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Influence of geometrical and operating conditions on the performance of the heat pipes: A review

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Abstract

A heat pipe is one of the most effective devices for transferring heat from the heat source to the sink. It is a vacuum-tight device that depends on the phase-change conversion associated with highly effective thermal conductivity. A comprehensive review of experimental and numerical investigations related to the influences of the controlled geometrical parameters and operating variables on the thermal characteristics of heat pipes and thermosyphons is presented. These variables include the diameter and length of the heat pipe, working fluids, energy inputs, filling ratio, tilt angle, coolant flow rate, etc. The thermal features of the heat pipe is described by thermal coefficients and temperature differences through the condenser and evaporator, thermal efficiency, and thermal resistance. It is realized that the thermal resistance reduces, and the thermal coefficients increase with the amount of power input. In addition, the optimum values of tilt angles and fill ratios depend on the other controlled variables. However, the optimum filling ratio ranged from 15%-60%. While the best inclination angle was between 60° and 90°.

Keywords: Heat pipe, Inclination angle, Fill ratio, Thermosyphon, Thermal resistance

1. Introduction

Multipurpose Energy conservation is vital since fuel prices are growing, which has prompted efforts to create more energy-efficient heat-transfer systems. Because of these circumstances, interest in heat pipe applications has increased. The primary goal of efficient thermal devices is to improve their capacity for heat transmission. Thermal media with better heat transmission capabilities are essential, given the reducing sizes of electronic devices and power production technologies.

A heat pipe (HP) is a two-phase thermal device that achieves a high rate of thermal energy associated with evaporating and condensing working fluid in a sealed enclosure. A wickless HP, also known as a two-phase closed thermosiphon (TS), uses gravity to return the working fluid to the evaporator. Whereas a wicked HP, in which capillary forces return the working fluid from the condenser [1]. The effect of greenhouse gasses on the environment and the adoption of the Kyoto Agreement by many industrial countries are driving demand for waste heat energy recovery in engineering applications with commercial applications [2]. HPs have been used in waste heat recovery systems, such as ground source heat pumps, heating and ventilation systems, air conditioning and refrigeration systems, and water heating systems [3, 4]. This is because of their simple structure, exceptional flexibility, good compactness, excellent reversibility, and high efficiency [5].

The current work offers a helpful overview of experimental and numerical studies related to heat transmission through heat pipes under the influences of operating conditions and geometry parameters. The effects of the working fluids, filling ratio and inclination angle are reported.

2. Types of Heat Pipe

The Various types of HPs are used in various applications. The most important types are wicked HP, flat-plate HP, rotating HP, wickless HP, or two-phase closed thermosiphon (TS) [6].

The working fluid in the wicked HP moves through the wick because of capillary action. This type of HP has the advantage of allowing it to be oriented in any direction. A schematic diagram of the wick heat pipe is presented in Figure 1 (a).

In a flat-plate HP, additional wick material can be placed between the evaporator and condenser, as introduced in Figure 1 (b), to improve the working fluid flow back to the evaporator. In some papers, the flat-plate HP is referred to as a vapor chamber or a flat two-phase thermosyphon [6].

In rotating HP, the working fluid is centrifuged and returned to the evaporator along the cavity’s tapered inner wall. This HP is also called a wickless heat pipe [6]. A rotating HP is shown in Figure 1 (c).

A loop HP is a two-phase device with capillary fluid pumping that is effective and efficient [7]. It may provide an advantage in addressing the problem with traditional heat pipes, which is their limited capability to transmit heat over long distances. Gerasimov and Maydanik [8] invented the first loop HP in 1972. The basic scheme of a loop HP is presented in Figure 1 (d).

The thermosyphon (TS) is usually divided into three sections: the bottom evaporator as heat is added and the liquid is vaporized; the top condenser as heat is rejected, the resulting vapor is condensed; and the middle adiabatically section [9]. Heat is supplied to the evaporator, where a liquid pool is presented in a TS, converting the liquid to vapor. Because of its high temperature and pressure, the resulting vapor passes through the adiabatic zone towards the condenser. The vapor's latent heat released in the condenser and condenses at the wall. Then, the condensed liquid goes back to the evaporator [10]. A cross-section of a closed two-phase thermosyphon is composed of an evacuated sealed tube with a small quantity of liquid, as shown in Figure 2. Heat is added to the evaporator and absorbed by the working fluid as latent heat [11].

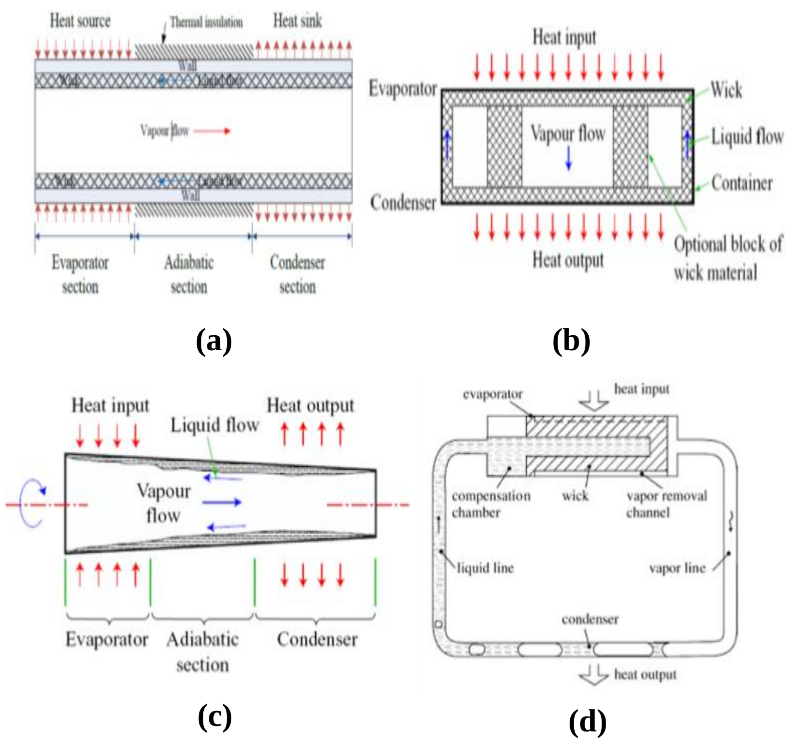


Figure 1 Schematic configuration of (a) Wick HP, (b) Flat-plate HP, (c) Rotating HP, and (d) Loop HP [6].

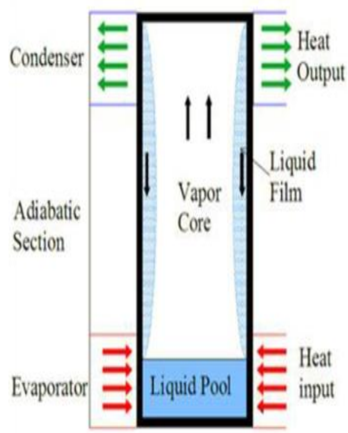


Figure 2 Configuration of a two-phase closed thermosiphon [11].

3. Geometrical, design and operating criteria

The geometry, filling ratio, tilt angle, vapor temperature, and working fluid all affect the thermal features of a thermosyphon [12]. Several studies have been carried out to analyze and improve the thermal performance of the thermosyphon.

3.1 Working Fluid

Jouhara and Robinson [13] presented an experimental investigation to evaluate the thermal behavior of a thermosyphon charged with water and fluorinated liquids (FC-77, FC-84, and FC-3283). The thermosyphon was constructed from copper with a length of 200 mm and an inner diameter of 6 mm. The lengths of the condenser and evaporator were 60 and 40 mm, respectively. Two liquid loadings (0.6 and 1.8 mL) were examined in the evaporator for water. The liquid loading of 0.6 mL (half-filled) was used to confirm combined liquid pool boiling and film evaporation boiling. While the over-filled liquid loading of 1.8 mL was employed to ensure pool boiling only conditions. For Fluor inert working fluids, only the overfilled evaporator condition was tested. The experimental findings revealed that a water-charged thermosyphon was more efficient than that of thermosyphons charged with flour inert fluids, especially for power levels above 40 W. For a power range of 30–40W, only FC-84 had a thermal performance better than water (Figure 3). In addition, the dielectric behavior of fluorinated inert liquids makes them suitable for cooling-sensitive electronic applications.

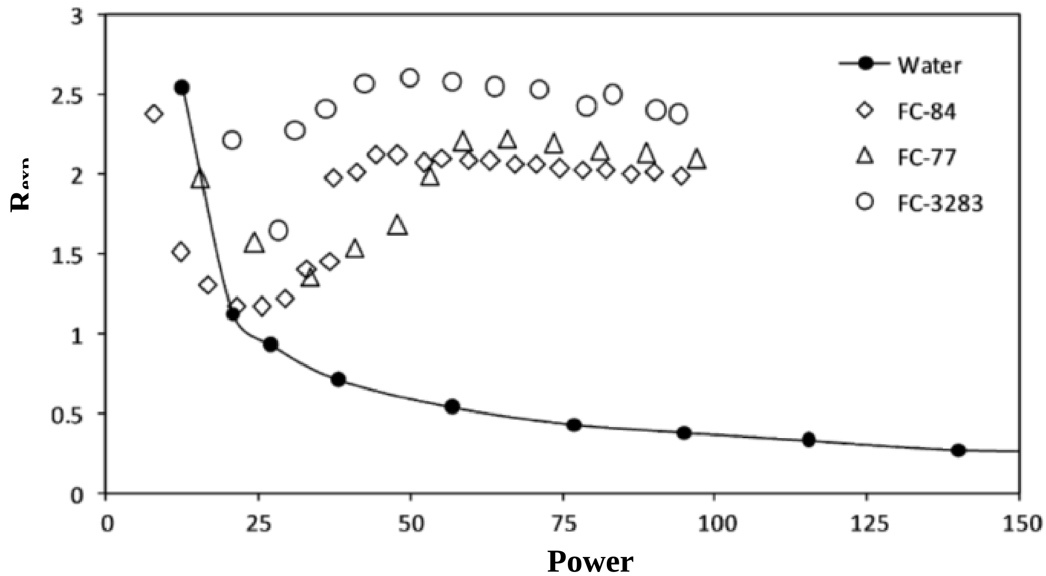


Figure 3 Experimental thermal resistance vs power input for various working fluids (Jouhara and Robinson [13]).

Guo et al. [14] experimentally inspected an aqueous ethanol solution as a working fluid in a HP. According to the findings, the heat transfer of the heat pipe with a 40% volume concentration of ethanol solution is preferable to water at low heat flux. Therefore, ethanol solution outperforms water as the working medium of the solar HP. The heat transfer features of the HP were examined for various tilt angles, heat inputs, and filling ratios. It was shown that for a 40% ethanol concentration, the optimum tilt angle with a solution was 45°. The optimum charge was 4 mL, or 11.8 vol.% of HP.

Mozumder et al. [15] explored the overall heat transfer coefficient and thermal resistance of HP for different fill ratios experimentally. Three different working fluids were used; water, acetone, and methanol. The optimal performance of HP was associated with reductions in thermal resistance and temperature differences across the condenser and evaporator and growth in the heat transfer coefficient. The findings revealed that the fill ratio of 85% achieved a higher performance (Figure 4 (a)). Also, the acetone working fluid had the highest heat transfer coefficient (Figure 4 (b)).

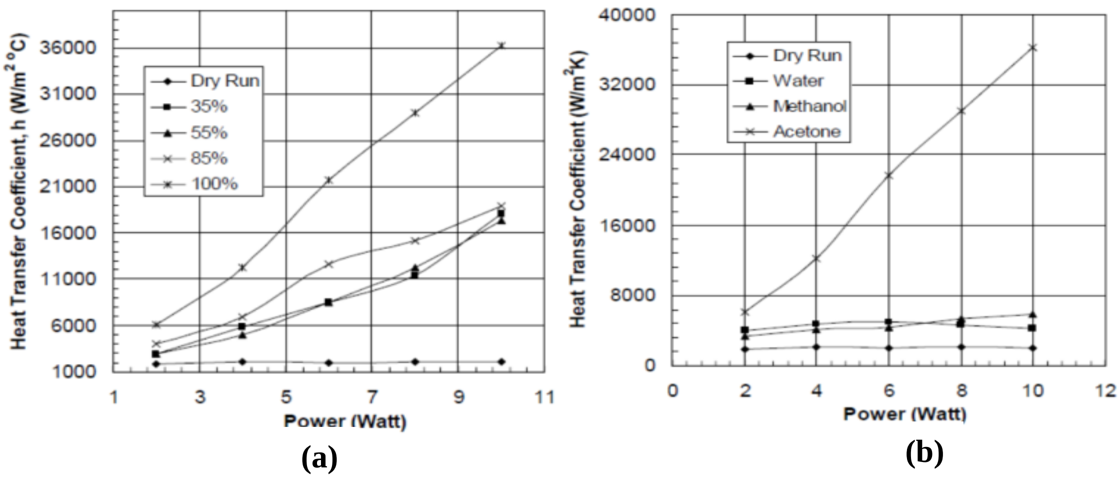


Figure 4 Variations of overall thermal coefficient with the input power for (a) various fill ratios and (b) different working fluids (Mozumder et al.

Fadhel et al. [16] applied a computational model to examine the performance of a TS charged with two refrigerants, R404a and R134a. The CFD model was validated by a reasonable agreement between predicted and measured temperature data. Therefore, the robust computational model can be used effectively with a relatively small error to simulate the thermal behavior of the TS involving phase-change shown in liquid film condensation and pool boiling.

Jouhara et al. [17] proposed a 3D CFD model to compute the condensation and boiling thermal behaviors in a thermosyphon involving the condenser-heat exchanger. Two working fluids were adopted: water and R134a. It was reported that the geyser boiling phenomenon (boiling of water at low power input) was indicated, as shown in Figure 5. This phenomenon was affected by the amount of power input, where no geyser boiling was detected at high power input. Simulated geyser boiling was validated with the visualizations resulting from experiments.

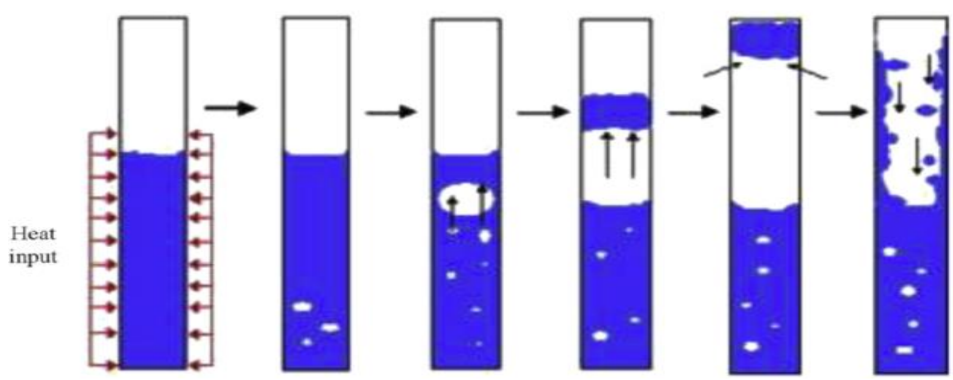


Figure 5 Geyser boiling process in a thermosiphon (Jouhara et al. [22]).

The influences of working fluids (ethylene glycol, water, and ethanol), power input, tilt angles, and cooling water flow rates on the thermosyphon's thermal traits were investigated experimentally by Gedik [18]**.** The findings showed that water had the capacity to perform at 200 W of heat input and 10 L/h of coolant flow rate. However, ethylene glycol and ethanol registered the highest performance at (200 W, 30 L/h) and (600 W, 10 L/h), respectively. Also, it was inferred that the heat inputs and tilt angle had important impacts on the thermal features of the TS.

Naresh [19] presented an experimental study of heat transfer of internally finned thermosyphon charged with either water or acetone at power levels from 50 to 275 watts. Six rectangular fins with a fixed cross-section were placed internally along the condenser section. Experiments were carried out with two working fluids, water and acetone, at fill ratios of 20, 50, and 80%. The results showed that adding the inner fins of the condenser resulted in more condensation. The improvement in the thermal performance of the condenser was 17%. Whereas the reduction in thermal resistance was 35.48%.

Ghorabaee et al. [20] presented an experimental study of the thermal performance of a heat pump using three working fluids: distilled water, nanofluid, and a mixture of nanofluid and surfactant. The Thermosyphon was made of a copper tube with a 15 mm outer diameter and a 1000 mm length. The effects of input power and inclination angle were investigated. The experimental results showed that as the concentration of nanofluid increased, thermal efficiency increased, and thermosyphon thermal resistance decreased. The best inclination angles for two nanofluids and conventional fluids were 60 degrees for water and 90 degrees for nanofluids. The thermal efficiency was increased by 20% when the right amount of surfactant was added. Thermosyphon's best thermal performance was achieved with a 200W input power for all working fluids.

3.2 Filling Ratio

Alizadehdakhel et al. [21] examined the effects of fill ratio and input power on the thermal quality of the thermosyphon experimentally and numerically. A volume of fluid (VOF) model was used to inspect the combined simultaneous effects of liquid-gas flow and condensation and evaporation processes. The performance of the thermosyphon was assessed as the energy absorbed in the condenser per the energy input in the evaporator. The experimental findings exhibited increased performance for the input power range from 350 to 500 W (Figure 6). However, the performance decreased at a power input larger than 500 W. In addition, the computational results proved the CFD model could be applied effectively to investigate the conjugate mass and heat associated with phase conversion processes in thermosyphon.

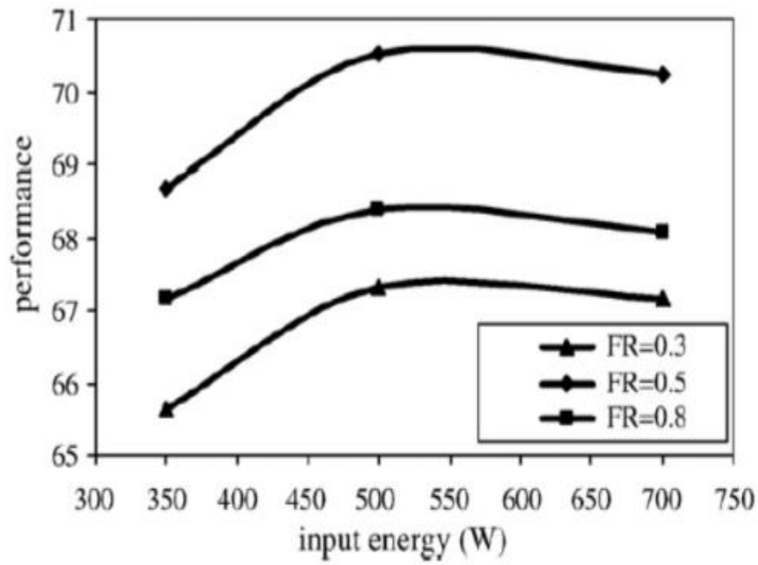


Figure 6 The performance of thermosyphon at different power inputs and fill ratios (FR) Alizadehdakhel et al. [16]).

Elmosbahi et al. [22] experimentally evaluated the solar-assisted heat pipe for various solar heat fluxes and fill ratios. The solar energy provided the heat input to the evaporator, while the flowing water acted as a heat sink for the condenser. The optimum performance of the HP was related to lower temperature variation along the evaporator and condenser sections, higher useful energy transmitted into the water, and a higher overall thermal coefficient. The findings revealed that the fill ratio of 9 mL (corresponding to 66.6%) achieved the highest performance, as indicated in Figure 7.

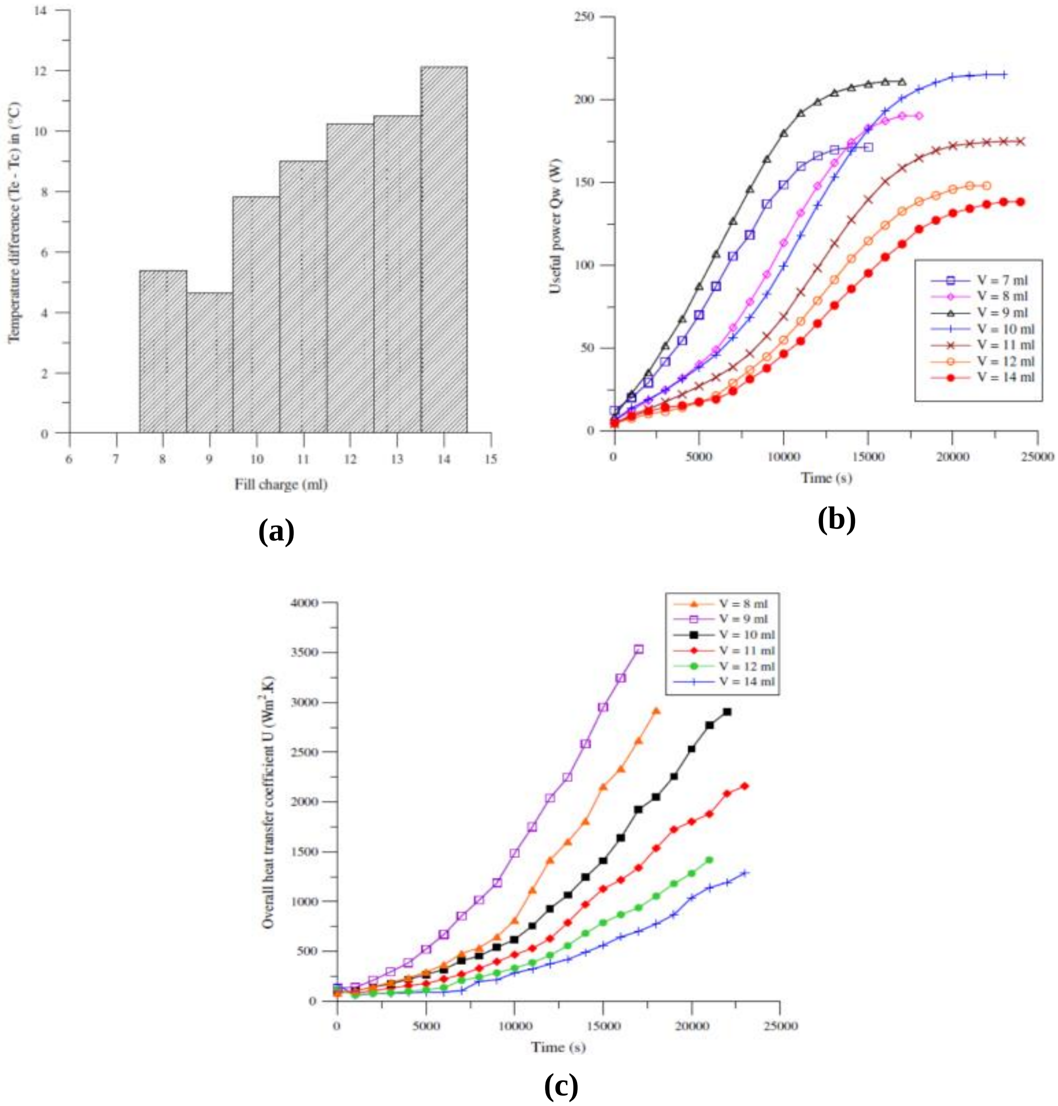


Figure 7 The performance criterion for different fill ratios (FR); (a) Temperature variation along with evaporator and condenser, (b) Useful power, and (c) Overall heat transfer coefficient Elmosbahi et al. [18].

Sukchana and Jaiboonma [23] experimentally explored the impacts of adiabatic length, filling ratio of the evaporator, and tilt angle on the thermal efficiency of HP. It was found that the filling ratios had a greater impact on thermal performance than the length of the adiabatic section. The filling ratio of 15% and heat flux of 5.92 kW/m^2 was calculated to achieve the best performance for shorter adiabatic lengths (Figure 8(a)). The efficiency of HP was improved with a tilt angle of up to 60^o, and performance degraded beyond this value, as shown in Figure 8 (b).

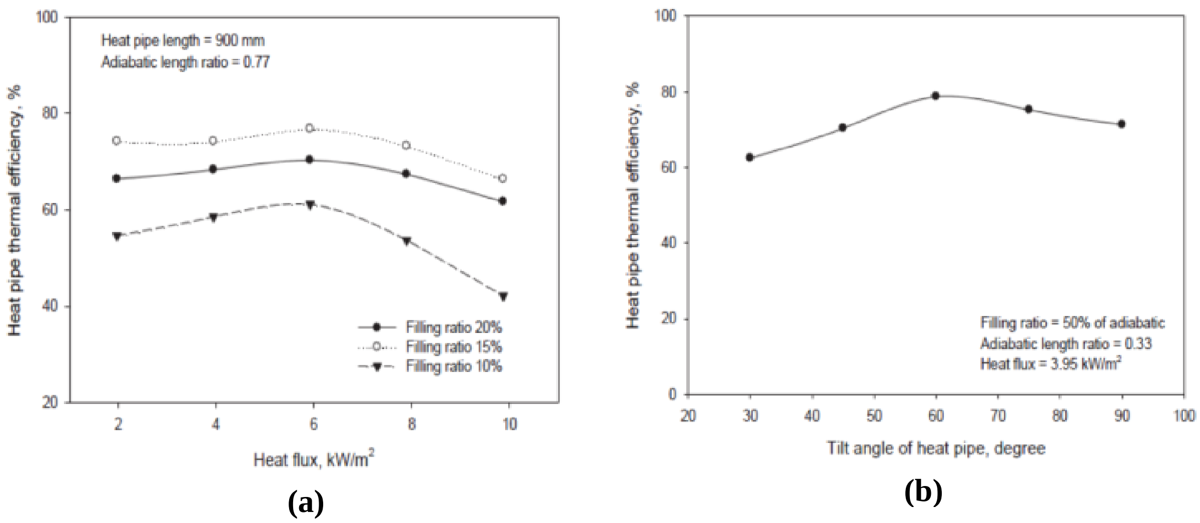


Figure 8 (a) Impacts of fill ratio and heat flux on the thermal efficiency of the HP, and (b) Variation of the performance of HP with the tilt angle (Sukchana and Jaiboonma [19]).

Kannan et al. [24] presented experimental work to evaluate the thermal features of a thermosyphon charged with various working fluids (acetone, water, methanol, and ethanol). Also, the influences of various values of the thermosyphon's diameters, operating temperatures, and filling ratios were discussed. The maximum performance was achieved by water rather than other working fluids for operating temperatures larger than 40 °C. The thermal characteristics were enhanced with an increase in filling ratios (up to 60%), operating temperatures, and the size of the TS.

Robinson et al. [25] experimentally explored the impact of boiling regimes for multiple ranges of input power on performing a small-size thermosyphon operated with a low filling ratio of 25%. The experimental findings showed that the geyser phenomenon dominated the boiling at lower input power with low heat transfer coefficients in the condenser and evaporator. These coefficients improved as the input power increased.

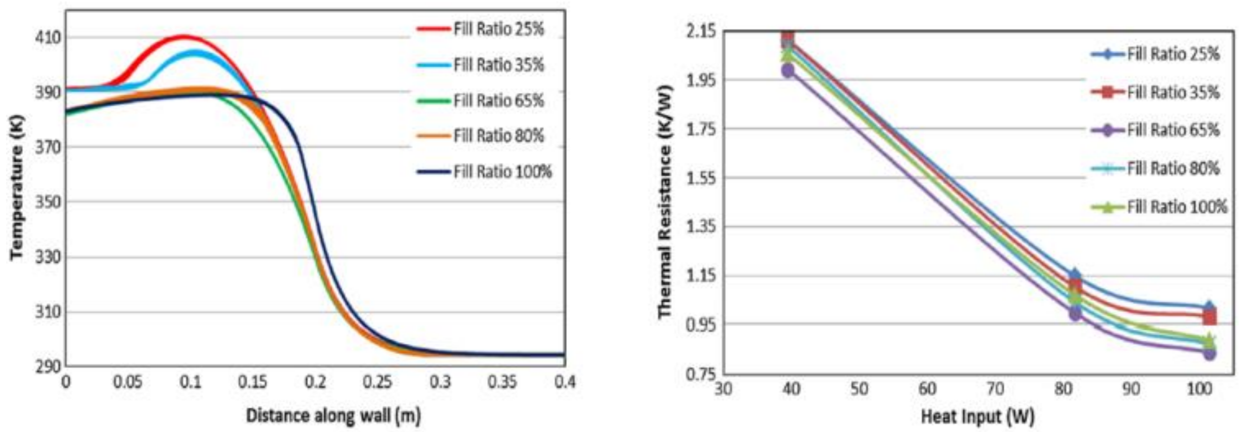
Paramet Thanawat et al. [26] experimentally explored the thermal behavior of a thermosyphon for various evaporator temperatures and filling ratios. The evaporator temperature positively affected the heat flux rate. Also, the thermosyphon's lowest thermal resistance and highest performance (highest thermal efficiency) were obtained at a filling ratio of 70% and an evaporator temperature of 90 ^{o}C.

Bhatt et al. [27] investigated gravity-assisted HP of multi-branch under the influence of various filling ratios and heat inputs. Each individual branch involves one condenser and two evaporators. It was observed that the optimum value of the filling ratio depended on the applied heat input. However, the highest thermal coefficient and the lowest heat resistance of HP were achieved at a power input of 160 W and a filling ratio of 50%.

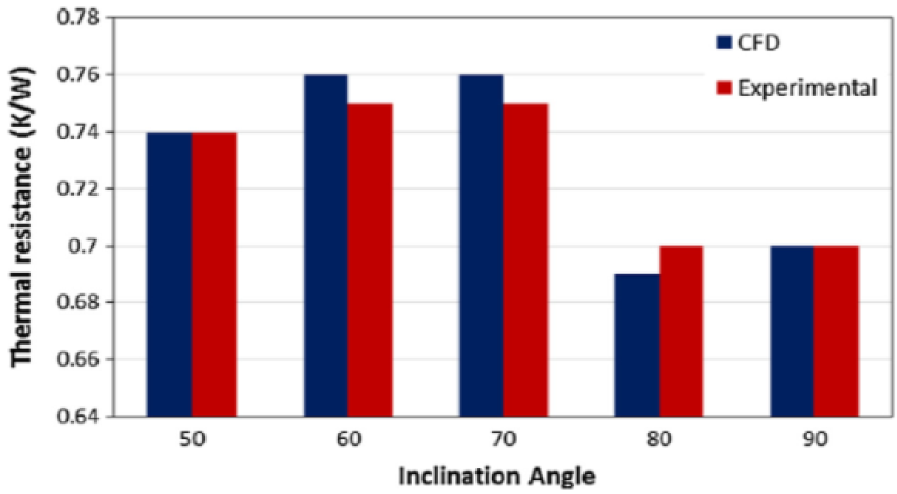
3.3 Tilt Angle

Hossain et al. [28] conducted experiments to inspect the thermal features of a micro heat pipe (MHP) under the impacts of heat inputs, inclination angle, working fluids, and coolant flow rates. The experimental findings showed performing MHP was affected positively and significantly by the heat input, while the effect of coolant flow rate was insignificant. Better performance of MHP was achieved at a tilt angle of 70°. Also, acetone exhibited the highest performance among other working fluids under the same controlled conditions.

Alammar et al. [29] used a validated CFD model to examine the influence of fill ratio and tilt angle on the behavior of a TS. They reported that the best thermal behavior was associated with reducing evaporator temperature and minimum thermal resistance. The fill ratio of 65% and tilt angle of 90^{o} achieved the best performance, as explained in Figure 9 Also, the impact of tilt angle and filling ratio was significant as the input power increased.



(a)



(b)

Figure 9 (a) Impact of fill ratio on the evaporator temperature (left), and on the thermal resistance (right); (b) Impact of tilt angle on the thermal resistance of the thermosyphon (Alammar et al. [23]).

Kim et al. [30] conducted experiments to evaluate the impact of fill ratio and tilt angle on thermal traits of a thermosyphon charged with water. At low heat flux (100 kW/m^2), the thermal coefficient of boiling was higher than that of the Rohsenow correlation. However, the latter was higher at higher heat flux than the former. At low heat flux, the thermal coefficient of condensation was higher than that of the Nusselt correlation, and it was affected more by the tilt angle than that of the boiling coefficient. The highest efficiency was obtained at a fill ratio of 0.5 and a tilt angle of 30°, as depicted in Figure 10.

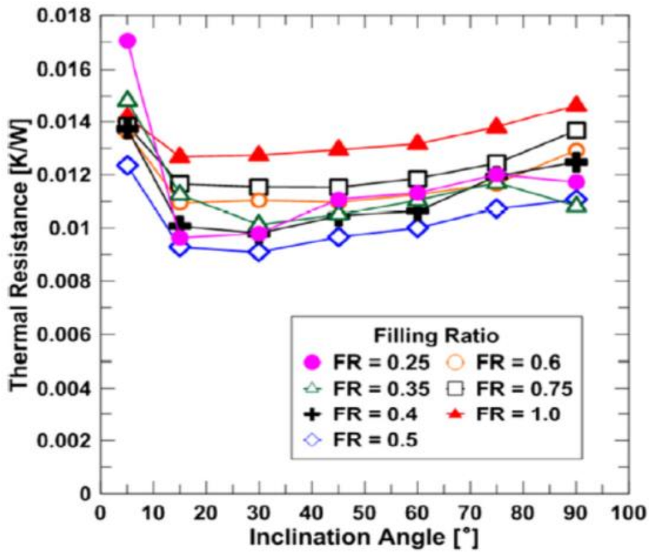
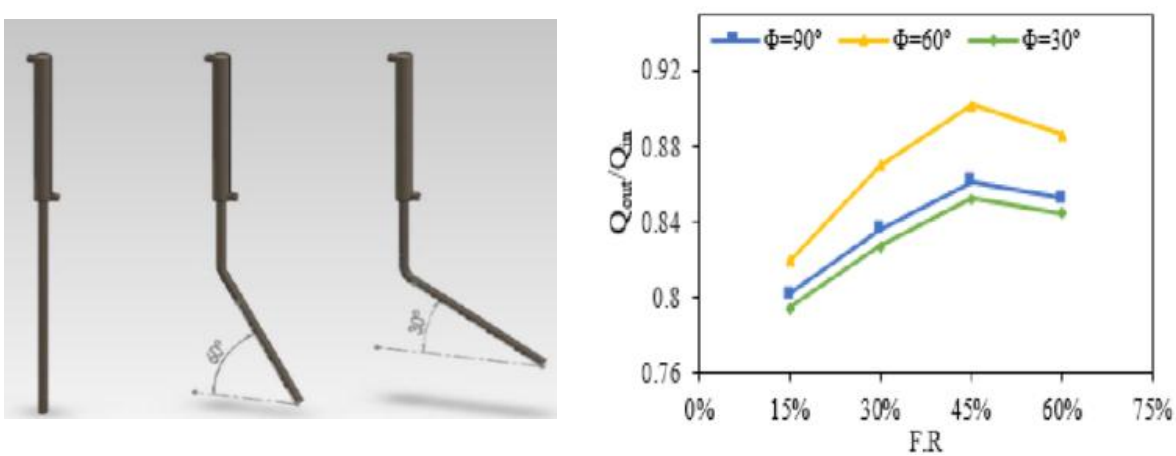


Figure 10 Impact of tilt angle and filling ratio on the resistance of TS (Kim et al. [25]).

Goldoust et al. [31] conducted experiments to evaluate the impact of the tilt angle of the evaporator section and filling ratio on the thermal behavior of the thermosyphon with the vertical adiabatic and condenser sections depicted in Figure 11. The findings revealed that the evaporator's optimum tilt angle and filling ratio were 60o and 45%, respectively. It was observed that the geyser boiling phenomenon occurred for fill ratios greater than 45%. A reasonable agreement was shown between the got boiling heat transfer coefficient and Rohsenow's correlation.



(a) **(b)**

Figure 11 (a) Thermosyphon with tilted angle, and (b) Variation of the thermal efficiency (Q_{out}/Q_{in}) with the fill ratio and tilt angle of the evaporator (Goldoust et al. [26]).

Arat et al. [32] presented an experimental inspection of the heat transfer traits of variable-pressure vacuumed heat pipes for different values of tilt angles and fill ratios. The experimental findings showed an acceptable agreement between the got boiling coefficients and the correlated ones in the literature. In addition, the heat pipe at an inclination angle of 90 and 10 ml of water filling the evaporator achieved the minimum thermal resistance.

An experimental and numerical investigation was carried out by Xu et al. [33] for evaporator wettability in terms of contact angle. The copper thermosyphon had a length of 240 mm and internal and external diameters of 22.2 mm and 25.4 mm, respectively. The effects of evaporator wettability and inclination angle on the heat performance of a thermosyphon charged with water were studied. For a modified thermosyphon, it was found that simulated temperatures agree well with experimental data, with a relative error of 0.12%. The results showed that as the inclination angle increased from 15 to 90, the number of bubbles attached to the evaporator wall decreased, lowering thermal resistance by 59.5%.

The summary of experimental and numerical studies related to the impact of controlled parameters on the thermal behavior of the heat pipes is shown in Table 1.

Table 1 Summary of studies on geometrical and operation criteria affected the performance of the heat pipes.

Authors (Year)	Type Of Study	Design Parameter	Working Fluids	Highlighted Results
Jouhara and Robinson (2010)	Experimental	Fluid loadings (0.6, and 1.8 mL). Input power (23.5- 200 W).	Water, FC-84, FC-77 and FC-3283.	For power rate greater than 40 W, the water-charger thermosyphon achieved the best performance than other Fluorinert fluids. For the power range of 30-40 W, the FC-84 had better thermal performance than water.
Guo et al. (2010)	Experimental	Tilt angle (30-90º). Input power (10 – 80 W). Charge quantity (2-8 mL).	Water and water-ethanol solution	The performance of a HP filled with 40% ethanol is superior to that of pure water at low heat flow. The optimum inclination angle and charge quantity values for a 40% ethanol concentration are 45º and 4 mL, respectively.
Mozumder et al. (2010)	Experimental	Filling ratio (35-100%). Input power (2-10 W).	Water, acetone and methanol	The fill ratio of 85% achieved higher performance. The acetone working fluid had the highest heat transfer coefficient.
Fadhel et al. (2015)	Numerical	Power input (19.74-100.44 for R134a, and 19.88-100.65 for R134a).	R134a and R404a	The validated computational results of CFD model proved that the model could be successfully applied to examine the

				performance of thermosyphon.
Jouhara et al. (2016)	Numerical	Filling ratio (50%). Input power (100- 250 W).	Water and R134a	The geyser boiling was observed at a low rate of input power.
Gedik (2016)	Experimental	Filling ratio (35%). Tilt angles (30º, 60º, and 90º) The input power (200-600 W) Condenser cooling water flow rates (10-30 L/h)	Water, ethanol and ethylene glycol	Water, ethylene glycol, and ethanol were the best working fluids at the conditions (200 W, and 10L/h), (200 W, and 30 L/h), and (600 W, and 10 L/h), respectively. The tilt angle and heat input affected the performance of the thermosyphon highly.
Naresh et al. (2017)	Experimental	Fill ratio (20, 50 and 80%) Input power (50-275 W). Condenser fan.	Water or acetone	Best performance of thermosyphon at 50% filling The presence of fins improved the performance of the thermosyphon by 17%.
Ghorabee et al. (2020)	Experimental	The filling ratio (50%) Tilt angles are 45º, 60º and 90º. Input power 100, 150 and 200 W.	Water and Titanium Dioxide Nanofluid.	It was found that the best inclination angles of TPCT are 60º for water and 90º for nanofluid.
Alizadehdakhel et al. (2010)	Experimental and Numerical	Filling ratio (30-80%). Input power (350-700 W).	Water	The performance was increased for the input power up to 500 W and then decreased slowly. The CFD model can be applied effectively to investigate the performance of thermosyphons.
Elmosbahi et al. (2012)	Experimental	Filling quantity (8-14 mL). Solar heat flux.	Methanol	The best performance was achieved when the working fluid filled 2/3 of the evaporator volume.
Suchana and Jaiboonma (2013)	Experimental	The filling ratio is 10, 15 and 20%. Inclination angles (15-90º). Input heat flux (1.97-9.87 kW/m^2).	R-134a	The fill ratios have a greater impact on thermal behavior than the length of the adiabatic section. The efficiency of HP increased with the tilt angle up to 60º and then decreased.
Kannan et al. (2014)	Experimental	Filling ratios (30-90%). The operating temperature is (30 ºC- 70 ºC). Input power (0-1200W). The inner diameter of the thermosyphon (6.7- 12 mm).	Water, methanol, ethanol, and acetone.	Water had a higher thermal performance than other working fluids at operating temperatures above 40 ° C. The highest thermal efficiency was at a filling ratio of 60%. Rising the diameter of the thermosyphon and operating temperature enhanced the heat transport rate.
Robinson et al. (2020)	Experimental	Filling ratio (25%). Input power (19-227 W).	Water	The geyser phenomenon and low heat transfer coefficients in condenser, and evaporator were observed at a lower input power.
Parametthanuwat et al. (2021)	Experimental	Filling ratios (0, 30, 50, and 70%). Evaporator temperature (50, 70, and 90 ºC)	Water	Increasing the evaporator temperature led to an increase in heat flux rate. The lowest thermal resistance and the highest performance of the thermosyphon were achieved at a filling ratio of 70% and evaporator temperature of 90 ºC.
Bhatt et al. (2022)	Experimental	Filling ratios (0.4-0.7). Equal load inputs (0–200 W).	Water	The highest thermal coefficient and the lowest thermal impedance of HP were achieved at a fill ratio of 50% and heat

		Unequal load inputs (0–100 W).		input of 160 W.
Hossain et al. (2010)	Experimental	Inclination angles (30-90º). Input power (0.612-8.71 W). Coolant flow rate (0.3-1.0 L/min).	Methanol, acetone, and ethanol	The heat input had a positive and significant impact to the performance of MHP, while the effect of coolant flow rate was insignificant. Better performance of MHP was achieved at a tilt angle of 70º. The acetone exhibited the highest performance among other working fluids under the same controlled conditions.
Alammar et al. (2016)	Numerical	Filling ratio (25-100%). Tilt angles (10-90º). Input power (39-101 W).	Water	The best performance was done at a tilt angle of 90º and a fill ratio of 65%. The impact of filling ratio and inclination angle was significant as the input power increased.
Kim et al. (2018)	Experimental	Filling ratios (0.25-1.0). Inclination angle (5-90º). The input power (10- 300 kW/m^2).	Water	The thermal coefficient of condensation was more influenced by the tilt angle than the boiling coefficient. The best heat transfer coefficient occurred at a filling ratio of 0.5 and a tilt angle of 30º.
Goldoust et al. (2019)	Experimental	Filling ratio (15-60%). Input power (100-250 W). Tilt angles of the evaporator (30 and 60°).	Water	The evaporator's optimum tilt angle and filling ratios were 60º and 45%, respectively. The geyser boiling phenomenon occurred for filling ratios greater than 45%.
Arat et al. (2021)	Experimental	Filling volumes (5, 10, 15, and 20 ml). Inclination angle (45, 60, and 90º). The input power (10- 300 kW/m^2).	Water	The vacuumed heat pipe with an inclination angle of 90◦ and 10 ml of water filling the evaporator achieved the minimum thermal resistance.
Xu et al. (2018)	Experimental	Tilt angle (15º, 30º, 60º and 90º). Filling ratio 25% of the total volume. Power input (10-14W).	Water	The results show that as the inclination angle increases from 15 to 90, the number of bubbles attaching to the evaporator wall decreases, lowering thermal resistance by 59.5 percent.

4. Conclusions

The impact of the controlled geometrical and operating factors on the thermal behavior of thermosyphons and HPs is reviewed. The geometrical parameters include the inclination angle of the heat pipe and lengths and sizes of the evaporator, condenser and adiabatic sections. At the same time, the operating conditions involve the heat input and the filling ratio of the working fluid in the evaporator. Heat transfer coefficients and temperature differences through condenser and evaporator, thermal resistance, and efficiency represent the main thermal features of the heat pipe. Generally, it is observed that the thermal resistance reduces with the amount of supplied heat to the evaporator for all cases. For the same conditions, using acetone and ethanol attained higher performance than water.

Fluor inert liquids may also be the best working fluid for cooling sensitive electron applications. On the other hand, the optimum values of the filing ratio and inclination angle relied on the other conditions. However, the optimum filling ratio ranged from 15%-60%. At the same time, the best inclination angle was between 60° and 90°.

Conflicts of interests

The authors declare no competing interests.

References:

[1] Ahmadi, M. H., Kumar, R., Assad, M. E. H., & Ngo, P. T. T. (2021). Applications of machine learning methods in modeling various types of heat pipes: a review. Journal of Thermal Analysis and Calorimetry, *146*(6), 2333-2341.

[2] Kutlu, L. (2020). Greenhouse gas emission efficiencies of world countries. International journal of environmental research and public health, *17*(23), 8771.

[3] K. Kerrigan, H. Jouhara, G.E. O'Donnell, A.J. Robinson, Heat pipe-based radiator for low grade geothermal energy conversion in domestic space heating, Simulation Modelling Practice and Theory 19 (2011) 1154-1163.

[4] Jouhara, H., Chauhan, A., Nannou, T., Almahmoud, S., Delpech, B., & Wrobel, L. C. (2017). Heat pipe based Systems-Advances and applications. Energy, *128*, 729-754.

[5] Y.C. Weng, H.P. Cho, C.C. Chang, S.L. Chen, Heat pipe with PCM for electronic cooling, Applied Energy 88 (2011) 1825-1833. https://doi.org/10.1016/j.apenergy.2010.12.004.

[6] Chan, C. W., Siqueiros, E., Ling-Chin, J., Royapoor, M., & Roskilly, A. P. (2015). Heat utilization technologies: A critical review of heat pipes. Renewable and Sustainable Energy Reviews, 50, 615-627.

[7] Zhang, Z., Zhao, R., Liu, Z., & Liu, W. (2021). Application of biporous wick in flat-plate loop heat pipe with long heat transfer distance. Applied Thermal Engineering, *184*, 116283.

[8] Zhao, Y., Yan, T., Liang, J., & Wang, N. (2019). *A new way of supercritical* startup of a cryogenic loop heat pipe. International Journal of Heat and Mass Transfer, *145, 118793.*

[9] Zhong, W., & Ji, W. (2021). Applications of coupling thermosyphons with phase change materials: A review. Energy and Buildings, 233, 110690.

[10] Dobriansky, Y., & Wojcik, R. (2019). State of the art review of conventional and anti-gravity thermosyphons: Focus on two working fluids. International Journal of Thermal Sciences, 136, 491–508.

[11] D.A. Patil, B.Y. Ravindra, Factors affecting the thermal performance of two phase closed thermosyphon: a review, Int. J. of Emerging Technology and Advanced Engineering 2 (2012) 202-206.

[12] M.B.H. Mantelli, Thermosyphon technology in industrial applications, Taylor & Francis, 2013, pp. 411-64.

[13] H. Jouhara, A. J. Robinson, Experimental investigation of small diameter two-phase closed thermosyphons charged with water, FC-84, FC-77 and FC-3283, Applied Thermal Engineering 30 (2010) 201–211. http://dx.doi.org/10.1016/j.applthermaleng.2009.08.007.

[14] H. Guo, H.Y. Du, F. Ye, C.F. Ma. Experimental investigation of solar heat pipes with ethanol solution as working fluid, 14th International Heat Transfer Conference IHTC14 (2010) 435-441. https://dx.doi.org/10.1115/IHTC14-23097.

[15] A.K. Mozumder, A.F. Akon, M.S.H. Chowdhury, S.C. Banik, Performance of heat pipe for different working fluids and fill ratios, Journal of Mechanical Engineering 41 (2010) 96-102. https:// dx.doi.org/10.3329/jme.v41i2.7473.

[16] B. Fadhl, L.C. Wrobel, H. Jouhara, CFD modelling of a two-phase closed thermosyphon charged with R134a and R404a, Applied Thermal Engineering 78 (2015) 482-490. http://dx.doi.org/10.1016/j.applthermaleng.2014.12.062.

[17] H. Jouhara, B. Fadhl, L.C. Wrobel, Three-dimensional CFD simulation of geyser boiling in a two-phase closed thermosyphon, International Journal of Hydrogen Energy 41 (2016) 16463-16476. http://dx.doi.org/10.1016/j.ijhydene.2016.02.038.

[18] E. Gedik, Experimental investigation of the thermal performance of a two-phase closed thermosyphon at different operating conditions, Energy and Buildings 127 (2016) 1096-1107. https:// dx.doi.org/10.1016/j.enbuild.2016.06.066.

[19] Naresh, Y., and C. Balaji. "Experimental investigations of heat transfer from an internally finned two phase closed thermosyphon." Applied Thermal Engineering 112 (2017): 1658-1666.

[20] Ghorabaee, Hamid, Mohammad Reza Sarmasti Emami, and Maryam Shafahi. "Effect of nanofluid and surfactant on thermosyphon heat pipe performance." Heat Transfer Engineering 41, no. 21 (2020): 1829-1842.

[21] A. Alizadehdakhel, M. Rahimi, A.A. Alsairafi, CFD modeling of flow and heat transfer in a thermosyphon, International Communications in Heat and Mass Transfer 37 (2010) 312-318. http://dx.doi.org/10.1016/j.icheatmasstransfer.2009.09.002.

[22] M.S. Elmosbahi, A.W. Dahmouni, C. Kerkeni, A.A. Guizani, S. Ben Nasrallah, An experimental investigation on the gravity assisted solar heat pipe under the climatic conditions of Tunisia, Energy conversion and management 64 (2012) 594-605. http://dx.doi.org/10.1016/j.enconman.2012.06.009.

[23] T. Sukchana, C. Jaiboonma, Effect of filling ratios and adiabatic length on thermal efficiency of long heat pipe filled with R-134a, Energy Procedia 34 (2013) 298-306. https://doi: 10.1016/j.egypro.2013.06.758.

[24] M. Kannan, R. Senthil, R. Baskaran, B. Deepanraj, An experimental study on heat transport capability of a two phase thermosyphon charged with different working fluids, American Journal of Applied Sciences 11 (2014) 584-591. http://dx.doi:10.3844/ajassp.2014.584.591.

[25] A.J. Robinson, K. Smith, T. Hughes, S. Filippeschi, Heat and mass transfer for a small diameter thermosyphon with low fill ratio, International Journal of Thermofluids 1-2 (2020) 100010, https://doi.org/10.1016/j.ijft.2019.100010.

[26] T. Parametthanuwat, N. Pipatpaiboon, N. Bhuwakietkumjohn, S. Sichamnan, Heat transfer characteristics of closed-end thermosyphon (CE-TPCT), Engineering Science and Technology, an International Journal 27 (2022) 101020. https://doi.org/10.1016/j.jestch.2021.05.024.

[27] A.A. Bhatt, S.V. Jain, R.N. Patel, Experimental Investigations on Performance Analysis of a Wickless Thermosiphon Heat Pipe with Two Heat Sources and Multiple Branches, Journal of Thermal Science and Engineering Applications 14 (2022) 101006. https://doi.org/10.1115/1.4054163.

[28] R.A. Hossain, M.A.K Chowdhuri, C. M. Feroz, Design, Fabrication and Experimental Study of Heat Transfer Characteristics of a Micro Heat Pipe, Jordan Journal of Mechanical and Industrial Engineering 4 (2010).

[29] A.A. Alammar, R.K. Al-Dadah, S.M. Mahmoud, Numerical investigation of effect of fill ratio and inclination angle on a thermosyphon heat pipe thermal performance, Applied Thermal Engineering 108 (2016) 1055-1065. http://dx.doi.org/10.1016/j.applthermaleng.2016.07.163.

[30] Y. Kim, D.H. Shin, J.S. Kim, S.M. You, J. Lee, Boiling and condensation heat transfer of inclined two-phase closed thermosyphons with various filling ratios, Applied Thermal Engineering 145 (2018) 328-342. https://doi.org/10.1016/j.applthermaleng.2018.09.037.

[31] A. Goldoust, M.R.S. Emami, A.A. Ranjbar, Experimental Investigation of the Evaporator Section Tilted Angle and Filling Ratio on the Thermal Characteristics of a Two-phase Closed Thermosyphon, International Journal of Heat and Technology 37 (2019) 569-574. https://doi.org/10.18280/ijht.370226.

[32] H. Arat, O. Arslan, U. Ercetin, A. Akbulut, Experimental study on heat transfer characteristics of closed thermosyphon at different volumes and inclination angles for variable vacuum pressures, Case Studies in Thermal Engineering 26 (2021) 101117, https://doi.org/10.1016/j.csite.2021.101117.

[33] Xu, Zhi, Yaning Zhang, Bingxi Li, Chi-Chuan Wang, and Yongji Li. "The influences of the inclination angle and evaporator wettability on the heat performance of a thermosyphon by simulation and experiment." International Journal of Heat and Mass Transfer 116 (2018): 675-684.

تأثير الظروف الهندسية والتشغيلية على أداء الأنابيب الحرارية: مراجعة

الخلاصة: *يعتبرالأنبوب الحراري من أكثر الأجهزة فعالية في نقل الحرارة بين مصدر الحرارة و مستقبل الحرارة. الانبوب الحراري عبارة عن جهاز محكم التفريغ ، ويعتمد على تغيير الطور (سائل-بخار) المرتبط بموصلية حرارية عالية الفعالية. يتم تقديم مراجعة شاملة للدراسات التجريبية والعددية المتعلقة بدراسة تأثيرات العوامل الهندسية والمتغيرات التشغيلية المتحكم بها على الخصائص الحرارية للأنابيب الحرارية والثرموسيفونات. تشمل هذه العوامل و المتغيرات قطر وطول الأنبوب الحراري، وموائع التشغيل، و الطاقة الداخلة الى المبخر ، ونسبة الملأ في المبخر ، وزاوية الميل للانبوب الحراري ، ومعدل تدفق سائل التبريد ، وما إلى ذلك من العوامل التي يمكن التحكم بها. يتميز السلوك الحراري لأنابيب الحرارة بمعاملات نقل الحرارة والاختلافات في درجات الحرارة من خلال المكثف والمبخر والكفاءة الحرارية والمقاومة الحرارية. من خلال المراجعة, يتم إدراك أن المقاومة الحرارية تقل ، وتزداد المعاملات الحرارية مع كمية الطاقة الداخلة. بالإضافة إلى ذلك ، تعتمد القيم المثلى لزوايا الميل ونسب الملء على المتغيرات الأخرى التي يتم التحكم فيها. ومع ذلك ، تراوحت نسبة الملء المثلى بين 15٪ -60٪. بينما كانت أفضل زاوية ميل بين 60 درجة و 90 درجة.*