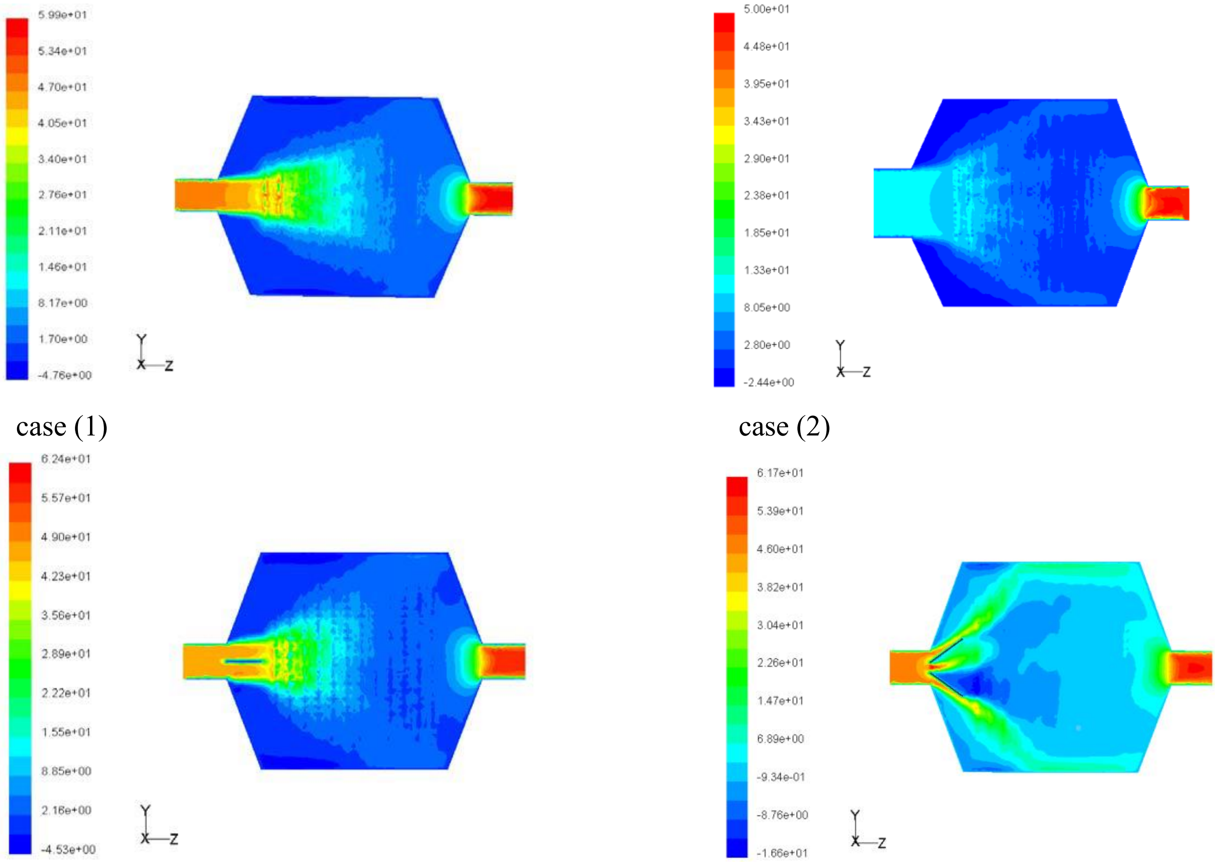
Author	Year	Study Focus	Key Finding
Savino et al. [23]	2008	Performance of wickless and composite wick heat pipes using water or water/alcohol mixtures	Performance of wickless and composite wick heat pipes using water or water/alcohol mixtures
Savino et al. [24]	2010	Evaluation of self-rewetting fluids (aqueous alcohols, brines, nanofluids) for microgravity heat pipes	Self-rewetting fluids exhibited superior thermal performance, with promising characteristics for space applications.
Akyurt [25]	1984	Evaluation of heat pipes for solar water heaters	Heat pipes demonstrated satisfactory performance, with compact condenser designs showing potential for large-scale applications.
Wu et al. [26]	2012	Influence of working fluid properties on thermal performance in pulsating heat pipes	Thermal resistance decreases with reduced surface tension, viscosity, and latent heat; latent heat was the most impactful property.
Esen & Esen [27]	2005	Thermal performance of a two-phase thermosyphon solar collector with different refrigerants	R410A showed the best performance; results provided insights for optimizing solar water heating systems.
Suman & Hod [28]	2005	Performance analysis of V-shaped micro heat pipes	Design and operational parameters significantly influence heat transfer; a method to calculate dry-out length was developed.

Wong et al.[29]	2012	Evaporation in flat-plate heat pipes with water, methanol, and acetone	Water had the highest heat load capacity; nucleate boiling was key for acetone and methanol, while water showed quiet surface evaporation.

4. CFD simulation of heat pipe

CFD simulations of heat pipes give a detailed insight into the thermal and fluid behavior that enable optimization for certain applications [30]. The researchers focus on heat transfer efficiency by analyzing the impact of heat flux, working fluid properties, and pipe material on performance. Phase-change dynamics, such as evaporation and condensation, are studied in relation to vapor-liquid interactions and transition rates. Capillary action, permeability, and porosity to investigate wick structure effects on enhancing liquid return are considered. Simulations visualize temperature gradients, identify thermal resistance zones, and assess operational limits such as dry-out, boiling, and sonic limits. Geometrical and material optimization studies are conducted to look into the influence of pipe dimensions and conductivity on the performance. Orientation and gravity effects are modeled for conditions such as vertical, horizontal, or microgravity scenarios, addressing liquid pooling and uneven flow. It also analyzes transient behavior, including start-up characteristics and response to variable heat loads [31, 32]. Researchers investigate several critical aspects using these simulations.

Saber & Ashtiani [33] employed Computational Fluid Dynamics (CFD) to analyze and optimize the performance of a Heat Pipe Heat Exchanger (HPHE), focusing on improving thermal efficiency and fluid flow distribution in the evaporator section. Inefficiencies of the base design were identified, including poor flow distribution that resulted in incomplete utilization of the heat exchanger's volume. Saber & Ashtiani also analyzed Case 1, 2, 3, 4, as illustrated in Figure 11, to investigate the effect of various design configurations on the performance of the HPHE. In Case 1, the base design was analyzed, and it was observed that the flow distribution from the entry to the middle of the HPHE was not uniform. This unbalanced flow created the situation where parts of the tube bundle were not fully used, reducing the effectiveness of the heat exchanger overall. In Case 2, the entry cross-sectional area was doubled from the base design, and such a modification considerably improved the flow distribution, with the hot gas spreading uniformly over the tube bundle. While the increased entry area facilitated better utilization of the HPHE volume, higher pressure drops were also introduced, which could lead to higher operational costs. This then shows the need to balance the improvement in flow distribution with the pressure drop constraints in practical applications. Case 3: the insertion of a horizontal plate baffle, which divides the flow into two parts just after the entry of the HPHE. This design modification was effective in improving the flow distribution to be much better than in the base design and provided better coverage over the tube bundle. Although the distribution of flow became more uniform, there was a presence of bypass flows in some areas, which restricted the overall performance improvement. Case 4- The imperfect cone baffle was introduced, which divided the flow into three paths in the upper, middle, and lower sections of the HPHE. The figure reflects the huge improvement in flow uniformity and, as a result, temperature distribution within the tube bundle. Thus, the imperfect cone design would prove to be the most effective configuration tested because bypass flows were minimized, while maximally exposing the tube surface to hot gas flow.



case (1)

case (2)

case (3)

case (4)

Fig. 11. Contours of axial velocity [33]

Höhne, 2022.[1] analyzed the use of Computational Fluid Dynamics (CFD) to simulate the two-phase flow and heat transfer in a heat pipe, with focusing on the evaporation, condensation, and phase change processes. They showed the evaporation process, vapor movement, and temperature stabilization during start-up show in a figure 12 and in a figure 13 depicts the locations of evaporation within the heat pipe. It includes a plot of the evaporation and rates, with the condensation rate shown as negative due to the source and sink terms. Figure 14 presents a 3D visualization of the liquid temperature at the wall of the heat pipe for two different heating power cases (172.87 W and 376.14 W). The isosurface of vapor is also visualized, colored by liquid temperature. This figure highlights the temperature difference between the two cases, especially the hotter evaporation area in the higher power case.

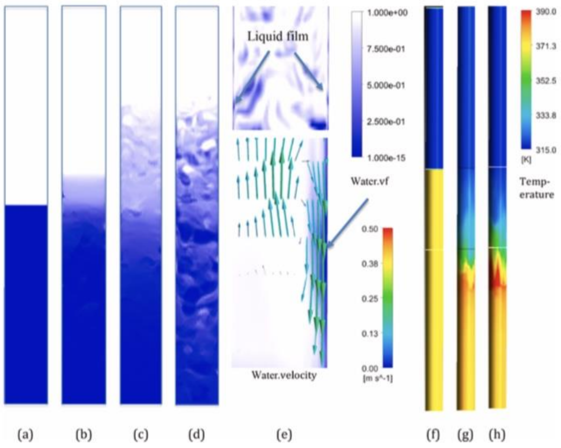


Fig. 12. Transient snapshots of the 172.87 W CFD calculation: Liquid volume fraction at (a) 0s, (b) 5s, (c) 10s and (d) 15s, (e) Zoom of film condensation region, Temperature at (f) 0s, (g) 10s and (h) 15s [1]

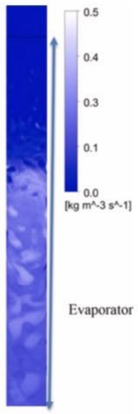


Fig. 13. snapshots of the evaporation rate [1]

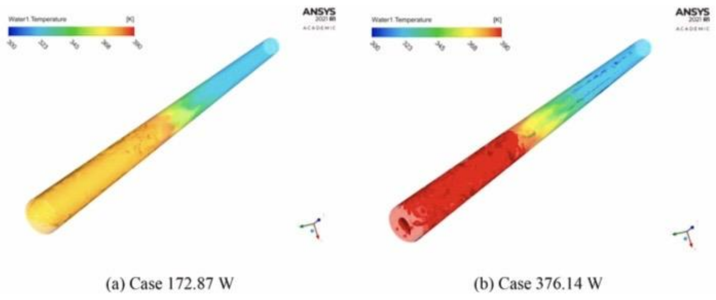


Fig. 14. Liquid temperature at 20s in 3D view, isosurface of vapor volume fraction [1]

Annamalai & Ramalingam [34] investigated, experimentally and numerically (CFD), the temperature distribution and performance of a heat pipe for two cases: 50 W and 100 W heat flux input. Figures 15 and 16 present the steady-state temperature profiles. For the 50 W case (Fig. 15), the temperature distribution for the vapor is given by 19a and that of the surface temperature for the evaporator and condenser are shown in 19b and 19c, respectively. Then again in case of 100 W-Fig. 16, there are shown vapor temperature-2a, evaporator surface temperature-20b and condenser surface temperature-20c. As evident, with the increase of the heat flux, at more correspondingly higher temperature the heat pipe reaches a steadied condition. The authors drew the following conclusion: performance is bounded by air cooling at the condenser because of low coefficient of convective heat transfer and suggested water cooling or installation of fins. Results from CFD and experimental data showed good agreement.

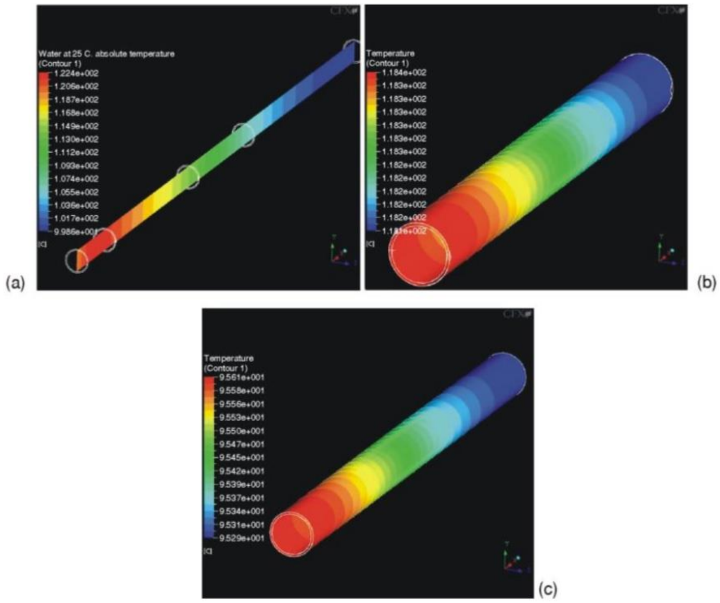


Fig. 15. Temperature distribution along the heat pipe – CFD results; P = 50 W (a) vapour temperature in the evaporator and condenser section, (b) evaporator surface temperature, (c) condenser surface temperature

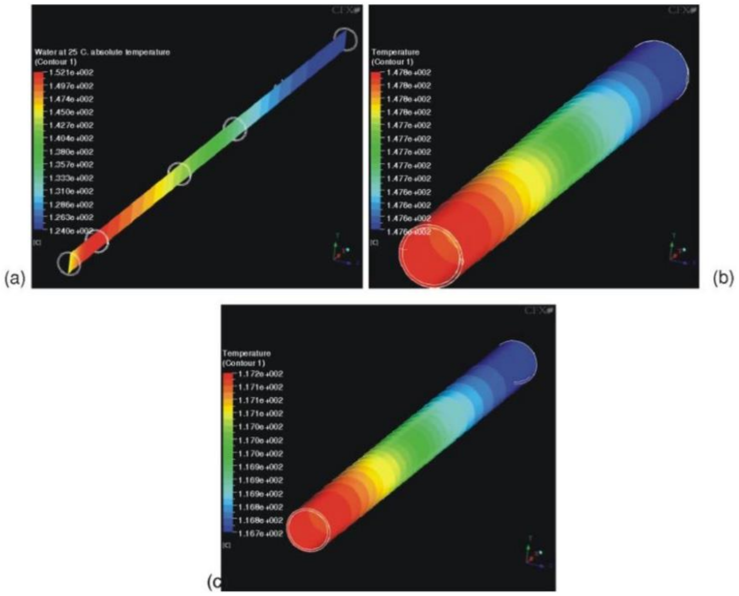


Fig. 16. Temperature distribution along the heat spipe – CFD results P = 100 W (a) vapour temperature in the evaporator and condenser section, (b) evaporator surface temperature, (c) condenser surface temperature

Yue et al. [32] Analyzed the heat transfer characteristics and flow mechanisms of the evaporator of an MCSHP for applications like telecommunication station cooling. They used a CFD model based on the VOF method to investigate the effects of different refrigerant filling ratios on cooling performance. Phase-change processes in the evaporator were modeled by using User-Defined Functions (UDFs). In addition, the complicated louvered fin structure outside the pipe was simplified for saving computation time with a negligible loss of thermal enhancement. Simulation results were compared against experimental data and showed excellent agreement regarding cooling capacity, outlet temperature, and wall temperature distribution. Figure 17 shows the distribution of liquid (blue) and vapor (red) at various locations and filling ratios, respectively. The refrigerant filling ratio was determined to be in the range of 68-100%, and a maximum cooling capacity of 4087 W was obtained at a filling ratio of 78%. Higher filling ratios increased the liquid fraction, thus flooding more of the evaporator surface with two-phase refrigerant and increasing the effective heat transfer area. The wall temperature distribution mirrored the bubble distribution and thus indicated the boundaries of the two-phase and superheated vapor regions. Although not completely filling the pipe, at 78% filling, the two-phase region expanded enough to maximize the cooling capacity without needing to go to a 100% ratio.

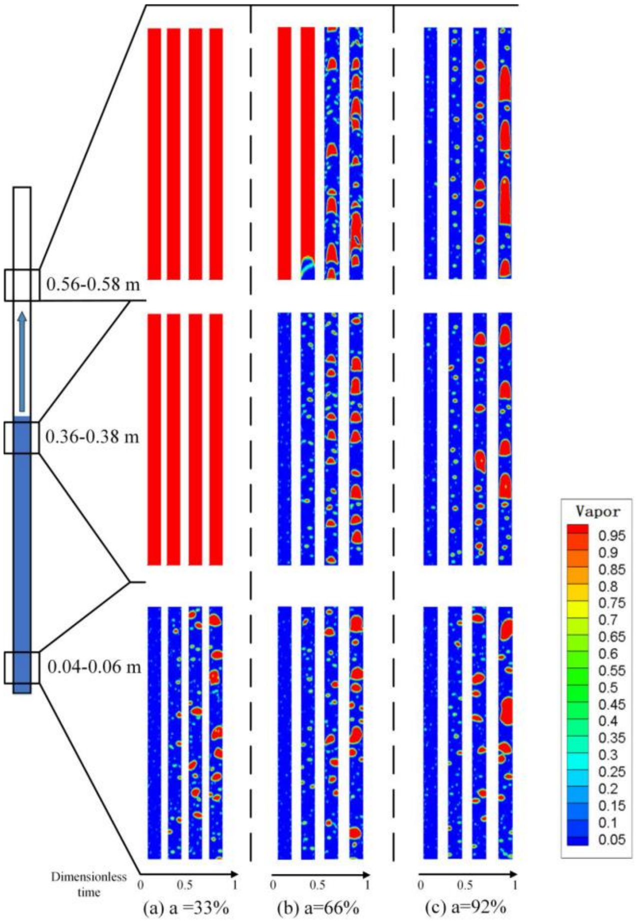


Fig. 17. Variation of flow regime at different locations and times (filling ratio is 33%, 66%,92%)[32]

5. Conclusion

High evaporation within heat pipes is really fundamental to achieving high thermal performances and energy efficiency for various applications. Advances in design, materials, and working fluids have significantly enhanced their capability further for the implementation of efficient heat management in a variety of industries that range from electronics to aerospace, energy harvesting, and others. CFD simulations, accompanied by experimental investigations, went a step further toward enhancing phase-change dynamics, thereby enhancing designs and operational strategies. However, thermal resistance optimization, the use of nanofluids, and operational constraints are some of the challenges that need to be resolved in order to fully exploit this technology. Future research should be directed toward the development of innovative solutions for these challenges, ensuring that heat pipes continue to contribute to sustainable practices and next-generation thermal systems

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