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Research Article

Performance study of aluminium oxide based nanorefrigerant in an air-conditioning system

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Abstract

The present issues related to global warming have attracted refrigerants with low Global Warming Potential (GWP). Two of the most promising low-GWP refrigerants, R32 (difluoromethane) and R290 (propane) are flammable. The addition of a flame retardant to R290 or R32 can enhance their flammable characteristics. Trifluoroiodomethane (R13I1) is a flame retardant with an enormously low global warming and can be used as a component of the refrigerant. In addition, dispersing nanoparticles in these refrigerants improves thermal conductivity. Nanorefrigerants are new refrigerants possessing better heat dissipation performance over traditional refrigerants. An ultra-low GWP mixture refrigerant consisting of R32, R161 and trifluoroiodomethane with aluminum oxide (Al_2O_3) nanoparticles is used in the present study. Simulation Model-based theoretical results of R410a and with R410a/Al_2O_3, mixture refrigerant (R32, R161 and trifluoroiodomethane) and nanorefrigerant (R32, R161 and trifluoroiodomethane with aluminum oxide nanoparticles) are carried. The study shows the coefficient of performance (COP) of R410a/Al_2O_3 and M (R32/R161/R13I1)/Al_2O_3 increased by 47.3% and 89.8% respectively. The power-saving up to 31.8% and 47.2% at a volume concentration of 0.09%. The comparison has been made with reference to the R410a/Al_2O_3 system. The thermophysical properties of refrigerants have been calculated using REFPROP (NIST properties of fluid reference). The theoretical model-based calculations are computed in MATLAB software. This study provides an insight in providing appropriate refrigerant substitutes for air conditioning systems.

1. Introduction

In recent decades, R410a has been used broadly as a working refrigerant in air-conditioning systems due to its suitable thermodynamic properties and cycle performance. Global warming has become a critical issue in refrigeration and air-conditioning heat pumps (RACHPs). This can be resolved by selecting very low Global Warming Potential (GWP) refrigerants [1]. In the past few years, manufacturers have also adopted environmentally friendly refrigerants such as R161, R32, R152a, R1270, R1150, R1234yf, etc. R161 (C_2H_5F) has a zero ozone depletion effect and tremendously low GWP_{100} (about 12), and also possesses the most promising thermophysical properties and is considered an alternative to R22 [2]. R13I1 a flame retardant provides outstanding environmental performance with Low Global Warming Potential (LGWP about 1) and zero ozone depletion effect [3].

Another issue is power consumption. Out of the total worldwide electricity consumption, it is estimated that about 17% of electricity is consumed by refrigeration frameworks [4]. From another report, 25 to 30% of electricity is consumed by refrigeration air-conditioning and heat pumps (RACHPs) [5], [6]. In order to acquire the refrigerant with environmental friendly and excellent thermophysical cycle performance, a mixture

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refrigerant composed of R32/R161/R13I1 (i.e., mass fraction 22/48/30) as an alternative for R410a [7]. The new mixture refrigerant is named as M which is shown in Fig. 1. This study examined the viability of using M refrigerant as a substitute for R410a was theoretically investigated from aspects of power-saving, greater cooling effect and environment indicators by dispersing of Al_2O_3 (Alumina) nanoparticles in M refrigerant which is completely ozone-friendly with low GWP (about 149) at volume concentration of 0.09%. And the results are compared with R410a. The mixture consisting of R32, R161 and R13I1 can be estimated by equation 1 [3] and the thermophysical properties of refrigerants are shown in Table 1. The current study of Al_2O_3 has been used as an account of superior thermal conductivity and good stability behavior. In addition, literature has shown that Alumina has the lowest precipitation rate and highest emulsification stability compared to other nanoparticles [8]. The concentration of Al_2O_3 in the current study is limited to 0.09% only. The reason for this is that higher concentrations lead to sedimentation, agglomeration and high pumping power. In addition, higher concentrations result in poor stability [9]–[11]. The benefits of the nanofluids using data from the literature, it has been discovered that, compared to conventional fluids, nanofluids exhibit a significantly greater and substantially temperature-dependent thermal conductivity with enhanced thermophysical and rheological properties, and low sedimentation and agglomeration problems [12].

$$GWP_{mix} = GWP_a \times X_a + GWP_b \times X_b + GWP_c \times X_c \tag{1}$$

where X_a, X_b and X_c denote the mass fraction of components a, b and c respectively.

Table 1. Thermophysical properties of R410a and M refrigerants [7][13].

Refrigerant	R410a	M
Molecular formula (mass %)	R32/R125 (50/50)	R13I1/R32/R161 (30/22/48)
Molecular weight	72.5	93.29
Critical pressure (bar)	49	32.3
Critical Temperature (°C)	72.5	97.7
GWP	2088	149
ODP	0	0
Temperature glide at 25°C	0.1	3.23
Safety classification	A1	~A2L

The use of nano additives in refrigeration and air-conditioning heat pumps (RACHPs) may increase the efficiency of the system [14]. Nanoparticles possess enhanced thermophysical properties and ameliorate the working fluid properties depending upon the particle concentration, operating temperature, and size [15]. The higher the energy efficiency rating, the more efficient the machine. The rating indicators may vary from country to country as shown in Fig. 2 [16].

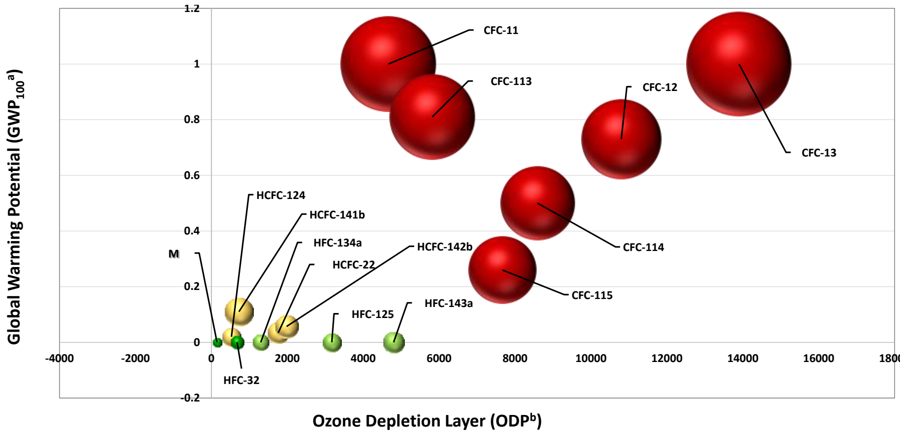

Fig. 1 GWP vs ODP and lifetime of HFCs, HCFCs, CFCs (circles)

Another advantage of nano additives in lubricating oil is to improve the solubility between the compressor lubricant and refrigerant, which offers enhancement in the performance of the system by recirculating more oil back to the compressor. More oil accumulation in the compressor sump which prevents direct contact between the piston and cylinder during motion, improves the mending, rolling, and polishing effects and reduction in the coefficient of friction [17]–[22].

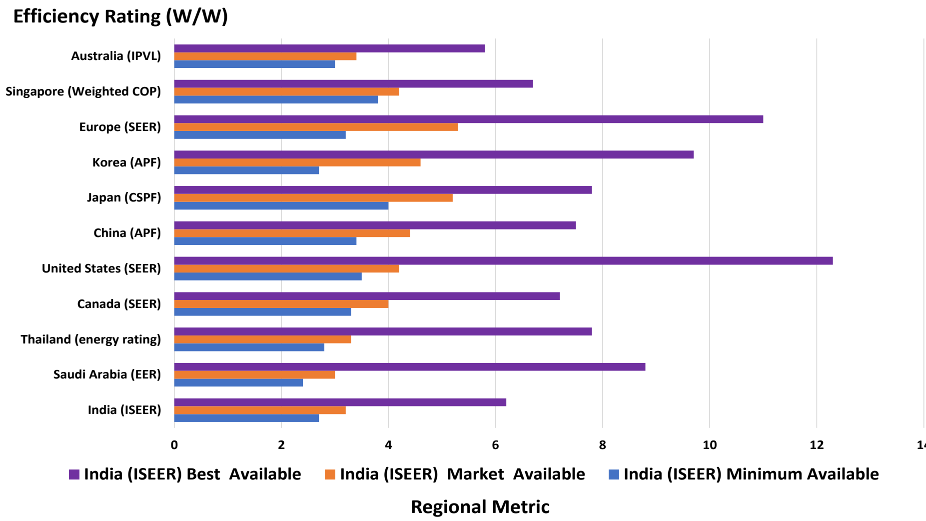

Fig. 2 Efficiency ratings of available AC units by regional metric

Adelekan *et al.* [23] experimental investigation of TiO_2 nano-additives dispersed in R600a refrigerant at 0.1g concentration and observed the highest refrigeration effect, least compressor power and high COP. Marcucci *et al*. [24] explored the use of diamond nanoparticles in polyol ester (POE) refrigerant oil at two mass concentrations, 0.1 and 0.5% in a refrigeration system. The cooling capacity increased by 4%, and 8%. The discharge temperature was decreased by approximately 4 °C. Babarinde *et al.* [25] carried out an experimental investigation of R600a/MWCNT- nanolubricant used in the domestic refrigerator instead of R134a with a various mass charge of Iso-Butane. The optimum results showed that the lower evaporator temperature was -11 ^{o}C, the highest COP and lower power consumption of 0.0639kW. Farid et al. [26] performed an experimental investigation of WO_3 and MWCNT hybrid nanofluids. The thermal conductivity of nanofluid and experimental equation is established to predict the thermal conductivity of nanofluid. According to the obtained results, the role of volume fraction concentration on the thermal conductivity of nanofluids is more effective compared to temperature. Ruhani *et al.* [27] developed a new model for the rheological behavior of Silica-Ethylene glycol/Water (30 vol.%: 70% vol.) hybrid Newtonian nanofluid. The current study investigates the relationship between shear stress and shear rate is linear and the desired fluid is Newtonian. The higher dispersion of the nanoparticles in the base fluid causes the relative viscosity to increase as the volume fraction increases. In another study, the experimental investigation of Multi-walled Carbon Nanotubes (MWCNTs)-titania-Zinc oxide/water-ethylene glycol (80:20) mono and hybrid nanofluid has been studied. The highest thermal conductivity of nanofluid was obtained at a volume fraction of 0.4% at 50^{o}C, which increased by 17.82% and a comparison has been made with base fluid at the same temperature [28], [29]. Yan *et al.* [30] carried out an experimental investigation on the rheological properties of hybrid nanofluid (MWCNTs-ZnO/Water-EG (80:20 volume%)) (non-Newtonian). The viscosity of hybrid nanofluid was evaluated in the temperature range of 25-50^{o}C with various concentrations of 0.075, 0.15, 0.3, 0.6, 0.9 and 1.2% respectively. At the maximum volume fraction concentration at 50, 40 and 30^{o}C, the viscosity is reduced by 21%, 17% and 8% to the reference temperature (25^{o}C).

Tian *et al.* [31] performed Artificial Neural Network (ANN) to investigate the effect of temperature and various volume fractions of Graphene oxide-Alumina hybrid nanoparticles on thermal conductivity. The thermal conductivity of GO-Al_2O_3/Water-EG hybrid nanofluid is significantly affected by the volume percentage of nanoparticles. Hossein and Toghraie [32] explored the use of various nanofluids on the performance of heat pipe. The use of nanofluid instead of water (base fluid) resulted in higher thermal efficiency. As thermal capacity increases, fluid pressure drops and the temperature difference between condenser and evaporator increases. Damola *et al.* [33] performed varied mass charges of LPG (0.2, 0.4 and 70 g) with various concentrations of TiO_2 nanoparticles in mineral oil (MO). The highest COP obtained of 2.8 with a 40 g charge of LPG utilizing a 0.4 g/L concentration of nano oil. Sabareesh *et al.* [22] experimentally evaluated the application of TiO_2 nano-additives in modifying the lubricating Mineral oil (MO) at concentrations of 0.005, 0.01 and 0.015vol% respectively. At 0.01% volume fraction, the maximum COP was enhanced by 17%, and compressor work was reduced by 11%. Ohunakin *et al.* [34] observed energy saving at a low concentration of SiO_2/MO and 50g of charge of LPG refrigerant using 0.4 g/L nanolubricant in a refrigeration system and compared it with pure R134a. The maximum reduction in discharge temperature has been attained with a 50g mass charge of LPG using 0.2g/L. Jiang *et al.* [35] has investigated the performance of a refrigerator (R600a) graphite nanolubricants with mass fraction of 0%, 0.05%, 0.1%, 0.2%, and 0.5% respectively. The power-saving upto 4.55% and certain reductions in condenser temperature, evaporator temperature, discharge pressure and discharge temperature. Kumar *et al.* [36] used the influence of Al_2O_3 nanoparticles in compressor lubricant (MO) at 0.06% mass fraction. It is observed that the power saving upto 11.5% and increment in freezing capacity when POE lubricant is replaced by a blend of MO and Al_2O_3 nano additives. Gill *et al.* [37] studied the performance of Iso-Butane refrigerant selected various mass charges (40g, 60 and 80g) at various concentrations of TiO_2-based nano lubricant of 0, 0.2, 0.4 and 0.6 g/L respectively. The results obtained lower compressor power consumption, reduction in discharge temperature and pull-down time by about 33.3%, 41.92% and 21% as compared with base refrigerant.

Yang *et al.* [38] explored the use of graphene nanosheets in lubricant at various concentrations of 30, 20 and 10 mg/L respectively. The refrigeration effect increased by 5.60% and the cooling capacity of the freezer increased by 4.70% at a concentration of 30 mg/L. The energy saving by utilizing the three concentrations of 20.3%, 19.2% and 15.4% in 24 hours, respectively compared with the base oil. Babarinde *et al.* [39] examined the performance of Iso-Butane environmentally friendly refrigerant in a domestic refrigerator. The graphene nano additives were dispersed in the pure lubricant at different concentrations of 0.6, 0.4 and 0.2 g/L in 50, 60 and 70g with various mass charges of R600a refrigerant. In terms of COP, pull-down time, power consumption and cooling capacity, the results showed that the nanolubricant in R600a outperformed over base lubricant.

Santhana *et al.* [40] investigated the influence of different nanoparticles CNT, ZrO_2, Al_2O_3, and SiO_2 dispersed in Poly-ol Ester (POE) oil at a concentration of 0.1% (w/v). In addition, SiO_2 in POE obtained the maximum increment in COP of 21.8% compared with Al_2O_3, ZrO_2, CNT nanolubricants and pure POE lubricants. Omer *et al.* [41] examined the performance of heat dissipation and thermophysical properties of CuO nano additives in R134a. The results showed that the viscosity and density of the nanorefrigerant significantly increased with the increment of volume concentrations. Nevertheless, these parameters have been reduced accordingly with the increase in temperature. Kosmadakis and Neofytou [42] utilize various nanoparticles in a heat pump working on a vapour compression system to show the enhancement of heat transfer rate during boiling and condensation. This numerical model-based study used suitable refrigerants (R1234yf and R134a) and nanomaterials such as Cu, CuO and Al_2O_3 respectively. The coefficient of performance of the heat pump increased upto 5-6% at 5 wt.% concentration of Al_2O_3 and thereby indicating the superior performance in comparison to CuO or Cu. In addition, there is a total pressure drop upto 3.50%.

From the above literature analysis, it is clear that currently there are no appropriate ultra-low GWP and eco-friendly nanorefrigerants for power saving in the air conditioning system. Furthermore, earlier studies all dealt with the R410a substitute with GWP higher than 150 and there are no nanorefrigerants that can serve as R410a alternatives with GWP less than 150 with suitable thermophysical properties. The ultra-low GWP nano refrigerant-based studies are almost negligibly available in academic libraries. This work considers a Matlab-based simulation study of nanorefrigerants such as R410a/Al_2O_3 and M (R32/R161/R13I1)/Al_2O_3 at 0.09% volume concentration. To add more novelty, a detailed comparison between the refrigerants has been made to arrive at the optimal refrigerant for commercial purposes based on low GWP and other viable parameters. The major benefits of this novel method are low global warming emissions, high coefficient of performance, and power saving.

2. Material and Methods

The properties of the pure refrigerant and nanorefrigerant such as pressure, temperature and enthalpy are calculated through the density of pure and nanorefrigerant at points 1 and 3 as shown in Fig. 8. The density of nanorefrigerant is calculated from the equation 2 [Pak and Cho [43]]. Therefore, (ρ_{NP}), (ρ_{NR}), (ρ_{PR}) and (ϕ) represents the density of nanoparticle, nanorefrigerant, pure refrigerant and volume concentration respectively. The density of Al_2O_3 (alumina) nanoparticles is considered as 3.9 g/cm^3 used in R410a and M (R32/R161/R13I1) refrigerants at a volume concentration of 0.09% by using Eq. 3.

$$\rho_{NR} = m_p \, \rho_{NP} + \left(1 - m_p\right) \rho_{PR} \tag{2}$$

$$\phi = \frac{m_p \,/\, \rho_p}{m_p/\,\rho_p + m_R/\rho_R} \text{ x } 100 \tag{3}$$

where,
ρ_{NR} = Density of nanorefrigerant in g/m^3,
ρ_{NP} = Density of nanoparticle in g/m^3,
ρ_{PR} = Density of pure refrigerant in g/m^3,
ϕ = volume concentration (%),
m_p = mass of nanoparticle in grams,
ρ_p = Density of particle in g/m^3,
m_R = mass of refrigerant in grams,
ρ_R = Density of refrigerant in g/m^3.

2.1 Theoretical Simulation-Based Model of (R32/R161/R13I1)/Al_2O_3 for Vapour Compression Air Conditioning System

A MATLAB/Simulink model is developed to calculate the performance of the air conditioner in terms of properties of pure and nanorefrigerant through the density of nanorefrigerant by using Eq. 2, to evaluate the net refrigeration effect (NRE), COP and power consumption in Simulink is depicted in Fig. 3. Theoretical comparative numerical analysis and the formulas used as coding (Eqs. 4-8) in MATLAB such as gauges, block parameters of various signals, compressor, condenser, expansion device and evaporator are also shown in Fig. 3.

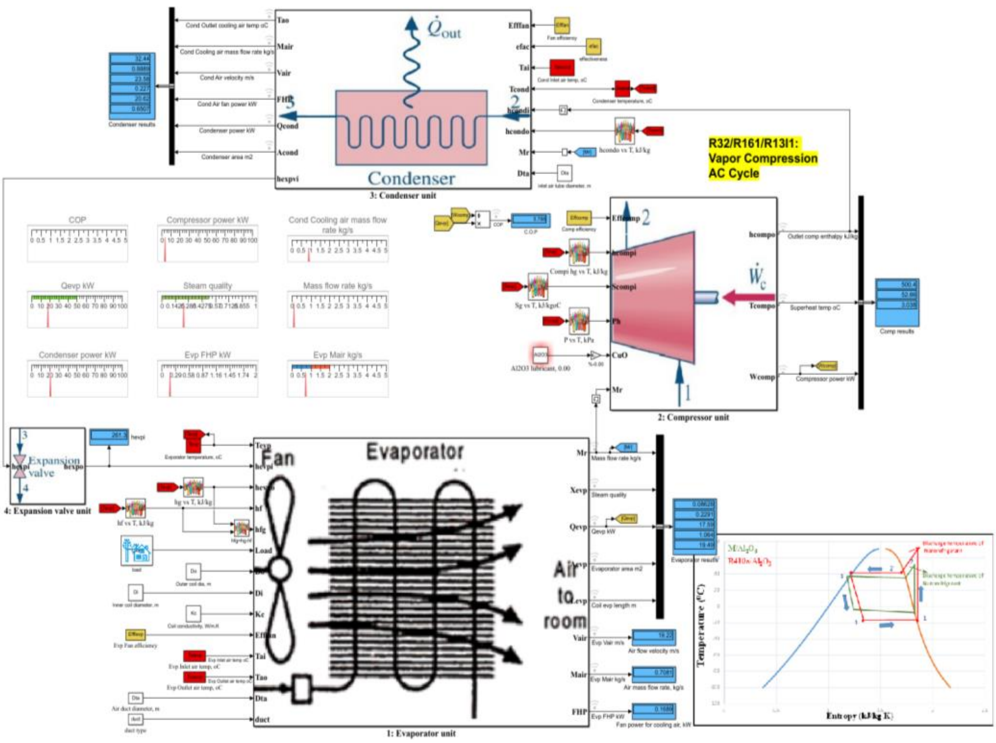

Fig. 3 Air conditioning system using M/Al_2O_3 nanorefrigerant in Simulink

2.2 Theoretical formulation used as coding in MATLAB

The results of M (R32/R161/R13I1)/Al_2O_3 nanorefrigerant have been investigated and compared with the performance of R410a/Al_2O_3 in the system using Eqs. (4)-(8).

Heat extracted (Q_e) is given by

$$Q_e = \dot{m}(h_1 - h_{f3}) \quad (kW) \tag{4}$$

Compressor work done (kW) or power input is given by

$$W_C = \dot{m}(h_2 - h_1) \quad (kW) \tag{5}$$

Heat rejected in a condenser (kW) is given by

$$Q_C = \dot{m}\,(h_2 - h_{f3}) \quad (kW) \tag{6}$$

Refrigerant mass flow rate is given by

$$\dot{m}_{ref} = \frac{Ref.\ capacity}{h_1 - h_{f3}} \quad (\frac{kg}{s}) \tag{7}$$

Coefficient of performance

$$C\,O\,P = \frac{Q_{evap}}{W_{Comp}} \tag{8}$$

where 'm' is the mass flow rate (kg/s), h_1 is the enthalpy of saturated vapour (kJ/kg), h_2 is the enthalpy of superheated vapour (kJ/kg) and h_{f3} is the enthalpy of saturated liquid (kJ/kg). Fig.4 represents the flowchart of the developed model.

2.3 Assumptions

The important assumptions for leading this kind of theoretical model-based study are.

- Pressure losses at the compressor inlet and outlet ports are neglected.
- Pipelines pressure losses are neglected.
- Heat losses and heat gains from or to the system are ignored.
- Isentropic, mechanical and electric motor compressor efficiencies are considered.
- Degree of undercooling and superheating before compression are neglected.
- No deposition of nanoparticles at the solid wall.

3. Results and Comparison

3.1 Effect of nanoparticle concentration

Fig. 5 shows the graphical representation of variation in COP and power saving with particle concentration for the two refrigerants in the form of bar charts. The charts clearly illustrate that incorporating Al2O3 in M (R32/R161/R13I1) refrigerant improves the COP and power saving compared with pure refrigerants. The coefficient of performance of R410a and M (R32/R161/R13I1) nanorefrigerants at 0.09 vol.%, increased by 47.3% and 89.8% compared to the pure refrigerants. The power consumption of both the nanorefrigerants is reduced by 31.8% and 47.2% respectively.

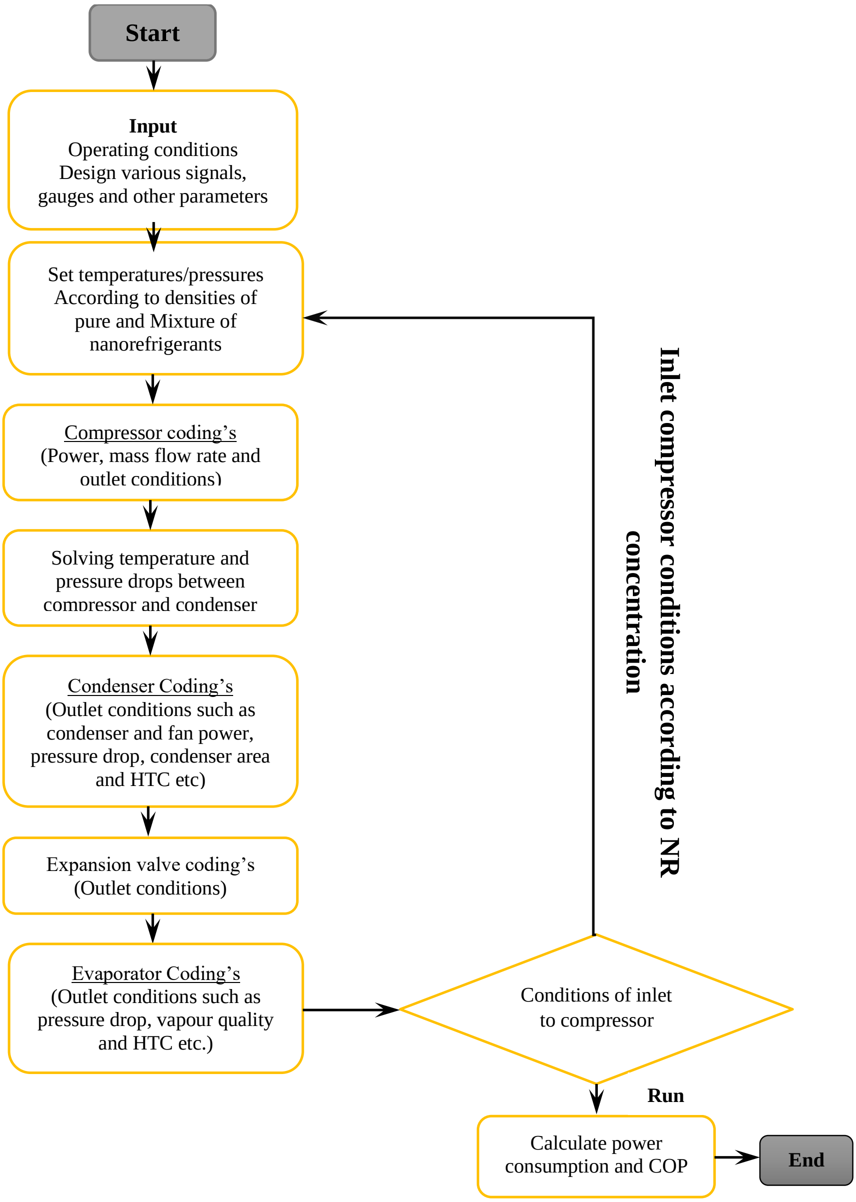

Fig. 4 Developed model flowchart

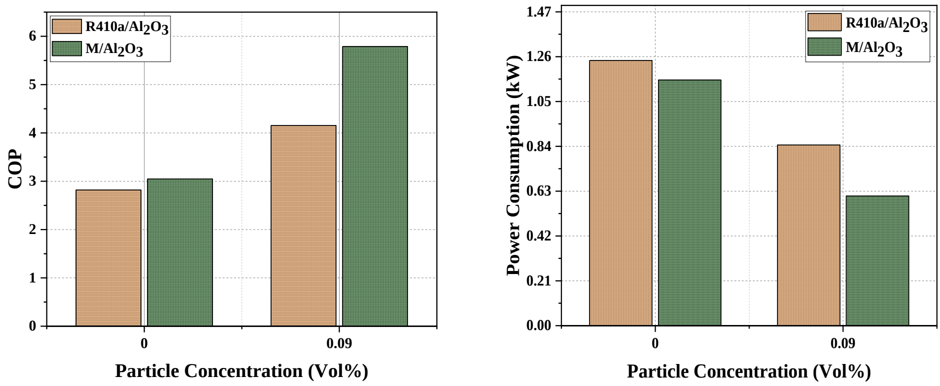

Fig 5. COP and power consumption of the system as the function of particle concentration

Fig. 6 shows the corresponding variation of discharge pressure. The discharge pressure of R410a/Al_2O_3 and M/Al_2O_3 was reduced by 2.6% and 4.51% compared with pure refrigerants of R410a and M.

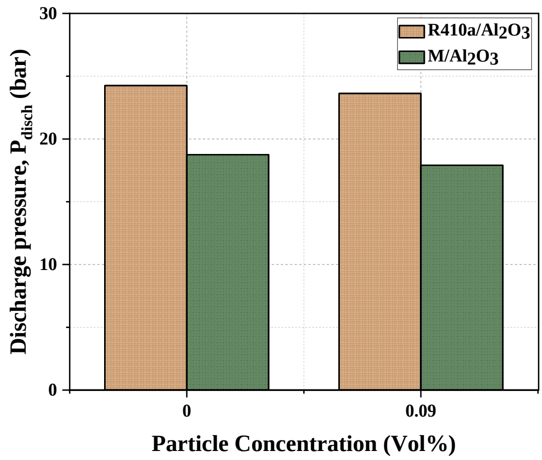

Fig. 6 Discharge pressure versus particle concentration

In addition, Figs. 7 and 8 illustrate the corresponding variation of discharge temperature. As the discharge temperature reduces the heat rejection and absorption increase through the condenser and evaporator. The discharge temperature of R410a/Al_2O_3 and M/Al_2O_3 was reduced by 11.86% and 19.4% compared with pure refrigerants of R410a and M.

3.2 Effect of Particle Concentration on Refrigeration Effect

Fig.9 shows the refrigeration effect versus particle concentration for R410a and M respectively. There is a marked increment in the refrigeration effect at a volume concentration of 0.09% for both refrigerants. The refrigeration effect of R410a/Al_2O_3 and M/Al_2O_3 increased by approximately 4.7% and 7% compared with pure refrigerants.

4. Numerical Method for Characterization of Nanorefrigerant

4.1 Effect of Nanoparticle Concentration on Thermal Conductivity

Fig.10 represents the thermal conductivity of Al_2O_3-R410a and Al_2O_3-R32/R161/R13I1 at a volume concentration of 0.09% and compared with pure refrigerants. The thermal conductivity of nanoparticles (spherical shape) is measured by using Eq. 9 [44]. The thermal conductivity of Al_2O_3-R410a and Al_2O_3-R32/R161/R13I1 is 0.105 W/mK and 0.124 W/mK respectively. The thermal conductivity of Al_2O_3-R32/R161/R13I1 nanorefrigerant is 18.1% more than that of Al_2O_3-R410a nanorefrigerant. The increase in Brownian motion, as well as the enhanced thermal conductivity of alumina nanoparticles, contributes to the improvement in suspension stability [45].

$$\frac{k_{eff}}{k_f} = \frac{k_p+2k_f+2\phi(k_p-k_f)}{k_p+2k_f-\phi(k_p-k_f)} \tag{9}$$

where ϕ, is the volume concentration of nanoparticles. k_{eff} is the effective thermal conductivity of the nanorefrigerant. k_f and k_p are the thermal conductivities of pure refrigerant and nanoparticles respectively.

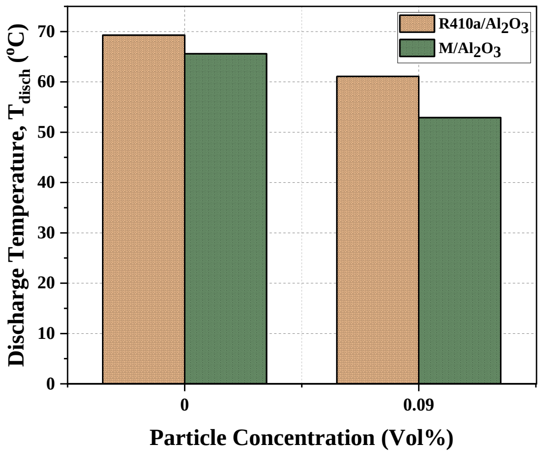

Fig. 7 Discharge temperature versus particle concentration

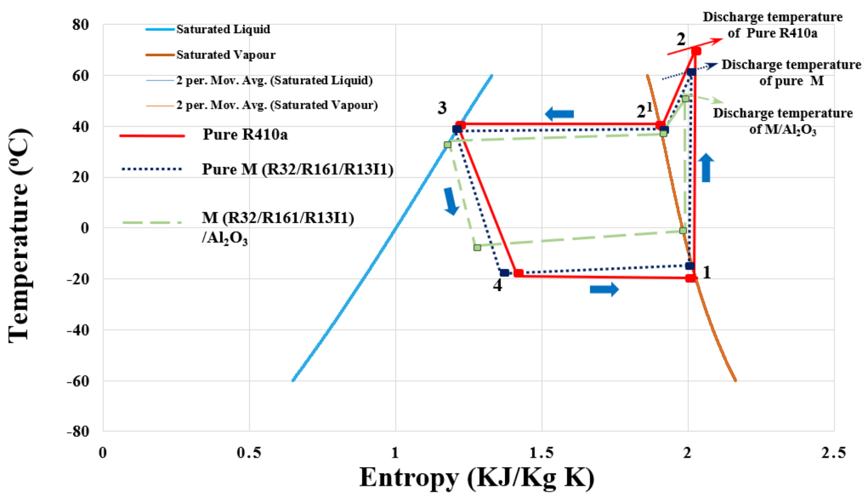

Fig. 8 T-s diagram for pure and nanorefrigerant

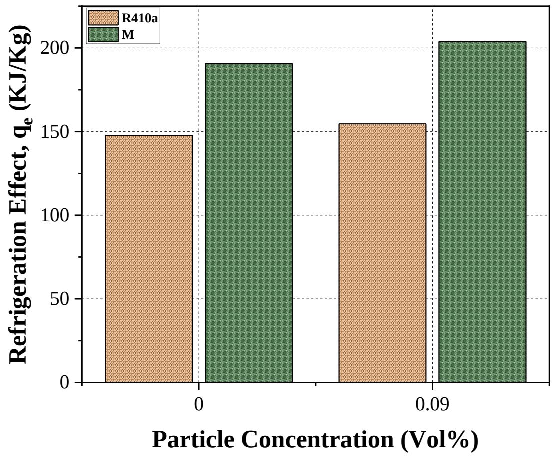

Fig.9 Refrigeration effect versus particle concentration

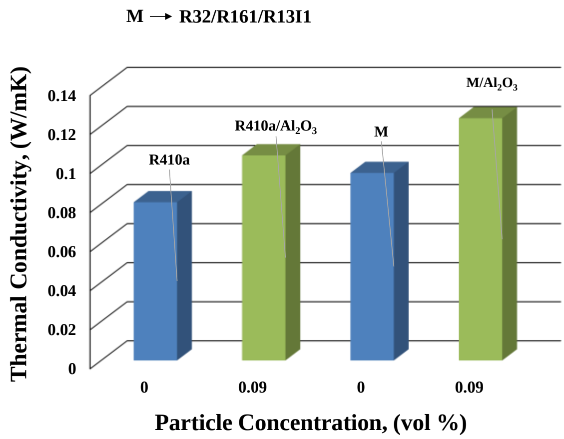

Fig. 10 Influence of nanoparticle (Al_2O_3) concentration on thermal conductivity

4.2 Effect of Nanoparticle Concentration on Viscosity

Fig.11 clearly shows the variation of viscosity of Al_2O_3-R410a and Al_2O_3-R32/R161/R13I1 at a volume concentration of 0.09% and compared with pure refrigerants. The viscosity of Al_2O_3-R410a and Al_2O_3-R32/R161/R13I1 nanorefrigerants was increased by 22.47% and 22.36% compared to the pure refrigerants. The pioneering model for estimating the viscosity of nanofluids was proposed by Einstein in Eq. 10 [46].

$$\mu_{nf} = \mu_{bf}(1 + 2.5\phi) \quad (10)$$

where μ_{bf} is the viscosity of the base fluid and μ_{nf} is the viscosity of the nanofluid.

4.3 Effect of Nanoparticle Concentration on Density

The density of R410a/Al_2O_3 and (R32/R161/R13I1)/Al_2O_3 nanorefrigerant was measured by utilizing above mentioned Eq.2. Fig.12 represents the variation of nanorefrigerant densities at a 0.09% volume concentration.

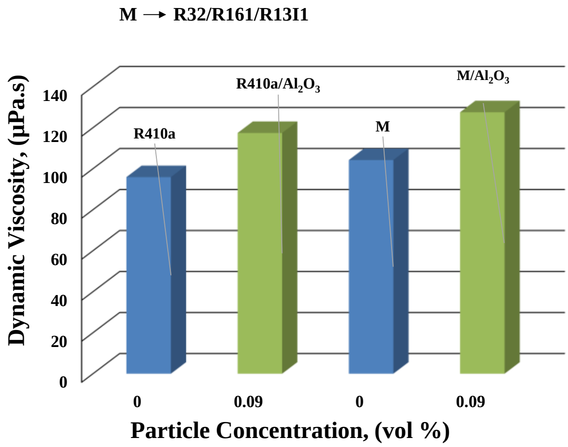

Fig.11. Influence of nanoparticle (Al_2O_3) concentration on dynamic viscosity

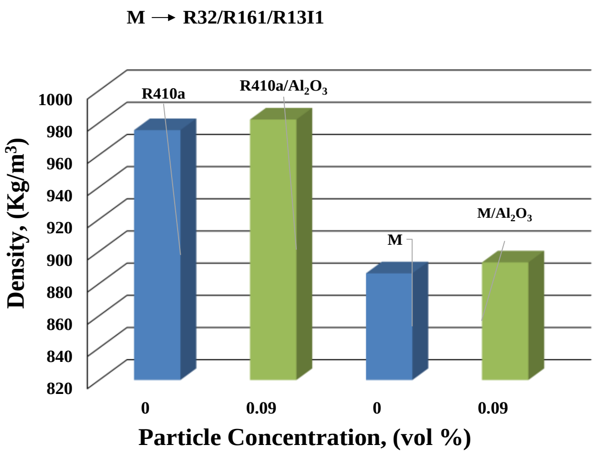

Fig. 12 Variation of the density of R410a/Al_2O_3 and M/Al_2O_3 with particle concentration

5. Conclusions

In the current study, the numerical determination of thermophysical properties, rheological properties, power-saving and long-term ultra-low global warming potential (GWP) mixture of nanorefrigerants (R32/R161/R13I1)/Al_2O_3 were carried out numerically in MATLAB software. The NIST REFPROP software program is used to generate thermophysical properties of the mixture of refrigerants and was developed in MATLAB. The current investigation reinforces the concepts of power saving and environmentally friendly behavior by incorporating an alumina-based nanorefrigerant into the air-conditioning system. The system exhibits improved performance at a volume concentration of 0.09% aluminium oxide. The simulation involving performance has been performed using MATLAB software.

- The COP of R410a and M (R32/R161/R13I1) nanorefrigerants has increased by 47.3% and 89.8%, respectively in comparison to pure refrigerants.

- The discharge temperature of R410a and M nanorefrigerants is reduced by 11.86% and 19.4% respectively and the comparison has been made with pure refrigerants.
- The discharge pressure of R410a and M nanorefrigerants was reduced by 2.6% and 4.51% at a volume concentration of 0.09% compared to pure refrigerants.
- The use of nano additives in R410a and M refrigerants lowers the power consumption of the system by 31.8% and 47.2% respectively.
- In addition, Al_2O_3 nano additives in R410a and M having a volume concentration of 0.09%, increased the net refrigeration effect from 76.7-82% and 79.3-87% respectively.
- Heat extraction is augmented from the evaporator by adding aluminium oxide nanoparticles to the refrigerants.
- The cooling effect or heat extraction of R410a/Al_2O_3 and M/Al_2O_3 nanorefrigerants increased by approximately 4.7% and 7% at a volume concentration of 0.09% compared to pure refrigerants.
- The viscosity and density are increased by adding Al_2O_3 nanoparticles to both refrigerants.
- The viscosity of R410a and M nanorefrigerants was increased by 22.47% and 22.36% at a volume concentration of 0.09% compared to the pure refrigerants.
- The thermal conductivity of R410a/Al_2O_3 and M/Al_2O_3 is 0.105 W/mK and 0.124 W/mK respectively.
- The thermal conductivity of M/Alumina nanorefrigerant is 18.1% more than that of R410a/Alumina.

Nomenclature

Al_2O_3	Aluminium Oxide
COP	Coefficient of Performance
NRE	Net Refrigeration effect, (%)
GWP	Global Warming Potential
$(GWP)_{100}$	Global Warming Potential over 100 years
ODP	Ozone Depletion Potential
M	Mixture (R32/R161/R13I3)
Q	Heat Transfer per Unit Mass, (kW)
Φ	Nanoparticle Volume Concentration, (%)
T	Temperature, (^{o}C)
GHG	Greenhouse Gas
NR	Nanorefrigerant
Vol.	Volume
m_r	Mass of Refrigerant, (kg s^{-1})
ρ	Density, (kg m^{-3})
POE	Poly-Easter Oil
MO	Mineral Oil

Subscripts

Comp	Compressor
Disch	Discharge
Sup	Superheated
c	Condenser
Evap	Evaporator

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