Received: 11 January 2020 | Accepted: 22 March 2020
DOI: 10.1002/htj.21735

RESEARCH ARTICLE

HEAT TRANSFER WILEY

Efficiency and effectiveness enhancement of an intercooler of two-stage air compressor by low-cost Al_2O_3/water nanofluids

Venkateswarlu Chintala[1] | **Vikesh S.**[2] | **Ashish Karn**[2]

[1]School of Engineering and Applied Science, National Rail Transportation Institute (NRTI), Vadodara, Gujarat, India

[2]Department of Mechanical Engineering, School of Engineering, Energy Acres, University of Petroleum and Energy Studies, Dehradun, India

Correspondence
Ashish Karn, Department of Mechanical Engineering, School of Engineering, Energy Acres, University of Petroleum and Energy Studies, PO-Bidholi, Dehradun 248007, Uttarakhand, India.
Email: akarn@ddn.upes.ac.in

Abstract

The present study was aimed to utilize low-cost alumina (Al_2O_3) nanoparticles for improving the heat transfer behavior in an intercooler of two-stage air compressor. Experimental investigation was carried out with three different volume concentrations of 0.5%, 0.75%, and 1.0% Al_2O_3/water nanofluids to assess the performance of the intercooler, that is, counterflow heat exchanger at different loads. Thermal properties such as thermal conductivity and overall heat transfer coefficient of nanofluid increased substantially with increasing concentration of Al_2O_3 nanoparticles. Specific heat capacity of nanofluids were lower than base water. The intercooler performance parameters such as effectiveness and efficiency improved appreciably with the employment of nanofluid. The efficiency increased by about 6.1% with maximum concentration of nanofluid, that is, 1% at 3-bar compressor load. It is concluded from the study that high concentration of Al_2O_3 nanoparticles dispersion in water would offer better heat transfer performance of the intercooler.

KEYWORDS

Al_2O_3/water nanofluids, effectiveness, efficiency, heat transfer enhancement, intercooler

1 | INTRODUCTION

Heat exchangers are widely used in various domains including industrial, transportation, and power generation sectors. Efficiency enhancement of heat exchangers is a key challenge for the chemical/processing industry, air conditioning and refrigeration industry, food industry, and waste heat recovery plants. Upsurge of electricity tariffs has made these industries to reduce their energy consumption for low operating costs and hence low product cost. Technologies to enhance the heat transfer capacity of heat exchangers have matured with employment of conventional heat transfer fluids or thermal oils. However, low thermal conductivity of these conventional fluids is a major bottleneck for developing energy-efficient and high-performance heat exchangers.[1] Recent developments in the field of nanotechnology has enabled the production of nonmetallic, metallic, or oxides particles of nanometer dimensions in an easy manner.[2] Nanomaterials have interesting mechanical, thermal, electrical, and optical characteristics and these can be suitably employed for different engineering applications. Nanoparticles with particle sizes of about 100 nm or below are dispersed in conventional coolants such as water, ethylene glycol, and oil to produce nanofluids.[3] Several studies in this field proved the attainment of significant improvements in thermal properties when nanoparticles were dispersed uniformly and stably in base fluids.[4] The addition of solid particles to the base liquid results in better heat conduction than sole liquid itself. Use of nanofluids may also decrease the demand for pumping power, which can save energy significantly. Due to their thermal properties, fluid can be circulated through the system resulting in reduced inventory. However, there is a need for low-cost nanoparticles to make a smooth transition from conventional coolants to nanofluids/coolants. Aluminum oxide (Al_2O_3) nanoparticles are one of such low cost and promising candidate for high heat transfer rates.[5-7]

Extensive research work has been expended so far on experimental and numerical studies to assess the thermal characteristics of nanofluids. For example, Nallusamy analyzed the effect of Al_2O_3-Water nanofluids (50 nm nanoparticles) on overall heat transfer coefficient of shell and tube heat exchanger in counter and parallel flow conditions.[8] Their studies indicated about 18% improvement in overall heat transfer coefficient.[8] Similarly, Mansour et al investigated the effects of Al_2O_3-dispersed particles in water at various fractions on development of thermal field under laminar flow condition inside an inclined tube.[5] They observed a slight improvement in overall heat transfer coefficient with an increase in volume concentrations.[5] Asadi et al[6] demonstrated the effects of Al_2O_3/MWCNT/thermal oil hybrid nanofluid at different concentrations ranging from 0.125% to 1.5% over temperature range of 25°C to 50°C and reported the maximum increase of 45% at 50°C with 1.5% concentration. Gaffar et al documented a significant improvement in the temperature field inside an inclined tube with uniform heat flux on outer surface when experimented with Al_2O_3/water.[9] The work of Albadr et al[10] on the effects of Al_2O_3/Water nanofluids with concentrations ranging from 0.3% to 2% in a horizontal shell and tube heat exchanger concluded that high concentration of Al_2O_3 nanoparticles increases the viscosity of nanofluid drastically, which further increases the friction factor. Rajput et al,[11] who investigated the use of Al_2O_3/Water nanofluid in a solar water heater-flat plate collector, discovered about 21.3% increase in the collector efficiency with increasing volume fraction of Al_2O_3 from 0.1% to 0.3%. On the other hand, Kapil et al[12] carried out the numerical investigation on mixed convective heat transfer with Al_2O_3/water nanofluid in an enclosed cavity. Nanoparticles concentration was varied from 1% to 5% for specific Reynolds numbers (1, 10, and 100) and reported a substantial improvement in heat transport with increasing concentration of nanoparticles.[12] Recently, Al_2O_3/Water nanofluids were also used for effective and rapid heat transfer during cutting process in manufacturing sector.[7,13]

It should be noted that the thermal behavior improvement with nanofluids depends on various parameters such as nanoparticles' size, particles' concentration, and operating temperature. In this context, a comparative assessment was carried out by Teng et al[14] with different diameters of Al_2O_3 nanoparticles (20, 50, and 100 nm) and different concentrations (0.5, 1.0, 1.5, and 2.0 wt%) in water. Smaller size nanoparticles at high temperature exhibited better thermal behavior.[14] Nanoparticle size and their concentration are other parameters that improve the heat transfer rates.[15] Increased surface area with addition of nanoparticles would help to improve the efficiency of thermal systems.[16,17] In another study, the heat transfer behavior of a shell and tube heat exchanger was assessed with Al_2O_3/Water and TiO/water nanofluids with different particle sizes.[18] Their experimental results revealed that Al_2O_3/Water nanofluid exhibited better thermal behavior than TiO/water nanofluid with high-diameter nanoparticles.[18] Dharmalingam et al[16] concluded that the operating temperature plays a key role to enhance the performance of nanofluid-based system. However, nanofluids utilization suffers a problem of poor suspension characteristics. A substantial drawback with suspension of micro-sized particles was agglomeration and settling of the particles.[19,20] Constant circulation may prevent this; however, it can clog the microchannels and wear out mechanical components.[20,21] Nanoparticles have a higher surface area when compared with microparticles. The number of atoms present on the surface of nanoparticles is high. Furthermore, the extremely minute size of particles may reduce erosion and clogging drastically. Sarkar et al[22] reviewed the possible applications of hybrid nanofluids in industries and concluded that improved thermal conductivity is one of the driving parameters for their effective utilization. Similarly, Kumar et al[23] studied the nanofluids employment in plate heat exchangers. Detailed assessment of parameters such as viscosity, thermal conductivity, specific heat, and heat transfer coefficient was carried out.[23] Different kinds of nanofluids such as CeO_2, Al_2O_3, TiO_2, and SiO were tested in a plate heat exchanger with different volume flow rates and concentrations.[24] Among these nanofluids, CeO_2 was the best for high heat transfer coefficients and improved performance.[24]

It is observed that the information available in literature on the use of nanofluids in practical applications is scanty. Studies on thermal behavior improvement of intercoolers used in multistage compressor are inadequate. Hence, an attempt has been made to use low-cost Al_2O_3/water nanofluid in an intercooler of two-stage air compressor at different volume fractions to study its effect on performance with varying loads. Experimental tests were carried out to assess heat transfer enhancement, efficiency and effectiveness, and improvement of the intercooler with various concentrations of Al_2O_3/water nanofluids at different loads on the air compressor.

2 | MATERIALS AND METHODS

2.1 | Materials used in the study

It is well-known that there are two major classification of nanofluids, that is, ceramic and metallic. In the present investigation, ceramic kind of nanofluid was used as a substitute for water in an intercooler of two-stage air compressor. In view of commercial availability and low cost, Al_2O_3 was chosen as metallic oxide and it was dispersed in base fluid, that is, distilled water. Al_2O_3 nanoparticles (Figure 1) were sourced from Nano Research Laboratory, India and distilled water was used to disperse the Al_2O_3 nanoparticles. Table 1 shows the physical properties of Al_2O_3 nanoparticles.

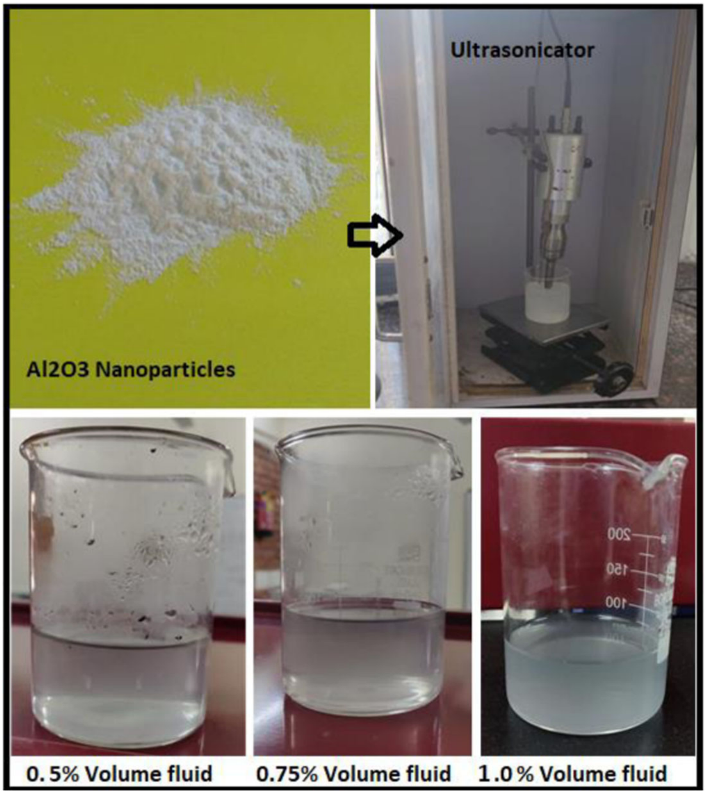

FIGURE 1 Preparation of nanofluid using an ultrasonicator [Color figure can be viewed at wileyonlinelibrary.com]

2.2 | Nanofluid preparation methodology

Al_2O_3/Water nanofluid of different %volume concentrations, that is, 0.5%, 0.75%, and 1.0% was prepared by a two-step process. The main reason behind choosing this method was to reduce the cost of preparation. Even though the two-step process is inefficient in producing stable nanofluid for longer duration, this methodology was chosen to demonstrate and assess the effect of Al_2O_3/water nanofluid on heat transfer behavior of an intercooler. Initially, the

TABLE 1 Physical properties of Al_2O_3 nanoparticles

Parameters	Properties
Particle size	80-100 nm
Density	3.89 g/cc
Thermal conductivity	42 W/m K
Specific heat	880 J/kg K
Melting point	2072°C
Solubility	Insoluble in water
Flash point	12°C
Appearance	White amorphous powder

samples of 100 ml were prepared to find the optimum conditions for ultrasonication for preparing stable dispersion of nanoparticles in distilled water (Figure 1). It was found that when the samples were ultrasonicated for 90 minutes at 40°C for 40 seconds "On" cycle and 20 seconds "Off" cycle, better dispersion was observed. After obtaining these optimum conditions, a total of 7 L of Al_2O_3/water nanofluid in different %volumes were prepared for actual experimentation on the intercooler of two-stage air compressor.

The prepared fluid, which consisted of dispersed nanoparticles, was then analyzed using a particle size analyzer (PSA) as shown in Figure 2. The PSA works on the principle of dynamic light scattering of fine particles and molecules, which are in constant random motion, called the Brownian motion. The speed of Brownian motion is highly temperature dependent, hence for accurate size measurement, precise control over temperature is essential. The scattering intensity at a specific angle fluctuates with time, and this is detected using a sensitive Avalanche photodiode detector. Autocorrelator was used to analyze the intensity changes, which generate a correlation function. This curve can be analyzed to understand the nanoparticles size and their distribution. A pictorial representation of the working of PSA is depicted in Figure 2. Technical specifications of PSA and ultrasonicator are given in Table 2. Produced good quality nanofluids were further used as working fluids for heat transfer process in the intercooler of two-stage air compressor. Nanoparticles size parameters are described in Table 3.

2.3 | Determination of properties of prepared nanofluid

Percentage volume concentration of Al_2O_3/water nanofluid was determined with reference to their individual specific weights as mentioned in Equation (1). Physical properties such as specific heat capacity (Cp_{nf}), effective thermal conductivity (K_{eff}), effective density (ρ_{eff}), and effective thermal diffusivity (α_{nf}) of Al_2O_3/water nanofluid were computed by well-known Equations (2) to (6) as follows:

$$\text{Volume concentration of nanofluid, } \%V\,(\phi) = \frac{(W \text{ of } Al_2O_3/\rho \text{ of } Al_2O_3)}{(W \text{ of } Al_2O_3/\rho \text{ of } Al_2O_3 + W_{\text{bf}}/\rho_{\text{bf}})}, \tag{1}$$

$$\text{Specific heat of } Al_2O_3\text{/water nanofluid, } Cp_{\text{nf}} = \phi Cp_{\text{np}} + (1-\phi)Cp_{\text{bf}}, \tag{2}$$

$$\text{Effective thermal conductivity of } Al_2O_3\text{/water nanofluid, } K_{\text{eff}} = \frac{(2K_2 + K_1 + \phi(K_2 - K_1))K_1}{(2K_2 + K_1 - 2\phi(K_2 - K_1))}, \tag{3}$$

$$\text{Effective density of } Al_2O_3\text{/water nanofluid, } \rho_{\text{eff}} = (1-\varnothing)\rho_{\text{w}} + \varnothing\rho_{\text{np}}, \tag{4}$$

$$\text{Effective thermal diffusivity of } Al_2O_3\text{/water nanofluid, } \alpha_{\text{nf}} = \frac{K_{\text{nf}}}{(\rho_{\text{nf}} \times Cp_{\text{nf}})}, \tag{5}$$

$$\text{Effective viscosity of } Al_2O_3\text{/water nanofluid, } \mu_{\text{nf}} = (1 + 7.3\varnothing + 123\varnothing^2)\mu_{\text{w}}. \tag{6}$$

Overall heat transfer coefficient (U), which indicates the overall ability of a series of conductive and convective barriers to transfer heat was determined by Equations (7) to (9).

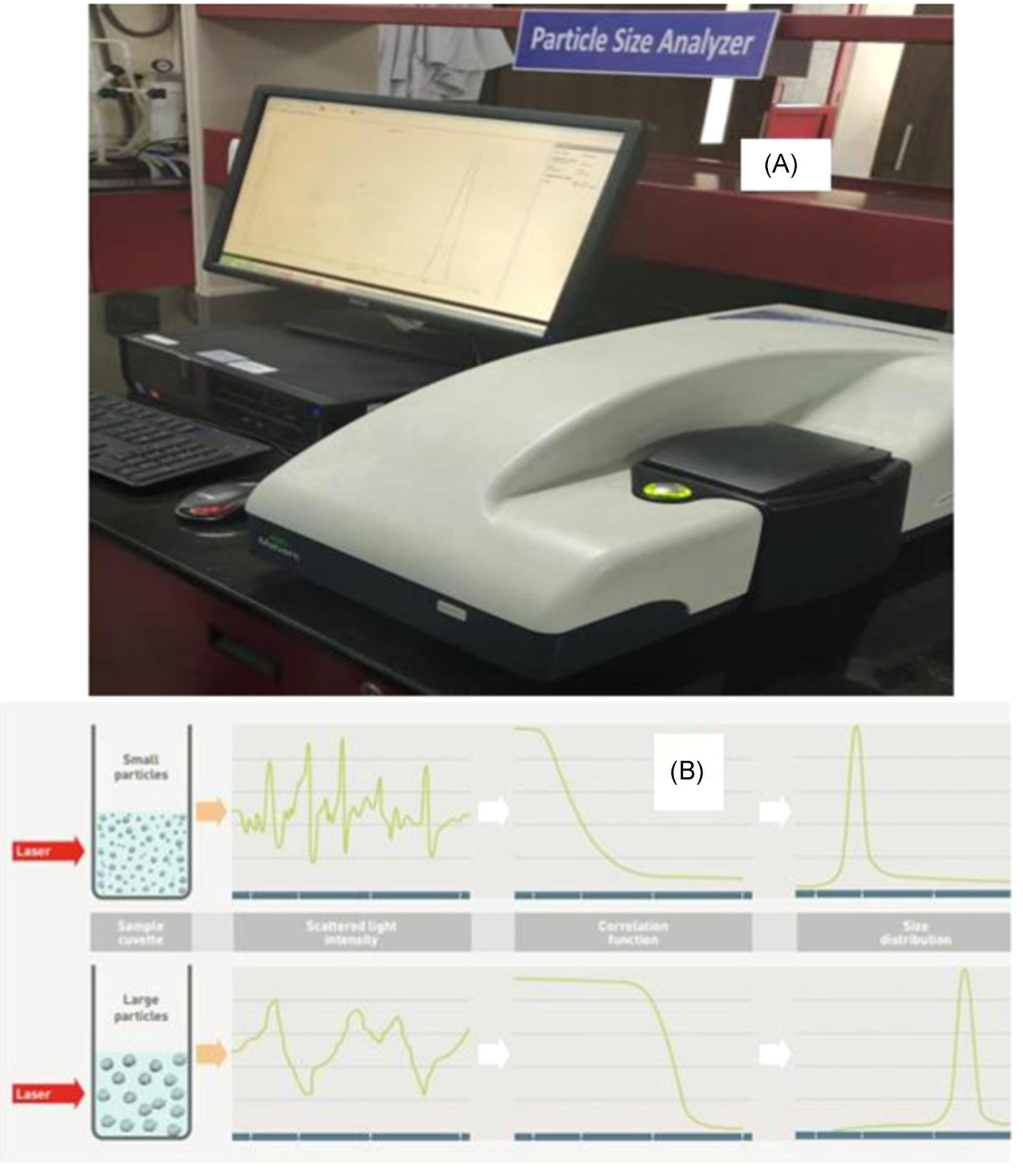

FIGURE 2 (A) Particle size analyzer and (B) its working principle [Color figure can be viewed at wileyonlinelibrary.com]

Similarly, the intercooler performance parameters such as effectiveness (ε) and isothermal efficiency were computed by Equations (10) to (14).

$$\text{Overall heat transfer coefficient, } U = \frac{Q}{A\Delta T_{\mathrm{m}}}, \tag{7}$$

$$\text{where, overall heat transfer, } Q = \frac{(Q_{\mathrm{h}} + Q_{\mathrm{c}})}{2}, \tag{8}$$

$$Q_{\mathrm{h}} = Q_{\mathrm{c}} = \dot{m}C_p\Delta T, \tag{9}$$

TABLE 2 Technical specifications of equipment used in the study

Equipment	Description	Specifications
Particle size analyzer	Measurement range (diameter)	0.3 nm-5.0 microns
	Measurement principle	Dynamic light scattering
	Minimum sample volume	20 µL
Ultrasonicator (Sonics vibra-cell VCX-750)	Power output	750 W
	Probe material	Titanium alloy Ti-6Al-4V
	Probe tip diameter	13 mm
	Probe length	136 mm
	Temperature probe limit	Maximum 100°C

$$\text{Effectiveness}, \varepsilon = \frac{Q}{C_{\min} \times \Delta T_{\max}}, \tag{10}$$

$$\text{Isothermal efficiency}, \eta_{\text{iso}} = \frac{E_{\text{iso}}}{E_s} \times 100\%, \tag{11}$$

$$\text{Isothermal power}, E_{\text{iso}} = \frac{qa \times \ln(r) \times Pa}{1000}, \tag{12}$$

$$\text{Compression ratio}, r = \frac{(Pd \times 10^5) + Pa}{Pa}, \tag{13}$$

$$\text{Shaft power}, E_{\text{s}} = \frac{2\pi NT}{60\,000}. \tag{14}$$

3 | EXPERIMENTAL TEST SETUP AND EXPERIMENTATION

A two-stage air compressor test rig, which consists of an intercooler was developed as indicated in Figure 3. The test rig consists of two cylinders and pistons, a reservoir tank, and an electric motor. Temperature sensors were provided at inlet and outlet of the intercooler. An orifice meter was provided to measure the intake air volume. To streamline the intake, a diaphragm base manifold was provided. Pressure gauge was mounted to the reservoir tank for measuring the compressed air pressure (load on the compressor). Safety valve and auto power cut switch were provided for safety. Technical specifications of the intercooler and compressor are presented in Table 4. The developed system for nanofluids utilization was retrofitted to fluid inlet and outlet pipes of the intercooler. Figure 4 indicates the schematic diagram and pictorial view

TABLE 3 Particle size with respect to intensity

Nanofluid	Size (d.nm)	% intensity	SD (d.nm)	*z*-average (d.nm)
0.5% volume fluid	332.0	100.0	99.40	449.4
0.75% volume fluid	456.2	94.0	121.4	440.5
1.0% volume fluid	285.9	100	61.5	382.4

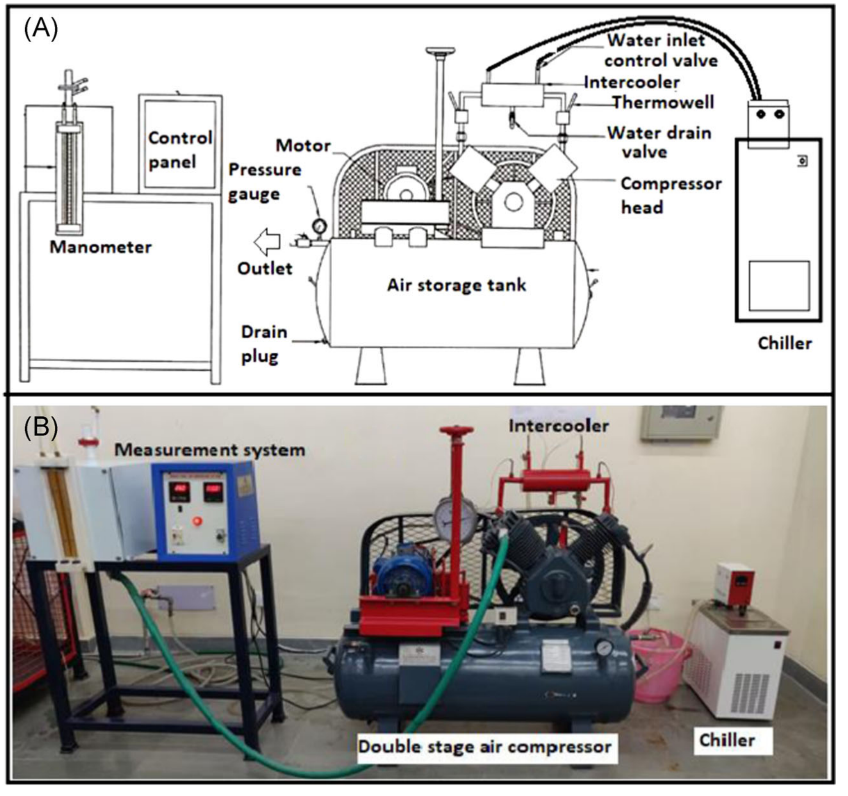

FIGURE 3 (A) Schematic diagram of the experimental test setup and (B) photographic view of the setup [Color figure can be viewed at wileyonlinelibrary.com]

of inlets and outlets of air and working fluid in the intercooler. This retrofit system consists of a nanofluid reservoir tank, 220 V 19 W water pump, and a fluid chiller (Figure 4).

The compressor sucks the air from the atmosphere, and compresses and delivers it to the air storage tank; the compression of the air is by means of a reciprocating piston in the stationary cylinder. In the two-stage compression process, initially the air is compressed partially in a low-pressure cylinder and then passes through the intercooler prior to entering the second stage compression process inorder to reduce its temperature. This is done to reduce the work of compression in the second stage. The intercooler was a counter flow, concentric tube

TABLE 4 Specifications of major components of two-stage air compressor

Component	Parameter	Specification
Compressor	Piston stroke length	0.078 m
	Cylinder bore	0.0935 m
Intercooler	Length	25.63 cm
	Outer diameter	9.64 cm
	Diameter of air flow pipe	3.23 cm
	Diameter of coolant inlet and outlet pipes	2.17 cm

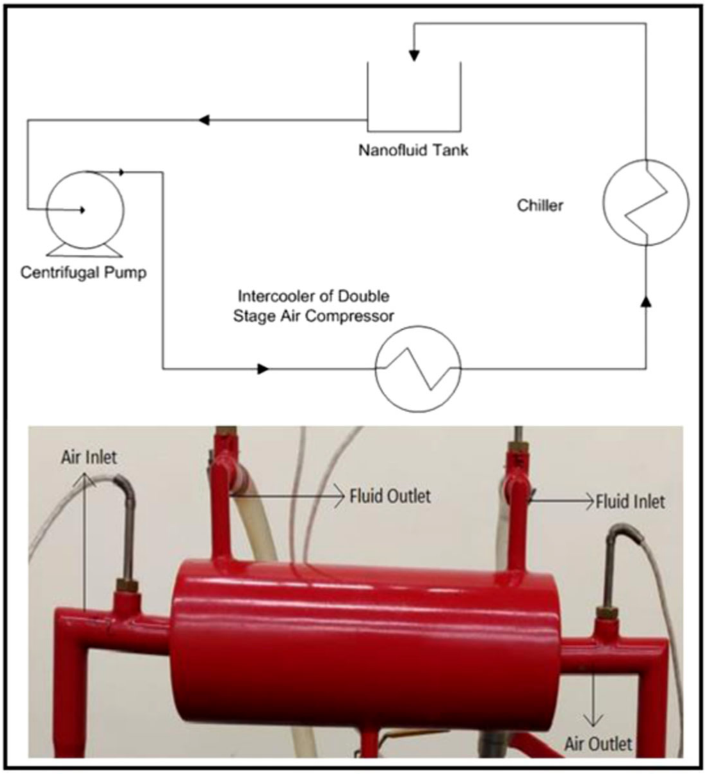

FIGURE 4 Circuit diagram depicting the flow of nanofluid and a close view of the intercooler [Color figure can be viewed at wileyonlinelibrary.com]

heat exchanger, where the compressed air was flowing through an inner tube and base water/nanofluid flowing in the outer one. Final compression is completed in the second stage, that is, in high-pressure cylinder.

The prepared Al_2O_3/water nanofluid was pumped into the intercooler through fluid inlet of the intercooler using a conventional water pump. After the heat is exchanged between the two fluids in the intercooler, the hot nanofluid exits through the fluid outlet pipe and enters into the chiller as shown in Figure 4. A chiller was used in this system for maintaining constant inlet temperature of the nanofluid throughout the experimentation. The cooled nanofluid exits from the chiller and flows back to the reservoir for recirculation. The nanofluids that had been successfully prepared replace the water flowing through the test rig. Detailed experimental tests matrix is given in Table 5, which lists out various measured parameters across different end conditions during experimentation. The experiments were conducted for all the fluids with a constant flow rate of 0.03 kg/s and hot air in the range of 5.05×10^{-3} kg/s.

4 | RESULTS AND DISCUSSION

On the basis of the experimental test results obtained with different concentrations of nanofluid, the efficiency and effectiveness of the intercooler of two-stage air compressor are discussed below. A comparative assessment between nanofluid concentrations and base fluid, that is, water is carried out. Physical properties of the prepared nanofluids are also assessed in this section.

TABLE 5 Experimental tests matrix

Experiment tests	Working fluid	Gauge pressure of compressed air storage tank (kg/cm^2)	Measured parameters
Trial 1	Water	2, 3, and 4	Intercooler temperatures, that is, air inlet, air outlet, fluid (water or Al_2O_3/water nanofluid) inlet, fluid outlet; Compressor temperatures, that is, air inlets and air outlets; speed of motor; manometer readings; weight balance reading
Trial 2	0.5% volume fluid	2, 3, and 4	
Trial 3	0.75% volume fluid	2, 3, and 4	
Trial 3	1.0% volume fluid	2, 3, and 4	

4.1 | Analysis of Al_2O_3/water nanofluid properties

Figure 5 depicts the specific heat capacity of Al_2O_3/water nanofluid for different concentrations. The specific heat decreased significantly with increasing concentration of Al_2O_3 nanoparticles. It is well-known that specific heat indicates the heat energy required to rise the unit temperature of unit weight of a substance. It could be postulated that the heat energy requirement to rise the unit temperature decreased significantly with addition of nanoparticles in the water. The heat energy requirement decreased from 4181 J/kg K without nanoparticles to 3938.9 J/kg K with 1.0% Al_2O_3 nanoparticles concentration.

Thermal conductivity of the Al_2O_3/water nanofluid increased considerably with increasing concentration of nanoparticles. It is evident from Figure 6 that the increment was higher with 1.0% concentration than other concentrations. With increasing thermal conductivity of nanofluid, heat transfer occurs rapidly and further helps to improve efficiency of the system. The maximum value of thermal conductivity of the nanofluid was attained at 0.677 W/m K with 1.0% volume concentration. The experimental results of Usri et al[25] also confirmed a substantial increase in thermal conductivity from about 0.34 to 0.48 W/m K with 13 nm Al_2O_3 nanoparticles dispersion in water at three different ratios of 40:60, 50:50, and 60:40. Similarly, Agarwal et al[26] reported 30% improvement of thermal conductivity with 2% Al_2O_3/water nanofluid. Mansour et al[27] in their experimental investigation, observed 12% improvement in

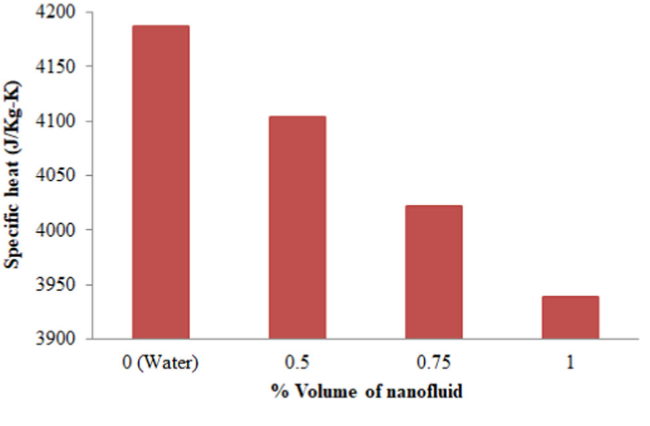

FIGURE 5 Specific heat capacity variation for different concentrations of nanofluid [Color figure can be viewed at wileyonlinelibrary.com]

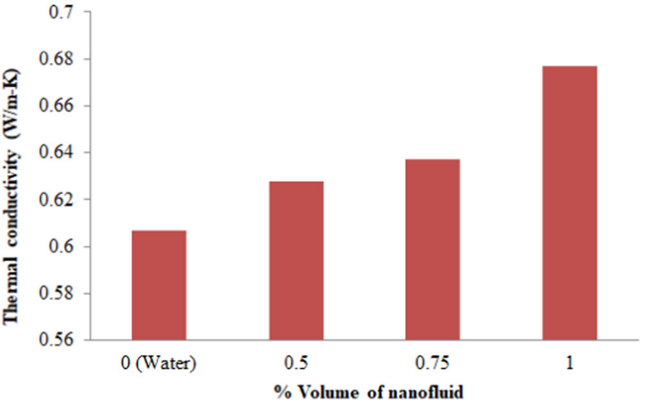

FIGURE 6 Thermal conductivity variation for different concentrations of nanofluid [Color figure can be viewed at wileyonlinelibrary.com]

thermal conductivity with 1% concentrated Al_2O_3/water nanofluid. The mechanism for improved thermal conductivity could be illustrated by Brownian motion of the nanoparticles.[28] Nanoparticles concentration, particles size, and operating temperature are the key parameters that control the motion of nanoparticles.[27,29-31] With increasing concentration of Al_2O_3 nanoparticles the Brownian motion increases substantially, which in turn improves the thermal conductivity of nanofluid.[28,32,33] The other reason for improved thermal conductivity of nanofluids could be due to an increase in surface-to-volume ratio. Lower the nanoparticle size in a nanofluid, higher the surface-to-volume ratio, which leads to high thermal conductivity.

Other important physical properties of Al_2O_3/water nanofluid such as viscosity and density are given in Table 6. It is evident from the table that both density and viscosity of the nanofluid increased with dispersion of nanoparticles. High rates of increase in the viscosity with high concentration of nanoparticles limits the application of nanofluids at high concentrations.[34,35] Experimental investigations of Chandrasekar et al[36] revealed that the viscosity increment was substantially higher than the thermal conductivity increment, which confines its employability in some industrial applications. In another study, the viscosity increased in the range of 18.1% to 300% compared with thermal conductivity enhancement range of 1.1% to 87% for the same experimental test conditions (mass concentration range of nanofluid: 3-50 wt% and temperature range, 293-313 K).[37] Ghanbarpour et al[38] also concluded that the thermal performance of a heat pipe decreased with higher concentration of Al_2O_3/water nanofluid (10% Al_2O_3 concentration) than lower concentration of Al_2O_3/water nanofluid (5% Al_2O_3 concentration). Main reasons for improved thermal behavior with lower concentration of nanofluid could be bombarding of vapor bubbles during bubble formation by nanoparticles, increasing capillary force, and increasing surface area with porous layer of Al_2O_3 nanoparticles in heat exchanger system.[38]

TABLE 6 Variation of physical properties with nanofluid concentration

% Volume concentration of nanofluid	Density (kg/m^3)	Viscosity (MPa s)
0 (Water)	1000	1.001
0.5	1072.25	1.259
0.75	1144.51	1.672
1.0	1216.75	2.239

In contrast, reduced thermal behavior with higher concentration could be formation of agglomerated nanoparticles blanket with weak adhesion of nanoparticles to heated surface, high viscosity, and high friction factor.[38] Chiam et al[39] also found about 50% increase in viscosity with dispersion of Al_2O_3 nanoparticles in water at 60:40 ratio. It may also be noted that high concentration of nanoparticles would increase friction factor in thermal systems, which restricts its application at high concentrations.[40,41] Prasad et al[42] concluded that the friction factor was increased by 1.38 times with 0.03% concentration of Al_2O_3/water nanofluid compared with base water in a concentric tube U-bend heat exchanger.

4.2 | Analysis of overall heat transfer coefficient of the intercooler with nanofluids

Figure 7 presents the comparison of overall heat transfer coefficients of 0.5%, 0.75%, and 1.0% volume concentrated nanofluids with base water at different output pressures of the compressor (ie, with increasing demand of the compressor). It is observed from the figure that the overall heat transfer coefficient increased with increasing concentration of nanoparticles for all compressor output pressures. This can be attributed to an increase in surface/volume ratio of nanoparticles, which is 1000 times more than microparticles. High surface area of nanoparticles enhances the heat conduction of nanofluids as heat transfer occurs on surface of the particles. Significant increase in thermal conductivity of the nanofluid (Figure 6) is evident in high heat transfer coefficients. Xuan and Li[31] also reported the similar results of significant increase in heat transfer coefficient (about 40%) with an increase in volume concentration of copper nanoparticles in Cu/Water nanofluid. Experimental investigations by Albadr et al[10] also reported an increment in the overall heat transfer coefficient from 385 to 450 $W/m^2 K$ with 0.7% concentration of Al_2O_3 nanoparticles in water. Experimental results of Nallusamy[8] also indicated a similar trend of increase in the overall heat transfer coefficient from 139 $W/m^2 K$ with base water to 160 $W/m^2 K$ with Al_2O_3/water nanofluid. In the present study, at moderate load of 4 bar pressure, the heat transfer coefficient increased from 286.3 $W/m^2 K$ without nanoparticles (base water) to 300.4 $W/m^2 K$ with 1.0% volume nanofluid. The percentage increment with respect to base water was higher (5.8%) at moderate load of 3 bar than other loads (5.2% at 2 bar and 4.9% at 4 bar).

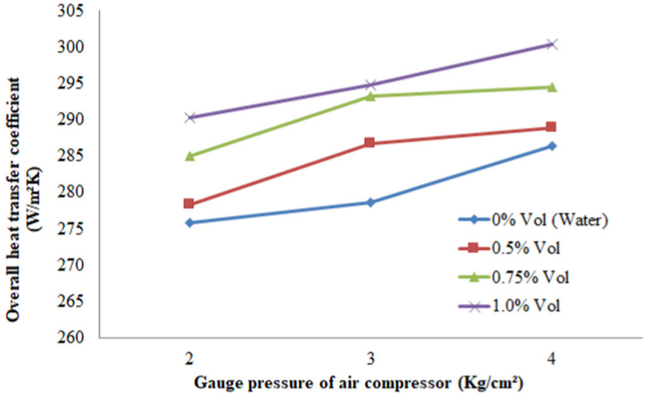

FIGURE 7 Comparison of overall heat transfer coefficients of different fluids [Color figure can be viewed at wileyonlinelibrary.com]

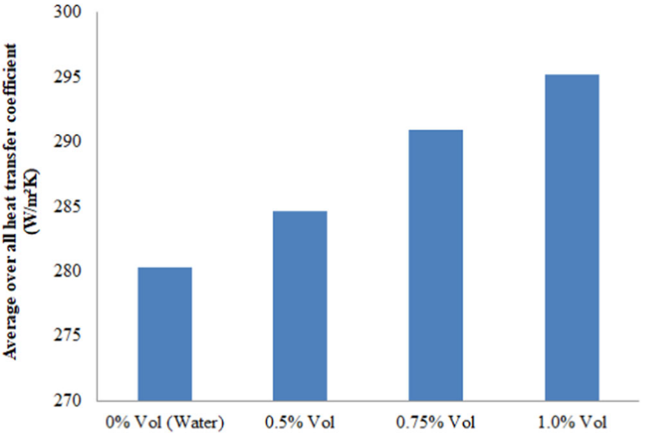

FIGURE 8 Average overall heat transfer coefficients of different fluids [Color figure can be viewed at wileyonlinelibrary.com]

An average overall heat transfer coefficient was computed for all loads on the compressor, that is, gauge pressures of 2 to 4 bar. Figure 8 presents the comparison of average overall heat transfer coefficients for different volume concentrations of Al_2O_3/water nanofluid. About 1.6% increment in the heat transfer coefficient was observed with 0.5% volume concentration of Al_2O_3/water nanofluid compared with base water. The maximum increment was about 5.3% with 1.0% volume concentration of Al_2O_3/water nanofluid compared with base water. Hence, it could be concluded that the heat transfer coefficient may increase continuously with increasing concentration of nanoparticles. The movement of suspended nanoparticles increases turbulence of fluids, which accelerates the energy exchange process, and this further leads to an increase in thermal conductivity of the fluids. Convective heat transfer was also enhanced by increasing the nanoparticles concentration. However, very high concentration of nanofluid may deteriorate the thermal performance of the system as discussed in aforementioned section (higher viscosity and friction factor of nanofluids).

4.3 | Analysis of effectiveness of the intercooler with nanofluids

Effectiveness of the intercooler increased appreciably with increasing concentration of Al_2O_3 nanoparticles as seen in Figure 9. It is evident from the figure that the maximum increase in

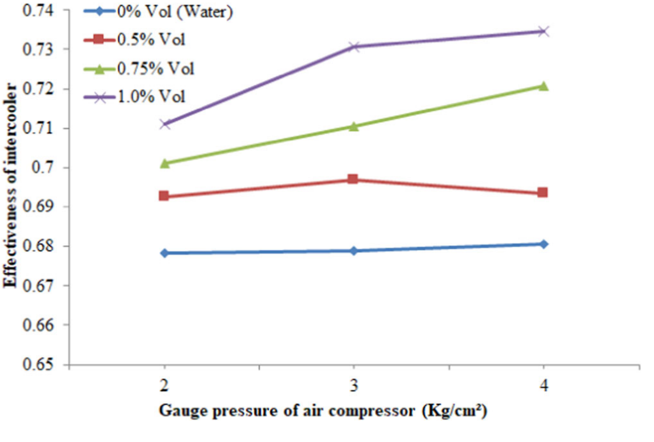

FIGURE 9 Comparison of effectiveness of heat exchanger for different fluids [Color figure can be viewed at wileyonlinelibrary.com]

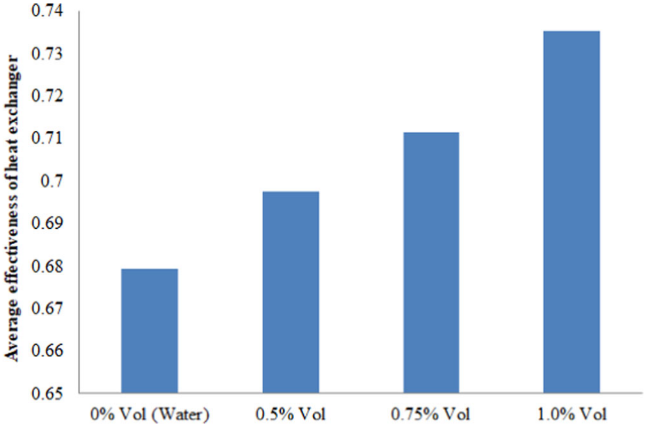

FIGURE 10 Average effectiveness of heat exchanger using different fluids [Color figure can be viewed at wileyonlinelibrary.com]

effectiveness was attained with 1.0% volume concentration when compared with other concentrations. Higher effectiveness indicates higher actual heat transfer rates by the nanofluid. As thermal conductivity of the nanofluid increased , rapid heat transfer occurred, which enhanced the system performance exceedingly. The highest effectiveness was about 0.734 with 1.0% volume concentration nanofluid at 4-bar load on the compressor.

Figure 10 presents the comparison of average effectiveness of the intercooler with an increase in %volume concentration. The percentage increments of 2.2%, 4.6%, and 6.7% were obtained with 0.5%, 0.75%, and 1.0% volume concentrations respectively as compared with base water (0% volume concentration); this is because of an increase in surface/volume ratio with increasing nanoparticles concentration. The observations made out of this experiment is in line with observations made by Yu and Xie,[43] where the thermal conductivity of aqueous Al_2O_3 nanofluids strongly depends on particle sizes and volume concentration.

4.4 | Analysis of efficiency of the intercooler with nanofluids

Figure 11 presents the comparison of isothermal efficiency on increasing load of the compressor for base water and three different volume concentrations. Substantial increase in isothermal

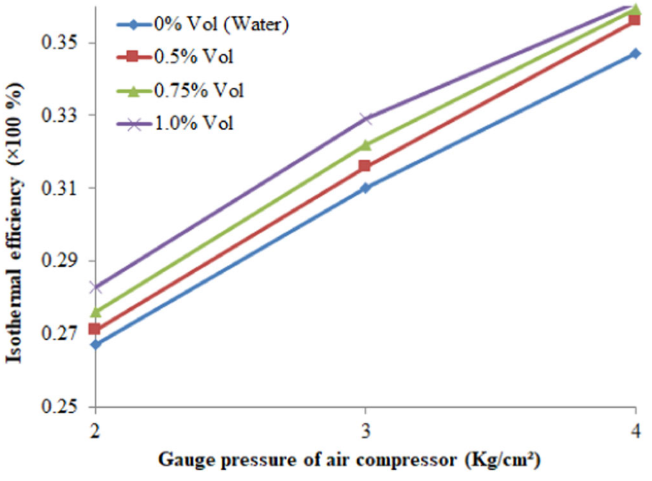

FIGURE 11 Comparison of isothermal efficiency of test rig using different fluids [Color figure can be viewed at wileyonlinelibrary.com]

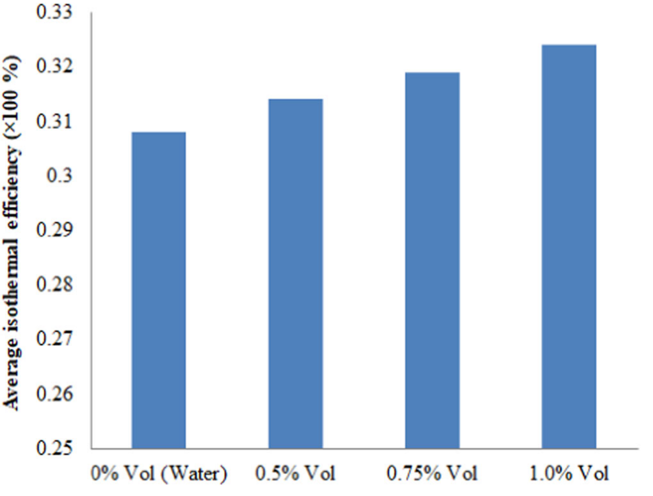

FIGURE 12 Average isothermal efficiency of test rig using different fluids [Color figure can be viewed at wileyonlinelibrary.com]

efficiency of the compressor with increasing loads was observed. It is evident from the figure that the efficiency increased drastically with increasing load on the compressor. For example, with 1.0% volume concentration nanofluid, the efficiency increased from 28.3% at 2-bar load to 36.1% at 4-bar load. The maximum efficiency was in the range of 34% to 36% with 1.0% volume concentration nanofluid.

Figure 12 presents the comparison of average isothermal efficiency over three loads for various volume concentrations of nanofluids and base water. Average isothermal efficiency of the intercooler increased about 3.5% and 5.3% with 0.5% and 0.75% volume nanofluids compared with base water. It could be postulated that the thermal conductivity and heat transfer rates increased due to suspended nanoparticles. Godson et al[44] reasoned that the chaotic movement of ultrafine nanoparticles increased the fluctuation and turbulence of nanofluids, which accelerated the heat transfer process and led to better efficiency of thermal systems.[44]

5 | CONCLUSIONS

On the basis of the experimental tests with three concentrations of Al_2O_3/water nanofluid, that is, 0.5%, 0.75%, and 1.0% volume concentrations, the following conclusions were drawn out.

- Heat transfer rates were higher with all concentrations of Al_2O_3/water nanofluid than base water.
- Among the three concentrations of nanofluids, 1.0% volume concentrated nanofluid exhibited better thermal properties such as thermal conductivity and specific heat.
- The maximum enhancement of overall heat transfer coefficient was achieved with 1.0% volume concentration of Al_2O_3/water nanofluid.
- Effectiveness and efficiency of the intercooler was increased substantially with increasing concentration of Al_2O_3 nanoparticles.

Overall, it can be concluded that high concentration of nanoparticles dispersion in water would increase the heat transfer rate and thus improve the efficiency of intercooler. However, high concentration of nanoparticles may adversely affect the viscosity and friction factor, which limits its employment in thermal systems.

NOMENCLATURE

Cp_{bf}	specific heat of base fluid
Cp_{nf}	specific heat of nanofluid
Cp_{np}	specific heat of nanoparticles
μ_w	viscosity of water
A	area of cross-section
C_{ps}	pecific heat capacity
$\varnothing$	percentage volume concentration
K_1	thermal conductivity of water
K_2	thermal conductivity of nanoparticles
K_{nf}	thermal conductivity of nanofluid
$\dot{m}$	mass flow rate
Q	overall quantity of heat
ΔT	temperature difference
ρ_{nf}	density of nanofluid
ρ_{np}	density of nanoparticle
ρ_w	density of water

ORCID

Ashish Karn http://orcid.org/0000-0003-0671-4285

REFERENCES

1. Pourfarzad E, Ghadiri K, Behrangzade A, Ashjaee M. Experimental investigation of heat transfer and pressure drop of alumina–water nano-fluid in a porous miniature heat sink. *Exp Heat Transfer*. 2018;31(6): 495-512.
2. Modak M, Sharma AK, Sahu SK. An experimental investigation on heat transfer enhancement in circular jet impingement on hot surfaces by using Al_2O_3/water nano-fluids and aqueous high-alcohol surfactant solution. *Exp Heat Transfer*. 2018;31(4):275-296.
3. Gupta SK, Misra RD. An experimental investigation on pool boiling heat transfer enhancement using Cu-Al_2O_3 nano-composite coating. *Exp Heat Transfer*. 2018;32(2):133-158.
4. Chougule SS, Sahu SK. Comparative study on heat transfer enhancement of low volume concentration of Al_2O_3–water and carbon nano-tube–water nano-fluids in transition regime using helical screw tape inserts. *Exp Heat Transfer*. 2014;29(1):17-36.
5. Ben Mansour R, Galanis N, Nguyen CT. Experimental study of mixed convection with water-Al_2O_3 nanofluid in inclined tube with uniform wall heat flux. *Int J Therm Sci*. 2011;50(3):403-410.
6. Asadi A, Asadi M, Rezaniakolaei A, Rosendahl LA, Afrand M, Wongwises S. Heat transfer efficiency of Al_2O_3-MWCNT/thermal oil hybrid nanofluid as a cooling fluid in thermal and energy management applications: an experimental and theoretical investigation. *Int J Heat Mass Transfer*. 2018;117:474-486.
7. Bumataria RK, Chavda NK, Panchal H. Current research aspects in mono and hybrid nanofluid based heat pipe technologies. *Heliyon*. 2019;5. 5(5):e01627.
8. Nallusamy S. Characterization of Al_2O_3/water nanofluid through shell and tube heat exchangers over parallel and counter flow. *J Nano Res*. 2017;45:155-163.
9. Momin GG. Experimental investigation of mixed convection with water-Al_2O_3 & hybrid nanofluid in inclined tube for laminar flow. *Int J Sci Technol Res*. 2013;2(12):195-202.
10. Albadr J, Tayal S, Alasadi M. Heat transfer through heat exchanger using Al_2O_3 nanofluid at different concentrations. *Case Stud Therm Eng*. 2013;1(1):38-44.

11. Rajput NS, Shukla DD, Rajput D, Sharm SK. Performance analysis of flat plate solar collector using Al_2O_3/distilled water nanofluid: an experimental investigation. *Mater Today Proc*. 2019;10:52-59.
12. Kapil M, Roy D, Sharma B, Rana SC, Pramanik S, Barman RN. A numerical study of 2-D convective heat transfer of nanofluid (Al_2O_3/H_2O) in a lid driven cavity with square cylinder at the centre. *Materials Today Proc*. 2019;11:700-707.
13. Ganesh NV, Al-Mdallal QM, Al Fahel S, Dadoa S. Riga—plate flow of gamma Al_2O_3-water/ethylene glycol with effective Prandtl number impacts. *Heliyon*. 2019;5(5):e01651.
14. Teng T-P, Hung YH, Teng TC, Mo HE, Hsu HG. The effect of alumina/water nanofluid particle size on thermal conductivity. *Appl Therm Eng*. 2010;30(14-15):2213-2218.
15. Khoshvaght-Aliabadi M, Hassani SM, Mazloumi SH. Enhancement of laminar forced convection cooling in wavy heat sink with rectangular ribs and Al_2O_3/water nanofluids. *Exp Therm Fluid Sci*. 2017;89:199-210.
16. Dharmalingam R, Sivagnanaprabhu KK, kumar BS, Thirumalai R. Nano materials and nanofluids: an innovative technology study for new paradigms for technology enhancement. *Procedia Eng*. 2014;97:1434-1441.
17. Nayak AK, Gartia MR, Vijayan PK. An experimental investigation of single-phase natural circulation behavior in a rectangular loop with Al_2O_3 nanofluids. *Exp Therm Fluid Sci*. 2008;33(1):184-189.
18. Farajollahi B, Etemad SG, Hojjat M. Heat transfer of nanofluids in a shell and tube heat exchanger. *Int J Heat Mass Transfer*. 2010;53(1-3):12-17.
19. Saidur R, Leong KY, Mohammad HA. A review on applications and challenges of nanofluids. *Renew Sustain Energy Rev*. 2011;15(3):1646-1668.
20. Eastman JA, Choi SUS, Li S, Yu W, Thompson LJ. Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. *Appl Phys Lett*. 2001;78(6):718-720.
21. Xia G, Jiang H, Liu R, Zhai Y. Effects of surfactant on the stability and thermal conductivity of Al_2O_3/de-ionized water nanofluids. *Int J Therm Sci*. 2014;84:118-124.
22. Sarkar J, Ghosh P, Adil A. A review on hybrid nanofluids: recent research, development and applications. *Renew Sustain Energy Rev*. 2015;43:164-177.
23. Kumar V, Tiwari AK, Ghosh SK. Application of nanofluids in plate heat exchanger: a review. *Energy Convers Manage*. 2015;105:1017-1036.
24. Tiwari AK, Ghosh P, Sarkar J. Performance comparison of the plate heat exchanger using different nanofluids. *Exp Therm Fluid Sci*. 2013;49:141-151.
25. Usri NA, Azmi WH, Mamat R, Hamid KA, Najafi G. Thermal conductivity enhancement of Al_2O_3 nanofluid in ethylene glycol and water mixture. *Energy Procedia*. 2015;79:397-402.
26. Agarwal R, Verma K, Agrawal NK, Singh R. Sensitivity of thermal conductivity for Al_2O_3 nanofluids. *Exp Therm Fluid Sci*. 2017;80:19-26.
27. Mansour R, Galanis N, Nguyen CT. Experimental study of mixed convection with water–Al_2O_3 nanofluid in inclined tube with uniform wall heat flux. *Int J Therm Sci*. 2011;50(3):403-410.
28. Jang SP, Choi SUS. Role of Brownian motion in the enhanced thermal conductivity of nanofluids. *Appl Phys Lett*. 2004;84(21):4316-4318.
29. Yang Y-T, Lai F-H. Numerical investigation of cooling performance with the use of Al_2O_3/water nanofluids in a radial flow system. *Int J Therm Sci*. 2011;50(1):61-72.
30. Ali M, Zeitoun O, Almotairi S. Natural convection heat transfer inside vertical circular enclosure filled with water-based Al_2O_3 nanofluids. *Int J Therm Sci*. 2013;63:115-124.
31. Xuan Y, Li Q. Heat transfer enhancement of nanofluids. *Int J Heat Fluid Flow*. 2000;21(1):58-64.
32. Abu-Nada E. Dissipative particle dynamics investigation of heat transfer mechanisms in Al_2O_3 -water nanofluid. *Int J Therm Sci*. 2018;123:58-72.
33. Vajjha RS, Das DK, Namburu PK. Numerical study of fluid dynamic and heat transfer performance of Al_2O_3 and CuO nanofluids in the flat tubes of a radiator. *Int J Heat Fluid Flow*. 2010;31(4):613-621.
34. Abu-Nada E. Effects of variable viscosity and thermal conductivity of Al_2O_3–water nanofluid on heat transfer enhancement in natural convection. *Int J Heat Fluid Flow*. 2009;30(4):679-690.
35. Zeinali Heris S, Nasr Esfahany M, Etemad SG. Experimental investigation of convective heat transfer of Al_2O_3/water nanofluid in circular tube. *Int J Heat Fluid Flow*. 2007;28(2):203-210.
36. Chandrasekar M, Suresh S, Chandra Bose A. Experimental investigations and theoretical determination of thermal conductivity and viscosity of Al_2O_3/water nanofluid. *Exp Therm Fluid Sci*. 2010;34(2):210-216.

37. Ghanbarpour M, Bitaraf Haghigi E, Khodabandeh R. Thermal properties and rheological behavior of water based Al_2O_3 nanofluid as a heat transfer fluid. *Exp Therm Fluid Sci*. 2014;53:227-235.
38. Ghanbarpour M, Nikkam N, Khodabandeh R, Toprak MS, Muhammed M. Thermal performance of screen mesh heat pipe with Al_2O_3 nanofluid. *Exp Therm Fluid Sci*. 2015;66:213-220.
39. Chiam HW, Azmi WH, Usri NA, Mamat R, Adam NM. Thermal conductivity and viscosity of Al_2O_3 nanofluids for different based ratio of water and ethylene glycol mixture. *Exp Therm Fluid Sci*. 2017;81:420-429.
40. Zeinali Heris S, Nassan TH, Noie SH, Sardarabadi H, Sardarabadi M. Laminar convective heat transfer of Al_2O_3/water nanofluid through square cross-sectional duct. *Int J Heat Fluid Flow*. 2013;44:375-382.
41. Noie SH, Heris SZ, Kahani M, Nowee SM. Heat transfer enhancement using Al_2O_3/water nanofluid in a two-phase closed thermosyphon. *Int J Heat Fluid Flow*. 2009;30(4):700-705.
42. Prasad PV, Gupta AVSSKS, Sreeramulu M, Sundar LS, Singh MK, Sousa ACM. Experimental study of heat transfer and friction factor of Al_2O_3 nanofluid in U-tube heat exchanger with helical tape inserts. *Exp Therm Fluid Sci*. 2015;62:141-150.
43. Yu W, Xie H. A review on nanofluids: preparation, stability mechanisms, and applications. *J Nanomater*. 2012;2012:1-17.
44. Godson L, Raja B, Mohan Lal D, Wongwises S. Enhancement of heat transfer using nanofluids—an overview. *Renew Sustain Energy Rev*. 2010;14(2):629-641.

How to cite this article: Chintala V, Vikesh S, Karn A. Efficiency and effectiveness enhancement of an intercooler of two-stage air compressor by low-cost Al_2O_3/water nanofluids. *Heat Transfer*. 2020;1–18. https://doi.org/10.1002/htj.21735