GU J Sci 31(2): 616-626 (2018)

Gazi University

Journal of Science

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Experimental Investigation of an Al_2O_3 / Distilled Water Nanofluid Used In the Heat Pipes of Heat Exchangers

Ahmet ÖZTÜRK[1,*], Mehmet ÖZALP[2], Adnan SÖZEN[3]

[1] *Artvin Çoruh University, Artvin Vocational School, Department of Machine Part, 08100 Artvin, Turkey*

[2] *Karabük University, Engineering Faculty, Department of Mechanical Engineering, 78050 Karabük, Turkey*

[3] *Gazi University, Technology Faculty, Department of Energy Systems Engineering, 06500 Ankara, Turkey*

Article Info

Received: 26/07/2017
Accepted: 07/03/2018

Keywords

Aluminum oxide
Heat pipe
Heat recovery
Nanofluid

Abstract

This study investigates the thermal performance of a heat pipe heat recovery system in air-to-air heat recovery systems using a nanofluid of Al_2O_3 (aluminum oxide) particles and distilled water. The experimental setup used 15 wickless vacuumed copper pipes with a length of 1000 mm, a 10.5 mm inner diameter and a 12 mm outer diameter. The evaporator section consists of 450 mm of heat pipes, the condenser section is 400 mm, and the adiabatic section is 150 mm. In experimental studies, 33% of the evaporator volume of the heat pipes was filled with working fluids. Experiments were carried out at temperatures between 25ºC and 90ºC by using five different cooling air flows (40 g/s, 42 g/s, 45 g/s, 61 g/s and 84 g/s), and two different heating powers (3 kW and 6 kW) for the evaporation section, to determine the heat removed from the condensation section. Experiments were performed for distilled water and Al_2O_3 nanofluid, respectively, and the results were compared with each other. As a result of the experiments, it was observed that using a nanofluid as the working fluid increased the efficiency of the heat pipe. The highest efficiency (η = 59%) was obtained in the experiments carried out using an Al_2O_3 nanofluid at a heating power of 3 kW and an air flow of 112 g/s.

1. INTRODUCTION

The energy need has been continuously increasing in Turkey, as it has been in other developing and growing countries. As a result of rapid advances in technology in Turkey, and thus industrial development, the heat used in numerous systems is simply thrown out. The way for Turkey to globally compete in the world is to use this energy efficiently. Nanofluids kept in their suspensions have superior heat transfer potentials compared to conventional fluids due to their excellent thermal conductivity.

One of the methods for increasing the performance of heat pipes is to increase the surface area and thermal capacity of the surface over which heat transfer occurs. The purpose of this study is to increase the heat conductivity of a working fluid by adding nano aluminum oxide (Al_2O_3) particles – a metal oxide – into water, and thus improve the performance. The solution prepared by adding nanoparticles into water is called a nanofluid. The physical changes significantly improving the heat transfer performance of the working fluid due to the addition of nanoparticles are as follows [1]:

- The particles suspended in the fluid increase the surface area and thermal capacity of the fluids.
- Particles increase the thermal capacity of the fluid.
- Particles intensify the interaction and collisions between the fluid and the flow passage surface.
- The mixing of the fluid increases the magnitude of the turbulence.
- The dispersion of nanoparticles causes a smooth transverse temperature gradient across the fluid.

*Corresponding author, e-mail: ahmetozturk@artvin.edu.tr

There are many studies that have been carried out recently on the use of nanofluids in heat pipes. They can be summarized as follows:
Sözen et al. [2] compared the thermal performance of Fly-ash and Al_2O_3 used in the heat pipe of a two-phase thermosyphon under different working conditions. They used a copper pipe of 13 mm inner diameter, 15 mm outer diameter and 1000 mm in length for the heat pipe. They carried out experiments for three cooling water flows: 5 g/s, 7.5 g/s and 10 g/s, and three different heating powers: 200 W, 300 W and 400 W. They found a 30.1% decrease and a 5.2% decrease in the thermal resistance of the heat pipe compared to distilled water, for Fly ash nanofluid and Al_2O_3 nanofluid, respectively. Qu et al. [3] performed an experimental study to investigate the effect on thermal performance of using a water-based, 56 nm diameter, Al_2O_3 nanofluid in a closed-circuit oscillating heat pipe. According to experimental results, they found that when the power input was 58.8 W, thermal resistance decreased by 32.5% in the nanofluid – prepared by mixing metal particles at 0.9% concentration with distilled water. Noie et al. [4] used a distilled water/Al_2O_3 nanofluid prepared at 1 to 3 vol. % in a two-phase thermosyphon. Experimental results revealed that when Al_2O_3 was used at different power inputs, rather than using distilled water, the efficiency of the two-phase thermosyphon increased by 14.7% compared to distilled water. Hassan et al. [5] studied the effects of the deposition of nanoparticles on the wick porosity of the heat pipe by using various nanofluids. They prepared Al_2O_3 nanofluid at 1, 2 and 3 vol. %. These nanofluids were lined with a porous wick and filled into completely vacuumed copper heat pipes. In the first experiments, a substantial improvement was achieved for the performance of the heat pipe when distilled water and nanofluid were used. The images of the heat pipe wick were obtained by using scanning electron microscopy (SEM) for repeated experiments. The obtained images showed the deposited layer of agglomerated nanoparticles on the wick mesh surface. The agglomeration of these particles caused a serious capillary and thermal resistance, thereby negatively affecting the performance of the heat pipe.

Vijayakumar et al. [6] investigated the thermal characteristics of a cylindrical wick heat pipe by using CuO and Al_2O_3 nanofluids. They also studied the effects of inclination angle and heat input on the thermal performance of the heat pipe. For CuO and Al_2O_3 nanofluids, the optimal performance was achieved at a 45º inclination angle. They revealed that the heat transfer ratios for the evaporator and condenser sections at a 45º inclination angle increased by 32.99% and 24.59% for CuO and Al_2O_3 nanofluids, respectively. Kumar et al. [7] studied improvements to the thermal performance of a heat pipe by using Al_2O_3 nanofluid. They revealed that the performance of the heat pipe was largely dependent on the amount of working fluid it was filled with. Temperatures at different points on the heat pipe, and input and output temperatures of the cooling water were measured. The results proved that the amount it is filled, the heat input and the inclination angle had apparent effects on the performance of the heat pipe.

Hung et al. [8] studied the thermal performance improvement of a heat pipe filled with a nanofluid. They obtained the Al_2O_3/water nanofluid via a direct synthesis method by using a cationic chitosan diluting agent. They used the Al_2O_3/water nanofluid at three different concentrations: 0.5%, 1.0%, and 3.0%, and four different filling amounts: 20%, 40%, 60%, and 80%. Experimental results revealed that they found a 22.7%, 56.3% and 35.1% thermal performance improvement for 30 cm-, 45 cm- and 60 cm-long heat pipes, respectively, when the Al_2O_3/water nanofluid was used instead of distilled water, and the heating power was 40 W. Hassan and Harmand [9] studied the performance of rotating heat pipes by using various nanofluids. They used Cu, CuO and Al_2O_3 nanoparticles as working fluids in different diameters and filled the pipes with different amounts of fluid. Comparing the experimental results, when the Cu-water nanofluid, including 4 vol. % of Cu nanoparticles of 5 nm diameter was used in a heat pipe, the maximum heat transfer ratio increased by 56%. Teng et al. [10] investigated how to increase the thermal efficiency of a heat pipe filled with nanofluids. In experiments, the Al_2O_3/water nanofluid used as the working fluid for the heat pipes was produced by the direct synthesis method and prepared for three different volume ratios: 0.5%, 1.0%, and 3.0%. They studied the effects of filling the pipes with different amounts of fluid and using different inclination angles for the heat pipe on its thermal efficiency. According to experimental results, the optimal condition of the heat pipe was achieved for nanoparticles with 1.0 vol. %. When the thermal efficiency of the nanofluid was compared with distilled water, a 16.8% increase was obtained for the nanofluid.

Senthil et al. [11] carried out an experimental investigation on thermal efficiency and the thermal resistance of heat pipes by having the heat pipes at different inclination angles. For this purpose, they used an Al_2O_3 nanofluid with 9.8 g/cm^3 density and 1.0 vol. % Al_2O_3 as the working fluid. The performance of the heat pipe was evaluated for different thermal loads and inclination angles. Furthermore, the study investigated the effects of the nanoparticle volume and filling amount on the thermal resistance of nanofluids. Results indicated that the suspension of Al_2O_3 nanoparticles in the working fluid increased the thermal efficiency of the heat pipe. Kim et al. [12] experimentally investigated the effect of particle shape in an acetone-based Al_2O_3 nanofluid on the thermal resistance of a flat plate heat pipe. The acetone-based Al_2O_3 nanofluid, including spherical, brick and cylindrical nanoparticles, was prepared by a two-phase method without using any surfactant or filler. Comparing the experimental results with the thermal resistance of the pure acetone flat plate heat pipe, the thermal resistance values of nanofluids – with spherical, brick and cylindrical nanoparticles – decreased by 33%, 29% and 16%, respectively.

Air to air heat exchangers are widely used equipment's in a variety of applications. Particularly considering the type used for fresh air preheating by using waste heat, heat pipe including systems are more preferred for increasing the fresh air inlet temperature with transferred heat to fresh air. In order to be operated these systems under low waste heat temperatures, the working fluid inside the heat pipe must be evaporated at low temperatures. In this study, Al_2O_3 nanoparticles-including nanofluid, which evaporates at lower temperatures than deionized water, was used to solve this problem. So, both heat pipe performance and the thermal performance of the heat recovery unit could be improved. In the literature, there is a lot of work on heat conduction only, and with this work, an application for use of thermal conduit for thermal purposes has been realized.

2. EXPERIMENTAL METHOD

2.1. Preparation of Nanofluid

Al_2O_3 particles were made into nanoparticles with a size of between 14 to 17 nm by processing and purifying them in an SPEX 8000 crusher and ball mill. Normally they have a distribution size of between 5 and 50 nm. Nanofluids contain 2 wt. % of nanoparticles. A 0.2% amount of Triton X-100 was added into the solution as a surfactant to prevent formation of precipitations. Al_2O_3 nanoparticles were treated in an ultrasonic bath with water for five hours to homogeneously disperse them in distilled water, resulting in the required nanofluid. The container was hermetically closed to avoid evaporation of the liquid during the preparation of the nanofluid.

In experiments, it is important to prevent the precipitation of the nanofluid. Firstly, the amorphous structure was transformed into a nanostructure by using high-energy ball milling (Spex-8000). Secondly, the surfactant called Triton X-100 was added into an Al_2O_3 solution. Finally, nano Al_2O_3 particles were dissolved in an ultrasonic bath. Because the density difference between metal oxide nanoparticles and deionized water is high, two techniques were proposed to prevent the precipitation of nanoparticles in the nanostructures and achieve a homogeneous distribution [8]. One method is to change the pH value of the nanofluid, and the other is to use a surfactant. The use of Triton X-100 as a surfactant in Al_2O_3 nanoparticles allowed the distribution of particles in the deionized water.

The technical properties of the ultrasonic bath used in this study are shown in Table 1.

Table 1. *Characteristics of the ultrasonic bath*

Characteristic	
Voltage (V/Hz)	230/50
Ultrasonic Power (Peak/W)	600/300
Ultrasonic Frequency (kHz)	28

2.1. Heat Exchanger

Figure 1 shows the designed heat exchanger bundle consisting of 15 heat pipes. Each heat pipe was made of a vacuumed copper tube, and all of them were manufactured independently of each other. The copper pipes had a 12 mm outer diameter, a 10.5 mm inner diameter and a length of 1000 mm. Heat pipes were manufactured as follows: the evaporator section was 450 mm, the adiabatic zone was 150 mm and the condenser zone was 400 mm. Ten K-type thermocouples were placed on five heat pipes randomly selected from the heat exchanger bundle. Five out of the ten K-type thermocouples were positioned in the condenser section, and the remaining five thermocouples were positioned in the evaporator section; each of the five thermocouples was placed on the same heat pipe.

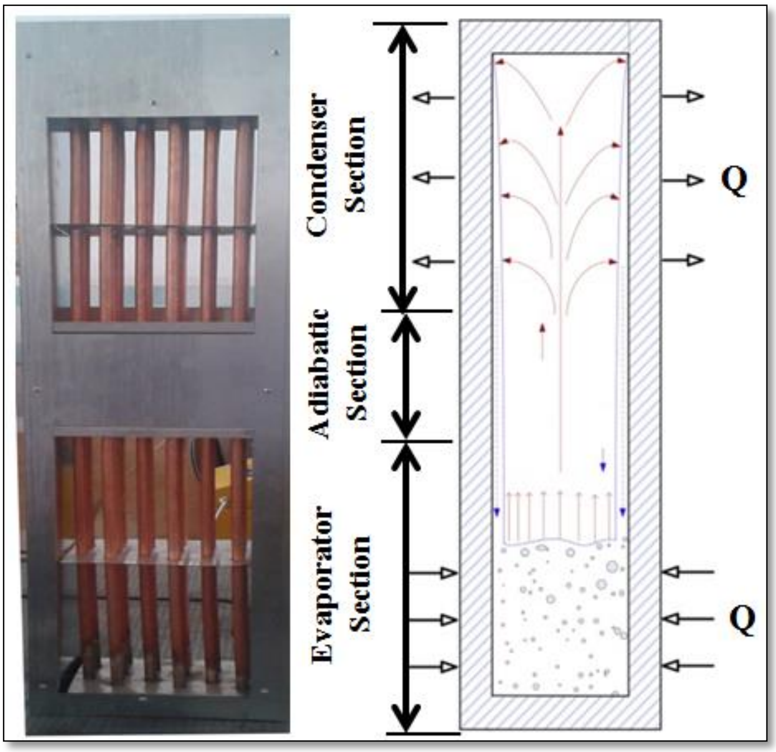

Figure 1. *The designed heat exchanger bundle*

The heat transfer mechanism takes place from the walls of the heat pipe towards the fluid. The fluid that starts evaporating from the evaporator section is transferred to the condenser section. The transferred heat is then transferred to a cold source. Vapor in the condenser section condenses and returns to the evaporator section through the pipe walls due to gravity. This process periodically occurs when heat input to the system is continuous. Briefly, it is possible to say that the heat is transferred from one section to another by utilizing the phase change of the working fluid.

2.1. Experimental Study

Figure 2 shows a schematic view of the experimental setup, while Figure 3 shows a photograph of the experimental setup. The test regions were constructed as follows: the air channels have two sections of 45 × 260 cm and two sections of 40 × 260 cm in area, and they are 1.3 m in length; there is one tube-body-type heat exchanger and two radial fans. One of these fans provides hot air to the evaporator section, while the other fan provides cold air to the condenser section. The velocity and mass flow rate of the air flow passing through the air channels was measured with an anemometer. As shown in Table 2, during the experimental study, the velocities and flows of both hot and cold air revealed similarities and differences.

As shown in Figure 2, 14 measurement points were determined in the experimental setup: one measurement point is on the evaporator inlet channel, one measurement point is on the evaporator outlet channel, one measurement point is on the condenser inlet channel, one measurement point is on the condenser outlet channel, five measurement points are on the heat pipes in the evaporator section and five measurement points are on the heat pipes in the condenser section. Temperatures were measured with K-type thermocouples and the temperature range was measured in steps of 0.1ºC. Thermocouples were placed in the middle of the evaporator and condenser sections, and in the air channels. The data obtained in these measurements were transferred to a computer through a data collection (ORDEL UDL 100) device in the experimental setup.

Table 1. *Air velocity and flow values used in the experiments*

	Stage 1 velocity test	**Stage 2 velocity test**	**Stage 3 velocity test**	**Stage 4 velocity test**	**Stage 5 velocity test**
Hot Air Velocity	2.03 m/s	2.24 m/s	1.70 m/s	2.05 m/s	1.15 m/s
Hot Air Flow	111 g/s	122 g/s	92 g/s	112 g/s	61 g/s
Cold Air Velocity	2.03 m/s	1.12 m/s	1.50 m/s	1.03 m/s	0.98 m/s
Cold Air Flow	84 g/s	45 g/s	61 g/s	42 g/s	40 g/s

The amount of working fluid used in the system was kept constant at 24 ml without considering the flow of the fluid used. This value corresponds to 1/3 of the evaporator volume in the heat pipe. During experiments, the heat pipe heat exchanger bundle was held horizontally at an angle of 90º. In the evaporation section, the heating power applied was 3 kW or 6 kW. The velocities and flows of the cooling air used in the condensation section were set at five different values, as shown in Table 2.

After vacuuming the heat pipes in the nanofluid setup, each of them was filled with distilled water first, followed by 2 wt. % Al_2O_3, prepared as a nanofluid.

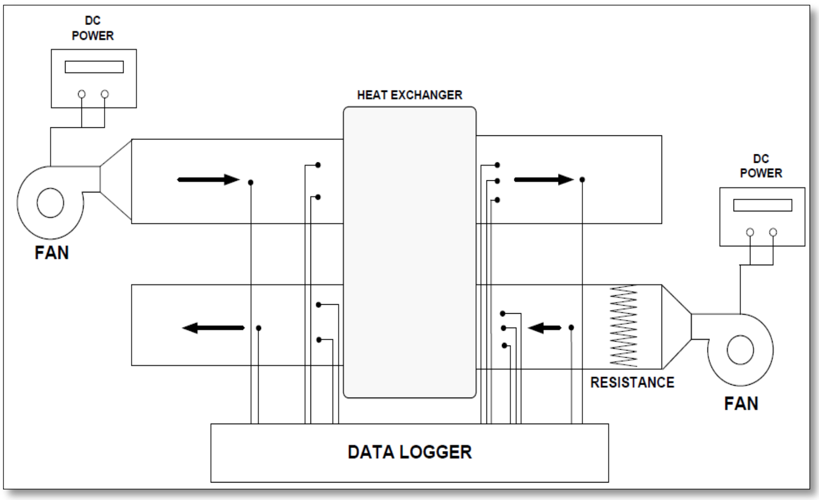

Figure 2. *Schematic view of the experimental setup*

Figure 3. *General view of the experimental setup*

3. RESULTS AND DISCUSSION

The efficiency of the heat pipe heat exchanger was investigated by using distilled water and Al_2O_3 working fluids at different powers (3 kW and 6 kW) in the evaporator section and different air flows in the condenser section.

The temperature difference between the inlet and outlet temperature of the cooling air used to remove the heat from the condenser section, the mass flow rate and the specific heat values of the air were all used to calculate the amount of heat transferred to the cooling fluid, and the amount of heat transfer was calculated as follows:

$$\dot{Q}_C = \dot{m}_C \,.\, \dot{c}_p \,.(T_{out} - T_{in}) \tag{1}$$

Thermal performance of a heat pipe is defined as the ratio of heat output of the condenser section to the heat input of the evaporator section and is calculated as follows [2]:

$$\eta\,(\%) = \frac{\dot{Q}_c}{\dot{Q}_e} = \frac{\dot{Q}_{out}}{\dot{Q}_{in}} \tag{2}$$

The efficiency of a heat pipe heat exchanger is found by using the equation below [13]:

$$\varepsilon = \frac{V_{ein}\, c_{p1}\, (t_{ein} - t_{eout})}{V_{cin}\, c_{p2}\, (t_{ein} - t_{cin})} \times 100 \tag{3}$$

Experiments were carried out filling the heat pipe with distilled water first and then the nanofluid with Al_2O_3 particles. Figure 4 compares the efficiency values of the fluids used for different intake air velocities and flows at the heating power of 3 kW, while Figure 5 shows the comparison of the efficiency values of the fluids used for different outlet air velocities and flows at the heating power of 3 kW. The experimental data were obtained after a minimum run of 30 minutes at each velocity stage. As a result of the experiments, the highest efficiency value of working fluids was achieved for the hot air inlet velocity of 2.05 m/s, and a fresh air inlet velocity of 1.03 m/s. Comparing the results obtained at a heating power of 3 kW, the maximum efficiency values were found to be 59% and 55% for Al_2O_3 and distilled water, respectively.

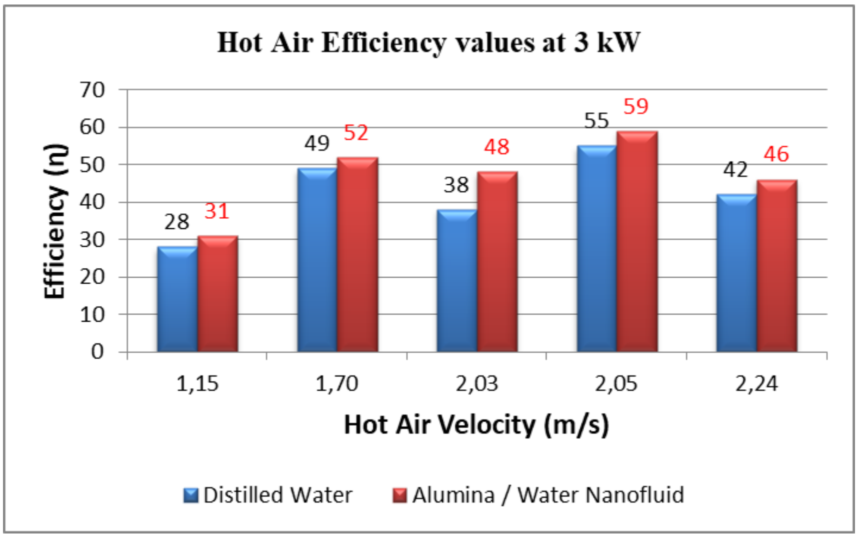

Figure 4. *Comparison of efficiencies of working fluids for various hot air velocities at 3 kW*

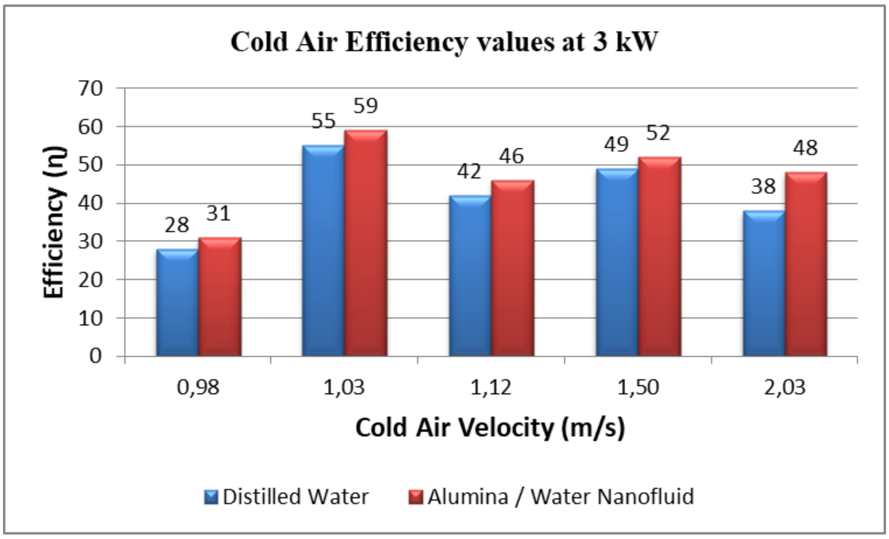

Figure 5. *Comparison of efficiencies of working fluids for various cold air velocities at 3 kW*

Efficiency values obtained for different air velocities at 3 kW are compared in recovery charts in Figure 6. According to the graphs, it can be observed that the maximum recovery achieved was 26.32% for an air velocity of 2.03 m/s.

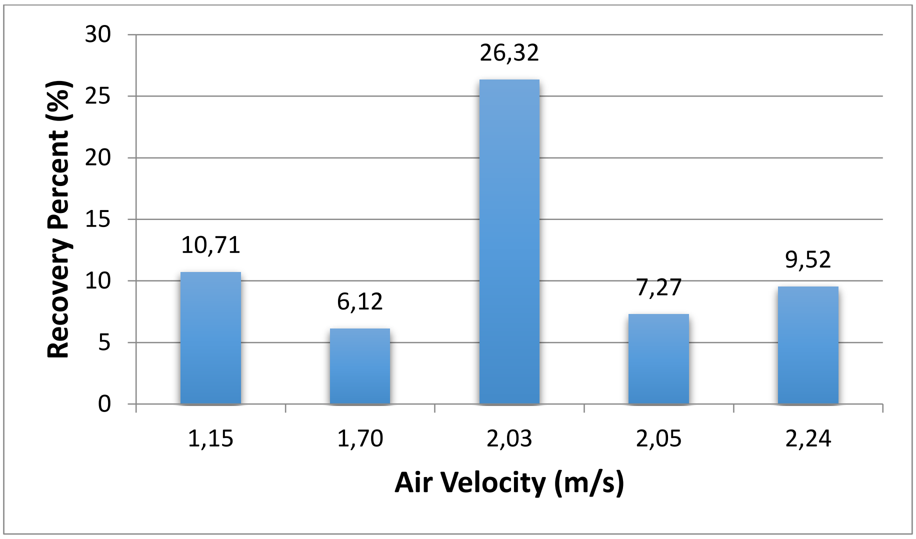

Figure 6. *Recovery percent for a power of 3 kW*

Figure 7 compares efficiency values of the fluids used for different intake air velocities and flows at the heating power of 6 kW, while Figure 8 shows the comparison of efficiency values of the fluids used for different outlet air velocities and flows at the heating power of 6 kW. As a result of experiments, the highest efficiency value of working fluids was obtained for the hot air inlet velocity of 1.15 m/s, and a fresh air inlet velocity of 0.98 m/s. Comparing the results obtained at the heating power of 6 kW, the maximum efficiency values obtained were found to be approximately 43% and 40% for Al_2O_3 and distilled water, respectively.

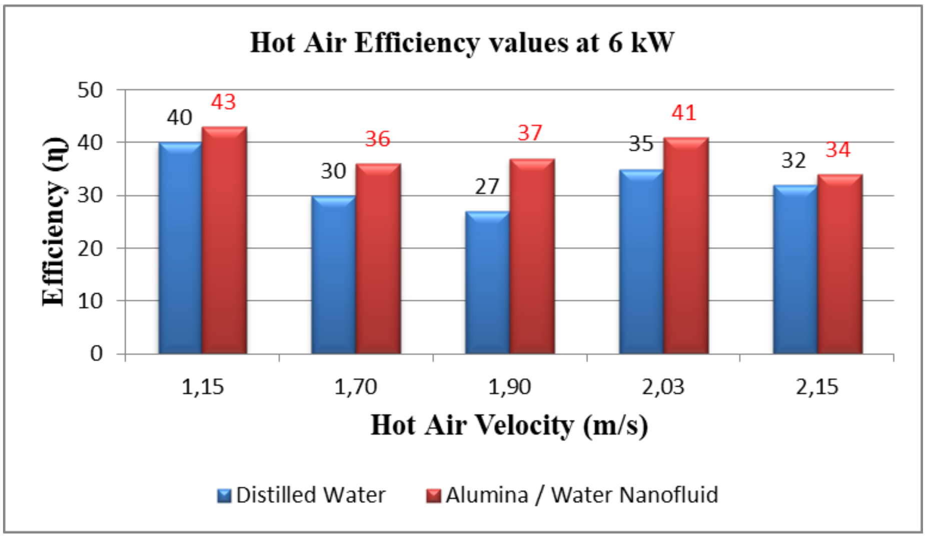

Figure 7. *Comparison of efficiencies of working fluids for various hot air velocities at 6 kW*

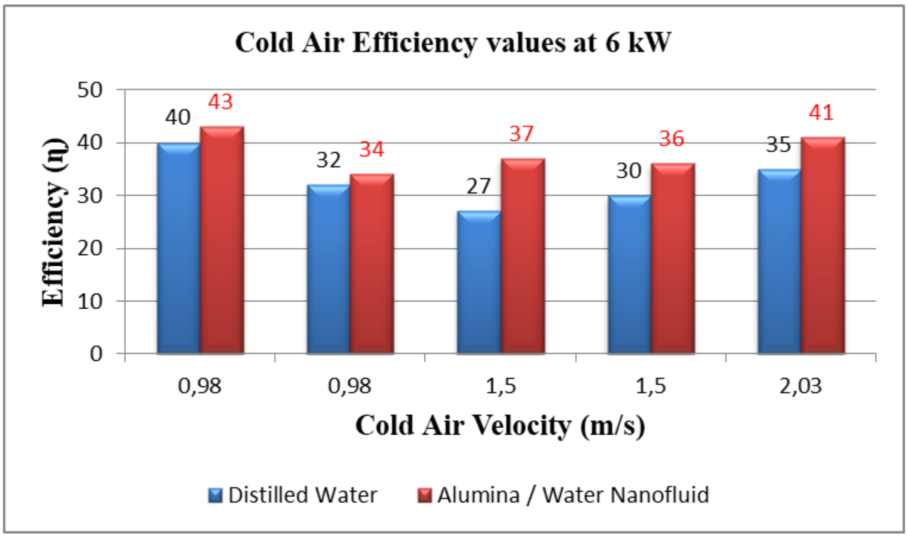

Figure 8. *Comparison of efficiencies of working fluids for various cold air velocities at 6 kW*

Efficiency values obtained for different air velocities at 6 kW are compared in recovery charts in Figure 9. Based on the graphs, it is seen that the maximum recovery was 37.04% for an air velocity of 1.90 m/s.

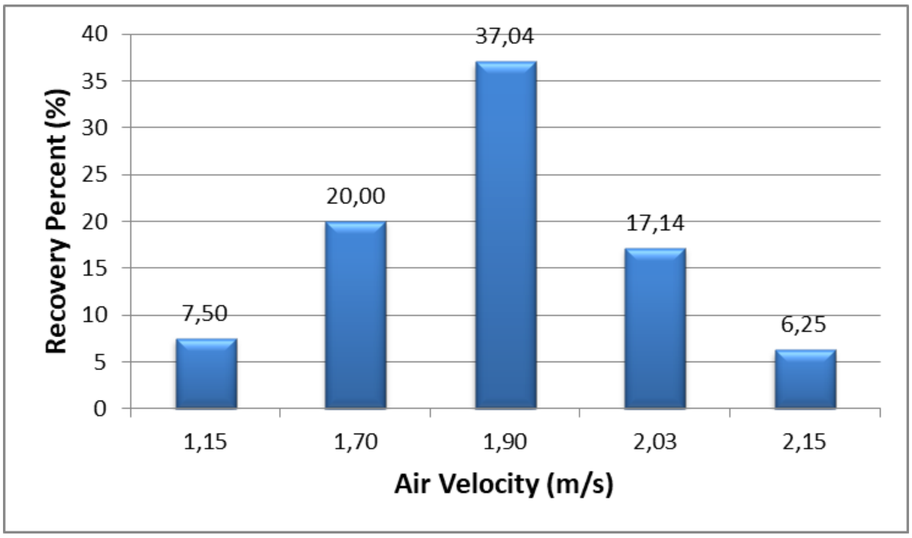

Figure 9. *Recovery percent for a power of 6 kW*

The main reason for these improvements was the presence of Al_2O_3 particles in the nanofluid used as the working fluid, and these nanoparticles increased the amount of heat transfer. An increased amount of heat transfer through the use of nanofluids was also revealed in these experiments. It was seen that the heat transfer rate increased when increasing the heating power of the working fluid and the return velocity of the working fluid to the evaporator section was also increased. However, unlike other experimental results, in the experiment carried out using a heating power of 6 kW and a cooling air flow of 40 g/s, it was observed that the average wall temperature in the condenser section was higher when the nanofluid was used. A smaller amount of cooling air flow in the condenser section, corresponding to increased thermal power, led to some amount of energy being trapped in the condenser walls during energy transfer. Despite increased heat transfer area due to the use of nanofluids, the cooling air flow of 40 g/s and the heating power of 6 kW were insufficient to produce efficient heat transfer between the cooling air and the working fluid.

As a result of the experiments performed, it was observed that the efficiency of the heat pipe increased with the use of a nanofluid as the working fluid. The highest efficiency (η = 59%) was achieved in the experiment using Al_2O_3 nanofluid at a heating power of 3 kW and an air flow of 112 g/s. Instead of using water as a working fluid in heat pipes (work in the literature), the use of nanofluids seems to improve the performance of thermal systems using heat pipes.

4. CONCLUSION

In this experimental study, carried out to determine the performance of the heat pipe heat exchanger, the working fluid was an Al_2O_3 nanofluid – obtained by mixing 2 wt. % of Al_2O_3 particles with distilled water – and distilled water. The evaluation of the performance data of the heat pipe heat exchanger is as follows:

i. Increasing air velocity of the evaporator section up to 2.0 m/s at a heating power of 3 kW increased the efficiency.
ii. It was observed that metal oxide particles in the nanofluid increased the conductivity of the working fluid and thus increased the efficiency of the heat exchanger.
iii. Increasing the amount of heat input decreased the efficiency in the heat pipe heat exchangers
iv. In working fluids, the thermal and energy recovery performance was higher for the Al_2O_3/ water compared to the distilled water.
v. Heat pipes used in the heat exchanger were wickless vacuumed pipes, and manufactured independently from each other.
vi. Gravitational force was used to return the working fluid to the evaporator section.
vii. Unlike other studies, 15 independent vacuumed heat pipes were used in the experiments.
viii. Higher efficiency values were obtained in the experiments in this study compared to other studies.

ACKNOWLEDGEMENT

This work was supported by Scientific Research Projects Coordination Unit of Karabük University. Project Number: "KBÜ-BAP-14/2-DR-018".

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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