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Research Article

An experimental investigation to study the performance characteristics of heat pipe using aqueous hybrid nanofluids

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ABSTRACT

The steady-state performance characteristics of a mesh-wick heat pipe were investigated experimentally across a heat load range of 25W-100W incorporating DI water, Al_2O_3 nanofluids, and Al_2O_3+GO hybrid nanofluids respectively. All the nano-suspensions were prepared following the two-step preparation method. Out of all the prepared Al_2O_3 nanofluids, 1.0 vol.% Al_2O_3 nanofluid exhibited the highest reduction in adiabatic vapor temperature. The hybrid combination of 75% Al_2O_3 +25% GO nanofluid in the heat pipe resulted in a maximum decrement of about 21.4%, and 59.5% in the average evaporator temperature, and thermal resistance respectively while offering maximum thermal efficiency enhancement of about 31.4% relative to the base fluid. The 75% Al_2O_3+25% GO hybrid nanofluid in the heat pipe offered the least thermal resistance at a gravity-assisted inclination of 60°. The current study contemplates the most favourable hybrid combination of Al_2O_3 and GO nanoparticles for its incorporation in the heat pipe and tries to identify the underlying reasons behind the performance characteristics achieved using hybrid nanofluids and finally projects the future research scope.

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INTRODUCTION

Heat pipes are heat exchangers that use the phase change of a fluid to transmit thermal energy from a source to a sink with negligible heat losses. Heat pipes are considered passive devices since it does not require any external mechanical power input [1]. Heat pipes are one of the extensively used thermal management devices used in a wide range of applications ranging from spacecraft and high computational devices to miniaturized electronic devices [2]. Researchers have been trying to augment the operation of the heat pipe to ensure competent thermal management of sophisticated devices. The performance of heat pipes has been reported to be influenced by a wide range of parameters ranging from working fluid type [3,4], the filling ratio [5,6], inclination angle [7,8], etc.

Nanofluids are revolutionary dual-phase fluids containing nano-sized particles suspended in base fluids such as water, alcohol, and other traditional fluids [9]. Previously, the researchers investigated a variety of nanoparticles and reported

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significant improvements in the thermal properties of conventional working fluids when mixed with the nanoparticles. Several studies have tried to investigate the reasons behind such noteworthy heat transfer performance of nanofluids [10]. The potential mechanisms responsible for the remarkable performance of nanofluids have been reported to be thermal conductivity augmentation, with a highly randomized motion of nanoparticles and the effect of interfacial layers being the primary causes [11]. The heat transfer and flow characteristics of nanofluids are strongly influenced by several factors like nanomaterial properties, particle shape, and size [12].

Owing to the efficient heat transfer ability of nanofluids, researchers have tried to test their performance in heat pipes [13–17]. Ghanbarpour et al. [18] studied the response of copper heat pipes utilizing 5% and 10% Al_2O_3 nanofluids. Due to the Brownian motion of nanoparticles, changes in wettability and capillary force in 5% Al_2O_3 nanofluid, and high viscosity, nanoparticle agglomeration in 10% Al_2O_3 nanofluid, the performance of the former nanosuspension was reported to be better than that of latter. Gürü et al. [19] investigated the effect of using DI water and bentonite nanofluid in a heat pipe. Thermal resistance was reduced by 39% at 200W heat load using bentonite nanofluid instead of DI water, due to a decrease in vapor bubble growth caused by nanoparticle addition.

Hassan et al. [20] investigated the response of a brass heat pipe using alumina nanofluids. Because of particle interactions at lower temperatures, the effective viscosity of 3% alumina nanofluid was found to be more temperature-dependent. At all cooling flow rates, the 3% alumina nanofluid-based heat pipe had the lowest wall temperatures. Aydın et al. [21] studied the effect of bauxite nanofluid on thermosyphon response. The nanoparticles added to distilled water lowered the boiling temperature in all cases and incorporating the 2% bauxite nanofluid yielded the best heat transfer characteristics.

Mono-nanofluids despite offering attractive thermophysical properties have been noticed to be incompetent in certain applications due to ever-increasing performance standards. To overcome the drawbacks of mono-nanofluids, another special class of heat transfer fluids has been developed called the hybrid nanofluids. Hybrid nanofluids are a type of nanosuspensions that have recently gained popularity owing to their superior thermal and flow properties compared to conventional nanosuspensions. Hybrid nanofluids are colloidal nano-suspensions containing a variety of dissimilar nanoparticle types that are stabilized simultaneously in the base fluid.

Swapnil et al. [22] investigated the steady-state response of a heat pipe utilizing aqueous hybrid nanofluids of Al_2O_3 and BN. In their study, they proposed a 2% Al_2O_3+BN hybrid nanofluid to improve heat pipe performance. Zufar et al. [23] used hybrid nanofluids to investigate heat pipe performance both experimentally and numerically. The thermal conductivity and viscosity of the working fluid were reported to affect heat pipe performance. MgO+MWCNT hybrid nanofluids were proposed by Henein et al. [24] as a promising solution for improving the response of heat pipe-based solar collectors. Increasing the concentration of MgO+MWCNT hybrid nanofluids was reported to result in increased exergy and energy efficiency. Vidhya et al. [25] prepared MgO and ZnO nanoparticles following the co-precipitation and sol-gel procedure. They prepared nanofluids of prepared nanoparticles using ethylene glycol and water as base fluids. They discovered that nanofluid density and viscosity were temperature dependent and resulted in a substantial performance augmentation.

Wang et al. [26] investigated the response of heat pipes utilizing TiO_2 & Al_2O_3 mono, and hybrid nanosuspensions. The heat pipe performance improved with the use of nanosuspensions and got influenced by heat pipe inclination. Zhao et al. [27] studied the response of a flat evaporator-type loop heat pipe utilizing cupric oxide nanofluids. They found that the operational heat load range of the heat pipe improved from 290W to 310W attributed to the high thermal conductivity of cupric oxide nanofluids. Bumataria et al. [28] investigated the effect of working fluid type on a mesh wick heat pipe performance. The CuO+ZnO hybrid nanofluids were reported to improve heat exchange due to the smaller contact angle and artificial nanoparticle coating on the wick (that produced a porous wall structure).

Ramachandran et al. [29] studied the response of a heat pipe using Al_2O_3+CuO hybrid nanosuspensions. The development of a porous and thin nanoparticle coating on the wick improved its wettability increasing the evaporator section nucleation site count further resulting in augmented thermal energy transfer. Han et al. [30] investigated the response of grooved heat pipes utilizing aqueous Ag and Al_2O_3 nanofluids, as well as hybrid combinations of the two. The Ag and Al_2O_3 nanofluids, and their hybrid combinations demonstrated higher temperature drop ratios and operating temperatures in heat pipe compared to water attributed to nanoparticle agglomerates during boiling.

According to the literature review, only a handful of research on hybrid nanofluids has been reported. However, no study based on the investigation of the heat transfer performance of heat pipe incorporating aqueous Al_2O_3+GO hybrid nanofluids as a heat transfer fluid has been conveyed, indicating the distinctiveness of the current study. The combination of Al_2O_3 and GO nanoparticles suspended in DI water has the potential to provide appealing thermophysical properties at low manufacturing costs. The current research focuses on the creation of stable nano-suspensions of Al_2O_3 and GO nanoparticles, as well as the experimental investigation of the steady-state response of a capillary-driven heat pipe incorporating the prepared nano-suspensions and DI water.

MATERIALS AND METHODS

Preparation of Nanofluids

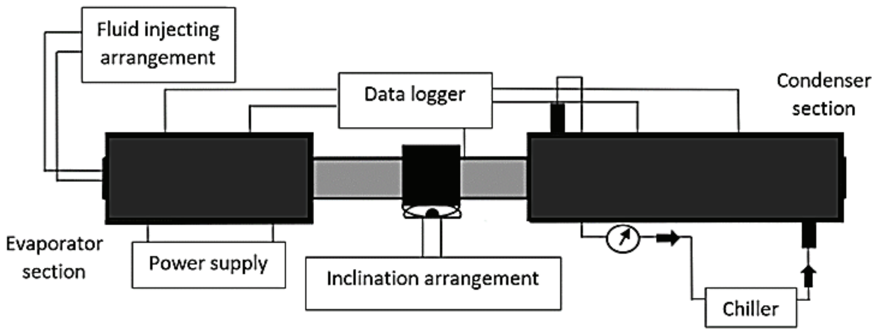
The Al_2O_3 and functionalized GO nanoparticles used in the current study to prepare the mono and hybrid nanofluids were purchased from Nano Research Lab, Jharkhand, India. The Al_2O_3 nanoparticles were of an average size of 30-50nm while the functionalized GO nanoparticles were of an average length of 450nm and thickness of 5nm respectively. The Al_2O_3 nanoparticles were spherical in shape while the GO nanoparticles were in the form of long flakes. All the nanosuspensions were prepared by following the two-step method that involves the homogeneous mixing of the nanoparticles within the base fluid followed by mechanical agitation. To impart stability to the nanofluids, the prepared nanofluids were mechanically agitated in an ultrasonic bath for 4 hours at a frequency of 20KHz.

Since the nanofluids pose a critical drawback of nanoparticle sedimentation due to agglomerate formation, so all the nanosuspensions were prepared by taking DI water as the base fluid mixed with Triton X-100 at a concentration of 0.5%. Triton X-100 was selected as a surfactant because it offers consistent performance even at higher temperatures.

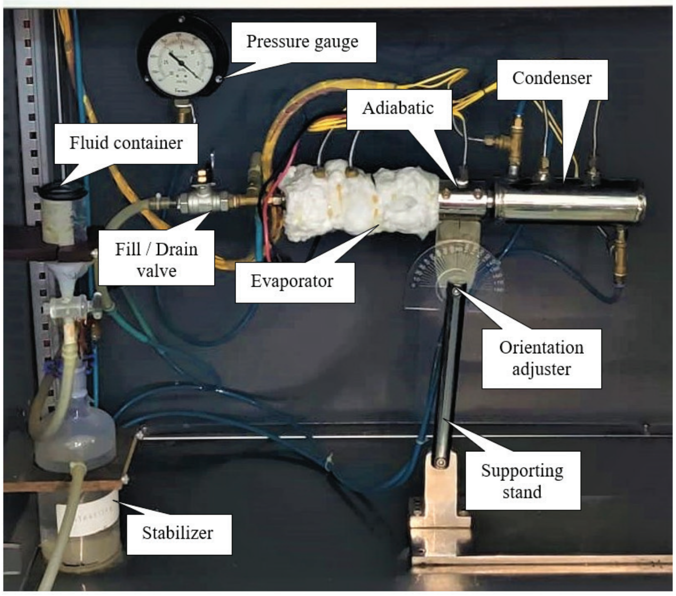
The stability of the prepared nanofluids was evaluated by carrying out a sedimentation visualization test. In it, all the prepared nanofluids were isolated from external disturbances for 2 weeks. It was observed that all the prepared nanofluids exhibited appreciable stability. Since such stability lifetime of the nanofluids for heat transfer applications is enough for thermal applications, it was considered for further investigation during the study. Table 1 summarizes the concentration of nanofluids prepared in the present work.

Table 1. Nanofluids prepared in the study

Nanosuspension	Volumetric Concentration	Nomenclature
100% Al_2O_3	0.50 %	MNF 1
100% Al_2O_3	0.75 %	MNF 2
100% Al_2O_3	1.00 %	MNF 3
100% Al_2O_3	1.25 %	MNF 4
25% Al_2O_3 + 75% GO	1 %	HNF 1
50% Al_2O_3 + 50% GO	1 %	HNF 2
75% Al_2O_3 + 25% GO	1 %	HNF 3



(a)



(b)

Figure 1. (a) Schematic, (b) actual photograph of the set-up.

Experimental Setup and Procedure

The present investigation was carried out on a mesh wick heat pipe. The schematic and actual photograph of the set-up is shown in Figures 1 (a), and (b) respectively. A 500W circumferential heater was used at the evaporator and a distilled water-based cooling jacket was employed at the condenser. The temperature of the coolant (distilled water) was maintained at 15 ^{o}C using a chiller unit. The adiabatic section of the heat pipe was insulated using glass wool. The heat pipe's wall temperature was measured using K-type thermocouples while the temperature of the cooling water was measured using T-type thermocouples.

The K-type thermocouples were placed on the heat pipe's interior & exterior to measure the inner and outer surface temperatures of the heat pipe. The scheme of thermocouple placement along the heat pipe length is illustrated in Figure 2. All the experiments in the present study were carried out by maintaining a vacuum pressure of 20 KPa employing a vacuum pump. To compare the influence of the prepared nanofluids, the heat pipe performance was also evaluated using DI water. The fluid fill ratio was taken to be 50% during the study. All the temperature measurements were made upon the attainment of a steady state in the heat pipe.

It was observed that the heat pipe when tested with DI water, it took about 35 minutes to attain a steady state. Eventually, it was decided to run every test for at least 35 minutes each to ensure that the heat pipe attained a steady state when tested with the other test fluids prepared in the present study. The technical specifications of the heat pipe are summarized in Table 2. The heat load from the heater was varied over a range of 25W to 100 W at the steps of 25W each to assess the heat pipe performance for low-wattage applications like electronics cooling.

The heat pipe thermal resistance (R) and efficiency (η) were evaluated by using the expressions given in equations 1 and 2 respectively [31]. Here, T_e and T_c are the temperatures of the evaporator, and condenser of the heat pipe respectively while Q_c and Q are the heat transfer across the condenser, and evaporator respectively.

Table 2. Heat pipe details

Parameter/Entity	Detail (Size (mm)/ Material/ Quantity/ Type)		
Container	Copper		
Outer radius	10		
Inner radius	8		
Evaporator length	50		
Adiabatic length	50		
Condenser length	75		
Wire mesh wick	**Material**	Stainless steel	
	Mesh layers	2 layers	
	Mesh/mm	2 mesh/mm	
	Wire radius	0.021 mm	
Thermocouples	**K-type**	Numbers	10
		Accuracy	±0.5°C
	T-type	Numbers	2
		Accuracy	±0.5°C

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

$$\eta = \frac{Q_c}{Q} * 100\ (\%) \quad (2)$$

Each experimental set was carried out five times to ensure the repeatability and reliability of the obtained test results. The average values of results were used for the final assessment and uncertainty analysis. Maximum uncertainties in thermal resistance and efficiency were evaluated to

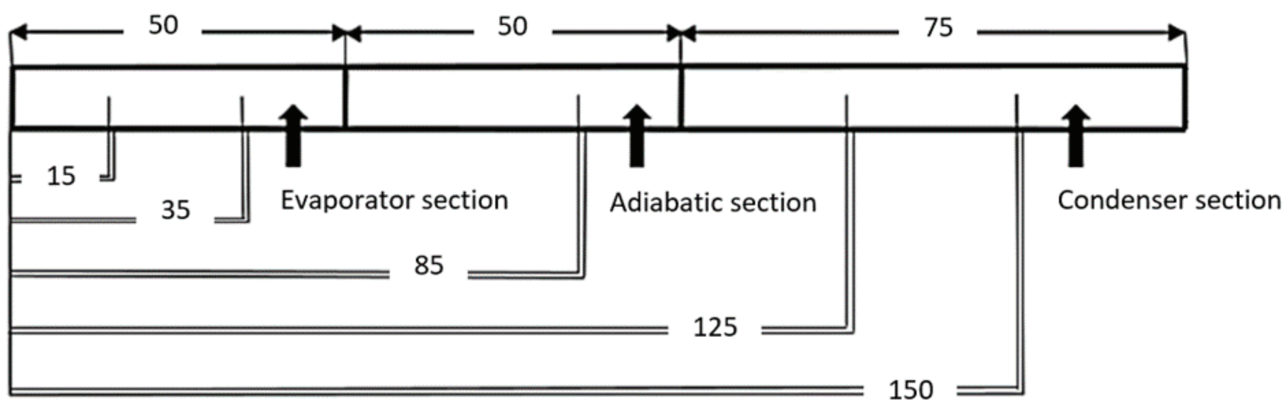


Figure 2. Thermocouple placement scheme.

be about 3.4% and 4% respectively following equations 3-5 [32].

$$\frac{\Delta q}{q} = \left[\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta L}{L}\right)^2\right]^{0.5} \quad (3)$$

$$\frac{\Delta R}{R} = \left[\left(\frac{\Delta q}{q}\right)^2 + \left(\frac{\Delta(\Delta T)}{\Delta T}\right)^2\right]^{0.5} \quad (4)$$

$$\frac{\Delta \eta}{\eta} = \left[\left(\frac{\Delta m}{m}\right)^2 + \left(\frac{\Delta c}{c}\right)^2 + \left(\frac{\Delta(\Delta T)}{\Delta T}\right)^2 + \left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2\right]^{0.5} \quad (5)$$

RESULTS AND DISCUSSION

The heat transfer performance of Al_2O_3 nanofluids (0.50 vol.% -1.25 vol.%) was studied by measuring the operational temperature of the heat pipe. Ideally, the operational temperature of a heat pipe is preferred to be low at a given set of operational conditions (like heat load, fluid fill ratio, orientation, etc.). In the present study, the operational temperature was selected as the temperature of the vapor at the adiabatic section termed adiabatic vapor temperature.

Figure 3 illustrates the variation of the operating temperature of the heat pipe filled with Al_2O_3 nanofluids with the heat load simultaneously contrasted with that filled with DI water. It was evident that the operating temperature varied with a variation in the heat load. This could be due to the variation in the heat flux available to the fluid at the evaporator. Another observation was made from the test results that the operating temperature also varied with a change in the fluid type utilized. The incorporation of the nanofluids as the working fluid instead of DI water resulted in reduced operating temperature. To exemplify, over the tested heat loads, the operating temperature attained using DI water was highest as compared to Al_2O_3 nanofluids. Such performance of DI water (relative to Al_2O_3 nanofluids) can be attributed to its poor thermophysical characteristics. The Al_2O_3 nanofluids of different concentrations exhibited different heat transfer characteristics within the heat pipe. Across the whole tested heat load range, the maximum operating temperature was attained using MNF 1 (0.5 vol.% Al_2O_3 nanofluid) while the least operating temperature was attained using MNF 3 (1.0 vol.% Al_2O_3 nanofluid) out of all the tested Al_2O_3 mono-nanofluids. Such variation in the operating temperature with the change in the nanofluid concentration can be attributed to a simultaneous change in the thermophysical properties.

The heat transfer response of the heat pipe improved with an increase in nanofluid concentration from 0.5 vol.% to 1.0 vol.%. However, when the heat pipe was tested with MNF 4 (1.25 vol.% Al_2O_3 nanofluid), the operating temperature was found to elevate relative to that attained using MNF 3 (1.0 vol.% Al_2O_3 nanofluid). So an optimum

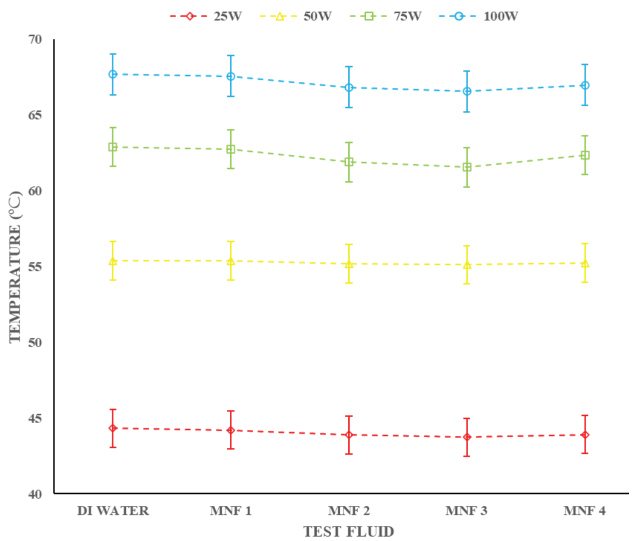


Figure 3. Variation of heat pipe operating temperature with heat load.

nanofluid concentration of 1.0 vol.% was found to exist at which the most appreciable performance was attained from the heat pipe attributed to enhancement in thermal conductivity and viscosity of nanofluid with an increase in concentration. Such increment in the thermal conductivity can be attributed to enhanced heat transfer area availability (due to solid metallic nanoparticles). With an increase in thermal conductivity, the heat transfer across the fluid enhances significantly. However, an increase in the nanofluid viscosity results in an adverse effect on the heat transfer performance of the working fluid due to its poor flow characteristics across the channel. At the concentration of 1.0 vol.%, the influence of the increment in thermal conductivity surpassed the increment in viscosity. This could also be the reason that MNF 4 performed relatively poorly as compared to MNF 3 since, at 1.25 vol% nanofluid concentration, the influence of increment in thermal conductivity got surpassed by the adverse effect of increment in viscosity. The performance of MNF 1 was found to be nearly similar to DI water due to negligible thermal conductivity augmentation at a low concentration of just 0.5 vol.%.

Since the optimum nanofluid concentration was found to be 1.0 vol.%, so the hybrid nanofluids of Al_2O_3 & GO nanoparticles were also made of a concentration of 1.0 vol.% each. Figure 4 (a-d) illustrates the wall temperature variation when tested with the hybrid nanofluids (HNF 1-3) at different heat loads on the heat pipe.

It is clear from the graph that there existed a temperature gradient across the length of the heat pipe for the whole tested heat load range such that the maximum temperatures were recorded at the evaporator while the least temperatures were recorded at the condenser. Such phenomena could be accredited to the distilled water flowing

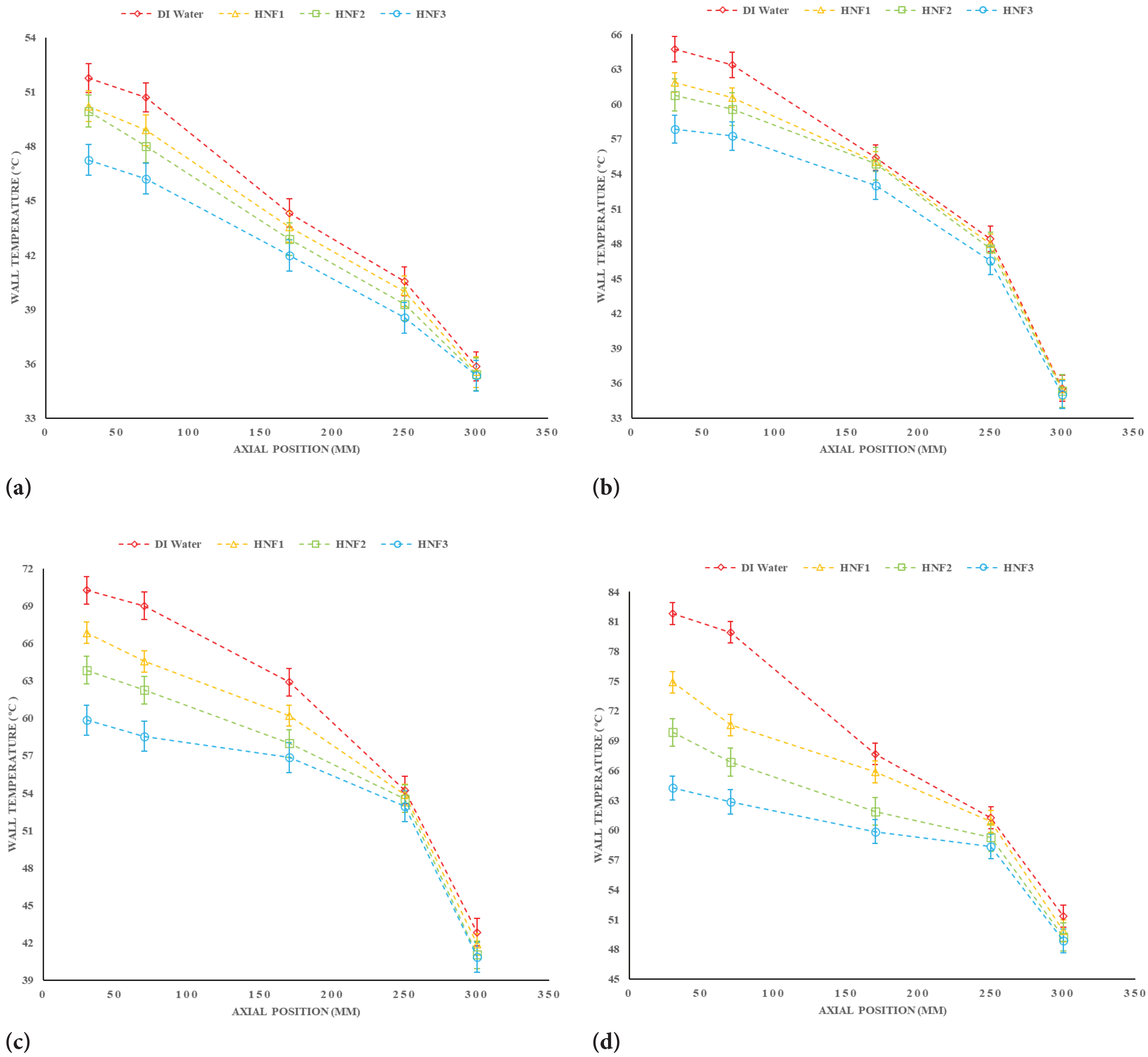


Figure 4. Variation of heat pipe wall temperature at heat loads (a) 25W, (b) 50W, (c) 75W and (d) 100W.

through the cooling jacket employed over the condenser section. The wall temperatures were found to elevate with increment in heat load, accredited to larger availability of heat flux to the working fluid at the evaporator.

Wall temperatures were observed to get reduced significantly using the hybrid nanofluids (HNF 1-3) relative to DI water. This can be accredited to the superior thermal conductivity of hybrid nanofluids (attained due to suspended GO and Al_2O_3 nanoparticles) relative to DI water. It was observed that the decrement attained in the wall temperatures (due to hybrid nanofluids) at lower heat loads was smaller relative to that attained at higher heat loads. To exemplify, the average evaporator temperature decrement attained using HNF 3 (relative to DI water) was found to be about 8.8% at 25W while the same was found to be about 21.4% at a heat load of 100W. Such enhancement in the temperature decrement attained with increasing heat loads could be attributed to the onset of nucleate boiling at the evaporator at higher heat loads.

The performance of other hybrid nanofluids (HNF 1-3) was also studied and it was found that a maximum temperature decrement of about 10.1%, 15.5%, and 21.4% was attained at the evaporator at an applied heat load of 100W using HNF 1, HNF 2 and HNF 3 respectively relative to DI water. Such differences in the respective performances of the prepared hybrid nanofluids (HNF 1-3) could be due to their differences in the proportions of GO and Al_2O_3 nanoparticles. To extensively study the performance of hybrid nanofluids, the evaluation of thermal resistance and efficiency of the heat pipe was also carried out.

Figure 5 illustrates the variation of thermal resistance at different heat loads when filled with hybrid nanofluids (HNF 1-3) and DI water. Irrespective of the type of working fluid incorporated, the thermal resistance of the heat pipe reduced with an increase in the applied heat load. To exemplify, the thermal resistance got reduced by 52.8% with a rise in the applied heat load from 25W to 100W using DI water, accredited to enhanced micro-convection currents at higher heat loads.

Thermal resistance was found to reduce significantly using hybrid nanofluids as compared to that attained using DI water. A maximum decrement of about 9.6%, 10.8%, and 24.9% was attained in the thermal resistance using HNF 1, HNF 2, and HNF 3 at a heat load of 25W respectively attributed to their advanced thermal conductivity. Out of all prepared hybrid nanofluids, HNF 3 offered the least thermal resistance at all the supplied thermal loads since a maximum thermal resistance decrement of about 21.9%, 24.0%, 41.7%, and 59.5% was attained at heat loads of 25W, 50W, 75W, and 100W respectively when tested with HNF 3. The superior performance of HNF 3 (relative to other hybrid nanofluids) can be attributed to the trade-off attained between thermal conductivity, and viscosity due to the GO & Al_2O_3 nanoparticles added in the proportions of 25% and 75% respectively. The relatively poor performance of HNF 2 and HNF 3 (despite having high thermal conductivities) can be attributed to the high concentration of GO nanoparticles in them (75% and 50% respectively) that resulted in increased viscosity. Such high viscosity due to suspended GO nanoparticles led to high flow resistance affecting the working fluid return to the evaporator through the wick during the heat pipe operation. This resulted in deprived accessibility of working fluid at the evaporator further leading to poor heat transfer.

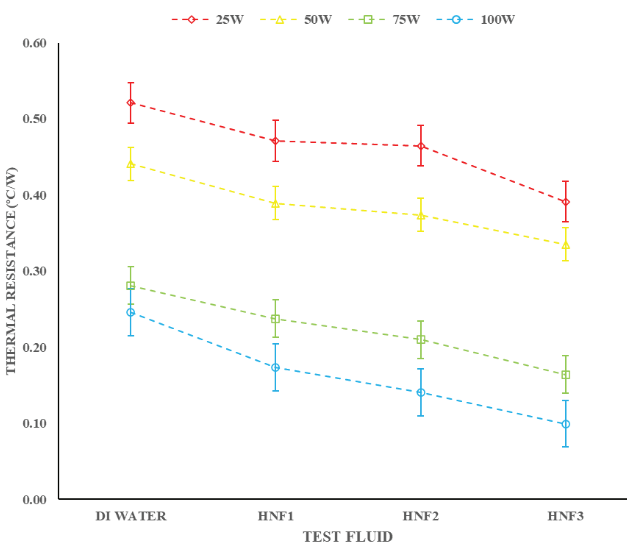


Figure 5. Variation of thermal resistance with heat load.

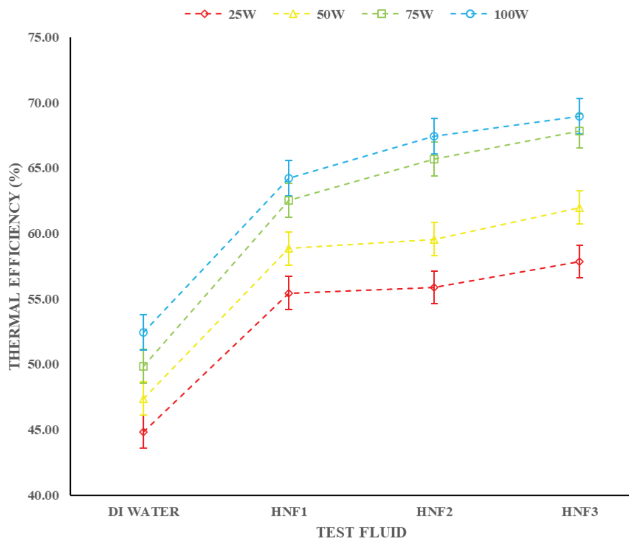


Figure 6. Variation of thermal efficiency of heat pipe with the applied heat load.

Figure 6 illustrates the variation of thermal efficiency with heat load when the heat pipe was filled with the prepared hybrid nanofluids and DI water. The thermal efficiency showcased an increasing trend when the heat load was raised from 25W to 100W accredited to the strengthening of micro-convective currents. A noteworthy improvement in thermal efficiency was attained using hybrid nanofluids. To exemplify, an increment of about 22.4%, 28.6%, and 31.4% was achieved in the thermal efficiency (relative to DI water) incorporating HNF 1, HNF 2, and HNF 3 respectively at a heat load of 100W. Such attractive performance of hybrid nanofluids can be attributed to their high thermal conductivity due to suspended nanoparticles. Another reason attributed for the same could be the highly randomized movement (Brownian motion) of the suspended GO and Al_2O_3 nanoparticles resulting in additional thermal transport across the base fluid further improving the thermal efficiency [33,34].

Out of all the prepared hybrid nanofluids, HNF 3 exhibited maximum thermal efficiency increments attributed to its suitable nanoparticle composition (proportion). Such nanoparticle composition of 75% Al_2O_3+25% GO in the base fluid (DI water) resulted in an optimized viscosity and thermal conductivity that eventually augmented the response of the heat pipe when used as test fluid.

Since the inclination angle also influences the heat transfer characteristics of heat pipes so it was further tried to investigate the inclination angle at which the most promising heat transfer can be achieved the using heat pipe. In accordance with it, HNF 3 was tested across the heat load range of 25W to 100W by varying the inclination angle over a range of 0° (horizontal position) to 90° (vertical position) at steps of 15° each. However, it was ensured during the

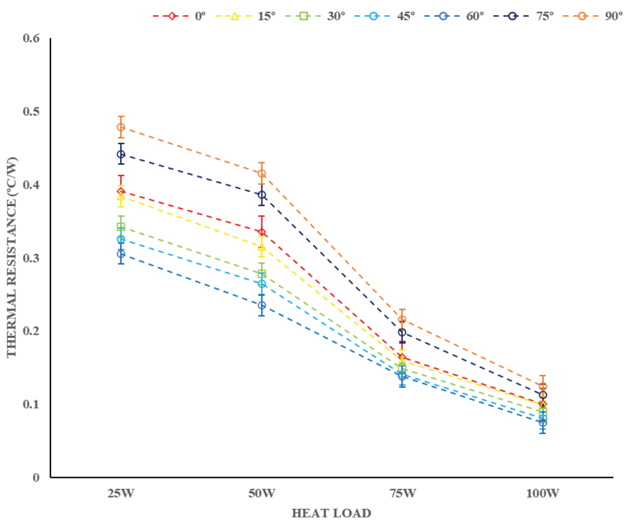


Figure 7. Variation of thermal resistance of heat pipe with heat load at different inclinations.

tests that the heat pipe was always oriented in gravity-assisted orientation for ensuring proper fluid flow across it.

Figure 7 illustrates the variation of the thermal resistance with heat load attained using HNF 3 at different inclination angles. Thermal resistance decreased with an increase in the inclination angle but only up to a certain limit. To exemplify, the thermal resistance at a heat load of 25W decreased by about 1.9%, 12.5%, 16.7%, and 21.9% when the inclination angle was kept at 15°, 30°, 45° and 60° respectively (relative to that at horizontal position). However, when the inclination was further kept at 75° and 90° then the thermal resistance increased by about 13% and 22.3% respectively (relative to that at the horizontal position).

Such variation in the heat pipe performance with a change in its inclination can be attributed to the corresponding influence on the fluid flow across the channel. To exemplify, the thermal resistance kept on decreasing till the inclination of 60° only. It could be due to the effect of gravitational force on the condensate return towards the evaporator (through the wick structure) such that sufficient working fluid was available at the evaporator to transfer the supplied thermal load.

The thermal resistance elevated at inclinations of 75° and 90° attributed to the inability of the vapor to reject absorbed heat energy across the condenser due to lower interaction time with the coolant flowing across the colling jacket. This establishes that the working fluid availability both at the evaporator and condenser section significantly influences the heat transfer across the heat pipe. So an optimum inclination angle of 60° was found in the present study at which the optimum performance was achieved from the heat pipe.

CONCLUSION

The presented work studied the heat pipe performance (steady-state) by incorporating Al_2O_3 nanofluids and Al_2O_3+GO hybrid nanofluids over a wide range of test conditions. The following are the major outcomes drawn from the study:

- Among the tested Al_2O_3 mono-nanofluids (0.5-1.25 vol.%), the 1.0 vol.% Al_2O_3 nanofluid (MNF 3) offered the least operating temperature within the heat pipe.
- The hybrid nanofluids offered a better response (relative to the mono-nanofluids) owed to their superior thermal conductivity and favourable viscosity.
- Incorporation of 75% Al_2O_3+25% GO hybrid nanofluid (HNF 3) resulted in a maximum decrement of about 21.4%, and 59.5% in the average evaporator temperature, and thermal resistance respectively at a heat load of 100W.
- The incorporation of 75% Al_2O_3+25% GO hybrid nanofluid (HNF 3) in the heat pipe resulted in a maximum enhancement of about 31.4% in efficiency at the heat load of 100W.
- The heat pipe inclination of 60° resulted in optimum heat pipe response when filled with 75% Al_2O_3+25% GO hybrid nanofluid.

FUTURE RESEARCH SCOPE

Some of the prospective studies that can be carried out on the nanofluid-based heat pipes are:

- The response of hybrid nanosuspension-based heat pipes can be evaluated for zero-gravity applications.
- The performance of hybrid nanoparticle-loaded phase change materials can be investigated.
- Techniques to improve the nanofluid stability should be investigated to allow the long-term application of heat pipes.
- Performance of hybrid nanoparticle coating on the heat pipe wick can be investigated.
- Viability of hybrid nanosuspension-based heat pipes can be evaluated from an economic perspective.

NOMENCLATURE

DI	Deionized
MNF	Mono-nanofluid
HNF	Hybrid nanofluid
R	Thermal resistance, °C/W
T	Temperature, °C
Q	Heat transfer, W

Greek symbols

η	Thermal efficiency

Subscripts

e	Evaporator
c	Condenser

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Gupta NK, Tiwari AK, Ghosh SK. Experimental study of thermal performance of nanofluid-filled and nanoparticles-coated mesh wick heat pipes. J Heat Transf 2018;140:1−7. [CrossRef]

[2] Jouhara H, Chauhan A, Nannou T, Almahmoud S, Delpech B, Wrobel LC. Heat pipe based systems - Advances and applications. Energy 2017;128:729−754. [CrossRef]

[3] Senthil R, Ratchagaraja D, Silambarasan R, Manikandan R. Contemplation of thermal characteristics by filling ratio of Al_2O_3 nanofluid in wire mesh heat pipe. Alexandria Eng J 2016;55:1063−1068. [CrossRef]

[4] Gupta NK, Tiwari AK, Ghosh SK. Experimental investigation of the thermal performance of mesh wick heat pipe. Heat Transf Res 2018; 49:1793−1811. [CrossRef]

[5] Zhou R, Fu S, Li H, Yuan D, Tang B, Zhou G. Experimental study on thermal performance of copper nanofluids in a miniature heat pipe fabricated by wire electrical discharge machining, Appl Therm Eng 2019;160:113989. [CrossRef]

[6] Gupta NK, Tiwari AK, Verma SK, Rathore PKS, Ghosh SK. A comparative study of thermal performance of a heat pipe using water and nanofluid, and a nanoparticle-coated wick heat pipe using water. Heat Transf Res 2019;50:1767−1779. [CrossRef]

[7] Das S, Giri A, Samanta S, Kanagaraj S. Role of graphene nanofluids on heat transfer enhancement in thermosyphon. J Sci Adv Mater Devices 2019;4:163−169. [CrossRef]

[8] Gupta NK, Sharma A, Rathore PKS, Verma SK. Thermal performance optimization of heat pipe using nanofluid: Response surface methodology. J Brazilian Soc Mech Sci Eng 2020;42:1−16. [CrossRef]

[9] Choi S. Nanofluid technology: Current status and future research. Korea-U.S. Technical Conference on Strategic Technologies, Vienna, VA (United States), 22-24 Oct 1998.

[10] Gupta NK, Verma SK, Rathore PKS, Sharma A. Effects of CuO/water nanofluid application on thermal performance of mesh wick heat pipe. Heat Transf Res 2020;51:837−850. [CrossRef]

[11] Chandrasekar M, Suresh S, Chandra Bose A. Experimental investigations and theoretical determination of thermal conductivity and viscosity of Al_2O_3/water nanofluid. Exp Therm Fluid Sci 2010;34:210−216. [CrossRef]

[12] Murshed SMS, Leong KC, Yang C. Enhanced thermal conductivity of TiO_2 - Water based nanofluids. Int J Therm Sci 2005;44:367−373. [CrossRef]

[13] Kumaresan G, Venkatachalapathy S, Godson L, Wongwises S. Comparative study on heat transfer characteristics of sintered and mesh wick heat pipes using CuO nano fluids. Int Commun Heat Mass Transf 2014;57:208−215. [CrossRef]

[14] Pandya NS, Desai AN, Kumar Tiwari A, Said Z. Influence of the geometrical parameters and particle concentration levels of hybrid nanofluid on the thermal performance of axial grooved heat pipe. Therm Sci Eng Prog 2021;21:100762. [CrossRef]

[15] Poplaski LM, Benn SP, Faghri A. Thermal performance of heat pipes using nanofluids. Int J Heat Mass Transf 2017;107:358−371. [CrossRef]

[16] Putra N, Septiadi WN, Rahman H, Irwansyah R. Thermal performance of screen mesh wick heat pipes with nanofluids. Exp Therm Fluid Sci 2012;40:10−17. [CrossRef]

[17] Gupta NK, Sharma A, Rathore PKS, Verma SK. Thermal performance optimization of heat pipe using nanofluid: Response surface methodology. J Brazilian Soc Mech Sci Eng 2020;42:590. [CrossRef]

[18] Ghanbarpour M, Nikkam N, Khodabandeh R, Toprak MS, Muhammed M. Thermal performance of screen mesh heat pipe with Al_2O_3 nanofluid. Exp Therm Fluid Sci 2015;66:213−220. [CrossRef]

[19] Gürü M, Sözen A, Karakaya U, Çiftçi E. Influences of bentonite-deionized water nanofluid utilization at different concentrations on heat pipe performance: An experimental study. Appl Therm Eng 2019;148:632−640. [CrossRef]

[20] Hassan MI, Singh PK, Tesfai W, Shatilla Y. An experimental study of heat pipe performance using nanofluids. Int J Green Energy 2015;12:225−229. [CrossRef]

[21] Yılmaz Aydın D, Çiftçi E, Gürü M, Sözen A. The impacts of nanoparticle concentration and surfactant type on thermal performance of a thermosyphon heat pipe working with bauxite nanofluid. Energy Sources A Recover Util Environ Eff 2021;43:1524−1548. [CrossRef]

[22] Swapnil K, Dhananjay P, Gaurav Z, Anand R, Kamble DP. Heat transfer enhancement of circular heat pipe with Al_2O_3 bn / water hybrid nanofluid. Int J Curr Eng Technol 2016;4:138–143.

[23] Zufar M, Gunnasegaran P, Kumar HM, Ng KC. Numerical and experimental investigations of hybrid nanofluids on pulsating heat pipe performance. Int J Heat Mass Transf 2020;146:118887. [CrossRef]

[24] Henein SM, Abdel-Rehim AA. The performance response of a heat pipe evacuated tube solar collector using MgO/MWCNT hybrid nanofluid as a working fluid. Case Stud Therm Eng 2022;33:101957. [CrossRef]

[25] Vidhya R, Balakrishnan T, Kumar BS. Investigation on thermophysical properties and heat transfer performance of heat pipe charged with binary mixture based ZnO-MgO hybrid nanofluids. Mater Today Proceed 2020;37:3423–3433. [CrossRef]

[26] Wang Z, Zhang H, Yin L, Yang D, Yang G, Akkurt N, et al. Experimental study on heat transfer properties of gravity heat pipes in single/hybrid nanofluids and inclination angles. Case Stud Therm Eng 2022;34:102064. [CrossRef]

[27] Zhao T, Ma Z, Zhang Z, Deng W, Long R, Liu W, et al. Experimental investigation of a loop heat pipe with a flat evaporator and cupric oxide nanofluids as working fluid. Energy Rep 2021;7:7693–7703. [CrossRef]

[28] Bumataria RK, Chavda NK, Nalbandh AH. Performance evaluation of the cylindrical shaped heat pipe utilizing water-based CuO and ZnO hybrid nanofluids. Energy Sources Part A Recover Util Environ Eff 2020. [Epub ahead of print]. doi: 10.1080/15567036.2020.1832628. [CrossRef]

[29] Ramachandran R, Ganesan K, Rajkumar MR, Asirvatham LG, Wongwises S. Comparative study of the effect of hybrid nanoparticle on the thermal performance of cylindrical screen mesh heat pipe. Int Commun Heat Mass Transf 2016;76:294–300. [CrossRef]

[30] Han WS, Rhi SH. Thermal characteristics of grooved heat pipe with hybrid nanofluids.Therm Sci 2011;15:195–206. [CrossRef]

[31] Pandey H, Agarwal S, Gupta NK. Temporal performance evaluation of CuO + GO hybrid nanofluids in heat pipe. Heat Transf Res 2022;53:75–96. [CrossRef]

[32] Moffat RJ. Describing the uncertainties in experimental results. Exp Therm Fluid Sci 1998;1:3–17. [CrossRef]

[33] Pandey H, Gupta NK. Analysis of heat transfer mechanisms in heat pipes: A review. J Enhanc Heat Transf 2022;29:61–96. [CrossRef]

[34] Gupta NK, Tiwari AK, Ghosh SK. Heat transfer mechanisms in heat pipes using nanofluids - A review. Exp Therm Fluid Sci 2018;90:84–100. [CrossRef]