Case Studies in Thermal Engineering 50 (2023) 103397

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

The effect of different variables and using of the internal adiabatic wall in the construction and performance of thermosiphon heat pipes: Experimental investigation

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ARTICLE INFO

Handling Editor: Huihe Qiu

Keywords:
Heat pipe
Nanofluid
Effective thermal conductivity
Internal adiabatic wall

ABSTRACT

Heat pipes are a practical and powerful tool for recovering thermal energy and conserving energy sources. Thermosiphon is one of the most widely used devices that can transfer large amounts of heat at high rates between hot and cold sources without the use of external energy. The amount of vacuum in the pipe, the percentage of fluid filling, the type of operating fluid, the pipe's length and the quantity of heat flux are the factors affecting the efficiency and effectiveness of the thermosiphon heat pipe. In this paper, the effects of different variables in the construction of heat pipes such as working fluid, pipe length, the use of mesh screen wick structure and the use of internal adiabatic wall on the thermosiphon heat pipes performance are investigated. The results show that using of an internal adiabatic wall eliminates and reduces limitations such as boiling, evaporator drying, thermosiphon flooding and vapor pressure and significantly improves the heat pipe's performance. So that, the effective thermal conductivity (K) is increased up to 350% using the internal adiabatic wall. However, in some nanofluids, such as water/multi-walled carbon nanotubes (MWCNT), with increasing the nanofluid's mass fraction, the startup speed in heat pipes with internal adiabatic wall is reduced by up to 20%.

1. Introduction

With the fast enlargement of technology in modern societies, the demand for thermal energy is affected by the energy crisis and environmental pollution. Energy conservation has become an important factor in problem-solving. Energy consumption in the industry

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https://doi.org/10.1016/j.csite.2023.103397
Received 17 April 2023; Received in revised form 10 August 2023; Accepted 17 August 2023
Available online 19 August 2023

includes heat loss by equipment and a large number of chemical reactions. The transfer of this heat to better use of energy or its discharge to other environments is essential in the industry. The heat pipe is a device with low thermal resistance and high efficiency that is widely used in chemical, metallurgical, electronics, geotechnical, petroleum and other fields [1–3].

So far, heat pipes have been used for heat transfer between hot and cold sources, and the development of technology to improve the performance of these devices has been considered by researchers. The first idea for heat pipes dates back to the mid-eighteenth century when it was developed by Perkins [4]. The first serious attempt at this technology was made by Gaualer, but this action also remained at the level of ideas and theoretical discussions, and finally in 1962 by Grover, the first heat pipe was designed, created and used [5]. In a study, Kumarisan et al. conducted the changing of the working fluid, heat flux and pipe angle effects on the heat pipe's performance with sintered and mesh wick. The findings indicated that the thermal resistance reduction for sintered heat pipe was 13.92% more than the mesh state under the same condition. Also, the maximum surface temperature reduction is obtained for the sintered wick at an angle of 45° and the mesh wick at an angle of 60°. Shafahi et al. [6] surveyed the effect of using nanofluids in the heat pipe. The findings showed that the use of Al_2O_3, TiO_2 and CuO nanoparticles improves the heat pipes' heat capacity by 5, 7 and 15%, respectively. Mishra et al. [7] investigated the high porosity wick effect on heat transfer of heat pipe. Jiang et al. [8] found that the sintering process is very important for porous wicks for use in heat pipes. Four steps of the sintering process were considered to join porous wick with heat pipe and sintering parameters including temperature, time, pressure and sintering direction were discussed. The findings indicated that the suitable sintering temperatures for copper powder were 159 μm and 81 μm at 950 and 900 °C, respectively. They also found that vertical sintering could effectively prevent gaps between the wick and the pipe's inner wall. Wang et al. [9] considering the advancement of equipment at sub-zero operating temperatures, investigated the heat pipes working fluid in different temperature ranges. They experimentally investigated the heat pipe's performance with CO_2 working fluid and the effect of heat capacity, filling ratio and condenser conditions on the heat pipe. The findings illustrate that the heat pipe's performance with CO_2 working fluid is satisfactory. In contrast, a comparison was made with the working fluid R134a and the results showed that its thermal resistance is 2–5 times that of the heat pipe with the CO_2 working fluid. Weibel et al. [10] experimentally investigated boiling from the surface of a heat pipe and proved that the heat loss was more than 500 W/cm^2. In an experimental study, Zhao et al. [11] surveyed the thermal power and the number of modules used in the condenser effects on thermoelectric performance, thermal resistance and generator temperature uniformity. The results show that with increasing thermal power in the evaporator, thermal resistance decreases and thermoelectric efficiency increases. Tsai et al. [12] utilized DI water and water-gold nanofluid in the heat pipe. They indicated that the heat resistance of a heat pipe applying nanofluid is lower than that of water. Liu et al. [13] investigated using the heat pipes in the cooling system of an optical telescope. The purpose of that study was to plan a heat pipe in the absence of gravity. Empirical outputs showed that the designed heat pipe starts at a temperature between 80 and 120 K and runs normally. Smoot et al. [14] experimentally conducted a three-layer heat pipe to study the layer effect on heat transfer capability. The addition of layers increases the total power and thermal conductivity. Seo et al. [15] studied the limitations in long-length heat pipes and found that the limitations in these pipes depend on the ratio of diameter to pipe length. And by including this modifier in the previous equation, they were able to obtain more accurate results. Wang and Nishio [16] observed the effect of the parameters such as internal diameter, filling ratio and its properties on a heat pipe and concluded that the smaller inner diameter of the pipe caused to higher amount of heat transfer. They also performed a numerical simulation to explain heat transfer and the behavior of the two-phase flow. One of the concerns of researchers is the heat pipes working conditions in the temperature between 350 and 500 °C. Therefore, Werner et al. [17] conducted the operation of a copper/nickel heat pipe with water at temperatures above 280 °C. The findings depicted that the thermal resistance at vapor temperature increases significantly. Ma et al. [18] developed a high-performance cooling device using nanoparticles in a heat pipe. The outputs of their experiments showed that when nanoparticles are used, the heat transfer capacity is remarkably enhanced. For instance, at power of 81 W, using the nanofluid can decrease the temperature gradient between the condenser and evaporator. Siricharoenpanich et al. [19] experimentally conducted the use of heat pipes in the CPU cooling system. Heat pipe angle, wick type and working fluid were investigated to identify the thermal behavior of the heat pipe. Working fluids R11, ethanol and R134a with a 50% filling ratio were used. Temperature changes of CPU derived from cooling system of heat pipe were compared with the conventional cooling systems temperature. It was observed that the physical properties of the working fluid have a remarkably effect on the thermal resistance. Khazaee et al. [20] researched the parameters effect such as pipe slope angle and heat flux input on the coefficient of heat transfer of a two-phase thermosiphon with ethanol working fluid and finally proposed a correlation for coefficient of heat transfer for the tested conditions. Guichet et al. [21] theoretically and experimentally investigated the heat pipe effect on cooling applications. Their aim was to study the thermal power effect from 0 to 1500 W on the evaporator and condenser performance. The effect of slope angle was also investigated and infrared imaging was performed from the heat pipe's surface. Sarmasti et al. [22] empirically studied the filling ratio effect on the thermal efficiency of a sloping two-phase thermosiphon. They performed experiments at fill rates of 20–60% at an angle of 15–90° to the horizon and used water. They illustrated that the highest thermosiphon's thermal efficiency is achieved at an angle of 60°. Srimuang et al. [23] Examined the ratio of fluid filling effect on the heat transfer properties of a flat thermosiphon. They used water, freon 123 and ethanol as the working fluid and performed experiments at filling rates of 20, 40, 60 and 80%.

Extensive numerical studies on the thermal behavior of heat pipes have also been performed. Borujerdi and Layeghi [24] presented a model for the analysis of the flow of vapor in a concentric annular heat pipe. Gupta et al. [25] optimized the heat pipe's efficiency with nanofluid using the response surface method and considered parameters such as power, nanofluid filling ratio, nanofluid concentration and slope angle. Benne and Homan [26] used a numerical method to investigate the behavior of a thermal storage device combined with a thermosiphon at a constant heat flux. Nemec et al. [27] suggested a model for calculating heat transfer limitation in which various types of fluid and wick structures were considered. Fadhl et al. [28] proposed a model to simulate the two-phase flow and heat transfer effect during thermosiphon operation. The simulation results showed that the temperature distribution and mass transfer are in good agreement with the empirical findings.

The primary objective of this study is to achieve the highest possible effective thermal conductivity through modifications in both the variables and the configuration of heat pipes. Enhancing the efficiency of heat pipes involves employing diverse working fluids and overcoming the limitations associated with them through the novel and inventive technique of incorporating an internal adiabatic wall. The impact of heat pipe dimensions and fluid composition on their performance was also examined.

2. Experimental procedure

This part describes the structure of the laboratory setup and how the experiments are performed. One segment pertains to the constituents of the testing apparatus utilized for evaluating the initial thermal activation rate of the heat pipes, while the other segment encompasses the computation of the effective thermal conductivity.

2.1. Material

2.1.1. Heat pipe material

The tests were conducted on heat pipes made of oxygen-free copper (OFC) with a purity of 99.99% and inner and outer diameters of 6.4 mm and 8 mm, respectively and lengths of 100- and 200-mm. Fig. 1a illustrates various analyzed heat pipes, and Fig. 1b displays cross-sectional views of a heat pipe featuring a wick structure.

2.1.2. Working fluid

One of the effective methods to enhance the heat transfer performance in thermal applications is to increase the thermal conductivity of fluids. The *K* of fluids in which solid particles are dispersed is far greater than that of ordinary fluids. Also, in the heat pipe design, the high surface tension is very important because it causes the heat pipe to act against the gravitational field and a capillary pump is created [29]. High latent heat also causes to transfer of heat to a small amount of fluid flow, resulting in a small pressure drop in the pipe. Therefore, in this paper, different working fluids effect was investigated. The used working fluids in this study include deionized water, Multi-Walled Carbon Nanotubes (MWCNT) with different mass fractions, water-silicon dioxide (SiO_2) and acetone. These fluids were used in different works by other scientists [31–33]. The pressure inside the heat pipes during charging was 10^{-5} mbar, which was created by a vacuum system equipped with a diffusion pump.

2.2. Structure of heat pipes

2.2.1. Thermosiphon

A thermosiphon is a non-wicked heat pipe in which gravity is used to establish the fluid flow between the condenser and evaporator. The performance of the thermosiphon depends on the operating fluid. Therefore, in this study, 4 different fluids were compared in terms of thermal performance.

2.2.2. Heat pipe with wick

The production of the capillary pump to transfer the fluid from the condenser to the evaporator can be created by using a wick in the heat pipe. In this paper, a copper mesh screen was used as a wick in the heat pipe.

2.2.3. Thermosiphon with internal adiabatic wall

The main idea of this research is to use the internal adiabatic wall in the heat pipe. In this type of pipe, an insulated inner wall made of bone fiber in the adiabatic part was used to remove some of the limitations of thermosiphon heat pipes. Fig. 2 illustrates a heat pipe section view with an internal adiabatic wall.

The tests of this study were performed in a laboratory with an ambient temperature of 23–28 °C and relative humidity of 50%. In this study, two different experiments were considered to study the working fluid and heat pipe type effects. Table 1 depicts the

a) b)

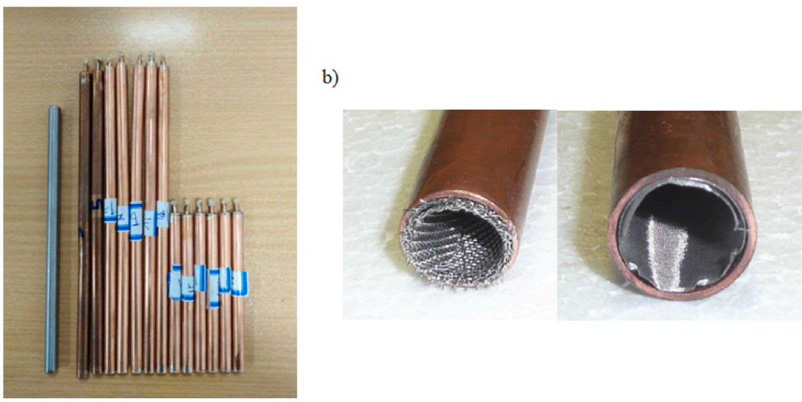

Fig. 1. a) Heat pipe samples and, b) heat pipe section.

considered parameters in the heat pipe.

2.3. Heat pipe startup speed

Fig. 3 shows the schematic of the empirical setup to test the heat pipe startup speed. To perform this test, the evaporator part of the manufactured heat pipes, which are at ambient temperature, is inserted into the boiling water container at once, and at the same time, the temperature changes over time are measured in the heat pipe's condenser for 20 s by a Multi-Input Thermometer.

2.4. Effective thermal conductivity of heat pipes

In this research, the thermal conductivity was investigated by generating heat with different input powers using a DC power supply in the evaporator part and using a fan as a heat sink in the condenser part. Fig. 4 illustrates the experimental configuration employed for assessing the value of effective thermal conductivity. The diagram displays the utilization of multiple thermocouples to monitor temperature variations. Additionally, a fan and power supply were incorporated in the condenser and evaporator sections of the heat pipe to control heat input and output. Ultimately, a data logger facilitated the recording of pertinent information. The powers considered included 1, 3, 5, 10, 15 and 20 W. As shown in Fig. 4, the position of the sensors is as follows:

Sensor 1: Heat sink temperature.
Sensor 2: Heat pipe temperature at the beginning of the evaporator part.
Sensor 3: Heat pipe temperature at the end of the evaporating part and the beginning of the adiabatic part.
Sensor 4: Heat pipe temperature at the end of the adiabatic part and the beginning of the condenser part.
Sensor 5: Heat pipe temperature at the end of the condenser part.
Sensor 6: Ambient Temperature.

2.5. Thermal analysis

The following equation was utilized to calculate the K in the tested heat pipes.

$$K = \frac{(Q_H - Q_L)L}{A_X\left(T_{p3} - T_{p4}\right)} \tag{1}$$

In the above equation, K is the effective thermal conductivity, Q_H is the input heat, Q_L is the heat loss from the heat pipe's adiabatic part (Eq. (2)), A_X is the cross-section along the length of the heat pipe (Eq. (3)), L is the distance between temperature sensors 3 and 4, T_{p3} and T_{p4} are the temperatures of points 3 and 4, respectively [30].

$$Q_L = hA_y(T_s - T_\infty) \tag{2}$$

$$A_X = \frac{\pi D^2}{4} \tag{3}$$

$$A_y = \pi DL \tag{4}$$

$$T_s = \frac{T_3 + T_4}{2} \tag{5}$$

In the above equations, h is the coefficient of convection heat transfer, T_s is the average temperature of the surface on the heat pipe in the adiabatic part, and A_y is the cross-sectional area in the circumferential direction between points 3 and 4 on the heat pipe.

A DC power was used to apply heat flux to the evaporator. The manufactured heat pipe is shown in Fig. 5 in the test of applying different powers to obtain the effective thermal conductivity. The procedure for applying input power involved several steps. Initially,

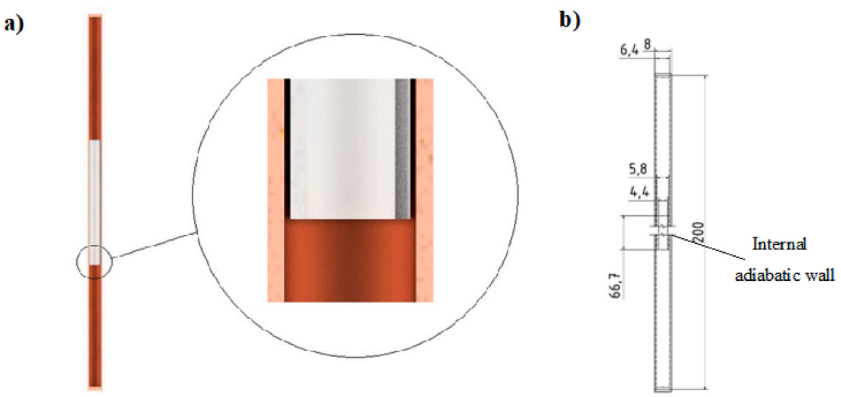

Fig. 2. Thermosiphon equipped with internal adiabatic wall a) heat pipe section b) heat pipe dimensions and insulation wall.

Table 1
Specifications of heat pipes for testing.

Sample	Pipe length (mm)	Fluid type	Type of heat pipe
2	200	DI water	Without wick
3	200	Acetone	Without wick
5	200	DI water	Without wick
6	200	DI water	Mesh wick
9	200	DI water	Without wick
10	100	DI water	Without wick
11	100	Acetone	Without wick
12	100	Water_ MWCNT 0.8%	Without wick
13	200	Water_ MWCNT 0.8%	Without wick
14	100	Water_ MWCNT 0.5%	Without wick
15	200	Water_ MWCNT 0.5%	Without wick
16	100	Water_ MWCNT 0.3%	Without wick
17	200	Water_ MWCNT 0.3%	Without wick
18	100	Water_ SiO_2 0.8%	Without wick
19	200	Water_ SiO_2 0.8%	Without wick
20	200	Acetone	Internal adiabatic wall
21	200	Water_ MWCNT 0.8%	Internal adiabatic wall
22	200	Water_ MWCNT 0.5%	Internal adiabatic wall
23	200	Water_ MWCNT 0.3%	Internal adiabatic wall
24	200	Water_ SiO_2 0.8%	Internal adiabatic wall
crs	200	DI water	Mesh wick
rod	100–200	–	Without wick

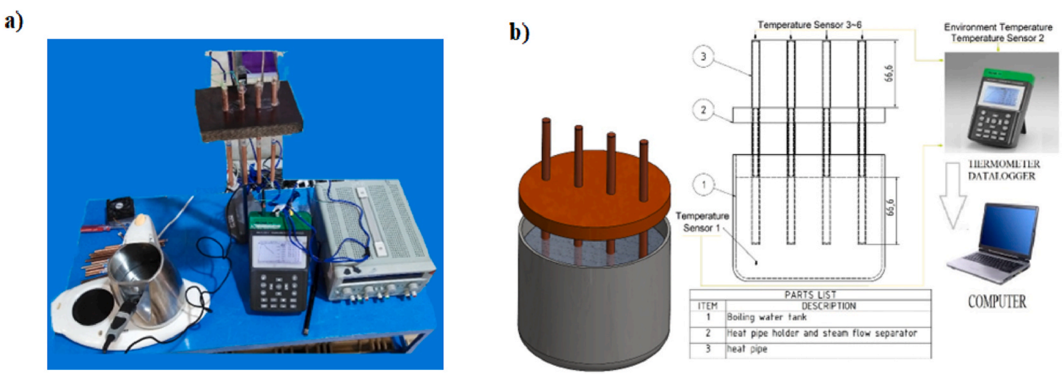

Fig. 3. Startup speed tests a) test setup b) setup of the laboratory and the location of the temperature sensors.

the appropriate length of the wire for the desired component was determined to encircle the heat pipe. Subsequently, the resistance value of the wire was measured using an ohmmeter. Finally, a power supply capable of adjusting the voltage was employed to achieve the intended input power.

3. Results

In this paper, to study the different fluid effects and the presence of an internal adiabatic wall in the two-phase thermosiphon heat pipe on the thermal conductivity and the startup speed, the pipes were compared under the same conditions.

3.1. Heat pipe startup speed

Figs. 6 and 7 show the temperature changes over time in 20 s for 100 mm and 200 mm heat pipes, respectively. The obtained results are related to temperature changes in the condenser part after placing the heat pipe in boiling water. According to Fig. 6, sample 18 with working fluid containing Water-SiO_2 has been able to transfer more heat to the condenser part. Also, by comparing the heat pipe with DI water and acetone (samples 10 and 11), it can be apperceived that the heat pipe with DI water has reached a higher temperature due to the high thermal conductivity and the low specific heat capacity than water has compared to acetone.

Samples 2, 5, and 9 have a length of 200 mm and operate with DI water as the working fluid. With the difference that samples 2 and 5 are charged with an internal pressure of 10^{-5} mbar, but sample 9 is charged at ambient pressure. As it is clear in Fig. 7, the graphs related to heat pipes 2 and 5 are exactly matched and this shows the reproducibility of the method of producing heat pipes. On the other hand, sample 9 has a low startup speed compared to samples 2 and 5, which is due to the pressure difference during charging.

As a result of nucleate boiling in heat pipes, a vapor bubble connected to the pipe wall is formed which leads to the creation of thermal resistance between the thermosiphon's wall and the working fluid in the evaporator part. Therefore, to decrease the thermal

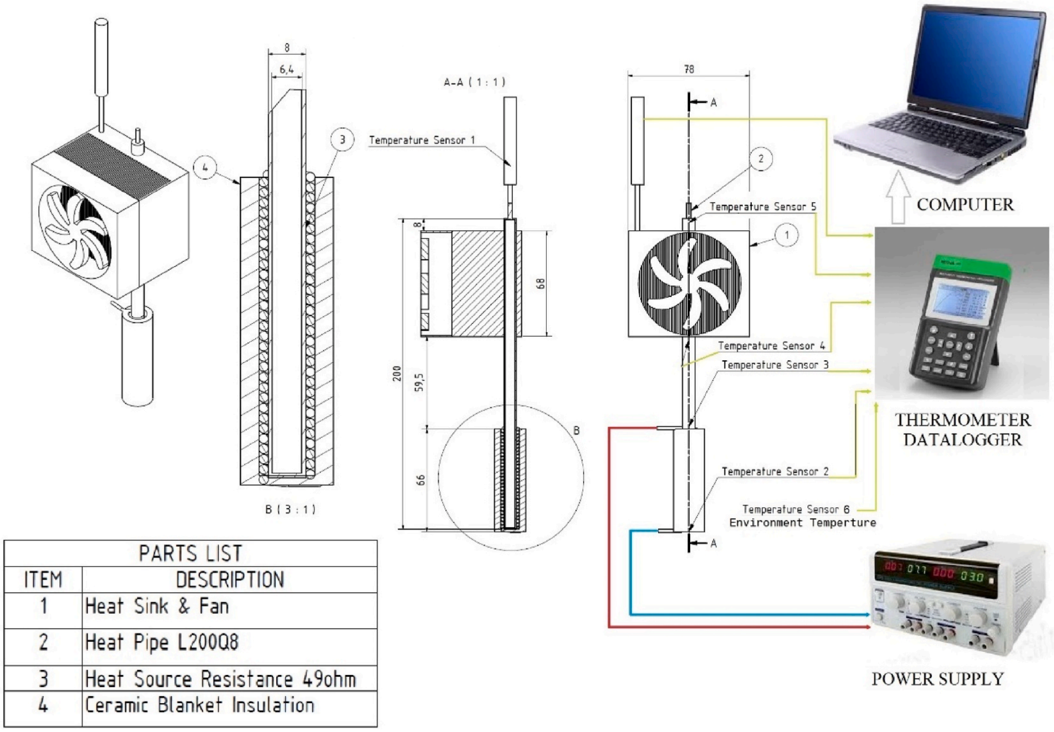

Fig. 4. Laboratory setup to calculate the *K* (schematic).

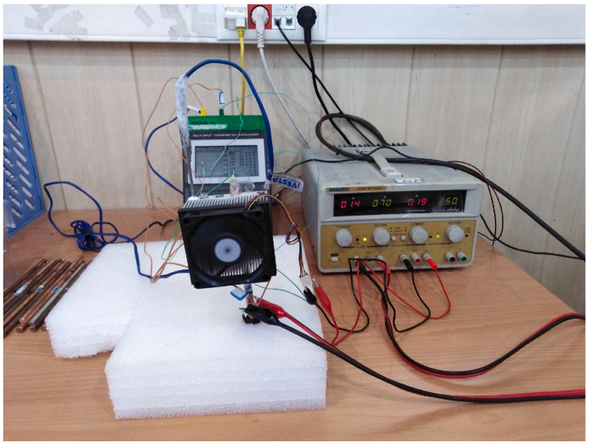

Fig. 5. Heat pipe in input power test.

resistance, a wick was utilized in the heat pipe. By comparing samples 2 and 6, the wick effect on the heat pipe's thermal behavior can be seen. As shown in this figure, utilizing the copper mesh wick has improved the heat pipe startup speed due to the capillary pump and returned fluid, and also reduced thermal resistance.

Fig. 8 shows the maximum temperature in 20 s in the condenser part for different heat pipes. Samples 3 and 20 have both lengths of 200 mm and the acetone as a working fluid, with the difference that sample 20 is made with an internal adiabatic wall. As it is clear in Fig. 8, the presence of an internal adiabatic wall led to an increase in temperature in the heat pipe condenser. By comparing the maximum temperature in heat pipes with Water_ MWCNT in the state with and without an adiabatic internal wall, it can be concluded that the use of an internal wall led to a decrease in temperature in these pipes.

3.2. Effective thermal conductivity

To check the stability of heat pipes after applying different input power in the evaporator part, the time that the heat pipe spends after applying power until its temperature changes in the evaporator part is less than 1 °C in 100 s which was measured. To test the heat

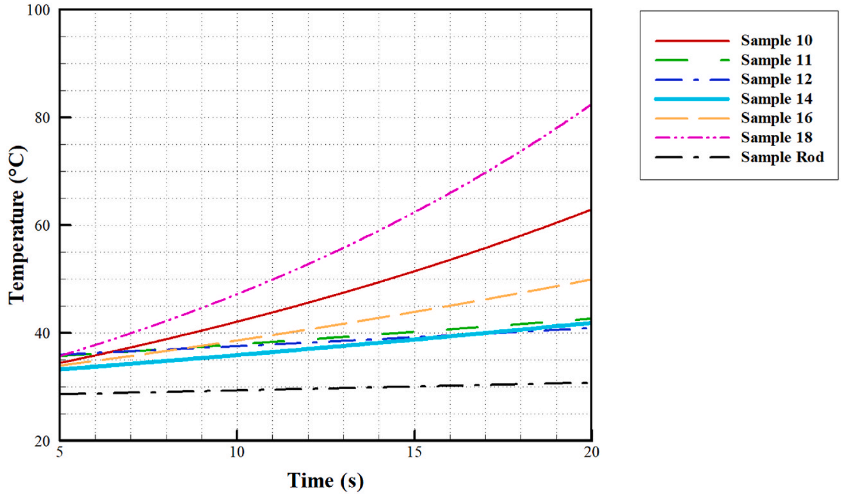

Fig. 6. The speed of startup of heat pipes (100 mm in length).

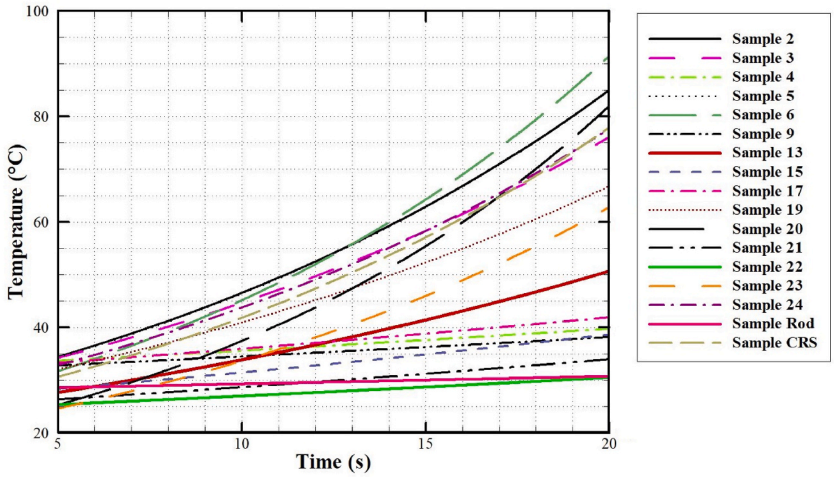

Fig. 7. The speed of startup heat pipes with a length of 200 mm.

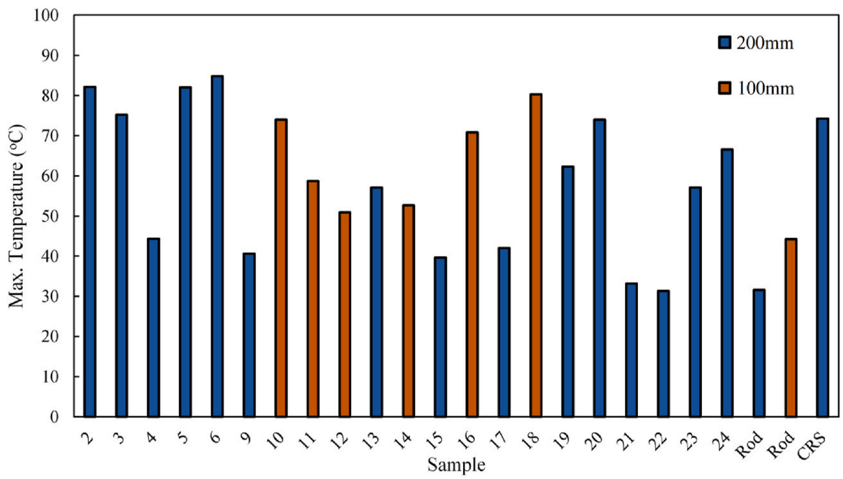

Fig. 8. Maximum temperature in the condenser part of different heat pipes.

pipe efficiency, the temperature of 5 different points of the pipe was measured at various times after applying the input power. Fig. 9 shows the comparison of the performance of the thermosiphon (sample 2) and the heat pipe with a wick (sample 6) in different input powers. At each stage, after achieving temperature stability in the evaporator part by applying more power, the temperature values were recorded for time. As can be seen in Fig. 9, temperature stability in the heat pipe with the wick has been obtained at lower times, which is due to the improvement of the returned fluid operation.

The performance comparison of heat pipe with acetone working fluid with and without an internal adiabatic wall in different powers is depicted in Fig. 10. As it is clear in the figure, the use of the internal adiabatic wall has increased the heat pipe's temperature at the end of the condenser part (point 5) at different powers. This increase in temperature shows that the use of an internal adiabatic wall led to a reduction in the pipe's thermal resistance. Also, using the internal adiabatic wall (sample 20) caused a decrease in the pipe surface's temperature in the evaporator part (point 2). This phenomenon shows that the use of the internal adiabatic wall increases the heat exchange between the fluid and the pipe wall.

One of the main goals of this paper was to peruse the effect of MWCNT with different mass fractions in water base fluid in heat pipes. Fig. 11 shows the trend of temperature changes versus time at different input powers with nanofluid containing water and MWCNT with mass fractions of 0.3 and 0.5%. In the boiling process, the solid phase of nanofluids is separated from the liquid and vapor phases, and over a long time, especially when the heat pipes are not active, the nanofluid used becomes unstable and its solid phase settles. As can be seen in the figure, in sample 15, with increasing power, the temperature also increased at different times, but at 20 W, the temperature drops significantly. This indicates the nanofluid's stability because of the deposition of MWCNT particles prevents contact between the pipe wall and working fluid, this factor led to the enhancement in the pipe wall's temperature in the condenser part.

The thermal conductivity of a material is constant at a certain temperature. However, by using heat pipes, the effective thermal conductivity of the pipe can be increased many times. The *K* of the examined heat pipes with a length of 200 mm is depicted in Fig. 12. By using Water_ MWCNT with a mass fraction of 0.3% and an internal adiabatic wall (sample 23), the effective thermal conductivity has increased about 350% compared to the copper rod at a power of 20 W. By comparing samples 2 and 6, it can be concluded that the presence of a wick has caused an enhancement in the thermal conductivity only in 20 W. Because of the increase in heat flux, vapor bubbles are produced on the evaporator's wall and they grow with the increase in temperature. The increase of bubbles near the wall prevents contact between the fluid and the pipe wall, so the use of a wick can reduce the thermal resistance and boiling limitation. By comparing the coefficient of thermal conductivity of samples 3 and 20, it can be seen that the use of the internal adiabatic wall brought about a decrease in heat loss and an enhancement in the thermosiphon's thermal conductivity coefficient. The working fluid is responsible for the main part of receiving, transferring and dissipating heat. In fact, as the main mediator of heat transfer, it plays a significant role in the heat pipe's efficiency. Although the use of SiO_2 particles enhances the working fluid's thermal conductivity, due to the settling of solid particles in the evaporator, leads to the instability of the heat pipe and the loss of thermosiphon performance. As seen in Fig. 12, the heat pipe with Water-SiO_2 nanofluid (sample 19) has a lower thermal conductivity than DI water (sample 2). In general, to use nanofluids as the working fluid in heat pipes, in addition to the high thermal conductivity, things such as nanoparticle mass fraction, nanofluid latent heat, surface tension, thermal stability, pressure and vapor viscosity should also be considered.

As already mentioned, this study's objective was to enhance heat pipes' thermal conductivity by exploring variable and configuration modifications. Additionally, it introduced a unique approach by incorporating an internal adiabatic wall. Furthermore, the research has analyzed the effects of heat pipe dimensions and working fluid on their overall performance. On the other side, various subjects, including fundamental research, design optimization, performance analysis, and practical implementations, are covered in published papers on heat pipes. However, the original use of an internal adiabatic wall and the dual emphasis on variable and configuration adjustments make this study stand out. By examining the influence of heat pipe dimensions and working fluid, the study

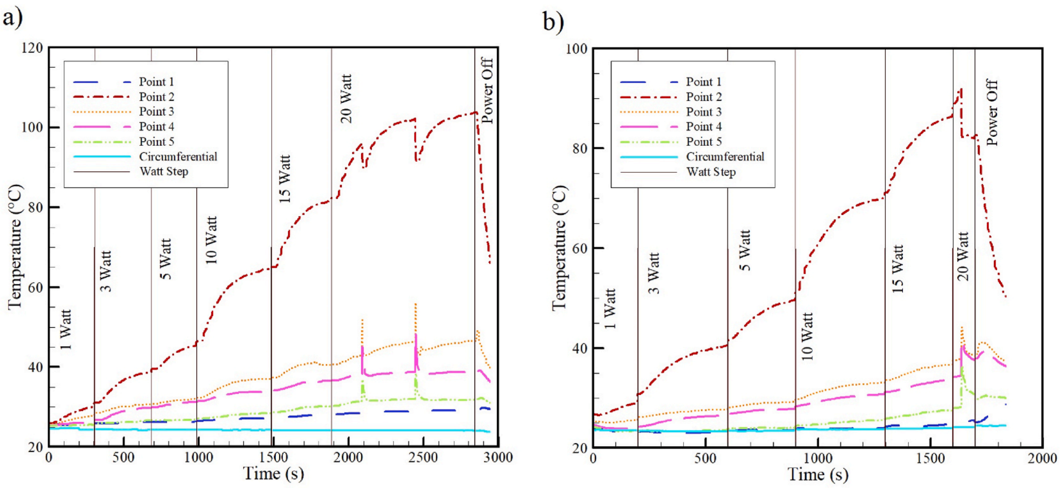

Fig. 9. Performance of heat pipes by applying different input power a) Sample 2 b) Sample 6.

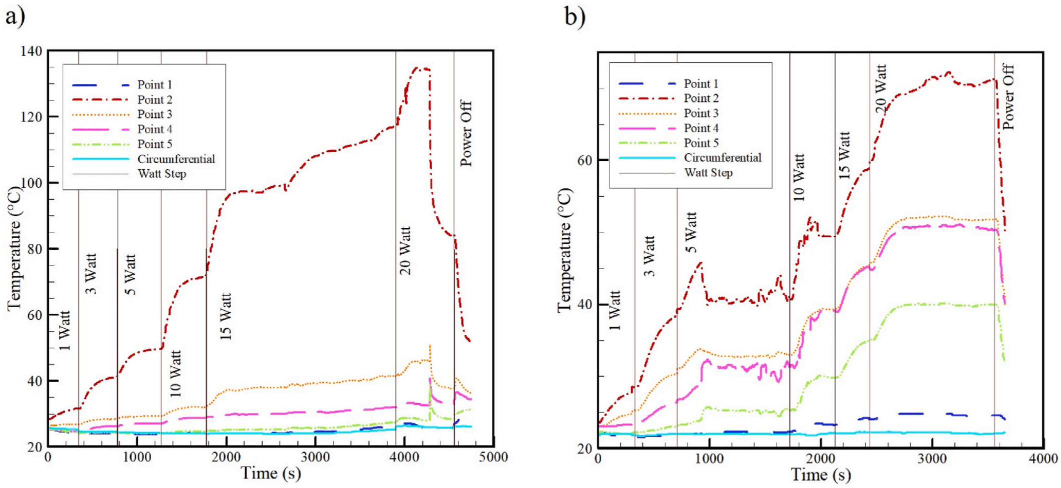

Fig. 10. Performance of heat pipes by applying different input power a) Sample 3 b) Sample 20.

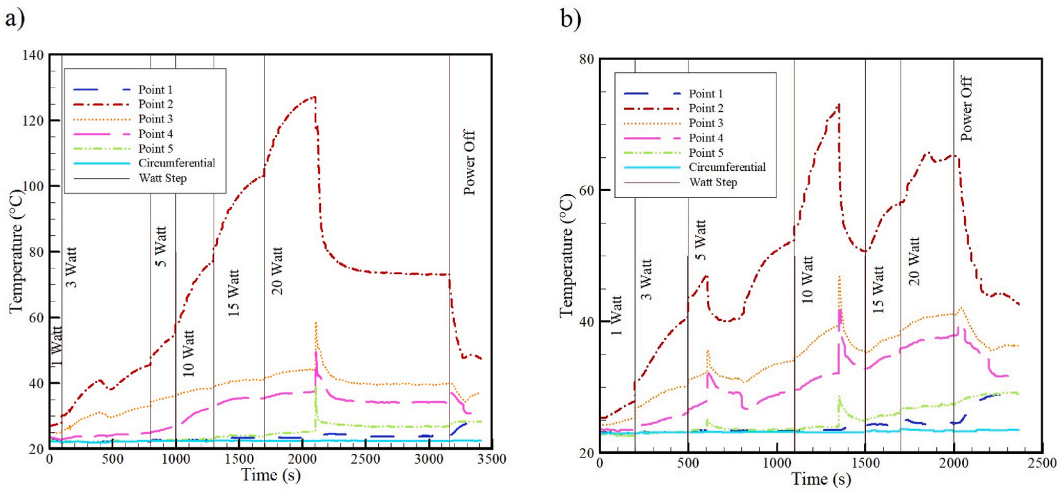

Fig. 11. Performance of heat pipes by applying different input power a) Sample 15 b) Sample 13.

offers valuable insights that can contribute to further advancements in the field.

4. Conclusion

In this paper, the effect of the working fluid, internal adiabatic wall, wick and pipe length on the startup speed, thermal stability and heat pipe's effective thermal conductivity were investigated. Some of the results of this research are as follows:

- Increasing the length of the pipe and using the wick increased the startup speed.
- Using an internal adiabatic wall in a pipe whose working fluid was acetone, water along with nanoparticles of SiO_2 and MWCNT with a mass fraction of 0.3% increased the startup speed of the heat pipe.
- The use of a copper mesh screen in the heat pipe had a significant effect in reducing the thermal resistance and caused a capillary pump in the pipe.
- Due to the reduction of heat loss, using the internal adiabatic wall in the heat pipe with nanofluid containing Water-MWCNT led to an enhancement in K to 1961 W/m ^{o}C.
- Increasing the mass fraction of nanofluid didn't always have a positive effect on the heat pipe performance, and due to the settling of the solid phase of the working fluid in the evaporator, the mass fraction and applied power are significantly important in the heat pipe's stability.

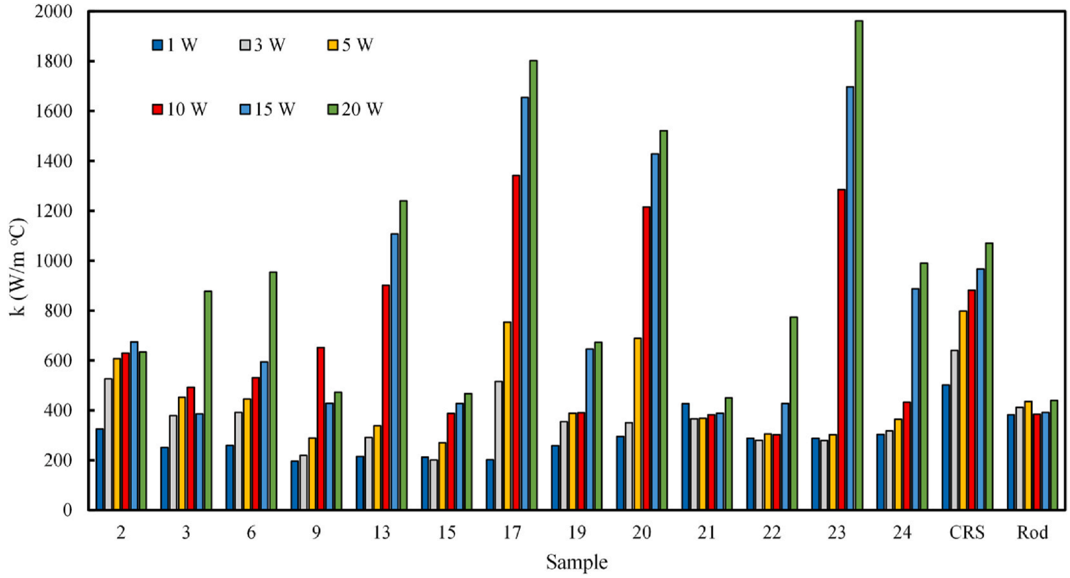

Fig. 12. Effective thermal conductivity in different input powers.

Author statement

- The corresponding author is responsible for ensuring that the descriptions are accurate and agreed by all authors.
- The role(s) of all authors are listed.
- Authors have contributed in multiple roles.

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Revision: Gongxing Yan, Dheyaa J. Jasim, Ahmed Salah Al-Shati.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgment

This work was supported by Sichuan Province Luzhou city of Science and technology planning project (2022-GYF-16), Scientific research and innovation team construction project of Luzhou vocational and Technical College (2021YJTD7).

References

[1] Z. Gao, S. Hong, C. Dang, An experimental investigation of subcooled pool boiling on downward-facing surfaces with microchannels, Appl. Therm. Eng. 226 (2023), 120283.
[2] S. Song, D. Chong, Q. Zhao, W. Chen, J. Yan, Numerical investigation of the condensation oscillation mechanism of submerged steam jet with high mass flux, Chem. Eng. Sci. 270 (2023), 118516.
[3] F. Liu, Z. Sun, H. Bian, M. Ding, X. Meng, Identification and classification of the flow pattern of hydrogen-air-steam mixture gas under steam condensation, Int. J. Therm. Sci. 183 (2023), 107854.
[4] G.P. Peterson, An Introduction to heat Pipes. Modeling, Testing, and Applications, Wiley Series in Thermal Management of Microelectronic and Electronic Systems, 1994.
[5] P. Dunn, D. Reay, Heat Pipes, Fourt Edition, Pergamon, 1994, pp. 172–173.
[6] M. Shafahi, V. Bianco, K. Vafai, O. Manca, An investigation of the thermal performance of cylindrical heat pipes using nanofluids, Int. J. Heat Mass Tran. 53 (1–3) (2010) 376–383.
[7] D. Mishra, T. Saravanan, G. Khanra, S. Girikumar, S. Sharma, K. Sreekumar, et al., Studies on the processing of nickel base porous wicks for capillary pumped loop for thermal management of spacecrafts, Adv. Powder Technol. 21 (6) (2010) 658–662.

[8] L-l Jiang, T. Yong, Z. Wei, L-z Jiang, X. Tan, L. Yan, et al., Design and fabrication of sintered wick for miniature cylindrical heat pipe, Trans. Nonferrous Metals Soc. China 24 (1) (2014) 292–301.
[9] H. Wang, Y. Bao, S. Zhu, M. Liu, Z. Rao, Experimental research on heat transfer performance of CO2 low temperature heat pipe, Int. J. Heat Mass Tran. 170 (2021), 120987.
[10] J.A. Weibel, S.V. Garimella, M.T. North, Characterization of evaporation and boiling from sintered powder wicks fed by capillary action, Int. J. Heat Mass Tran. 53 (19–20) (2010) 4204–4215.
[11] Y. Zhao, W. Li, H. Diao, Y. Wang, M. Ge, Experimental research of solar thermoelectric generator based on flat heat pipe, Energy Rep. 8 (2022) 245–250.
[12] C. Tsai, H. Chien, P. Ding, B. Chan, T.Y. Luh, P. Chen, Effect of structural character of gold nanoparticles in nanofluid on heat pipe thermal performance, Mater. Lett. 58 (9) (2004) 1461–1465.
[13] C. Liu, Y. Chen, D. Feng, H. Zhang, J. Miao, Y. Feng, et al., Experimental study on temperature uniformity and heat transfer performance of nitrogen loop heat pipe with large area and multi-heat source, Appl. Therm. Eng. 210 (2022), 118344.
[14] C. Smoot, H. Ma, Experimental investigation of a three-layer oscillating heat pipe, J. Heat Tran. 136 (5) (2014).
[15] J. Seo, J.-Y. Lee, Length effect on entrainment limitation of vertical wickless heat pipe, Int. J. Heat Mass Tran. 101 (2016) 373–378.
[16] Heat transport characteristics in closed loop oscillating heat pipes, in: S. Wang, S. Nishio (Eds.), Heat Transfer Summer Conference, 2005.
[17] T.C. Werner, Y. Yan, D. Mullen, E. Halimic, Experimental analysis of a high temperature water heat pipe for thermal storage applications, Therm. Sci. Eng. Prog. 19 (2020), 100564.
[18] H. Ma, C. Wilson, B. Borgmeyer, K. Park, Q. Yu, S. Choi, et al., Effect of nanofluid on the heat transport capability in an oscillating heat pipe, Appl. Phys. Lett. 88 (14) (2006), 143116.
[19] A. Siricharoenpanich, S. Wiriyasart, A. Srichat, P. Naphon, Thermal management system of CPU cooling with a novel short heat pipe cooling system, Case Stud. Therm. Eng. 15 (2019), 100545.
[20] I. Khazaee, R. Hosseini, A. Kianifar, S.H. Noie, Experimental consideration and correlation of heat transfer of a two-phase closed thermosyphon due to the inclination angle, filling ratio, and aspect ratio, J. Enhanc. Heat Transf. 18 (1) (2011).
[21] V. Guichet, B. Delpech, N. Khordehgah, H. Jouhara, Experimental and theoretical investigation of the influence of heat transfer rate on the thermal performance of a multi-channel flat heat pipe, Energy 250 (2022), 123804.
[22] M.E.M. Sar, S. Nouei, M. Khoshnoudi, Effect of Aspect Ratio and Filling Ratio on Thermal Performance of an Inclined Two-phase Closed Thermosyphon, 2008.
[23] W. Srimuang, S. Rittidech, B. Bubphachot, Heat transfer characteristics of a vertical flat thermosyphon (VFT), J. Mech. Sci. Technol. 23 (9) (2009) 2548–2554.
[24] A. Nouri-Borujerdi, M. Layeghi, A numerical analysis of vapor flow in concentric annular heat pipes, J. Fluid Eng. 126 (3) (2004) 442–448.
[25] N.K. Gupta, A. Sharma, P.K.S. Rathore, S.K. Verma, Thermal performance optimization of heat pipe using nanofluid: response surface methodology, J. Braz. Soc. Mech. Sci. Eng. 42 (11) (2020) 1–16.
[26] K. Benne, K. Homan, Dynamics of a closed-loop thermosyphon incorporating thermal storage, Numer. Heat Tran., Part A: Applications 54 (3) (2008) 235–254.
[27] P. Nemec, A. Čaja, M. Malcho, Mathematical model for heat transfer limitations of heat pipe, Math. Comput. Model. 57 (1–2) (2013) 126–136.
[28] B. Fadhl, L.C. Wrobel, H. Jouhara, Numerical modelling of the temperature distribution in a two-phase closed thermosyphon, Appl. Therm. Eng. 60 (1–2) (2013) 122–131.
[29] Z.-Z. Luo, S. Cai, S. Hao, T.P. Bailey, Y. Luo, W. Luo, et al., Extraordinary role of Zn in enhancing thermoelectric performance of Ga-doped n-type PbTe, Energy Environ. Sci. 15 (1) (2022) 368–375.
[30] M. Yang, C. Li, L. Luo, R. Li, Y. Long, Predictive model of convective heat transfer coefficient in bone micro-grinding using nanofluid aerosol cooling, Int. Commun. Heat Mass Tran. 125 (2021), 105317.
[31] A. Boroomandpour, D. Toghraie, M. Hashemian, A comprehensive experimental investigation of thermal conductivity of a ternary hybrid nanofluid containing MWCNTs-titania-zinc oxide/water-ethylene glycol (80: 20) as well as, Synth. Met. 268 (2020), 116501.
[32] S.R. Yan, D. Toghraie, L.A. Abdulkareem, A. Alizadeh, P. Barnoon, M. Afrand, The rheological behavior of MWCNTs–ZnO/Water–Ethylene glycol hybrid non-Newtonian nanofluid by using of an experimental investigation, J. Mater. Res. Technol. 9 (4) (2020) 8401–8406.
[33] Y. Zhu, M. Zamani, G. Xu, D. Toghraie, M. Hashemian, A. Alizadeh, A comprehensive experimental investigation of dynamic viscosity of MWCNT-WO3/water-ethylene glycol antifreeze hybrid nanofluid, J. Mol. Liq. 333 (2021), 115986.