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Experimental Analysis of Thermal Performance for Heat Pipe Heat Exchanger with ZnO Nanofluid

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Abstract: The present experimental study investigates the performance of a heat pipe heat exchanger for recovering waste heat using nanofluids. An aqueous ZnO nanoparticle solution was employed as the nanofluid at the saturation levels of 0%, 1%, and 2% by weight. An increasing trend was observed in the heat transfer coefficient with increased mass concentration and air flow rate. The maximum heat transfer coefficient observed on the evaporator and condenser sides is 669.1 W/m^2 and 229 W/m^2, respectively. The thermal resistance decreased with the flow rate and concentration levels of the condenser and evaporator sides. The effectiveness of the heat pipe heat recovery unit has increased with concentration, and the highest value of 0.27 is observed at a 2% mass fraction. These findings provide insights for optimizing the design and operation of heat pipe heat recovery systems for industrial waste heat recovery applications.

Keywords: Heat pipe; nanofluid; heat exchanger, heat pipe heat exchanger, effectiveness.

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1. Introduction

Waste heat recovery in any thermal system is gaining importance rapidly as it offers several advantages like improved energy efficiency, increased cost savings, and, above all, reduced environmental impact [1]. Besides, a small temperature differential makes recovery difficult at lower temperatures. In such scenarios, heat pipes offer several advantages over other heat transfer devices, such as heat exchangers. They have a very high effective thermal conductivity, which allows them to transfer large amounts of heat over long distances with little temperature drop [2-3]. Heat pipes are an ideal solution for waste heat recovery in low-temperature applications, where the temperature difference between the hot and cold sides is relatively small. With high efficiency, they can transfer heat from low-temperature sources, such as exhaust gases from engines or industrial processes, to a heat sink, such as air or water [4-6]. Further enhancing the performance of heat pipe heat recovery (HPHR) systems, nanoparticles are blended with base fluid and tested [7-9]. Researchers evaluated the impact of such nanofluids on overall heat transmission by analyzing their performance.

Abdallah *et al*. [9] experimented with HPHE (heat pipe heat exchanger) having copper oxide nanofluid for air conditioning applications. The mass percentage of nanofluid in the water base is varied (1%, 3%, and 5%), and its effect on HPHE performance is investigated for different inlet fluid temperatures. An effectiveness of 0.6 is achieved for a 3% mass fraction of nanofluid at an inlet temperature of 55 ^{o}C. A performance improvement is recorded with the rise in temperature of inlet fluid and mass fraction of nanofluid. The application of nanofluid in oscillating heat pipes and loop heat pipes was studied by Riehl *et al*. [10-11]. The performance for both systems was found to have improved with the introduction of nanofluid compared to the base fluid. However, at higher heat loads, the porous structure creates significant pressure limitations on the flow of nanofluid, directly affecting the evaporator temperature of the LHP. In another study, they recorded the heat transport to rise with nanofluid concentration for loop pipes with a good matching between numerical and experimental analysis. Cobanoglu *et al*. [12] investigated the effect of Fe203 nanofluid elements in water-glycol on the low-pressure side of refrigeration system application. The three nanofluid concentrations (1%, 0-05%, and 0.01%) were considered. An improvement of 13.5 % was computed in heat transfer with nanofluid having 1 % Fe203. The nanofluid is recommended as a secondary fluid for heat transport in the refrigeration system. Si02-Zno nanoparticles in water base were tested by Mukherjee *et al*. [13] for variation of nano element concentration from 0.025 % to 0.1% by weight. The tests were carried out for Reynold's numbers 7743 to 23228. An enhancement in thermal conductivity of about 30% was noticed for 0.1% nanoparticle fluid at 60oC.

Carbon nano-tube integrated heat pipes made from aluminum were tested by Arya *et al*. [14] for varying concentration proportions and heat load. The thermal resistance decreased with heat load, and the minimum value for 0.3% CNT nano-tubes is noted. The filling ratio is optimum at 0.8, beyond which the performance declines. Aghayari *et al*. [15] configured the iron-oxide/water nanofluids for different Reynolds numbers (14000 to 34600) and mass fractions (0.08 to 0.1). The heat transmission coefficient was found to have increased by 28 % for 0.1% mass fraction over pure water, and its maximum value is obtained at the highest Re number. Razvarz *et al*. [16] examined heat pipe performance with aluminum oxide nanoparticles for inclinations of 30o to 90o and aggregation of 1% to 3%. The thermal efficiency was found to rise to 60o and then decline. Also, a pipe with 1% aggregation performed better than the other configurations. An HPHE for electronic cooling was fabricated by Veeramachaneni *et al*. [17]. The fluids used have 0.01% and 0.02% (by volume) of copper-graphene nanofluid. An improvement of 36.9% was recorded for 0.02% volume fraction nanofluid over the base fluid. The thermal conductivity rose for 0.02% nanofluid up to a heat input of 120W, after which thermal conductivity became the same as water.

Xu *et al*. [18] investigated using combined Al2O3 (25%) and TiO_2 nanoparticles in water to evaluate their effect on thermal resistance and efficiency. The study was performed for a 30%, 50%, and 70% filling ratio and cooling fluid flow of 0.40, 0.48, and 0.56 L/min. The minimum thermal resistance of 0.089 oC/w was noticed for a 50% filling ratio (for combined fluid) at the cooling fluid flow of 0.40 L/min. Thermal efficiency is trending upward with heating power input. A rise of 10.6% in efficiency was computed for combined fluid compared to pure water. A visualization study to understand the effect of Si02 particles suspended in a water base was carried out by Zhang *et al*. [19]. The concentrations were incremented from 0.5 % to 2% with a step of 0.5 and power input from 10W to 50 W at step 10. The thermal resistance is decremented with power input, and a minimum value is obtained for 1% concentration. The heat transport efficiency for the 1% configuration is maximum at 40.1%. It is commented that this concentration gives improved wettability and decreased capillary resistance , resulting in improved efficiency compared to other concentration levels. Rudresha *et al*. [20] investigated heat pipes for filing ratios ranging from 45% to 85% with step 10, which had fluid as ethylene glycol. The thermal resistance was observed to decline with increased heat input. The minimum thermal resistance value computed is 0.13oC/W, which is noted at a 55% filing ratio. Also, the highest HTC of 526.4 W/m^2 is obtained at the same filling ratio (55%) with a maximum heat input of 600W. Qian *et al*. [21] investigated the effect of heat flux, filling ratio, and mass concentration of the heat transport using a gravity-assisted heat pipe using a nanofluid. The nanofluid mass fraction, heat flux, and filling ratio varied from 0 to 2, 20% to 80%, and 20 to 200 kW/m2, respectively. It is concluded that heat transmission declines with a rise in the filling ratio. The heat transport is found to rise till a mass fraction of 1% and then decreases. However, the effect of heat flux was more prominent than the previous two and showed a linear relation with heat transfer.

Elfaghi *et al*. [22] studied heat pipe systems numerically to understand the effect of particle volume fraction and Reynolds number on thermal properties. The Reynolds number varied from 6000 to 12000 for the 25, 15, and 0.5% aluminum oxide nanofluid volume fraction. The numerical analysis shows that the HTC and, in turn, Nusselt numbers increase with the Re numbers, resulting in improved heat transmission. Thermal resistance for TiO_2 nano-particle-induced fluid was measured by Han *et al*. [23] at different concentrations of TiO_2. The decrease recorded was 15.5% and 4.3% for 0.02% TiO_2 and 0.01% TiO_2 deposition compared to the smooth surface. Haque *et al*. [24] tested different nanoparticle depositions in pure water for different filling ratios (0.4 to 0.8) and varying inclinations (0^o to 90^o). The observations show that the maximum HTC has been recorded at a tip of 60o to 90o and a 50% filling ratio. Pooyoo *et al*. [25] concluded that thermal conductivity improves by introducing nanoparticles from the simulation study conducted on aluminum oxide nanofluids suspended in water. Ali *et al*. [26] assessed the effect of concentration (0.05-1.5%) and temperature (10^oC to 90^oC) for CuO, TiO_2, and ZnO nanoparticles in base fluid Therminol-55. The maximum improvement of 24.3 % in thermal conductivity is observed for CuO/Therminal combination for particle suspension of 1.5%. Also, the nanoparticle suspension was found to have increased the thermal conductivity for all three suspensions with temperature.

The research investigates the application of ZnO nanofluid in a heat pipe through experimentation for applying low-temperature waste heat recovery. The study aims to boost the system's thermal performance by adding ZnO nanoparticles to the base fluid, which is pure water. The current study also studies the influence of nanoparticle mass concentration on system effectiveness at various heat inputs.

2. Materials and Methods

2.1. Experimental setup.

The configuration presented in Figure 1 illustrates the Heat Pipe Heat Recovery (HPHR) unit setup, which enables heat recovery from high-temperature fluid to low-temperature fluid. The HPHR unit has distinct sections for the condenser and evaporator, where the working fluid condenses and evaporates. The condenser segment is positioned above the evaporator, allowing a gravity-driven condensate return. Copper tubing links the ascending vapor and descending condensate tubes within the HPHR unit. The system has two air channels (ducts) that serve as conduits for the airflow generated by the blower and are mounted at the entrance of each channel. A heat exchanger positioned in the middle of the channel houses the bundle of heat pipes. Both channels have an approximate length of 2.5 m with a small gap between them to separate hot air flow from cold airflow. The channel has a cross-section of 0.3m x 0.15m with a hydrodynamic diameter of 0.2 m. The heat pipe unit is positioned approximately at the center of the channels. The conical sections are placed at the entrances where blowers are located to facilitate a smooth airflow transition into the main channel. The length of these sections is 0.6m. The blowers at these ducts' entry can produce different air flows. A digital anemometer was utilized to measure the speed of the airflow and the mass flow rate passing through the air ducts. To regulate the mass flow rate of hot and cold air to the heat exchanger, independent dimmer stat are connected to the blowers attached to the lower and upper channels. This allows for the speed of the blowers, and therefore the mass flow rate, to be controlled through the main supply.

The setup depicted in Figure 1 is intended to investigate the performance of an HPHR heat exchanger utilizing a nanofluid with a variable source temperature. The heating load on the heater regulates the waste heat source temperature. A Dimmerstat (controlling voltage), connected between the main supply and the electrical heater, contains the amount of electrical energy supplied to the heater.

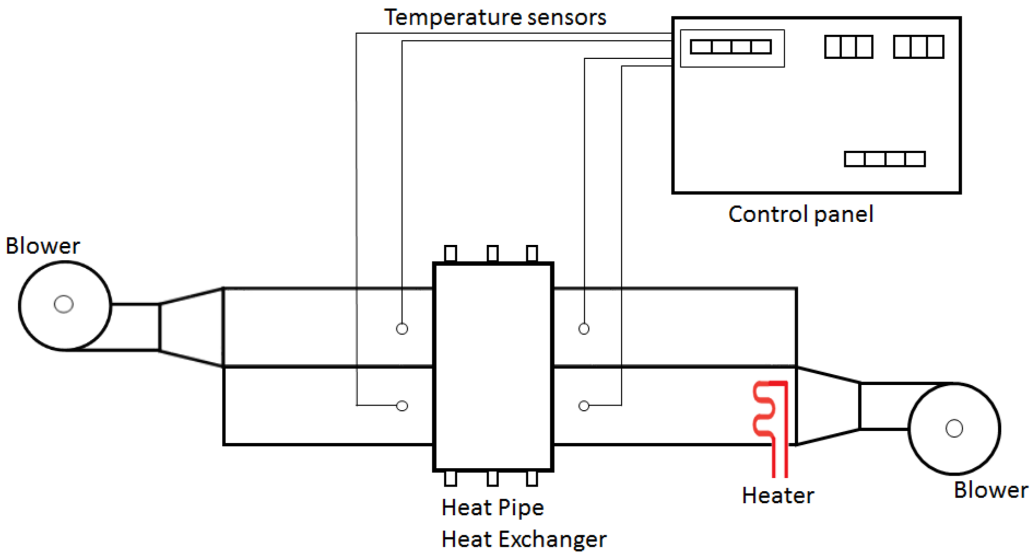

Figure 1. Experimental setup.

The HPHR unit is comprised of eight heat pipes made of copper, with each heat pipe having a diameter of 16 mm. The evaporator section of the heat exchanger comes into contact with the hot air flow, while the condenser section is connected to the cold air (i.e., the air to be heated). The eight heat pipes in the HPHR unit are arranged in a staggered configuration. Each heat pipe has an evaporative section, adiabatic section, and condenser section of 0.275m, 0.05 m, and 0.275m, respectively. The core section of the heat pipe has a radius of 0.007m. The nanofluid used in the base of pure water is zinc oxide (ZnO). It is an environmentally friendly material with enhanced power comparable to water's, exceeding other nano-metal oxides [27]. According to prior research, a particle size of 70 nm was selected to prepare the nanofluid. This is because studies have shown that decreasing particle size can improve the thermal properties of nanofluids up to a certain point. To optimize the balance between thermal conductivity and cost-effectiveness, a nanofluid with a volume fraction of 2% was utilized for the current study.

As the hot air flows through the lower channel, the working fluid inside the evaporator section of the HPHR unit undergoes evaporation. The vapor generated rises to the condenser section, which comes in contact with cold fluid passing over the unit. As a result of heat exchange between vaporized heat pipe fluid and outside cold air, the fluid undergoes condensation. Due to gravity, the condensed fluid returns to the evaporation section and completes the cycle. This cycle persists as long as a temperature gradient exists between the condenser and evaporator sections.

2.2 Data reduction.

The performance of an HPHR unit can be studied by calculating the thermal resistance and heat transfer coefficient (HTC) across the condenser and evaporator sections. Additionally, the effectiveness of the heat exchange system can also be calculated. Equation 1 is employed to calculate the thermal resistance.

$$R_{th} = \frac{\Delta T}{Q} \quad (1)$$

where ΔT represents the temperature differential, and Q represent the heat exchange across the particular section (condenser and evaporator).

The heat transfer coefficient (HTC) is computed using Equation 2, where A denotes the heat transfer area across that section.

$$h = \frac{Q}{A\,\Delta T} \quad (2)$$

"The effectiveness of a heat exchanger is the ratio of the actual heat transfer rate to the maximum theoretically possible heat transfer rate." Assuming the nonexistence of water vapor condensation and constant specific heat for the airflow in a heat exchanger, the HPHR system's effectiveness (ε) can be expressed as:

$$\varepsilon = \frac{T_{h,in} - T_{h,out}}{T_{h,in} - T_{c,in}} \quad (3)$$

In Equation 3, T_{hi} & T_{ho} respectively indicate the hot fluid's inlet and outlet temperature, while the cold fluid's inlet temperature is T_{ci}.

3. Results and Discussion

3.1 Variation of thermal resistance

Experimental investigations were carried out to examine how the thermal performance of the heat pipe is affected by varying concentrations of nanoparticles. The tests were conducted using nanofluids with 1%, 2%, and di-ionized water concentrations. The experiments were conducted under identical conditions for input heat powers of 250W, 500W, 1000W, and 1250W. Also, the varying mass flow rates are used to enable a comparison of the test results.

As shown in Figure 2, thermal resistance values were measured and plotted for varying heat input. The results indicate that nanoparticle-containing working fluid can significantly reduce thermal resistance. For example, when compared to deionized water, ZnO-containing nanofluid showed a mean thermal resistance reduction from 0.051 K/W to 0.015 K/W during the experiment conducted for heat input of 500 W. This drop represented a 27.3% reduction in thermal resistance when nanofluid was used as the working fluid.

Upon analyzing the thermal resistance results, it was observed that the highest improvement rate was achieved at 1250 W at a flow rate of 0.236 m^3/s, resulting in a 32% reduction in thermal resistance. Figure 2 also represents nanoparticle concentration's impact on thermal resistance, which was also investigated for different air flow rates. The results indicate that thermal resistance decreased with an increase in nanoparticle concentration.

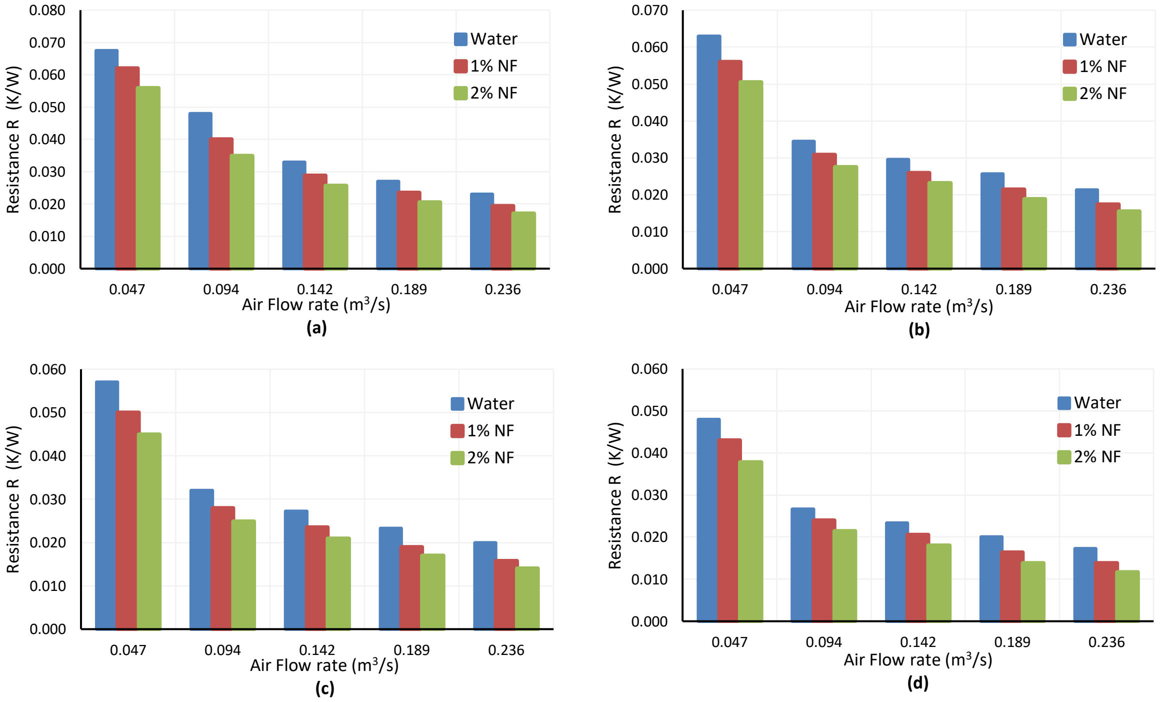

Figure 2. Variation of thermal resistance with air flow rate for heat input (a) 250W (b) 500W (c) 1000W (d) 1250W.

3.2. Variation of heat transfer coefficient (HTC).

Figure 3 shows the variation of HTC in the condenser and evaporator section with a change in the mass flow rate of the air. The Figure also depicts the effect of the concentration ratio of nanofluid on the variation of HTC. The results show a significant increase in the evaporator HTC of the heat pipe as the input heat power escalates. This is mainly because the working fluid's vaporization rate increases significantly at higher heat loads. Additionally, the number of nucleation sites and the rate of bubble formation also increase considerably with increasing heat loads, which facilitates the evaporation of the working fluid at higher rates [28].

Also, a rise in HTC is observed with nanofluid and increasing nanofluid concentration. The evaporator HTC of pure water is the lowest in all scenarios. This supports the impression that the presence of nanoparticles improves the heat pipe's evaporator and condenser HTC. As the concentration of nanoparticles in the base fluid increases, the evaporator HTC also increases. In the case of water/Zno nanofluids, the maximum evaporator HTC of 699.1 W/m^2 is achieved at a concentration of 0.20% mass fraction and a heat load of 1250W. It was observed that the HTC increases with an increase in air flow rate, and the maximum values were obtained at the highest flow rates. The maximum rise of 31.6 % in HTC on the evaporator side for 2% nanofluid concentration is detected compared to pure water at a filling ratio of 100% and a heating power of 1250 W. For 1% nanofluid concentration, the maximum rise of 15 % is noticed at the same conditions. The average gain of 12 % is calculated from a 1 % to 2% nanofluid increase.

The variation of condenser HTC at different mass flow rates is shown in Figure 4. Similar behavior is demonstrated by condenser side HTC, where a maximum HTC of 229 W/m^2 is detected. The maximum rise of 14.5 % and 29% is noticed for 1 % and 2 % nanofluid concentration over pure water. The HTC rise was found to rise with increasing mass flow rate for both condenser and evaporator units.

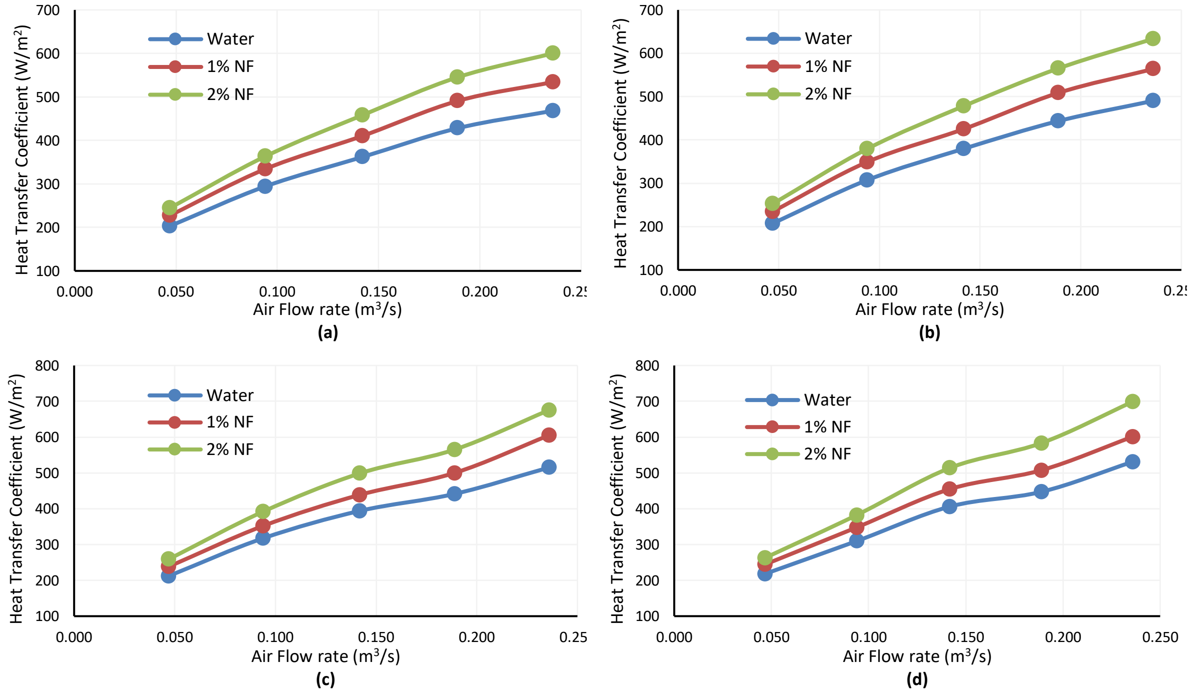

Figure 3. Variation of heat transfer coefficient on evaporator side with air flow rate for heat input **(a)** 250W **(b)** 500W **(c)** 1000W **(d)** 1250W.

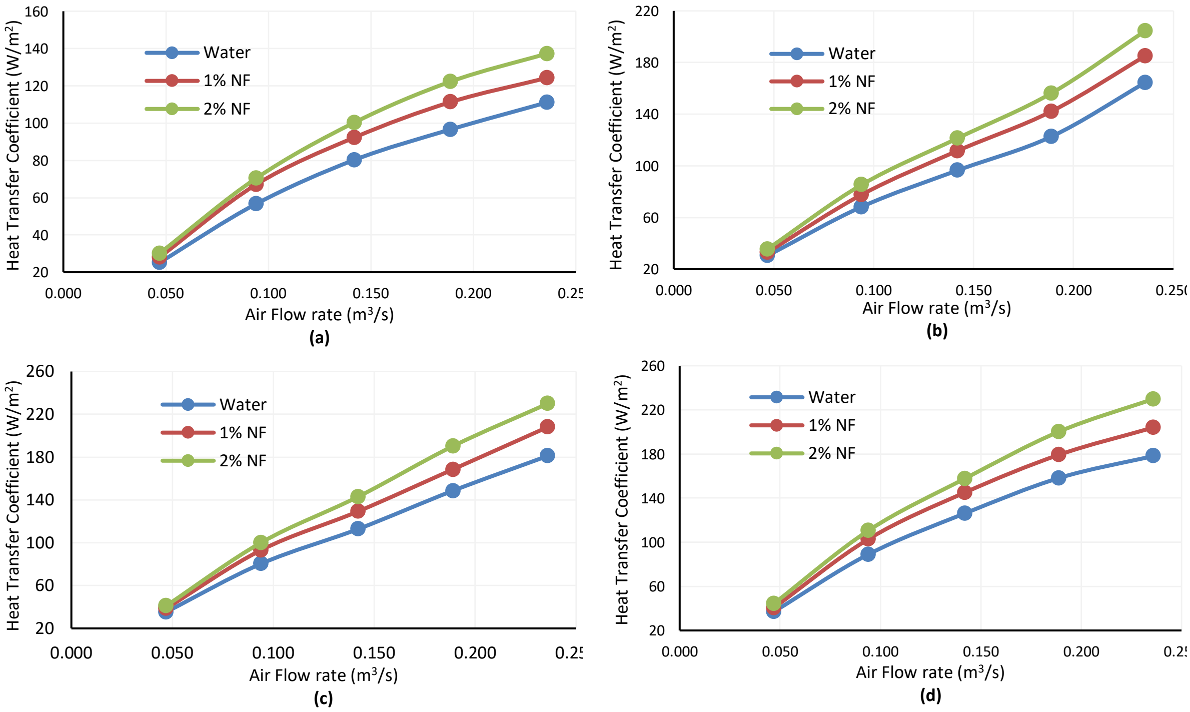

Figure 4. Variation of heat transfer coefficient on condenser side with air flow rate for heat input **(a)** 250W **(b)** 500W **(c)** 1000W **(d)** 1250W.

3.3. Effectiveness of heat transfer unit.

The variation of effectiveness for the considered HPHE system at different flow rates of air is depicted in Figure 5. The variations are plotted for pure water and nano-fluids with 1% and 2% concentrations. The nanoparticle-integrated fluid was found to exhibit higher effectiveness when compared to pure water. This increased effectiveness may be attributed to improved heat transfer properties due to nanoparticle integration and the high surface area-to-volume ratio. The highest effectiveness of 0.27 for 2 % nanofluid and 0.26 for 1 % nanofluid is computed for1250 W input power condition. The maximum rise in effectiveness observed is 17.2% for 250 W input power at 0.24 m^3/s flow rate. The mass flow rate has been found to have a negative impact on the effectiveness of HPHE, as the effectiveness decreases with an increase in mass flow rate. An average decline in effectiveness of 15% was calculated between the highest and lowest flow rates. The decrease in effectiveness may be attributed to an increase in flow rate, which can reduce the air's residence time within the heat exchanger. This leads to decreased time available for heat transfer between the air and the heat pipe, reducing heat transfer efficiency.

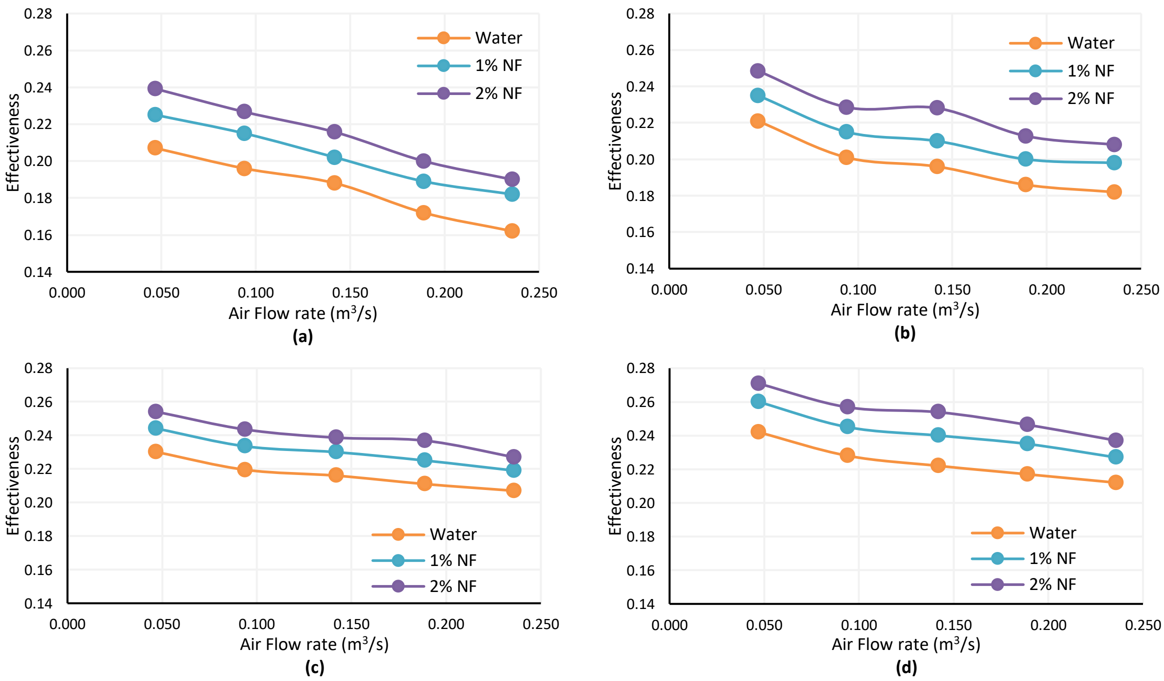

Figure 5. Variation of effectiveness with air flow rate for heat input **(a)** 250W **(b)** 500W **(c)** 1000W **(d)** 1250W.

4. Conclusions

Using nanofluid as a working fluid in a heat pipe exhibits the potential to amplify heat transfer performance and curtail energy consumption. The paper presents a thermal behavior study for a heat pipe heat recovery unit with ZnO nanoparticles suspended in pure water. The inclusion of nanoparticles resulted in higher HTC for the condenser as well as the evaporator section. The maximum HTC of 699.1 W/m^2 and 229 W/m^2 is obtained for evaporator and condenser sections at a concentration of 2% nanofluid. Though effectiveness has increased with nanofluid concentration, it showed a negative trend with the airflow rate. The highest effectiveness of 0.271 is computed at 0.047 m^3/s flow rate and 1250 W heat input. The rise in heat input positively impacts HTC and the effectiveness of the recovery unit, with maximum values recorded at 1250 W heat input. The maximum rise in effectiveness observed is 17.2% for 250 W input power at 0.24 m^3/s flow rate.

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Conflicts of Interest

The authors declare no conflict of interest.

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