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Nanorefrigerant effects in heat transfer performance and energy consumption reduction: A review☆

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A R T I C L E I N F O

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A B S T R A C T

The heat transfer performance and energy consumption of various thermal devices may be augmented by active and passive techniques. One of the passive techniques is the addition of nanoparticles to the common heat transfer fluids so that the thermal transport properties of the prepared suspension (called nanofluid) will be enhanced as compared to the base fluid. Nanorefrigerants are a special type of nanofluids which are mixtures of nanoparticles and refrigerants and have a broad range of applications in diverse fields for instance refrigeration systems, air conditioning systems, and heat exchangers. This review is performed in order to clarify the effect of nanorefrigerant properties on heat transfer and pressure drop compared to pure refrigerant. Moreover, studies related to the thermophysical properties, and applications of nanorefrigerants to some specific areas such as domestic refrigerators, heat pipes and air conditioners are also summarized.

1. Introduction

Nanotechnology is a section of science and technology regarding the modification and use of particles in the atomic and molecular order. In this aspect, a particle is considered a tiny thing that acts as a single piece with respect to its carriage and specifications. While fixed physical properties are expected from bulk material, the properties of materials alter in relation to their nano scale size. These particles can be categorized, based on their diameter, into three groups, including coarse particles (10,000–2500 nm), fine particles (2500–100 nm), and ultrafine particles or nanoparticles (1–100 nm). Especially in heat transfer applications, the use of ultrafine particles is required because using the particles with a higher size leads to some problems like fouling, sedimentation, erosion and higher pressure drop [9].

Normally, the use of common heat transfer fluids such as water, engine oil, and ethylene glycol results in the limitations in efficiency and performance of the thermal devices with a given size. The heat transfer augmentation can be enabled by the treatment of suspended solid particles into these conventional fluids as a chemical additive. Thermal conductivity is considered the most important thermophysical property to enhance the heat transfer performance of these suspensions. Suspending nanoparticles in a base fluid, where the thermal conductivity of particles is remarkably higher than the base fluid, is used to enhance the thermal conductivity of conventional fluids. The composition of nanoparticles and the base fluid is called nanofluids, which are an advanced type of heat transfer fluids [9].

Nanorefrigerant is one kind of nanofluids, in which the host fluid is conventional pure refrigerant. Experimental studies showed that the nanorefrigerant has higher thermal conductivity than the host refrigerant [16,17] and the refrigeration system using nanorefrigerant has better performance than that of using conventional pure refrigerant [7,39,40]. However, the aggregation and sedimentation of nanoparticles in the nanorefrigerant may reduce the stability of nanorefrigerant and limit the application of nanorefrigerant in the refrigeration system.

Nanorefrigerant was proposed on the basis of the concept of the nanofluids, which was prepared by mixing the nanoparticles and traditional refrigerant. There were three main advantages followed for the nanoparticle used in the refrigerator (**O.A.** [4]).

Firstly, nanoparticles can enhance the solubility between the lubricant and the refrigerant. For example, Wang et al. [40] found out that TiO_2 nanoparticles could be used as additives to enhance the solubility between mineral oil and hydrofluorocarbon (HFC) refrigerant. The refrigeration systems using the mixture of R134a and mineral oil appended with nanoparticles TiO_2, appeared to give better performance by returning more lubricant oil back to the compressor, and had the similar performance compared to the systems using Polyol-ester (POE) and R134a.

Secondly, the thermal conductivity and heat transfer characteristics of the refrigerants should be increased, which have been approved by a lot of investigations. For instance, Jiang et al. [16,17] measured the thermal conductivities of CNT–R113 nanorefrigerants and found out that the measured thermal conductivities of four kinds of 1.0 vol.% CNT–R113 nanorefrigerants increase to 82%, 104%, 43% and 50%, respectively. Wang et al. [38] carried out an experimental study of boiling heat

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transfer characteristics of Al_2O_3 nanoparticles dispersed in R22 refrigerant, and found out that nanoparticles can enhance the heat transfer characteristic of the refrigerant, and the bubble size diminishes and moves quickly near the heat transfer surface. Xiao-Min et al. [37] investigated the pool boiling heat transfer of the R11 refrigerant mixed with nanoparticles TiO_2, and the results indicated that the heat transfer enhancement reached 20% at a particle loading of 0.01 g/L. Park and Jung [32] investigated the effect of carbon nanotubes (CNTs) on nucleate boiling heat transfer of halocarbon refrigerants of R123 and R134a. Test results showed that CNTs increase nucleate boiling heat transfer coefficients for these refrigerants. Especially, a large enhancement up to 36.6% was observed at low heat fluxes. Peng et al. [33,34] found out that the heat transfer coefficient of CuO–R113 was larger than that of pure refrigerant R113, and the maximum enhancement of heat transfer coefficient was 29.7%. Ding et al. [11] investigated the migrated mass of nanoparticles in the pool boiling process of both nanorefrigerant and nanorefrigerant–oil mixture, and found out that the migrated mass of nanoparticles and migration ratio in the nanorefrigerant were larger than those in the nanorefrigerant–oil mixture.

Finally, nanoparticles dispersed in lubricant should decrease the friction coefficient and wear rate. Lee et al. [24] investigated the friction coefficient of the mineral oil mixed with 0.1 vol.% fullerene nanoparticles, and the results indicated that the friction coefficient decreased by 90% in comparison with raw lubricant, which leads us to the conclusion that nanoparticles can improve the efficiency and reliability of the compressor. Jwo et al. [18] carried out the performance experiment of a domestic refrigerator using hydrocarbon refrigerant and 0.1 wt.% Al_2O_3–mineral oil as working fluid, the results indicated that the power consumption was reduced by about 2.4%, and the coefficient of performance was increased by 4.4%.

This review paper focuses on the latest advances in the augmentation of heat transfer and energy consumption reduction by using nanorefrigerants. Studies related to the applications of nanorefrigerants in refrigeration systems, horizontal smooth tubes and air conditioning systems are reviewed. Tables 3–5 provide a summary of the review performed in this paper.

2. Studies on nanorefrigerant applications

The studies on nanorefrigerants applications are classified into three sections. The first section concerns research on refrigeration systems, and the following sections review the, horizontal smooth tubes and air conditioning systems.

2.1. Refrigeration systems

A domestic refrigerator reliability and performance with nanoparticles in the working fluid were investigated experimentally. Mineral oil with TiO_2 nanoparticles mixtures was used as the lubricant instead of Polyol-ester (POE) oil in the 1,1,1,2-tetrafluoroethane (HFC134a) refrigerator. The compatibility of nonmetallic materials in the system with the HFC134a and mineral oil–nanoparticles mixtures was studied before the refrigerator performance tests. The refrigerator performance with the nanoparticles was investigated by using energy consumption tests and freeze capacity tests. The results indicated that HFC134a and mineral oil with TiO_2 nanoparticles work normally and safely in the refrigerator. The refrigerator performance was better than the HFC134a and POE oil system, with 26.1% less energy consumption used with 0.1% mass fraction TiO_2 nanoparticles compared to the HFC134a and POE oil system as shown in Table 1. The same tests with Al_2O_3 nanoparticles showed that the different nanoparticle properties have little effect on the refrigerator performance. Thus, nanoparticles can be used in domestic refrigerators to considerably reduce energy consumption [7].

Table 1
Energy consumption of HFC134a/POE oil and HFC134a/mineral oil/ TiO_2 nanoparticle systems [7].

Mass fraction %	POE	0.06 TiO_2	0.1 TiO_2	0.1 (50 days later)
Energy consumption kW h/day	1.077	0.849	0.796	0.8
Energy saving %		21.2	26.1	25.7

Table 2
Energy consumption results Bi et al. [8].

Concentration (g/L)	0	0.1	0.5
Energy consumption (kW h)	0.9567	0.8999	0.8649
Energy saving (%)	/	5.94	9.6

Jwo et al. [18] discussed the replacement of the R-134a refrigerant and polyester lubricant with a hydrocarbon refrigerant and mineral lubricant. The mineral lubricant included added Al_2O_3 nanoparticles (0.05, 0.1, and 0.2 wt.%) to improve the lubrication and heat-transfer performance. Experimental results indicated that the 60% R-134a and 0.1 wt.% Al_2O_3 nanoparticles were optimal. Under these conditions, the power consumption was reduced by about 2.4%, and the coefficient of performance was increased by 4.4%. These results showed that replacing R-134a refrigerant with hydrocarbon refrigerant and adding Al_2O_3 nanoparticles to the lubricant effectively reduced power consumption.

Bi et al. [8] investigated experimentally the work on the nanorefrigerant. TiO_2–R600a nanorefrigerant was used as a working fluid of domestic refrigerator. The results indicated that TiO_2–R600a worked normally and efficiently in a refrigerator. Compared with a refrigerator using pure R600a as working fluids, 0.1 and 0.5 g/L concentrations of TiO_2–R600a can save 5.94% and 9.60% energy consumption respectively and the freezing velocity of a nanorefrigerant system was quicker than the pure R600a system as shown in Table 2. In addition, the results were similar to the author's early research of using TiO_2–R134a as working fluids. So the above works have demonstrated that nanoparticles can improve the performance of the domestic refrigerator.

Abdel-Hadi et al. [2] experimentally investigated the effect of using nano CuO–R134a in the vapor compression system on the evaporating heat transfer coefficient. An experimental test rig was designed and constructed for this purpose. The test section was a horizontal tube in tube heat exchanger made from copper. The refrigerant evaporated inside an inner copper tube and the heat load provided from hot water passed in an annulus surrounding the inner tube. Measurements performed for heat flux ranged from 10 to 40 kW/m^2, using nano CuO concentrations that ranged from 0.05 to 1% and particle size from 15 to 70 nm. The measurements indicated that for a certain nano concentration as heat flux or mass flux increases the evaporating heat transfer coefficient increased. The measurements indicated also that the evaporating heat transfer coefficient increased with increasing nano CuO concentrations up to certain value then decreased. Comparison with the available published data showed good agreement.

Convective heat transfer is very important in the HVAC, refrigeration and microelectronics cooling applications. R134a is the most widely adopted alternate refrigerant in refrigeration equipment, such as domestic refrigerators and air conditioners. Though the global warming up potential of R134a is relatively high, it is affirmed that it is a long term alternate refrigerants in lots of countries. The addition of nanoparticles to the refrigerant results in improvements in the thermophysical properties and heat transfer characteristics of the refrigerant, thereby improving the performance of the refrigeration system. Stable nanolubricant has been prepared for this study. The experimental studies indicated that the refrigeration system with nanorefrigerant works normally. It is found that the freezing capacity was higher and the power consumption reduces by 25% when POE oil was replaced by a mixture of mineral oil and alumina nanoparticles. Calculations showed that the enhancement factor in the evaporator is 1.53 when nanorefrigerants are used instead of pure refrigerant [36].