An experimental insight into the effects of silver-doped cupric oxide nanoparticles on the performance of hydrocarbon refrigeration system

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Abstract

Refrigerators are inevitable in domestic and many industrial habitats. Indeed, the performance of refrigerants used in refrigerators can be enhanced when mixed with nanoparticles. In this regard, this study uses cupric oxide nanoparticle to enhance the refrigerant performance. Pure nano-cupric oxide and silver-doped nano-cupric oxide are mixed with R290 in the ratio 1:100. The doped nano-cupric oxide is characterized by XRD followed by EDX. TEM is used for photographic verification of nano-size, and the DRS test is used to calculate and compare band gap. The refrigerator gives better results with the prepared nano-refrigerants. The result is much better with silver-doped nano-cupric oxide than with pure nano-cupric oxide. The coefficient of performance of silver-doped nano-cupric oxide increased up to 29%. On the other hand, the power consumption of the refrigerator is also found to reduce up to 28%, thus helping save energy.

Keywords HC refrigerant · Nano-cupric oxide · Silver doping · Characterization and performance

1 Introduction

Refrigeration is a process that cools a space or material below the atmospheric temperature. There are numerous natural refrigeration methods but the artificial refrigeration techniques came to limelight since the 1770s [1]. Refrigeration works on two basic thermodynamic cycles: gas cycles and vapour cycles. Many medium load and domestic refrigeration systems work in vapour cycles. The reverse Carnot cycle is the ideal cycle for heat pump and refrigeration [2]. Practically, a refrigeration system does not work in reverse Carnot cycle because there is pressure drop in the system [2].

The refrigeration system working in vapour cycle is basically of two types: vapour compression refrigeration and vapour absorption refrigeration. Between these two, vapour compression refrigeration is majorly used. In

vapour compression system, the refrigerant used is in the gaseous state. The refrigerants are chosen based on several properties which affect the performance of the refrigerator to a greater extent [3]. Thus, the performance of the refrigerator is vital in energy saving. The chosen refrigerant should also be less hazardous to the environment, which is denoted by the Ozone depletion potential (ODP) and Global warming potential (GWP) values. Per Montreal protocol and Kyoto protocol state that the refrigerant of the family hydrofluorocarbons (HFC) used in the recent past was phased out due to high GWP of 1300 in the last 100 years, though its performance was appealing [4]. In this perspective, Hydrocarbon (HC) refrigerants are a promising refrigerant as they have zero GWP and low ODP. The performance of several HC refrigerants is equivalent to R22 and is also better than R134a [4, 5].

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Nano-science has embraced majority of the fields in technology. The properties of elements in the nanoscale are tailored to meet the requirements. Several surface properties are found to be improved as the surface area of the particle is increased when made nano-size [6]. Nanoparticles are also used in heat transfer applications as the thermo-physical and rheological properties of the base fluid are enhanced [7, 8]. The application of nanoparticles has proven to give a positive result in the field of refrigeration as well. The oxides of several d-block elements are semiconductors, though some d-block elements are not good electrical conductors. Copper is a d-block element which is a good thermal and electrical conductor. Copper has two stable oxides out of which cupric oxide (CuO) is a semiconductor with better thermal properties in nano-size when blended with a base fluid [9]. Several research studies have disclosed that CuO nanoparticles with base refrigerant improved the heat transfer characteristics and cooling capacity with lesser energy consumption [10]. Also, the concentration of nanoparticles is an important factor which affects the boiling heat transfer coefficient [11].

Henderson et al. [12] studied the heat transfer characteristics of CuO nanoparticles dispersed with R-134a and R-134a/polyolester mixtures. It was observed from their experiments that there is an excellent dispersion of CuO nanoparticles with the mixture and the heat transfer coefficient enhanced up to 76% for 0.08% CuO volume fraction.

In addition to CuO nanoparticles, several research studies majorly reported the use of alumina (Al_2O_3), titanium oxide (TiO_2) and silver nanoparticles to improve the performance of refrigeration system. Studies by Javadi and Saidur [13] reported that the thermal properties of the nanoparticles along with the base fluid depend on the stability of the suspension and the size of the particles. Therefore, the appropriate suspension and size would provide the expected result. Their study disclosed that the combination of R-134a refrigerant with 0.1% TiO_2 -mineral oil nano-refrigerant could save 25% energy and significantly reduce carbon dioxide emissions. Reports by Subramani and Prakash [14] portrayed that Al_2O_3 nano-lubricant in vapour compression refrigeration system drastically reduce the power consumption by 25% and also improve the coefficient of performance by 33%. Silver (Ag) is another d-block element which has good thermal properties. Ag also has drastic improvements in its properties in the nano-size. When Ag is doped on to nano-CuO, the properties are furthermore improved as reported by Zhang et al. [15].

Overall, it is clear that the use of nano-refrigerant in the refrigeration cycle improves the performance of the system. However, to restrict the use of chlorofluorocarbons and hydrofluorocarbons in refrigeration system, researchers investigated the potential of eco-friendly natural refrigerants such as R290 and R600a in the refrigeration system [16].

Halimic et al. [17] reported that the use of R290 in a vapour compression refrigeration system instead of R12 resulted in similar coefficient of performance (COP) and even higher cooling capacity.

Bi et al. [18] investigated the performance of TiO_2 -R600a nano-refrigerant in a domestic refrigerator and reported 9.6% energy consumption is achieved using 0.5 g/L TiO_2 -R600a nano-refrigerant.

Based on the above considerations, the objective of the present work is to assess the performance of eco-friendly nano-refrigerant. In this perspective, CuO-R290 nano-refrigerant and Ag-doped CuO-R290 nano-refrigerant were prepared and compared in terms of COP, refrigerating effect and power consumption.

2 Nanoparticle preparation and silver doping

For the experimental studies, CuO of grade 99% and size 100 μm was purchased from Sigma Aldrich and milled down to nanoscale by ball mill for 20 h. Nano-CuO is doped with Ag (2%) to enhance its surface properties. Doping is done by UV process using silver nitrate (AgNO_3) salt and ethanol solution for 9 h by the method suggested by Nguyen [19]. Finally, Ag is doped on to the surface of nano-CuO and characterized for further studies.

2.1 Characterization

The Ag-doped CuO nano-refrigerant was characterized by the powder X-ray diffraction (XRD) followed by energy-dispersive X-ray spectroscopy (EDX), transmission electron microscopy (TEM) and diffuse reflectance spectroscopy (DRS).

The XRD pattern was recorded with Cu target (Cu-K α radiation, $\lambda = 1.54 \text{ \AA}$) under continuous scan mode with a scan range of 10° – 90° and a scan speed of $10^\circ/\text{min}$. In addition, the average crystallite size (t) has been calculated from the line broadening using Scherrer equation ($t = 0.9\lambda/B\cos\theta$, where λ is the wavelength and B is full width of half maximum).

The percentage composition of various elements with impurities present in Ag-doped CuO nano-refrigerant is characterized by energy-dispersive X-ray spectroscopy (EDX). The size of the prepared nanoparticle was observed under transmission electron microscopy (TEM). In addition, diffuse reflectance spectra were recorded at room temperature for pure CuO nano-refrigerant and Ag-doped CuO nano-refrigerant.

3 Experimental setup

For the experimental study, a refrigeration test rig was designed and fabricated as shown in Fig. 1. The setup consists of compressor, whose working matches the physical properties of R290. The setup consists of air cooled forced draught condenser, DX evaporator and capillary tube for expansion. The setup also consists of a filter–drier as an accessory.

At first, pure R290 is charged into the setup maintaining a pressure of 60–80 psi. The inlet and outlet temperature and pressure of the evaporator and condenser are noted corresponding to temperature changes of the material refrigerated in the cooling chamber. The material to be refrigerated is water, and the capacity of the cooling chamber is 8 litres. The corresponding time taken and power consumption reading taken from the energy meter are taken simultaneously, and the COP is calculated.

The nano-CuO is charged with R290 in the ratio 1:100, maintaining the same pressure. The steps are repeated and the corresponding COP is calculated for the

nano-refrigerant. The process is repeated for Ag-doped CuO and R290 mixture, mixed in the same proportion.

4 Results and discussion

4.1 X-ray powder diffraction (XRD)

The crystalline nature of prepared Ag-doped nano-CuO particles was identified from their corresponding powder XRD patterns (Fig. 2). The strongest diffraction peaks were well matched with single-phase monoclinic structure of CuO (standard JCPDS File No: 05-661). The three strongest diffraction peaks with $2\theta = 35.40^\circ$, 38.63° and 48.67° , respectively were indexed to (002), (111), and (020) planes and their lattice parameters are $a = 4.68 \text{ \AA}$, $b = 3.42 \text{ \AA}$, $c = 5.13 \text{ \AA}$. Similarly, the diffraction peak of Ag at $2\theta = 38.4$ and (111) plane is in good agreement with the reported value (JCPDS File No: 89-3722). Moreover, the average crystallite size of the nanoparticles calculated using Scherrer equation is 24 nm.

4.2 Energy-dispersive X-ray analysis (EDX)

The composition analysis of elements by EDX (Fig. 3) confirmed the presence of Cu (71.44%) as major phase and Ag (3.16%) as minor phase with trace impurity Fe (0.83%). Indeed, iron (Fe) is one of the main impurities of milling system and its degree is dependent on the milling time and initial size of particle under the milling energy [20].

4.3 Transmission electron microscopy (TEM)

Figure 4 shows the TEM image of the prepared Ag-doped CuO nanoparticles. The size of particle observed in TEM image is in the range of 16.7–28.7 nm which is in good agreement with average crystallite size of the nanoparticles calculated by Scherrer formula using XRD.

Fig. 1 Experimental setup of HC refrigeration system

Fig. 2 XRD pattern of Ag-doped CuO nanoparticles

Fig. 3 EDX spectrum of Ag-doped CuO nanoparticles **Fig. 4** TEM image

4.4 Diffuse reflectance spectroscopy (DRS)

The spectrum absorption for pure nano-CuO and Ag-doped nano-CuO is shown in Fig. 5a, b. The band gap of the nano-CuO is found from DRS test using de Broglie's wavelength equation, and the band gap is found to be 3.1 eV. On the other hand, the band gap of the Ag-doped nano-CuO refrigerant (2.97 eV) was found to be lower than that of pure nano-CuO. This decreasing band

gap of doped nano-CuO disclose that the conductivity increases with decreasing band gap value which is the amount of energy needed to promote an electron from the highest occupied energy level or valence band to the conduction band immediately above it [21].

4.5 Coefficient of performance (COP)

The COP of pure R290 and CuO nano-refrigerants with and without doping is compared based on the decreasing temperature of water, and the results are shown in the Fig. 6. The COP was calculated using the energy meter reading and the cooling load. The COP of Ag-doped nano-CuO refrigerant blend is more than pure nano-CuO refrigerant blend and pure R290. This implies that either the refrigerating effect or the work input to the refrigerator with Ag-doped nano-CuO refrigerant blend is greater than pure CuO nano-refrigerant and pure refrigerant. Overall, the COP of the CuO nano-refrigerant is found to be increased by 29% than the COP of pure R290. It has also been found that the COP of Ag-doped nano-CuO blended with R290 has risen by 6% than the COP of CuO nano-refrigerant. This trend can be explained by the compressor's reduced power consumption. Moreover, the greater sub-cooling effect of Ag-doped nano-CuO refrigerant in the condenser could also have improved the COP.

Fig. 5 **a** DRS plot of pure nano-CuO. **b** DRS plot of Ag-doped nano-CuO

4.6 Refrigerating effect

The refrigerating effect of the refrigerants, i.e., the refrigerating effect of pure R290 refrigerant, CuO-blended nano-refrigerant and Ag-doped CuO nano-refrigerant is calculated corresponding to the falling temperature of water and they are compared. As the experimental COPs are found to be better, the refrigerating effect is also found to be better. The result of comparison can be interpreted graphically as shown in Fig. 7. It was observed that the refrigerating effect of pure R290 was 50 W, and for CuO-blended nano-refrigerant and Ag-doped CuO nano-refrigerant, it was noted as 73 W and 163 W, respectively. The refrigerating effect is elevated because the thermal properties of Ag-doped nano-CuO are better than pure nano-CuO. Also, the overall conductivity of the

Fig. 6 Variation of COP of refrigerants

Fig. 7 Variation of refrigerating effect of refrigerants

refrigerant is also increased due to the nano-transitional elements mixed with it [22, 23].

4.7 Power consumption

The power consumed by the refrigerator with R290 refrigerant and with pure and Ag-doped CuO nano-refrigerant is notably different. The comparison is interpreted graphically and is shown in Fig. 8. On plotting the corresponding power consumption with respect to falling temperature of water, it was found that refrigerator working with Ag-doped CuO nano-refrigerant consumes on an average less power (~ 87 W) than with pure R290 and pure CuO

Fig. 8 Variation of power consumption of refrigerants

nano-refrigerant. This is because the refrigerating effect is more for Ag-doped nano-CuO refrigerant. Also, the increase in cooling capacity increased the evaporation temperature which in turn resulted in the reduced power consumption of the nano-refrigerant. As power conservation is very important in this era, Ag-doped CuO nano-refrigerant has given positive results. Environmental degradation is also reduced as an HC refrigerant is used as the base fluid refrigerant.

5 Concluding remarks

Based on the experimental work conducted with performance of eco-friendly nano-refrigerents, the following conclusions are drawn.

- The performance of the doped nano-refrigerant is dependent on the size of the nanoparticle. The performance is appealing only at the optimum size. If the size is further increased or decreased, the expecting results cannot be achieved as the size of the nanoparticle decides the surface area exposed for heat transfer within the refrigerant.
- The band gap energy of the nanoparticle plays a vital role in the thermal properties of the particle, which in turn affects the performance of the refrigerant. Since the band gap energy of Ag-doped nano-CuO is lesser than pure nano-CuO, the performance of Ag-doped nano-CuO blend with R290 is found to be better than that of CuO and R290 blend.

- The COP of the CuO nano-refrigerant is found to be increased by 29% than the COP of pure R290. The COP of Ag-doped nano-CuO blended with R290 is found to be increased by 6% than the COP of CuO nano-refrigerant. Also, the refrigeration effect is also found to be high for Ag-doped CuO nano-refrigerant on comparison with the other experimented refrigerants.
- CuO nano-refrigerants have reduced the power consumption of the refrigerator by 15% on comparison with pure R290 and Ag-doped CuO nano-refrigerant has reduced the power consumption by 28%. Thus, the experimental result concludes that Ag-doped CuO nano-refrigerant has better performance than pure R290 and thus aids in energy conservation.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

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