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Article

Experimental Investigation on the Performance of Heat Pump Operating with Copper and Alumina Nanofluids

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Abstract: In the present study, an attempt is made to enhance the performance of heat pump by utilizing two types of nanofluids namely, copper and alumina nanofluids. These nanofluids were employed around the evaporator coil of the heat pump. The nanofluids were used to enhance the heat input to the system by means of providing an external jacket around the evaporator coil. Both the nanofluids were prepared in three volume fractions 1%, 2% and 5%. Water was chosen as the base fluid. The performance of the heat pump was assessed by calculating the coefficient of performance of the system when it was operated with and without nanofluid jacket. A significant enhancement in the coefficient of performance was noticed when copper and alumina nanofluids were employed in the system. Also, the coefficient of performance was found to have a direct relationship with the tested volume fractions. For the highest volume fraction of 5%, the performance of the heat pump was found to enhance by 23% with alumina nanofluid, while for copper nanofluid, a very significant enhancement in performance by 72% was observed. Thus, utilizing of nanofluids in heat pumps can be very beneficial towards performance enhancement and the idea can also be extended to other thermal systems such as steam power plant, automobile radiator, industrial heat exchangers and refrigeration systems.

Keywords: Nanoparticles; copper nanofluid; alumina nanofluid; heat pump; coefficient of performance

Nomenclature

Q	heat transfer, kW
Cp	specific heat, kJ/Kg °K
m	mass, kg
k	thermal conductivity, W/m °K

Greek Symbols

Φ	volume fraction
ρ	density
Δ	difference

Subscripts

e	evaporator
c	condenser
w	water
t	total
p, np	nanoparticle
nf	nanofluid
f, bf	base fluid
eff	effective
R	refrigeration
HP	heat pump

1 Introduction

Application of nanofluids is the way forward in enhancing the performance of various thermal systems. One such system is the heat pump which is the focus of the current study. Nanofluids are being researched and tested extensively due to their superior thermo physical properties as compared to base fluids. To this extent, Narei et al. [1] carried out a numerical study to examine the effect of aluminum oxide (Al_2O_3) nanofluid on reduction in bore length of heat exchanger in ground sourced heat pump. As compared to water, Al_2O_3 nanofluid utilization resulted in reduction of bore length by 1.3%. The effect of zinc oxide (ZnO) nanofluid on the performance of a heat exchanger was experimentally investigated by Kumar et al. [2]. They reported that the use of ZnO nanofluid resulted in reduction of volume flow rate and increase in the heat transfer rate at the same pumping power as compared to pure water case. A comprehensive review on the thermo physical properties of nanofluids and their utilization in heat pumps/refrigeration systems was carried out by Bhattad et al. [3]. They suggested that nanoparticles can be applied in such systems as nano refrigerants and nano lubricants to enhance the system performance.

Bondre et al. [4] investigated the effect of Al_2O_3 nanoparticles by mixing them with refrigerant and using them as nano refrigerants. Various volume fractions of 0.05%, 0.1% and 0.2% were tested. Based on their findings, it was observed that the coefficient of performance (COP) of the system enhanced by 17% while the power consumption was reduced by a significant 32%. Another study involving the use of titanium oxide (TiO_2) in ammonia refrigeration system was carried out by Jiang et al. [5]. It was observed that the COP of the system enhanced by 27% at volume fraction of 0.5%.

Babu et al. [6] investigated the effect of using TiO_2 and Al_2O_3 nanoparticles as nano lubricants in the refrigeration system. The nanoparticles were tested for 0.1 and 0.2 g per liter of oil. The energy consumption was reported to reduce with the utilization of nano lubricant. Similar study on the thermo physical properties of TiO_2 and Al_2O_3 nano lubricant was carried out by Zhelezny et al. [7]. They concluded that the use of nanoparticles in oil increases the viscosity and decreases the surface tension of the nano lubricant. Another recent study focusing on nano lubricant was carried out by Nair et al. [8] wherein the effect of Al_2O_3 nanoparticles mixed in compressor mineral oil was studied. They reported an enhancement in COP by 6.5%.

Nanofluids also have their application in photo voltaic thermal systems. In this domain, an experimental and numerical study was carried out by Nasrin et al. [9] to investigate the effect of multi wall carbon nano tubes (MWCNT) on the performance of photo voltaic thermal system. An increase in overall efficiency by 3.81% was reported with the utilization of MWCNT. Similarly, for air conditioning systems, an experimental study was carried out by Hatami et al. [10] to investigate the effect of silicon dioxide (SiO_2), TiO_2 and carbon nano tube (CNT) nanofluids on the heating process of the condenser. They recommended using SiO_2 nanofluid as it resulted in lower energy consumption as compared to other nanofluids. In the case of air cooled heat exchanger, the effect of hybrid carbon nanofluids consisting of amorphous carbon, graphene oxide, and graphite-2H was experimentally investigated by Hung et al. [11]. They reported an increase in heat transfer by 13% for volume fraction 2% and flow rate of 2 L per minute.

Several studies are found in the recent literature wherein the nanoparticles are either mixed with the refrigerant or the compressor oil and the effect of resulting nano-refrigerant or nano-oil on the performance of the system is investigated. However, there are very few studies found in literature wherein nanoparticles are used around the evaporator as external fluid jacket and one such study was done by Hussain et al. [12]. Further, their study focused on testing only one type of nanofluid (Al_2O_3) and at low volume fractions (less than 1%). Another such study done by Vasconcelos et al. [13] focused only on investigating the effect of CNT nanofluid as a secondary loop around the evaporator section. Hence, the present study is required and is significant as it is based on investigating the performance of heat pump for two types of nanofluids (Al_2O_3 and Cu) and at higher volume fractions (1%–5%).

2 Experimental Set-Up

The experimental setup consists of four devices (compressor, condenser, expansion valve and evaporator) combined together to form the conventional heat pump as shown in Fig. 1. The experimental setup used in this research utilizes equipment manufactured by Libold Didactic Group based in Germany. The heat reservoirs are external jackets filled with fluids inside which the heating and cooling coils are submerged. The fluid jacket surrounding the evaporator coil is filled and tested for various fluids such as water, alumina nanofluid and copper nanofluid and the effect of these fluids on the performance of the system is evaluated. On the other hand, the fluid jacket surrounding the condenser coil is always filled with water and it serves as the heat sink for the refrigerant. The expansion valve is provided with a thermostatic control to adapt to the fluctuations in the system. Further, spiral tubing is provided at the inlet and exit of compressor in order to minimize the compressor vibrations from being transmitted to other components in the setup.

The power consumption of the compressor was measured by a digital wattmeter. As per the manufacturer's claim, the data acquisition system scans at a rate of 10,000 values per second. Pressure gauges are attached across the evaporator and condenser sections to measure the lower and higher pressure limits of operation. The temperature of the fluids in the external jackets was measured using Type-K thermocouples. These thermocouples were positioned inside the fluid jackets and are in contact with the fluids whose temperature is to be measured. The thermocouples are stationed to be horizontally and vertically centered in the fluid jackets.

In the present study, the effect of two types of nanofluids namely, copper and alumina nanofluid is investigated. Selection of these nanofluids was done based on their availability, cost and superior thermophysical properties as compared to other fluids. Three volume fractions 1%, 2% and 5% were tested for these nanofluids. The nanofluids were prepared using the two step method. In the first step, the nanoparticles were acquired in powder form and mixed with water as the base fluid. In the second step, the mixture is subjected to ultasonication process for 2 h in order to achieve a stable and homogeneous mixture.

Prior to any set of experimentation, the system was made to run initially for ten minutes and checked to attain steady state condition. Subsequently, experiments were carried out for water–water, alumina nanofluid-water, and copper nanofluid-water combinations around the evaporator and condenser coils, respectively. Every experiment was performed for duration of fifteen minutes. Every experiment was repeated five times and the mean of five data sets was taken into consideration for assessing the performance of the system. The initial temperature of water in the condenser jacket was always kept at 10°C while the initial temperature of all tested fluids in the evaporator jacket was kept at 60°C. The ambient temperature for all the experiments was 28°C. The performance of the heat pump is evaluated by comparing the COP when the system was run with water-water and nanofluid-water around the evaporator–condenser coils, respectively. The complete experimental setup is shown in Fig. 1. The system operates with R-134a refrigerant. The internal helix diameter is 13 cm for both the evaporator and condenser coils. The type-K thermocouple has nickel-chrome (NiCr–Ni), 1.5 mm tip. The connecting tubes are 2 m in length and 6 mm in diameter.

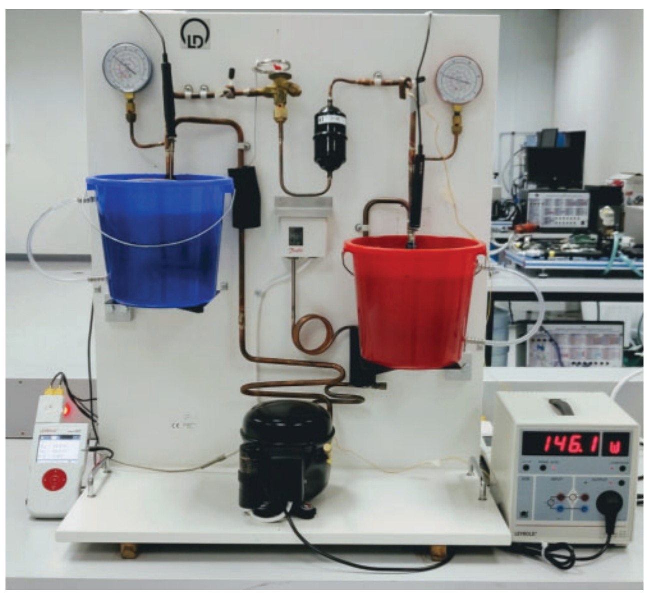

Figure 1: Experimental setup of heat pump

The schematic of the heat pump system with nanofluid is shown in Fig. 2.

The testing conditions were chosen to be as listed in Tab. 1.

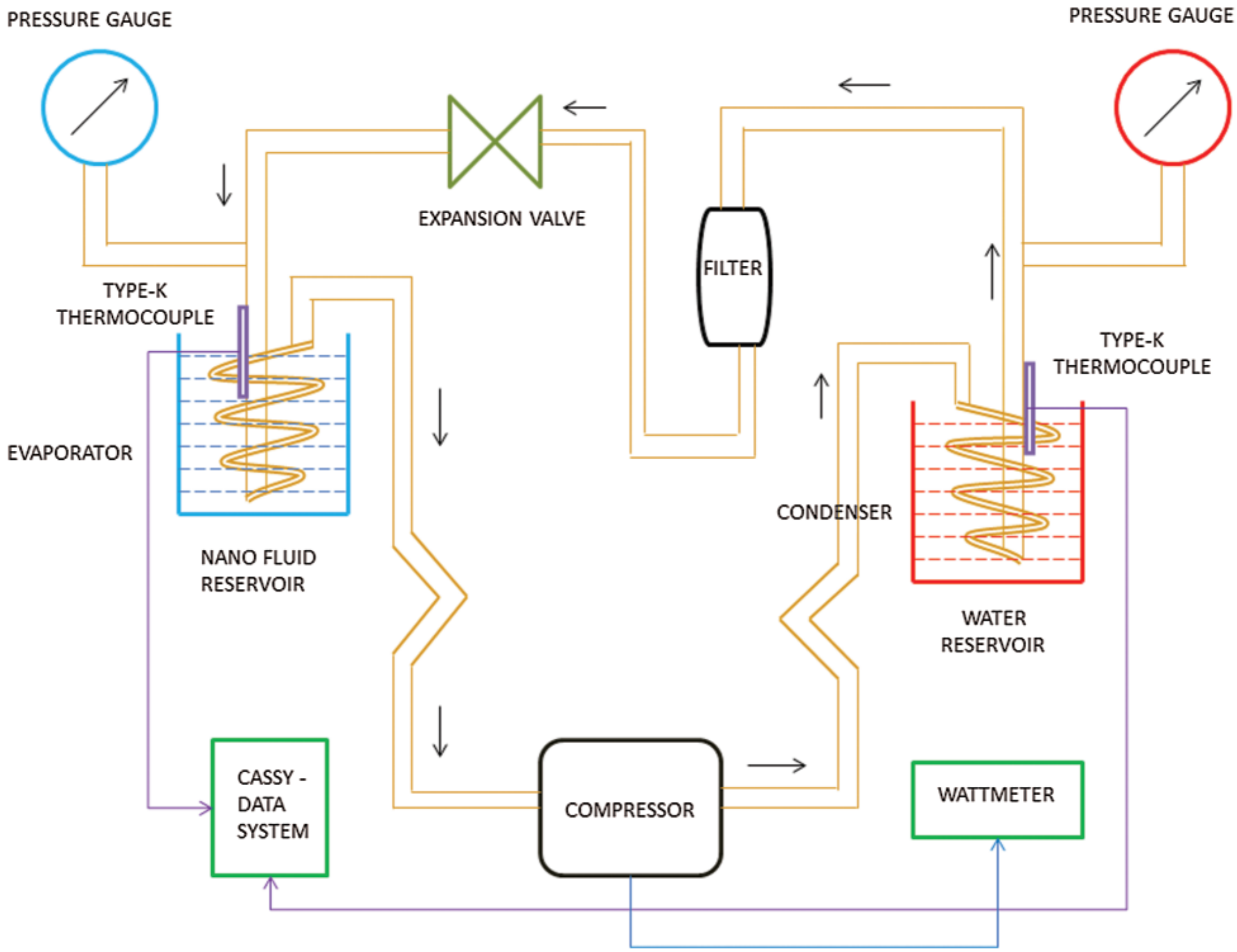

Figure 2: Schematic diagram of experimental setup

Table 1: Testing conditions

S.No	Parameter	Specification
1	Nano fluid volume fraction	1%, 2% and 5%
2	Al_2O_3 nanoparticle size	70 nm
3	Cu nanoparticle size	70 nm
4	Base fluid	Water
5	Ambient temperature	28°C
6	Evaporator and condenser capacity	7 liter
7	Evaporator loading	Water, Al_2O_3 and Cu nanofluids
8	Condenser jacket	Water

3 Data Reduction and Analysis

The heat transfer in evaporator section is calculated as:

$$Q_{nf-e} = m_{nf} C_{p-nf} \Delta \mathrm{T}_{e-nf} \tag{1}$$

The heat transfer in condenser section is determined as:

$$Q_{w-c} = m_w C_{p-w} \Delta \mathrm{T}_{c-w} \tag{2}$$

The total heat dissipated is estimated by applying the conservation of energy principle.

$$Q_{nf-e} + W_{in} = Q_{t-c-w} \tag{3}$$

Further, the total heat dissipated consists of heat contained with the fluid in the condenser jacket and heat losses taking place through various components of the complete system. These heat losses are estimated using the below equation.

$$Q_{t-c-w} = Q_{w-c} + Q_{losses} \tag{4}$$

The performance of refrigeration system is evaluated as:

$$COP_{ref} = \frac{Q_{e-nf}}{W_{in}} \tag{5}$$

The performance of heat pump is assessed using the equation:

$$COP_{HP} = \frac{Q_{t-c-w}}{W_{in}} \tag{6}$$

The volume fraction of nanoparticles is determined using the equation:

$$\phi = \left[\left(\frac{m_{nf}}{\rho_{nf}} \right) \Big/ \left(\frac{m_{nf}}{\rho_{nf}} + \frac{m_{bf}}{\rho_{bf}} \right) \right] \tag{7}$$

The density of the nanofluid is estimated using [14].

$$\rho_{nf} = \left[(1-\phi) \left(\rho_{bf} \right) + \left(\phi \rho_{np} \right) \right] \tag{8}$$

The specific heat capacity of nanofluid is determined using [15].

$$C_{p-nf} = \left[\frac{(1-\phi) \left(\rho_{bf} \right) C_{p-bf} + \left(\phi \rho_{np} C_{p-np} \right)}{\rho_{nf}} \right] \tag{9}$$

The effective thermal conductivity of the nanofluid is estimated using [16].

$$k_{eff} = k_f \left[\frac{k_p + 2k_f - 2\phi \left(k_f - k_p \right)}{k_p + 2k_f + \phi \left(k_f - k_p \right)} \right] \tag{10}$$

Although a lot of care was taken while carrying out the experiments, there always exists some uncertainty with experimental work which results from the measuring instruments. The uncertainty of measuring tools is listed in Tab. 2. The method described in [17] was used to calculate the uncertainty in COP. The resulting uncertainty was found to be less than 2.5%.

$$\frac{u_{cop}}{cop} = \sqrt{\left(\frac{u_{Q_{w-e}}}{Q_{w-e}}\right)^2 + \left(\frac{u_{W_{in}}}{W_{in}}\right)^2} \quad (11)$$

Table 2: Experimental uncertainty

S.No	Instrument	Parameter	Range	Uncertainty
1	Type-K thermocouple	Temperature	−50°C to 1100°C	±1.25%
2	Pressure gauge	Pressure	−1 to 10 bar (evaporator) −1 to 30 bar (condenser)	±1%
3	Wattmeter	Power	0.000 μWs to ±9999 kWh	±1%

4 Results and Discussion

The thermal conductivity of copper and aluminum is higher when compared to pure water whose thermal conductivity if 0.6 W/m °K. Therefore, the idea of utilizing Cu and Al_2O_3 nanoparticles and mixing it with water as the base fluid leads to higher thermal conductivity of the resulting nanofluid. Fig. 3 shows the variation of thermal conductivity of copper and alumina nanofluids at volume fractions of 1%, 2% and 5%. A maximum enhancement in thermal conductivity by 16% was achieved for copper nanofluid at the highest volume fraction.

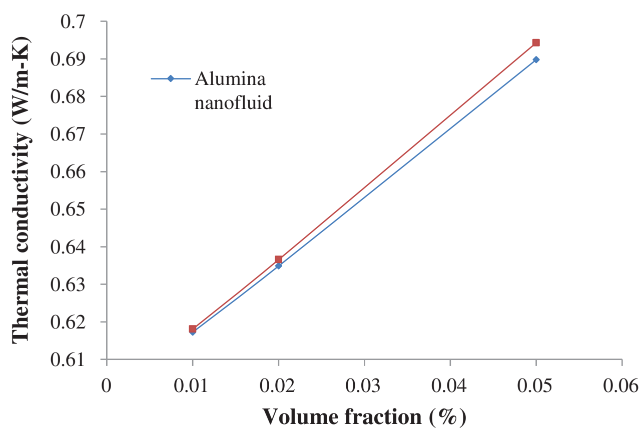

Figure 3: Variation of thermal conductivity with volume fraction

All of the experiments were repeated on different days under the same operating conditions so as to collect five data sets and then the average of these five data sets is considered for evaluating the performance of the system. Between the data sets, the standard deviation of the measured water temperature in the condenser jacket was 0.2. Similarly, the standard deviation of the measured temperatures of copper and alumina nanofluid around the evaporator coil was found to be less than 0.5. The initial temperature of water and nanofluids in the evaporator jacket was kept at 60°C for all the experiments. In the first case when the system was run with water as the fluid in the evaporator jacket, a decrease in temperature of the water by 20°C was observed. Next, when system was run with alumina nanofluid in the evaporator jacket, a maximum decrease in temperature by 28°C was observed for the highest volume fraction. Similarly, with the use of copper nanofluid, a significant decrease in nanofluid temperature by 50°C was observed for the highest volume fraction of 5%.

The heat transfer taking place across the evaporator section is represented in Fig. 4. Both copper and alumina nanofluids were observed to increase the rate of heat transfer. The increase in heat transfer while the refrigerant passes through the evaporator coil is due to the presence of nanofluid around the evaporator coil. The nanofluid serves as a heat source to the heat gained by the refrigerant in the evaporator coil. The enhancement in heat transfer is attributed to the increased thermal conductivity of the tested nanofluids due to the formation of thermal interfaces in the nanofluid [18].

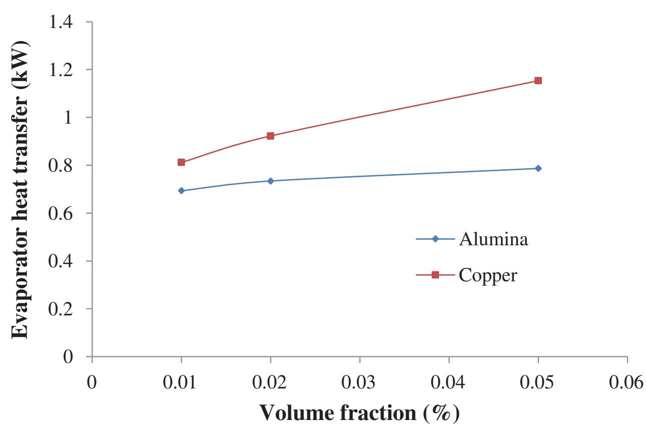

Figure 4: Variation of evaporator heat transfer with volume fraction

Further, copper nanofluid exhibited higher rates of heat transfer as compared to alumina nanofluid. The heat transfer rate was found to be directly proportional to the volume fraction of the nanoparticles and this is attributed to the Brownian motion of the particles [19–21]. As compared to pure water as the fluid jacket, alumina nanofluid was found to enhance the heat transfer by 6%, 13% and 21% for volume fraction of 1%, 2% and 5%, respectively. In case of copper nanofluid, the heat transfer enhancement was found to be more significant by 25%, 42% and 77% for volume fraction of 1%, 2% and 5%, respectively.

The addition of nanoparticles to the base fluid causes an increase in the thermal conductivity of the nanofluid while at the same time there is a decrease in specific heat capacity of the nanofluid. The specific heat capacity and thermal conductivity play an important role in the enhanced heat transfer across the evaporator section. The phenomena of micro conduction across the evaporator coil is also a contributing factor to the significant enhancement in heat transfer [22].

Before the commencement of any experiment, the system was allowed to run for ten minutes so as to minimize the fluctuations and reach steady state conditions. Once the system reached stability, the data was recorded. The system was observed to be operating with 12 bar as condenser pressure and 3 bar as evaporator pressure.

The variation of compressor power with utilization of nanofluid is illustrated in Fig. 5. Both copper and alumina nanofluids caused a reduction in compressor power consumed by the heat pump. It can also be observed that for higher tested volume fractions of nanoparticles, there is a further drop in the compressor power requirement. The compressor power requirement was lesser when the system was operated with copper nanofluid in comparison to alumina nanofluid. The reduction in compressor power with alumina nanofluid was by 2%, 4.4% and 6% for volume fraction of 1%, 2% and 5%, respectively. When copper nanofluid was employed, the reduction in compressor power was by 3%, 5.5%, and 7.2% for volume fraction of 1%, 2% and 5%, respectively. The reduction in compressor power is attributed to possible superheating of the refrigerant due to enhancement in heat transfer across the evaporator due to the presence of nanofluid jacket. This behavior of the system with reduction in compressor power is in line with the results reported by Hussain et al. [12].

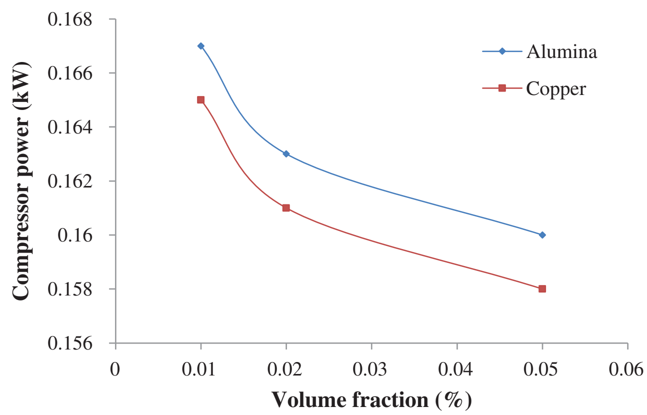

Figure 5: Variation of compressor power with volume fraction

Energy balance was applied across the complete system to determine the total heat dissipated from the system. This heat is simply the summation of evaporator heat input and compressor power. The total heat dissipated across the condenser section is illustrated in Fig. 6. Copper nanofluid showed higher heat dissipation as compared to alumina nanofluid. Further, the heat dissipation was found to enhance with increase in volume fraction of the nanoparticles. For alumina nanofluid, the heat dissipation was found to enhance by 5%, 9% and 15% for volume fraction of 1%, 2% and 5%, respectively, while for copper nanofluid, the enhancement was more significant by 19%, 32% and 60% for volume fractions of 1%, 2% and 5%, respectively. This enhancement in total heat dissipated across the condenser is attributed to the increase in heat transfer across the evaporator due to the presence of nanofluid jacket.

The initial temperature of water in the condenser jacket was kept at 10°C for all the experiments. For the first case with water in the evaporator jacket, an increase in the condenser jacket water temperature by 22°C was observed. Next, when alumina nanofluid was used in evaporator jacket, there was a maximum increase in condenser jacket water temperature by 28°C for highest volume fraction. Similarly, when copper nanofluid was used in evaporator jacket, the water temperature in condenser jacket rose by a maximum of 38°C for the highest volume fraction.

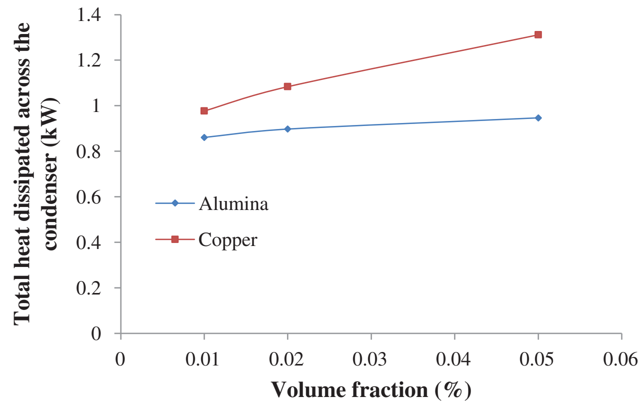

Figure 6: Total heat dissipated across the condenser for various volume fractions

The amount of heat contained with the fluid around the condenser section is shown in Fig. 7. This heat was estimated by measuring the temperature differential of the fluid for the complete duration of the system run time. An increase in heat transfer was observed when nanofluids were employed in the system. The utilization of copper nanofluid resulted in higher heat transfer as compared to alumina nanofluid. Furthermore, with increase in volume fractions, the heat transfer was found to increase. In case of alumina nanofluid, the heat transfer was found to enhance by 18%, 23% and 27 % for volume fraction of 1%, 2% and 5%, respectively. For copper nanofluid, the enhancement in heat transfer was more significant by 36%, 50% and 73% for volume fraction of 1%, 2% and 5%, respectively. The behavior of the system with enhancement in heat transfer to the fluid across the condenser is in line with the results reported by Hussain et al. [12].

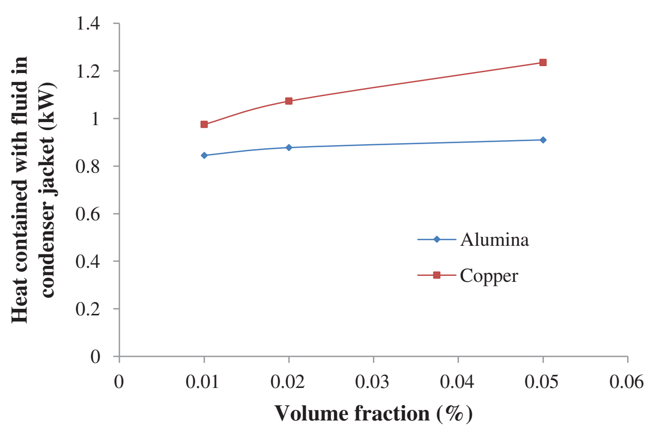

Figure 7: Variation of heat contained with condenser fluid

The heat losses taking place through the system are estimated using the conservation of energy principle. These heat losses are the heat losses taking place through various components in the complete system. The heat losses were found to increase with increase in volume fraction of the tested nanofluids. At the highest volume fraction of 5%, the heat losses with copper nanofluid were found to be higher than alumina nanofluid and this behavior is attributed to the increase in heat input to the system due to the presence of nanofluid which gives rise to the possibility of higher heat rejection from the system.

The performance of the system when operating as a heat pump is evaluated by calculating the coefficient of performance and illustrated in Fig. 8. The COP was calculated by taking into account the total heat dissipated across the condenser section. It can be observed that the use of alumina and copper nanofluids around the evaporator as external fluid jacket causes an enhancement in the performance of the system. Among the two types of nanofluids tested, utilization of copper nanofluid resulted in superior performance of the system as compared to alumina nanofluid. Further, the system performance was found to enhance with increase in volume fraction of the nanoparticles. In case of alumina nanofluid, the enhancement in COP was by 7%, 14.5% and 23% for volume fractions of 1%, 2% and 5%, respectively, while for copper nanofluid, there was a more significant enhancement in COP by 23%, 40% and 73% for volume fractions of 1%, 2% and 5%, respectively. This enhancement in system performance is due to the increase in heat dissipated across the condenser section.

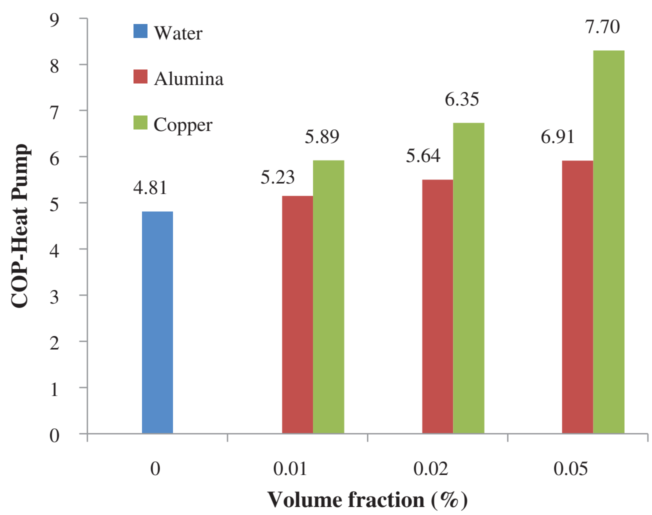

Figure 8: Variation of COP of heat pump with alumina and copper nanofluids

The performance of the system was also evaluated by considering it as a refrigeration system and is illustrated in Fig. 9. Again, both the nanofluids resulted in an enhancement in performance of the system. For the case of alumina nanofluid, the enhancement in COP was by 9%, 18% and 29% for volume fractions of 1%, 2% and 5%, respectively, while for copper nanofluid, a more significant enhancement in COP by 29%, 50% and 92% was observed for volume fractions of 1%, 2% and 5%, respectively. This enhancement in performance is attributed to the increase in heat transfer across the evaporator due to the presence on nanofluid jacket around the evaporator coil. The nanofluid medium causes a decrease in thermal resistance with increasing volume fraction [23] and this leads to significant improvement in system performance. The decrease in thermal resistance is due to the formation of porous layers of nanoparticles in the evaporator jacket. Further, these porous layers are not same for alumina and copper nanoparticles [24] and hence there is variation in the enhancements obtained by copper and alumina nanofluids.

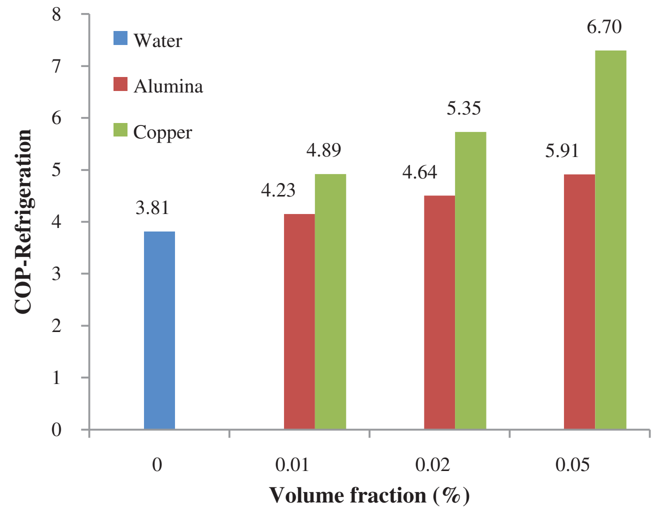

Figure 9: Variation of COP of refrigeration system with alumina and copper nanofluids

The thermal and physical properties of nanofluids depend largely on the size of the nanoparticles. With increasing size, there is an increase in heat transfer until it reaches an optimum value [25]. Therefore, the study can be extended further to investigate the possibility of further enhancement in system performance with bigger size nanoparticles. Affordability and availability of nanoparticles is a major concern with their utilization in thermal systems. Hence, nanoparticles which are economical and easily available are most likely to be preferred for use in thermal systems. The idea of using nanofluids can be linked to any practical system which involves exchange of heat between two fluids as is the case with heat exchangers which finds a place in lot of applications such as refrigeration system, heat pump, steam power plant, and automobile radiators.

5 Conclusions

In the present study, the performance of heat pump was experimentally investigated under the influence of copper and alumina nanofluids for three volume fractions. The nanofluids were employed in evaporator section as an external jacket. The major conclusions from this study are listed below.

1. The heat transfer across the evaporator and condenser region is significantly enhanced upon the utilization of nanofluids as external jacket around the evaporator coil.
2. The power consumption of the compressor is reduced when the system is operated with tested volume fractions (1%, 2% and 5%) of the nanofluid.
3. The coefficient of performance of heat pump enhances when nanofluid is employed as external jacket around the evaporator. Further, the performance enhances with increase in volume fraction of the nanofluids.
4. Copper nanofluid yields superior system performance as compared to alumina nanofluid due to superior thermal conductivity of copper nanofluid.

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Conflicts of Interest: The authors declare that they have no conflict of interest to report regarding the present study.

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