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Performance Evaluation of Heat Pipe Heat Exchanger with Nanofluid: An Experimental Study

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Abstract: A heat pipe heat exchanger is fabricated and tested to recapture heat energy in low-temperature applications. The heat transfer fluid used has nanoparticles of zinc oxide suspended in water. The heat transmission performance of the arrangement is evaluated for variable heat supply at distinct mass flow rates. The mass flux for cold and hot air streams is changed for a specific heat input, and observations are recorded. The heat input values are incremented from 25 W to 1500 W while the flow rate of air is incremented from 0.047 to 0.236 m^3/s. Maximum effectiveness of 0.28 is noted for heat input of 1500 W at a flow rate of 0.047 m^3/s. The variation of heat transfer coefficient is studied for change in flow rate of air and source temperature of the air supplied. It is found that the coefficient of heat transfer increases with source temperature. The enhancement of performance is credited to better thermal conductivity due to the introduction of nanoparticles.

Keywords: nanofluid; heat pipe; effectiveness; heat transfer coefficient; heat exchanger.

1. Introduction

In the current era of high energy utilization and increasing impact on the environment by greenhouse gases, saving and reutilizing as much energy as possible is imperative. One such technique is waste heat recovery. Waste heat recovery is normally thought of as a high-temperature application, but studies have shown that heat recovery at low temperatures can also contribute to the goal of energy saving. Heat exchangers with heat pipes can significantly affect waste heat recovery applications. Using heat pipes, a relatively higher amount of heat can be transported than conventional methods. Moreover, they provide the benefit of a smaller cross-sectional area and no additional power consumption. Simplicity in design, wide range of temperatures from an application point of view, and capacity to manage and carry larger heat rates at different temperatures are distinctive characteristics of heat pipes [1-3].

Researchers have studied heat pipes for heat recovery applications to evaluate and improve their performance by enhancing the contact between fluid flowing and the pipe. Yodrak *et al*. [4] have built and tested heat pipes for heat recovery in the furnace for hot forging applications. The heat pipe was designed for air pre-heater with inlet temperature varying from 370 to 420°C with working fluid as water. It is detected that heat transmission increases with the internal diameter of the pipe and inlet hot gas temperature. Also, the staggered arrangement of pipes provides improved performance over the inline arrangement. For air conditioning application, the influence of the ratio of flow rates between fresh air to return air on the heat transport ability of the heat exchanger is studied by Mostafa *et al*. [5]. When the fresh air to return air ratio is halved, the fresh air temperature increases by about 20% and the performance of the device improves by almost 26%.

Abd-Elhady *et al*. [6] examined the heating capability of evacuated heat pipes charged with thermal oil. It is reported that heat pipe molded with copper foam and thermal oil results in a 25% increase in efficiency compared to finned tubes. It is said that replacing the air gap with a heat transfer medium helps improve performance. The feasibility of oscillating heat pipes in HVAC application is studied by Mahajan *et al*. [7]. The heat pipe system was found to have an effectiveness of 0.48 with pre-cooling of the incoming air by 8^{o}C. It is estimated that the contemplated system may reduce the consumption of energy by about 16% on an annual basis. Delpech et al. [8] designed and investigated a heat pipe heat exchanger for heat recovery from the ceramic kiln. It is estimated that it is possible to recover 863 kWh of heat from a ceramic kiln which can be used to heat air before supplying it to the kiln. In an extended study, the authors used radiative heat pipes to recuperate heat through natural convection and radiation in an enclosed kiln.

Also, the heat pipe's performance is evaluated with different working fluids. It is worth considering substituting the typical working fluid with a modified fluid with good heat transmission capabilities to enhance the effectiveness of heat pipe heat exchangers. "Nanofluid is a stable solid-liquid suspension created by mixing nanoparticles with the traditional working fluid". A loop heat pipe charged with silica (SiO_2–H_2O) nanofluid is manufactured and investigated by Gunnasegaran *et al*. [9] to check its thermal performance under varying heat input. When nanofluid is used in a heat pipe, the thermal resistance is found to decrease by 28% to 44% compared to pure water as heat pipe fluid. Kole *et al*. [10] observed a 15% increase in thermal performance when 0.5% of Cu-water nanofluid is used in heat pipes. Kumaresan *et al*. [11] manufactured heat pipes having sintered mesh. The performance of heat transfer is evaluated considering different working fluids. The resistance to heat flow is found to reduce by 14% when the sintered mesh is used in the heat pipes for the condition of the same heat input. The presence of nanoparticles was found to increase the thermal conductivity of heat pipes.

Mashaei *et al*. [12] studied cylindrical heat pipes with nanofluid for heat dissipation in satellite cooling. The study compares the results when water is initially utilized as the working medium. Aluminum oxide nanoparticles are in the water base, and the next working fluid has titanium oxide nanoparticles in the water base. It is revealed that introducing nanoparticles improves the heat transfer coefficient by reducing thermal resistance. A similar study was carried out by Venkatachalapathy *et al*. [13], wherein the performance of cylindrical heat pipes having copper oxide nanoparticles suspended in water is investigated. It is observed that the efficiency of heat transmission rises with an increase in the angle of inclination and heat load on the pipe. It is stated that a thin coat of nanoparticles deposited on the wick arrangement improves wettability and boosts the effectiveness of heat pies. The thermal performance of miniature heat pipes using nanofluid is investigated by Shi *et al*. [14]. The resistance to heat flow decreases by 23% to 40% when SiO_2/water nanofluids are used instead of deionized water as a working medium in the heat pipe. Mohanraj *et al*. [15] researched a flat plate heat pipe with CuO nanofluid that provides enhanced heat transfer compared to a heating pipe using ionized water. A cooling system containing a loop heat pipe is tested for a concentric PV system by Senthilkumar *et al*. [16]. When compared with a heat sink, it is inferred that hindrance to the flow of heat is comparatively less in the case of the heat pipe. Also, enhancement in coefficient heat transfer is observed and attributed to increased nucleation places because of greater solar radiation intensity.

The effect of orientation of the pipe on its performance was studied experimentally by Sankar *et al*. [17]. It is reported that for a tilt of 60^o, the increase in efficiency is about 23 % for induced fluid compared to water. Yao *et al*. [18] investigated grooved heat pipes with heating sources mounted at different locations. It is observed that thermal resistance reduces gradually with heating length. Also, thermal effectiveness was found to improve with an inclination of the pipe. The change in performance of stationary and moving heat pipes was evaluated by Voigt *et al*. [19] for different wick structures. Thermal resistance was found to be on the lower side compared to a static arrangement. The heat transfer limit was more affected for grooved heat pipes than sintered and meshed pipes.

Shuoman *et al*. [20] inspected thermosyphon heat pipes for varying heat loads and concentrations. The heat transfer coefficient was observed to triple for change of heat input in the range of 1250 W to 500 W. For variation in concentration of nano-material in parent fluid ranging from zero percent to two percent, the coefficient of heat transfer was found to move from 90 W/m^oC to 300 W/m^oC. Zhang *et al*. [21] investigated the variation of thermal conductivity, a difference in temperature between the condenser and evaporator sections, and the capability of heat transport for pipes with micro-grooving for different heat source locations. Thermal conductivity is found to vary linearly with the heat load. As the span between the sink and the source diminishes, the heat transmission significantly improves.

A numerical study for cooling of battery using heat pipe and phase change material is conducted by Chen *et al*. [22]. It was stated that maintaining high thermal conductivity values helps minimize the PCM's liquid part and regain the heat absorption ability. Also, the reduced temperature of the battery pack can be maintained for high heat transfer coefficient values and increased melting point of phase change material. Temimy *et al*. [23] investigated heat pipes in a vertical orientation for different filling ratios. The tube packing is inserted in the pipes to reduce the vortices, negatively affecting the heat transmission. The insertion helped the condensate to move to the evaporator section at a reduced temperature and improved the heat transfer. The pipe provided optimum performance at 55 % of the filling ratio. Rangabashiam *et al*. [24] analyzed a solar collector system integrated with a heat pipe infused with nanofluid for Indian environmental conditions. It is observed that there is an optimal value for nanoparticles infusion in the base fluid at which the solar system provides the best performance. For the case study, at 0.6% aluminum oxide and 0.2% magnesium oxide, the maximum collector efficiency of 79% is recorded.

A numerical study for the recovery of waste heat in the ceramic industry is conducted by Jouhara *et al*. [25]. The response of the heat exchanger is found to be quick to the change in temperature when employed with heat pipes. The heat recovery was found to be a function of Kiln temperature. Hakim *et al*. [26,27] constructed an HVAC system with a heat pipe installed in the duct carrying air around the cooling coil. The experimentation is carried out for heat pipes' single- and double-row arrangements. The double row arrangement is observed to give a significant change in performance as compared to the single row arrangement. It is claimed integration of heat pipes in the HVAC system decreases the consumption of energy during reheating and pre-cooling of the air. In an extended study, it is observed that the thermal resistance remains a function of Reynold's number and the number of rows of pipes.

Literature studies have unveiled that heat pipes significantly improve thermal transmission and can play a significant role in heat dissipation solutions. It has been tested for numerous applications like electronics cooling, photovoltaic system, solar collector, etc. [28-31]. It is also revealed that the thermal properties of heat pipes are greatly improved when nanoparticles with appropriate concentrations are suspended in base fluids. It is also specified that the presence of nanoparticles in the base fluid boosts heat transmission capacity and lowers resistance to heat flow [32-35]. In the present study, a heat pipe heat exchanger charged with nanoparticles of ZnO in the base of water is prepared. The work is aimed at the recovery of heat at low temperatures. The thermal performance of the heat pipe heat exchanger is evaluated for different airflow rates at varying heat input values.

2. Materials and Methods

2.1. Test section.

To inspect the performance of the heat exchanger with heat pipe having charged with nanoparticles of ZnO/H_2O, the experimental set-up was prepared. Figure 1 depicts the schematic for the test set-up. The primary purpose is to check the feasibility of a heat pipe heat exchanger for heat recovery at low temperatures. The set-up consists of a heat pipe heat exchanger and duct arrangement through which air flows from which heat is to be recovered. The heat pipe heat exchanger comprises eight hard-drawn copper seat pipes 16 mm in diameter each. The evaporator of the heat pipe is in contact with air at high temperatures. The low-temperature air passes through the condenser. The air from which heat recovery is to be done passes through the lower section of the heat exchanger while the cooling agent moves through the upper section of the heat exchanger arrangement. A blower is in the test set-up to supply airflow. For regulating the speed of the blower, a single-phase dimmer stat is mounted with the help of which voltage to the blower can be regulated, varying the flow rate of air. The ducts are provided with polyurethane foam insulation to reduce any heat loss to the surrounding. The control panel shows the various parameters necessary. It consists of a voltmeter, an ammeter, and temperature indicators.

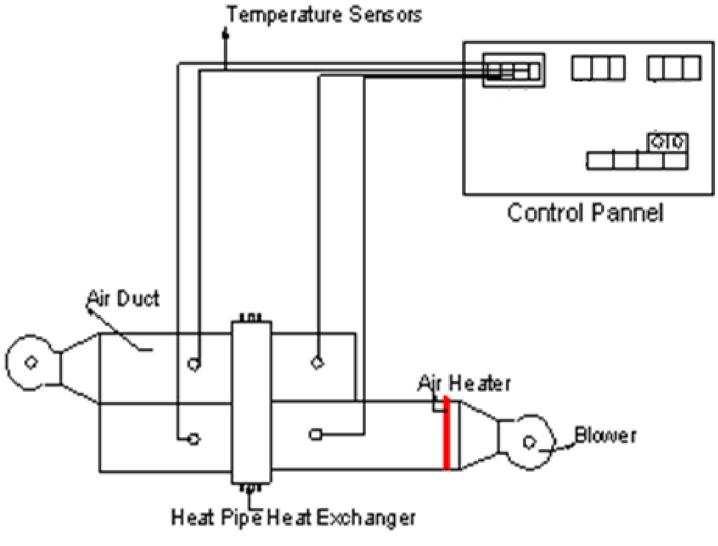

Figure 1. Experimental set-up layout.

For the proposed work, Zinc Oxide (ZnO) is selected as a nanofluid in the water base. The study of the effect of the particle size of nanofluid on thermal properties suggests that as the particle size decreases, the fluid's thermal properties improve. This happens up to a certain magnitude of particle size. From the previous studies, a particle size of 70 nm is chosen for nanofluid preparation. To take advantage of cost reduction by increasing thermal conductivity, nanofluid having a volume fraction of 2% is used for the present study.

2.2. Data reduction.

The heat supplied to heat the air is calculated from voltage and ammeter readings obtained. The efficiency of a heat exchanger with a heat pipe is expressed as thermal effectiveness. "The ratio of the actual heat transfer taking place to the maximum heat transfer possible by the heat exchanger is called thermal effectiveness". For the assumption that there is no water condensation present and specific heat remains constant for the flow of air passing through a heat exchanger, the effectiveness of the heat pipe heat exchanger is expressed as,

$$effectiveness\ (\varepsilon) = \frac{T_{hi} - T_{ho}}{T_{hi} - T_{ci}}$$

where T_{hi} and T_{ho} represent the inlet and outlet temperature of hot fluid while Tci denotes the inlet temperature of cold fluid.

Heat pipes are subjected to different heat transfer limits reliant on the type of fluid used in the pipe, the size, and the operating temperature range. The viscous limit normally occurs at lower operating temperatures, while sonic limits are related to vapor velocities on account of changes in vapor densities. The formation of bubbles in the wick structure puts a boiling limit, and the entrainment limit represents the liquid to be entrained by the vapor returning to the condenser. The heat pipe will work within the requisite temperature limits only when the axial heat flux calculated for various limits will be greater than a single heat pipe's proposed heat load capacity. The heat flux amount applied to the heat pipe for variable temperature should be less than the maximum value.

The different limits for considered heat pipes are calculated for different operating temperatures. The limits are plotted on a graph of heat flux wattage versus temperature, as shown in Fig. 2.

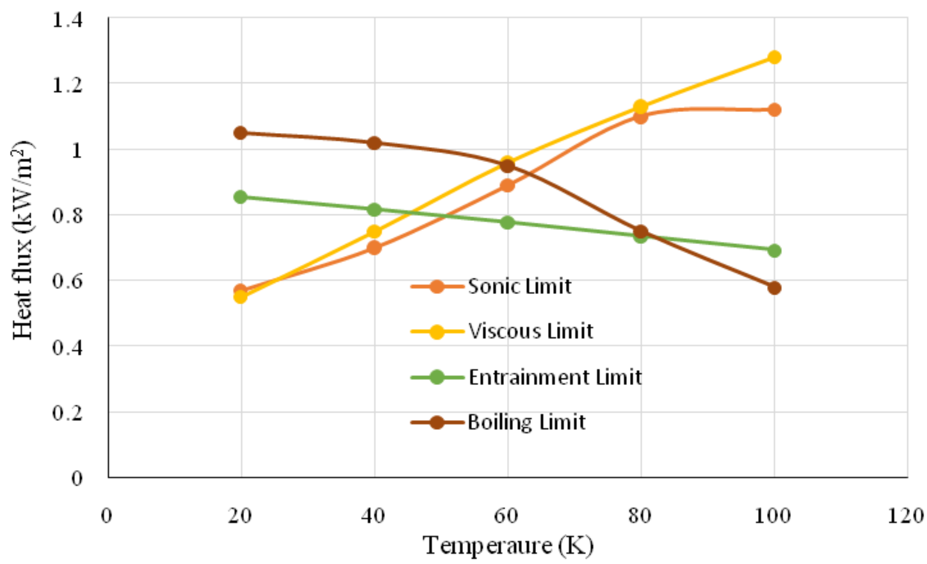

Figure 2. Limits of heat pipe at different temperatures.

3. Results and Discussion

Heat recovery performance by heat pipe heat exchangers having nanofluid is found for variable source temperatures. The source temperature is varied by regulating the load on the heater, to which energy supplied is controlled using dimmer stat. The mass flow rate of the air to the duct is also varied, and the performance is investigated. This is accomplished by changing the speed of the blower, which in turn varies the flow rate of the air being passed through the duct. During experimentation, the flow rate of the cold and hot streams of air is changed for specific heat input. The inlet and outlet air temperatures are recorded at a steady state for the cold stream and hot stream of air. The power supplied to the system by an electric heater is calculated, and air velocity is recorded using a vane anemometer. To assess the thermal performance of the heat pipe heat exchanger, the effectiveness is calculated under different operating conditions, and the results obtained are described in the succeeding discussion.

3.1. Airflow rate and effectiveness of heat exchanger.

To understand the deviation in the effectiveness of a heat exchanger with a flow rate of air passing through it, the heater input is set for particular wattage input, and the air's mass flow rate varies. The temperatures recorded are used to compute the effectiveness of the certain heat input at a given flow rate. The heat input values varied from 250 W to 1.5 kW. Figure 3 depicts the air mass flow rate on the effectiveness of the heat exchanger. It is observed that with the increase in heat input, the effectiveness decreases for the specific mass flow rate of air. It may owe to a lower temperature differential existing between two fluids. At lower mass flow rates, comparatively better heat exchange performance is observed compared to higher flow rates. This limits the use of mass flow rate that can be applied in applications. Interestingly, it is not the lowest heat input at which the lowest effectiveness is observed. The combined effect of mass flow rate and heat input may have caused higher heat pipe performance at lower heat input values.

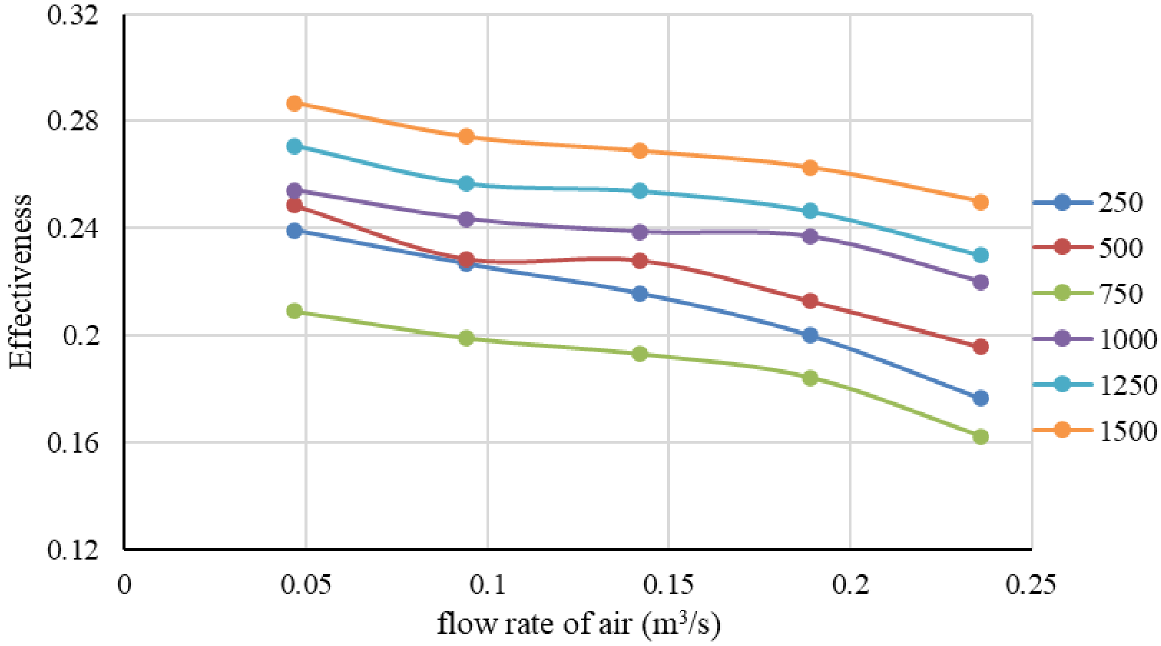

Figure 3. Effectiveness changes with the flow rate of air.

3.2. Effect of airflow rate on temperature difference at evaporator unit.

The temperature differential is noted at the evaporator section of the heat pipe due to the absorption of heat that changes the mass flow rate of air passing through it. The temperature differential recorded for different mass flow rates at specified heat inputs is shown in Fig. 4. It has been shown that when the mass flow rate of air increases, the corresponding temperature differential reduces for given heat input. This behavior is observed for all heat inputs. As the airflow rate increases, the air temperature differential decreases drastically. It may be due to higher heat transfer rates at higher flow rates. A higher temperature differential is observed for high heat input wattage relative to lower heat inputs. A temperature differential of 8.9 °C and 2.2 °C is observed for the lowest and highest mass flow rate, respectively.

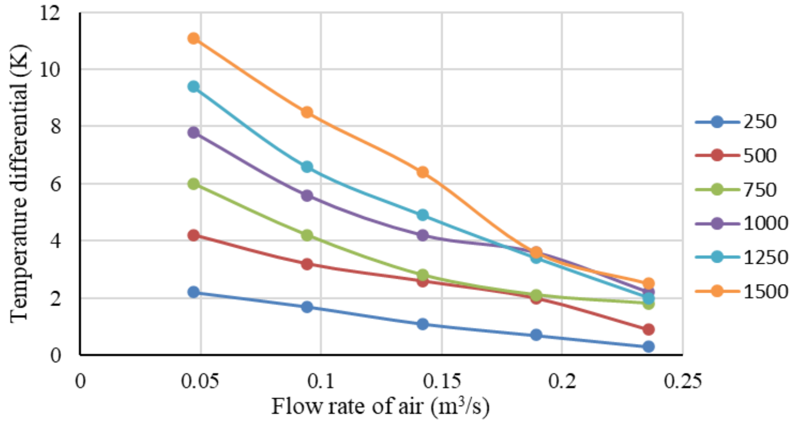

Figure 4. Temperature differential at the evaporator section for the different flow rates of air.

3.3. Variation in heat transfer coefficient with heat input at the evaporator section.

The experimentation is also used to understand the variation in the heat transfer coefficient with a change in heat input for varying airflow rates. The results obtained are plotted on a chart of heat transfer coefficient calculated versus air velocity at particular heat input. Figure 5 shows the change in the heat transfer coefficient with air velocity. It is found that the heat transfer coefficient rises with the escalation in velocity almost for all heat input. The lower heat transfer coefficients are experienced at lower heat input values than larger heat inputs. But the heat transfer coefficient differed more at higher velocities than at lower values.

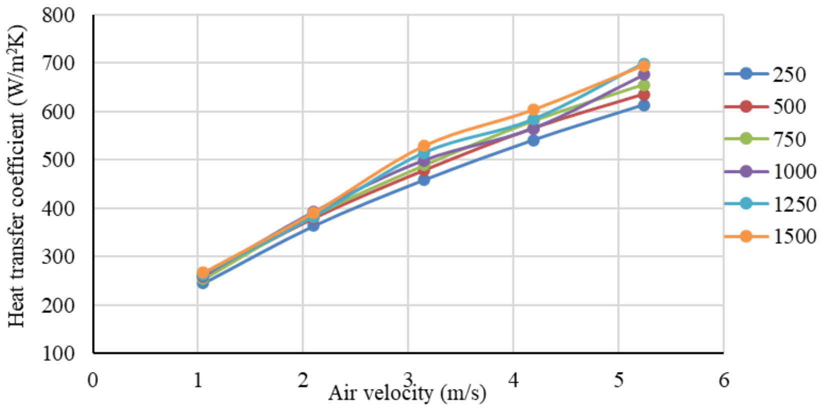

Figure 5. Variation in the coefficient of heat transfer with air velocity at evaporator section.

3.4. Variation in heat transfer coefficient with heat input at condenser section.

As for the evaporator, the coefficient of heat transfer is also calculated for the condenser section for different heat input values at varying air flow rates. The results obtained for the coefficient at different air velocities are plotted as shown in Fig. 6. The coefficient of heat transfer was observed to rise with heat input and airflow rates. The difference between heat transfer coefficients was found to be on the higher side for different heat inputs at higher airflow rates. A higher difference between heat transfer coefficients is observed for the condenser section compared to the evaporator section.

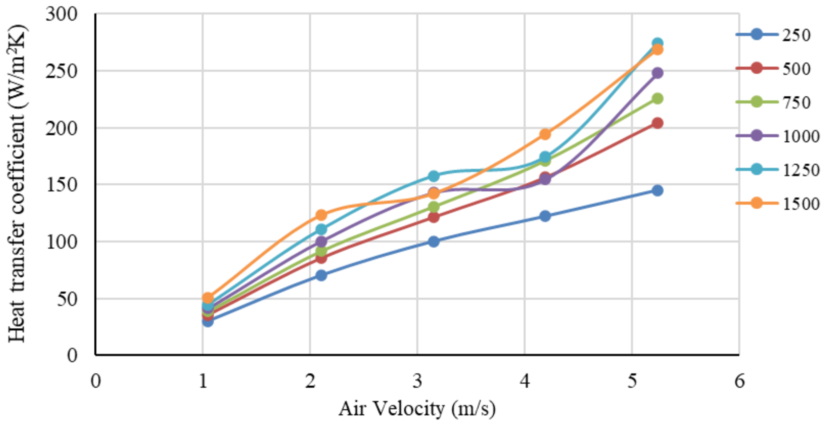

Figure 6. Variation in the coefficient of heat transfer with air velocity at condenser section.

3.5. Variation of Nusselt Number with heat input at the evaporator section.

The resistance to heat transmission in a flowing fluid scenario is often studied using the Nusselt number. The change in the values of the Nusselt number with alteration in heat input at the evaporator is studied, and the results are plotted concerning airflow rate, as shown in Fig. 7. The Nusselt number was found to rise with heat input and air flow rate. As the flow rate of the air increases, the deviation between Nusselt number values is found to increase for different heat inputs. This also emphasizes that the performance of the heat exchanger with heat pipe enhances as the heat input increases to the system.

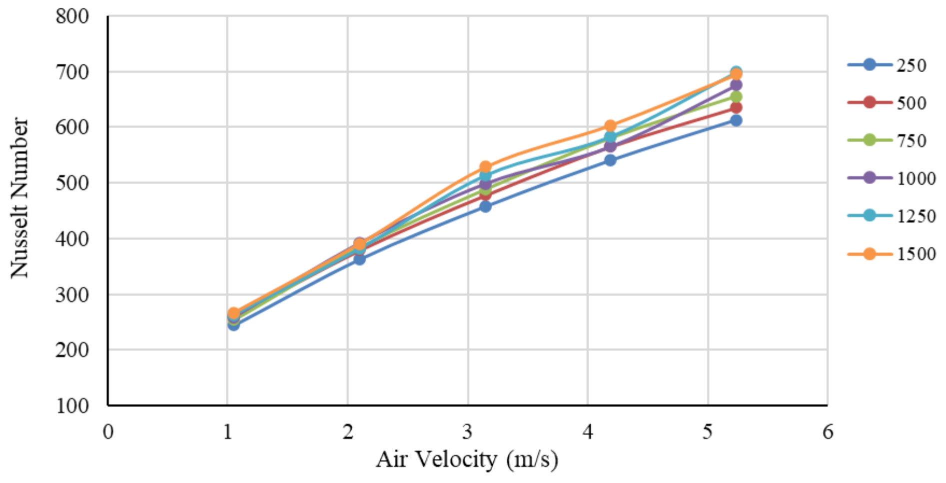

Figure 7. Nusselt Number change with heat input at the evaporator section.

3.6. Variation of Nusselt Number with heat input at condenser section.

Nusselt number is also calculated at the condenser section for varying input heat flux values. The variation of the Nusselt number is revealed to be the same in the situation of the evaporator. Figure 8 depicts the change in the Nusselt number for varying input heat flux values at the condenser. The values experienced are relatively lower for the condensation region than the evaporator region for the same input conditions of heat input and flow velocity.

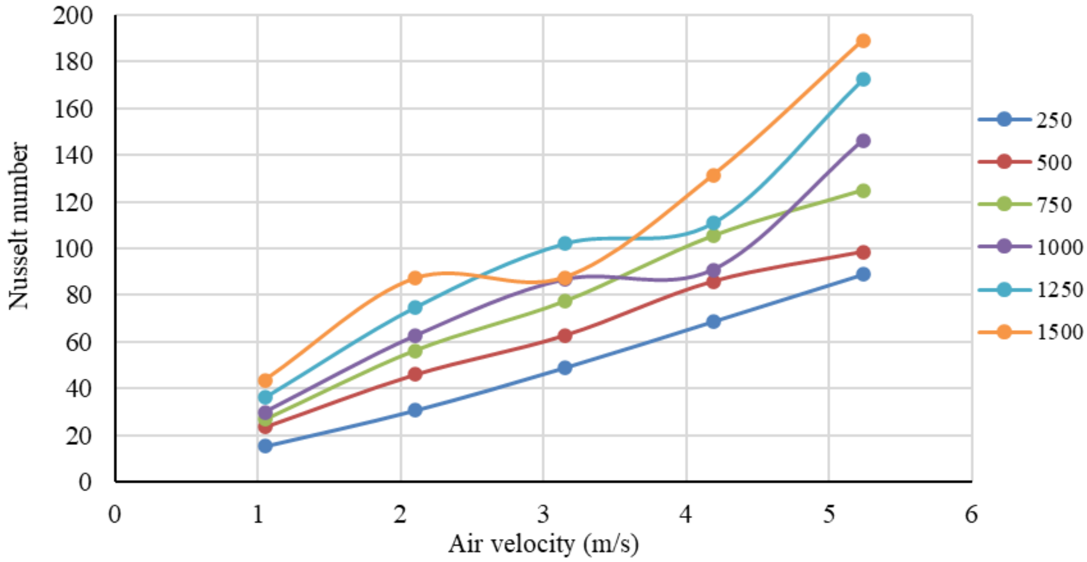

Figure 8. Nusselt Number change with heat input at condenser section.

4. Conclusions

The work reports the experimental analysis of a heat exchanger with a heat pipe that contains nanofluid zinc oxide (ZnO) suspended in a water base. The thermal performance of the arrangement is evaluated by computing its effectiveness. The impact of air stream flow rate and temperature at the source on the performance of the heat exchanger is evaluated by experimental analysis. The flow rate of the air streams is speckled from 0.048 m^3/s to 0.24 m^3/s. Different thermal feed was provided to the heater ranging from 0.25 kW to 1.5 kW. The system is designed to work at low temperatures for heat recovery.

It is noticed that with the source's temperature rise, the heat transmission through the heat pipe heat exchanger having nanoparticles of ZnO/H_2O improves. This improves the system's effectiveness, and the best value obtained for the effectiveness is 0.28. It is also observed that the heat changer heat pipe with ZnO/H2O nanoparticles performs superior to heat pipes that are charged with conventional fluids. The effectiveness of the heat pipe heat exchanger charged with nanofluid is due to nanofluid's enhanced heat transmission capability. The proposed heat exchanger system with heat can be employed effectively and efficiently to recover heat from low-temperature sources.

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Conflicts of Interest

The authors declare no conflict of interest.

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