



Experimental Study on Energy Efficiency Enhancement in Thermal Systems Using Pulsating Heat Pipes with Al₂O₃ Nanofluid for Sustainable Development



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ABSTRACT

The rapid development of electronic technologies has increased the demand for efficient and compact thermal management systems. Conventional cooling methods have already faced severe challenges imposed by the high heat generation rate and spatial constraints of modern devices. Pulsating heat pipes (PHPs) have been proposed as promising solutions owing to their passive working nature, compact structure, and excellent heat-transfer performance. However, the performance of the PHPs is strongly dependent on the properties of the working fluid and operation parameters. In this work, Al₂O₃/ethanol nanofluid is used to enhance the thermal efficiency of a copper PHP system. Experimental tests were conducted to examine the effects of filling ratio, inclination angle, and heat load on effective thermal conductivity and the overall heat transfer coefficient. The best thermal performance of Al₂O₃/ethanol nanofluid was achieved at a 50% filling ratio and 30° inclination, showing approximately a 15% increase in thermal conductivity compared with pure ethanol. Such an enhancement could be attributed to improved micro-convection and increased nanoparticle interactions in both the evaporator and condenser sections, which intensify heat transfer during phase transition. Moreover, the nanofluid showed superior thermal stability and repeatability over a 38-day testing period. This study demonstrates the capability of the Al₂O₃/ethanol nanofluid to overcome fluid-based limitations in PHPs and provides insights into optimizing system design. Future studies could scale up the experimental setup, test alternative combinations of nanofluids and base fluids, and integrate optimized PHP configurations into real platforms for electronic cooling.

Keywords: Pulsating heat pipe; Al₂O₃/ethanol nanofluid; Heat transfer; Thermal conductivity; Filling ratio; Electronic cooling.

1. INTRODUCTION

With the rapid increase in the operating frequency and heat generation of electronic devices, effective heat dissipation management has become a critical challenge in electronic component design. The trend towards miniaturization further increases the demand for efficient thermal management systems that can dissipate heat using compact devices. Efficient heat transfer systems are essential for maintaining the performance and reliability of high-power electronics such as CPUs, LEDs, power transistors, and RF amplifiers.

Since the reliability of electronic components is sensitive to operating temperature, it is crucial to optimize cooling solutions that achieve high heat removal rates. Over the past decade, numerous studies have focused on improving thermal management using various types of heat pipes, materials, working fluids,

filling ratios, and operating conditions. Recent research has particularly emphasized the use of nanofluids, fluids containing suspended nanoparticles, due to their superior heat transfer properties. This body of work reviews developments in nanofluid-based heat pipe technologies, covering preparation methods, characterization techniques, and performance influencing factors such as nanoparticle size, shape, concentration, and heat load.

Among the different heat pipe configurations, cylindrical, flat, loop, rotating, and thermosyphon, the pulsating heat pipe (PHP) stands out as an effective and simple passive cooling device. The PHP consists of a capillary tube arranged in multiple turns and partially filled with a working fluid. When a temperature difference between the evaporation and condensation sections exceeds a threshold, spontaneous oscillations of liquid plugs and vapor bubbles occur inside the tube. This oscillatory motion enhances heat transfer not only through the latent heat of vaporization but also by the

sweeping action of the moving fluid across hot and cold surfaces. Due to this mechanism, PHPs provide higher thermal performance, simpler construction, and better reliability compared to traditional heat pipes.

The working fluid inside the heat pipes plays a vital role. Various fluids, including water, ethanol, and ethylene glycol, have been used traditionally. The introduction of nanofluid-based fluids with uniformly dispersed nanoparticles like aluminum oxide (Al_2O_3), copper oxide (CuO), and other metal oxides has demonstrated significant improvement in thermal conductivity and heat transfer characteristics. Nanoparticles vary in shape and size and are suspended in traditional fluids to enhance thermal performance.

PHPs with nanofluid have promising applications in cooling electronic components, automotive radiators, satellite equipment, air conditioning systems, and other areas where efficient thermal management is essential within the temperature range of 20–60 °C.

During the last decade, many works in the literature have successfully shown that the addition of nanoparticles to conventional working fluids significantly increases heat pipe performance. For example, there is a noticeable absence of systematic comparisons between base fluids and ZnO–ethanol nanofluids across varying inclination angles and filling ratios in PHP systems (Savalia *et al.* 2025). Existing studies on hybrid wick structures improve heat-pipe performance, but gaps remain regarding their behavior with different working fluids and under varied operating conditions (Chavhan *et al.* 2024). The existing studies predominantly focus on fill ratio and inclination effects on conventional gravity heat pipes, with limited investigation into nanofluid-based pulsating heat pipes incorporating aluminum oxide nanoparticles for enhanced thermal performance (Chen *et al.* 2025). The effects of internal diameter on pulsating heat pipe start-up and stable operation have been experimentally visualized. There remains limited research integrating nanofluids such as aluminum oxide-ethanol to explore how nanoparticle addition alters these phenomena and overall thermal performance (Cheng *et al.* 2025). (Noie *et al.* 2009) studied the enhancement of heat transfer using Al_2O_3 /water nanofluid in a two-phase closed thermosyphon with a 1000 mm copper pipe. They showed an efficiency increase of up to 14.7% by adding 1–3 vol.% Al_2O_3 nanoparticles over pure water. In support, studies by (Kamyar *et al.* 2013) using Al_2O_3 and titanium silicate (TiSiO_4) nanofluid prepared by ultrasonic homogenization proved that a filling ratio of 50% and nanoparticle concentration of 1 wt.% attained the highest heat flux and heat transfer effectiveness. In addition, (Liu *et al.* 2011) reported improved thermal

performance and system efficiency of an open thermosyphon using CuO/water nanofluid in solar air collector applications. ZnO and Al_2O_3 nanoparticles are gaining attention due to their very good thermal conductivity and stability. It has been shown in various studies that Al_2O_3 -based nanofluid can greatly reduce thermal resistance in pulsating heat pipes. (Bumataria and Chavda, 2021) showed that in a closed-loop PHP, a higher concentration of Al_2O_3 nanofluid effectively reduced thermal resistance to enhance overall heat transfer performance. (Liu *et al.* 2011) studied the nanofluids Cu, CuO, and SiO_2 at different concentrations and nanoparticle sizes, deducing that, in general, smaller nanoparticles enhance heat transfer much better than larger ones. Similarly, (Huminic *et al.* 2011) demonstrated that iron oxide nanofluid, compared to deionized water, reduced thermal resistance in thermosyphon heat pipes, with nanoparticle sizes of about 4–5 nm. They studied iron oxide/DI water nanofluids, synthesized by a one-step technique. With the use of XRD and HRTEM techniques, they observed reduced thermal resistance in thermosyphons compared to pure water operation. (Kamyar *et al.* 2013) examined Al_2O_3 and TiSiO_4 /water nanofluids under 0–4 kW/m² thermal loading. Results showed a maximum heat flux of 25 kW/m² and an effectiveness of 0.3 at a 50% filling ratio using 1 wt.% Ag/water. (Liu *et al.* 2013) tested an open thermosyphon for solar collectors with CuO/water nanofluid. At 0.8–1.5 wt.% concentration and filling ratio of 60%, the outlet temperature and overall efficiency were significantly enhanced over water. (Huminic and Angel, 2013) further tested Fe_2O_3 /water nanofluids under different angles (60°–90°) and heat inputs up to 90 W. Their combined experimental and numerical analysis confirmed lower thermal resistance and better overall heat transfer. (Menlik *et al.* 2015) employed MgO/water nanofluid with 1–5 vol.% nanoparticle concentration, achieving up to 26% increase in heat transfer rate at 200 W. (Mehrali *et al.* 2016) focused on nitrogen-doped graphene (NDG) nanofluid. At only 0.06 wt.% loading, they reported a 58.6% drop in thermal resistance and a 99% improvement in heat transfer coefficient, particularly at steeper inclinations. (Yang *et al.* 2019) used zirconia-acetone nanofluid tailored for high heat flux applications (~200 kW/m²). With optimized tilt angle (65°) and filling ratio (60%), the evaporator heat transfer coefficient increased by 36.3% at 0.1 wt.% (Bumataria *et al.* 2024). The work likely highlights that oxide-based nanofluids, particularly those prepared via a two-step method at around 1 wt.% concentration, have shown superior performance in PHP applications. (Mameli *et al.* 2014) performed tests designed for microgravity environments using Al_2O_3 /ethanol, showing improved transfer rates and operational stability of thermosyphon-pulsating heat pipe hybrids. (Zufar *et al.* 2020) compared hybrid fluids (Al_2O_3 –CuO/ethanol

and $\text{SiO}_2\text{-CuO}$ /ethanol) in pulsating heat pipes. $\text{SiO}_2\text{-CuO}$ blends demonstrated 57% lower thermal resistance relative to water, although $\text{Al}_2\text{O}_3\text{-CuO}$ provided higher thermal conductivity. (Kavusi *et al.* 2017) further studied zirconia-acetone nanofluid in rod-type thermosyphons. At 0.1 wt.% and a filling ratio of 0.65, they reported ~10.6% increase in thermal efficiency but noted excessive tilt angle suppressed performance due to fluid accumulation at the bottom section. (Kim *et al.* 2016) reported that graphene oxide nanofluids improved thermal performance up to 25%, although higher concentrations (0.03%) sometimes reduced performance compared to 0.01%. (Vijaykumar *et al.* 2017) used CuO and Al_2O_3 /water nanofluids. The maximum thermal efficiency achieved was ~30.4% for CuO at 1 wt.% concentration and ~26.2% for Al_2O_3 at 1.5 wt.%.

Although significant effort has been made, a comprehensive understanding of the coupled effects of main parameters, such as inclination angle, filling ratio, and nanoparticle concentration, in real operation scenarios is still deficient. Long-term thermal stability and performance consistency of nanofluid-loaded PHPs have not been well investigated. Comparative analysis between base fluids and nanofluids under an identical experimental setup is also limited.

Oxide-based nanofluids, especially those containing aluminum and copper nanoparticles, have demonstrated strong potential for enhancing the thermal performance of heat pipes while maintaining cost efficiency, with optimal results typically achieved around a 1.0 wt.% concentration; lower levels may cause insufficient wetting and dry-out, while excessive concentrations can diminish heat transfer. A filling ratio (FR) near 50% is generally most favorable, and improvements stem from increased nucleation sites, higher thermal conductivity, and porous surface formation due to nanoparticle deposition. Hybrid nanofluids, which blend multiple nanoparticle types, further surpass single-component nanofluids in thermal conductivity and stability, but comprehensive optimization requires systematic research into nanoparticle concentration, pipe design, fluid properties, operating conditions, and heat input parameters.

Therefore, the current study is devoted to an experimental investigation of the thermal performance of a copper pulsating heat pipe charged with Al_2O_3 /ethanol nanofluid. The study will investigate the impact of filling ratio, inclination angle, and heat load on effective thermal conductivity and heat transfer coefficient, besides examining the thermal stability of the system for long-term operation. This work is bound to elucidate the physical mechanisms controlling nanofluid PHPs and provide a backbone for the development of future thermal

management systems in next-generation electronic cooling.

2. EXPERIMENTAL METHODOLOGY

2.1 Fabrication of PHP

The pulsating heat pipe, shown in Fig. 1, was constructed using copper due to its superior thermal conductivity, with an internal diameter of 6.5 mm and a wall thickness of 1.5 mm. The pipe was bent into three loops within a supporting frame of 150 mm × 200 mm dimensions. The evaporator, adiabatic, and condenser sections were each designed to be 50 mm in length (Mane and Alekseik, 2024). The calculated internal volume of the fabricated PHP was approximately 38,160 mm³ (Kumar and Abraham, 2024). The entire assembly was carefully sealed to ensure an airtight and leak-free operation.

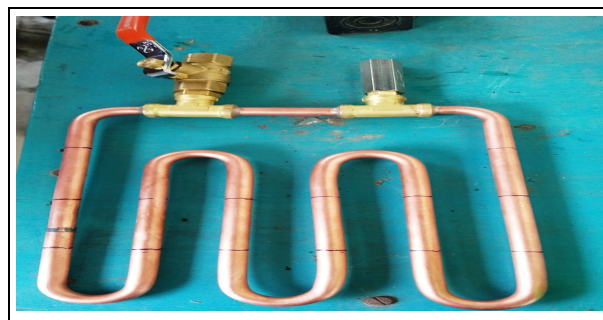


Fig. 1: The fabricated heat pipe

2.2 Strategies for Preparing and Formulating Nanofluids

Aluminum oxide nanoparticles are purchased from Platonic Nanotech Pvt. Ltd., Jharkhand, India. The purity of the nanoparticles is 99.9%, and the average particle size is 30–50 nm. An Al_2O_3 -ethanol nanofluid with a concentration of 1 wt.% was prepared for the experiments. Initially, Al_2O_3 nanoparticles were dispersed (Rahman *et al.* 2024) in ethanol using a magnetic stirrer for 2 hours to achieve uniform mixing. To further minimize agglomeration and ensure stable dispersion, the mixture was subjected to ultra-sonication with a homogenizer for an additional 2 hours. The prepared nanofluid samples were stored in borosilicate glass containers of 50 mL and 250 mL capacity.

2.3 Evacuation and Charging of Working Fluid

A schematic representation of the experimental setup and actual setup are shown in Fig. 2 and Fig. 3, respectively. Before charging the working fluid, the PHP was evacuated using a vacuum pump connected to a pressure gauge and three leak-proof control valves. This

process effectively removed air and moisture from the system. The working fluid was then filled to 30% (Miao *et al.* 2024) of the total internal volume, corresponding to approximately 25 mL.

2.4 Experimental Setup and Testing

Temperature measurements were obtained at both the evaporator and condenser sections (Lee *et al.* 2024) using calibrated K-type thermocouples. The performance tests were carried out initially with pure ethanol as the working fluid. The same set of experiments was subsequently repeated using the Al₂O₃-ethanol nanofluid, allowing a direct comparison of thermal performance between the two working fluids.

This streamlined methodology ensures the reproducibility and reliability of the derived results under well-defined experimental conditions.

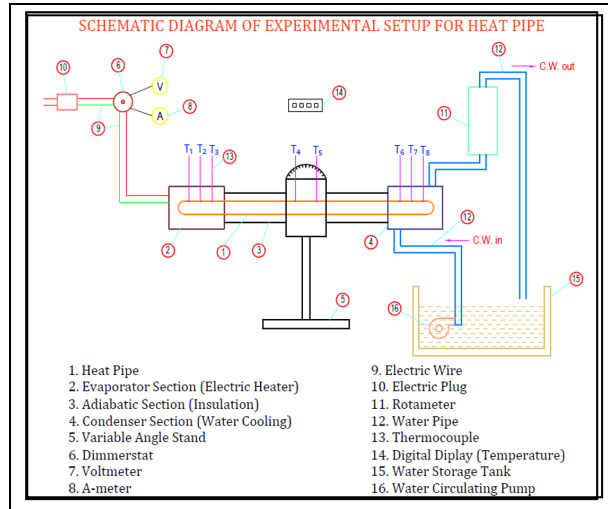


Fig. 2: Schematic diagram of experimental setup



Fig. 3: Actual experimental setup

3. DATA ACQUISITION AND CALCULATIONS

Temperature readings at both the evaporator and condenser sections were obtained using calibrated thermocouples and logged every 60 seconds with a digital data acquisition system, with steady-state values used for all calculations. The average temperatures for the evaporator (T_e) and condenser (T_c) were calculated by averaging the corresponding sensor data over the steady-state period, $T_c = \left(\frac{T_6 + T_7 + T_8}{3} \right) + 273.15 \text{ (K)}$, $T_e = \left(\frac{T_1 + T_2 + T_3}{3} \right) + 273.15 \text{ (K)}$. The mean temperature difference (ΔT) was determined as $T_e - T_c$. The surface area and cross-sectional area of the heat pipe were quantified from its physical dimensions. Surface area of the heat pipe, $A_{se} = \pi d L_p$. Effective thermal conductivity, $K_{eff} = \frac{Q \times L_p}{A_c \times \Delta T_p}$, (Where: L_p = Pipe length = 150 mm, d_i = Internal diameter = 6.5 mm, A_c =Cross-sectional area (mm²), ΔT_p =Temperature difference between evaporator and condenser (K) for evaporator-condenser-adiabatic sections) was calculated using the standard energy balance for pulsating heat pipes, and the overall heat transfer coefficient, $U_p = \frac{Q}{A_{sp} \times \Delta T_p}$ was derived from the measured heat input and temperature difference. Thermal resistance $R = \frac{T_e + T_c}{Q}$ was computed as the ratio of the temperature difference to the heat input. All calculations followed the procedures outlined by (Smrity and Yin, 2024), ensuring reproducibility and clarity of derived performance parameters.

Uncertainty Analysis:

Table 1. Possible error in measurement devices

S. No.	Device Name	Parameter	Unit	Max. value	Error
1	Digital A-V Meter	Voltage (V)	V	0-280	1
		Current (I)	A	0-5	0.01
2	RTD, PT-100	Surface Temperature (T)	C°	-99-400	0.1
3	RTD, PT-100	Water Temperature (T)	C°	-99-400	0.1
4	Rotameter	Cooling water flow (M)	LPH	1200	50

Table 2. Uncertainty in results

S. No.	Result	Symbol	% Uncertainty
1	Temperature difference	ΔT	7.05
2	Heat input	Q	0.4089
3	Thermal Resistance	R	7.059
4	Thermal conductivity	K	6.82
5	Heat transfer coefficient	H	7.06

3.1 Effect of Inclination Angle and Filling Ratio (Al₂O₃–ethanol)

3.1.1 Zero-degree (0°) Inclination Angle (Filling Ratio – 50%)

Table 3. PHP at 0° inclination (vertical) with 50% filling ratio

	Filling Ratio=50%					Position = Vertical					Fluid = Al ₂ O ₃ –ethanol									
Power (Watts)	Evaporator Temperature (°C)					Adiabatic Temperature (°C)					Condenser Temperature (°C)				Mass Flow Rate of Water (kg/s)		Inlet Water Temp.	Outlet Water Temp.	Heat Rejected	Eff. Thermal Conductivity
	T1	T2	T3	T4	TE	T5	T6	T7	T8	TA	T9	T10	T11	T12	TC	m	T _i	T _o	Q _r (kJ/s)	K _{eff}
30	49	51	53	49	50.5	38	36	33	33	35	27	27	27	27	27	0.003696	25.7	26.7	0.015	677.599
40	53	55	52	54	53.5	37	38	36	36	36.75	27	28	28	27	27.5	0.003696	25.7	26.8	0.017	816.593
50	51	59	54	53	54.25	40	41	41	40	40.5	28	28	28	28	28	0.003696	25.7	26.9	0.019	1011.020
60	54	58	60	55	56.75	42	43	51	42	44.5	28	28	29	28	28.25	0.003696	25.7	27.7	0.031	1117.443
70	52	61	64	53	57.5	48	42	48	44	45.5	28	29	29	28	28.5	0.003696	25.7	28.4	0.042	1281.207
80	52	65	70	52	59.75	51	53	54	49	51.75	29	29	30	28	29	0.003696	25.7	28.8	0.048	1380.906
90	53	67	69	54	60.75	53	52	59	53	54.25	29	30	31	30	30	0.003696	25.7	29.3	0.056	1553.519
100	55	63	72	59	62.25	55	54	57	59	56.25	29	32	30	32	30.75	0.003696	25.7	29.6	0.060	1685.034
110	58	62	71	62	63.25	57	58	53	54	55.5	30	33	30	33	31.5	0.003696	25.7	29.8	0.063	1838.942
120	58	65	70	63	64	56	59	56	58	57.25	31	32	33	33	32.25	0.003696	25.7	30.6	0.076	2006.119
130	63	68	74	59	66	57	58	55	60	57.5	32	32	34	34	33	0.003696	25.7	31.7	0.093	2090.973
140	62	69	73	65	67.25	61	64	53	62	60	35	34	36	35	35	0.003696	25.7	32.3	0.102	2304.185
150	65	73	76	69	70.75	63	65	58	65	62.75	36	35	37	37	36.25	0.003696	25.7	32.9	0.111	2307.763

3.1.2 30° Inclination Angle (Filling Ratio – 50%)

Table 4. PHP at 30° inclination with 50% filling ratio

	Filling Ratio=50%					Position = 30°					Fluid = Al ₂ O ₃ –ethanol									
Power (Watts)	Evaporator Temperature (°C)					Adiabatic Temperature (°C)					Condenser Temperature (°C)					Mass Flow Rate of Water (kg/s)	Inlet Water Temp.	Outlet Water Temp.	Heat Rejected	Eff. Thermal Conductivity
	T1	T2	T3	T4	TE	T5	T6	T7	T8	TA	T9	T10	T11	T12	TC	M	T _i	T _o	Q _r (kJ/s)	K _{eff}
30	47	49	50	52	49.5	45	48	50	45	47	28	28	28	28	28	0.003696	25.7	27.7	0.031	740.631
40	48	51	52	54	51.25	50	49	51	47	49.25	28	28	29	29	28.5	0.003696	25.7	28.6	0.045	933.249
50	48	52	53	55	52	57	52	54	53	54	29	29	30	30	29.5	0.003696	25.7	29.1	0.053	1179.523
60	51	55	52	58	54	58	54	55	56	55.75	30	29	31	31	30.25	0.003696	25.7	29.5	0.059	1340.932
70	51	54	55	59	54.75	58	57	56	54	56.25	31	30	31	32	31	0.003696	25.7	29.7	0.062	1564.421
80	54	55	57	60	56.5	63	56	55	57	57.75	31	30	32	33	31.5	0.003696	25.7	30.8	0.079	1698.514
90	57	57	60	63	59.25	60	62	56	56	58.5	32	31	33	34	32.5	0.003696	25.7	31.7	0.093	1785.821
100	59	58	63	64	61	59	65	59	52	58.75	33	32	34	34	33.25	0.003696	25.7	32.2	0.101	1912.741
110	60	62	66	62	62.5	59	62	58	57	59	34	33	35	34	34	0.003696	25.7	32.9	0.111	2048.646
120	58	63	67	63	62.75	61	66	60	59	61.5	35	35	36	35	35.25	0.003696	25.7	33.5	0.121	2316.155
130	60	64	68	59	62.75	62	65	59	57	60.75	36	36	37	36	36.25	0.003696	25.7	33.9	0.127	2603.854
140	61	65	67	65	64.5	64	69	60	59	63	37	36	37	38	37	0.003696	25.7	34.3	0.133	2702.181
150	64	68	69	66	66.75	65	68	61	60	63.5	38	37	38	39	38	0.003696	25.7	34.7	0.139	2769.316

3.1.3 60° Inclination Angle (Filling Ratio – 50%)**Table 5. PHP at 60° inclination with 50% filling ratio**

	Filling Ratio=50%					Position = 60°					Fluid = Al ₂ O ₃ –ethanol									
Power (Watts)	Evaporator Temperature (°C)					Adiabatic Temperature (°C)					Condenser Temperature (°C)					Mass Flow Rate of Water (kg/s)	Inlet Water Temp.	Outlet Water Temp.	Heat Rejected	Effective Thermal Conductivity
	T1	T2	T3	T4	TE	T5	T6	T7	T8	TA	T9	T10	T11	T12	TC	M	T _i	T _o	Q _r (kJ/s)	K _{eff}
30	56	61	61	58	59	43	51	56	53	50.75	29	29	29	29	29	0.003696	26.7	27.8	0.017	530.786
40	56	62	59	60	59.25	49	52	56	52	52.25	29	29	29	30	29.25	0.003696	26.7	28.2	0.023	707.714
50	58	62	61	57	59.5	51	62	57	53	55.75	29	29	30	30	29.5	0.003696	26.7	28.9	0.034	884.643
60	59	60	60	56	58.75	48	61	56	53	54.5	30	30	30	30	30	0.003696	26.7	29.7	0.046	1107.726
70	59	61	60	56	59	47	63	56	54	55	30	31	30	31	30.5	0.003696	26.7	30.2	0.054	1303.684
80	61	65	65	58	62.25	58	60	57	52	56.75	31	31	31	32	31.25	0.003696	26.7	30.5	0.059	1369.769
90	62	64	66	60	63	60	63	57	54	58.5	31	31	32	32	31.5	0.003696	26.7	30.7	0.062	1516.530
100	62	64	65	65	64	60	66	54	57	59.25	32	32	33	33	32.5	0.003696	26.7	31.6	0.076	1685.034
110	63	66	65	67	65.25	62	65	59	56	60.5	32	32	34	34	33	0.003696	26.7	32.1	0.084	1810.431
120	60	70	67	60	64.25	64	68	60	57	62.25	33	33	34	34	33.5	0.003696	26.7	32.5	0.090	2071.358
130	61	67	65	62	63.75	64	67	62	57	62.5	33	33	34	34	33.5	0.003696	26.7	32.8	0.094	2281.062
140	63	69	64	67	65.75	65	64	61	62	63	34	34	35	35	34.5	0.003696	26.7	33	0.097	2377.919
150	65	72	71	68	69	65	69	62	60	64	34	35	36	35	35	0.003696	26.7	33.8	0.110	2341.701

3.1.4 0° (Vertical) Inclination Angle (Filling Ratio – 30%)**Table 6. PHP at 0° inclination (vertical) with 30% filling ratio**

	Filling Ratio=30%					Position = 0					Fluid = Al ₂ O ₃ –ethanol									
Power (Watts)	Evaporator Temperature (°C)					Adiabatic Temperature (°C)					Condenser Temperature (°C)					Mass Flow Rate of Water (kg/s)	Inlet Water Temp.	Outlet Water Temp.	Heat Rejected	Eff. Thermal Conductivity
	T1	T2	T3	T4	TE	T5	T6	T7	T8	TA	T9	T10	T11	T12	TC	M	T _i	T _o	Q _r (kJ/s)	K _{eff}
30	45	46	43	47	45.25	38	40	35	36	37.25	29	29	30	29	29.25	0.003696	25.7	27.1	21.660	995.223
40	46	49	45	45	46.25	39	40	35	36	37.5	30	29	30	30	29.75	0.003696	25.7	27.8	32.490	1286.753
50	48	50	51	48	49.25	39	41	37	38	38.75	30	30	31	31	30.5	0.003696	25.7	28.6	44.867	1415.428
60	49	49	54	50	50.5	41	39	39	39	39.5	31	30	31	31	30.75	0.003696	25.7	29.3	55.697	1612.513
70	49	51	53	52	51.25	43	42	41	40	41.5	32	31	32	32	31.75	0.003696	25.7	30	66.527	1905.384
80	53	52	55	50	52.5	44	41	41	39	41.25	33	31	33	32	32.25	0.003696	25.7	30.5	74.263	2096.931
90	55	54	55	55	54.75	45	43	42	43	43.25	33	32	33	33	32.75	0.003696	25.7	31.1	83.546	2171.395
100	59	58	60	62	59.75	47	44	43	46	45	34	33	34	34	33.75	0.003696	25.7	31.8	94.376	2041.483
110	67	60	69	71	66.75	48	47	47	47	47.25	34	34	34	35	34.25	0.003696	25.7	31.9	95.923	1796.505
120	78	73	74	76	75.25	49	50	48	50	49.25	35	34	34	35	34.5	0.003696	25.7	32.3	102.112	1563.050
130	83	86	81	84	83.5	51	53	49	54	51.75	35	35	35	35	35	0.003696	25.7	33.1	114.489	1422.724
140	99	75	87	85	86.5	50	51	54	58	53.25	35	35	35	36	35.25	0.003696	25.7	33.7	123.772	1449.951
150	101	84	85	81	87.75	61	57	63	59	60	36	35	36	36	35.75	0.003696	25.7	34.2	131.507	1531.112

3.1.5 0° (Vertical) Inclination Angle (Filling Ratio – 50%)**Table 7. PHP at 0° inclination with 50% filling ratio**

	Filling Ratio=50%					Position = (Vertical)					Fluid = Al ₂ O ₃ -ethanol									
Power (Watts)	Evaporator Temperature (°C)					Adiabatic Temperature (°C)					Condenser Temperature (°C)					Mass Flow Rate of Water (kg/s)	Inlet Water Temp.	Outlet Water Temp.	Heat Rejected	Eff. Thermal Conductivity
	T1	T2	T3	T4	TE	T5	T6	T7	T8	TA	T9	T10	T11	T12	TC	m	T _i	T _o	Q _r (kJ/s)	K _{eff}
30	49	51	53	49	50.5	37	35	34	34	35	27	27	27	27	27	0.003696	25.7	26.7	15.471	677.599
40	53	55	52	54	53.5	36	37	37	37	36.75	27	28	28	27	27.5	0.003696	25.7	26.8	17.019	816.593
50	51	59	54	53	54.25	39	40	42	41	40.5	28	28	28	28	28	0.003696	25.7	26.9	18.566	1011.020
60	54	58	60	55	56.75	41	42	52	43	44.5	28	28	29	28	28.25	0.003696	25.7	27.7	30.943	1117.443
70	52	61	64	53	57.5	47	41	49	45	45.5	28	29	29	28	28.5	0.003696	25.7	28.4	41.773	1281.207
80	52	65	70	52	59.75	50	52	55	50	51.75	29	29	30	28	29	0.003696	25.7	28.8	47.962	1380.906
90	53	67	69	54	60.75	52	51	60	54	54.25	29	30	31	30	30	0.003696	25.7	29.3	55.697	1553.519
100	55	63	72	59	62.25	54	53	58	60	56.25	29	32	30	32	30.75	0.003696	25.7	29.6	60.339	1685.034
110	58	62	71	62	63.25	56	57	54	55	55.5	30	33	30	33	31.5	0.003696	25.7	32	97.470	1838.942
120	58	65	70	63	64	55	58	57	59	57.25	31	32	33	33	32.25	0.003696	25.7	32.4	103.659	2006.119
130	63	68	74	59	66	56	57	56	61	57.5	32	32	34	34	33	0.003696	25.7	33.4	119.130	2090.973
140	62	69	73	65	67.25	60	63	54	63	60	34	34	36	35	34.75	0.003696	25.7	33.9	126.866	2286.461
150	65	73	76	69	70.75	62	64	59	66	62.75	36	35	37	37	36.25	0.003696	25.7	34.6	137.696	2307.763

3.1.6 0° (Vertical) Inclination Angle (Filling Ratio – 70%)**Table 8. PHP at 60° inclination with 70% filling ratio**

	Filling Ratio=70%					Position = (Vertical)					Fluid = Al ₂ O ₃ -ethanol									
Power (Watts)	Evaporator Temperature (°C)					Adiabatic Temperature (°C)					Condenser Temperature (°C)					Mass Flow Rate of Water (kg/s)	Inlet Water Temp.	Outlet Water Temp.	Heat Rejected	Eff. Thermal Conductivity
	T1	T2	T3	T4	TE	T5	T6	T7	T8	TA	T9	T10	T11	T12	TC	M	T _i	T _o	Q _r (kJ/s)	K _{eff}
30	57	59	50	63	57.25	32	33	30	32	31.75	31	32	32	34	32.25	0.003696	25.7	26.2	7.736	636.943
40	58	58	52	67	58.75	33	34	32	33	33	32	33	34	35	33.5	0.003696	25.7	26.3	9.283	840.848
50	57	64	56	68	61.25	34	36	33	34	34.25	33	35	35	36	34.75	0.003696	25.7	26.7	15.471	1001.482
60	61	76	63	74	68.5	36	37	35	36	36	35	36	37	38	36.5	0.003696	25.7	26.7	15.471	995.223
70	66	74	67	79	71.5	39	38	37	39	38.25	38	37	39	41	38.75	0.003696	25.7	27.1	21.660	1134.503
80	68	76	66	78	72	41	39	40	41	40.25	40	38	42	43	40.75	0.003696	25.7	27.2	23.207	1358.811
90	73	86	74	79	78	45	43	38	44	42.5	44	42	40	46	43	0.003696	25.7	27.8	32.490	1364.877
100	79	85	77	85	81.5	46	46	42	45	44.75	45	45	44	47	45.25	0.003696	25.7	27.9	34.037	1464.236
110	83	105	118	84	97.5	49	47	44	46	46.5	48	46	46	48	47	0.003696	25.7	28.3	40.226	1156.167
120	86	111	115	112	106	52	49	45	47	48.25	51	48	47	49	48.75	0.003696	25.7	29	51.056	1112.564
130	104	107	122	96	107.25	53	50	47	48	49.5	52	49	49	50	50	0.003696	25.7	29.5	58.792	1205.277
140	110	112	123	100	111.25	53	54	51	53	52.75	52	53	53	55	53.25	0.003696	25.7	29.7	61.886	1281.207
150	113	111	125	107	114	54	53	52	55	53.5	53	52	54	57	54	0.003696	25.7	29.9	64.980	1326.964

3.2 Experimentation on Ethanol

Table 9. PHP at 0° inclination with 50% filling ratio

	Filling Ratio=50%					Position = Vertical					Fluid = Ethanol									
Power (Watts)	Evaporator Temperature (°C)					Adiabatic Temperature (°C)					Condenser Temperature (°C)					Mass Flow Rate of Water (kg/s)	Inlet Water Temp.	Outlet Water Temp.	Heat Rejected	Effective Thermal Conductivity
	T1	T2	T3	T4	TE	T5	T6	T7	T8	TA	T9	T10	T11	T12	TC	m	Ti	To	Qr (kJ/s)	K _{eff}
30	57	61	58	62	59.5	34	35	40	41	37.5	28	28	28	28	28	0.003696	25.7	26.6	0.014	505.510
40	56	62	59	61	59.5	36	38	41	43	39.5	28	28	29	28	28.25	0.003696	25.7	26.7	0.015	679.406
50	56	60	63	60	59.75	37	39	40	45	40.25	29	28	29	29	28.75	0.003696	25.7	26.8	0.017	856.106
60	58	65	65	67	63.75	40	43	44	46	43.25	29	29	29	29	29	0.003696	25.7	27.6	0.029	916.464
70	59	65	64	66	63.5	42	45	47	49	45.75	29	29	30	29	29.25	0.003696	25.7	28.2	0.039	1084.817
80	63	62	68	73	66.5	45	51	49	54	49.75	30	29	30	30	29.75	0.003696	25.7	28.7	0.046	1155.452
90	63	64	72	71	67.5	50	56	59	60	56.25	30	30	30	30	30	0.003696	25.7	29.2	0.054	1273.885
100	64	62	75	75	69	49	53	66	61	57.25	31	30	31	31	30.75	0.003696	25.7	29.5	0.059	1387.675
110	67	66	74	79	71.5	54	52	65	60	57.75	31	31	31	32	31.25	0.003696	25.7	29.7	0.062	1450.594
120	68	66	76	77	71.75	56	58	61	59	58.5	32	31	32	32	31.75	0.003696	25.7	30.5	0.074	1592.357
130	70	67	75	81	73.25	57	59	57	56	57.25	33	32	33	33	32.75	0.003696	25.7	31.6	0.091	1703.756
140	72	71	73	80	74	60	60	54	60	58.5	33	33	33	34	33.25	0.003696	25.7	32.1	0.099	1823.558
150	72	74	78	77	75.25	59	60	59	57	58.75	34	33	34	34	33.75	0.003696	25.7	32.7	0.108	1918.502

4. RESULTS AND DISCUSSION

The experiment compared pure ethanol and Al₂O₃–ethanol nanofluid in a PHP, evaluating thermal performance through parameters like temperature gradient, conductivity, resistance, and heat transfer, while considering filling ratio, inclination, and heat input effects.

4.1 Effective Thermal Conductivity Trends

The effective thermal conductivity (K_{eff}) of the Al₂O₃–ethanol nanofluid PHP increases significantly with heat input for all inclinations (Fig. 4). At 150 W, and 30° inclination, K_{eff} exceeds 2769.316 W/mK (Table 4), compared to values below 740.631 (Table 4) W/mK at 30 W. This enhancement is attributed to intensified phase-change activity and micro-convective currents induced by suspended nanoparticles. The trend shows that nanofluid consistently outperforms the base fluid due to enhanced thermal conductivity, Brownian-driven micro-mixing, and augmented evaporative heat transfer.

4.2 Influence of Inclination Angle

Performance varies considerably with the orientation of the heat pipe. At lower heat inputs, the difference among the three tested angles (0°, 30°, and 60°, (Table 3,4,5)) is less pronounced, but as power

increases, distinct trends emerge. The 30° position consistently exhibits the highest effective thermal conductivity at all but the very lowest heat inputs, peaking at approximately 2769 W/mK at 150 W (Table 4). The 60° orientation also achieves strong performance, approaching 2341.701 W/mK (Table 4), while the vertical 0° (Table 3) position delivers lower, yet steadily rising, conductivity.

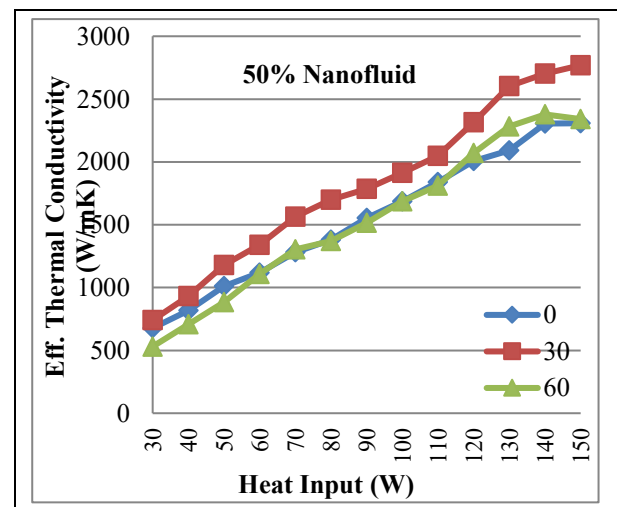


Fig. 4: Effective thermal conductivity with 50% filling ratio at 0-, 30- and 60-degree inclinations (Table 3, 4, 5)

Table 10. Summary of effective thermal conductivity at maximum heat input (150 W)

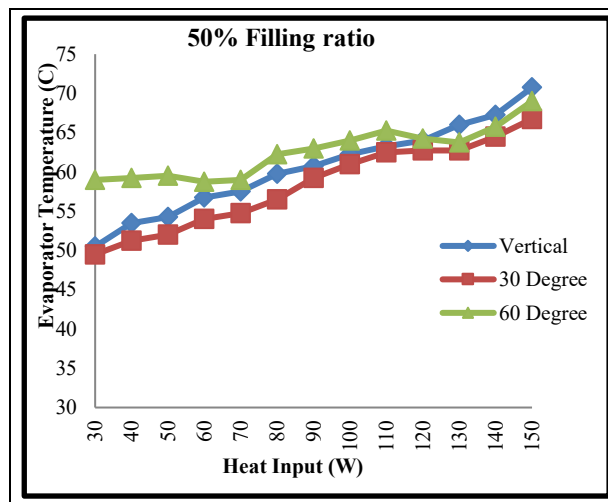
Condition	K_{eff} (W/mK)
Ethanol (50% FR, 0°)	1918.502 (Table 9)
Nanofluid (50% FR, 0°)	2307.763 (Table 3)
Nanofluid (50% FR, 30°)	2769.316 (Table 4)
Nanofluid (50% FR, 60°)	2341.701 (Table 5)

This suggests that moderate tilt (30°–60°, (Table 4,5)) optimizes the return of condensate and vapor flow pathways, thereby improving the phase change process and heat transfer efficiency. The vertical position, in contrast, may limit the gravitational effects needed for optimal fluid circulation, as supported by the slightly reduced values in the vertical datasets.

4.3 Temperature Distribution and Heat Rejection

Evaporator temperatures increase steadily with rising heat load, exceeding ~70 °C at the highest input values (Fig. 5) in (Table 6, 7). Adiabatic and condenser regions show smaller gradients, reflecting effective heat transport via phase change.

Heat rejection (Q_r) and condenser outlet water temperature rise proportionately with input power, confirming increasing thermal throughput as the PHP becomes more active.

**Fig. 5: Evaporator temperature with 50% filling ratio at 0-, 30- and 60-degree inclinations (Table 6, 7)**

4.4 Comparative Orientation Analysis

Across all conditions, the 30° inclination resulted in both higher heat rejection rates (Table 4) and improved thermal conductivity 2769.316 W/mk (Table

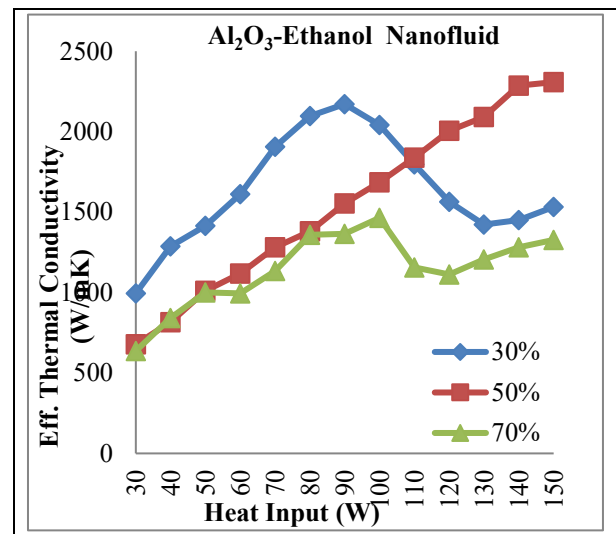
4), suggesting it provided the optimal balance between gravitational assist and capillary-driven fluid movement inside the heat pipe (Table 4). Conversely, while 60° (Table 5) inclination also offered strong heat transfer, at higher power inputs, the enhancement plateaued, indicating the possible onset of limitations in vapor flow or liquid return.

The superior performance at 30° (Table 4) arises from optimal gravitational assist and minimal hydraulic resistance, while excessive tilt at 60° (Table 5) can cause uneven liquid film formation, limiting vapor expansion at high heat loads.

Table 11. Orientation-based comparison at 150 W (50% FR)

Inclination	K_{eff} (W/mK)	Heat Rejection (Qualitative Trend)
0° (Table 3)	Low 2307.763	Moderate
30° (Table 4)	Highest (2769.316)	Highest
60° (Table 5)	High (234.701)	High but plateaus at peak loads

4.5 Effect of Filling Ratio

**Fig. 6: Effective thermal conductivities at 0-degree inclination with 30%, 50% and 70% filling ratios (Table 6, 7, 8)**

The filling ratio was found to exert a significant influence on the thermal performance of the Al_2O_3 –ethanol PHP, with distinct behavioral trends observed at 30%, 50%, and 70% (Table 6, 7, 8) working fluid volumes. At a 30% FR (Table 6), the effective thermal conductivity increased rapidly with rising heat input, reaching values near 2171.395 W/mK at 90W input; however, at the highest power input, a slight decline was recorded. This reduction can be attributed to the onset of localized dry-out conditions, where insufficient liquid is available for effective meniscus reformation and evaporator rewetting. In contrast, the 50% FR (Table 7)

demonstrated the most consistent and superior performance across the entire power range. Here, the nanofluid maintained the optimal balance between available liquid inventory and vapor generation space, enabling vigorous oscillatory motion and efficient phase-change cycling. As a result, this condition delivered the highest thermal conductivity values, approaching 2307.763 W/mK at peak heat loads. Conversely, increasing the FR to 70% (Table 8) led to a noticeable reduction in overall heat transfer effectiveness. Although conductivity continued to rise with heat input, the maximum values remained below those achieved at lower FRs. Excess liquid at 70% FR (Table 8) restricted vapor bubble expansion and impeded oscillatory flow, resulting in diminished evaporation kinetics and increased hydraulic resistance. Overall, the results confirm that a 50% FR (Table 7) provides the most favorable operating environment for nanofluid-based PHPs by minimizing dry-out risks while avoiding the flow choking associated with excessive fluid charge.

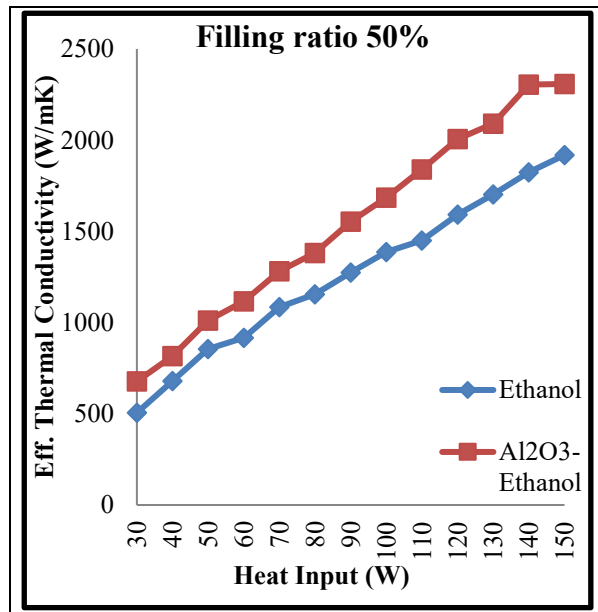


Fig. 7: Comparison of K_{eff} at zero-degree inclination with 50% FR

Table 12. Comparative summary of filling ratios at the highest heat load (nanofluid, 0°)

Filling Ratio (FR)	K_{eff} Trend	Limiting Mechanism
30% (Table 6)	Moderate High (drop at peak)	Dry-out, inadequate return
50% (Table 7)	Highest, stable	Optimal liquid-vapor balance
70% (Table 8)	Lowest	Vapor choking, reduced oscillations

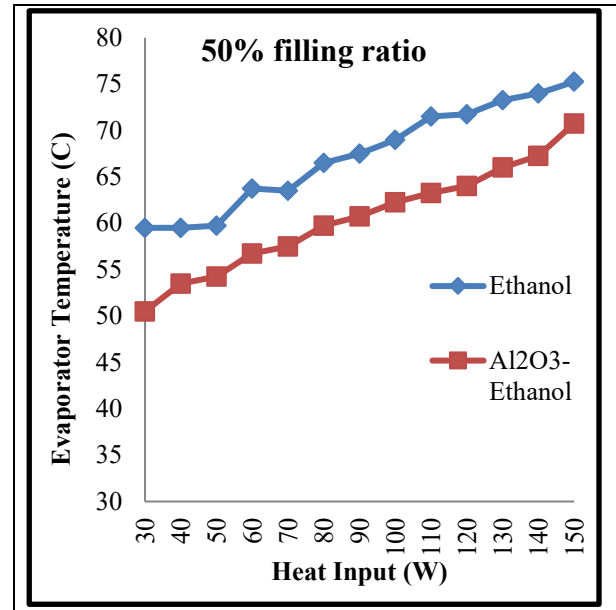


Fig. 8: Comparison of evaporation temperature at zero-degree inclination with 50% FR



Fig. 9: Photographic evidence of the stability of the Al₂O₃-ethanol nanofluid over the observation period

4.6 Comparisons of Nanofluid with Only Ethanol

The superior performance of Al₂O₃-ethanol nanofluid can be attributed to intensified thermal conduction and improved particle-liquid interactions, which foster micro-convection within the system. The consistent gains in K_{eff} with heat input and nanoparticle presence align with the literature, affirming nanofluid potential for advancing high-performance two-phase heat transfer systems (Fig 7 and 8). These results support the application of nanofluids in vertical thermosyphons, providing strong evidence of efficacy for scalable energy and thermal management solutions in engineering contexts.

4.7 Stability of Nanofluid

Although the present study did not directly quantify the influence of nanoparticle stability on thermal performance, the long-term dispersion behavior of the Al₂O₃–ethanol nanofluid provides credible supporting evidence for its reliable operation within the PHP. The nanofluid remained visually stable for more than 36 days, with no observable sedimentation in the periodic photographic documentation captured during the stability check (Fig 9). These observation photos confirm that nanoparticles remained uniformly suspended throughout the base fluid, indicating the absence of agglomeration or settlement during the monitoring period. Such sustained stability is widely acknowledged in existing literature as essential for maintaining consistent thermo-physical properties, particularly thermal conductivity and viscosity. A stable suspension ensures uniform nanoparticle distribution, which promotes micro-convective movement and provides active nucleation sites during phase-change processes. It also reduces the likelihood of particle deposition or localized blockage inside the oscillating channels, thereby supporting uninterrupted fluid oscillations within the PHP. Therefore, although stability effects were not experimentally analyzed in relation to heat transfer, the photographic evidence of long-term dispersion reinforces the reliability of the reported thermal enhancements and aligns with the established understanding that nanoparticle stability plays a vital role in sustaining improved two-phase heat transport in nanofluid-based PHP systems.

5. CONCLUSION

The study confirms that the incorporation of Al₂O₃ nanoparticles into ethanol significantly enhances the thermal performance of the pulsating heat pipe. The nanofluid consistently achieved higher effective thermal conductivity and improved heat rejection compared with pure ethanol, with the most notable enhancement occurring at a 50% filling ratio. This improvement is attributed to the inherently higher thermal conductivity of Al₂O₃ particles, the micro-convection generated by nanoparticle Brownian motion, and their ability to increase surface wettability and nucleation activity within the evaporator. The results further establish that a 30° inclination offers the most favorable balance between condensate return and vapor transport, enabling more stable oscillatory behavior under increasing heat loads.

Long-term dispersion photographs confirmed that the nanofluid remained stable for up to 38 days, providing confidence in the durability of its thermo-physical properties and supporting the reliability of the observed thermal enhancements. Overall, the findings demonstrate that Al₂O₃–ethanol nanofluid is a promising working medium for high-performance thermal

management. The future work could focus on scaling up the system, evaluating different nanoparticle types, and optimizing PHP designs for industrial and electronic cooling applications.

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DECLARATION OF CONFLICTING INTEREST

The authors declare that no known competing financial or personal interests could have appeared to influence the work reported in this manuscript. The research was conducted independently, and no commercial entity had any involvement in the study design, data interpretation, or decision to publish.

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DATA AVAILABILITY

The data generated and analyzed during this study can be obtained from the corresponding author upon reasonable request.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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