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ORIGINAL PAPER

Influences of alumina and fly ash nanofluid usage on the performance of recuperator including heat pipe bundle

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Abstract
Energy efficiency becomes one of the most attracting study areas in the world because of the rising environmental issues. It is widely known that a plenty of energy efficiency applications are performed in heat transfer devices. In this regard, it is aimed to improve the thermal performance of recuperator, an air–air heat exchanger, including heat pipe bundle by utilizing a nanofluid, which is the mixture of nanoparticles of a metal oxide and deionized water, by this experimental study. The tests were conducted by filling the heat pipe at the rate of 1/3 of heat pipe volume both deionized water and alumina nanofluid, respectively. Coolant air was used to determine how much heat could be extracted from the condenser section. The findings obtained from the tests show that thermal performance of a heat pipe bundle-including recuperator was remarkably enhanced when nanoparticles containing working fluid was used as the working fluid in place of deionized water. The maximum improvement was achieved as 37.04% during the tests conducted at 6 kW heater power.

Keywords Air–air heat exchanger · Nanofluid · Alumina · Fly ash · Thermal performance · Energy efficiency

Introduction

Along with today's changing and rapidly developing technology and the increasing global warming, the use of environmentally sensitive energy saving devices has become a necessity. Most of the devices used for this purpose are recuperators in terms of being cheap, low maintenance costs and being able to produce them properly. Efficiency of the air–air heat exchangers vary depending on the temperature difference between the fluids. The greater the temperature differences between the fluids, the greater the proportion of the recovered energy. In systems where low temperature differences occur, the energy obtained from conventional heat recovery unit is in the trace amounts. For this reason, new designs are needed to save energy by recovering heat at low temperature differences. There is a great attention, particularly in recent years, towards nanotechnologic materials, and hence, nanoparticle form of the materials (TiO_2, Al_2O_3 and so on) has been frequently used to upgrade the system performance in industrial equipments (Laslouni et al. 2015; Haghighatzadeh et al. 2017; Ahmetoglu et al. 2016; Mutuk et al. 2016; Evcin et al. 2015; Göde et al. 2015). In other saying, nanotechnology becomes one of the most important parts of our life ranging from medicine to industry, especially in performance improvement applications in thermal systems (Sözen et al. 2018a, b; Öztürk et al. 2018; Xuan and Li 2000; Senthil et al. 2016; Qu et al. 2010). The related previous studies can be summarized as follows.

The heat recovery characteristics of a new-type flat micro-heat pipe array heat exchanger using δ-Al_2O_3-R141b nanofluid with different volume fractions were experimentally investigated. They performed their experiments with air volume flow rates varying from 60 to 120 m^3/h, also by setting inlet air temperature of the evaporator and condenser sections between at 27 °C–40 °C and at 24 °C, respectively. They reported that heat recovery efficiency could be enhanced remarkably by using nanofluid as working fluid (Zhang et al. 2013).

Effectiveness of a heat pipe heat exchanger and energy saving in air-conditioning systems using methanol–silver

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nanofluid as the working fluid was experimentally investigated. They designed and tested a heat pipe heat exchanger system comprising 36-plate finned copper thermosyphons arranged in three rows. They achieved an increment in energy saving around 8.8–31.5% for cooling and about 18–100% for reheating the supply air stream of the system (Firouzfar et al. 2012).

Heat transfer and turbulent flow of water/alumina nanofluid in a parallel and counter flow double pipe heat exchanger were investigated. They used single phase and standard k-ε turbulent model in order to determine the wall temperatures, thermal efficiency, Nusselt number, and convection heat transfer coefficient. They also examined the effects of nanoparticles volume fraction, flow direction, and Reynolds number on base fluid and nanofluid. They found out that maximum rate of average Nusselt number was 32.7% and thermal efficiency enhancement was 30%. Also noting that exit temperature of fluid and wall temperature increased as nanoparticles volume fraction was raised (Bahmani et al. 2018).

Performance improvement in the shell and tube heat exchanger by using nanofluid was numerically investigated. Influences of the nanoparticle shapes (platelets, blades, cylindrical, and bricks) on thermal performance of the heat exchangers aforementioned were examined. They obtained that heat exchanger thermoeconomic parameters can be improved higher in bricks nanoparticle shape and it is generally followed by blades, cylindrical, and platelets shapes, respectively (Hajabdollahi and Hajabdollahi 2017).

Improvement in the heat transfer rate of a concentric tube heat exchanger was experimentally investigated using alumina and fly ash nanofluids as the working fluid. Experiments they had were performed for parallel and counter current flow layouts. They reported that using nanofluid as the working fluid, heat transfer rate remarkably enhanced, particularly using fly ash nanofluids (Sözen et al. 2016).

Heat transfer enhancement by cylindrical blades that form turbulence inside the heat exchanger pipe was experimentally and numerically studied. They used different blade spacing and various blade angles to investigate the effects of the geometry on heat transfer rate. Nusselt number, Reynolds number, and effect of friction factor for all geometries were also investigated separately. They concluded that installed geometry inserts in the heat exchanger tube led to a significant increase in Nu number and energy saving (Karagoz et al. 2017).

Compact cross-flow air–air heat exchanger for aircraft gas turbine was designed using logarithmic mean temperature difference method, and its performance was studied experimentally. They presented and discussed the calculated results and obtained experimental findings by comparing each other and reveal a new experimental correlation (Li et al. 2017).

An air–air heat exchanger was utilized for a drying process. A mint dryer including an air–air heat recovery unit was designed and tested under varying conditions. It was found out in this study that using heat recovery unit in a dryer up to 48% energy saving can be obtained (Aktaş et al. 2017).

Many studies reveal that heat pipes can operate for all conditions regardless of how many the temperature difference is. Hence, a heat recovery at low working temperatures was tried to be achieved by designing a recuperator including heat pipe bundle in this experimental study. The tests were performed by using deionized water, alumina, and fly ash nanofluids as the working fluids of the heat pipes of the system. Obtained results were then discussed and compared. When previous studies were examined, no such research was found in the literature. Therefore, this study will be an application of the heat recovery at low temperatures.

This experimental study was performed in 2017 in Karabük University, Turkey.

Materials and methods

Preparation of nanofluids

Fly ash was obtained from the flue gas released from the cyclones of the Yatağan thermal power plant (Turkey). Initially, alumina and fly ash materials were grained to reduce the particle size to nano scales about ~ 50 nm. Then, a suitable surfactant (Triton X-100) and a base material [deionized water at the rate of 2% (vol)] were mixed with the obtained nanoparticles separately. This prepared suspension is called as nanofluid. The surfactant ensures nanoparticles to hang into base material and hence provides the stability of the mixture. Moreover, surfactant was doped into the suspension to decrease the surface tension and upgrade the wetting capability of the mixture. Before each experiment, each mixture was kept in an ultrasonic bath during 5 h to prolong the sedimentation of the nanoparticles in time.

Experimental study

A recuperator including heat pipe bundle was designed and tested in this study (Fig. 1). The test rig includes 7 items; two confined air channels for cold and hot fluid passages being of 45 × 260 cm area, two space being of 40 × 260 cm area and 1.3 m length, one tube heat exchanger, and two radial fans. Fans provide the required air passages for hot air to evaporator section and cold air to condenser section of the heat pipe system (Fig. 2).

Deionized water is generally used as a working fluid in heat pipes. Similarly, there has been an increasing trend towards the

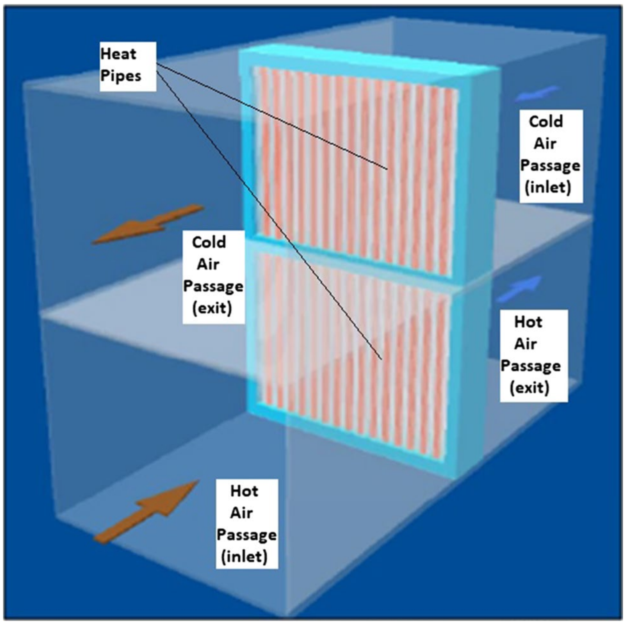

Fig. 1 A schematic view of the recuperator including heat pipe bundle

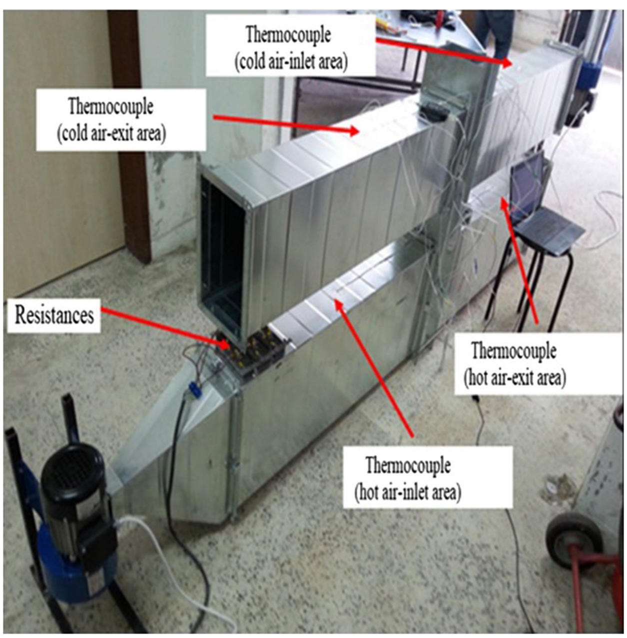

Fig. 2 A general view of the experimental setup

use of next-generation working fluids, which are called nanofluids with higher thermal conductivity in order to increase the performance of the heat pipes. Nanofluids are the working fluids in the form of a suspension of a nano-sized material and a base fluid (generally deionized water). In the experimental work, the efficiency of the recuperator including heat pipe bundle was investigated at various inlet temperatures (varying from 16 to 20 °C) and different airflow rates in the condenser section using deionized water, alumina and fly ash nanofluid working fluids. The velocities and air mass flow rates were measured via an anemometer. In Table 1, the air velocities were presented. Four airflow passage layouts (Case 1 to Case 4) were performed for each working fluid, and then, obtained results were compared to each other. Experiments were conducted for deionized water, alumina nanofluid, and fly ash nanofluid, respectively.

Uncertainty analysis

Uncertainty analysis is a sensitive and powerful method for analysing the experimental results (Sözen et al. 2018a, b). In an experimental study, some errors can take place derived from the some experiment conditions. Uncertainty analysis of the errors is significant to acquire wished experimental standards. A method presented by (Kline and McClintock 1953) was preferred for the uncertainty analysis of the results.

Temperature, input power, and air velocity were measured in this study. Therefore, overall uncertainties of these measured variables must be determined. The overall uncertainty of the temperature measurement (U_T) arises from the following three errors: accuracy of thermocouples ($u_{\text{thermocouple accuracy}}$), thermocouples' junctions ($u_{\text{thermocouple junctions}}$), and reading of the data from instruments (u_{reading}). So, the uncertainty of temperature (U_T) can be calculated as:

$$\begin{aligned} U_T &= \left[\left(u_{\text{accuracy, thermocuple}}\right)^2 + \left(u_{\text{junctions, thermocouple}}\right)^2 + \left(u_{\text{reading}}\right)^2 \right]^{1/2} \\ &= \left[(0.45)^2 + (1)^2 + (0.5)^2\right]^{1/2} = 1.205 \end{aligned} \tag{1}$$

The overall uncertainty of the input power (U_{IP}) derives from the accuracy of power supply ($u_{\text{power supply}}$) and reading of the data from instrument (u_{reading}). Therefore, the uncertainty in input power (U_{IP}) can be calculated as:

$$\begin{aligned} U_{\text{IP}} &= \left[\left(u_{\text{power supply}}\right)^2 + \left(u_{\text{reading}}\right)^2 \right]^{1/2} \\ &= \left[(1)^2 + (1)^2\right]^{1/2} = 1.414 \end{aligned} \tag{2}$$

The overall uncertainty of the air velocity measurements (U_V) can derive from the following two errors: accuracy of anemometer ($u_{\text{accuracy, anemometer}}$) and reading of the data from

Table 1 Air velocities and air mass flow rates utilized in experiments

	Case 1	Case 2	Case 3	Case 4
Hot air velocities (m/s)	1.15	1.90	2.05	2.15
Hot air mass flow rates (g/s)	61	101	109	114
Cold air velocities (m/s)	0.93	0.98	1.03	1.50
Cold air mass flow rates (g/s)	38	40	42	61

this device ($u_{reading}$). The uncertainty in the velocity measurement is:

$$\begin{aligned} U_V &= \left[\left(u_{\text{accuracy, anemometer}} \right)^2 + \left(u_{\text{reading}} \right)^2 \right]^{1/2} \\ &= \left[(0.01)^2 + (0.01)^2 \right]^{1/2} = 0.0141 \end{aligned} \tag{3}$$

As far as the overall uncertainties of the measured variables were concerned, it is said that they were in an acceptable range.

Results and discussion

Heat transfer quantity to intake air was calculated by using inlet and outlet temperatures of the intake air, as well as mass flow rate and specific heat capacity of the air.

$$\dot{Q}_c = \dot{m}_c c_p \left(T_{\text{exit}} - T_{\text{inlet}} \right) \tag{4}$$

The ratio of heat output of the condenser section to the heat input of the evaporator section is thermal performance of the heat pipe bundle and is defined and computed as:

$$\eta = \frac{\dot{Q}_c}{\dot{Q}_e} = \frac{\dot{Q}_{\text{exit}}}{\dot{Q}_{\text{inlet}}} \tag{5}$$

Finally, the efficiency of the recuperator including heat pipe bundle was described as the ratio of the supplied heat to evaporator to the extracted heat from the condenser. That is:

$$\varepsilon = \frac{\dot{m}_{\text{e,inlet}} c_{\text{p,e}} \left(T_{\text{e, exit}} - T_{\text{e, inlet}} \right)}{\dot{m}_{\text{c,inlet}} c_{\text{p,c}} \left(T_{\text{c, exit}} - T_{\text{c, inlet}} \right)} \tag{6}$$

In Eq. (3), c and e represents the condenser and evaporator, respectively.

The efficiency values obtained at varying air velocities for hot air passage carried out in the 3 kW heater power are shown in Fig. 3. It is clear from Fig. 3 that nanofluid usage as the working fluid enhances the efficiency of the heat pipe. The maximum efficiency was obtained as 68% when fly ash nanofluid was used as the working fluid. This value was achieved at 1.9 m/s hot air velocity.

Efficiencies obtained at varying air velocities for cold air passage carried out in the 3 kW heater power are presented in Fig. 4. Similarly, Fig. 4 exhibits that nanofluid usage as the working fluid enhances the efficiency of the heat pipe. The maximum efficiency was obtained as 68% when fly ash nanofluid was used as the working fluid. This value was achieved at 1.5 m/s cold air velocity.

The findings for 6 kW heater power are illustrated in Figs. 5 and 6. As can be understood from these figures, same trend in efficiency was observed. The maximum efficiency was obtained as 45% in the experiments using fly ash nanofluid and realized at 1.15 m/s hot air and 0.98 m/s cold air velocities, respectively.

The efficiency values for alumina nanofluid were lower than that of the fly ash nanofluid for all conditions. To illustrate, at 36 kW heater power and 1.9 m/s hot air velocity, efficiency values for alumina and fly ash nanofluid were 37 and 42%, respectively.

It is significant to note that the best results in efficiency were obtained for fly ash nanofluid compared to alumina nanofluid. However, nanofluid usage as the working fluid considerably enhanced the heat transfer rate compared to deionized water.

The experiments were performed only by changing the hot and cold air velocities. Temperature was measured several times, and a lot of values were obtained. Nonetheless, maximum and minimum temperatures for alumina nanofluid are illustrated in Table 2 for giving idea. It can be seen from Table 2 that temperature values vary from 16 to 83 °C.

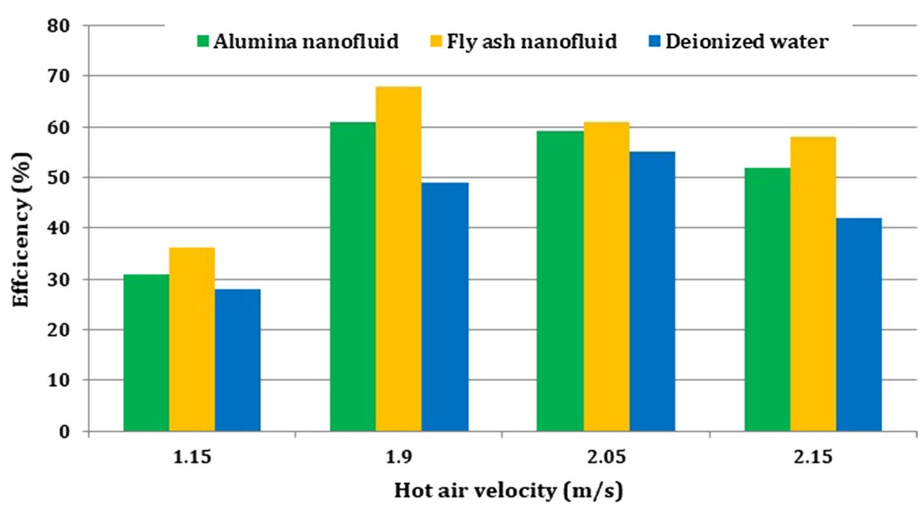

Fig. 3 Hot air efficiency values at 3 kW heater powers

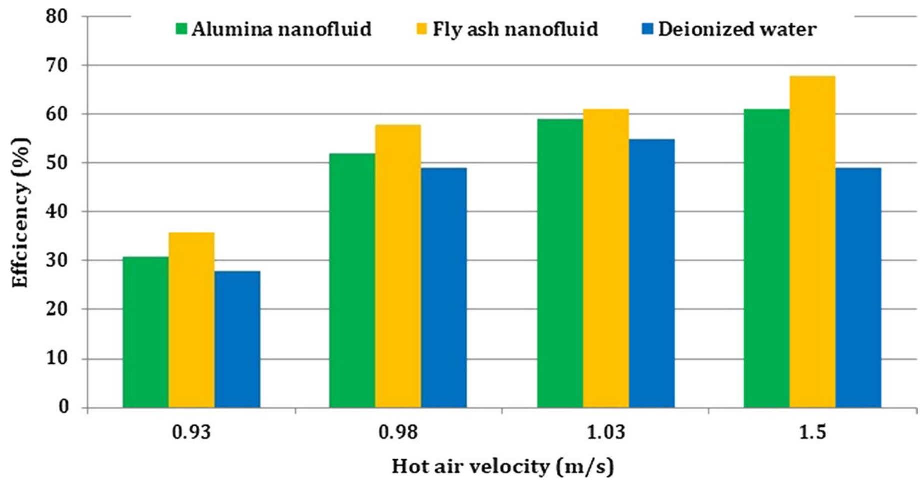

Fig. 4 Cold air efficiency values at 3 kW heater powers

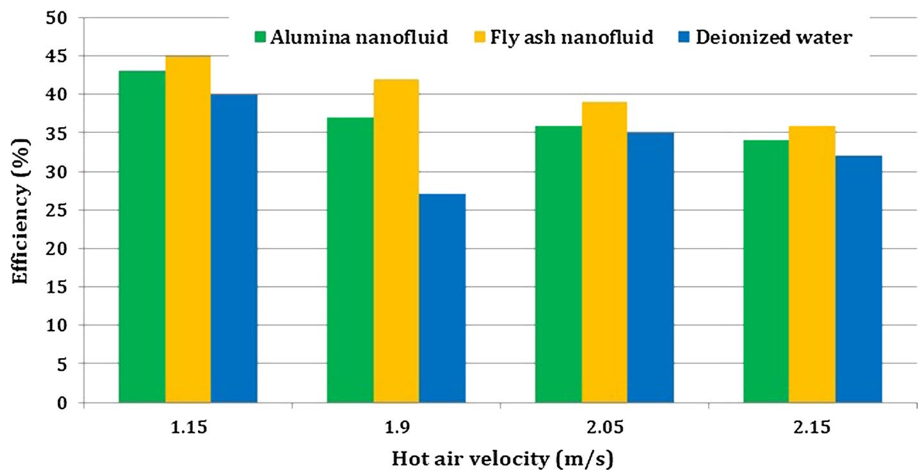

Fig. 5 Hot air efficiency values at 6 kW heater powers

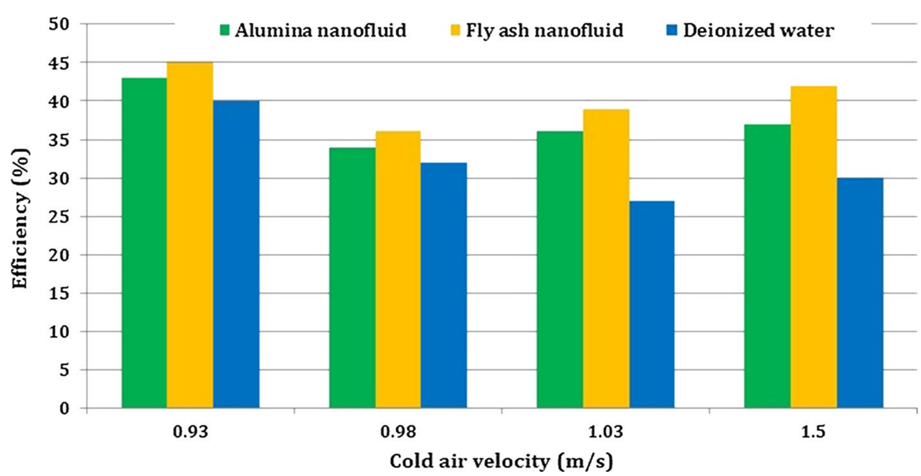

Fig. 6 Cold air efficiency values at 6 kW heater powers

Conclusion

In this experimental work, 2% (wt) concentrated alumina nanofluid, fly ash nanofluid, and deionized water were used as the working fluid to determine the performance of a recuperator including heat pipe bundle. As a result of the experiments:

- It was observed that the increase in the air velocity of the evaporator section up to 2 m/s has increased the efficiency in the experiments performed at 3 kW heater power.
- The thermal performance of the recuperator containing heat pipe bundle is significantly increased when the nanofluid is used as the working fluid in heat pipes.

Table 2 Acquired max. and min. temperature values for alumina nanofluid

Hot air velocity (m/s)	Cold air velocity (m/s)	3 kW		6 kW	
		Max. temperature (°C)	Min. temperature (°C)	Max. temperature (°C)	Min. temperature (°C)
1.15	0.98	53	16	83	20
1.90	1.50	43	17.6	63.5	18.9
2.05	1.03	41	18.5	58.6	17.6
2.15	0.93	40	18.6	58	17.5

- Even though the best results were attained from fly ash nanofluid, alumina nanofluid can be preferred instead of deionized water.
- It is proved that nanofluids can be used to improve the thermal performance of the heat pipe including air–air heat exchangers.

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List of symbols

$\dot{m}$: Mass flow rate (kg s^{-1}); R: Thermal resistance (KW^{-1}); $\dot{Q}$: Heat transfer rate (W); T: Temperature (K); ΔT: Temperature difference (K); ε: Efficiency; c: Condenser; c_p: Specific heat capacity (kJ kg^{-1} K^{-1}); e: Evaporator; i: Inlet; e: Exit; U: Uncertainty; η: Thermal performance

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