Research Article

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Sustainable Thermal Performance Analysis of a Pulsating Heat Pipe Using Zinc Oxide-ethanol Nanofluid

Dainikkumar Vasantbhai Savalia*, Pankajkumar Arvindbhai Anadani, Rajshree Kokate and Urvi Paras Upadhyay

Parul Institute of Engineering & Technology - Diploma Studies, Parul University, Vadodara, GJ, India

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*dainiksavalia@gmail.com

ABSTRACT

Enhancing heat transfer efficiency is critical for sustainable thermal management in modern applications such as electronics cooling, solar thermal systems, and waste heat recovery. This study investigates the thermal performance of a pulsating heat pipe (PHP) using zinc oxide (ZnO)-ethanol nanofluid, with the aim of developing an environmentally friendly and energy-efficient heat transfer system. Experiments were conducted using both base fluid (ethanol) and ZnO-ethanol nanofluid under identical conditions to assess the effects of filling ratio, inclination angle, and nanoparticle concentration. The experimental setup involved the fabrication of a PHP with three loops (6.5 mm internal diameter, 1.5 mm wall thickness), subjected to thermal tests at 30% filling ratio. Nano fluid preparation included magnetic stirring and ultrasonic homogenization of ZnO nanoparticles in ethanol at 1 wt% concentration. Results reveal a 16% enhancement in effective thermal conductivity with the ZnO-ethanol nanofluid compared to ethanol alone. Optimum performance was observed at a 50% filling ratio and 30° inclination angle. Additionally, the ZnO nanofluid showed higher heat rejection and stability of 42 days. The study highlights the superior thermal efficiency and sustainability potential of ZnO-ethanol nanofluids in passive thermal management.

Keywords: Pulsating heat pipe; Nano fluid; Zinc oxide; Ethanol; Sustainable heat transfer; Energy efficiency.

1. INTRODUCTION

Increased energy demand and the growing need for sustainable energy systems have motivated the development of efficient thermal management devices. Pulsating Heat Pipes (PHPs) are recognized as one of the most promising passive heat transfer devices due to their simple structure, low cost, and effective thermal performance (Mane and Alekseik, 2024). Enhancing their performance using nanofluids is a sustainable solution, as it offers better heat transfer capabilities while utilizing eco-friendly materials (Samylingam *et al.* 2024).

Zinc oxide (ZnO) nanoparticles are particularly attractive due to their non-toxic nature, chemical stability, and high thermal conductivity (Behera *et al.* 2025). In a study by Jothivenkatachalam *et al*. (2023), the synthesized chitosan–ZnO nanocomposites exhibited improved thermal stability, enhanced photocatalytic performance under natural sunlight, and superior anti-bacterial activity, demonstrating its overall functional efficiency. When dispersed in ethanol, a biodegradable and renewable solvent, the resulting nanofluid presents a sustainable heat transfer medium suitable for applications in electronics cooling, solar collectors, and energy recovery systems. Efficient heat transfer is crucial in various areas of modern technology (Chavhan and Singh, 2024). Many electronic devices and solid-state components generate waste heat that must be effectively removed to prevent damage. This has driven the development of more efficient heat transfer methods, such as heat pipes. Heat pipes are good at transferring large amounts of heat with minimal temperature differences between the heat source (evaporator) and heat sink (condenser) (Chavhan *et al.* 2024), offering significant advantages over traditional conductors like aluminum or copper rods.

2. LITERATURE REVIEW

Pulsating heat pipes are passive two-phase heat transfer devices known for their high thermal conductivity and simplicity. The integration of nanofluids (suspensions of nanoparticles in base fluids) into PHPs has been extensively studied to enhance thermal performance. Nanofluids improve heat transfer through increased thermal conductivity, Brownian motion, and enhanced surface wettability (Miao *et al.* 2024). Recent studies have demonstrated the effectiveness of various nanofluids in enhancing PHP performance. Kumar *et al.* (2024) reviewed the

application of nanofluids in different types of heat pipes, highlighting that nanofluids can significantly improve heat transfer performance depending on nanoparticle type, concentration, and operating conditions.

ZnO nanoparticles have attracted attention due to their high thermal conductivity and stability. Experimental investigations have shown that ZnO-based nano fluids can effectively reduce thermal resistance in PHPs. A recent study showed the effect of ZnO/water nanofluid concentrations on the thermal resistance of a closed-loop PHP and found that increasing ZnO concentration led to decreased thermal resistance (Bumataria *et al.* 2021). The performance of PHPs is influenced by various operational parameters, including filling ratio, inclination angle, and heat input (Lee *et al.* 2024). Studies have shown that there exists an optimal filling ratio and inclination angle that maximize thermal performance (Chen *et al.* 2025). Deviations from these optimal values can lead to reduced efficiency due to factors like flow instabilities and gravitational effects.

The long-term stability of nanofluids is crucial for their practical application in thermal systems (Rahman *et al.* 2024a). Research indicates that ZnO-ethanol nanofluids exhibit stable dispersion over extended periods, making them suitable for sustainable heat transfer applications. Their stability ensures consistent performance and reduces maintenance requirements in thermal management systems (Chaudhari *et al.* 2024).

3. EXPERIMENTAL ETHODOLOGY

3.1 Fabrication of PHP

The PHP was fabricated from copper with an internal diameter of 6.5 mm and wall thickness of 1.5 mm. It includes three loops formed in a 150 mm × 200 mm frame. The evaporator, adiabatic, and condenser sections were each 50 mm in length. The total internal volume of the PHP is approximately 38,160 mm³ (Kumar and Abraham, 2024). The experimental setup is shown in Fig. 1.

3.2 Nanofluid Preparation

A ZnO-ethanol nanofluid with 1 wt% concentration was prepared by mixing ZnO nanoparticles in ethanol using a magnetic stirrer (2 hours). Any agglomerations were broken *via* ultrasonication using a homogenizer (2 hours). The prepared nanofluid was stored in borosilicate glass containers (50 mL and 250 mL) (Rahman *et al.* 2024b).

3.3 Evacuation and Filling Process

Before filling, the PHP was evacuated using a vacuum pump setup with a pressure gauge and three leak-proof control valves to remove residual air and moisture. The fluid was filled to 30% of the internal volume (approx. 25 mL) (Cheng and Wong, 2024).

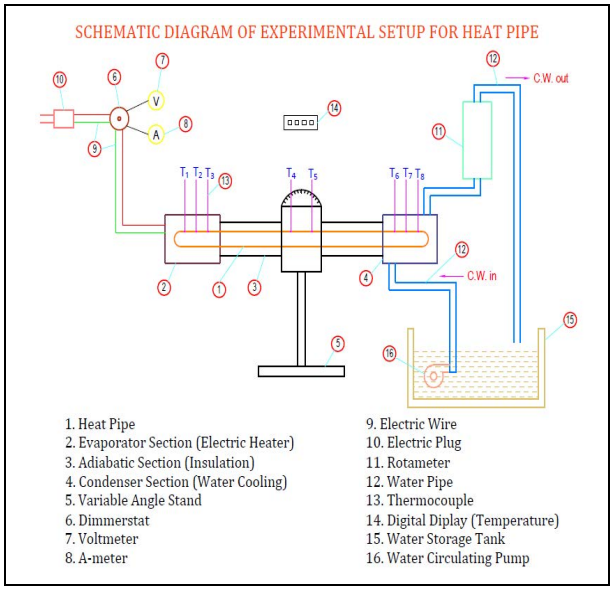


Fig. 1: Schematic diagram of experimental setup

3.4 Experimental Setup and Testing

Temperature readings were taken at the evaporator and condenser sections using K-type thermocouples. Experiments were first conducted using ethanol, then repeated with the ZnO-ethanol nanofluid to allow performance comparison.

4. DATA ACQUISITION AND CALCULATIONS

Proposed calculation steps (Smrity and Yin, 2024)

Average temperature of evaporator section

$$T_e = \left(\frac{T_1+T_2+T_3}{3}\right) + 273.15(K) \quad \ldots (1)$$

Average temperature of condenser section

$$T_c = \left(\frac{T_6+T_7+T_8}{3}\right) + 273.15(K) \quad \ldots (2)$$

Average temperature different between evaporator and condenser

$$\Delta T_p = T_e - T_c \quad \ldots (3)$$

Surface area of heat pipe

$$A_{se} = \pi d L_p \quad \ldots (4)$$

Cross sectional area of heat pipe

$$A_c = \frac{\pi}{4} {d_p}^2 \quad \ldots (5)$$

Thermal conductivity of heat pipe

$$K = \frac{Q \times L_p}{A_c \times \Delta T_p} \quad \ldots (6)$$

Over all heat transfer co-efficient of heat pipe

$$h_p = \frac{Q}{A_{sp} \times \Delta T_p} \quad \ldots (7)$$

Thermal resistance

$$R = \frac{T_e + T_c}{Q} \quad \ldots (8)$$

Tables 1-9 show the calculated parameters for various conditions.

4.1 Effect of Inclination Angle and Filling Ratio (ZnO-ethanol)

4.1.1 Zero degree (0°) Inclination Angle (Filling Ratio – 30%)

Table 1. PHP at 0° inclination with 30% filling ratio

Filling Ratio=30%						Position = vertical						Fluid = ZnO-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	41	42	45	39	41.75	41	43	32	33	37.25	39	41	30	31	35.25	0.003696		26.2	27.8	0.025	2449.780
40	42	41	44	43	42.5	42	43	32	33	37.5	40	41	30	31	35.5	0.003696		26.2	28.4	0.034	3033.060
50	44	42	47	41	43.5	42	44	34	35	38.75	40	42	32	33	36.75x	0.003696		26.2	29.3	0.048	3931.745
60	43	48	49	45	46.25	44	42	36	36	39.5	42	40	34	34	37.5	0.003696		26.2	29.9	0.057	3639.672
70	49	45	49	47	47.5	46	45	38	37	41.5	44	43	36	35	39.5	0.003696		26.2	30.4	0.065	4644.374
80	48	44	60	52	51	47	44	38	36	41.25	45	42	36	34	39.25	0.003696		26.2	31	0.074	3613.859
90	50	49	54	49	50.5	48	46	39	40	43.25	46	44	37	38	41.25	0.003696		26.2	31.7	0.085	5164.400
100	52	59	61	53	56.25	50	47	40	43	45	48	45	38	41	43	0.003696		26.2	32.3	0.094	4005.929
110	56	61	65	66	62	51	50	44	44	47.25	49	48	42	42	45.25	0.003696		26.2	32.6	0.099	3485.756
120	68	74	75	77	73.5	52	53	45	47	49.25	50	51	43	45	47.25	0.003696		26.2	33.1	0.107	2426.448
130	73	76	82	85	79	54	56	46	51	51.75	52	54	44	49	49.75	0.003696		26.2	33.3	0.110	2359.047
140	100	76	88	86	87.5	53	54	51	55	53.25	51	52	49	53	51.25	0.003696		26.2	34.2	0.124	2049.930
150	102	85	86	82	88.75	64	60	60	56	60	62	58	58	54	58	0.003696		26.2	34.9	0.135	2589.198

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

Table 2. PHP at 0° inclination with 50% filling ratio

Filling Ratio=50%						Position = vertical						Fluid = ZnO-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	50	52	54	50	51.5	53	55	34	40	45.5	26	26	26	26	26	0.003696		25.7	26.7	0.015	624.454
40	54	56	53	55	54.5	51	57	48	45	50.25	26	27	27	26	26.5	0.003696		25.7	26.8	0.017	758.265
50	52	60	55	54	55.25	52	58	51	48	52.25	27	27	27	27	27	0.003696		25.7	26.9	0.019	939.443
60	55	59	61	56	57.75	54	59	50	51	53.5	27	27	28	27	27.25	0.003696		25.7	27.7	0.031	1044.168
70	53	62	65	54	58.5	56	58	52	52	54.5	27	28	28	27	27.5	0.003696		25.7	28.4	0.042	1198.548
80	53	66	71	53	60.75	58	59	54	55	56.5	28	28	29	27	28	0.003696		25.7	28.8	0.048	1296.575
90	54	68	70	55	61.75	60	64	55	53	58	28	29	30	29	29	0.003696		25.7	29.3	0.056	1458.647
100	56	64	73	60	63.25	59	63	57	55	58.5	28	31	29	31	29.75	0.003696		25.7	29.6	0.060	1584.435
110	59	63	72	63	64.25	57	60	53	53	55.75	29	32	29	32	30.5	0.003696		25.7	29.8	0.063	1729.968
120	59	66	71	64	65	58	60	59	57	58.5	30	31	32	32	31.25	0.003696		25.7	30.6	0.076	1887.238
130	64	69	75	60	67	59	61	55	54	57.25	31	31	33	33	32	0.003696		25.7	31.7	0.093	1971.489
140	63	70	74	66	68.25	62	64	52	20	49.5	34	33	35	34	34	0.003696		25.7	32.3	0.102	2169.634
150	66	74	77	70	71.75	61	62	57	55	58.75	35	34	36	36	35.25	0.003696		25.7	32.9	0.111	2181.311

4.1.3 Zero degree (0°) Inclination Angle (Filling Ratio – 70%)

Table 3. PHP at 0° inclination with 70% filling ratio

Filling Ratio=70%						Position = vertical						Fluid = ZnO-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	58	60	51	64	58.25	34	35	31	33	33.25	26	26	26	26	26	0.003696	25.8	26.2	0.006	493.754
40	59	59	53	68	59.75	35	36	33	34	34.5	26	26	27	26	26.25	0.003696	25.8	26.3	0.008	633.774
50	58	65	57	69	62.25	36	38	34	35	35.75	26	27	27	26	26.5	0.003696	25.8	26.7	0.014	742.357
60	62	77	64	75	69.5	38	39	36	37	37.5	27	27	27	26	26.75	0.003696	25.8	26.7	0.014	744.962
70	67	75	68	80	72.5	41	40	38	40	39.75	27	27	27	27	27	0.003696	25.8	27.1	0.020	816.593
80	69	77	67	79	73	43	41	41	42	41.75	27	27	28	27	27.25	0.003696	25.8	27.2	0.022	928.150
90	74	87	75	80	79	47	45	39	45	44	28	28	28	27	27.75	0.003696	25.8	27.8	0.031	932.111
100	80	86	78	86	82.5	48	48	43	46	46.25	28	28	28	27	27.75	0.003696	25.8	27.9	0.032	969.471
110	84	106	119	85	98.5	51	49	45	47	48	28	28	29	28	28.25	0.003696	25.8	28.3	0.039	831.123
120	87	112	116	113	107	54	51	46	48	49.75	29	29	29	28	28.75	0.003696	25.8	29	0.050	813.984
130	105	108	123	97	108.25	55	52	48	49	51	30	29	29	28	29	0.003696	25.8	29.5	0.057	870.689
140	111	113	124	101	112.25	55	56	52	54	54.25	30	29	30	29	29.5	0.003696	25.8	29.7	0.060	898.006
150	114	112	126	108	115	56	55	53	56	55	30	30	30	29	29.75	0.003696	25.8	29.9	0.063	933.934

4.1.4 30° Inclination Angle (Filling ratio – 30%)

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

Filling Ratio=30%						Position = 30						Fluid = ZnO-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	40	42	43	42	41.75	40	41	35	35	37.75	33	32	33	32	32.5	0.003696	26.2	27.9	0.026	1721.467
40	42	42	43	43	42.5	41	41	36	36	38.5	33	33	33	32	32.75	0.003696	26.2	28.5	0.036	2177.582
50	44	42	46	41	43.25	43	42	36	37	39.5	33	33	33	33	33	0.003696	26.2	29.4	0.050	2589.198
60	47	49	50	46	48	44	43	44	42	43.25	34	34	34	33	33.75	0.003696	26.2	29.7	0.054	2234.887
70	51	50	49	48	49.5	46	44	42	41	43.25	35	35	36	34	35	0.003696	26.2	30.2	0.062	2562.413
80	46	47	50	51	48.5	48	45	45	43	45.25	37	37	37	36	36.75	0.003696	26.2	31.2	0.077	3613.859
90	49	49	53	49	50	49	48	46	46	47.25	38	38	38	37	37.75	0.003696	26.2	31.8	0.087	3899.649
100	52	57	59	52	55	51	52	42	48	48.25	38	38	39	37	38	0.003696	26.2	32.4	0.096	3122.268
110	58	61	60	55	58.5	52	58	46	52	52	38	39	39	38	38.5	0.003696	26.2	32.8	0.102	2919.321
120	65	67	66	61	64.75	53	51	53	48	51.25	39	39	39	38	38.75	0.003696	26.2	33.4	0.111	2449.780
130	72	71	77	80	75	57	54	50	58	54.75	39	40	40	39	39.5	0.003696	26.2	33.8	0.118	1943.722
140	84	74	80	82	80	61	58	64	52	58.75	40	40	41	40	40.25	0.003696	26.2	34.8	0.133	1869.433
150	105	72	81	79	84.25	66	57	69	66	64.5	40	41	41	40	40.5	0.003696	26.2	35.3	0.141	1819.836

4.1.5 30° Inclination Angle (Filling ratio – 50%)

Table 5. PHP at 30° inclination with 50% filling ratio

Filling Ratio=50%						Position = 30						Fluid = ZnO-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	53	54	57	53	54.25	46	58	49	44	49.25	27	27	27	27	27	0.003696	25.7	27.7	0.031	584.351
40	54	57	59	58	57	51	58	50	46	51.25	27	27	28	28	27.5	0.003696	25.7	28.6	0.045	719.709

50	56	58	58	55	56.75	58	60	53	52	55.75	28	28	29	29	28.5	0.003696	25.7	29.1	0.053	939.443
60	58	59	61	56	58.5	59	62	54	55	57.5	29	28	30	30	29.25	0.003696	25.7	29.5	0.059	1088.791
70	57	60	66	61	61	59	61	53	53	56.5	30	29	30	31	30	0.003696	25.7	29.7	0.062	1198.548
80	59	62	64	63	62	64	57	54	56	57.75	30	29	31	32	30.5	0.003696	25.7	30.8	0.079	1348.027
90	58	61	64	63	61.5	61	63	56	55	58.75	31	30	32	33	31.5	0.003696	25.7	31.7	0.093	1592.357
100	58	61	66	62	61.75	60	66	58	51	58.75	32	31	33	33	32.25	0.003696	25.7	32.2	0.101	1799.273
110	59	62	74	59	63.5	60	63	57	56	59	33	32	34	33	33	0.003696	25.7	32.9	0.111	1914.309
120	60	62	71	67	65	62	67	59	58	61.5	34	34	35	34	34.25	0.003696	25.7	33.5	0.121	2071.358
130	61	64	72	68	66.25	63	66	58	56	60.75	35	35	36	35	35.25	0.003696	25.7	33.9	0.127	2225.875
140	65	65	77	66	68.25	65	70	59	58	63	36	35	36	37	36	0.003696	25.7	34.3	0.133	2304.185
150	63	67	88	63	70.25	66	69	60	59	63.5	37	36	37	38	37	0.003696	25.7	34.7	0.139	2394.521

4.1.6 30° Inclination Angle (Filling ratio – 70%)

Table 6. PHP at 30° inclination with 70% filling ratio

Filling Ratio=70%						Position = 30					Fluid = ZnO-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	58	54	62	57.5	39	41	40	42	40.5	26	26	27	26	26.25	0.003696	25.8	26.4	0.009	509.554
40	59	61	58	66	61	42	40	41	44	41.75	27	26	27	26	26.5	0.003696	25.8	26.6	0.012	615.404
50	57	62	57	65	60.25	45	41	43	43	43	27	26	27	26	26.5	0.003696	25.8	26.7	0.014	786.349
60	58	64	60	68	62.5	46	47	42	46	45.25	27	27	27	27	27	0.003696	25.8	26.9	0.017	897.102
70	60	63	62	71	64	42	51	45	47	46.25	27	27	28	27	27.25	0.003696	25.8	27.1	0.020	1011.020
80	64	85	70	74	73.25	51	54	49	48	50.5	27	28	28	27	27.5	0.003696	25.8	27.4	0.025	928.150
90	70	94	105	73	85.5	54	58	53	58	55.75	28	28	28	28	28	0.003696	25.8	28.2	0.037	830.795
100	81	75	71	77	76	53	55	55	59	55.5	28	28	29	28	28.25	0.003696	25.8	28.3	0.039	1111.593
110	84	72	77	83	79	59	61	59	64	60.75	28	29	29	29	28.75	0.003696	25.8	28.9	0.048	1161.919
120	90	81	95	101	91.75	62	64	63	66	63.75	29	29	29	29	29	0.003696	25.8	29.3	0.054	1015.048
130	96	87	98	104	96.25	63	62	64	69	64.5	30	30	30	29	29.75	0.003696	25.8	29.9	0.063	1037.626
140	97	103	121	100	105.25	66	63	69	70	67	31	30	30	31	30.5	0.003696	25.8	30.6	0.074	994.113
150	99	106	118	102	106.25	67	66	68	72	68.25	31	31	30	32	31	0.003696	25.8	31.4	0.087	1058.044

4.1.7 60° Inclination Angle (Filling ratio – 30%)

Table 7. PHP at 60° inclination with 30% filling ratio

Filling Ratio=30%						position = 60					Fluid= ZnO-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	41	37	39	41	39.5	36	34	24	25	29.75	30	30	29	30	29.75	0.003696	26.2	27.2	0.015	1633.186
40	45	45	48	44	45.5	40	41	24	25	32.5	30	30	30	31	30.25	0.003696	26.2	27.8	0.025	1392.224
50	44	48	46	42	45	40	42	26	27	33.75	32	31	31	31	31.25	0.003696	26.2	28.9	0.042	1930.129
60	42	45	45	44	44	42	40	28	28	34.5	32	31	32	31	31.5	0.003696	26.2	30	0.059	2547.771
70	43	42	48	45	44.5	44	43	30	29	36.5	32	32	32	32	32	0.003696	26.2	30.5	0.067	2972.399
80	49	50	51	47	49.25	45	42	30	28	36.25	33	32	32	33	32.5	0.003696	26.2	31.2	0.077	2535.095
90	51	48	55	51	51.25	46	44	31	32	38.25	33	33	33	34	33.25	0.003696	26.2	31.9	0.088	2653.928
100	50	51	59	51	52.75	48	45	32	35	40	34	34	33	34	33.75	0.003696	26.2	32.4	0.096	2793.608

110	60	62	63	58	60.75	49	48	36	36	42.25	34	34	34	35	34.25	0.003696	26.2	32.7	0.101	2203.261
120	67	68	65	62	65.5	50	51	37	39	44.25	35	35	34	35	34.75	0.003696	26.2	33.3	0.110	2071.358
130	68	70	79	85	75.5	52	54	38	43	46.75	35	36	36	36	35.75	0.003696	26.2	33.5	0.113	1735.902
140	94	77	83	87	85.25	51	52	43	47	48.25	36	37	36	36	36.25	0.003696	26.2	34.1	0.122	1516.530
150	89	81	87	90	86.75	62	58	52	48	55	37	38	37	38	37.5	0.003696	26.2	34.6	0.130	1616.606

4.1.8 60° Inclination Angle (Filling ratio – 50%)

Table 8. PHP at 60° inclination with 50% filling ratio

Filling Ratio=50%						Position = 60						Fluid= ZnO-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	T 11	T12	TC	m	T_i	T_o	Q_r (KJ/s)	K_{eff}
30	57	62	62	59	60	44	52	55	52	50.75	28	28	28	28	28	0.003696	26.7	27.8	0.017	497.611
40	57	63	60	61	60.25	50	53	55	51	52.25	28	28	28	29	28.25	0.003696	26.7	28.2	0.023	663.482
50	59	63	62	58	60.5	52	63	56	52	55.75	28	28	29	29	28.5	0.003696	26.7	28.9	0.034	829.352
60	60	61	61	57	59.75	49	62	55	52	54.5	29	29	29	29	29	0.003696	26.7	29.7	0.046	1035.679
70	60	62	61	57	60	48	64	55	53	55	29	30	29	30	29.5	0.003696	26.7	30.2	0.054	1218.196
80	62	66	66	59	63.25	59	61	56	51	56.75	30	30	30	31	30.25	0.003696	26.7	30.5	0.059	1286.753
90	63	65	67	61	64	61	64	56	53	58.5	30	30	31	31	30.5	0.003696	26.7	30.7	0.062	1425.991
100	63	65	66	66	65	61	67	53	56	59.25	31	31	32	32	31.5	0.003696	26.7	31.6	0.076	1584.435
110	64	67	66	68	66.25	63	66	58	55	60.5	31	31	33	33	32	0.003696	26.7	32.1	0.084	1704.713
120	61	71	68	61	65.25	65	69	59	56	62.25	32	32	33	33	32.5	0.003696	26.7	32.5	0.090	1944.863
130	62	68	66	63	64.75	65	68	61	56	62.5	32	32	33	33	32.5	0.003696	26.7	32.8	0.094	2139.601
140	64	70	65	68	66.75	66	65	60	61	63	33	33	34	34	33.5	0.003696	26.7	33	0.097	2234.887
150	66	73	72	69	70	66	70	61	59	64	33	34	35	34	34	0.003696	26.7	33.8	0.110	2211.607

4.1.9 60° Inclination Angle (Filling ratio – 70%)

Table 9. PHP at 60° inclination with 70% filling ratio

Filling Ratio=70%						Position = 60						Fluid= ZnO-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	T 10	T 11	T 12	TC	m	T_i	T_o	Q_r (KJ/s)	K_{eff}
30	58	57	56	65	59	36	37	38	39	37.5	26	26	26	26	26	0.003696	25.8	26.3	0.008	482.532
40	59	56	55	63	58.25	38	40	39	41	39.5	27	26	27	26	26.5	0.003696	25.8	26.4	0.009	668.706
50	61	64	57	64	61.5	39	41	38	43	40.25	27	26	27	26	26.5	0.003696	25.8	26.5	0.011	758.265
60	60	65	61	66	63	42	45	42	44	43.25	27	26	27	27	26.75	0.003696	25.8	26.6	0.012	878.542
70	62	69	66	67	66	44	47	45	47	45.75	27	27	27	27	27	0.003696	25.8	27	0.019	952.692
80	75	71	68	75	72.25	47	53	47	52	49.75	28	27	28	27	27.5	0.003696	25.8	27.6	0.028	948.890
90	80	87	72	73	78	52	58	57	58	56.25	28	27	28	28	27.75	0.003696	25.8	27.9	0.032	950.661
100	79	88	71	75	78.25	51	55	64	59	57.25	28	28	28	28	28	0.003696	25.8	28.2	0.037	1056.290
110	86	94	76	80	84	56	60	68	72	64	29	28	29	28	28.5	0.003696	25.8	28.6	0.043	1052.007
120	89	96	94	92	92.75	61	65	64	66	64	29	29	30	29	29.25	0.003696	25.8	29.2	0.053	1003.059
130	93	98	82	102	93.75	64	71	67	67	67.25	30	29	30	29	29.5	0.003696	25.8	30.1	0.067	1073.963
140	116	125	95	101	109.25	66	73	69	70	69.5	30	30	30	30	30	0.003696	25.8	30.1	0.067	937.665
150	119	104	110	91	106	70	77	70	69	71.5	31	30	31	30	30.5	0.003696	25.8	31.4	0.087	1054.541

4.2 Experimentation on Ethanol

Table 10. 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	T 10	T 11	T 12	TC	m	T_i	T_o	Q_r (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

5. RESULT AND DISCUSSION

The experimental investigation was conducted on a PHP using both pure ethanol and ZnO-ethanol nanofluid under identical conditions to assess the improvement in thermal performance. The results are presented with a focus on key thermal parameters such as temperature gradient, thermal conductivity, thermal resistance, and overall heat transfer coefficient. The influence of filling ratio, inclination angle, and heat input on performance was also evaluated.

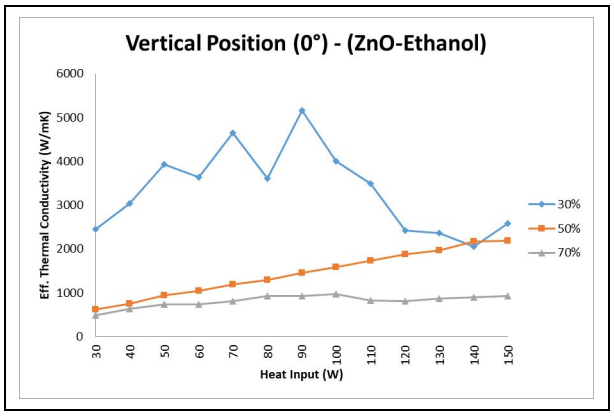


Fig. 2: Effective thermal conductivity at 0-degree inclination with 30%, 50% and 70% filling ratio

5.1 Temperature Distribution and Heat Transfer Behavior

The average temperature of the evaporator and condenser sections was recorded for various tests. The temperature difference between these sections was consistently lower for the ZnO-ethanol nanofluid, indicating better heat transfer. The reduced temperature drop confirms more efficient energy transport due to nanoparticle-enhanced thermal conduction pathways and induced micro-convection.

5.2 Thermal Conductivity

A significant enhancement in effective thermal conductivity was observed with the addition of ZnO nanoparticles (Fig. 2). At optimum conditions (50% filling ratio, 30° inclination, and increased heat load), the effective thermal conductivity increased by 16% compared to the base ethanol. This improvement is attributed to the high surface-to-volume ratio of ZnO nanoparticles, which facilitates better interaction with the base fluid molecules and improves heat diffusion.

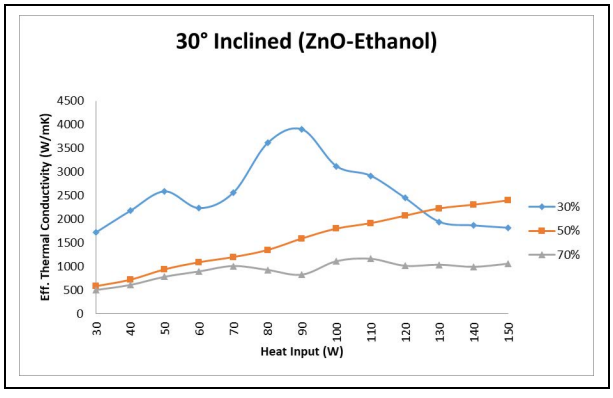


Fig. 3: Effective thermal conductivity at 30 degree inclination with 30%, 50% and 70% filling ratio

5.3 Thermal Resistance

Thermal resistance was calculated using the temperature gradient and heat input. The ZnO-ethanol nanofluid demonstrated lower thermal resistance, confirming superior heat transfer capability. The lowest resistance was observed at a 50% filling ratio and 30° inclination angle, aligning with the observed increase in thermal conductivity. Effective thermal conductivity at 30 and 60 degree inclination with 30%, 50% and 70% filling ratio is shown in Fig. 3 and Fig. 4, respectively.

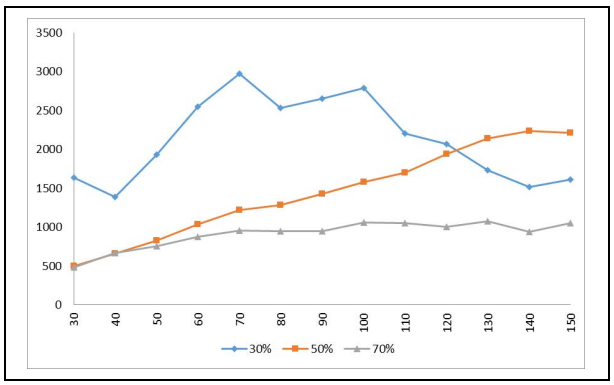


Fig. 4: Effective thermal conductivity at 60 degree inclination with 30%, 50% and 70% filling ratio

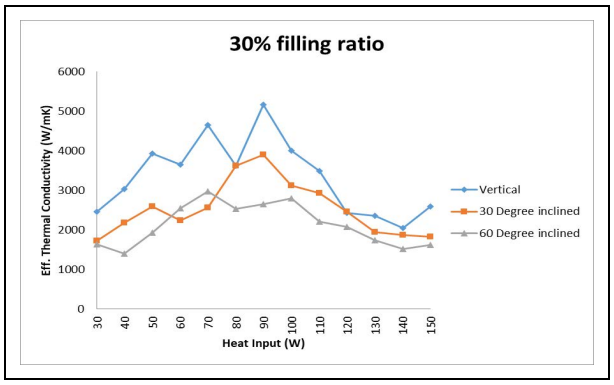


Fig. 5: Effective thermal conductivity at 30% filling ratio with 0, 30 and 60 degree inclination

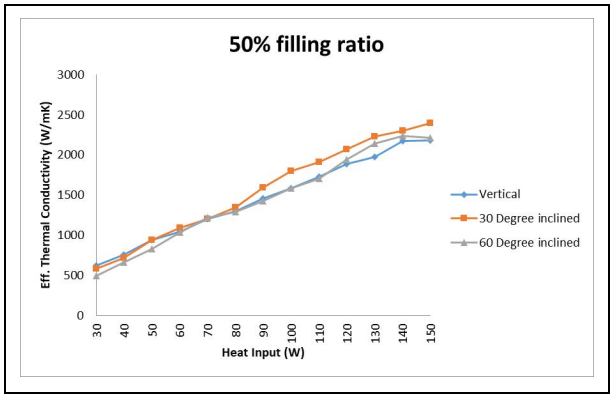


Fig. 6: Effective thermal conductivity at 50% filling ratio with 0, 30 and 60 degree inclination

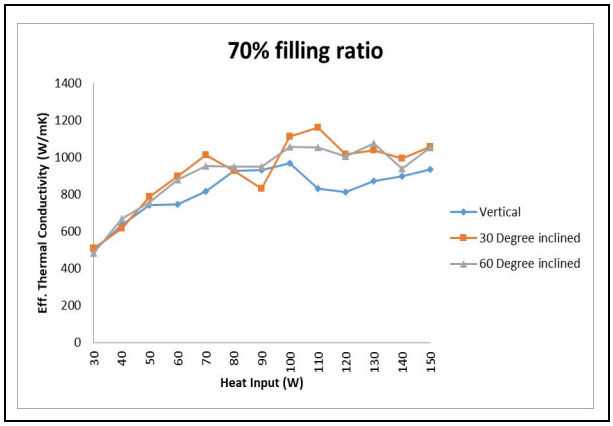


Fig. 7: Effective thermal conductivity at 70% filling ratio with 0, 30 and 60 degree inclination

5.4 Overall Heat Transfer Coefficient

The overall heat transfer coefficient (U) also improved significantly in the presence of ZnO nanoparticles. The increased thermal conductivity and enhanced heat transfer mechanisms, such as Brownian motion, nanoparticle clustering, and liquid film thinning of the nano fluid contributed to this improvement.

5.5 Effect of Filling Ratio and Inclination Angle

The PHP exhibited its best performance at a 50% filling ratio, where the balance between vapor and liquid slugs facilitated continuous oscillation. At lower or higher filling ratios, flow instabilities reduced the thermal performance. Additionally, the inclination angle of 30° was found optimal. At this angle, gravitational effects aided the return of the condensate to the evaporator, enhancing the PHP's oscillatory motion.

Fig. 5-7 show effective thermal conductivity at various filling ratios with 0, 30- and 60-degree inclination.

5.6 Comparison with Base Fluid (Ethanol)

All the key performance parameters (thermal conductivity, heat transfer coefficient, and thermal resistance) exhibited noticeable improvement when using ZnO-ethanol nanofluid compared to ethanol alone. The comparative performance plots clearly show the advantage of using ZnO nanoparticles in heat pipe applications for sustainable and energy-efficient thermal systems. Fig. 8 shows the effective thermal conductivity at 50% filling ratio with ethanol and ZnO-ethanol nanofluid. Fig. 9 shows the effect of evaporator temperature on various heat inputs at 50% filling ratio with ethanol and ZnO-ethanol nanofluid.

5.7 Stability of Nanofluid

The ZnO-ethanol nanofluid maintained stable dispersion for over 42 days without visible

sedimentation, as verified by periodic photographic analysis. This long-term stability ensures reliable performance in practical applications and underlines the fluid's potential for sustainable heat transfer systems.

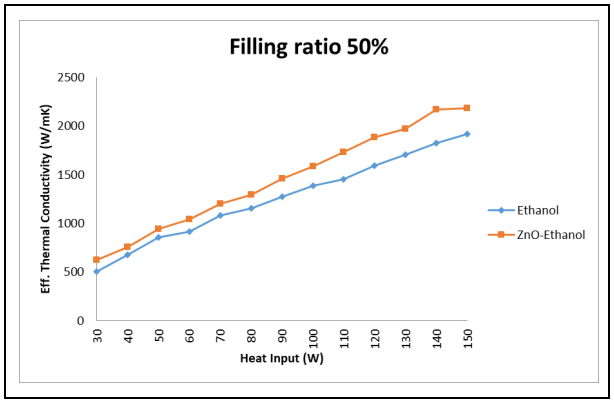


Fig. 8: Effective thermal conductivity at 50% filling ratio with ethanol and ZnO-ethanol nanofluid

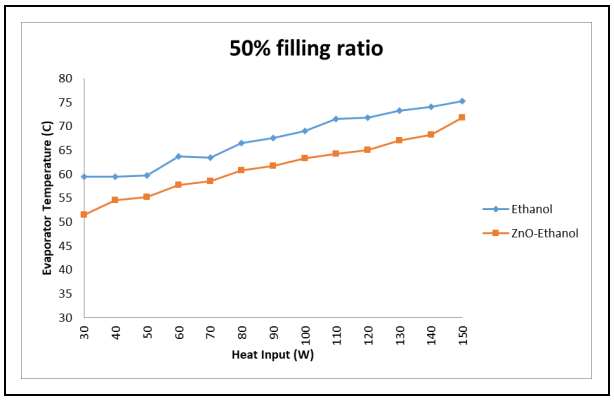


Fig. 9: Effect of evaporator temperature on various Heat input at 50% filling ratio with ethanol and ZnO-ethanol nanofluid

6. CONCLUSION

This research experimentally investigated the thermal performance of a pulsating heat pipe utilizing ZnO nanoparticles dispersed in ethanol as a nanofluid. A comparative analysis between pure ethanol and ZnO-ethanol nanofluid was conducted under varying operational conditions, such as filling ratio, inclination angle, and heat input. The study demonstrated that the inclusion of ZnO nanoparticles significantly enhanced the heat transfer characteristics of the pulsating heat pipe.

The experimental results revealed a 16% increase in effective thermal conductivity when ZnO was added to ethanol, with the most efficient heat transfer observed at a 50% filling ratio and 30° inclination angle. The use of ZnO-ethanol nanofluid also contributed to lower thermal resistance and improved overall heat transfer coefficients. The stability of the nanofluid was maintained for over 42 days, confirming its feasibility for sustained thermal management applications.

By incorporating nanotechnology into PHPs, this research offers a promising, sustainable, and energy-efficient solution for advanced thermal systems such as electronics cooling, renewable energy systems, and waste heat recovery. The findings not only align with the goals of environmental sustainability but also support the development of compact, high-performance heat exchangers with reduced energy consumption.

The work may be extended by investigating other environmentally friendly nanoparticles, optimizing PHP geometries, and exploring hybrid nanofluids for further performance enhancement.

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DECLARATION OF CONFLICTING INTREST

The authors declare that there is no conflict of interest regarding the publication of this research work. All experiments were independently conducted, and no commercial or financial relationships influenced the outcome of this study.

FUNDING STATEMENT

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DATA AVAILABILITY

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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