International Communications in Heat and Mass Transfer 68 (2015) 91–97

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

# Applications of nanorefrigerant and nanolubricants in refrigeration, air-conditioning and heat pump systems: A review☆

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ARTICLE INFO

Available online 4 September 2015

*Keywords:*
Nanolubricants
Nanorefrigerants
Refrigeration system
Air conditioning system

ABSTRACT

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, air conditioning systems, and heat pumps. In this paper thermal–physical properties of nanoparticles suspended in refrigerant and lubricating oils of refrigerating systems were reviewed. The effects of nanolubricants on boiling and two phase flow phenomena are presented as well. Based on results available in the literatures, it has been found that nanorefrigerants have a much higher and strongly temperature-dependent thermal conductivity at very low particle concentrations than conventional refrigerant. This can be considered as one of the key parameters for enhanced performance for refrigeration and air conditioning systems. Because of its superior thermal performances, latest up to date literatures on this property have been summarized and presented in this paper as well. The results indicate that HFC134a and mineral oil with $TiO_2$ nanoparticles work normally and safely in the refrigerator with better performance. The energy consumption of the HFC134a refrigerant using mineral oil and nanoparticles mixture as lubricant saved 26.1% energy with 0.1% mass fraction $TiO_2$ nanoparticles compared to the HFC134a and POE oil system.

## 1. Introduction

Nanofluids are engineered colloids made of a base fluid and nanoparticles (1–100 nm). Common base fluids include water, organic liquids (e.g. ethylene, tri-ethylene-glycols, refrigerants, etc.), oils and lubricants, bio-fluids, polymer solutions and other common liquids. Materials commonly used as nanoparticles include chemically stable metals (e.g. gold, copper), metal oxides (e.g., alumina, silica, zirconia, titania), oxide ceramics (e.g. $Al_2O_3$, CuO), metal carbides (e.g. SiC), metal nitrides (e.g. AIN, SiN), carbon in various forms (e.g., diamond, graphite, carbon nanotubes, fullerene) and functionalized nanoparticles. Use of nanofluids is a new research frontier related to nanotechnology and has found a wide range of potential applications ([7]; [32,33]). According to the application, nanofluids are classified as heat transfer nanofluids, tribological nanofluids, surfactant and coating nanofluids, chemical nanofluids, process/extraction nanofluids, environmental (pollution cleaning) nanofluids, bio- and pharmaceutical nanofluids and medical nanofluids (drug delivery, functional and tissue–cell interaction).

Heat transfer nanofluids were first reported by Choi [8] of the Argonne National Laboratory, USA. Since then, a number of studies have been conducted on the thermal properties (mainly thermal conductivity) and single-phase and boiling heat transfer performance. It has been demonstrated that nanofluids can have significantly better heat transfer characteristics than the base fluids. Furthermore, a number of patents have been reported [6]. From the available research of nanofluids, the following key features of nanofluids have been found:

- Larger thermal conductivities compared to conventional fluids
- A strongly non-linear temperature dependency on the effective thermal conductivity
- Enhance or diminish heat transfer in single-phase flow
- Enhance or reduce nucleate pool boiling heat transfer which is due either to the systematic scatter in experiments or to the large scenarios which may be encountered
- Yield higher critical heat fluxes under pool boiling conditions.

Moreover, a new concept described as the application of nanoparticles as additives into refrigerants which the obtained suspension is called "Nanorefrigerant." Refrigerant is a material used in heat transfer cycles which undergoes a phase change most of the time due to excessive heat transfer rate experienced during the process. Despite most of the fluids can find themselves a place in refrigeration cycles, only fluorocarbons or chlorofluorocarbons were considered as refrigerant according to general opinion. Two methods (one-step method and two-step method) are used for synthesis of nano-refrigerants. Two-step method

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☆ Communicated by W.J. Minkowycz

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.08.014
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**Table 1**
Studies related to $Al_2O_3$ nanoparticles [from Celen et al. [5]].

| Researcher | Refrigerant | Lubricant | Average particle diameter size | Evaluation |
|---|---|---|---|---|
| Jwo et al. [15] | R134a/R12 | POE/MO | 20–30 nm | HR-12/$Al_2O_3$MO performed the lowest power consumption about 2.4%. |
| Kedzierski [17] | R134a | RL68H | 20 nm | Nanoparticles having large volume fraction and small size were capable of enhancing heat transfer. |
| Subramani and Prakash [34] | R134a | POE | <50 nm | 25% less energy consumption. |
| Kumar and Elansezhian [22] | R134a | PAG | 40 nm, 50 nm | 10.32% less energy consumption and increased COP. |
| Kedzierski [18] | R134a | RL68H | 10 nm | Boiling performance enhanced up to 113% on a rectangular finned surface. |
| Kedzierski [19] | R134a | RL68H | 10 nm, 60 nm | The correlation which was able to predict the kinematic viscosity of the nanolubricant within ±15% of the measurement was developed. |
| Tang et al. [36] | R141b | POE | <200 nm | R141b/δ-$Al_2O_3$ with SDBS enhanced the pool boiling heat transfer. |

is commonly used to prepare nanorefrigerants. In this method, the nanomaterials are synthesized as dry powders by thermal decomposition and photochemical methods, transition metal salt reduction, ligand reduction and displacement from organometallics, metal vapor synthesis and electrochemical synthesis methods [4]. After production, the nanosized powder is put into the oil to form nanoparticle/oil mixture. Then, this mixture is dispersed by using different type of dispersion techniques such as ultrasonic agitation, magnetic force agitation, homogenizing, high-shear mixing [41]. In one-step method, vapor phase nanophase powders are condensed into a liquid having low vapor pressure and dissolved in liquid at the same time. The nanoparticles are produced by applying a physical vapor deposition method or liquid chemical method [35].

Recently scientists used nanoparticles in refrigeration systems because of its remarkable improvement in thermo-physical, and heat transfer capabilities to enhance the efficiency and reliability of refrigeration and air conditioning system. Elcock [12] found that $TiO_2$ nanoparticles can be used as additives to enhance the solubility of the mineral oil with the hydrofluorocarbon (HFC) refrigerant. Authors also reported that refrigeration systems using a mixture of HFC134a and mineral oil with TiO2 nanoparticles appear to give better performance by returning more lubricant oil to the compressor with similar performance to systems using HFC134a and POE oil. Eastman et al. [11] investigated the pool boiling heat transfer characteristics of R11 refrigerant with $TiO_2$ nanoparticles and showed that the heat transfer enhancement reached 20% at a particle loading of 0.01 g/L. Liu et al. [23] investigated the effects of carbon nanotubes (CNTs) on the nucleate boiling heat transfer of R123 and HFC134a refrigerants. Authors reported that CNTs increase the nucleate boiling heat transfer coefficients for these refrigerants. Authors noticed large enhancements of up to 36.6% at low heat fluxes of less than 30 $kW/m^2$. Thus, the use of nanoparticles in refrigeration systems is a new, innovative way to enhance the efficiency and reliability in the refrigeration system.

The potential of some refrigerants to mix with nano-particles are mentioned as follows: Hydro fluorocarbons (HFCs) and hydrocarbons (HCs) are the most commonly used substitute refrigerants in refrigeration units of domestic refrigerators, chillers, air conditioners, and so on. When the refrigerants are mixed with nanoparticles, the system performance is enhanced while the energy consumption is reduced as compared to the pure refrigerant. Polyolester (POE) oil, another type of refrigerant, is preferred over mineral oil for use in lubricant applications due to its strong chemical polarity. In addition, the use of suspended nanoparticles in the lubrication of compressors increases the system's efficiency, causing no choking in the system [5].

This review paper focuses on the latest advances in the augmentation of heat transfer by using nanorefrigerants. Studies related to the thermophysical properties, heat transfer, pressure drop, flow and pool boiling, and applications of nanorefrigerants are reviewed. Tables 1–6 provide a summary of the review performed in this paper. It can be seen from Tables 1–6 that $Al_2O_3$, CuO, $TiO_2$, Cu, Ti, Al, diamond, $SiO_2$ nanoparticles having different concentrations were used with the R134a, R600a, R113, R141b, R123, R12, and R410a in order to form a nanorefrigerant.

In the literatures a number of reviews on thermal and rheological properties, and different modes of heat transfer of nanofluids have been reported by many researchers [10,13,25,37]. However, to the best of authors' knowledge, there is no comprehensive literature on the nanoparticles as additives with conventional refrigerants and oils used in refrigeration system. It is authors' hope that this review will be useful to fill identified research gaps and to overcome the challenges of nanorefrigerants.

## 2. Studies on nanorefrigerants/nanolubricants

The studies on nanorefrigerants/nanolubricants are classified into six sections. The first section concerns research on studies related to $Al_2O_3$ nanoparticles, and the following sections review the, studies related to CuO nanoparticles, studies related to $TiO_2$ nanoparticles, studies related to CNT nanoparticles, studies related to Cu nanoparticles and studies related to other nanoparticles.

### *2.1. Studies related to $Al_2O_3$ nanoparticles*

Jwo et al. [15] studied R12/$Al_2O_3$/MO nanorefrigerant at weight fractions of 0.05, 0.1, and 2% of $Al_2O_3$ particles in a refrigerator which originally works with R134a. R134a was replaced by R12, after POE was replaced by MO and finally, $Al_2O_3$ nanoparticles were added in the R12/MO mixture, and measurements were performed for each one. Results showed that the system that uses R12 refrigerant has a lower compression ratio as compared to the system with the working fluid of R134a. On the other hand, when the working fluid has 0.1 wt% of nanoparticles, the energy consumption is reduced by 2.4% as compared to the system in which R-134a is operating refrigerant.

**Table 2**
Studies related to CuO nanoparticles [from Celen et al. [5]].

| Researcher | Refrigerant | Lubricant | Average particle diameter size | Evaluation |
|---|---|---|---|---|
| Bartelt et al. [1] | R134a | POE | 30 nm | Maximum enhancement of 101% obtained for 2% mass fraction. |
| Ding et al. [9] | R113 | RB68EP | 40 nm | The deviations between the model predictions and experimental data were in the range of 7.7–38.4% |
| Kedzierski and Gong [21] | R134a | RL68H | 30 nm | The boiling heat transfer enhancement was 20%. |
| Kedzierski [16] | R134a | RL68H | 30 nm | R134a/nanolubricant mixtures with 1 vol.% CuO had larger boiling heat flux than mixtures with 2 vol.% CuO in nanolubricants. |
| Henderson et al. [14] | R134a | POE | 30 nm | 23% less energy consumption. |