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Nano-refrigerants and nano-lubricants in refrigeration: Synthesis, mechanisms, applications, and challenges

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ABSTRACT

Addressing global energy security and environmental concerns, the utilization of nano-refrigerants and nano-lubricants has emerged as an innovative path for enhancing heat transfer. This research focuses on enhancing the thermophysical properties, heat transfer efficiency, and tribological characteristics of nano-fluids—nanoparticles dispersed in refrigerants or lubricants. These nanofluids have demonstrated significant potential in applications such as cooling, air conditioning systems, and heat transfer equipment including pumps and pipes. A comprehensive understanding of parameters like thermal conductivity, viscosity, pressure drop, pumping power, and energy performance is delivered, with the aim of enhancing the overall efficiency of refrigeration systems, particularly the coefficient of performance (COP). Additionally, the review covers existing research on flow and pool boiling heat transfer, nano-lubricant tribological enhancement, and nano-refrigerant condensation. The study also addresses the challenges associated with the use of nano-refrigerants and nano-lubricants and offers a prospective outlook for their usage. These novel nanofluids are anticipated to emerge as effective solutions for increasing the COP and reducing energy consumption in the industrial sector, thus extending beyond the scope of previous efforts in this field. This review could serve as a valuable resource for a broad audience interested in this novel approach to energy efficiency.

1. Introduction

Numerous nations are improving renewable and sustainable energy by aiming at net-zero emissions by 2050. Efficient energy usage is one of the global challenges. The usage of heating, ventilation, and air conditioning (HVAC) systems requires a significant amount of energy. Refrigeration, which is a notable advancement of the 20th century, is responsible for 20% of the overall energy consumption worldwide [1]. Initially, natural refrigerants were used in the history of refrigerants, but they were later replaced by synthetic refrigerants due to their better performance, safety, and durability, which were considered crucial factors [2]. The less effective and more likely to cause global warming are the older refrigerants (GWP). Due to their low critical temperature, pressure, and standard boiling point, refrigerants are essential in all types of air conditioning and refrigeration (AC&R) systems, including those used in homes, businesses, industries, and automobiles. Because of their effectiveness and availability, the first generation of refrigerants includes compounds like ethers, carbon dioxide (CO_2), ammonia (NH_3), sulfur oxide (SO_2), hydrocarbons (HCs), and chlorofluorocarbons (CFCs). These refrigerants' performance was frequently constrained and they commonly demonstrated toxicity, flammability, or both. A class of refrigerant called chlorofluorocarbons (CFCs) contains chlorine. These refrigerants were commercialized in 1931. However, they have since been found to have negative environmental impacts and are expensive to use [3]. The phase-out of CFC refrigerants is progressing at a slow pace, highlighting the uncertainties and difficulties surrounding the accessibility of Hydrochlorofluorocarbons (HCFCs), which were designated as the transitional alternative for CFCs and were considered as the

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second generation of refrigerants. The third generation of refrigerants comprised of low Ozone depletion potential (ODP) refrigerants. The depletion of the ozone layer has led to changes in the Earth's temperature, which has caused global warming issues [4]. Following 2010, the fourth generation of refrigerants emerged, focusing on the usage of refrigerants with low global warming potential (GWP), low ozone depletion potential (ODP), and brief lifespans to reduce greenhouse gas emissions. HCFCs include lower chlorine than CFCs, resulting in a reduced ODP. Some of the examples include R22, R123, R290, R1234yf, and R141b. It is argued that R290 delivers remarkable performance, but it has high flammability [5]; R1234yf is considered an alternative refrigerant, but it shows minimal performance than R290 [6]. Fig. 1 shows the merits and demerits of each generation of refrigerants.

Refrigerants perform an essential function consuming a significant amount of energy in AC&R systems. Apart from the energy prospect, refrigerants possess unfavorable environmental impacts where ODP, and GWP are the two widely accepted indicators. Table 1 presents different refrigerants' properties in terms of the parameters mentioned above. Ammonia (R717) and Butane (R600) are refrigerants commonly used in various refrigeration systems. These substances have environmental and toxicity concerns that are important to consider. While they are eco-friendlier compared to some other refrigerants in terms of ODP and GWP, R717 poses risks due to its toxicity, and butane due to its flammability and potential contribution to ground-level ozone formation. Proper handling, storage, and disposal of these refrigerants are essential to minimize their impacts on the environment and human health.

The thermodynamic properties of refrigerants recognizes the behavior and performance of system and consists of operating pressure, critical temperature and pressure, boiling point, specific power consumption, specific enthalpy, and specific entropy, etc. [7]. A refrigerant should possess a high critical temperature, low freezing temperature, and low boiling point to ensure that the design temperature in the evaporator functions correctly [8]. Chemical properties of fluids, such as toxicity, flammability, and reactivity with other substances like lubricants, are also important factors Hydrofluorocarbons (HFCs), hydrocarbons (HCs), and their blends are chemically stable under varying operating temperatures, demonstrate superior compressor compatibility, and exhibit notable stability when chemically interacting with lubricants. [8]. However, HFCs have a high global warming potential (GWP) due to their ability to trap heat in the earth's atmosphere, contributing to climate change. As a result, the Kigali Amendment to the Montreal Protocol, passed in 2016, established a timeline for phasing out HFCs to reduce their impact on climate change [9]. HFCs (fluorocarbons) are synthetic refrigerants designed to replace ozone depleting substances such as CFCs and HCFCs. Its low flammability, primarily due to strong carbon-fluorine (C-F) bonds, contributes to its safety profile in refrigeration and air conditioning systems. However, the flammability of HFCs depends on their specific chemical composition. B. HFC-32 is slightly more flammable due to the presence of hydrogen atoms.

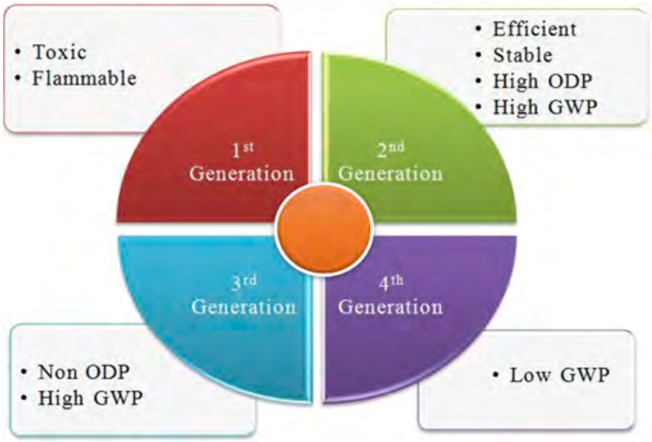


Fig. 1. Characteristics of various refrigerant generations.

In summary, the history of refrigerants has moved from natural substances to synthetic compounds such as HFCs due to safety and efficiency concerns. However, the environmental impact of these synthetic refrigerants has led to international agreements to develop new alternatives with lower GWP and ODP values.

The critical temperature refers to the threshold beyond which a substance cannot be converted into a liquid by applying pressure to its gas or vapor phase. In refrigeration systems, a high critical temperature is desirable to ensure broad condensing temperature range, since the vapor temperature at the compressor discharge is often much greater than the actual condensing temperature. This can improve heat transfer. Conversely, low critical temperatures can lead to increased power consumption in refrigeration systems. Such high boiling refrigerants can be beneficial for water chillers installed with centrifugal compressors.

Lubricants and refrigerants are essential parts of air conditioning and refrigeration systems. Traditional refrigerants and lubricants, however, have a number of drawbacks, such as poor thermal conductivity, inadequate lubricity, and unstable at high temperatures. These restrictions may lead to decreased performance overall, higher component wear and tear, and decreased energy efficiency. Improved heat transfer coefficients, greater thermal conductivities, and improved lubricating qualities are only a few advantages of using nanoparticles in these fluids. As a result, exploring the potential of nanofluids to enhance the effectiveness and efficacy of refrigeration and other systems is an innovative field of study [10].

Choi invented the first "Nanofluids," or nanoparticles (100 nm) dispersed in base fluids (water, ethylene glycol, and oil) [11]. One of the intriguing uses for nanofluids is in the field of renewable energy. Nanofluids possess exceptional features such as thermal properties, stability, etc. Several investigations have concluded that nanofluids show significant convective heat transfer capabilities than base fluid [12]. The key concern in the performance of automotive radiators are proper heat management systems. Nanofluids were envisioned as a smart coolant in automotive radiators have been visualized in a study by Choi [13]. These nanofluids have demonstrated encouraging outcomes in renewable energy sector applications, including enhancements in effective thermal conductivity and convective heat transfer properties. Hence, the magnificent properties of nanofluid as reported, open up the novel concept of nano-refrigerants for the researchers. There are two broad categories of nanofluid uses: coolants and lubricants. Although in refrigerant-based systems the nanoparticles are simply added to the refrigerant, the nanoparticles are first mixed with the lubricant-based systems and then added to the refrigerant [14].

1.1. Novelty of this article

Extensive literature reviews are available on the thermophysical, heat transport, and application features of nano-refrigerants and nanolubricants [15]. To the best of the authors' knowledge, there is no exhaustive literature review available on nano-refrigerants and nanolubricants that highlights synthesis, processes to increase performance, and research on particle agglomeration, migration, and deterioration of nanoparticles, as well as their applications, which is the key focus of this review. This article is distinguished by its holistic perspective, considers thermal characteristics and nanoparticle behavior. The authors sincerely hope that the proposed review paper may be a valuable inclusion in the literature to provide an overview of nano-refrigerants and nanolubricants and the enhancement of their parameters. Furthermore, it will be a valuable addition to providing comprehensive knowledge on scientific advancements of nano-refrigerants and nano-lubricants.

The structure of this review article is as follows: Section 1 offers an introduction that covers a general overview of refrigerants. Section 2 briefly delves into the development and synthesis methods of nano-

Table 1
Properties of different types of refrigerants.

Generation	Refrigerant	Chemical Formula	ODP	GWP	Molecular Mass (g/mol)	Boiling Point (°C)	Density (g/cm^3)	Thermal Conductivity (mW/mK)	Dynamic Viscosity (mPa.s)	Critical Temperature (K)
1st	R12	CCl2F2	1	10,900	120.91	−29.8	1.49	75.9	0.2487	385.12
2nd	R22	CHClF2	0.055	1810	86.47	−40.8	1.17	69.6	0.2815	–
3rd	R134a	CH2FCF3	0	1430	102.03	−26.3	1.25	92	0.1905	374.06
4th	R123	C2HCl2F3	0.06	77	152.93	27.6	1.46	83.7	0.4080	456.83
5th	R1234yf	C3H2F4	0	6	114	−30	1.1	64	0.0115	367.85
6th	R600 (Isobutane)	C4H10	0	<1	58.12	−11.7	0.0025	115.3	0.2025	408
7th	R717 (Ammonia)	NH3	0	0	17.031	−33.34	0.00073	559.2	170.1	–
Other	R152a	C2H4F2	–	77	66.05	−24.9	2.7	108.9	0.219	386.41
Other	R141b	C2H3Cl2F	0.12	725	116.95	32	1.25	88.8	0.3780	477.5
Other	R1234ze	C3H2F4	0	6	114.04	−19	0.489	57	0.0117	382.51

refrigerants and nano-lubricants. Section 3 presents a concise summary of numerical studies on nano-refrigerants. Section 4 explores the mechanisms for enhancing properties such as thermal conductivity, viscosity, system COP, pressure drop and pumping power, pool boiling, flow boiling, condensation heat transfer characteristics, and tribological properties of nano-lubricants, along with solubility and miscibility. Section 5 briefly overviews nanoparticle aggregation and degradation behavior in nano-refrigerants for improved stability. Moreover, Section 6 provides insights into nano-refrigerants' applications in AC&R systems, heat pipes, and heat pumps. Section 7 discusses the economic analysis. Lastly, Section 8 identifies scopes and challenges in the novel research frontier based on this review.

2. Development of nano-refrigerants and nano-lubricants

Nano-refrigerant is a subcategory of refrigerant in which nanoparticles are uniformly disseminated in the base refrigerant to improve heat transfer, while in nano-lubricant the nanoparticles are mixed with oil to minimize compressor power. Nano-refrigerants and nano-lubricants have shown promising thermodynamic efficiency and mechanical performance in vapor compression refrigeration systems due to their enhanced thermophysical and tribological properties, respectively.. In a vapor compression refrigeration (VCR) system, the majority of the lubricant is situated in the compressor, while the remaining portion is combined with the refrigerant at a specified ratio. The HVAC equipment manufacturer estimates that the compressor uses up to half of the system's lubricant, while the evaporator and drier use up to 20% each, and the condenser and hoses use up to 10% each [16]. Nano-refrigerants enhance heat absorption or cooling in the VCR system, while nano-lubricants boost compressor efficiency. [17,18].

Research on nano-refrigerants can be divided into two primary methodologies. One set of researchers investigates the incorporation of nanoparticles directly into the base refrigerant, while another group examines the suspension of nanoparticles in lubricant to assess its effectiveness,. Nano-refrigerants and nano-lubricants are created when particles are dispersed within the refrigerant-lubricant blend. As nanoparticles interact with the refrigerant, for example, nano-refrigerants exhibit improved heat transfer properties in comparison to tribological characteristics. On the other hand, nano-lubricants demonstrate superior tribological performance, as the nanoparticles are more concentrated in the compressor lubricant than in the refrigerant. The enhancement of the refrigerant's thermal characteristics improves the system's flow and pool boiling heat transfer qualities and pool flowing condensation heat transfer. Due to the remarkable thermal conductivity of nano-refrigerants, higher heat transfer coefficients can be achieved with significantly less pumping power [19]. The longer lifespan of mechanical parts is increased by the improved tribology properties of nano-lubricant, which also increase the compressor's coefficient of friction and wear rate. However, the main hindrance in the performance is the increased viscosity by increasing nanoparticles concentration. Therefore, an ideal nanoparticle concentration is required for refrigeration system performance.

Adding nanoparticles to refrigerant has the following characteristics [3]:

- Nanoparticles, when used as additives, can enhance the compatibility between refrigerants and lubricants.
- The incorporation of nanoparticles can boost refrigerants' thermal and thermophysical properties.
- Dispersing nanoparticles into the lubricant can decrease the friction coefficient and wear rate.

The first experiment using nano-refrigerants with lubricant was conducted by Wang et al. [20], and it showed that the performance of COP of the refrigeration system enhanced using TiO_2-R134a-MO nano-refrigerant. Following, the improved theory of thermal conductivity of nano-refrigerants was predicted by Jiang et al. [21] based on particles aggregation theory.

Numerous researchers have carried out numerous experiments to improve lubrication, lower friction, and reduce wear on mechanical parts. Studies on nanolubricants had been conducted for a variety of applications by the 20th century. In 2007, the first experimental studies on nano-lubricants for cooling systems were conducted. When CuO-POE-R134a nano-lubricant-refrigerant was tested for its effectiveness in heat transfer during pool boiling, Kedzierski and Gong [22] saw improvements of up to 275%. They also discovered that a notable improvement in heat transfer happened with just a slight rise in thermal conductivity. The same kind of nano-lubricants were then examined by Bartelt et al. [23], who focused on the flow boiling of the R134a-POE mixture in a horizontal tube.

2.1. Synthesis of nano-refrigerants

The preparation of well-dispersed nanofluids and nano-refrigerants have always been a massive concern for researchers. In the one-step process, nanoparticles are first created, and then they are dispersed in the base fluid using any practical technique. This method shows how quickly nanoparticles settle in the base fluid; it is important to make sure that nanoparticles are not clumped together before being dispersed in the base fluid. The two-step approach is preferred in this regard because it is simpler and more economical, as shown in Fig. 2. Metals like copper, nickel, and aluminum, oxides such as Al_2O_3, TiO_2, CuO, and SiO_2 and so on, are used as nanoparticles. Variation of type, concentration, size and shape, and preparation method must be analyzed for refrigeration system efficiency. Migration and aggregation behavior is presented later in Section 6. Peng et al. [24] synthesized CuO-R113 based-nano-refrigerant using ultrasonication to stabilize the dispersion of nanoparticles, and the stable suspension was observed for up to 12 h after the preparation.

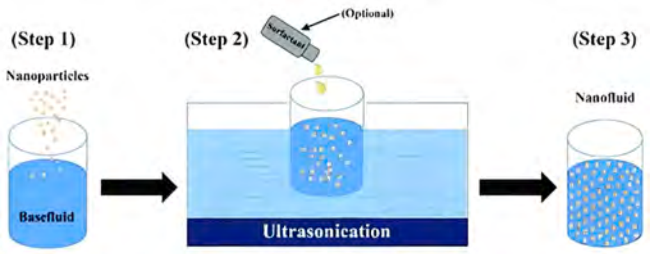


Fig. 2. Two-step liquid state nano-refrigerant preparation technique [26].

Trisaksri and Wongwises [25] synthesized nano-refrigerant using R141b refrigerant mixed with TiO_2 nanoparticles by ultrasonication for 6 h to avoid sedimentation.

Nanoparticles may be dispersed into the refrigerant and kept from evaporating using an orbital incubator shaker [27]. Table 2 provides an overview of the synthesis of nano-refrigerants.

2.2. *Synthesis of nano-lubricants*

In the one-step approach, the nano-lubricant is produced entirely chemically. First, the nanomaterials are manufactured in the form of a dry powder through a physical or chemical process. Next, the nanomaterials are combined with or without surfactants, depending on the formulation, in order to disperse them throughout the base lubricant [37]. Nano-lubricants can be made using a variety of nanoparticles, including metals, metal oxides, sulfides, nanocomposites, and carbon-based materials, depending on the composition [38]. The tribological characteristics of Fe, Cu, and Co nanoparticles combined with SAE 10 mineral oil as a base lubricant were studied by Padgurskas et al. [39]. They discovered that copper, both by itself and in combination with a nano-lubricant, was the most efficient nanoparticle at reducing wear and friction. According to a different study by Yang et al. [40], the addition of Cu nanoparticles in paraffin oil reduced wear by 26% and friction by 23%. SiO_2-based nano-lubricants, according to Kang et al. [41], exhibit better stability because of their low specific gravity and small diameter, which prevent them from easily settling.

Stability of a dispersion can be increased through the addition of surfactants or dispersants. However, nanoparticle aggregation or sedimentation may negatively impact performance and cause increased friction. Various surfactants, including oleic acid, sodium-dodecyl, sorbitol monooleate (SPAN 80), and others, can be used to improve dispersion stability. Several methods have been devised to assess the stability of nano-lubricants, such as zeta potential analysis, sedimentation techniques, and spectral absorbency analysis [42]. Surface charge analysis, or zeta potential characterization, can be used to ascertain whether or not nanoparticles are colloidal. The high zeta potential value of the suspension means electrically stabilized, whereas lower zeta potential means lower stability and results in agglomeration. The most efficient technique to evaluate the stability is the Spectral absorbency analysis. This technique makes use of quantitative assessments of the stability of different materials in lubricants by use of ultraviolet–visible (UV–vis) absorption spectroscopy. This metric is an accurate way to assess the nano-dispersion lubricant's stability [43].

Table 2
Summary on the synthesis of nano-refrigerants.

Researchers	Nano-refrigerant	Preparation technique	Findings
Tazarv et al. [28]	R141b-TiO_2-CTAB[†]	Ultrasonication for 90 min	Stable for one week
Henderson et al. [29]	R134a-SiO_2-POE[†]	POE mixed with SiO_2; Ultrasonication for 24 h; blend with R134a	Particle agglomeration
Lin et al. [30]	R141b-MWCNT with surfactants	Two-step	Better stability with SDBS[†] surfactant
Peng et al. [31]	R141b-TiO_2	Two-step	Tested aggregation behavior
Diao et al. [32]	R141b-Cu-SDBS	Sonication for 8 h	Critical heat flux was reduced by SDBS
Yang et al. [33]	R141b-MWCNT-Span 80	Two-step	Stability verified by spectrophotometer
Kumar et al. [34]	R152a-ZnO	Stirred for 10 h and ultrasonication for 15 h	To prevent a decrease in system performance, surfactants were not utilized
Mahbubul et al. [35]	R141b-Al_2O_3	Two-step	No stability testing
Bi et al. [36]	R600a-TiO_2	Two-step	No stability testing

[†] CTAB: Cetrimonium bromide, POE: polyolester, SDBS: Sodium Dodecyl Benzene Sulphonate.

This complete review of the one-step nano-lubricant synthesis process provides exciting questions and research prospects. The procedure, which comprises powdered nanomaterial production and dispersion into the base lubricant, depends on the nanoparticles utilized. Cu nanoparticles reduced wear and friction, according to Padgurskas et al. [39] and Yang et al. [40]. More comparative research are needed to compare Cu nanoparticle efficiency to other possibilities. Nano-lubricants' stability, which is crucial to their performance, needs further study. Surfactants and dispersants improve dispersion stability, although their effect on lubricant tribological performance is unknown [44]. The effects of nanoparticle features like size, shape, and material composition on stability metrics like zeta potential could also be investigated. To conclude, while the one-step approach is promising, optimizing nano-lubricant production and stability will require more rigorous and extensive research, particularly on how nanoparticle type, surfactant choice, and nanoparticle properties affect lubricant characteristics [45-47].

3. Numerical studies

There are limited numerical analyses looking into how well nano-refrigerants transfer heat. For the thermal design optimization and economic analysis of a shell-and-tube evaporator using nanorefrigerant, Turgut [48] used a multi-agent optimization method (R134a-Al_2O_3). The results showed that the use of Al_2O_3 nanoparticles significantly enhanced the heat exchanger, and that both single-objective and multi-objective frameworks resulted in lower energy costs. A numerical thermal analysis on a home refrigerator using R134a-CuO nano-refrigerant and FLUENT software was performed by Coumaressin and Palaniradja [49]. Fig. 3 illustrates how they found that the evaporating heat transfer coefficient increased significantly with concentrations up to 0.55 vol%

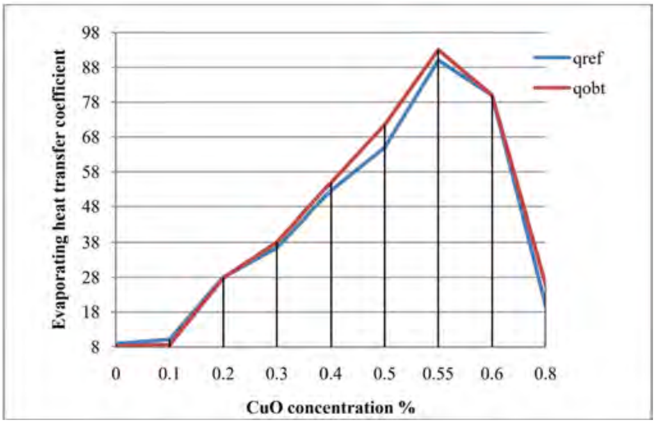


Fig. 3. The evaporating heat transfer coefficient variation with CuO nanoparticle concentration [49].

before it began to decrease. Hernandez et al. [50] investigation focused on the thermal effectiveness of nano-refrigerant-based refrigeration systems. Using Al_2O_3 nanoparticle-infused R113, R123, and R134a refrigerants, the simulation was run using ANSYS FLUENT. The size of the nanoparticles was found to have little bearing on the thermal properties. Table 3 provides a summary of all prior research on nano- refrigerants.

4. Mechanisms for improvement in nano-refrigerants and nano-lubricants

4.1. Thermal conductivity

Nanofluids, created by suspending nanoscale particles in a base fluid, represent a unique category of heat transfer fluids known for their superior thermal conductivity. They exhibit a higher heat transfer coefficient compared to traditional refrigerants, resulting in improved refrigeration system performance. A key thermophysical characteristic of nano-refrigerants is their thermal conductivity, which affects the boiling and convective heat transfer coefficients.

Numerous studies have demonstrated that nanofluids' thermal conductivity increases with temperature. Numerous variables, such as volume concentration, temperature, nanoparticle size and shape, preparation technique, and base refrigerant material, have an impact on the thermal conductivity of nano-refrigerants.. The heat transfer between the refrigerant and the refrigerated space or heat source can be accelerated by the high thermal conductivity of nanoparticles, and it gets even better as the temperature of the nano-refrigerant rises. The Brownian motion and dispersion of nanoparticles contribute significantly to the temperature increase, and this is also attributed to the consideration of the interfacial layer during this process [60,61].

Models of thermal conductivity have been constructed by researchers, with Maxwell's seminal work serving as the foundation [62]. Maxwell [62] proposed an expression for the effective thermal conductivity of a two-phase mixture that includes both a continuous and discontinuous phase. This expression can be written as:

$$\frac{k_{eff}}{k_f} = \frac{k_s + 2k_f + 2\varphi(k_f - k_s)}{k_s + 2k_f - \varphi(k_f - k_s)} \tag{1}$$

In the mentioned equation, k_s and k_f stand for the thermal conductivity of the nanoparticles and the fluid, respectively. While φ stands for the concentration of the nanoparticles. The idea that the discontinuous phase is spherical serves as the foundation for the model's underlying assumption. Additionally, the thermal conductivity is determined by the thermal conductivity of the nanoparticles, the thermal conductivity of the base fluid, and the particle volume concentration.

For calculating the thermal conductivity of nano-refrigerant, Sitprasert et al. [63] proposed a relationship that takes into account factors like size, interfacial layer, and nanoparticle volume concentration:

$$k_{nf} = \frac{(k_s - k_l)\varphi k_l[2\beta_1^3 - \beta^3 + 1] + (k_s + 2k_l)\beta_1^3[\varphi\beta^3(k_l - k_f) + k_f]}{\beta_1^3(k_s + 2k_l) - (k_s - k_l)\varphi k_l[2\beta_1^3 + \beta^3 - 1]} \tag{2}$$

$$\beta = 1 + \frac{t}{r_s}; \beta_1 = 1 + \frac{t}{2r_s}; t = 0.01(T - 273)r_s^{0.35}$$

$$k_l = C\frac{t}{r_p}k_f; C = 30(only\ for\ Al_2O_3\ nanoparticles)$$

In the above equation, k_l is the thermal conductivity of interfacial layer, T in Kelvin scale temperature, and r_s is the average radius of nanoparticles.

Hamilton and Crosser [64] considered sphericity of the nanoparticle, which both previous models omitted, where they introduced a shape factor (n), and presented a correlation of thermal conductivity as:

$$\frac{k_{nf}}{k_f} = \frac{k_s + k_f(n-1) + \varphi(k_s - k_f)(n-1)}{k_s + k_f(n-1) - \varphi(k_s - k_f)} \tag{3}$$

where $n = \frac{3}{\alpha}$, α is the sphericity of particles which is 0.5 for cylinders and 1.0 for spherical.

Yu and Choi [65] modified the Maxwell model and found the correlation that is shown below by presuming that the base fluid molecules

Table 3

Summary of literature for different nano-refrigerants.

Author	Refrigerant	Nanoparticles	Concentration	Findings
Alawi et al. [51]	R134a	Al_2O_3, ZnO, SiO_2, CuO	1-5	• Thermal conductivity also rises as nanoparticle concentration and temperature rise, whereas it declines as particle size increases. • The viscosity of the nano-refrigerant increases along with the increase in nanoparticle concentration.
Alawi et al. [52]	R141b	Al_2O_3, ZnO, SiO_2, CuO	0-2	• The Al_2O_3-R141b nano-refrigerant was found to improve heat transfer significantly. • The optical volume concentration was observed at 2 vol.% with 20 nm as a diameter.
Alawi & Sidik [53]	R134a	CuO	1-5	• With increasing volume concentration, viscosity and density were shown to rise. • Concentration and temperature both have a positive effect on nano- refrigerant's thermal conductivity and specific heat. • The optimum volume fraction was considered for the improvement of refrigeration efficiency.
Hernandez et al. [50]	R134a, R123, R133	Al_2O_3	1-5	• The thermal conductivity and the heat transfer coefficient increased when nanoparticles were added to a refrigerant, and there was also a significant increase in the pressure drop. • R134a at 1 vol.% was observed to have remarkable candidates due to minimal environmental impact and exceptional thermal performance.
Mahbubul et al. [54]	R123	TiO_2	0-5	• Volume fraction significantly affects pressure drop properties. • As volume concentration increases, the pressure gradient also increases.
Mahbubul et al. [55]	R134a	Al_2O_3	1-5	• As nanoparticle concentration and temperature increase, thermal conductivity improves. • With a higher concentration, nano-refrigerant's viscosity, pressure drop, and heat transfer coefficient experience notable enhancements.
Sanukrishna et al. [56]	R134a	TiO_2	0-4	• The heat transfer coefficient enhances as heat flow and particle concentration increase. • A 30.2% improvement in the heat transfer coefficient was noted at 0.5 vol.%.
Ajayi et al. [57]	R134a, R600a	Cu and Al	0-0.1	• Because of its low GWP, R600a was considered a possible substitute for R134a. • Nano-refrigerants significantly reduced the power requirements of refrigeration systems.
Tashtoush et al. [58]	R134a, R123, R290, R141b	CuO, Al_2O_3	0-4 wt.%	• The increase in pressure drop was correlated with the diameter of the evaporator tube, nanoparticle density, concentration, and mass flux. • The maximum COP of 24.7% was observed with R134a-CuO for 2 wt.%.
Alawi et al. [59]	R134a	SWCNT	1-5	• Both the thermal conductivity and the specific heat of the nano-refrigerant are expected to increase as the nanoparticle concentration and temperature continue to rise. • As the volume fraction increases, the nano-viscosity refrigerant's and density improve.

near the solid surface of the nanoparticles form layered structures resembling solids. In other words, they assumed that this is the case:

$$\frac{k_{eff}}{k_f} = \frac{k_p + 2k_f - 2\varphi(k_f - k_p)(1+\eta)^3}{k_p + 2k_f + \varphi(k_f - k_p)(1+\eta)^3} \tag{4}$$

The assumption also accounts for the fact that the fluid's thermal conductivity is lower than that of the nanolayer. Timofeeva et al. [66] introduced a correlation that can be used to calculate the thermal conductivity of nanofluids and is as follows:

$$\frac{k_{eff}}{k_f} = (1 + 3\varphi) \tag{5}$$

Bruggeman [67] suggested a model for effective thermal conductivity, which is presented as:

$$\frac{k_{eff}}{k_f} = \frac{(3\varphi - 1)\frac{k_p}{k_f} + [3(1-\varphi) - 1] + \sqrt{\Delta_B}}{4} \tag{6}$$

$$\Delta_B = (3\varphi - 1)\frac{k_p}{k_f} + [3(1-\varphi) - 1]^2 + \frac{8k_p}{k_f} \tag{7}$$

Hassan et al. [68] investigated the impact of adding nanoparticles of Al_2O_3, SiO_2, ZrO_2, and CNT to R134a-based nano-refrigerants on their thermal conductivity. According to the findings of the researchers, increasing the amount of nanoparticles present in the refrigerant led to an increase in the substance's capacity to conduct heat. Fig. 4 was where they presented their findings to the audience. Ma et al. [69] explored the effective thermal conductivities of nano-refrigerants that contained Al_2O_3, TiO_2, and SiO_2 nanoparticles, using R141b as the base refrigerant. Fig. 5 displayed the results of their investigation, and they concluded that both temperature and nanoparticle concentration influenced the effective thermal conductivity. They observed the maximum value of 1.385 for Al_2O_3-R141b nano-refrigerant.

Long et al. [70] conducted an experiment in which they investigated the impact that factors such as concentration, temperature, and particle size had on the thermal conductivity of R141b-based nano-refrigerants that contained nanoparticles of Al_2O_3, TiO_2, and SiO_2. The research findings, illustrated in Fig. 6, revealed that the thermal conductivity increased both as the temperature and the size of the nanoparticles increased. At 298 K, researchers observed a maximal increase in thermal conductivity of 16.87% in SiO_2-R141b nano-refrigerants with a concentration of 0.1 vol%. Using the transient plane source (TPS) method, Jiang et al. [71] analyzed the effect of CNT diameters and aspect ratios on the thermal conductivity of nano-refrigerants, as depicted in Fig. 7 (a). As shown in Fig. 7(b), the thermal conductivities of CNT nano-refrigerants significantly increased with higher nanoparticle concentration. Furthermore, thermal conductivity improved by decreasing CNT diameter or increasing CNT aspect ratio. The updated Yu-Choi model demonstrated greater accuracy than previous models in predicting CNT nano-refrigerants' thermal conductivities, with mean and maximum variances of 5.5% and 15.8%, respectively. Mahbubul et al. [35] studied the thermal conductivity of an Al_2O_3-R141b nano-refrigerant at different nanoparticle concentrations and temperatures. They discovered that increasing nanoparticle concentration and temperature increased thermal conductivity, which they attributed to nanoparticle clustering and alignment.

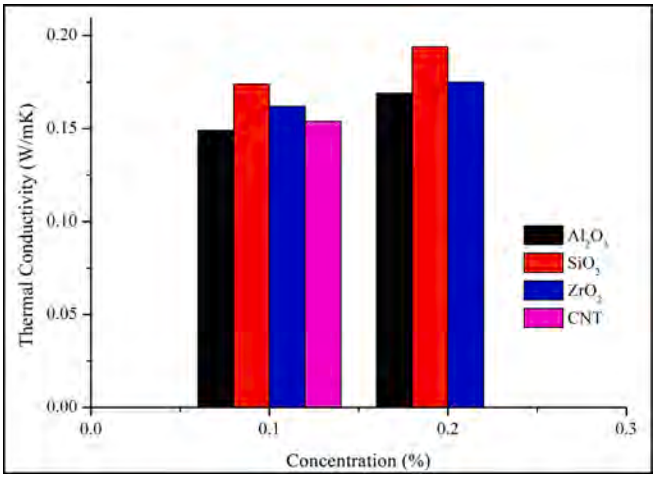


Fig. 4. Thermal conductivity of different R134a based nano-refrigerants [135].

Nemade et al. [72] conducted research to determine how the form of nanoparticles influences the thermophysical parameters of a nano-refrigerant based on ZnO and R134a. The thermal conductivity increased by 25.26% and 42.5% for spherical and cubic-shaped ZnO nanoparticles, respectively. The results were presented in Fig. 8. Hwang et al. [73] conducted research to determine whether or not the addition of a variety of nanoparticles that were dispersed in a variety of base fluids could improve the thermal conductivity and lubrication of a given material. Nanoparticles such as MWCNT, fullerene, copper oxide, silicon dioxide, and silver were contained within these particles. With the exception of a water-based fullerene nanofluid, which exhibited a lower thermal conductivity than the base fluid (0.4 W/m-K), they discovered that the thermal conductivity of nanofluids generally increased with a rise in the nanoparticle concentration. Fig. 9 shows that the MWCNT-mineral oil nanofluid demonstrated the largest thermal conductivity enhancement in comparison to the MWCNT-H_2O nanofluid, and the CuO-EG nanofluid demonstrated more improvement than the CuO-H_2O nanofluid did. Thermophysical properties of TiO_2-PAG nano-lubricant were explored by Prakash and Sanukrishna [74], observed that the thermal conductivity increased with higher concentration and lower temperature. Fig. 10 is an illustration of the obtained results.

When the temperature of the nano-refrigerants rises, the Brownian motion of the nanoparticles accelerates, causing the particles to move with a greater degree of vigor. This heightened motion has the potential to contribute to the enhancement of the role that micro convection plays in the transportation of heat.

Nano-lubricants, too, play an important part in a variety of applications; nevertheless, there hasn't been a lot of research done on how to improve the thermal conductivity of nano-lubricants. The study of boiling heat transfer and two-phase flow phenomena presents a considerable problem due to the lack of exact thermal conductivity values for nano-refrigerants and nano-lubricants.

4.2. *Viscosity*

Viscosity is a characteristic that emanates from the intermolecular frictional forces within fluid layers as they move in relation to each other. Both the thermal conductivity and the viscosity are important thermophysical factors that have an effect on the pressure drop that occurs in systems Viscosity can be correlated numerically with the concentration of nanoparticles in a volume, while temperature is also crucial but has received little attention regarding correlations. Brinkman made modifications to the Einstein model [75].

Brinkman introduced a correlation for viscosity that incorporates volume concentration and the viscosity of the base fluid [75], which is expressed as:

$$\mu_{eff} = \mu_f * \left(\frac{1}{(1-\phi)^{2.5}}\right) \tag{8}$$

Corcione [76] devised a model to evaluate the accuracy of the Brinkman model for viscosity, yielding improved results compared to the Brinkman model, as follows:

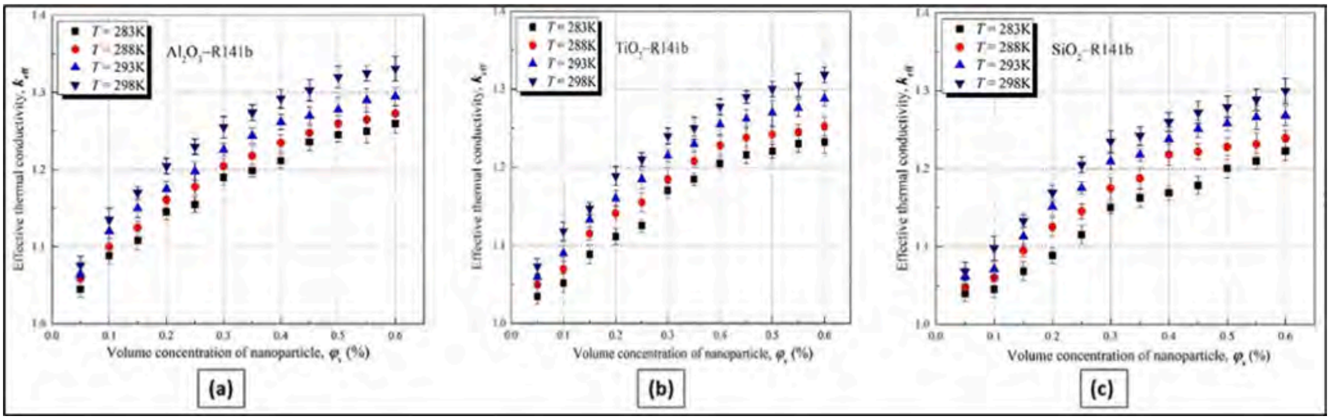


Fig. 5. Nano-refrigerants effective thermal conductivity: (a) Al_2O_3, (b) TiO_2, and (c) SiO_2 [69].

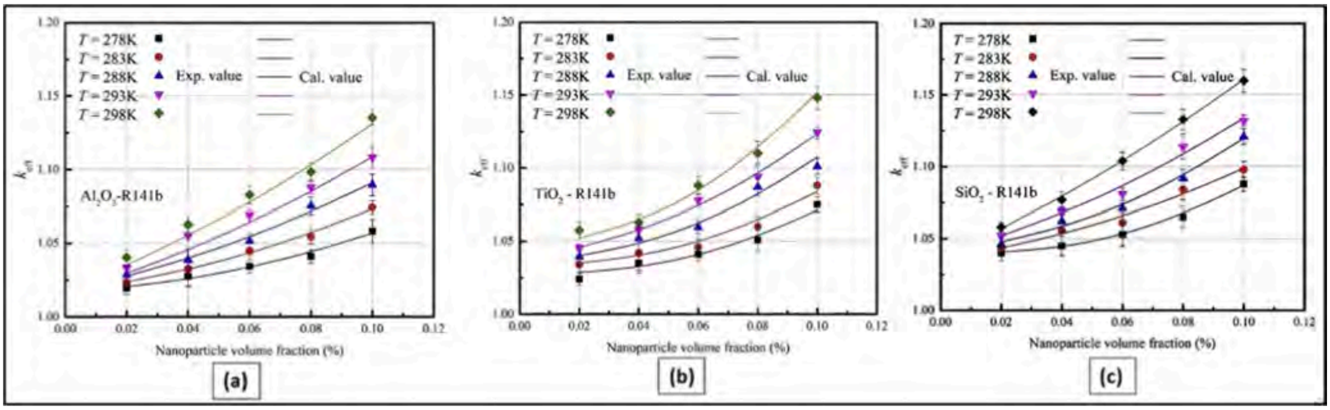


Fig. 6. Effective thermal conductivity of nano-refrigerants: (a) Al_2O_3, (b) TiO_2, and (c) SiO_2 [70].

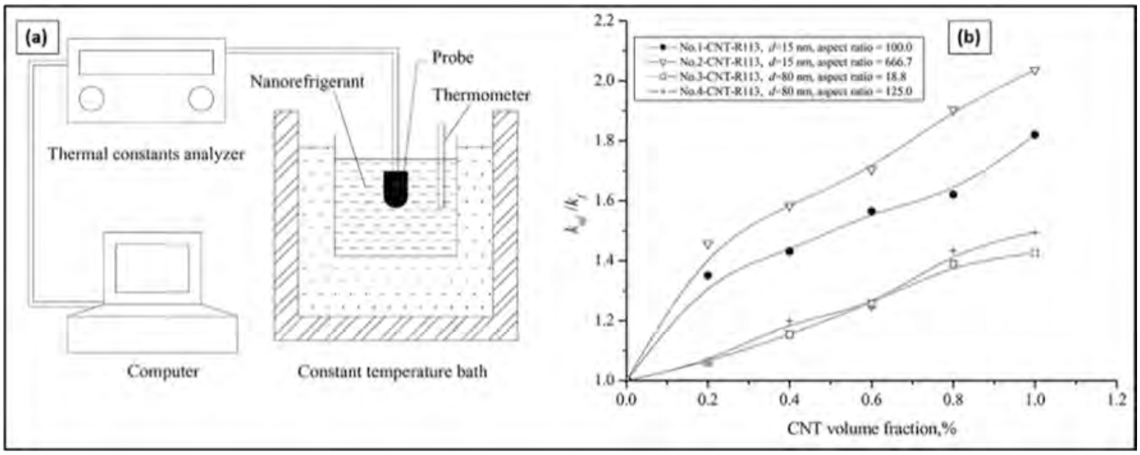


Fig. 7. (a) The schematic of the experimental arrangement, and (b) the ratio of thermal conductivity for CNT-R113 nano-refrigerants [71].

$$\mu_{eff} = \mu_f{*}\left(\frac{1}{1 - 34.87\left(\frac{d_p}{d_f}\right)^{-0.3}{*}\varphi^{1.03}}\right) \tag{9}$$

Where d_f refers to the diameter of base fluid, expressed as:

$$d_f = 0.1\left(\frac{6M}{N\pi\rho_{f0}}\right)^{\frac{1}{3}}$$

In the equation that was just presented, the letter M stands for the molecular weight of the base fluid, the letter N stands for Avogadro's number, and the letter ρ_{f0} is the mass density of base fluid.

Wang et al. [77] proposed a model for figuring out the nanofluids' viscosity, which they formulated as follows:

$$\mu_{eff} = \mu_f{*}\left(1 + 7.3\phi + 123\phi^2\right) \tag{10}$$

A model to determine the viscosity using spherical nanoparticles was proposed by Gherasim et al. [78] and it is as follows:

$$\mu_{eff} = \mu_f{*}\left(0.904e^{14.8\phi}\right) \tag{11}$$

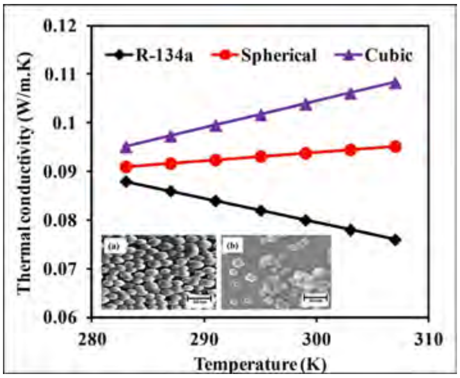


Fig. 8. Impact of ZnO nanoparticles, with spherical and cubic shape, on the thermal conductivity of R134a refrigerant. The SEM images of the ZnO nanoparticles with a spherical and cubic shape are displayed in the inset as (a) and (b), respectively [72].

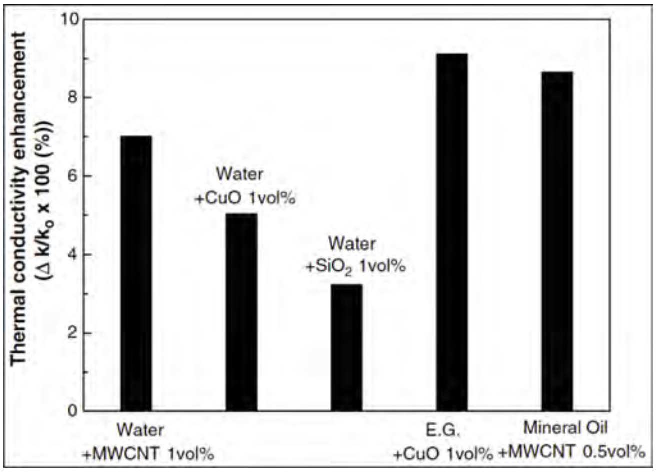


Fig. 9. Nanofluid and nanolubricant thermal conductivity [73].

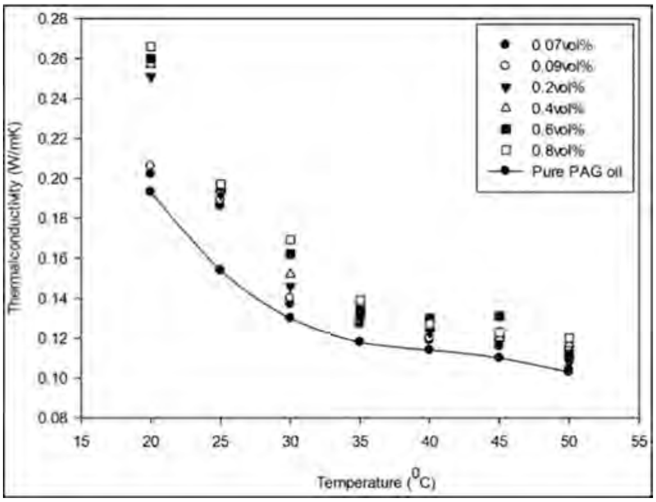


Fig. 10. Effect of temperature on thermal conductivity of nano-lubricant [74].

A model to determine the viscosity of Al_2O_3-water and TiO_2-water nanofluids was presented by Pak and Cho [79] presented as follows:

$$\mu_{eff} = \mu_f * \left(1 + 39.11\phi + 533.9\phi^2\right) \tag{12}$$

Narayanasarma and Kuzhiveli [80] evaluated rheological properties of nano-lubricant containing POE oil with SiO_2 nanoparticles. The results are illustrated in Fig. 11, displays the viscosity of nano-lubricant examined at various volume concentrations ranging from 0.01% to 0.2%, shear rates from 1 to 1500 s^{-1}, and temperatures between 25 and 100 °C. Also, the figure indicates that the viscosity of the nano-lubricant lessens as the temperature rises and rises as the particle concentration climbs. At lower temperatures, the nanoparticle cluster causes an increase in viscosity because it blocks the flow of lubricating oil molecules and prevents them from moving freely. Similarly, Azmi et al. [81] assessed the viscosity of a composite nano-lubricant containing Al_2O_3-SiO_2-PAG. At a concentration of 0.1% and a temperature of 333 K, the relative viscosity of a composite nano-lubricant was found to be 9.71% higher than the base lubricant, behaving as a Newtonian fluid. As seen in Fig. 12, the dynamic viscosity increased along with an increase in volume concentration but reduced together with an increase in temperature. This trend was also observed in a study by Sidik and Alawi [53] involving CuO nanoparticles suspended in R134a refrigerant. Similarly, Kumar et al. [82] investigated the viscosity of mineral oil-based nano-lubricant with CuO nanoparticles and found a slight increase in viscosity by 17%. The viscosity of nano-refrigerants comprising R141b and R134a refrigerant that was combined with Al_2O_3 nanoparticles was investigated by Mahbubul et al. [27,55]. The viscosity of both kinds of nano-refrigerants went up when the volume concentration went up, but it went down when the temperature went up.

The research that was shown previously indicates that when the temperature increases, there is a corresponding reduction in the viscosity of the liquid. The reason for this is because when the temperature increases, the Van der Waals forces, which are responsible for holding the particles together, become less powerful. Because of this, the clusters end up dispersing, and the intermolecular linkages that are responsible for keeping the molecules together end up weakening. The high ratio of surface area to volume that is characteristic of nanoparticles is one more feature that plays a role in the increased viscosity that is exhibited by nano-refrigerants. In a nutshell, it is preferable for the lubricants that are used in refrigeration compressors to have low viscosity values because this results in less work being done by the compressor. It is not required to take into account the slight increase in viscosity that takes place as a result of the inclusion of nanoparticles in these systems because the increase is not significant enough to warrant such consideration.

4.3. *Specific heat capacity and latent heat*

According to the findings of the research carried out by Ajayi et al. [83] and Alawi et al. [84] the incorporation of bio-based nanoparticles into a fluid has the potential to increase the fluid's specific heat capacity as well as its latent heat, which in turn increases the fluid's capacity to transport heat. In addition, Alawi et al. [84] discovered that the heat capacity of R141b-Al_2O_3 increased with both temperature and volume fraction. They also discovered that the nano-refrigerant with a particular volume percent had the lowest specific heat value due to the reduced specific heat of the nanoparticles. On the other hand, they found that the R141b refrigerant had a heat capacity that was 2.6% larger than the R141b-Al_2O_3 nano-refrigerant. This is significant because an increase in heat capacity results in an increase in the system's internal energy [85]. Alawi et al. [84] noticed that the specific heat increases dramatically with rising temperature at the output. This results in higher output temperature and more efficient performance of the refrigeration systems that operate using nano-refrigerants.

Rahman et al. [76] discovered that the specific heat of R407C-SWCNT decreased with the addition of nanoparticles due to the lower specific heat of the SWCNT nanoparticle. This resulted in a 4.1% to 4.93% reduction in specific heat at 283 K and 308 K in comparison to the specific heat of R407C refrigerant, while the internal energy of the system increased with higher specific heat values.

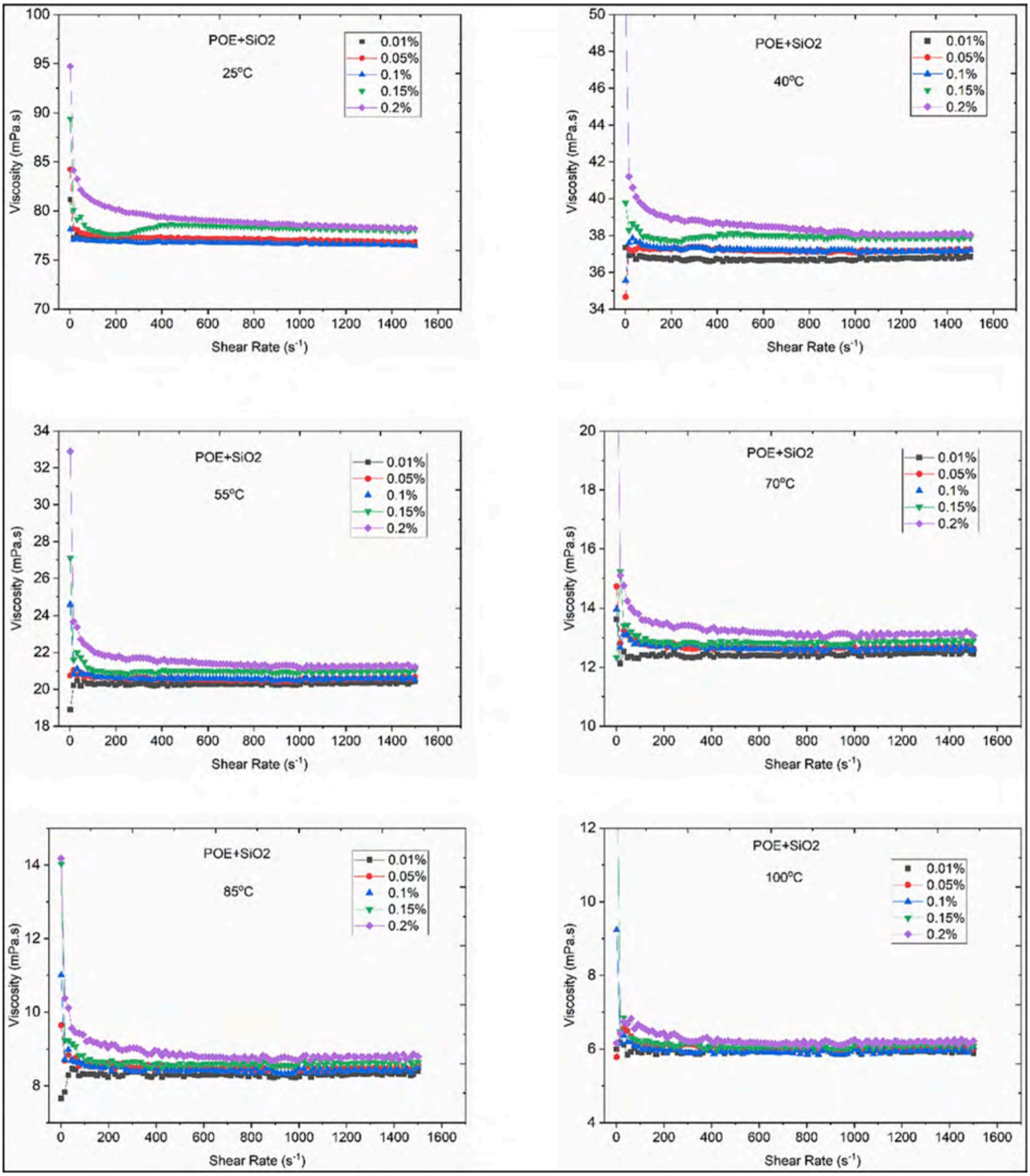
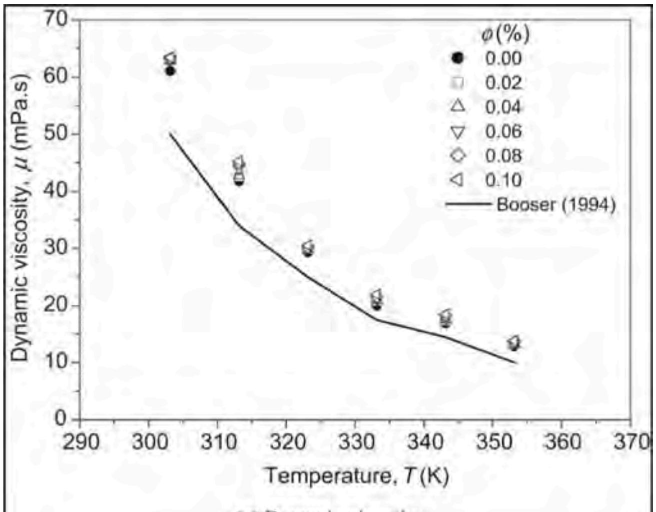


Fig. 11. Viscosity variation of SiO_2-POE nano-lubricant at different temperature, volume concentration, and shear rate [80].

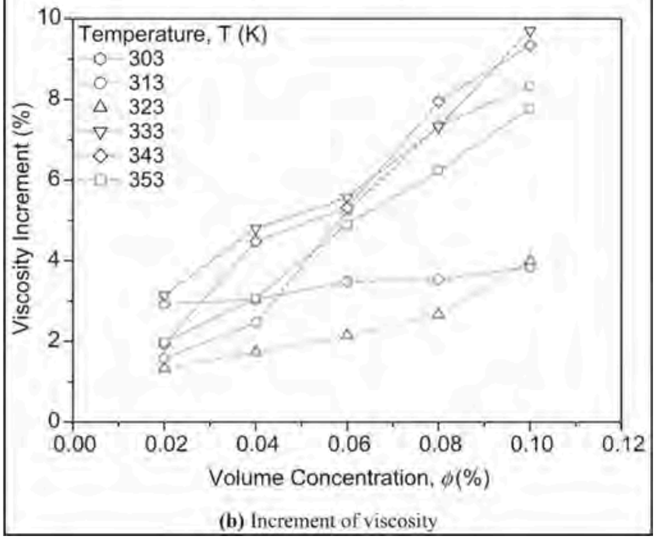
4.4. Pressure drop and pumping power

Despite the fact that higher viscosity leads to greater pressure drop and pumping power, which ultimately results in higher energy consumption, the improved heat transfer rate that can be achieved using nanofluids is more essential than the increased pumping power that is required to achieve it. [86]. Precise pressure drop estimation is essential for the efficient operation of refrigeration systems since nanoparticles can significantly influence the pressure drop behavior of refrigerants boiling inside tubes, thus affecting the overall system performance. Nair et al. [87] reported a higher pressure drop and higher friction factor for nano-refrigerant. Due to the low particle concentration viscosity, Bartelt et al. [23] found that the R134-POE-CuO nano-refrigerant did not have a significant influence on the pressure drop penalty. The influence of nanoparticles on the frictional pressure drop of R113 refrigerant was studied by Peng et al. [88] who then created a correlation to estimate refrigerant-based nanofluids. The experimental study depicted in Fig. 13 indicated that the frictional pressure drop of nano-refrigerant increased with an increase in mass fraction of nanoparticles, resulting in a maximum enhancement of 20.8%. The following correlation was developed to estimate the frictional pressure drop of nano-refrigerant:

$$\Delta P_{nf} = F.\Delta P_f \tag{13}$$



(a) Dynamic viscosity



(b) Increment of viscosity

Fig. 12. Viscosity of nano-lubricant with respect to (a) temperature and (b) volume concentration [81].

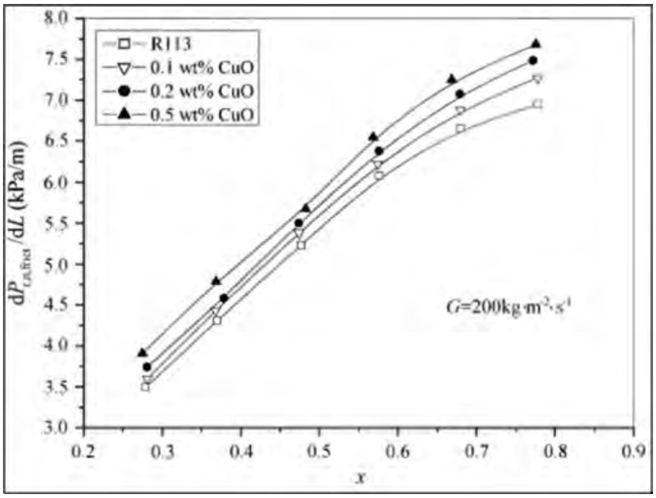


Fig. 13. Maximum frictional pressure drop of CuO-R113 nano-refrigerant vs. vapor quality at G = 200 kg/m^2.s [88].

$$F = exp\left\{\varphi \times \left[2.19 \times 10^7 \times \frac{d_p}{D_i} + 37.26 \times \frac{\rho_p}{\rho_{l,r}} - 0.63 \times m - 217.73 \times x \times (1 - x)\right]\right\} \tag{14}$$

In the above equation, d_p is the mean diameter for nanoparticle, D_i represents the internal diameter, m represents the mass flow rate, ρ_p and $\rho_{l,r}$ being the density of particle and refrigerant, respectively, and refers to the dryness fraction.

Mahbubul et al. [55] reported the pressure drop and pumping power of nano-refrigerants in a smooth horizontal tube increased significantly as the concentration of nanoparticles increased, as shown in Fig. 14. Additionally, Fig. 14 illustrates that the Al_2O_3-R134a nano-refrigerant has a lower pressure drop increase than Cu/EG nanofluids. This drawback of copper nanoparticles should be considered when developing nano-refrigerants to reduce energy consumption. Sun et al. [33] conducted another study that revealed a gradual increase in the unit pressure drop of MWCNT-R141b nano-refrigerant as the vapor quality increased. As shown in Fig. 15, pure refrigerant had the lowest unit pressure drop under the same vapor quality, whereas 0.3 wt% MWCNT-R141b had the highest unit pressure drop. The increased pressure drop resulted from the addition of MWCNT and the dispersant, which increased viscosity.

4.5. Energy performance and COP

A refrigeration system's coefficient of performance (COP) is affected by a variety of factors, including ambient temperature, particle concentration, and relative temperature. When selecting a refrigerant, an excellent COP value and environmental-friendliness are considered to be important criteria. Mahbubul et al. [89] studied the impact of temperature on the thermal and rheological properties of the COP of an Al_2O_3-R134a based nano-refrigerant. The results, shown in Fig. 16, show that an increase in temperature resulted in an increase in COP. Furthermore, the density of the nano-refrigerant is greater than that of the base refrigerant, resulting in a better COP ratio than R134a refrigerant (as shown in Fig. 16(a)). Furthermore, due to the higher thermal conductivity of nanoparticles, a maximum increase in COP of 15% was observed (as shown in Fig. 16(b)). Study by Shek et al. [90] presented an enhancement in COP of 17.02% for thermal conductivity by adding

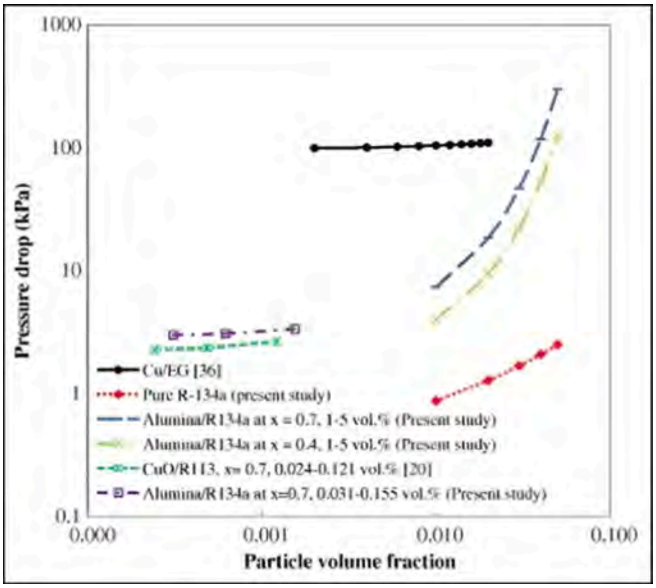


Fig. 14. Pressure drop vs. particle volume fraction for different nano-refrigerants [55].

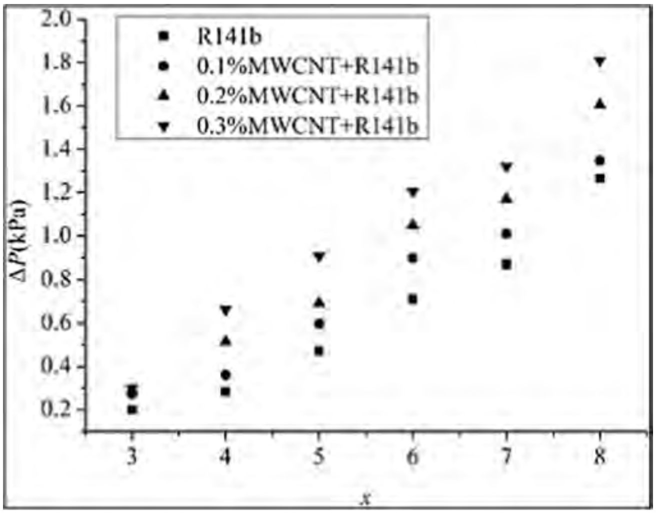


Fig. 15. The unit pressure drop with different nano-refrigerant mass fractions [33].

SWCNT into R407C refrigerant. Their study also observed that consumption in compressor work was reduced by 4%. The COP of the system is a dimensionless term and can be calculated using the following equation [91]:

$$COP = \frac{\dot{Q}_c}{W_{in}} \tag{14}$$

where $\dot{Q}_c$ is the cooling capacity and W_{in} is the power consumption by the compressor.

Jalili et al. [92], conducted an experiment to evaluate the effectiveness of utilizing water mixed with different MWCNT concentrations as a secondary fluid to cool the evaporator in a refrigeration system. Their findings indicated a 6.5% increase in the inlet temperature of the evaporator as the concentration of MWCNT increased, whereas the outlet temperature decreased by 14.5%. In a separate experimental study by Kumar and Elansezhian [93] on the effect of Al_2O_3-R134a nano-refrigerant with PAG oil on the energy consumption of the refrigeration system, it was found that energy consumption was reduced by 10.3%.. In another study, Kumar and Elansezhian [94] replaced R134a with R152a due to the lower value of GWP of 140 only and investigated the performance with ZnO nanoparticles. It was indicated that ZnO nano-refrigerant operated safely in the system and increased with 21% less energy consumption. The maximum COP value of 3.56 was achieved with 0.5% of ZnO concentration. The effectiveness of MWCNT-water utilized as a secondary fluid in a refrigeration unit containing R22 was examined by Vasconcelos and their team [95]. They found that the nanofluid's outstanding thermal conductivity enhanced cooling capacity by 22.2% at coolant intake temperatures between 30 and 40C. At coolant inlet temperatures between 30 and 40 °C, they discovered that the nanofluid's excellent thermal conductivity increased cooling capacity by 22.2%. As a result, the COP rose by up to 33.3%. To enhance the COP and the energy efficiency, Padmanabhan and Palanisamy [96] analyzed a refrigeration system using TiO_2 nano-refrigerant and two types of lubricant (mineral oil (MO) and POE oil). Fig. 17 shows the comparison of COP of R436B, R436A, and R134a based nano-refrigerants. The maximum COP was observed for R134a + MO + TiO_2.

A study on the refrigeration performance of a system using R134a as a refrigerant, POE and SUNISO 3GS oil as lubricants, and Al_2O_3 as nanoparticles was done by Subramani and Prakash [97]. Their findings showed that using SUNISO 3GS oil instead of POE oil led to an 18% reduction in power consumption. Furthermore, when SUNISO 3GS was mixed with nanoparticles, a 25% decrease in power consumption was observed, as shown in Fig. 18(a). As shown in Fig. 18(b), the actual COP of the system was computed by comparing the cooling load and power input to theoretical values.. Wang et al. [98] conducted a performance test on residential refrigerator compressors and R600a refrigerants utilizing nano-oils for R134a. The study's findings indicated that the use of nano-oils with R600a refrigerant improved the COP by up to 5.33%, as depicted in Fig. 19. The figure also displays a 1.01% improvement in the system when nano-oils were used with R134a refrigerant. The addition of TiO_2 nanoparticles in the refrigerator improved its performance in contrast to pure refrigerant, with a 9.6% energy reduction achieved with

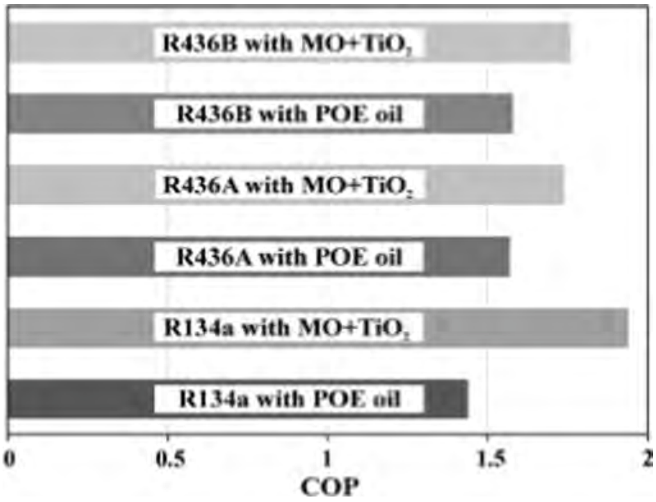


Fig. 17. COP of R436B, R436A, and R134a with POE oil and MO + TiO_2 at air temperature compared with the environment state [96].

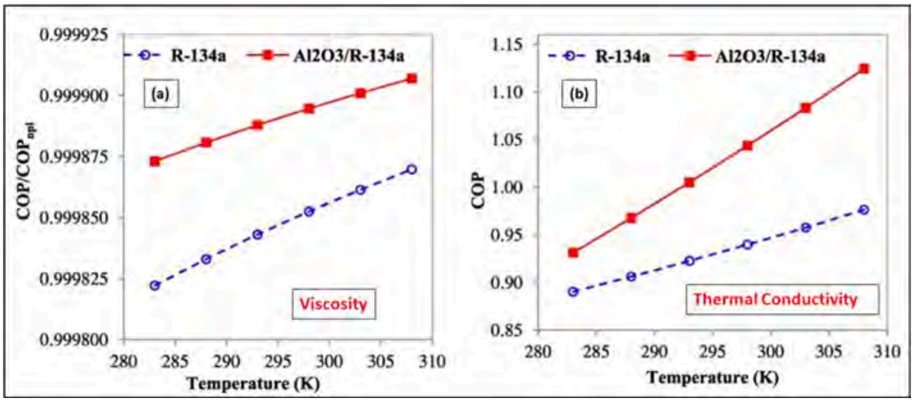


Fig. 16. Effect of (a) viscosity and (b) thermal conductivity on COP of nano-refrigerant [89].

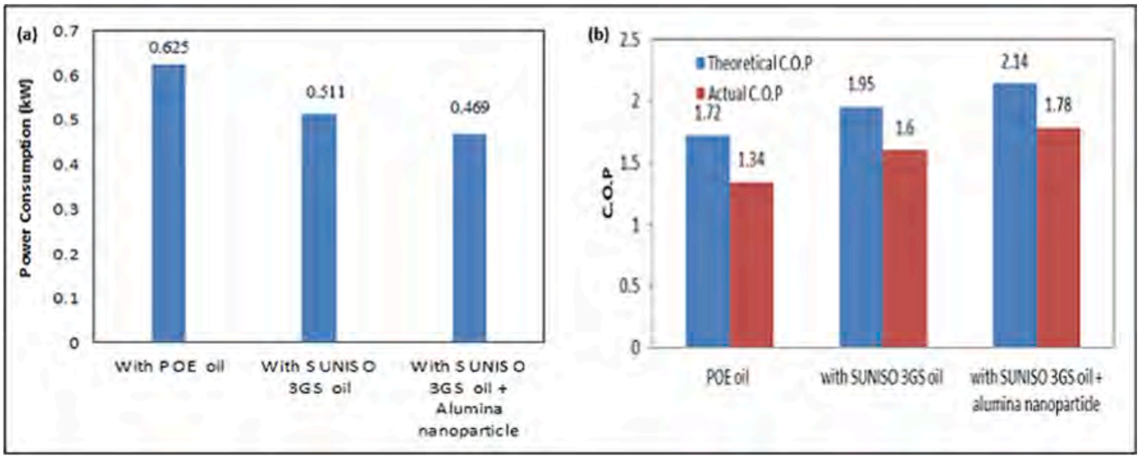


Fig. 18. Comparison of nano-refrigerant (a) power consumption and (b) coefficient of performance (COP) [97].

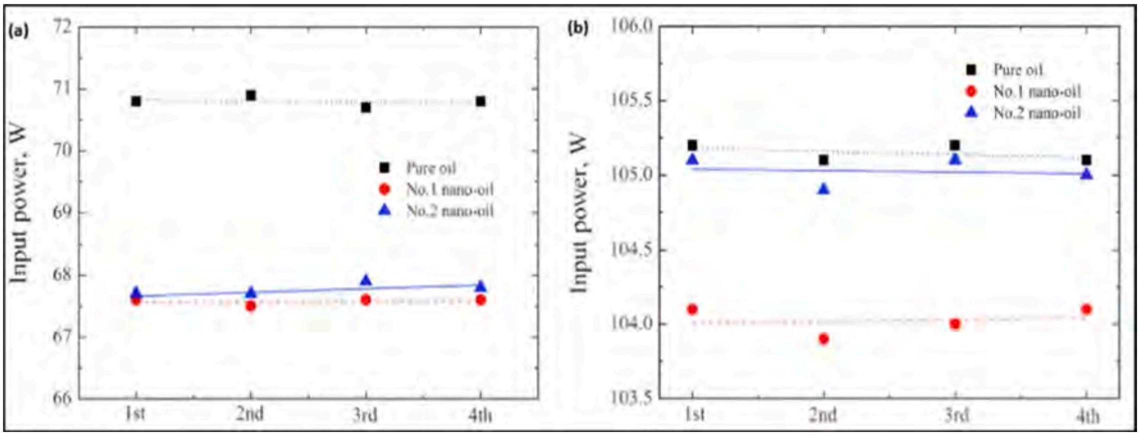


Fig. 19. COP for refrigerant compressors (a) R600a and (b) R134a [98].

0.5 g/L of TiO_2-R600a nano-refrigerant, according to an experimental investigation conducted by Bi et al. [36]. The effectiveness of a vapor compression cycle (VCC) using R134a refrigerant with Al_2O_3 nanoparticles was examined theoretically and empirically by Soliman et al. [99]. According to the theoretical calculations, using nano-refrigerant improved the heat transfer coefficient in the evaporator by 50%. When employing R-134a and POE oil containing Al_2O_3 nanoparticles, the trial findings showed a 10.5% improvement in the system's performance and a 13.5% decrease in energy consumption, as shown in Fig. 20.

The increase in COP can be attributed to the incorporation of more nanoparticles, which generates a larger effective surface area for heat transfer [38]. Moreover, the exceptional thermal conductivity of nanoparticles contributes to the enhancement of the nano-thermal refrigerant's conductivity [55]. When higher levels of energy become more accessible, the heat transfer rate increases, resulting in an overall

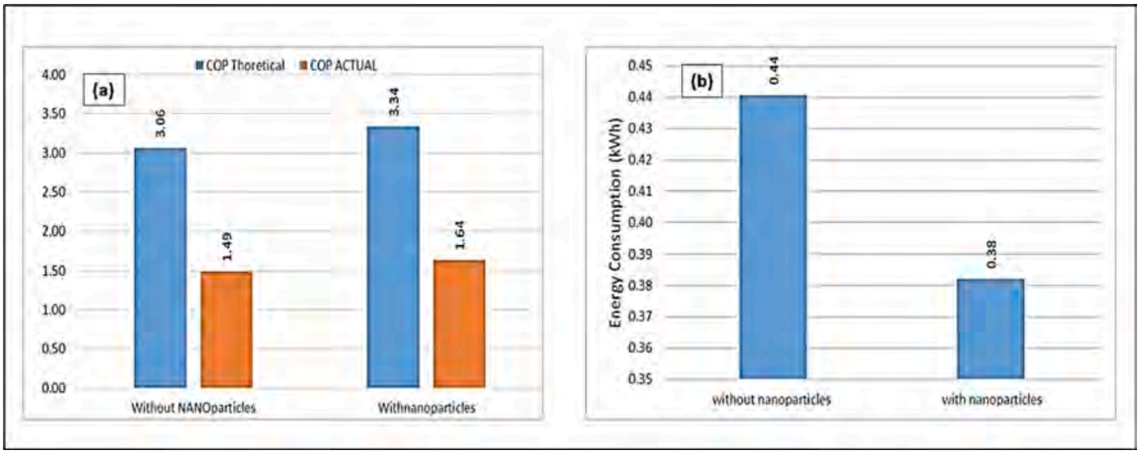


Fig. 20. (a) The actual and theoretical COP, (b) Energy consumption of refrigerant and nano-refrigerant [99].

increase in the system's COP [100]. Overall, using nano-refrigerants can lead to increased system performance, reduced energy consumption, and improved environmental impact. The overall results of these studies indicate the potential for using nanoparticles in refrigeration systems to improve performance, efficiency, and energy savings. However, challenges such as agglomeration and the need for additional surfactants should also be considered. We can conclude that specific heat of the nano refrigerants is less as compared with the pure refrigerants and will increase linearly with respect to temperature and specific heat capacity will have an impact on the COP of the system.

4.6. Pool boiling heat transfer

Scientists have recently focused on how nanomaterials affect heat transfer efficiency. Critical heat flux (CHF) and heat transfer coefficient (HTC) improvements are linked to a variety of factors, including surface roughness, the amount and placement of nanoparticles, concentration, surface wettability, and capillary effect. The thermophysical characteristics of nanoparticles are also important in improving HTC, as they affect both thermal conductivity and surface tension [38]. Researchers examined pool boiling of nanorefrigerants to better comprehend the boiling behavior of nanofluids and the increase in critical heat flux (CHF) values. Flow boiling has several uncertainties, including flow regime, turbulence, constant mixing, and density changes, making it difficult to study the migration of nanoparticles. To investigate nanoparticle migration, pool-boiling experiments were conducted. Das et al. [101] examined the pool boiling of Al_2O_3-H_2O nanofluids in small diameter tubes and found that the altered boiling characteristics of the nanofluids could not be explained by changes in properties or alterations in Nusselt and Reynolds numbers resulting from changes in characteristic length. As shown in Fig. 21, the Nusselt number and Reynolds number characteristics varied differently for each particle concentration and shifted downward. The effect of Au nano-additive on the pool boiling heat transfer of refrigerants was studied by Ray et al. [102], and Liu and Yang [103]. The study revealed that the addition of gold particulates enhanced the potential for heat transfer during pool boiling. Figs. 22 and 23 illustrate the relationship between boiling heat transfer coefficients and heat flux for R141b and Au-R141b nanoparticles. At a concentration of 1.0%, the nano-heat refrigerant's transfer coefficient was double that of the base refrigerant. These findings indicate a significant enhancement in the boiling heat performance of refrigerant R-141b as a result of adding nanoparticles. In a similar investigation, Park and Jung [104] investigated the effect of carbon nanotubes (CNTs) on the nucleate boiling heat transfer of R123 and R134a refrigerants. Fig. 24(a) depicts the experimental apparatus for nucleate boiling heat transfer, while Fig. 24(b) and 25(c) illustrate the results for the heat transfer coefficient of R123- and R134a-based nano-refrigerants, respectively. At low heat flux, the addition of CNTs increased the nucleate boiling heat transfer coefficient by 36.6%, but as the heat flux increased, the enhancement in heat transfer decreased. Park and Jung [105] discovered that adding CNTs to R22 refrigerant increased boiling heat transfer coefficients by up to 28.7% at low heat fluxes of less than 30 kW/m^2. Nonetheless, this enhancement was constrained by vigorous bubble generation at higher heat fluxes. In addition, Diao et al. [32] examined the pool boiling properties and critical heat flux of Cu-R141b nanorefrigerant at ambient pressure, using SDBS as a surfactant to stabilize the suspensions. Fig. 25 depicts the experimental apparatus, while Fig. 26 depicts the boiling curves derived from the results of the experiment. The boiling heat transfer coefficient of the Cu-R141b-SDBS nano-refrigerant was higher than that of the base refrigerant, and the increment ratio of the nano-refrigerant increased with the nanoparticle concentration, according to the study. In a study by Kedzierski [106] investigated the pool boiling of R134a-Al_2O_3-POE oil mixtures on a Turbo-BII-HP surface. According to the findings, incorporating nanolubricants could improve R134a boiling on a reentrant cavity surface if the nanoparticles were well-dispersed and present in high concentrations. Table 4 provides a summary of various research works on pool boiling heat transfer in nano-refrigerants.

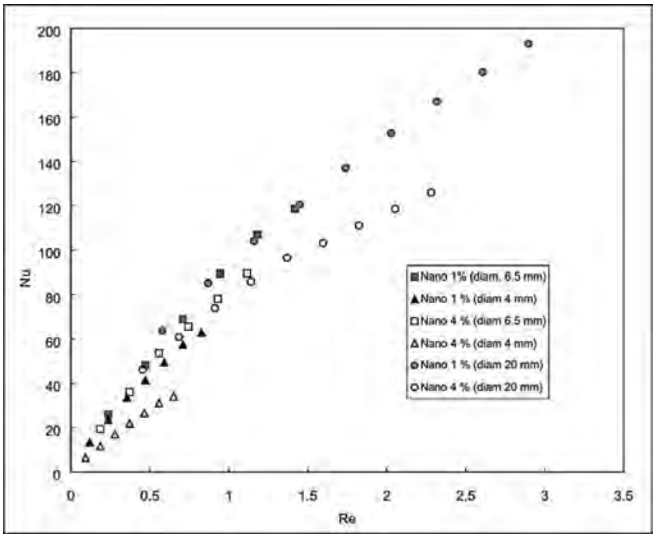


Fig. 21. Variation of nanofluid Nusselt number with Reynolds number characteristics [101].

Various investigations [107-109] have identified a variety of factors that can affect the performance of boiling heat transfer. These include the use of surfactants, the interaction of nanoparticles with surfactant molecules, and nanoparticle deposition during heating. Surfactants have been discovered to improve pool boiling performance by lowering the surface tension of the fluids. The interaction of nanoparticles and surfactant molecules can also reduce the surface tension of the working fluids, improving the performance of pool boiling heat transfer. Finally, nanoparticles can be deposited during simmering, causing the heating surface characteristics to change continuously. This interaction between nanoparticles and the heating surface has the potential to increase the number of active nucleation sites, resulting in improved boiling heat transfer.

4.7. Flow boiling heat transfer

HVAC and other heat systems use a boiling phenomenon known as forced convective or flow boiling.. According to the findings of a study [113], boiling can result in the formation of a variety of flow patterns, some of which include single-phase liquid flow, bubbly flow, slug flow, annular flow, mist flow, and single-phase vapor flow. These flow patterns can be caused by boiling at low temperatures. During flow boiling, the type of flow pattern that is observed is determined by a number of factors, including the fluid that is being used, the surface orientation, the degree of liquid subcooling, system pressure, wall temperature, mass flux, surface microstructure (including porosity), surface wettability, the degree of oxidation, and surface roughness [114]. According to published reports, nanofluids with improved thermal conductivity also exhibit improved convective flow behavior [115]. Researchers led by Peng et al. [24] investigated how the presence of nanoparticles affects the rate at which R113-CuO nano-refrigerant transfers heat during flow boiling inside a smooth horizontally oriented tube. They created a correlation to predict the heat transfer capabilities of nano-refrigerants and discovered that the maximum increase in heat transfer coefficient when compared to the base refrigerant was 29.7%, as shown in Fig. 27. This was the case because they found that the nano-refrigerants were more effective at transferring heat than the base refrigerant. In addition to this, they put out a correlation for nano-refrigerants, which demonstrated that the predictions were correct for 93% of the experimental data within a variance of 20% of the actual value.

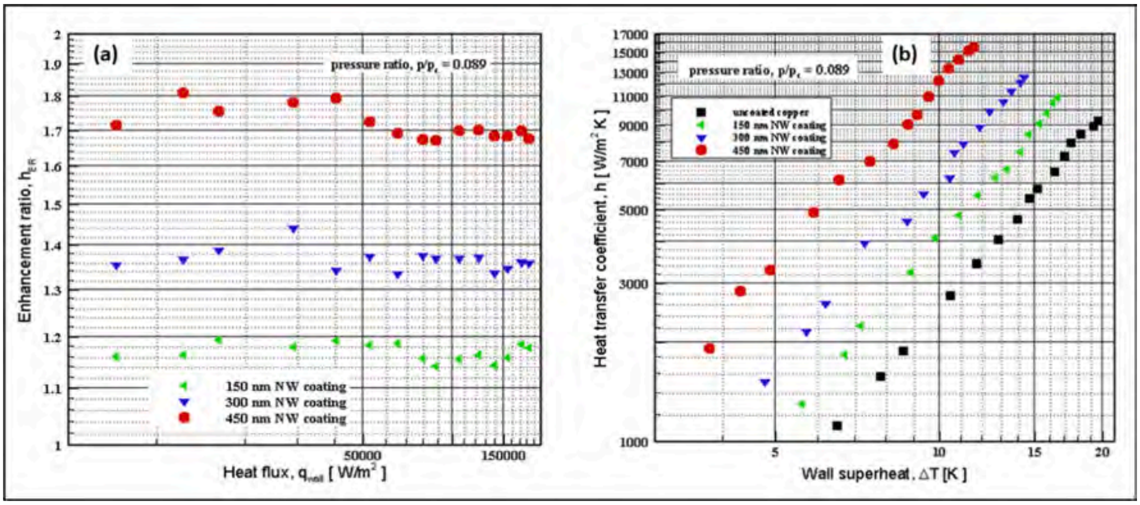


Fig. 22. (a) Boiling enhancement ratio versus heat flux, (b) Heat transfer coefficient variation with wall superheat [102].

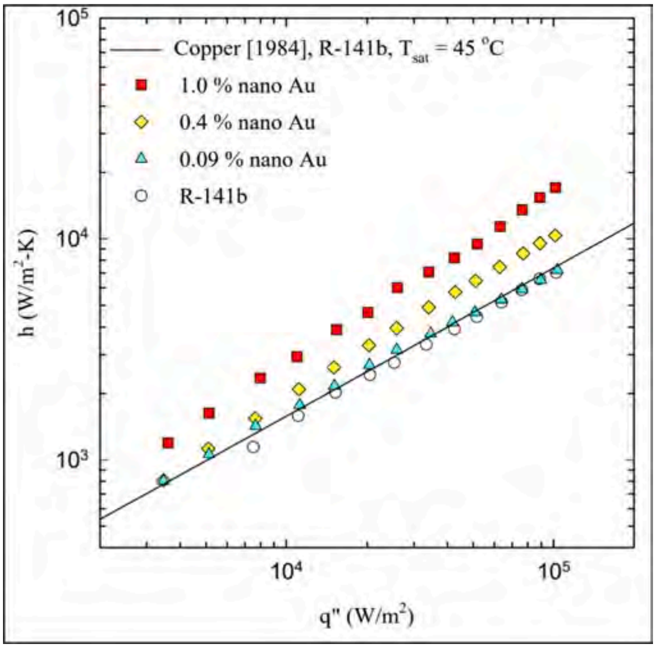


Fig. 23. Heat transfer coefficients for various concentrations of Au-R141b nano-refrigerant [103].

$$\propto_{r,n} = exp\left\{\varphi\left[0.8\frac{\lambda_n}{\lambda_{r,L}} - 39.94\frac{(\rho C_p)_n}{(\rho C_p)_{r,L}} - 0.028G - 733.26x(1-x)\right]\right\}\alpha_r$$

where, λ_n and $\lambda_{r,L}$ indicate the thermal conductivity of nanoparticles and pure refrigerant, ρ_n and $\rho_{r,L}$ are the densities of nanoparticles and liquid pure refrigerant. The isobaric specific temperatures of nanoparticles and liquid pure refrigerant are denoted by the symbols $C_{p,n}$ and $C_{p,r,L}$, respectively; the volume fraction of nanoparticles is denoted by the symbol φ is the volume fraction of nanoparticles. α_r be determined by using the parameters of the base refrigerant in the calculation.

Sun and Yang [116] conducted a study on the performance of different nano-refrigerants (Al-R141b, Al_2O_3-R141b, Cu-R141b, and CuO-R141b) during flow boiling in a horizontal tube. They experimented with different mass fractions, qualities, and mass velocities of the nanoparticles and found that the heat transfer coefficient of nano-refrigerants increased as the volume fraction, quality, and mass velocity of the nanoparticles increased.. In a different study, Sun and Yang [117], investigated the flow boiling heat transfer characteristics of four nano-refrigerants in a copper tube with internal threads (Al-R141b, Al_2O_3-R141b, Cu-R141b, and CuO-R141b). According to their findings, the maximum heat transfer coefficient of each of the four types of nano-refrigerants increased by 17–25%. The Cu-R141b nano-refrigerant had the highest maximum heat transfer coefficient of 25%, which can be attributed to copper nanoparticles' superior thermal conductivity. Fig. 28 was utilized to compare the heat transfer enhancement at three different mass fluxes. Moreover, Liu et al. [118] did a study to investigate the influence of SiO_2 nanoparticles on the two-phase flow-boiling of R134a and R134a-POE oil. The goal of this study was to determine how the nanoparticles affected the fluids' behavior. When SiO_2 nanoparticles were directly dispersed in R134a, the heat transfer coefficient was reduced by 55%. Nonetheless, when they used the R134a-POE-SiO_2 nano-refrigerant, they noticed exceptional dispersion and a more than 100% increase in heat transfer coefficient.

An experiment was carried out by Akhavan and Baqeri [119] to investigate the effect of CuO nanoparticles on the flow boiling of R600a-POE lubricant. Their laboratory equipment included a pump, a test evaporator, a subcooler, and a condenser, as shown in Fig. 29 (a). As can be seen in Fig. 29(b), the test evaporator consisted of a horizontal copper tube with a smooth inside. According to the findings of the study, the incorporation of nanoparticles led to an improvement in heat transfer that was as much as 63 percent better, with larger nanoparticle concentrations resulting in higher heat transfer rates Fig. 29 presents a comparison of the flow boiling heat transfer coefficient between pure refrigerant and refrigerant combined with lubricant (c). In a different investigation that Baqeri and Akhavan [120], undertook, they looked at the forced convective boiling heat transfer of R600a-oil-CuO in a smooth horizontal tube. According to their findings, as the nanoparticle concentration increased to a maximum of 2%, the convective boiling heat transfer coefficient increased. However, when the nanoparticle concentration was increased beyond 5%, a drop in the coefficient was seen. At a concentration of 2.0%, it was shown that a maximum improvement in heat transfer of 46.5% could be achieved. In addition, Sun et al. [33] carried out research to explore the heat transfer performance of MWCNT-R141b nano-refrigerants as well as the flow properties of MWCNT-R141b nano-refrigerants inside of a corrugated tube. They found that the nano-refrigerant showed the best heat transfer enhancement effects at a concentration of 0.3 wt%, with a maximum Nusselt number improvement of 40%. Fig. 30(a) depicts the impact of surfactant on various nanoparticle concentrations in R141b refrigerant. The graph demonstrates that the enhancing effect of Span-80 surfactant was roughly 1.21 times greater at a concentration of one weight percent. As can be seen in Fig. 30, the key component found to have an effect on

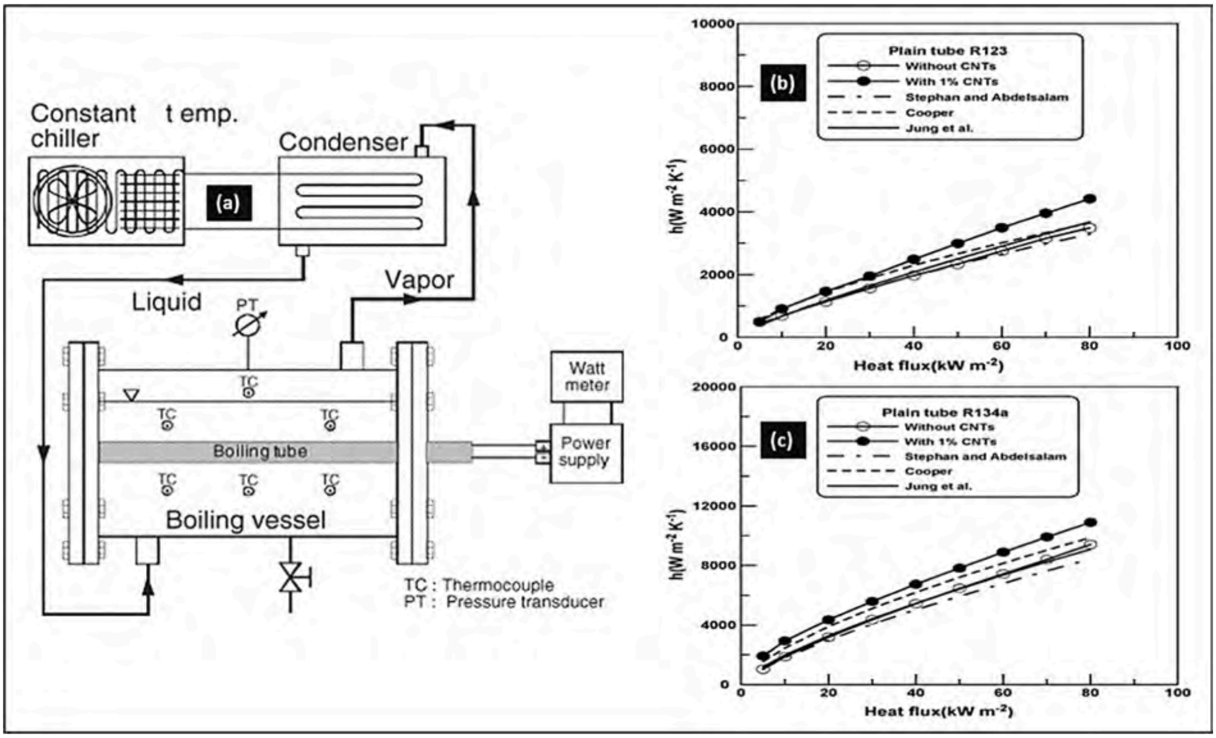


Fig. 24. (a) Schematic of the setup, Boiling heat transfer coefficients for (b) CNTs-R123 and (c) CNTs-R134a [104].

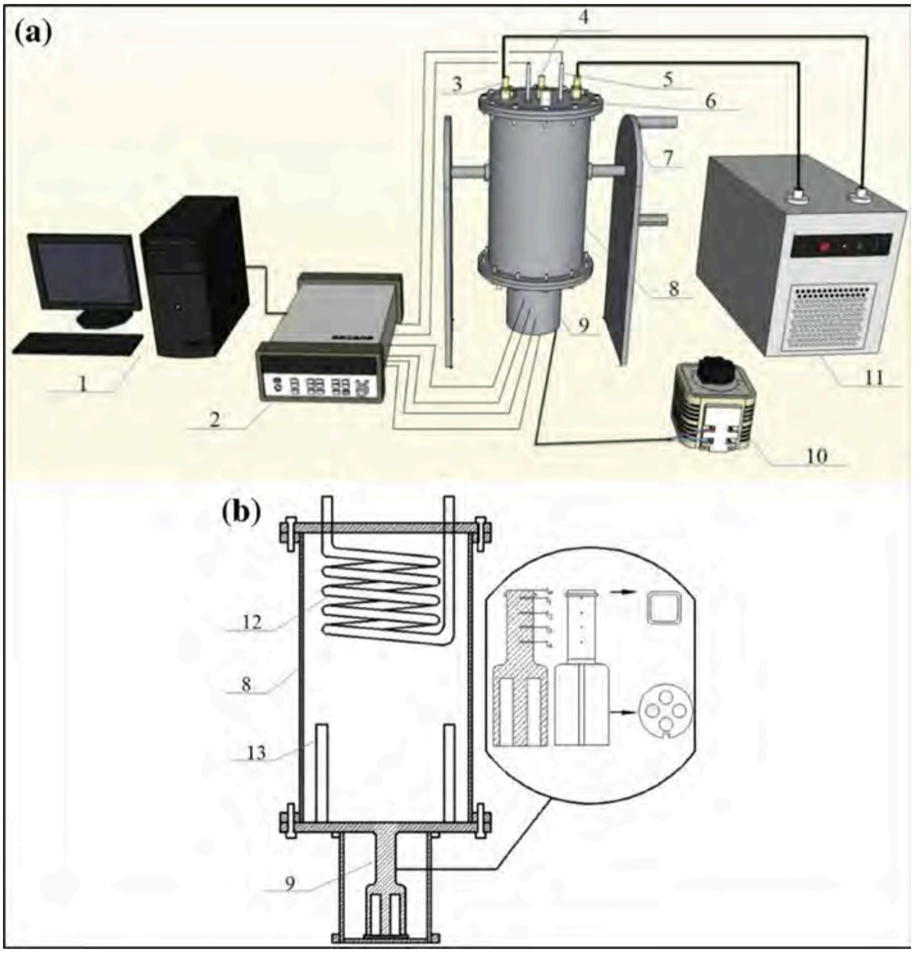


Fig. 25. (a) Experimental apparatus schematic (b) internal anatomy of the test vessel and main heater [32].

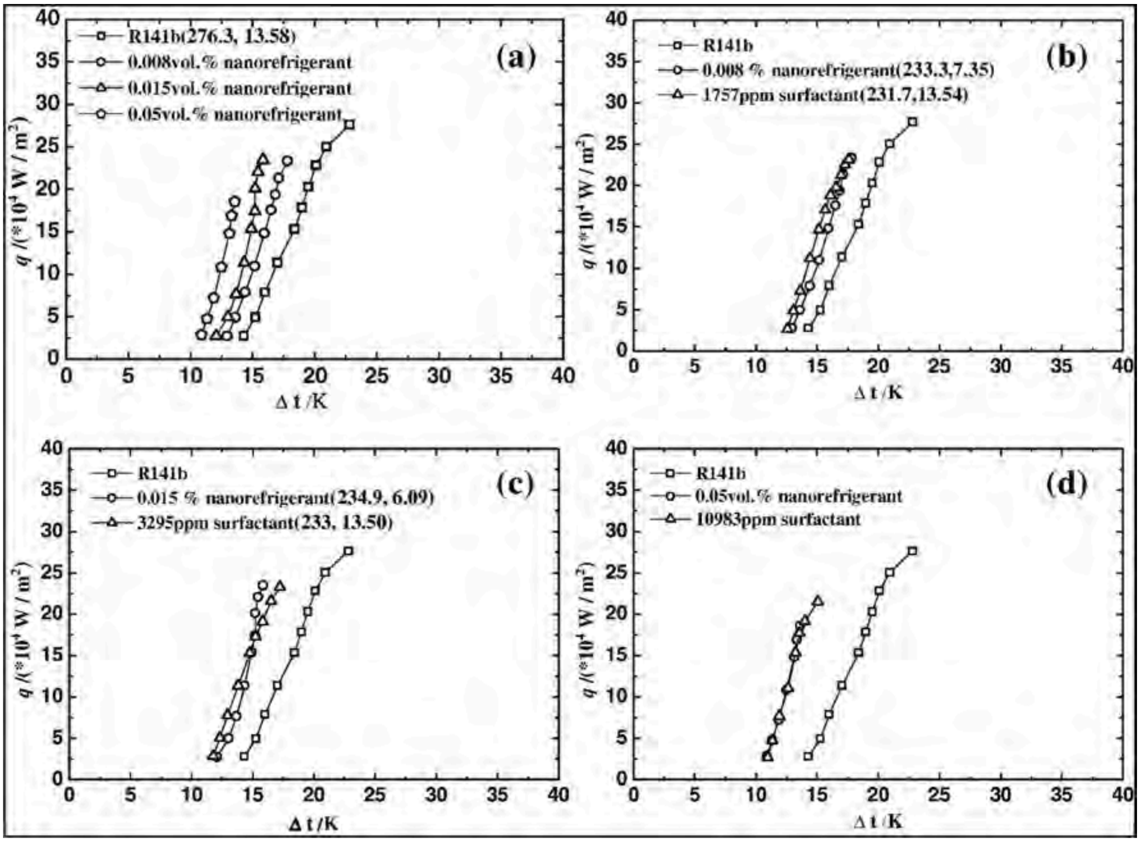


Fig. 26. Boiling curves for R141b-based nano-refrigerant [32].

Table 4
Summary of pool boiling studies for nano-refrigerants.

Authors	Refrigerant	Nanoparticle/ Lubricant	Surfactant	Particle concentration	Findings
Tang et al. [110]	R141b	Al_2O_3	SDBS	0.001, 0.01, and 0.1 vol.%	• Nanoparticles enhanced the pool boiling characteristics. • When nanoparticles are present at a concentration of 0.1 vol.% and there's no surfactant, they can negatively impact pool boiling performance because of significant deposition. • However, when SDBS is present, boiling heat transfer enhancement is increased at both 0.01 vol.% and 0.1 vol.%.
Ding et al. [111]	R113	Cu-VG 68	SDS, CTAB and Span-80	0.2 to 1 vol.%	• It was discovered that the addition of surfactants improves nucleate pool boiling heat transmission, although their efficacy decreases at higher concentrations.
Wongwises and Trisaksri [25]	R141b	TiO_2	-	0.01, 0.03, and 0.05 vol.%	• As heat flux increases, an increase in nanoparticle concentration can degrade pool boiling heat transfer. • The influence of pressure on boiling heat transfer coefficients is less pronounced at higher nanoparticle concentrations than at lower concentrations.
Sun et al. [33]	R141b	MWCNT	Span-80	0.1, 0.2, and 0.3 vol.%	• When compared to pure refrigerants, MWCNT-R141b nano-refrigerants at 0.3 wt% showed the most effective heat transfer enhancement.
Diao et al. [32]	R141b	Cu	SDBS	0.008, 0.015, and 0.05 vol.%	• The addition of Cu-R141b-SDBS nano-refrigerant was found to enhance pool boiling heat transfer.
Ding et al. [112]	R113	Diamond-VG68	-	0 to 15 wt.%	• A substantial increase of 63.4% was observed in nucleate pool boiling heat transfer.
Liu and Yang [103]	R141b	Au	-	0.09, 0.4, and 1 vol.%	• Increasing nanoparticle concentration was found to improve the boiling heat transfer coefficient.
Ding et al. [24]	R113	CuO	-	0 to 0.5 wt.%	• According to the analysis, the heat transfer coefficient of the nano-refrigerant was 29.7% better than that of the conventional refrigerant.

the enhancement of heat transmission is the mass fraction of nanoparticles (b). The maximum value of Nu_{NF}/Nu_{UF} rose as the mass flow rate rose, whereas the average value of Nu_{NF}/Nu_{UF} stayed relatively the same throughout the process.

The following factors [24,120] can be used to provide a condensed explanation of the factors that led to the improvement in heat transfer:

- The presence of nanoparticles has the potential to thwart the formation of boundary layers by reducing the height of these layers as a result of the disturbances that are caused by the presence of nanoparticles.

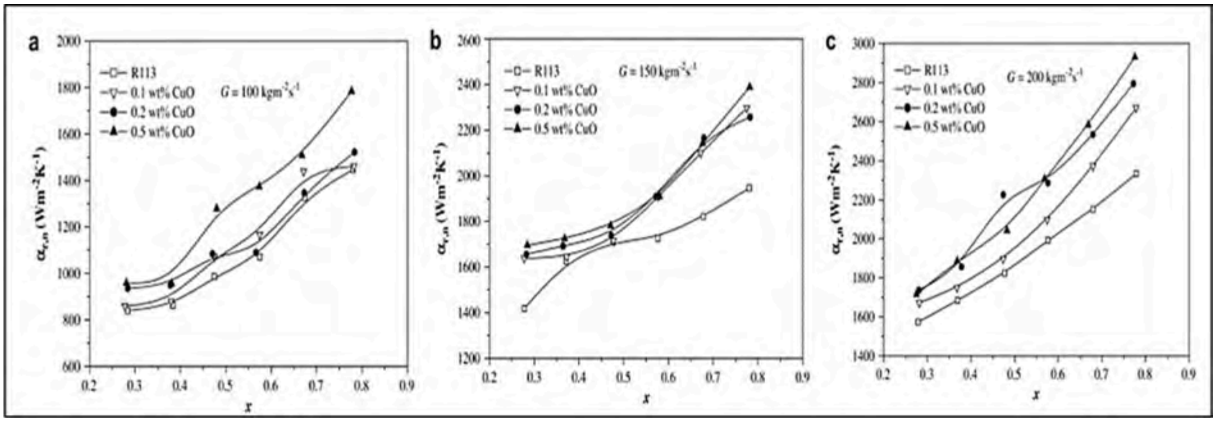


Fig. 27. The heat transfer coefficient of the nano-refrigerant was measured at three different mass fluxes: (a) G = 100 kg/m^2-s, (b) G = 150 kg/m^2-s, and (c) = 200 kg/m^2-s [24].

- The formation of a layer of molecules that have been adsorbed onto the surface of nanoparticles can contribute to an increase in the rate at which heat is transferred.
- As the vapor quality improves, the flow regime may shift towards annular flow, which ultimately results in a large increase in the efficiency of convective heat transfer.
- The wettability of the surface can be improved, which will facilitate the change in flow pattern from a stratified to an annular pattern.
- The remarkable thermal conductivity of the mixture is probably to blame for the observed improvement in heat transfer.
- The Brownian motion of nanoparticles while they are suspended in a liquid can help to increase the rate of convective heat transfer. A reduction in the thickness of the boundary layer can be caused by an increase in the mass flux as well as the Reynolds number. This can result in a rise in the temperature gradient near the wall and an improvement in heat transmission.

4.8. *Tribological improvement of nano-lubricants*

In the past, nanoparticles were utilized in order to improve the tribological performance of lubricant while simultaneously reducing the amount of friction and wear that occurred. Yet, increasing friction produces significant wear and tear, which limits the life span of mechanical devices. Friction is an important component of energy in mechanical systems. The COP of the system using nano-lubricants can be enhanced by reducing the compressor work of the system [44].

Nanoparticles have been added to compressor lubricants such as polyester oil (POE), mineral oil (MO), and polyalkylene glycol to improve the efficiency of refrigeration systems (PAG). Lee et al. [121] used mineral oil as the base lubricant in their study, and fullerene nanoparticles were added at a concentration of 0.1%. The purpose of the study was to determine whether or not nano-lubricants could reduce friction coefficients in a disk-on-disk type tribotester. As can be seen in Fig. 31(a), the findings indicated that the friction coefficient of the nano-lubricant saw a reduction of 90% in comparison to that of the base lubricant. Krishna et al. [122] studied the performance of a refrigeration system that used TiO_2-MO nano-lubricants. They found that the friction coefficient decreased as the particle concentration increased, but then increased beyond a volume concentration of 0.01%, as shown in Fig. 31 (b). With a nanoparticle concentration of 0.01%, they found that the heat transfer rate was improved by 3.6%, and the effort required by the compressor was cut by 11%.

Refrigeration systems usually use lubricants such as POE and PAG because they are compatible with HFC refrigerants. Bobbo et al. [123] they looked at how effective nano-lubricants with POE as a base and SWCNH and TiO_2 as nanoparticles are, and how their solubility affects their efficiency. They compared these nano-lubricants, which have extreme-pressure and anti-wear properties, to a standard lubricant in terms of their ability to lubricate. The results showed that although TiO_2 nanoparticles performed well under high pressure, nano-lubricants had little effect on the anti-wear properties. Zawawi et al. [124] investigated tribological performance of Al_2O_3-SiO_2/PAG nano-lubricants at volume concentrations ranging from 0.01 to 0.10%. The test was conducted on a piston ring tribology test bench, as shown in Fig. 32(a), and the schematic is shown in Fig. 32(b). It was observed that the friction coefficient was reduced by up to 4.78% for 0.06% concentration. The variation of friction coefficient for different nanoparticle concentration is shown in Fig. 32(c). The change in the coefficient of friction over time is not significant. Fig. 32(d) shows how the wear rate changes with different piston speeds and volume concentrations. The results demonstrate that the wear rate decreases as the volume concentration increases and is suitable for volume concentrations up to 0.02%. Based on this study, it is recommended to use a volume concentration of 0.02% for Al_2O_3-SiO_2-PAG nano-lubricants in refrigeration applications.

Several factors can influence the tribological properties of nano-lubricants, including nanoparticle size, shape, concentration, and stability of nanoparticle dispersion. It is essential to determine the ideal concentration of nanoparticles in lubricants in order to achieve maximum reductions in friction and wear. According to research by Rajubhai et al. [125] the optimal concentration for minimizing friction and wear in lubricants was found to be 0.075 wt%. In the same way, Shaari et al. [126] stated that 0.1 wt% of nano-lubricant exhibited minimal friction and wear. Similarly, Aljuwayhel et al. [44] showed that 0.1 vol% of nanodiamond in POE oil exhibited minimum coefficient of friction (COF). The tribological performance of nano-lubricants is also strongly influenced by the nanoparticle size. Particles of a lower size can more easily permeate the rubbing surface. That's why it's important to take nanoparticle size and hardness into account when making nano-lubricants. The tribological properties of nano-lubricants are significantly influenced by the morphology and dispersion stability of nanoparticles. Aggregation of nanoparticles can lead to sedimentation, which in turn can lead to a decrease in tribological improvements. As a result, maintaining the desired level of dispersion stability for nanoparticles is essential for providing effective and dependable lubricating performance.

4.9. *Solubility and miscibility*

Nano-lubricants can enhance the solubility and compatibility between refrigerants and lubricants in refrigeration systems. Wang et al. [20] improved solubility and compatibility for the first time with the use of nano-lubricants. To improve the solubility of refrigerant-lubricant mixtures, TiO_2 nanoparticles were incorporated into mineral oil and HFC refrigerants. Subsequently, Shi et al. [127] conducted a study on

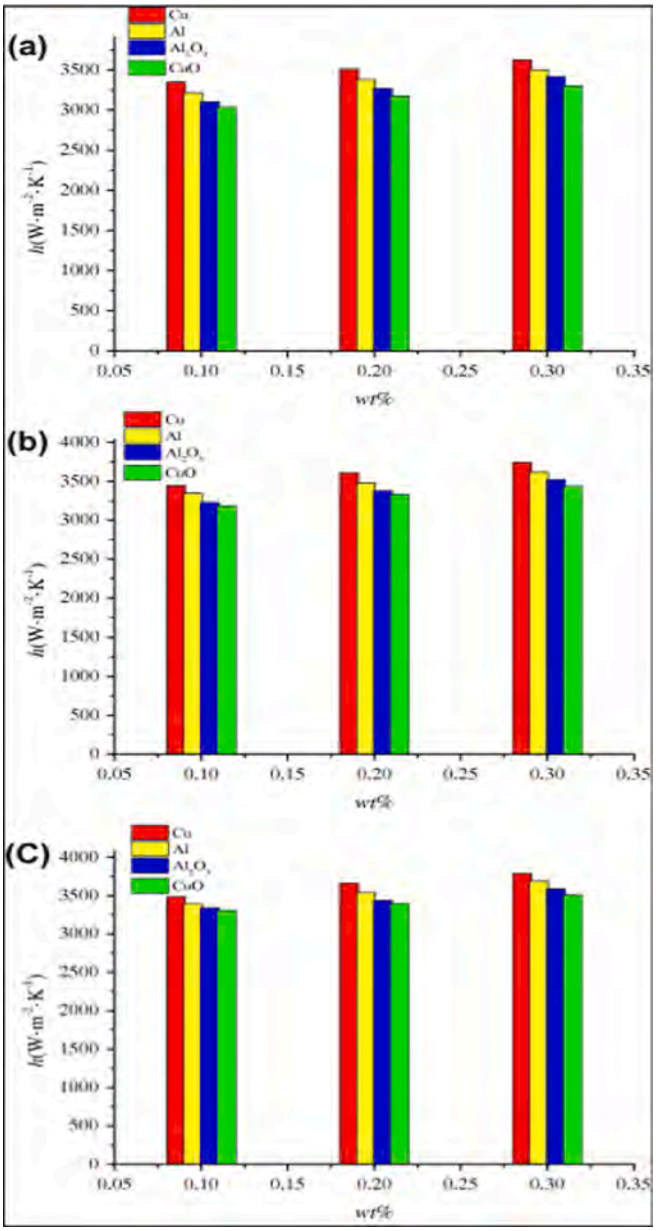


Fig. 28. The effect of different nanoparticles on the heat transfer coefficient of a nano-refrigerant at various mass fluxes: (a) 120, (b) 210, and (c) 330 kg/m^2-s [117].

domestic refrigerators that utilized mineral oil and R134a mixed with TiO_2 and Al_2O_3 nanoparticles, where they discovered that the inclusion of nanoparticles led to an enhanced mineral oil return ratio. In a separate research by Wang et al. [128] the effectiveness of residential air conditioners was examined through the utilization of nano-lubricants that included $NiFe_2O_4$ mixed with mineral oil and R410A refrigerant. The experimental apparatus is shown in Fig. 33(a). The solubility of the studied nano-lubricant was increased up to 12%, as displayed in Fig. 33 (b).

Cremaschi et al. [129] investigated the effect that the combination of Al_2O_3-based nano-lubricants and R410A refrigerant had on solubility and compatibility. The solubility test was carried out with the assistance of an apparatus that had been developed specifically for the purpose and featured the following four parts: a temperature-controlled bath; a sample bottle; a pressure transducer; and a large reservoir (see Fig. 34(a) for an illustration of these parts). The weight of the refrigerant present in the solution with the nano-lubricant was determined using this device. The results showed that type 1 and type 2 nano-lubricants had lower solubility than the base lubricant, and T2S20 had lower solubility than T1S20, as demonstrated in Fig. 34(b) and 35(c). However, the research carried out by Cremaschi and colleagues [129] found that the incorporation of nanoparticles into the lubricant did not have any effect on the attributes of solubility possessed by POE oil. According to the findings of their investigation, the solubility of nano-lubricants was significantly lower.

4.10. Condensation of nano-refrigerants

It is essential to investigate the behavior of nanoparticles during condensation since their migration may affect the condensation rate. It is crucial to ensure that adding nanoparticles does not negatively impact the condensation process. Akhavan-Behabadi et al. [130] looked at the process of condensation using a nano-refrigerant that was made up of R600a, POE oil, and CuO nanoparticles. According to their findings, the coefficient of heat transfer increased as a result of an increase in the nanoparticles concentrations, as can be seen in Fig. 35. Fig. 35 demonstrates that as vapor quality increases, the impact of nanoparticles on enhancing heat transfer increases due to the excitement of nucleation cites. This trend can be seen in the graph. In a similar manner, Ghorbani et al. [131] carried out an experimental study to determine the heat transfer coefficient that occurred during the condensation process of nano-refrigerants based on R600 and R600a that contained CuO-POE oil. The findings showed that the coefficient of heat transfer improved with increasing mass flux and vapor quality. This suggests that the use of R600a-CuO-POE in flattened tubes could improve heat transfer when compared to a round tube.

5. Nanoparticle migration, degradation, and aggregation behavior in nano-refrigerants

The migration of nanoparticles and degradation properties of nano-refrigerants are critical and should be examined scientifically due to the deterioration of nanoparticle concentration during phase change process. There are two mechanisms for migration of nanoparticles such as individual escaping way and bubble adhesion way, described as:

5.1. Individual escaping way

Due to Brown motion, each nanoparticle has a unique speed, making it possible for them to break free of the liquid phase of the refrigerant and enter the gas phase. Nevertheless, this evaporation is inhibited by the liquid phase refrigerant's surface tension. Nanoparticles can only move from the liquid phase of the refrigerant into the gas phase if their velocity is high enough to overcome the surface tension barrier. Each fleeing manner and the procedure through which it occurs describe this type of migration, as shown in Fig. 36.

5.2. Bubble adhesion way

During the boiling process, nanoparticles have the potential to affix themselves to nano-refrigerant bubbles and rise along with them, as postulated by the flotation theory [132]. This migration channel, also known as the bubble adhesion route, allows nanoparticles to move from the liquid phase of the refrigerant and into the gas phase when the bubbles break. This procedure can be broken down into five distinct steps. To begin, nanoparticles and bubbles collide with one another, which causes the space between them to gradually shrink, which promotes the collision of the two entities. Second, as shown in Fig. 37(a), a stable three-phase contact angle is produced when the liquid layer that is sandwiched between the bubble and the nanoparticle thins out, breaks apart, and collapses. This process takes place after the liquid layer has collapsed. Fig. 37(b) illustrates how the nanoparticles that are securely connected to bubbles eventually make their way to the surface of the

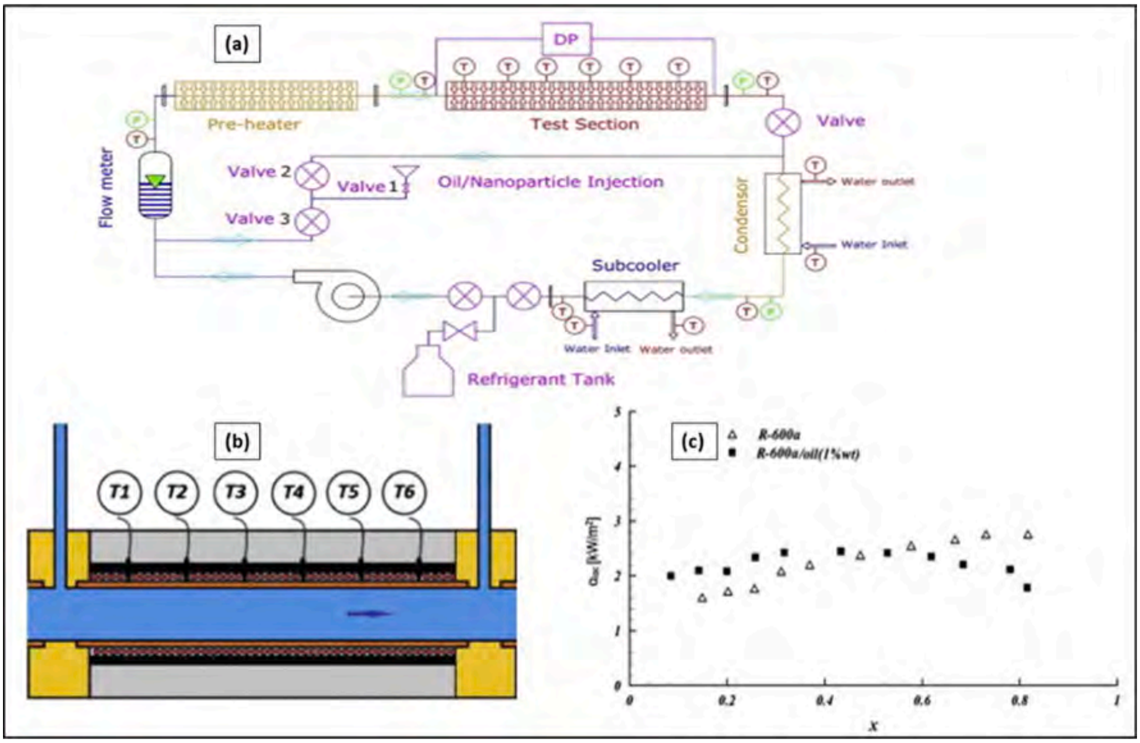


Fig. 29. The diagram depicts (a) the experimental setup, (b) the test segment, and (c) the flow boiling heat transfer coefficient for pure refrigerant and refrigerant-lubricant [119].

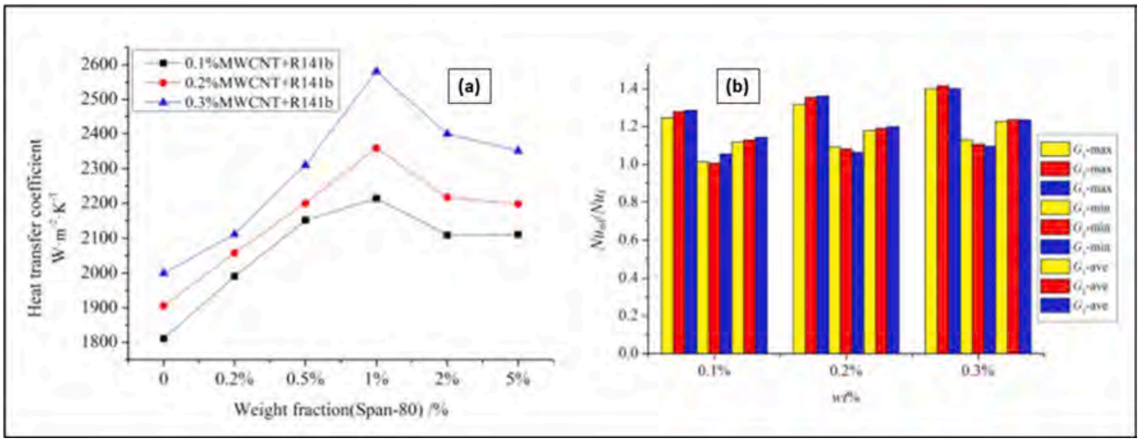


Fig. 30. (a) Effect of surfactant on heat transfer (b) Effect of mass flow rate on Nu_{NF}/Nu_{UF} [33].

liquid, as the third step. As can be seen in Fig. 37(c), the surface tension of the liquid is overcome by bubbles that have nanoparticles attached to them, causing the bubbles to break free from the surface of the liquid. Last but not least, as seen in Fig. 37(d), the bubbles quickly rupture, and the high-velocity gas flow transports the nanoparticles away.

Lin et al. [133] defined degradation as “the continuous diminution of the nanoparticle loading during alternation process of condensation and evaporation”. This study concluded that the nano-lubricant-refrigerant mixture degraded slowly at lower nanoparticle loading during continuous alteration processes of condensation and evaporation, as shown in Fig. 38, with particle loading of 0.1 – 1%, due to the fact that the increment in nanoparticle loading reduced the distance between them in liquid and vapor phase, which caused aggregation and sedimentation, therefore decreased the degradation of the mixture.

As the heat fluxes and nanoparticle mass percentage increase, the frequency of bubble formation and departure also increases, leading to larger volumes of bubbles and additional variables that influence migration. This attracts more particles to the bubbles, resulting in further migration. With the same particle loading, the minimum liquid level aids in the quick evaporation of the refrigerant. As a result, there wouldn’t be enough time for the particles to clump together. The migratory behavior of nano-refrigerants comprising Al_2O_3 and TiO_2 nanoparticles was explored by Kamyar et al. [134], taking into account the impact of nanoparticle type, size, and concentration. They discovered that nanoparticle loading and nanoparticle size both had an effect on nanoparticle migration.

In addition, the aggregation of nanoparticles can result in fluctuations in particle size over time, which can have a major effect on the thermal conductivity, viscosity, and convective heat transfer [135-137]. Researchers have studied the behavior of particle aggregation to improve the development of sustainable nano-refrigerants. The key parameters that affect the aggregation of nanoparticles include

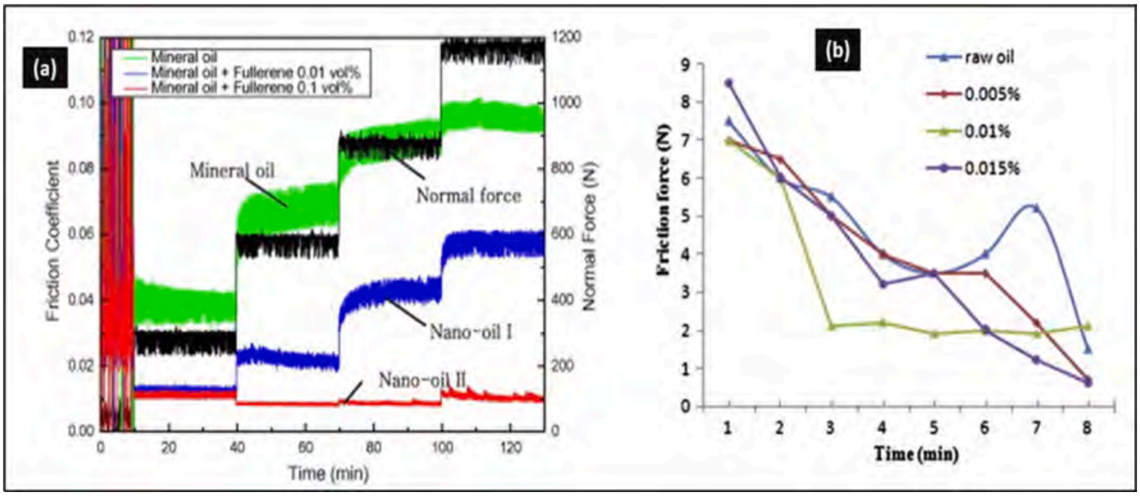


Fig. 31. (a) The steady-state friction coefficient is dependent on the normal force, as demonstrated in [121], (b) The frictional force changes with different concentrations of nanoparticles [122].

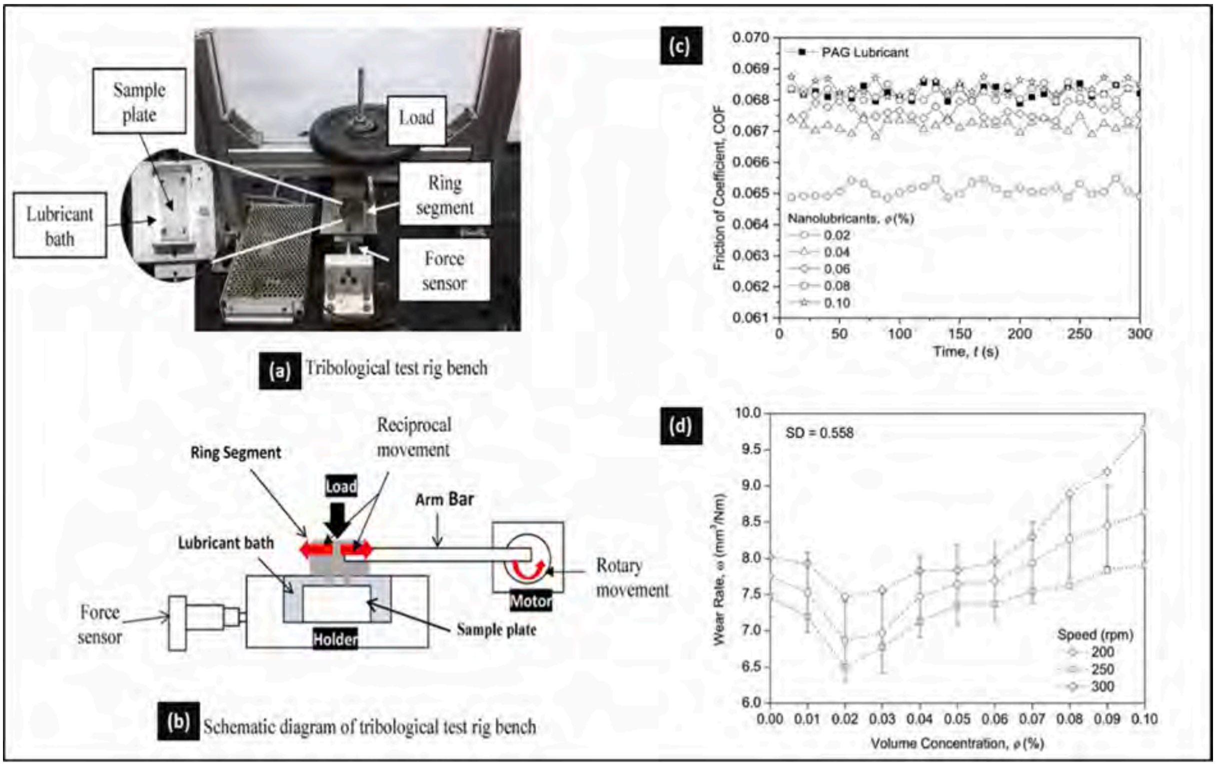


Fig. 32. (a) Tribological test rig and (b) schematic diagram, (c) Change of coefficient of friction, and (d) Variation of wear rate at various volume concentrations and speeds [124].

temperature, particle size, nanoparticle concentration, and surfactant type and concentration.

An experimental investigation into the effect that a number of different factors and surfactants have on the aggregation of TiO_2 nanoparticles in R141b refrigerant was carried out by Ding et al. [31]. Dynamic light scattering techniques were utilized by the researchers to determine the evolution of nanoparticle sizes over time. When they increased the particle size from 25 to 100 nm, they noticed a 127.6% rise in the steady-state hydrodynamic diameter. On the other hand, the particle concentration didn't have a significant impact on the particle size at all. In addition, the effect of surfactant concentration on the hydrodynamic diameter particle size differed based on the type of surfactant that was used in the experiment. Using the dynamic light scattering (DLS) technique, Ding et al. [138] studied the effect that particle size, particle concentration, and temperature had on the aggregation behavior of nanoparticles in a nano-refrigerant-oil mixture. The experiments used TiO_2 nanoparticles, R141b refrigerant, and ATMOS NM56 lubricating oil. The study recorded the time evolution of hydrodynamic diameters of aggregated nanoparticles in nano-refrigerant-oil mixtures for various primary particle sizes and oil concentrations, as shown in Fig. 39. According to the findings, the hydrodynamic diameter of the nanoparticles increased with time, but the rate of increase slowed down as the primary particle size rose (d_p). The interaction energy barrier increased as dp grew, while the surface free

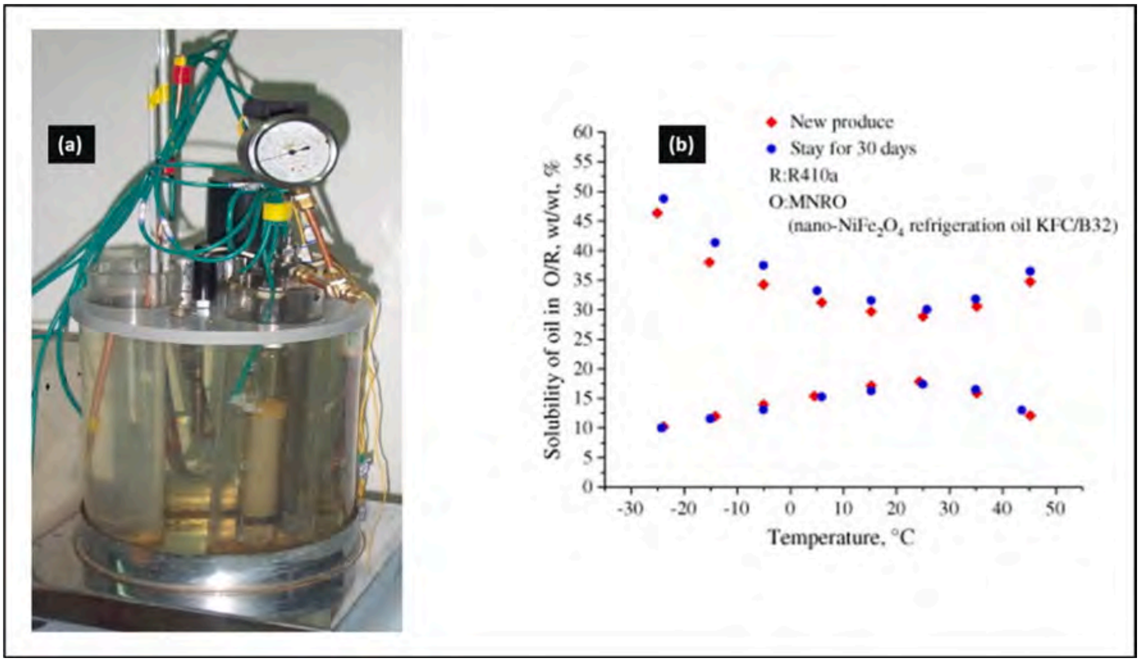


Fig. 33. (a) Experimental apparatus of oil-refrigerant solubility, (b) Solubility of the nano-lubricant with refrigerant R410A [128].

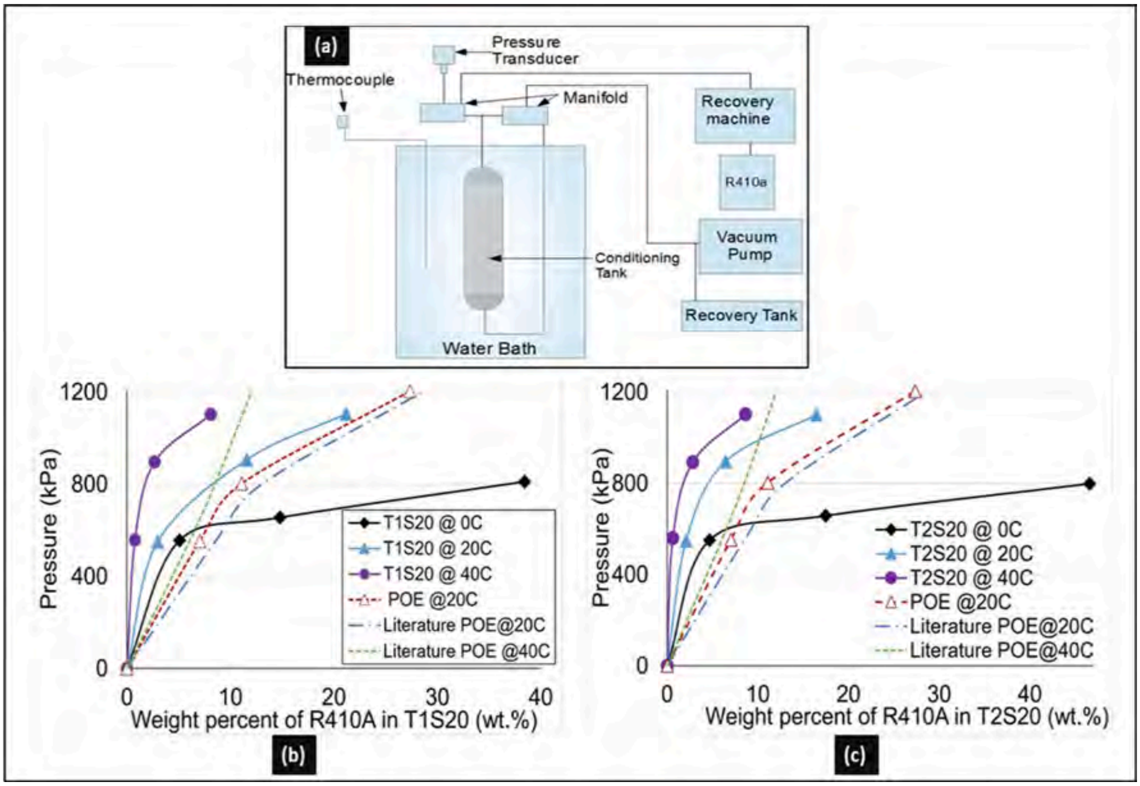


Fig. 34. (a) Experimental setup for solubility of nano-lubricants, Pressure vs R410A refrigerant in (b) T1S20 and (c) T2S20 nano-lubricants [129].

energy decreased. This led to a lower aggregation rate, which led to a decrease in the rate of rise in hydrodynamic diameter (d_h) [139].

6. Applications

6.1. Experimental studies on heat pipe with nano-refrigerant-nano-lubricant

Efficient heat removal is crucial in the development of electronic components. In the past, copper heat sinks were commonly used to dissipate heat from the motherboard of personal computers. Heat pipes

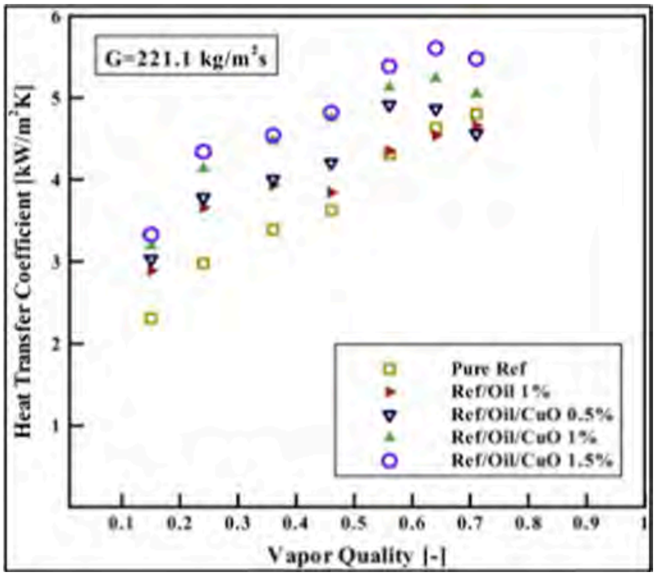


Fig. 35. Condensing heat transfer coefficients of refrigerant, refrigerant-lubricant, and nano-lubricant-refrigerant against vapor quality [130].

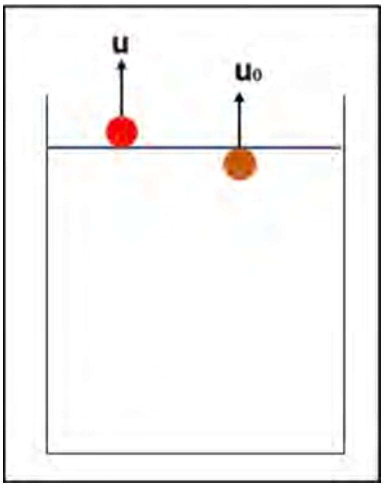


Fig. 36. Migration way schematic.

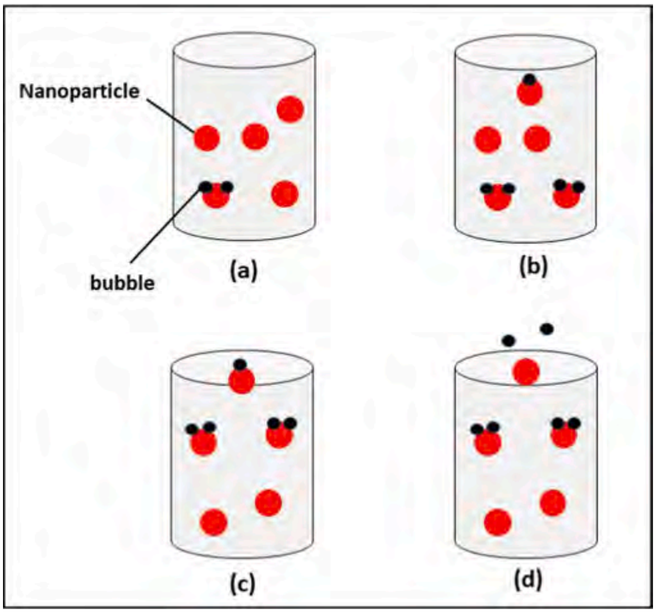


Fig. 37. This figure illustrates the migration process: (a) nanoparticles and bubbles attach to each other, (b) the nanoparticles attached to bubbles move towards the surface of the liquid, (c) bubbles carrying attached nanoparticles escape from the liquid phase to the gas phase, and (d) the nanoparticles attached to the escaping bubbles break apart and enter the gaseous phase.

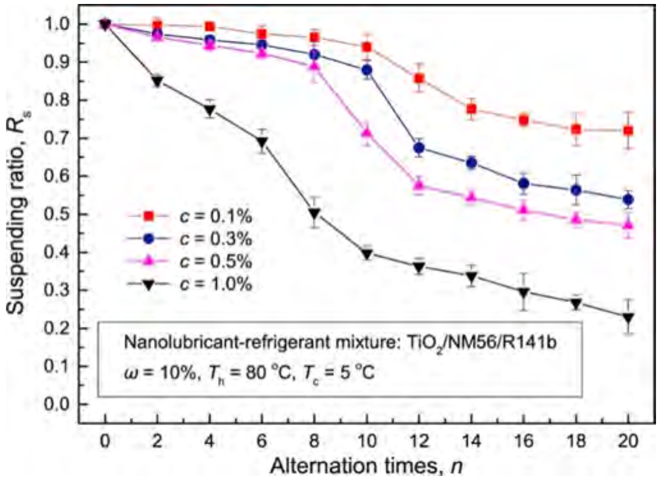


Fig. 38. Influence of nanoparticle loading on degradation of nano-lubricant-refrigerant mixture [133].

are commonly used in modern electronic devices to improve heat transfer. Examples of these devices are laptops and notebooks. The evaporator, the adiabatic portion, and the condenser are the three components that make up a heat pipe. The evaporator segment of a heat pipe is responsible for taking in heat, while the condenser section is responsible for expelling it. The adiabatic area features comprehensive insulation. After being evacuated, the heat pipe is next filled with a working fluid, which is often a heat removal fluid of a standard type. Yet, recent research has shown that employing nanofluids can lead to potentially significant improvements in thermal characteristics. As a result, the use of nanofluids may be an attractive alternative to traditional fluids for use as a working fluid in heat pipes in order to improve heat transmission. The utilization of heat pipes in contemporary heat exchangers as well as the utilization of micro and small heat pipes for the cooling of electronic components has been researched [140,141]. Recent research has shown that including nano-sized particles in the working fluids of heat pipes considerably increases both their capacity for heat transfer and their flow properties. Miniature heat pipes were invented by Lin et al. [142] for the purpose of removing heat from high heat flux electrical gadgets. devices. Naphon et al. [143] investigated the use of TiO_2-R11 nano-refrigerant to improve the efficiency of heat pipes. Fig. 40(a) depicts their experimental setup. The researchers used nanoparticle concentrations of 0.01, 0.05, 0.10, 0.50, and 1 vol% in their study, and Fig. 40(b) shows the effect of nanoparticle concentration on heat pipe efficiency. A nanoparticle concentration of 0.10% demonstrated a remarkable heat pipe efficiency with an efficiency ratio of 1.4. The bigger surface area, increased heat capacity, and improved thermal conductivity were all factors that contributed to the improvement in efficiency. When the concentration of nanoparticles grew, the efficiency of the process improved. However, when the concentration was higher than 0.10%, the evaporator section's evaporation rate slowed down, which resulted in a decrease in the efficiency of the process. According to the findings of the experiments, utilizing the nano-refrigerant resulted in an increase in the heat pump's overall efficiency.

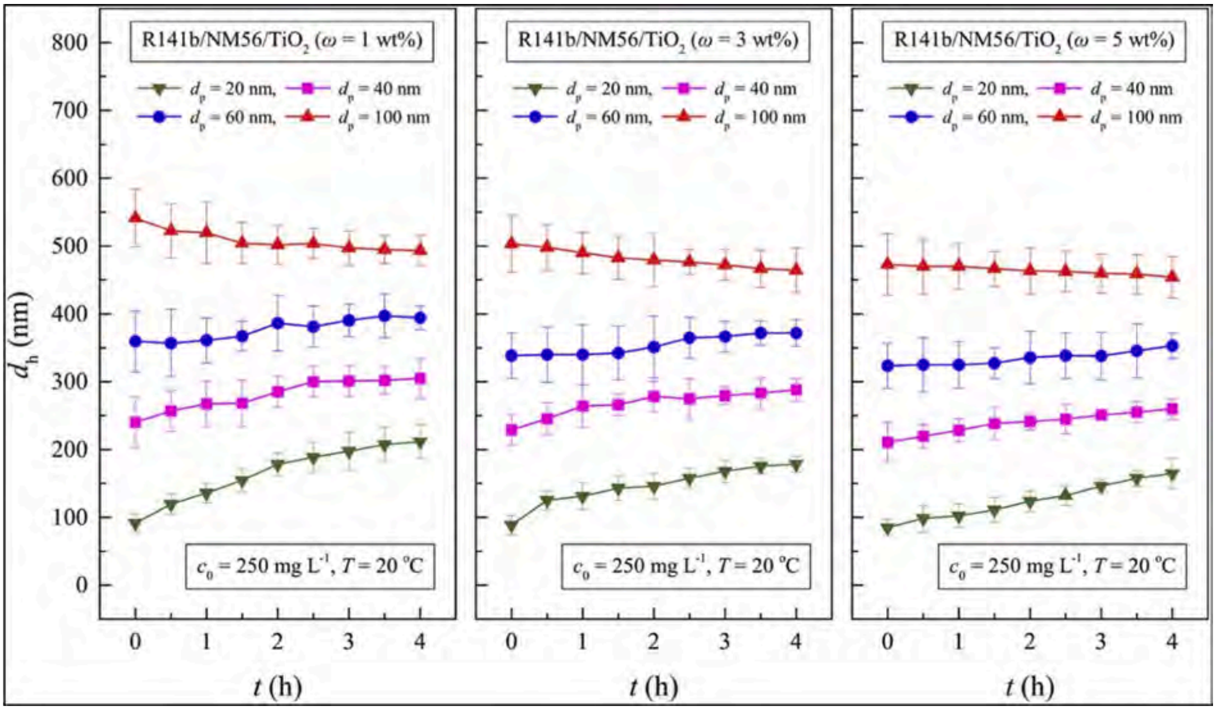


Fig. 39. This figure describes the changes in hydrodynamic diameter (d_h) over time for nanoparticle aggregates in a nano-refrigerant-oil mixture with varying primary particle sizes (d_p) and oil concentrations (ω) [138].

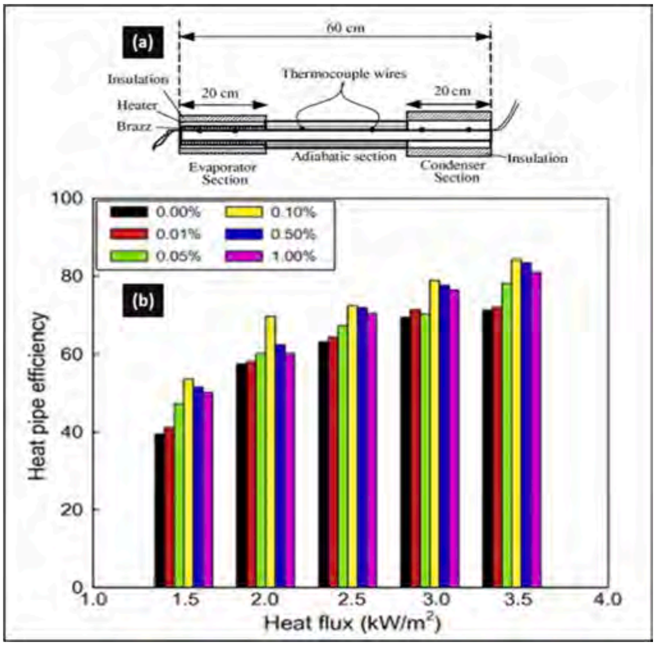


Fig. 40. (a) An illustration of the test section (b) An examination of how the concentration of nanoparticles affects the performance of the heat pipe [143].

6.2. Experimental studies on heat pumps with nano-refrigerant-nano-lubricant

Heat pumps are electrical appliances that transform energy from external heat sources into helpful heat, which can be utilized for domestic and industrial purposes like providing hot water and heating spaces. However, heat pumps are only suitable for about 3% of building heating requirements [144]. The use of nanoparticles in combination with base fluids in heat pumps has a wide range of potential benefits; nevertheless, there have only been a few research projects conducted on this subject. Yildiz et al. [145] carried out a thermodynamic investigation with the purpose of looking into the effect that a number of different nano-lubricants have on air-to-water heat pumps. Throughout the course of the research, POE oil was infused with Al_2O_3, CuO, and TiO_2 nanoparticles, each of which had a distinct variety. The experimental setting and schematic diagram of the air-to-water heat pump that was used in the study can be seen in Fig. 41. As can be seen in Fig. 42(a), the researchers performed the calculations necessary to determine the COP values of the heat pump system for a variety of nano-lubricants and condenser water flow rates. According to the findings, the coefficient of performance (COP) increases alongside an increase in the water flow rate for both pure POE and nano-lubricants. Fig. 42(b) presents an illustration of the energy consumption of the heat pump system at varying flow rates with and without the use of nano-lubricant. According to the findings of the study, there was a correlation between an increase in flow rate and a decrease in energy consumption. This was due to the fact that an increase in flow rate resulted in a greater amount of heat being released into the environment.

6.3. Nano-refrigerant refrigeration and air-conditioning experiments

Even the most insignificant efforts to conserve energy can contribute to the preservation of our natural resources considering the anticipated growth in global energy consumption brought on by the proliferation of heating, ventilation, and air conditioning (HVAC) systems in commercial and residential settings. The effectiveness of using a mineral lubricant and a hydrocarbon refrigerant as a replacement for POE lubricant and R134a refrigerant was investigated in a study that was carried out by Jwo et al. [146]. To enhance lubrication and thermal performance, Al_2O_3 nanoparticles (0.05, 0.1, and 0.2 wt%) were added to the mineral lubricant. According to the data, the optimal mixture was 60% R134a and 0.1 wt% Al_2O_3 nanoparticles. This combination led to a drop of 2.4% in the amount of energy that was used while also leading to an improvement of 4.4% in COP. Isobutane (R600a) and graphite nano-lubricants were used in the study that was conducted by Lou et al.

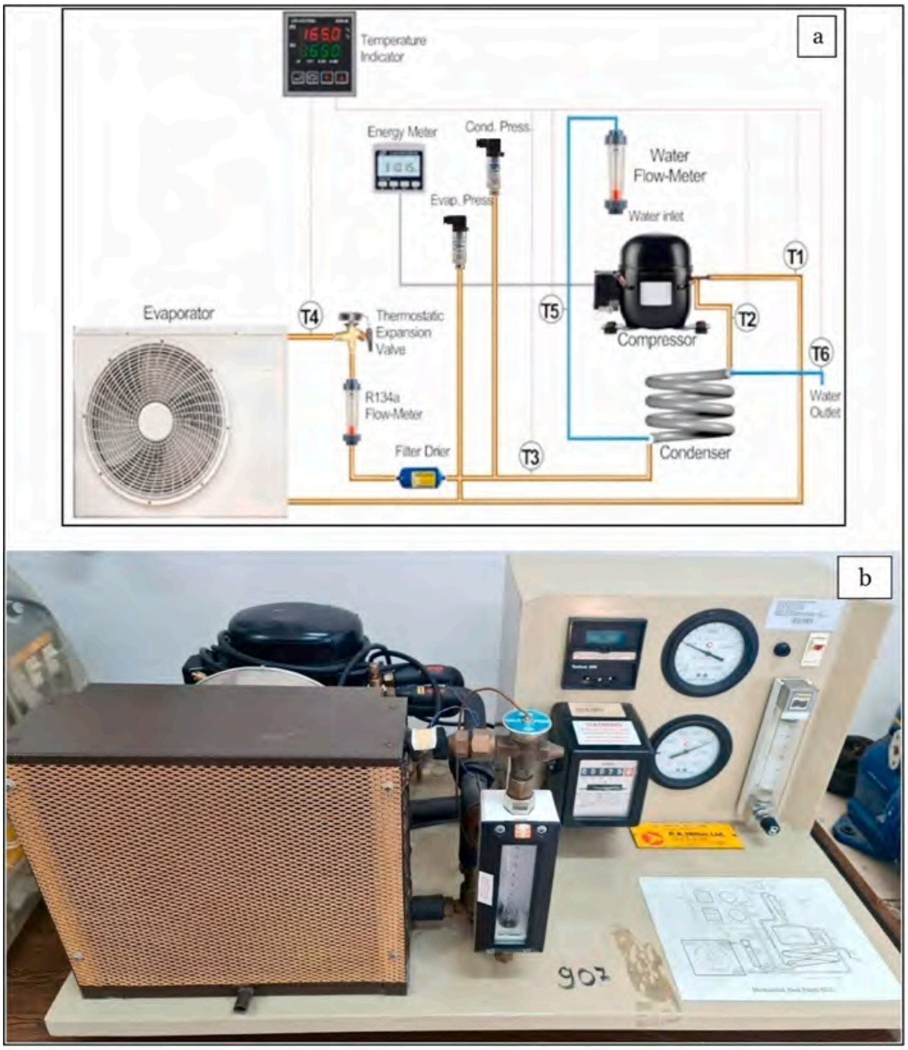


Fig. 41. (a) Schematic and (b) Experimental setup of heat pump [145].

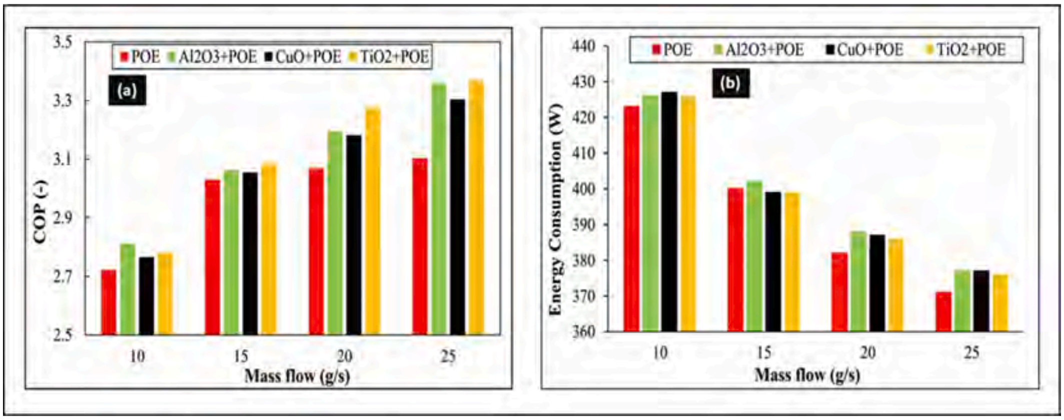


Fig. 42. (a) Coefficient of Performance, also known as COP, and (b) Energy consumption of various nano-lubricants at varying flow rates [145].

[147] to evaluate the efficiency of a home refrigerator. The experimental set-up that was utilized for the investigation can be seen in Fig. 43. The researchers investigated the potential applications of graphite nano-lubricants in household refrigerators with mass fractions ranging from 0% to 0.5% using a test setup. The findings demonstrated that the use of graphite nano-lubricants had no effect on the refrigerator's normal and safe operation. It is proven in Fig. 43(c) that the utilization of a graphite nano-lubricant with a mass fraction of 0.1 wt% can lower the amount of power that is required to run a refrigerator by 4.55%. The performance of SiO_2-PAG nano-lubricant was evaluated by Azmi et al. [91] in the context of a vehicle air conditioning system, with different mass fractions. Fig. 44(a) shows the experimental setup used in the study. The

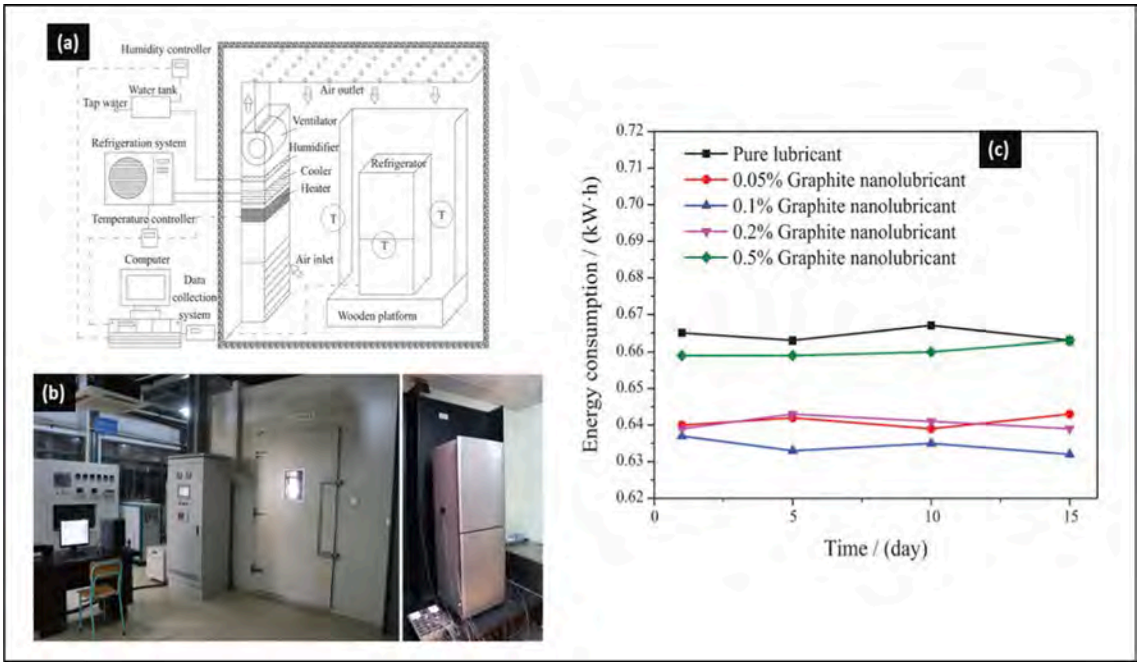


Fig. 43. (a) A schematic representation of the refrigeration test system, and (b) an actual photograph of the system. (c) The energy consumption of nano-lubricant at various mass fractions [147].

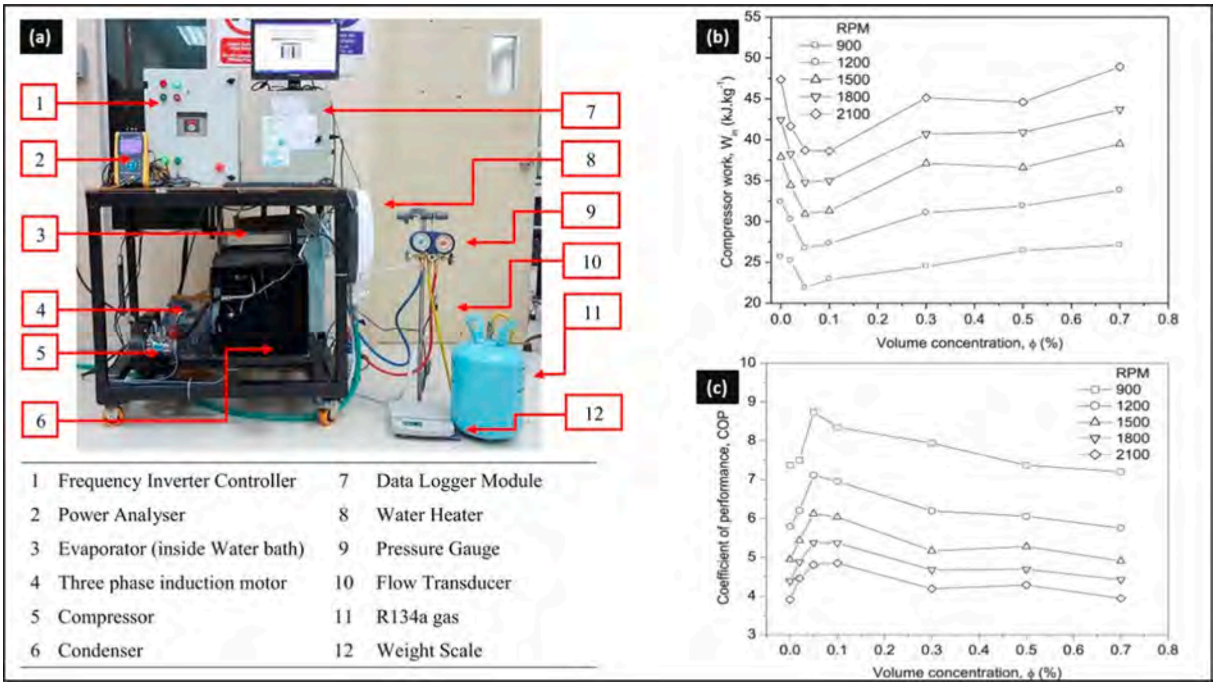


Fig. 44. (a) The experimental setup of a car air conditioning system, (b) The work of the compressor, and (c) the coefficient of performance of SiO_2-PAG nano-lubricant at various compressor speeds [91].

study indicated that at a volume concentration of 0.05%, the compressor work was minimal. Although the compressor work improved with increasing volume concentration, it remained lower for nano-lubricants than for pure PAG lubricant. Fig. 44(b) illustrates these results. The maximum increase in COP enhancement for SiO_2/PAG nano-lubricants was 24%, as shown in Fig. 44(c). A study on the usage of a nano-lubricant consisting of R134a refrigerant, mineral oil, and TiO_2 and Al_2O_3 nanoparticles was carried out by Manoj Baby et al. [148] as part of an attempt to enhance the reliability and efficiency of refrigeration systems. The researchers found that the use of nanoparticles with R134a and MO lubricant was safe in refrigeration systems and that the performance of the nano-lubricant was superior to that of the R134a and POE lubricant system. An experiment was carried out by Kumar et al. [149] on a vapor compression refrigeration system using an environmentally friendly refrigerant (R152a) that had 0% ODP and a low GWP. According to the findings of the study, the Zno/R152a nano-refrigerant exhibited outstanding performance in the system. This resulted in a reduction in power consumption of 21%, a reduction in suction pressure of 10.5%, and a reduction in evaporator temperature of 6%. So, increasing the effectiveness of air conditioning systems in automobiles can help lessen the impact that these vehicles have on the environment and reduce the amount of petroleum that is consumed globally.

7. Economic analysis

Assessing the economic viability of a venture is pivotal, and gauging the preliminary expenditures is a crucial aspect of performing a customary economic feasibility evaluation. However, determining the cost of refrigeration systems is challenging due to several factors, including installation costs, plant equipment, competitive market conditions, working fluids, nanoparticle costs, and labor costs. Diminishing the dimensions of the heat exchanger can curtail the preliminary investment expenses, yet augmenting the pressure drop can lead to increased yearly operating expenses. Hence, precisely predicting the total investment cost may not be feasible. Therefore, utilizing a systematic and scientific approach to determine the necessary data for future reference is crucial. The energy-saving potential and life-cycle cost (LCC) can be employed to assess the efficiency of refrigeration systems utilizing nanofluids.

The annual cost is determined by the amount of energy saved annually and the cost of each energy unit, as stated in [150]:

> “Cost reduction equals annual energy consumption avoided divided by the unit cost of energy.”

Using the simple payback approach, one may determine the amount of time necessary to recoup one’s initial investment by using the formula [151]:

> “The payback period is equal to the incremental cost divided by the annual cost savings.”

Javadi et al. [152] found that the use of nanoparticles in refrigerants could result in energy savings and a reduction in greenhouse gas emissions. They also concluded that the payback period for implementing nano-refrigerants could be satisfactory, making it an economically viable option. Gurbuz et al. [153] conducted an economic appraisal of a refrigeration system to explore the correlation between the exergy destruction rate and the preliminary investment expenses. They reported that using $ZnOAl_2O_3$ nanoparticles at 2 wt% is preferable as it resulted in the minimum levelized cost of cooling.

8. Challenges and future outlook

Nanotechnology has paved the way for the creation of nano-refrigerants and nano-lubricants, both of which are great candidates for substituting traditional fluids in refrigeration systems. This has been made possible as a result of the advancements made in nanotechnology. It has been demonstrated that the use of these innovative fluids improves the system’s thermal qualities, as well as its ability to save energy, dissolve, and transport heat. Unfortunately, the usage of these fluids is associated with a number of problems, which can negatively impact the functioning of the system.

One of the main challenges is achieving the dispersion stability of nanoparticles in the base fluid when preparing nano-refrigerants and nano-lubricants. Another concern is the long-term degradation of the mixture due to temperature fluctuations, particle aggregation, and surfactants. To address these challenges, scholars have explored different techniques such as UV–Vis spectral absorbency and high mass velocity to improve stability and dispersion [91,138].

In contrast to the predominantly single-phase technique that is utilized in contemporary research on nano-refrigerants, numerical studies on nano-refrigerants should adopt a two-phase approach to simulation in order to acquire correct results [154]. Moreover, physical mechanisms associated with two-phase and thermal phenomena should be investigated experimentally to establish a consistent database for nano-refrigerant properties.

The lubrication mechanism of nanoparticles is complex and requires further research to develop environmentally friendly nano-lubricants that do not contain harmful substances. However, increased viscosity can have adverse effects on refrigeration system performance, and the effect of viscosity should be observed to minimize the pumping power requirements associated with pressure drop.

Furthermore, oil separators usually being installed to isolate nanoparticles within the compressor loop and minimize their accumulation effect on systems mechanical parts. However, there remains a possibility that a few nanoparticles may have escaped and retained in the refrigeration system. Therefore, to fully comprehend the importance of nanolubricant in the compressor loop, future investigations should examine the efficacy of the oil separator in effectively isolating nanoparticles [155].

Further experimental research is needed to estimate the potential benefits of nanofluids in two-phase flow nano-refrigerants. Interdisciplinary research approaches can help develop better prediction methods useful for basic research, such as numerical software tools, to monitor real-time performance and keep minimum uncertainties.

Nanofluids require surfactants to maintain long-term stability, but the improvement in performance due to surfactants is dependent on specific conditions and parameters. It is essential to make use of trustworthy software tools and computational models in order to build air cooling and refrigeration (AC&R) systems that make use of nanofluid additives. In addition, the optimal concentration of carbon-based nanofluids required to achieve maximal AC&R performance has not yet been discovered.

If the viscosity of nanofluids increases, it may lead to a higher power consumption of the compressor, and further studies are needed to determine which components have the most significant irreversibility when using carbon-based nanofluids in AC&R systems. Additionally, a techno-economic analysis is necessary to assess the cost-effectiveness of carbon-based nanofluids in AC&R applications.

It is crucial to conduct long-term studies on the operating performance of nanorefrigerants and nanolubricants to assess their stability and potential separation from the carrier fluid during extended use, which could lead to reduced system performance. Despite these challenges, the application of nano-refrigerants and nano-lubricants has the potential to significantly improve refrigeration system performance and serve as an eco-friendly alternative to traditional refrigerants.

Hybrid nanofluids which are in the experimentation stage faces a lot of problem in adapting to the current wider range of applications. Many investigations are required to study about their stability by utilizing various surfactants along with a sound knowledge about the relation of rheological properties and the thermophysical properties of nanofluids [45-47].

9. Conclusions

The current review offers a thorough analysis of the thermophysical properties and heat transfer performance of nano-refrigerants and nanolubricants, both showing promising potential for enhancing refrigeration systems. The key findings of this research can be summarized as follows:

- Nano-refrigerants and nano-lubricants, made by blending nanoparticles with refrigerant and lubricants respectively, have shown potential for positively influencing heat transfer efficiency, thermal characteristics, and tribological properties. This enhancement leads to a decrease in compressor effort, promising energy savings and improved system performance.
- Key operational factors such as nanoparticle concentration, temperature, and particle characteristics like migration, degradation, and aggregation, have a considerable impact on the performance of these nano-fluids. Notably, the thermal conductivity and viscosity of

nanofluids are dependent on nanoparticle concentration and temperature, thus affecting the heat transfer performance.
- The exploration of potential nano-additives including Al_2O_3, CuO, SiO_2, TiO_2, and CNTs shows promise in further enhancing the efficiency of refrigerants and lubricants. However, achieving nanoparticle dispersion stability within the base fluid is a significant challenge that needs further research to devise successful methods for enhancing stability.
- Limited experimental research and a deficiency in computational models and tools for AC&R system designs that include nanofluid additives highlight areas for future work. In addition, identifying the appropriate concentration of carbon-based nanofluids for AC&R performance and examining the long-term performance of nano-refrigerants and nano-lubricants are key areas for future exploration.

In conclusion, the use of nano-refrigerants and nano-lubricants presents a substantial opportunity for improving the effectiveness and efficiency of refrigeration systems. With continued research and development, these innovative solutions have the potential to serve as sustainable and eco-friendly alternatives to conventional refrigerants that contribute to environmental pollution.

Author contributions

All authors have revised and agreed on the published version of the manuscript.

Data Availability Statement

Data will be made available on request.

CRediT authorship contribution statement

Zafar Said: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Shek M.A. Rahman:** Conceptualization, Investigation, Methodology, Visualization, Writing – review & editing. **Maham A. Sohail:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Ammar M. Bahman:** Conceptualization, Formal analysis, Investigation, Project administration, Visualization, Validation, Resources, Writing – original draft, Writing – review & editing. **Mohammad A. Alim:** Conceptualization, Writing – review & editing. **Saboor Shaik:** Conceptualization, Investigation, Writing – review & editing. **Ali M. Radwan:** Conceptualization, Investigation, Writing – review & editing. **Ibrahim I. El-Sharkawy:** Conceptualization, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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