International Journal of Heat and Technology
Vol. 43, No. 4, August, 2025, pp. 1483-1490
Journal homepage: http://iieta.org/journals/ijht

Thermal Evaluation of the Effect of Filling Ratio and Inclination Angle on Thermosiphon Heat Pipe Collector

Norhan I. Dawood[1*], Jalal M. Jalil[1], Sahar R. Faraj[1], Abdul-Hamza H. Aboud[2]

[1] Electromechanical Engineering Collage, University of Technology, Baghdad 10066, Iraq
[2] Iraqi Ministry of Electricity and Renewable Energy, Baghdad 10013, Iraq

Corresponding Author Email: eme.22.42@grad.uotechnology.edu.iq

https://doi.org/10.18280/ijht.430425

Received: 3 May 2025
Revised: 13 July 2025
Accepted: 22 July 2025
Available online: 31 August 2025

Keywords:
thermosiphon heat pipe, filling ratio, inclination angle, thermal resistance

ABSTRACT

The utilization of cleaner energy is essential in the field of engineering. Thermosiphon heat pipes, as potential high-efficiency equipment, significantly impact the thermal management of energy systems. The present study experimentally evaluates the thermal performance of a thermosiphon heat pipe flat plate collector filled with water as the working fluid under different operation circumstances including inclination angles, filling ratios, solar intensities, and flow rates. Experiments were conducted utilizing a thermosiphon heat pipe with a 120 cm length divided into three main sections of evaporator, adiabatic, and condenser sections. Water was tested at fill ratios of 0.25, 0.45, and 0.65 and inclination angles of 40°, 65°, and 90°. Moreover, solar radiation ranges from 400, 600, and 800 W/m^2 with a flow rate of 0.1, 0.3, 0.5, and 0.7 L/m. The optimal results were observed at a filling ratio of 0.65 throughout all operational circumstances of THPFPC. In addition, the thermal performance of THPFPC rises when the collector angle of inclination decreases from 90° to 40°. Consequently, the collector thermal resistance diminishes as the fill ratio increases across all three inclination angles, with the highest thermal resistance observed at a fill ratio of 0.25 under a solar intensity of 400 W/m².

1. INTRODUCTION

Resources, such as fossil fuels, are finite and will ultimately be depleted. Identifying innovative methods for energy resource provision and waste energy recovery is essential. Many industries inefficiently utilize a significant portion of their input energy. Most thermodynamic system interactions involve energy transfer, specifically in the form of heat. Heat is either added to or removed from the system to maintain sustained operation. Heat pipes serve as effective heat transfer devices across multiple industries. Numerous researchers focus on the recovery of excess thermal energy in heat pipes; however, further investigation is necessary to advance novel heat recovery techniques and enhance current technologies [1]. Almost every range of temperature seen during operations of heat transfer is currently covered by the many uses of heat pipes. Historically, heat pipes merely consisted of pipes constructed from a material with a high heat conduction capacity, which underwent internal treatment to enable the medium's passage. In the meantime, scientists investigated a number of ways to make heat pipes more efficient. All it takes to create a heat pipe is a linear or curved tubular structure that holds a working fluid and its vapors in a state of equilibrium. Experimental and numerical investigations into the efficiency of thermosyphon heat pipes have made extensive use of a wide range of configurations, working fluids, heat inputs, cooling methods, and filling ratios [2]. Solar water heaters (SWHs) utilize solar radiation to heat water for uses such as washing dishes and even heating water for homes. Solar water heating has the potential to significantly reduce energy costs and carbon emissions, making it an environmentally economical and environmentally sustainable substitute for conventional water heating techniques. In order to meet the demands for hot water for a variety of purposes, solar collectors (SC) and solar water heaters (SWH) have been the subject of extensive research worldwide [3]. More than 90% of solar thermal capacity is accounted for by FPCs and ETCs, according to recent data [4]. From a structural standpoint, FPCs typically have convective heat losses via the glass cover, despite their simpler construction and cheaper maintenance costs. Since their performance drops significantly in the winter, they are better suited to sunny climes [5]. Conversely, ETCs exhibit high efficiencies in cold regions, as the vacuum envelope between the inner and outer tubes minimizes exposure to external temperatures [6].

Contemporary society relies heavily on a multitude of critical resources, with energy being one of the foremost. Energy plays a vital role in our contemporary society, with electrical and thermal energy being the most widely used forms. Energy is produced through the use of fossil fuels comprising petroleum, coal, nuclear power, and several other finite resources, which are anticipated to be exhausted in the forthcoming years. The significant increase in energy consumption has placed considerable pressure on conventional energy sources, leading to their exhaustion [7, 8].

Therefore, numerous studies have been reported on the studies of enhancing heat pipes thermal performance. The thermal performance improvement in HP-ETSC by the utilization of diverse acetone-based nanofluids has been investigated by Eidan et al. [9]. Different filling ratios and tilt angles are examined. The findings indicate that optimal thermal performance occurs at a filling ratio of 70% and an angle of inclination of 45° in comparison to other examined values throughout their study. Based on their investigation, it is advised that HP-ETSC systems utilize nanofluids to improve thermal performance (20-54%) and efficiency (15-38%). Farge et al. [10] experimentally examined the thermosyphon thermal performance utilizing distilled water as the working fluid across various filling ratios and input power. The findings indicated that a fill ratio of 60% demonstrated optimal dissipation of heat at the maximum temperature of operation. At a fill ratio of 60% the researchers observed a 14.6% reduction in thermal resistance of the thermosyphon, compared to a filling ratio of 50%, at an input power of 300 W. The impact of tilt angles on the thermal efficacy of a heat-pipe photovoltaic/thermal (HP PV/T) system has been documented by Zhang et al. [11]. The outcomes of the simulation indicate that the thickness of the liquid film in the evaporator or condenser stabilizes at a constant value under inclined conditions. The thermal resistance of the condenser varies with inclination angle, initially decreasing before increasing, whereas the evaporator exhibits an inverse trend. Both simulation and experimental results denote that the optimal angle of inclination is 40°. Arat et al. [12] conducted an experimental investigation into the thermal performance of vacuumed copper pipes, utilizing various volume values and angles of inclination at varying vacuum pressures. The researchers achieved optimal thermal resistance in the evacuated copper pipe utilizing 10 ml of water volume at an angle of inclination 90° throughout the duration of the experiment.

Soud and Abdul Ghafoor [13] investigated the impact of working fluids upon the thermal performance of a heat pipe in a horizontal orientation equipped with a wick structure, with different working fluids including water, ethanol, methanol and a fill ratio constituted 0.5 of the evaporator volume. The findings indicate that the heat pipe filled with Methanol exhibits a thermal resistance of 0.85166 ℃/W, representing the lowest thermal resistance value observed. Moreover, Soud et al. [14] studied the heat pipe's thermal efficiency and tested the impacts of working fluids in a vertical position with a wick. The chosen working fluids included methanol, water, ethanol, and various binary combinations of these substances in ratios of 50% to 50%, 30% to 70%, and 70% to 30%. The results demonstrate that the heat pipe filled with methanol fluid exhibits the lowest thermal resistance value of 0.7666 ℃/W. On the other hand, Rashid et al. [15] investigated the improvement of ETSC's performance using two distinct approaches. The initial approach entails the integration of a fine electrical curtain positioned prior to the ETSC. The alternative method involves the use of an NF instead of relying exclusively on water. The results demonstrated that system performance improved when utilizing TiO_2(50 nm)+PW as a working fluid, achieving enhancements of 3.906%, 5.34%, and 7.407%.

To address the operational demands of heat pipes under intricate settings and elevated density of heat flux, and to suggest appropriate thermal management strategies, Wang et al. [16] experimentally studied the hybrid and single nanofluids with a 5% mass fraction, analyzed with the gravitational gradient of a heat pipe at different angles. At varying angles of inclination, the hybrid nanofluid with an identical mass fraction exhibits an inverse trend relative to the single nanofluid, resulting in reduced heat pipe thermal resistance and enhanced the efficiency of heat transfer. A flat plate heat pipe array (FPHPA) with independent channels is developed by Xue et al. [17] to address the heightened heat dissipation requirements of 5G base stations. To examine the FPHPA thermal performance across various heat powers (30-300 W) and filling ratios (FR), an independent filling system with multiple channels the researcher facilitated two experimental scenarios: uniform and asymmetric fill of all channels. Results demonstrate that 30%-70% FR shows superior thermal performance and can substitute for the aluminum plate. The optimized FPHPA enhances the performance of heat transfer, resulting in a reduction of the wall temperature of the average area.

The implementation of photovoltaic/thermal (PV/T) systems equipped with distinct heat pipes present considerable potential for enhancing solar energy efficiency by mitigating challenges such as winter freezing and scaling. Difficulties such as frame blocking resulting from heightened insulation requirements may impede overall efficiency. The configuration of the adaptable independent heat pipe was optimized by Zheng et al. [18], examining the effects of variables such as the height variation between the condenser and evaporator, as well as the fill ratio, on thermal performance. The study examined the system's thermal performance under various side-altitude tilt angles and solar flux. The experimental results indicate that the improved structure markedly increases thermal efficiency, maintaining it within the range of 69.37% to 79.71%. In addition, Zhang et al. [19] examined the initialization and thermal transfer efficiency of high-temperature sodium heat pipes, essential for waste heat recovery and advanced nuclear reactor systems. The researchers investigated the effects of different filling ratios and inclination angles on the performance of heat pipes under a constant heat input. Findings indicated that by increasing the filling ratio from 10% to 20% it resulted in a notable decrease in the temperature difference between the condenser and evaporator sections. In addition, the effective thermal resistance diminishes across all heat inputs, which reflects improved performance resulting from enhanced the interaction between liquid and vapor phases.

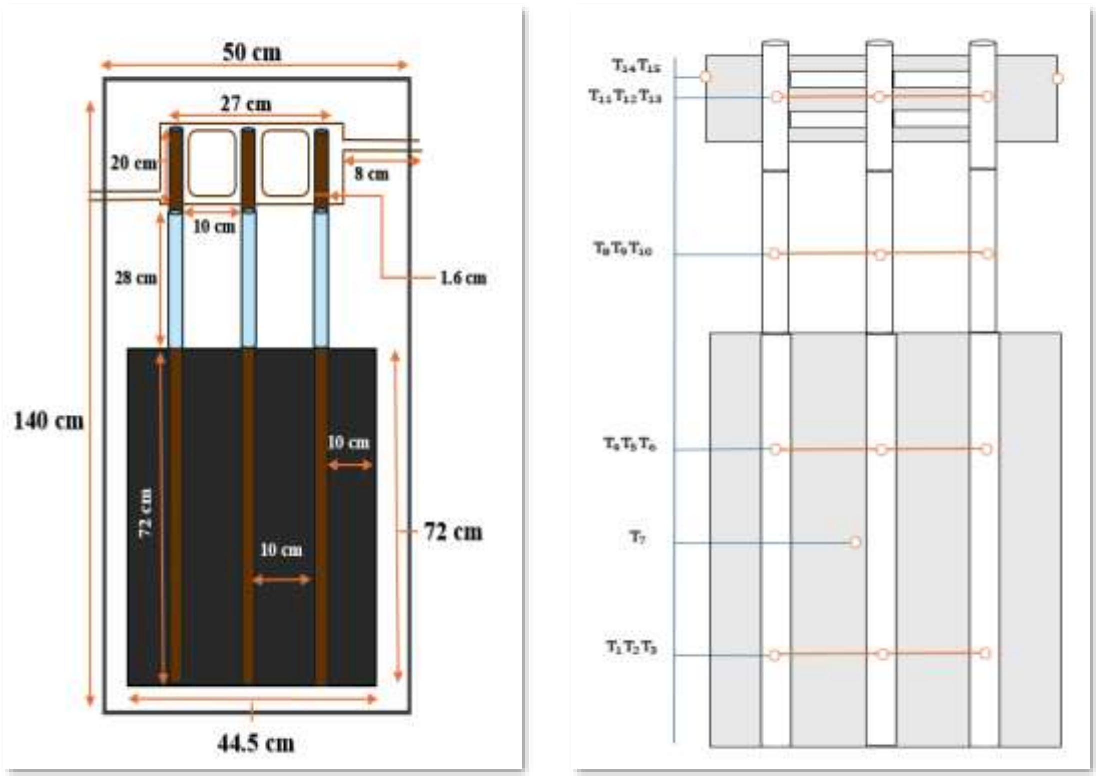
Limited research has provided a systematic analysis of the flow characteristics and heat transfer of THPFPC, and there is no consensus or quantitative conclusion regarding the impacts of fill ratio and inclination angle on thermal performance. The present research aims to experimentally discuss and consider the effect of varying the filling ratio, inclination angle, solar intensity as well as flow rate on the thermal performance of thermosiphon heat pipe water flat plate collector. Results from different operating conditions have been compared in order to present the optimal filling ratio and inclination angle for the present system.

The present study regarding thermosiphon heat pipe flat plate collector was conducted under indoor laboratory conditions employing solar simulator halogen lamps to provide consistent radiation. While this approach ensured precision and repeatability, it also simplified the environmental variables conventionally encountered in outdoor experiments, such as unpredictable solar intensity, ambient temperature variations, and wind effects. Consequently, the thermal performance and fluid dynamics observed in this study may differ under real outdoor conditions. Therefore, while the results demonstrate the potential of the thermosiphon system under controlled laboratory conditions, further research is necessary to assess its feasibility, durability, and efficiency in actual outdoor solar energy applications. Nevertheless, further experiments will be applied in order to investigate the thermal performance of the present system under the influence of nanoparticles.

2. EXPERIMENTAL SETUP AND PROCEDURE

An experimental system was set up in order to measure the temperature of the THPFPC. In the experiment, three thermosiphon heat pipes with an outer diameter of 1.6 cm and a length of 72 cm for the evaporator section, the heat pipe adiabatic section is made of quartz glass pipes with a length of 28 cm followed by a copper made condenser section with a length of 20 cm, as presented in Figure 1(a). The evaporator, condenser, and absorber plate were treated with a dark black coating shade to enhance the absorption of incident solar radiation and minimize the reflection of thermal solar radiation. The evaporator section was connected to the absorber plate as shown below.

The general dimensions of the present collector system were 140 cm in height, 50 cm in width, and 15 cm in the depth as shown in the sketch below.



(a) (b)

Figure 1. Schematic figures of THPFPC shows (a) dimensions of the collector, (b) thermocouples distribution

Figure 2. Experimental set-up of the thermosiphon heat pipe flat plate collector presents the three angles of inclinations

The temperature distribution in the different sections of the solar collector was measured with a k-type thermocouple. In total 12 thermocouples were attached to the 3 sections of the thermosiphon heat pipes as shown in Figure 1(b). In addition, two thermocouples for the water inlet and outlet, two for the glass cover and finally a single thermocouple was set to measure the absorbent plate temperature. The aluminium absorber plate was coated matt black to enhance the heat absorption ability with the dimensions 72 cm in length, 45 cm in width and 0.5 cm in thickness. Each individual THP was bonded mechanically to the absorber plate. The condenser section of the THP is mounted into a water jacket heat exchanger (manifold). The water jacket is a copper pipe that wraps around each condenser heat pipe. The water flows through the manifold and collects heat from the condenser heat pipe section.

A single 0.4 cm thick transparent-tempered glass was used as glazing on the front side of the THPFPC. The glass cover dimensions were 140 cm in length and 50 cm in width. Figure 2 displays the projectors that have been employed in the experimental work. Lights are installed at a mean gap of 22 cm center-to-center. The 500 W halogen lamp, works at 220 V. The overall intensity of the simulator's irradiation can be modified within a range of 100 to 500 W/m^2.

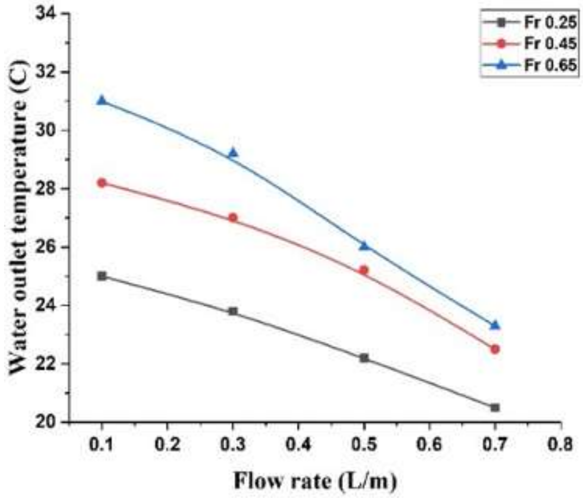
The dimmer was employed to assess the intensity of radiation originating from the simulators. The halogen projectors, assisting as solar simulators, were managed using an iron frame. The distance between the lower edge of the projectors and the top surface of the solar collector (glass surface) is equal to 70 cm, to make the radiation distribution approximately uniform throughout the device. The radiation intensity of the solar simulator was measured at the collector's surface and for different points using the SM206-SOLAR solar meter, which quantifies radiation strength within a range of 0 to 2000 W/m^2 and possesses a reaction time of one second. Experiments have been studied under an indoor environment at a room temperature of approximately 25°C.

3. RESULTS AND DISCUSSION

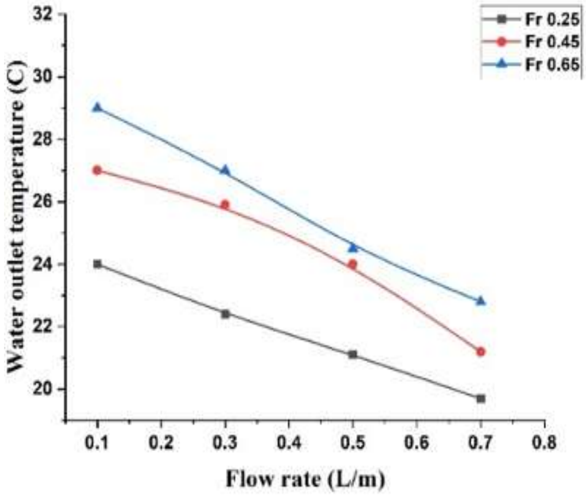
The consequent outputs of the present experimental model of the THPFPC are illustrated in this part to clearly show the thermal performance of the solar collector under varying conditions, specifically different filling ratios 0.25, 0.45, 0.65, inclination angles 40°, 65°, 90°, solar intensities (400, 600, 800) W/m^2, and flow rates of (0.1, 0.3, 0.5, 0.7) L/m. Both the working fluid's heat-absorbing capacity and the available void space for dispersing the working fluid vapor produced by the phase change occurrence are major determinants of thermal performance. In light of this, it is necessary to investigate the inclination angle in conjunction with the filling ratio.

3.1 Effect of filling ratio and inclination angle on THPFPC thermal performance

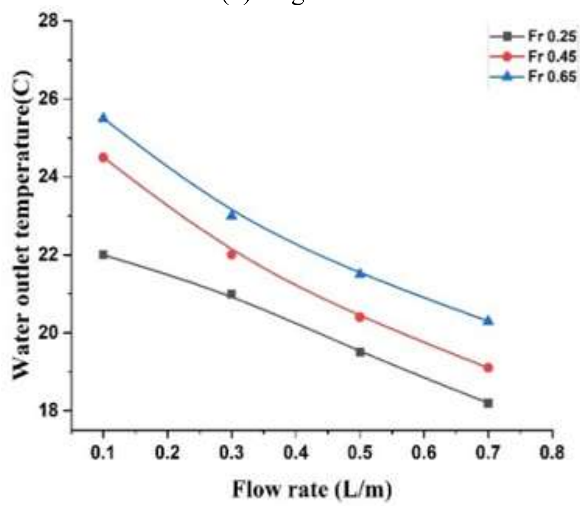
Initially, heat is transferred from the evaporator wall to the liquid as a result of constant solar radiation. Once the working fluid attains its saturation temperature, boiling commences, leading to a phase change. As a result, vapor rises to heat the upper half of the heat pipe, and the temperature rises gradually until it reaches a constant state. The impact of the volume of the charged liquid on the thermal performance for the different inclination angles of the THPFPC is shown in the figure below.



(a) Angle 40°



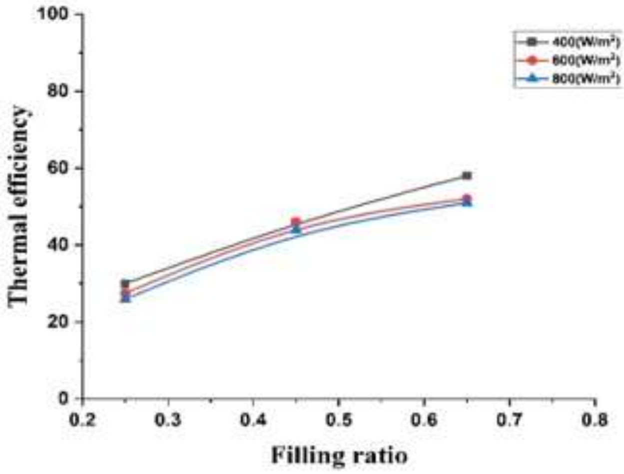
(b) Angle 65°



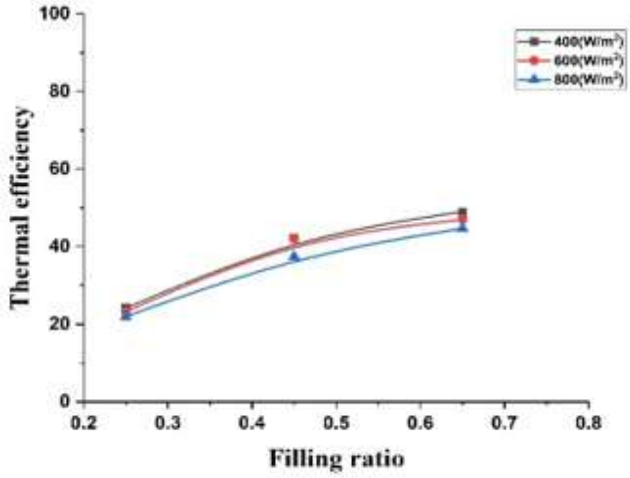
(c) Angle 90°

Figure 3. The relation between water outlet temperatures from the collector manifold related to various filling ratios and flow rates for angles 40°, 65°, 90°

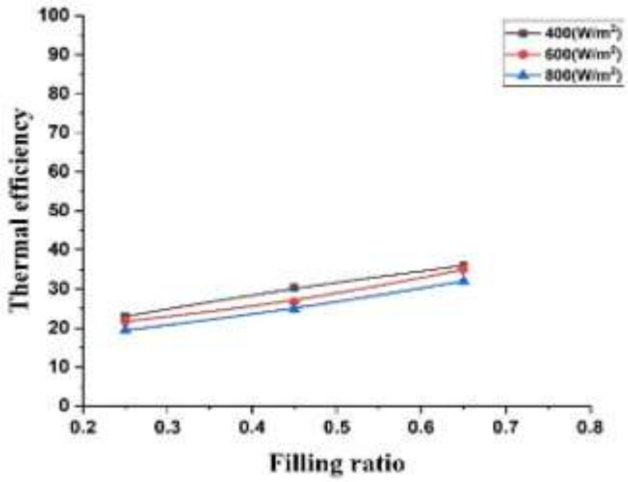
Figure 3 above illustrates the variance of water outlet temperature for the inclination angles of 40°, 65°, 90°, and the impact of the variation of filling ratio for the specified ranges of flow rate. The figure depicts that the water outlet temperature is directly proportional to the evaporator filling ratio. It has been noted that the effect of changing fill ratio and increasing solar intensity on the water outlet temperature is more significant in the case of 40° inclination angle. In addition, the lowest water outlet temperature is seen at a filling ratio of 0.25 for all solar intensities and inclination angles, owing to the probability of dry out caused by inadequate condensate return. Obviously, the water outlet temperature has steadily increased with increasing solar radiation, and the higher the solar radiation intensity the higher the water flow temperature will be for the three angles.



(a) Angle 40°



(b) Angle 65°



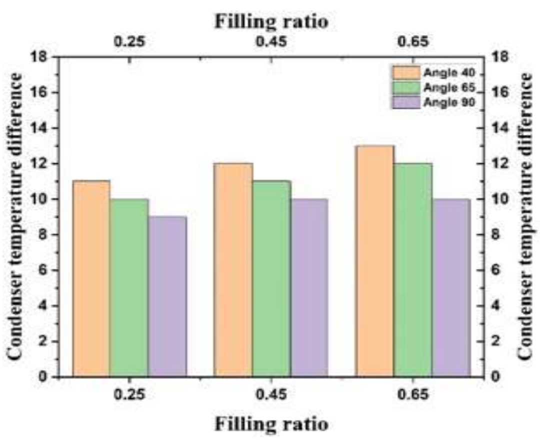
(c) Angle 90°

Figure 4. Variation of THP thermal efficiency with filling ratios and solar intensities for angles 40°, 65°, 90°

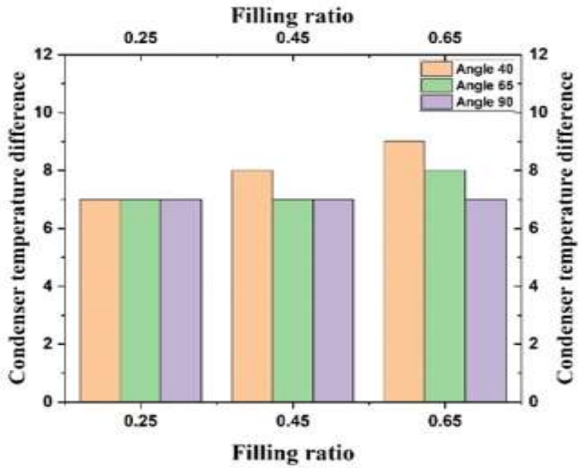
The highest water outlet temperature was achieved at an inclination angle of 40° and a filling ratio of 0.65, by maintaining an adequate liquid level for boiling to avoid drying out and ensuring sufficient vapor space for effective condensation, which is equal to 31℃ at solar radiation of 800 W/m^2 and a flow rate of 0.1 L/m. Conversely, when the THPFPC approach vertical position of angle 90°, and fill ratio of 0.25 the water outlet temperature will ultimately be reduced until approaching the least of 16.9℃ at 0.7 L/m and 400 W/m^2. The best thermal performance for the present THPFPC was observed at an inclination of 40° followed by 65°, which explained the high rate of evaporation of the working fluid in the evaporator section which in turn led to the high temperature of the condenser section for the mentioned angles.

Fill ratio is an essential factor in the performance of thermosiphon heat pipes, as it influences the efficacy and dependability of thermal systems. Thermal efficiency is a direct metric for assessing the precision and quality of THPs. A higher filling ratio increases the availability of working fluid for phase change, thereby enhancing heat transfer efficiency. Figure 4 shows that the trends of thermal efficiency are ascending, which is caused by the increment of water flow rate of THP for the different inclination angles. From Figure 4(a), the maximum value of thermal efficiency was observed at an inclination angle of 40° with about 58% at solar intensity of 400 W/m^2 and flow rate of 0.7 L/m, as for angle 65° the highest thermal efficiency achieved was about 50% as displayed in Figure 4(b). Conversely, the least efficient case was for an angle 90° equal 9% at a flow rate of 0.1 L/m at 800 W/m^2 as shown in Figure 4(c).

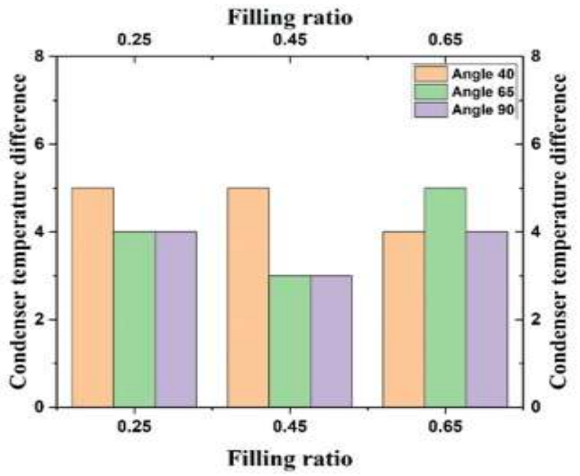
Figure 5 illustrates a comparison of the variation of condenser temperature difference for the different inclination angles and filling ratios with the flow rates at a specific solar intensity of 800 W/m². A similar trend is shown for the four flow rates in which the highest and lowest condenser temperatures occur at flow rates of 0.1 and 0.7 L/m, respectively. These higher temperatures at lower flow rates are attributed to the contact time the inlet water had during the processes. Furthermore, the figure shows that angle 40° has a major effect on the condenser's temperature differences for the various processes. Figure 5 shows that the highest temperature difference between the 1st and 2nd condenser pipes at an inclination angle of 40° is 13 and 9℃, respectively. Moreover, for the 3rd condenser pipe, the highest temperature difference was achieved at inclination angles of 40° and 65° equally with 5℃. As presented above, the temperature difference of the liquid tends to decline as the angle increases.



(a) Pipe 1



(b) Pipe 2

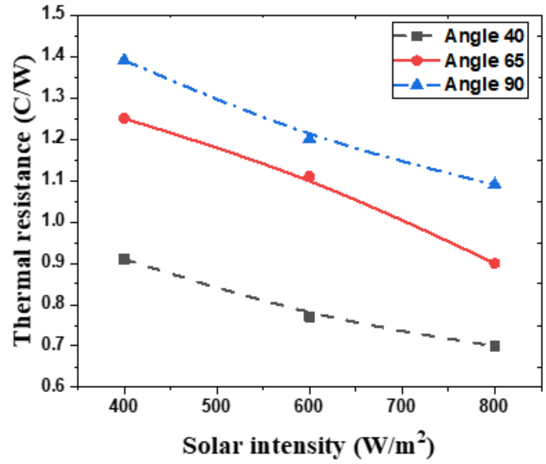


(c) Pipe 3

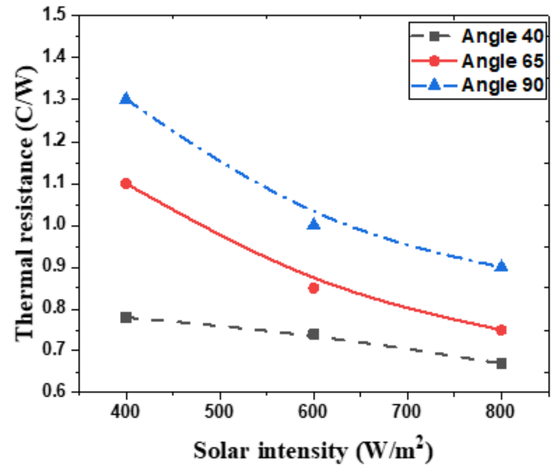
Figure 5. The temperature difference of the condenser section for the various inclination angles, filling ratios and solar intensity of 800 W/m^2

3.2 Effect of filling ratio and inclination angle on thermal resistance

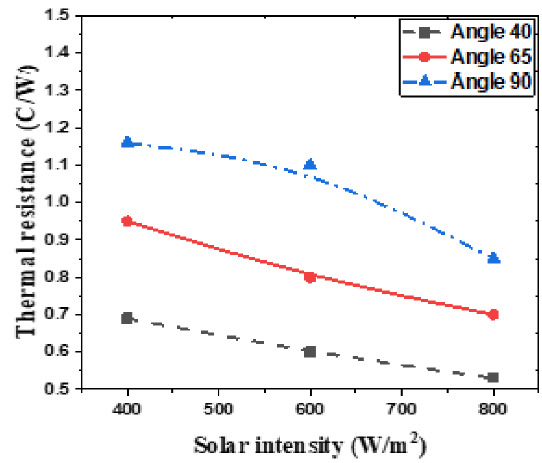
A comprehensive evaluation of the carrying fluid's impact on the system's temperature profile was conducted by measuring the heat pipe's thermal resistance throughout various solar radiation and inclination angles. Higher filling ratio increases the amount of working fluid accessible for phase change, thereby enhancing the efficiency of heat transfer. Conversely, Figure 6 shows that the thermal resistance declines from its peak values at a fill ratio of 0.25 to the minimum value at a fill ratio of 0.65 for all inclination angles and solar intensities, in line with patterns determined by Xue et al. [17]. The cause can be related to the volume of fluid within the tube. At a filling ratio of 0.65, the fluid height within the tube exceeds that observed at ratios of 0.25 and 0.45. In other terms, an increased amount of input power is required. Moreover, the thermal resistance of the thermosiphon heat pipe increases with increasing values of the inclination angle for all input conditions. Figure 6 indicates that thermal resistance is minimized at a filling ratio of 0.65, particularly with 40° angle of inclination. Angle 40° depicts a practical balance between decreased resistance of counterflow and the return of condensate driven by gravity. It is possible to observe the significant impact that solar radiation has on the degree of reduction in thermal resistance. Increasing the amount of solar radiation that is applied causes a greater amount of working fluid to evaporate and traverse in the direction of the condenser. Consequently, increasing solar intensities to specific amounts enhances the fluid dynamics and thereby raises the acceleration of fluid phase change, leading to a reduction in the evaporator thermal resistance. As a result, improved heat transfer performance was accomplished.



(a) Filling ratio of 0.25



(b) Filling ratio of 0.45



(c) Filling ratio of 0.65

Figure 6. Variation of the system thermal resistance related to solar intensities and filling ratios for the three inclination angles

The thermal resistance of the heat pipe is characterized as:

$$R = \frac{(T_e - T_c)}{Q} \quad (1)$$

T_e and T_c represent the mean temperatures at the evaporator and condenser sections, respectively. While Q denotes the heat provided to the heat pipe.

4. UNCERTAINTY ANALYSIS

Instrumental, observational, and measurement errors all have the potential for causing experimental uncertainty. Multiple causes of uncertainty were addressed throughout this experimental examination, including flow velocity, mass flow rate, temperature, and sun intensity. Singh and Vardhan [20] published an overall measurement of uncertainty and error analysis. Thus, the total uncertainty of direct and indirect measurements can be determined using Eq. (1).

$$\frac{\delta R}{R} = \sqrt{(\frac{\partial R}{\partial x_1}\delta x_1)^2} + \sqrt{(\frac{\partial R}{\partial x_2}\delta x_2)^2} + \cdots + \sqrt{(\frac{\partial R}{\partial x_n}\delta x_n)^2} \quad (2)$$

where, $\delta R/R$ is known as relative error, ∂x_1, ∂x_2, ∂x_3 ...: ∂x_n are feasible errors in the measurements of x_1, x_2, x_3, x_n.... and ∂R presents absolute uncertainty. The uncertainty values observed during studies in terms of equipment performance were relatively small, and all of the readings collected during measurements in this study were within the acceptable range.

5. CONCLUSIONS

This work experimentally investigates the effect of filling ratios and inclination angles on the thermal performance of thermosiphon heat pipe flat plate collector for different solar intensities and flow rates. Moreover, experiments were performed to evaluate the impact of inclination angles, filling ratios, and heat inputs on the thermal resistance of the collector. The main conclusions are summarized as follows:

1. The findings indicate that a greater filling ratio supplies additional working fluid for phase transitions, hence improving the heat pipe's heat transfer and thermal efficiency. The best results were observed with a 0.65 filling ratio for all operating conditions of THPFPC. The 0.65 fill ratio promotes balanced condensation and boiling dynamics, reducing the possibility of flooding and dry-out that can impair performance in traditional systems.
2. The thermal performance of THPFPC increases with the decrease of the collector inclination angle from 90° to 40° as optimal thermal performance was achieved at an inclination of 40° with a thermal efficiency of 58%. As in solar water collectors utilizing THP, a tilt angle of 40° may improve heat transmission effectiveness, especially in mid-latitude regions where this angle corresponds effectively with seasonal exposure to sunlight.
3. The collector thermal resistance decreases with the increment of fill ratio for the three inclination angles as the highest thermal resistance was noticed for fill ratio of 0.25 for solar intensity of 400 W/m^2. Under water fill ratio of 0.65 thermal resistance reached the lowest value of 0.06 at solar intensity of 800 W/m^2.
4. Solar intensity of 800 W/m^2 and flow rate of 0.1 L/m, showed the best thermal performance for all operating conditions of filling ratios and inclination angles.
5. Future research could employ nanoparticles and study their effect on thermal performance to further enhance the present THPFPC. Consequently, the FORTRAN 90 program would be a considerable tool for numerical simulation to obtain the required numerical results.

REFERENCES

[1] Maleknezhad, A., Ghahremani, A., Shafii, M.B. (2023). Simultaneous power generation and heat recovery within a novel thermosyphon heat pipe: An experimental study and correlation development. Case Studies in Thermal Engineering, 50: 103482. https://doi.org/10.1016/j.csite.2023.103482

[2] Mathry, A.H., Al-Mousawi, F.N., Dhaidan, N.S., Al-Shohani, W.A.M., Alammar, A.A. (2024). Impact of design and operating parameters on the thermal performance of heat pipes: A review. Journal of Engineering Research, 13(2): 985-1000. https://doi.org/10.1016/j.jer.2024.02.004

[3] Naveenkumar, R., Venkateshkumar, R., Mohanavel, V., Franklin, C., Ismail, S.O., Ravichandran, M., Kannan, S., Soudagar, M.E.M. (2025). Recent developments in solar water heaters and solar collectors: A review on experimental and neural network analyses. Results in Engineering, 25: 104394. https://doi.org/10.1016/j.rineng.2025.104394

[4] Allouhi, A., Jamil, A., Kousksou, T., El Rhafiki, T., Mourad, Y., Zeraouli, Y. (2015). Solar domestic heating water systems in Morocco: An energy analysis. Energy Conversion and Management, 92: 105-113. https://doi.org/10.1016/j.enconman.2014.12.055

[5] Sabiha, M.A., Saidur, R., Mekhilef, S., Mahian, O. (2015). Progress and latest developments of evacuated tube solar collectors. Renewable and Sustainable Energy Reviews, 51: 1038-1054. https://doi.org/10.1016/j.rser.2015.07.016

[6] Sokhansefat, T., Kasaeian, A., Rahmani, K., Heidari, A.H., Aghakhani, F., Mahian, O. (2018). Thermoeconomic and environmental analysis of solar flat plate and evacuated tube collectors in cold climatic conditions. Renewable Energy, 115: 501-508. https://doi.org/10.1016/j.renene.2017.08.057

[7] Jamar, A., Majid, Z.A.A., Azmi, W.H., Norhafana, M., Razak, A.A. (2016). A review of water heating system for solar energy applications. International Communications in Heat and Mass Transfer, 76: 178-187. https://doi.org/10.1016/j.icheatmasstransfer.2016.05.028

[8] Sharma, A., Awasthi, A., Singh, T., Kumar, R., Chauhan, R. (2022). Experimental investigation and optimization of potential parameters of discrete V down baffled solar thermal collector using hybrid Taguchi-TOPSIS method. Applied Thermal Engineering, 209: 118250. https://doi.org/10.1016/j.applthermaleng.2022.118250

[9] Eidan, A.A., AlSahlani, A., Ahmed, A.Q., Al-fahham, M., Jalil, J.M. (2018). Improving the performance of heat pipe-evacuated tube solar collector experimentally by using Al_2O_3 and CuO/acetone nanofluids. Solar Energy, 173: 780-788. https://doi.org/10.1016/j.solener.2018.08.013

[10] Farge, Z.T., Ismael, J.S., Thyab, R.M. (2021). Experimental investigation of thermosyphon thermal performance using different filling ratio. Engineering and Technology Journal, 39(1A): 34-44. https://doi.org/10.30684/etj.v39i1A.1639

[11] Zhang, T., Zheng, W., Wang, L., Yan, Z., Hu, M. (2021). Experimental study and numerical validation on the effect of inclination angle to the thermal performance of solar heat pipe photovoltaic/thermal system. Energy, 223: 120020. https://doi.org/10.1016/j.energy.2021.120020

[12] Arat, H., Arslan, O., Ercetin, U., Akbulut, A. (2021). 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: 101117. https://doi.org/10.1016/j.csite.2021.101117

[13] Soud, A., Abdul Ghafoor, Q. (2022). Study of the effect of working fluids on the thermal performance of a horizontal heat pipe with stainless steel wick. Engineering and Technology Journal, 40(7): 1-11. https://doi.org/10.30684/etj.2022.131137.1014

[14] Soud, A., Abdul Ghafoor, Q., Nazzal, A. (2022). Heat pipe thermal performance analysis by using different working fluids. Engineering and Technology Journal, 41(1): 1-12. https://doi.org/10.30684/etj.2022.132052.1086

[15] Rashid, H., Sultan, K., Anead, H. (2022). Thermal performance of an evacuated-tube solar collector using nanofluids and an electrical curtain controlled by an artificial intelligence technique. Engineering and Technology Journal, 40(1): 8-19. https://doi.org/10.30684/etj.v40i1.2021

[16] Wang, Z., Zhang, H., Yin, L., Yang, D., Yang, G., Akkurt, N., Liu, D., Zhu, L., Qiang, Y., Yu, F., Xu, Q., Xiong, Y. (2022). Experimental study on heat transfer properties of gravity heat pipes in single/hybrid nanofluids and inclination angles. Case Studies in Thermal Engineering, 34: 102064. https://doi.org/10.1016/j.csite.2022.102064

[17] Xue, Q., Xia, G., Zhou, W. (2024). Experimental investigation on the optimization of different filling ratios for large-size flat plate heat pipe array. Applied Thermal Engineering, 236: 121857. https://doi.org/10.1016/j.applthermaleng.2023.121857

[18] Zheng, L., Cao, J., Peng, J., Lu, Z., Hong, X., Cuce, E., Liu, W., Pei, G., Ji, J. (2025). Optimization on the structure and filling ratio of a flexible separate heat pipe applied for tracking-type photovoltaic/thermal systems. Renewable Energy, 239: 122046. https://doi.org/10.1016/j.renene.2024.122046

[19] Zhang, P., Li, Z., Su, Z., Wang, H. (2025). Experimental investigation of influence of filling ratio and inclination angle on the startup and heat transfer performance of high-temperature sodium heat pipe. Applied Thermal Engineering, 269: 125982. https://doi.org/10.1016/j.applthermaleng.2025.125982

[20] Singh, I., Vardhan, S. (2021). Experimental investigation of an evacuated tube collector solar air heater with helical inserts. Renewable Energy, 163: 1963-1972. https://doi.org/10.1016/j.renene.2020.10.114

NOMENCLATURE

THPFPC	thermosiphon heat pipe flat plate collector
SWHs	solar water heaters
SC	solar collector
HPETSC	heat pipe- Evacuated tube solar collector
HP-PV/T	heat pipe photovoltaic thermal
ETSC	evacuated tube solar collector
NF	Nano fluid
DI	De ionic
FPHPA	flat plate heat pipe array
FR	filling ratio
PV/T	photovoltaic/ thermal
THP	thermosiphon heat pipe
R	thermal resistance
T_e	evaporator temperature
T_c	condenser temperature
Q	provided heat

Greek symbols

$\delta R/R$	relative error
∂X_n	feasible errors
∂R	present absolute uncertainity