Hindawi
Journal of Nanomaterials
Volume 2022, Article ID 8618152, 18 pages
https://doi.org/10.1155/2022/8618152

Review Article

Fundamentals, Thermophysical Properties, and Heat Transfer Characteristics of Nanorefrigerants: A Review

M. Feroskhan,[1] T. Venugopal,[1] Naif Mana Almakayeel,[2] T. M. Yunus Khan,[3] Saleh Alghamdi,[2] Ali Saeed Almuflih,[2] and N. Gobinath[1]

[1]*School of Mechanical Engineering, Vellore Institute of Technology (VIT), 600127, Chennai, India*
[2]*Department of Industrial Engineering, College of Engineering, King Khalid University, Abha 62529, Saudi Arabia*
[3]*Department of Mechanical Engineering, College of Engineering, King Khalid University, PO Box394, Abha 61421, Saudi Arabia*

Correspondence should be addressed to N. Gobinath; gobinath.n@vit.ac.in

Received 19 April 2022; Revised 11 May 2022; Accepted 13 May 2022; Published 6 June 2022

Academic Editor: Samson Jerold Samuel Chelladurai

Cooling applications that utilize latent heat property of fluids involve large heat transfer and throw more space for energy conservative research studies. Heating ventilation air-conditioning and refrigeration systems, which have now grown as an integral part in human life, circulate refrigerants and necessitate developments to become energy-efficient. The heat removal characteristics of the fluids in such large capacity systems can be enhanced using nanoparticles seeded in to them. Being smaller in size, the nanoparticles possess larger effective surface area and believed to help in expediting the conduction rate of heat from the refrigerants in the HVAC-R systems. Spectrums of nanoparticles are studied for their heat transfer behavior either in pure refrigerants or with refrigerant/oil mixtures. Suspension of the particles in the refrigerants for a prolonged time is found to be critical and must be validated prior to its implementation in the systems. Seeding of nanoparticles exclusively in a phase change fluid inside the refrigeration systems is reported to be of challenging. Additionally, to harvest the benefits of nanoscale particles, literature proposes the usage of surfactants which may lead to complex situation in a vapor compression refrigeration system. In the present work, all the relevant study details specifically on synthesis and characterization, thermophysical properties, and heat transfer characteristics about the nanorefrigerants are presented.

1. Introduction

Engineering equipment cooling is of paramount importance as it is governing the functional performance of such equipment in direct and contributes to a better material life. A new vertical is observed through nanofluids in cooling applications, owing to its special characteristics than its bulk counterpart. In 1995, Choi proposed that highly conductive nanoscale particles could enhance the fluid thermal conductivity, upon its uniform dispersion [1]. Applied engineering processes that involve thermal equipment/systems are found to be inherent with cooling fluids for their heat removal purpose, and henceforth, thermophysical properties of such fluids can significantly make the systems to become more energy saving [2]. Thermophysical properties of engineering fluids can be improved in one way by using nanoparticles [3–7].

The concept of nanofluids was extended to nanorefrigerant, in a view to make energy efficient air-conditioning, refrigeration, and heat pump systems with enhanced heat transfer properties than that with conventional refrigerants. Nanorefrigerants are prepared by dispersing nanoparticles in pure refrigerants [8]. Considerable researches have been devoted to investigate the possible applications of nanorefrigerants in air-conditioning, refrigeration, and heat pump systems [9–11]. Rahman et al. [12] observed that the addition of single-walled carbon nanotubes in R407c refrigerant reduced the compressor work by 4% for running an air-conditioning system. In a similar work, Kosmadakis and Neofytou [13] claimed that the efficiency of organic Rankine cycle running with R245fa and R1234ze(Z) can be enhanced by seeding alumina and copper nanoparticles. The authors, in a different work conducted numerically, reported that the coefficient of performance (CoP) of a heat pump could be enhanced up to 6% by using different kind of nanoparticles in the refrigerant [14]. Jiang et al. [15] reported that the nanoparticles seeded in a refrigerant could increase its thermal conductivity. Nanoparticles derived from highly conductive materials can enhance the thermal conductivity of the refrigerant, and the thermal conductivity increases with increase in the particles' addition [16, 17]. Furthermore, the improvement in the refrigerant thermal conductivity by any volume addition of nanoparticle is influenced by the operating temperature [17]. Extensive studies in the literature on nanofluids established strong dependency of its thermal conductivity on its types, geometry (shape and size), percentage addition, and to some extent the inclusion of surface reactive agents [18–20]. The investigations clearly show that thermal conductivity of either water based nanofluids or of nanorefrigerants is influenced by many factors. From their experimental work, Wang et al. [21] observed that nanoparticles dispersed in the refrigerant additionally found to be a potential agent which enhanced the mineral oil's solubility in refrigerant. This enhanced property in any refrigerant helps to return back more oil to the compressor and leads to better life of the compressor. Viscosity of nanorefrigerants is one of the significant transport properties, which controls the pumping power requirement and furthers the performance of air-conditioning/refrigeration systems with nanorefrigerants. The viscosity of the original base fluid is found to be increasing with the uniform dispersion of nanoparticles, and the trend of viscosity variation with temperature will be as same as the convention heat transfer fluids [16]. The intense research in nanorefrigerants showed that viscosity of nanorefrigerant varies with particles' concentration [2, 22]. Also, there are results which claim that the viscosity of nanofluids strongly depends on nanoparticles' shape [23] and its size [24].

Dispersion of nanoparticles in pure refrigerants contributes to thermal conductivity enhancement, and also, it helps to introduce more secondary nucleation sites on the viscous layer through its interaction with the bubbles during boiling of refrigerants; hence, it enhances the boiling heat transfer coefficient of the refrigerant [25, 26]. Figure 1 shows the enhancement of pool boiling heat transfer coefficient of R113 with the mixture of oil and diamond nanoparticles. It is witnessed from the captured graph that the lubricant oil tends to reduce the heat transfer rate compare with the pure R113, whereas the dispersed diamond particles enhanced the heat transfer characteristics of R113. Using a similar study, Diao et al. [27] claimed that addition of surfactants provides more nucleation sites which is attributed for the boiling heat transfer enhancement of the refrigerant, R141b. Nevertheless, they claimed that mechanism of surfactants' interaction with copper nanoparticles affects the boiling heat transfer coefficient. Devoted research on boiling of refrigerants conformed that nanoparticles enhance the pool boiling heat transfer characteristics of refrigerants when dispersed in it [28, 29]. Naphon et al. [30] reported that increasing concentration of TiO_2 nanoparticles deteriorates the boiling heat transfer coefficient of R141b refrigerant; however, the heat transfer coefficient can be improved by increasing the boiling pressure. Their results are analogous with research findings

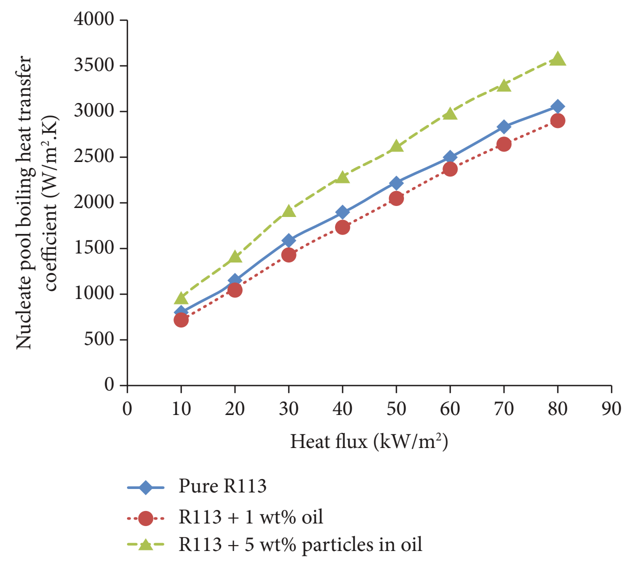

Figure 1: Variation of heat transfer coefficient of R113 with lubricant oil and diamond nanoparticles [26].

by Trisaksri et al. [31]. Peng et al. [32], in their experimental study on R113, showed that reduction in size of copper nanoparticles from 80 nm to 20 nm enhanced the heat transfer coefficient under nucleate boiling regime for the refrigerant/oil mixture by 23.8% under the same conditions.

The important factor which controls the performance of any air-conditioning or refrigeration systems is likely to be the two-phase heat transfer coefficient of the refrigerant. To elucidate the heat transfer characteristics of nanorefrigerants during its flow in the evaporator section of air-conditioning/refrigerating systems, many researches were carried out and significant results were reported. Peng et al. [33] studied the heat transfer characteristics of refrigerant R113 when it flows in a horizontal tube and reported the effect of CuO nanoparticles in their studies. Their research showed a large improvement in the heat transfer coefficient of the refrigerant due to the CuO particles' addition, and the enhancement was found to be higher at high mass fraction of 0.5 wt% of nanoparticles. Also, they claim that at high mass fluxes, the addition of nanoparticles in refrigerants will not provide any appreciable enhancement in the heat transfer coefficient. However, Henderson et al. [34] in 2010 reported that silica nanoparticles when loaded directly with R-134a refrigerant decreased the boiling heat transfer coefficient with its increasing concentration. Their investigation revealed that stable dispersion of nanoparticles in refrigerants plays significant role in enhancing the flow boiling heat transfer coefficient of refrigerants. This paper would be useful to understand the research status about the nanorefrigerants till date and its heat transfer characteristics.

2. Synthesis and Characterization

The physical mechanisms behind the nanoparticle-base fluids interactions are likely to be the reason for the enhancement of thermophysical properties of the base fluids. Furthermore, the stable suspension of particles in the base fluid is an essential condition to manifest these properties of the base fluids, positively. Stability of nanoparticles in the dispersed fluids could be achieved by any one of the three methods: ultrasonication, controlling the pH value of the nanofluids, using surfactants. Peng et al. [33] prepared CuO suspended R113 nanorefrigerant using ultrasonication process for which they conducted visibility test to ensure the stable suspension. Interestingly, the authors found the suspended CuO nanoparticles in the refrigerant uniformly even after 12 h of their preparation. The authors did not report any segregation of particles, and no concentration gradient was found either. This study reveals that the particles can be made dispersed for many hours in the refrigerants provided if it is sonicated effectively. In this context, it is needful to know from the literature, methods of synthesizing variety of nanorefrigerants, and the characterization techniques used to establish the stability of nanorefrigerants. A few review papers were published on the synthesis methods of general nanofluids but not specifically on nanorefrigerants [34–38]. Varieties of nanorefrigerants are synthesized for different heat transfer studies in the recent past [11, 39]. This section of work, as formulated in Table 1, will serve the purpose of identifying and selecting the suitable nanoparticles, refrigerants, dispersion method, and (or) surfactants for specific applications to have maximum possible stable suspension.

3. Thermophysical Properties

Nanorefrigerants have been under investigation so far by many researchers for achieving a better heat transfer performance from the refrigeration/air-conditioning systems. The heat transfer characteristics of nanorefrigerants are experimentally found enhanced comparing to the pure refrigerants by many researchers [27, 30, 31]. Thermophysical properties of nanorefrigerants are necessarily to be examined to analyze the two-phase flow of it in evaporator or condenser region. To optimize the performance of the nanorefrigerants in the systems to gain maximum benefits, it is essential to investigate the key thermophysical properties of the nanorefrigerants, say thermal conductivity, viscosity, density, surface tension, and latent heat, and it is essential to be aware of the pressure drop characteristics of the nanorefrigerants during its flow. This section reviews the studies about the thermophysical properties of nanorefrigerants.

3.1. Thermal Conductivity. Nasiri et al. [18] carried out experiments to elucidate the effect of CNT structures on thermal conductivity of water based nanofluids. In their study, SWNT (single wall CNTs), DWNT (double wall CNTs), FWNT (few wall CNTs), and two different MWNT (multiwall CNTs) are used to prepare water based nanofluids. It is observed from their study that SWNTs provide more stability in the nanofluids when compare with other type of CNTs in nanofluids through the higher absorbance of UV-Vis spectrometer study. Also, SWNTs with large aspect ratio give greater enhancement in thermal conductivity of water while the other types of CNTs provide a little lesser enhancement. The reason for larger enhancement of thermal conductivity of water with SWNTs may be due to any of the following reasons: the manipulation of nanolayer thickness would result in enhanced effective thermal conductivity [4], increase in effective surface area [65], micromotion of the nanofluids [66], at small diameter of CNTs, increase in nanolayer thickness [67].

In 2009, Jiang et al. [44] proposed a model to predict the thermal conductivities of CNT nanorefrigerants, including the effects of particle size and aspect ratio. The model was based on Yu and Choi [4] model as given in Equation (1), and the authors provided a model for obtaining the empirical constant (α) based on their experimental results as given in Equation (2). Their experiment works confirmed that thermal conductivity of CNT nanorefrigerants is greater than CNT-nanofluids and well agreed to the developed model. Also, the diameter and the aspect ratio of CNTs are found to have strong influence on the thermal conductivity enhancement of nanorefrigerants.

$$k_{\mathrm{nf}} = \left(1 + \frac{3\psi^{-\alpha}\varphi A}{1 - \varphi A}\right) * k_f, \tag{1}$$

$$\alpha = 1.55 + 16.7\left(\frac{d}{L}\right)^{0.71}, \tag{2}$$

where K_{nf} and K_f are the thermal conductivities of nanofluid and base fluid, ψ is the particle sphericity, φ is the particle concentration in the base fluid, and A is the CNT conductivity parameter. This developed model was found to predict their experimental values closer than Xue model [68] and Hamilton-Crosser model [69]. Similarly, in 2012, Pelvic et al. [70] presented lattice Boltzmann model to estimate the thermal conductivity of fluids dispersed with nanoparticle that includes the effects of both temperature and particle's geometry as found by Jiang et al. [44].

Mahbubul et al. [17] used a model proposed by Sitprasert et al. [71] as given in Equation (3), to estimate the thermal conductivity of Al_2O_3/R-134a nanorefrigerant and compared their results with other standard models. Their investigation on thermal conductivity of nanorefrigerant shows the trend of variation of thermal conductivity with nanoparticle size and temperature as shown in Figure 2.

$$\mathrm{k_{r,n}} = \frac{(k_p - k_l)\varnothing k_l\left[2\beta_1^{\,3} - \beta^3 + 1\right] + (k_p + 2k_l)\beta_1^{\,3}\left[\varnothing\beta^3(k_l - k_r) + k_r\right]}{(k_p + 2k_l)\beta_1^{\,3} - (k_p - k_l)\varnothing\left[\beta_1^{\,3} + \beta^3 - 1\right]}, \tag{3}$$

where $K_{\mathrm{r,n}}$ is the nanorefrigerant thermal conductivity, and k_p, k_l, and k_r are the conductivities pertaining to particles, interfacial layer, and pure refrigerants, respectively. β and β_1 are parameters depend on interfacial layer thickness, temperature, and particle radius.

Mondragon et al. [72] characterized thermal conductivity of water based nanofluids experimentally and fit their results with the existing models for thermal conductivity. They prepared stabilized nanofluids by maintaining the pH value of nanofluids far away from the isoelectric point of the specific fluid. Nevertheless, their observation shows that

Table 1: Studies on stability of various nano-based refrigerants.

Authors	Nanoparticles and refrigerants		Parameters	Characterization	Method of stabilization	Inferences
Liu et al. [40]	Au	R141b	1 vol%	TEM, dynamic light scattering analysis	—	No discussion on stability
Xiao-Min et al. and Park et al. [29, 41]	CNT's	R22, R123, and R134a	1 vol%	—	—	No discussion on stability
Bartelt et al. [42]	CuO	R134a+oil RL68H	4 vol% in oil, 0.5, 1, and 2 mass% of suspension in R134a, avg size: 30 nm	—	Ultrasonic agitation of nanolubricant for 24 h	Flow boiling study
Bi et al. [9]	TiO_2 and Al_2O_3	R134a+mineral oil	1 mass%, 50 nm	Light transmission ratio index	Ultrasonic agitation	Stable suspension
Ding et al. [43]	CuO	R113+RB68EP oil	40 nm	TEM	No surfactants	Considered to be stable
Kedzierski et al. [25]	CuO	R134a (with polyolester)	1 vol% in polyolester, size: 30 nm	Light scattering technique	Surfactant and ultrasonication for 24 h	Particles will dispersed after weeks with avg size 35 nm
Trisaksri et al. [31]	TiO_2	R141b	0.01, 0.03, and 0.05 vol%	TEM	Ultrasonication for 6 h	Stable dispersion was found
Peng et al. [33]	CuO	R113	0.1, 0.2, and 0.5 wt%, avg size: 40 nm	TEM	Ultrasonic processing for 30 min	Stable dispersion was found
Jiang et al. [44]	CNT's	R113	Size: 15-80 nm 0.2, 0.4, 0.6, 0.8, and 1 vol%	TEM	Ultrasonic process for 30 min	No discussion on stability
Henderson et al. [34]	SiO_2 and CuO	R134a+polyolester	0.05 and 0.5 vol% of SiO_2, 0.02, 0.04, and 0.08 vol% of CuO,	Not mentioned	Hexamethyl-disilazane coated on SiO_2, and CuO mixture is ultrasonic agitated for several min	SiO_2 is stable with coating. CuO needs ultrasonic mixing for stable dispersion
Peng et al. [26]	Diamond	R113 (oil VG68)	3 wt% in oil, 5, 10, and 15 wt% of suspension in R113, size: 10 nm	SEM	Ultrasonication for 12 h	Observed the stable suspension after 12 h
Peng et al. [45]	CNT's	R113+oil VG68 mixture	1, 3 and 5 wt% of CNT nanolubricant mixed with R113	TEM	Ultrasonication for 120 min	Stable dispersion was found
Bobbo et al. [46]	SWCNH's and TiO_2	R134a+POE oil	SWCNH's–100 nm and TiO_2–21 nm 0.5 g/L	TEM for SWCNH's	Ultrasonic vibration for 45 min	No discussion On stability
Kedzierski [47]	Al_2O_3	R134a (with polyolester)	5.6% in polyolester, 0.5, 1, and 2 mass% of suspension with R134a, size: 20 nm	Light scattering technique	Surfactant and ultrasonication for 24 h	Particles dispersed properly with avg size 10 nm

Table 1: Continued.

Authors	Nanoparticles and refrigerants		Parameters	Characterization	Method of stabilization	Inferences
Peng et al. [32]	Cu	R113+oil VG68	Size: 20, 50, and 80 nm, 0-5 wt% of suspension	TEM	Ultrasonication for 1 h	Stable dispersion was ensured
Peng et al. [48]	Cu	R113	0.1, 0.5, and 1.0 wt% in R113, avg size: 20 nm.	TEM, Spectro-photometer	Surfactants: SDS, CTAB, and Span-80 and ultrasonication for 1 h	Found stable for 24 h
Peng et al. [49]	Cu, Al, Al_2O_3, and CuO	R113, R141b, and n-pentane+RB68EP oil	0.2–1.37 vol%, size: 20 nm	TEM	No surfactants	No discussion on stability
Bi et al. [10]	TiO_2	R600a	0.1 and 0.5 g/L	Light transmission ratio index	—	Stable suspension
Abdel-Hadi et al. [50]	CuO	R134a	Size: 15-70 nm 0.1–1%	—	Mixed by gravity effect	Flow boiling study
Mahbubul et al. [51]	TiO_2	R123	Up to 5 vol% avg size: 21 nm	Not mentioned	No surfactants	Flow analysis
Subramani et al. [52]	Al_2O_3	R134a	0.06 mass% of nanolubricant avg size: 50 nm	Not mentioned	Ultrasonic agitation for 24 h	Stable dispersion for 3 days
Kumar et al. [53]	Al_2O_3	R134a+PAG oil	0.2% concentration, size: 40-50 nm	Not mentioned	Magnetic stirrer for mixing and ultrasonic shake for 30 min	Ensured stable dispersion
Hu et al. [54]	Cu	R113+oil VG68	Nanolubricant; 1,3, and 5 wt%, surfactant; 0-10,000 ppm	TEM	Surfactants: SDS, CTAB, and Span-80 and ultrasonication for 1 h	Stable for 24 h
Mahbubul et al. [16, 22]	Al_2O_3	R141b	Size: 13 nm 0.5, 1, 1.5, and 2 vol%	TEM	Orbital incubator shaking for 24 h at 240 rpm	Stable suspension was ensured
Sun et al. [55, 56]	Cu, Al, Al_2O_3, and CuO	R141b	0.1, 0.2, and 0.3 wt% in R141b, avg size: 40 nm	Visible spectro-photometer	Surfactant: Span-80 and ultrasonic shaking for 30 min	Dispersion was stable
Tang et al. [57]	δ-Al_2O_3	R141b	0.001, 0.01, and 0.1 vol%	SEM	Surfactant: SDBS and ultrasonication for 10 h	Predicted to be stable for 54 days
Nephon et al. [30]	TiO_2	R141b	0.01, 0.025, 0.05, and 0.075 vol%, avg. size: 21 nm	Not mentioned	Ultrasonication for 3 h	Synthesized just before experiments and found stable
Baqeri et al. [58]	CuO	R600a/POE	0.5, 1, 1.5, 2, and 5 wt%	—	Ultrasonic shaking	Found stable for 12 h
Mahbubul et al. [59]	Al_2O_3	R141b	Size: 13 nm 0.05–0.15 vol%	SEM, TEM	Mechanical shaking for 24 h at 240 rpm	Proper dispersion of particles
Akhavan-Behabadi et al. [60, 61]	CuO	R600a+(oil RL68H)	0.5, 1, and 1.5 wt%, avg size: 50 nm	Not mentioned	Ultrasonic shaking for 1 h	Visually ensured stable dispersion

Table 1: Continued.

Authors	Nanoparticles and refrigerants		Parameters	Characterization	Method of stabilization	Inferences
Diao, et al. [27]	Cu	R141b	0.008, 0.015, and 0.05 vol% avg size: 30 nm	SEM	SDBS and ultrasonic shaking for 8 h	Obtained stabilized suspension
Yang et al. [62]	MWCNT's	R141b	0.1, 0.2, and 0.3 wt%	Visible spectro-photometer	Surfactant: Span-80 and ultrasonic shaking for 30 min	Stable dispersion was found
Kedzierski et al. [63]	Al_2O_3	R134a (with polyolester)	1.6, 2.3, and 5.1 vol% in polyolester, 0.5 and 1 mass% in R134a	Dynamic light scattering technique	Surfactant and ultrasonication for 24 h	Particles dispersed properly with avg size 10 nm
Alawi et al. [64]	TiO_2	R123	0.5-2 vol% size: 20 nm	—	—	Flow boiling study

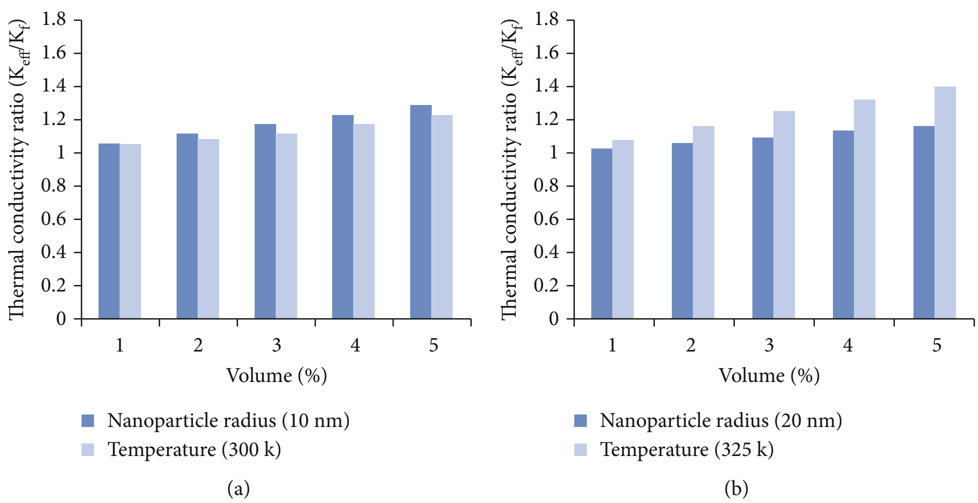

Figure 2: Thermal conductivity variation with particle size and temperature [17].

volume fraction of nanoparticles (SiO_2, Al_2O_3, and CNTs) up to 1% in the base fluid does not provided any enhancement in the thermal conductivity of the fluid, which is contradicting with the results of other researchers [18, 22]. Lamas et al. [73] analyzed various methods predicting effective thermal conductivity of nanofluids and observed the significant differences between the models.

The research outcomes reported by Gu et al. [19] in 2013 are analogous to Nasiri et al. [18], and they have conducted experiments with three types of nanofillers to examine their contribution in thermal conductivity enhancements of water. They found out that at the same volume fraction of 0.2%, thermal conductivity enhancement is 12.1% for silver nanofluids, 2.7% for copper nanofluids, and 3.7% for CNT's based nanofluids. They claimed that thermal conductivity enhancement of nanofluids not depends only on thermal conductivity of nanoparticles; further, the shape of the nanoparticles has influence on it. It is proposed that the enhancement in thermal conductivity of nanofluids is due to effective heat transport through the chain-like aggregates of nanoparticles formed in the nanofluids. They reported a greater enhancement of thermal conductivity for silver nanofluids even though silver particles are having thermal conductivity (~429 W/m·K) lesser than CNT's (~2000 W/m·K) and proposed that the enhancement also depends on the shape of the nanoparticles as proposed in earlier studies [23, 44].

In 2013, Mahbubul et al. [22] studied the thermal conductivity variations of Al2O3/R141b nanorefrigerant with nanoparticles' concentration and temperature. They reported that the thermal conductivity enhancement in nanorefrigerants depends on the type of nanoparticles present in the refrigerant and type of refrigerants. Increase in the temperature intensified the Brownian motion, which further rises micro convection in heat transport, according to the researchers. They similarly observed the trend of thermal conductivity variation with particle volume fraction and temperature as obtained by Alawi and Sidik [2]. Thermal conductivity of 0.5, 1.0, 1.5, and 2.0% volume fractions of Al_2O_3/R141b nanorefrigerant was measured and compared with similar research results. It was reported that the increase in thermal conductivity with Al_2O_3/R141b nanorefrigerant is higher than that of Al2O3/R113 nanorefrigerant. The difference is due to thermal conductivity difference between R113 (0.067223 W/m·K) and R141b (0.089447 W/m·K) at 30°C.

Nikkam et al. [74] experimentally investigated the base liquid effect on thermal conductivity enhancement with SiC nanoparticles. Three weight fractions of α-SiC nanoparticles of 3, 6, and 9% are mixed separately with distilled water, at first. It was electrostatically stabilized to a pH value of 9.5 for all nanofluids. The maximum increase in thermal conductivity (15.2%) of nanofluids compare to the pure distilled water is obtained with 9 wt% of α-SiC nanoparticles at 20°C and minimum enhancement of 1% in thermal conductivity with 3 wt% of α-SiC nanoparticles at the same temperature. The same three fractions are mixed with distilled water/ethylene glycol mixture (50 : 44.5 by vol%), and a maximum enhancement in their thermal conductivity is obtained as 20% with 9 wt% of α-SiC nanoparticles at 20°C. They observed that more nanoparticles loaded in the base liquids generally increase the thermal conductivity of it. From their studies, it is clearly inferred that SiC nanofluid with distilled water/ethylene glycol as base liquid has nearly 5% greater enhancement in thermal conductivity than water as the base liquid.

Jiang et al. [75] experimentally proved that the nanoparticles' concentration has significant role on effective thermal conductivity of nanorefrigerants over its temperature and hydrodynamic size. The authors performed experimental studies on R141b refrigerant with oxides of aluminum, titanium, and silicon nanoparticles; the authors developed five different statistical models, and the experimental results were used both for training the models and its testing. The authors suggested radial basis function (RBF) model for close prediction of thermal conductivities of nano-based refrigerants.

3.2. Viscosity. In 2008, Bi et al. [9] performed experiments to examine the potential applications of TiO_2 nanoparticles in a domestic refrigerator with R134a refrigerant. They observed with enhanced performance of the R134a refrigerator with the nanoparticles added in the mineral oil. They predicted that the improved frictional characteristic in the compressor was one of the reasons for the enhanced performance of the refrigerator system. From their studies, it is made clear that the nanoparticles would certainly alter the viscosity of the base fluid. Studies on viscosity of nanolubricant in refrigeration systems or nanorefrigerants are limited in the literature relative to the studies on thermal conductivity. Nevertheless, the pressure drops across the heat transfer region, and hence, the pumping power losses are significant criteria which depend on the viscosity of the fluids. The following section presents various studies about the viscosity of nanorefrigerants.

Mahbubul et al. [51] studied the viscosity of R123 with TiO_2 nanoparticles of five different volume concentrations. They observed a linear increment in the refrigerant viscosity with the increase in the nanoparticle volume concentration. Sabareesh et al. [76], in their experimental investigation, analyzed the viscosity effect on the compressor work in a vapor compression refrigeration system. The variation of lubricant oil viscosity with added TiO_2 nanoparticles at different working temperatures is captured from their studies, and the trend is shown in Figure 3. The authors reported that for 0.01% by volume of nanoparticles in the mineral oil, the average reduction in the compressor work was 11%. They proposed that adding optimal volume of nanoparticles in the lubricant would increase the viscosity and minimize the power consumption of the system by improving the friction characteristics of the compressor. Additionally, any further increase would result with agglomeration of the nanoparticles, according to the researchers.

Mahbubul et al. [16, 22] performed experimental investigation and numerical validations on the viscosity of Al_2O_3/R141b nanorefrigerant at variable concentration of nanoparticles and temperatures. For their work, Al_2O_3 nanoparticles of average size 13 nm at four different volume fractions of 0.5, 1.0, 1.5, and 2.0 were suspended separately in the refrigerant R141b. The authors reported that the viscosity of refrigerant increased with increasing volume fractions of nanoparticles, and the values are matched with the Brinkman model as given in Equation (4). Also, viscosity of nanorefrigerant was found reduced with increase in temperature, which is due to intensified Brownian motion with the increase of temperature of the nanorefrigerant, according to the researchers. Further investigation on how these phenomena influence the performance of a nanorefrigerant in the systems was carried out in their later studies [17]. Their analysis on the viscosity of Al_2O_3/R134a nanorefrigerant remains similar to other observations [2, 32, 77].

$$\mu_{\mathrm{r.n}} = \mu_{\mathrm{r}} \left(\frac{1}{(1-\varnothing)^{2.5}} \right), \quad (4)$$

where $\mu_{\mathrm{r,n}}$ and μ_r are the viscosities of nanorefrigerant and pure refrigerant, respectively. $\varnothing$ is the volume fraction of particles in the refrigerant.

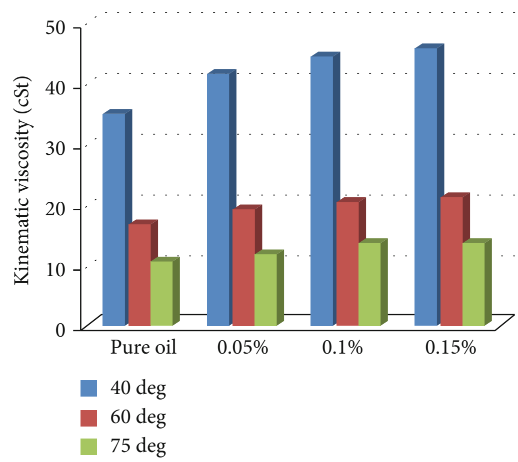

Figure 3: Variation of viscosity of mineral oil with added nanoparticles [76].

3.3. Studies on Other Properties. Very few studies have been carried out on properties like surface tension, density, and pressure drop characteristics. No specific studies were found on latent heat of nanorefrigerant in the literature. These properties are also expected to have significant influence in controlling the performance of the nanorefrigerants in the systems like thermal conductivity and viscosity. Nevertheless, the quantum of investigations on these properties from the literature is considered not to be sufficient to have a common conclusion about the influence of them on the nanorefrigerant heat transfer characteristics. Thermal conductivity of nanoparticles is not the only reason which controls the thermal performance of the refrigerant in which it is added [19]. Addition of nanoparticles to refrigerant will increase its viscosity, and furthermore, the nanorefrigerant would experience a pressure drop during its flow across the evaporator region [64]. Hence, the optimum value for nanoparticles in the nanorefrigerant has to be formulated. Rheological studies of Al_2O_3 nanoparticles with R141b refrigerant by Mahbubul et al. [59] showed that the nanorefrigerant exhibits near Newtonian behavior at high shear rates which is advantageous in practical conditions since the compressor in the HVAC-R systems would ensure a high shear rate for the nanorefrigerants and prevents the agglomeration of nanoparticles. In a similar study carried out by Madhesh et al. [78] on water based nanofluids, the concentration of hybrid nanoparticles of Cu-TiO_2 was found to play a vital role in the friction factor and hence the pressure drop of the nanofluid. They claimed that the viscous drag effects and the density gradient at high volume fraction (say at 2 vol%) of hybrid nanoparticles increased the friction factor, hence the pressure drop of nanorefrigerant during its flow. Despite the pumping power loss inferred due to the hybrid nanoparticles in the refrigerant, appreciable heat transfer characteristics were found with the Cu-TiO_2 nanoparticles by the researchers.

Khaleduzzaman et al. [79] could represent collectively the influence of particles concentration, temperature, and surfactants on the surface tension of nanofluids together. They showed that increasing nanoparticles concentration increased the surface tension of nanofluids, while increase in the temperature of nanofluids and surfactants volume resulted in the reduction of surface tension of the nanofluids. More studies on the surface tension of nanorefrigerants are to be carried out to understand its influence on the thermal performance of refrigerants with nanoparticles. Similar studies [16, 17, 77, 80] related to pressure drop, density, and specific heat of nanorefrigerants available in the literature cleared that the nanoparticles seeded in refrigerants alter the properties of it. However, to elucidate the sequence of physical mechanisms behind the enhanced thermal performance of nanorefrigerants, it is necessary to desperately carry out much more experiments for the same combination of refrigerant-nanoparticles.

Zhelency et al. [81] have performed experiments in R600a refrigerant with Al_2O_3 and TiO_2 nanoparticles to determine the density, viscosity, and capillary constants for the nano-based refrigerants. The authors found that the addition of nanoparticles considerably increased the pseudocritical temperature and pseudocritical density of the refrigerants; nonetheless, the particles tend to reduce the surface tension of the refrigerants.

4. Pool Boiling

Kedzierski et al. [25] performed experiments to identify the effects of CuO nanolubricants on the heat transfer performance of R134a refrigerant under pool boiling conditions. They results found with remarkable are as follows: for a constant heat flux, the pure lubricant (RL68H) added with the refrigerant degrades the heat transfer coefficient of the refrigerant. The possible reason behind this degradation is being the reduction of bubble sizes, and hence, it is accompanied with less vapor generation. Also, addition of CuO nanoparticles enhanced the heat transfer coefficient of the refrigerant mixture (R134a/RL68H) as can be witnessed from Table 2. The prediction for this enhancement is attributed to the fact that boiling induces the nanoparticles to move to the heat transfer surface and their stable suspension in to a layer called lubricant excess layer, predicted by Kidzierski [82]. Also, the accumulation of the induced nanoparticles in the lubricant excess layer may agglomerate and function like a porous surface, in enhancing the boiling heat transfer coefficient, according to the researchers. Similar observations were made by Kedzierski [47] with Al_2O_3 nanoparticles.

Peng et al. [26] examined the influence of diamond nanoparticles on the nucleate pool boiling heat transfer characteristics of R113/VG68, refrigerant/oil mixture. Their work showed that the three lubricant oil concentrations of 1 wt%, 3 wt%, and 5 wt% in refrigerant R113 resulted with a reduced nucleate pool boiling heat transfer coefficient compare to that of the pure refrigerant R113. For 3 wt% and 5 wt% of oil concentration, the heat transfer coefficient decreases by 14.4% and 19.8%, respectively, at an average from the value for pure R113. The possible reasons enumerated by the researchers for the trend of decreasing heat transfer coefficient with the increase in the oil concentration are reduced bubble growth due to increased viscosity, increased surface tension, and accumulation of oil molecules at the surface forcing refrigerant to diffuse through the layer. Conversely, at any fixed concentration of nano/oil mixture in R113, the nucleate pool boiling heat transfer coefficient of the refrigerant was found increased with increase in nanoparticles concentration in the oil as 5 wt%, 10 wt%, and 15 wt%. Enhancement of nucleate pool boiling heat transfer coefficient due to nanoparticles addition was attributed to the increased thermal conductivity of the nano/oil/R113 mixture compare to the pure R113, which furthermore reduces the degree of superheat of the bubble growth. More the nanoparticles, more the interactions between bubbles and nanoparticles and leads to an enhanced heat transfer coefficient for the nano/oil/R113 mixture, according to the researchers. These effects of nanolubricating oil on the pool boiling heat transfer coefficient of R113 remain unchanged even for Cu-VG68 nanolubricants [32] and CNT's based nanolubricants [45].

Diao et al. [27] investigated the pool boiling characteristics of Cu-R141b nanorefrigerant with SDBS surfactants at atmospheric pressure, experimentally. Their experimental results showed that the surfactants, added with R141b refrigerant, certainly enhanced the boiling heat transfer coefficient of the refrigerant. According to the researchers, surfactants reduced surface tension of the refrigerant, which consequently increased the active bubble nucleation sites; it is attributed to the fact of enhanced pool boiling heat transfer coefficient of R141b. Furthermore, adding nanoparticles in the solution of R141b-SDBS deteriorated the enhancement in the boiling heat transfer coefficient, for which the authors quoted the reasons proposed by Peng et al. [48]. They proposed that the interaction between nanoparticles and surfactants not favored the reduction in the surface tension. Also, the nanoparticles deposition on the heating surface made more interactions between the surface and the particles, which developed thermal resistance for the heat transfer phenomenon. For these factors, the nanoparticles showed a

Table 2: Enhancement of heat transfer coefficient of R134a suspended with CuO nanoparticles in lubricant [42].

Mass flux ($kg/m^2{\cdot}s$)	Pool boiling heat transfer coefficient of R-134a ($kW/m^2{\cdot}K$)	
	1% pure lubricant	1% CuO (nanolubricant)
125	0.428	0.65
152	0.572	0.848
177	0.506	0.752
191	0.554	0.878
204	0.548	0.782
224	0.632	0.938
250	0.602	1.082
261	0.524	0.956
280	0.662	1.052
300	0.71	1.004
331	0.758	1.184
350	0.818	1.382
367	0.836	1.262
387	0.89	1.322

Table 3: Reduction of wall superheat in R141b system with nanoparticles addition at experimental heat flux values [27].

Experimental heat flux ($*10^4$ W/m^2)	Degree of superheat (K) Pure R141b	R141b 0.008% Cu particles	R141b+Cu+SDBS
2.7	14	12.8	12.3
5.3	15.3	13.6	12.8
8.2	15.8	14.4	13.6
11.6	17	15.2	14.3
14.9	18	16	14.8
17.8	18.8	16.7	15.7
20.5	19.3	17	16.2
22.9	20.2	17.2	16.7

reduce enhancement in the boiling heat transfer coefficient of R141b compare to that of the enhancement provided by SDBS surfactants to R141b. Table 3 shows the distinguished values of wall superheat variation at different heat flux values, for pure R-141b, R141b-Cu solution, and R141b-SDBS-Cu nanorefrigerant.

Naphon et al. [30] have experimentally studied the pool boiling heat transfer characteristics of R141b refrigerant with TiO_2 nanoparticles at different pressures. At constant heat flux value, increasing nanoparticles concentration in R-141b was visually observed with reduction in the bubbles' size. This phenomenon resulted in reduction of pool boiling heat transfer coefficient of R-141b with TiO_2 nanoparticles. Their claim is contradicting with the results of other type of nanorefrigerants [25, 26]. The clear physical mechanism behind this reduction is to be elucidated. Their observations included that increasing pressure of the pool boiling tests from 50 to 150 kPa could have increased the heat transfer coefficient of the refrigerant provided nanoparticles' type and fractions in the mixture being immaterial.

In 2013, Hu et al. [54] analyzed the effects of surfactant types, surfactant concentration, nanolubricant concentration, and heat flux on the nucleate pool boiling heat transfer coefficient of R113 refrigerant. Their investigation on R113 involved with Cu nanoparticles, VG68 lubricant oil, and three different surfactants, and each one is from anionic, cationic, and nonionic group, namely, SDS, CTAB, and Span-80, respectively. The surfactants of up to 5000 ppm in the refrigerant/nanoparticles mixture enhance the heat transfer coefficient, which is mainly due to reduction in surface tension of the mixture and increased secondary nucleation sites. Figure 4 shows the heat transfer enhancement of R113 with Cu nanoparticles of 1 wt% directly seeded in the refrigerant and Cu nanolubricant of 1 wt% mixed with the refrigerant. As witnessed from the figure, particles suspended in lubricant might ensure stable suspension and cause increasing surface tension, which could be attributed to the trend of increase in the heat transfer coefficient than the other cases.

Any further increase in the surfactants' concentration deteriorates the nucleate pool boiling heat transfer coefficient of refrigerant/nanoparticles mixture; above 5000 ppm, the presence of surfactants was considered to be the reason for increased viscosity of the mixture and reduced interactions between nanoparticles and heating surface. The magnitude of enhancement in the heat transfer coefficient of R113/Cu-VG68 mixture depends on the type of surfactants. For a definite mass fraction of nanolubricant in R113, the maximum enhancement was observed with SDS surfactants and the minimum enhancement with Span-80 surfactants. The optimum value of surfactants which provides maximum enhancement for the pool boiling heat transfer coefficient of R113/nanolubricant increased with increase in the nanolubricant concentration in the mixture. Also, they concluded that increasing the nanolubricant concentration reduces the heat transfer coefficient enhancement for the mixture R113/Cu-VG68, which is analogous to the results already presented [32].

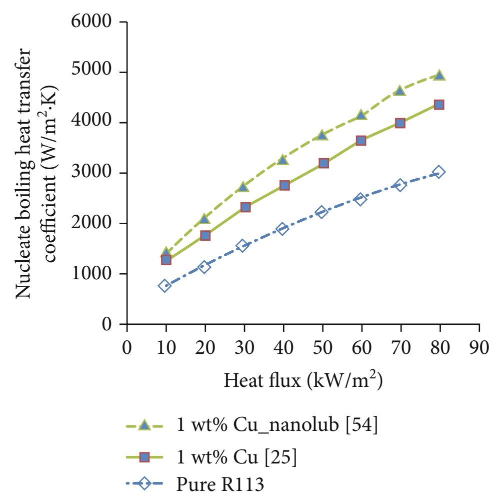

Figure 4: Nucleate boiling heat transfer characteristics of nano-based R113.

Tang et al. [57] have made experimental outcomes about the influence of δ-Al_2O_3 nanoparticles along with the SDBS surfactants on the nucleate pool boiling heat transfer characteristics of refrigerant, R141b. They found out that at low volume fraction of δ-Al_2O_3 nanoparticles, say 0.001 vol% in the mixture of R-141b/δ-Al_2O_3/SDBS, increasing the surfactants resulted with reduction in the enhancement of pool boiling heat transfer coefficient of R-141b; while at 0.1 vol% of nanoparticles, increasing surfactants in the mixture of R-141b/δ-Al_2O_3/SDBS favors in increasing the enhancement of heat transfer coefficient. At 0.01 vol% of δ-Al_2O_3

nanoparticles, increase in surfactants increased the heat transfer coefficient compare to that of the pure refrigerant. They strongly believed that at low volume fractions of nanoparticles, the enhanced boiling performance of R-141b is suppressed by the addition of surfactants. Nevertheless, at 0.01 vol% and 0.1 vol%, the presence of surfactants avoids agglomeration of nanoparticles, which was conformed to the study of the boiling surface. Henceforth, surfactants ensured an enhanced pool boiling heat transfer coefficient at these volume fractions.

In another study, Kedzierski [63] examined the influence of Al_2O_3/RL68H nanolubricant's concentration on boiling characteristics of R134a on a reentrant cavity surface. Their work showed that the boiling superheat for R134a with 0.5% mass fraction of RL68H oil was reduced by 0.1 K and 0.4 K at 30 kW/m^2 and 107 kW/m^2, respectively. Also, an increase in the oil mass fraction to 1% in the R134a/RL68H mixture degraded the boiling heat transfer of R134a further, similar to the observations reported by other researchers [26, 54]. The critical inference from the experiments is that addition of 0.5% mass of Al_2O_3 nanoparticles in R134a/RL68H mixture provided better heat transfer performance for R134a, compare to the performance of pure R134a and R134a/RL68H mixture. Also, it was reported that any further increment in the mass fraction of nanoparticles did not improve the heat transfer performance of nanorefrigerant by the researcher. It was agreed that more the nanoparticles addition with refrigerant, more the agglomeration in the lubricant excess layer which further reduced the enhancement in the boiling performance of the refrigerant as suggested by Kedzierski [83]. In this experimental study, an acoustic transducer was fixed to prevent visual agglomeration of Al_2O_3 nanoparticles in the lubricant excess layer and could obtain with an improved boiling heat transfer. The lubricant oils present in the refrigeration systems favor to form nanoaggregates exclusively in the adsorption layer, where more concentration of oil can be found [84].

Umesh et al. [85], in 2015, produced experimental characterization on the nucleate pool boiling heat transfer coefficient of pentane with CuO nanoparticles and SDBS surfactant on enhanced surfaces. Their work related to the effect of nanoparticles on the boiling heat transfer characteristics of pentane showed that the heat transfer coefficient of pentane-CuO was enhanced compare to that of the pure pentane, and this enhancement reduced with increase in the volume fraction of nanoparticles in pentane from 0.005% to 0.01%. They proposed that 0.005% volume fraction of CuO nanoparticles in pentane suspended uniformly and agitated the fluid to have enhanced heat transfer performance. They observed with CuO nanoparticles settling on the cavities of the surface and quoted that the increased surface wettability and reduced of some micronucleation sites for being the reason of degradation in the heat transfer coefficient of pentane as proposed by Kim et al. [86].

Eid et al. [87] conducted pool boiling studies of R141b refrigerant with alumina nanoparticles on a flat heater surface of circular cross section at different heat flux values ranging from 13 kW/m^2 to 145 kW/m^2, 6 different concentrations of alumina particles, and 3 different normalized pressures. The authors observed that the surface roughness plays a significant role on the boiling characteristics of the refrigerant, and they witnessed an enhancement of 124% in the pool boiling heat transfer coefficient at the heater surface roughness of 2.87 microns, with 0.05% of alumina particles.

Zendehboudi and Tatar [88] developed RBF neural network model to predict the nucleate pool boiling heat transfer coefficient and the nanoparticles' impact alone on the heat transfer of nanorefrigerant. For this purpose of model development, the authors done exhaustive data collection for training and for testing as well, and the authors could predict the intended parameters so accurately. The RBF model is a kind of artificial neural network model that comprises an input, an output, and a hidden layer. The input parameters are fed in the input layer, and in the hidden layer, the optimization is being carried out based on Euclidian distance calculations (genetic algorithm is used in their work), and the predicted output can be obtained from the output layer.

5. Flow Boiling

The flow boiling heat transfer characteristics of refrigerants play a significant role to have efficient heat transfer at evaporator/condenser region in RAC systems, which further optimizes the direct and indirect energy consumption of these systems. Established results claim that nanoscale particles when added with refrigerants enhance the boiling heat transfer coefficient during its flow along with refrigerant in the evaporator region. Contradictorily, Henderson et al. [34] reported with a noticeable decrease in heat transfer coefficient of R134a when added with SiO_2 nanoparticles and believed that the degradation might be due to their difficulties in obtaining stable dispersion of nanoparticles in refrigerant. Considerable research shows that nanoparticles can improve the heat transfer performance of refrigeration or air-conditioning systems, positively [10, 50, 52]. The augmentation of heat transfer coefficient varies between researches, and it may be attributed to the differences in environment, types of particles and refrigerants, and instruments. Furthermore, it can be observed from the research that the enhancement of flow boiling heat transfer coefficient of refrigerant due to addition of nanoparticles strongly depends on vapor quality, mass flux, heat flux, and initial nanoparticles' concentration. In this section, the influence of all the aforementioned parameters on the enhancement of flow boiling heat transfer coefficient of refrigerants will be presented based on the obtained research results from the literature.

Peng et al. [33] found based on their experimental work that the flow boiling heat transfer coefficient of R113 can be enhanced to a maximum value of 29.7% using copper oxide nanoparticles. Their results showed that this enhancement of local heat transfer coefficient of R113 is more at higher vapor qualities ($x = 0.7, 0.8$) than at lower vapor qualities ($x = 0.3, 0.4$). The flow nature of refrigerant changes with vapor quality, and it is attributed to the variation in the heat transfer coefficient enhancement by the researchers. Also, it is found from their work that the enhancement in the heat transfer coefficient of CuO/R113 nanorefrigerant compare to the pure refrigerant is more at lower mass flux than the enhancement obtained at higher mass flux. Their investigation clearly shows that for the mass fraction of 0.5 wt% of CuO nanoparticles in R113, the enhancement of boiling heat transfer coefficient at 100 $kgm^{-2}{\cdot}s^{-1}$ of mass flux is 29.7% while this enhancement at 200 $kgm^{-2}{\cdot}s^{-1}$ of mass flux is 25.6% for the same mass fraction of nanoparticles. The mechanism behind the influence of mass flux on the enhancement in flow boiling heat transfer coefficient of nanorefrigerant is not explained. Their research never failed to show the effect of nanoparticles' concentration on the flow boiling heat transfer coefficient of nanorefrigerant. They showed that increase in the mass fraction of nanoparticles in the refrigerant would increase the flow boiling heat transfer coefficient of the nanorefrigerant compare to the pure refrigerant. The presence of nanoparticles in refrigerant during its flow happens to disturb and reduce the boundary layer in the evaporator region, being the reason for enhancing the flow boiling heat transfer, according to the researchers.

Henderson et al. [34], in 2010, experimentally investigated the effect of SiO_2 nanoparticles on the flow boiling heat transfer coefficient of R-134a refrigerant. They reported that direct dispersion of SiO_2 nanoparticles in R134a without any surface activators deteriorated the heat transfer performance of the refrigerant during its flow in the evaporator test section. Their observation concluded that from the SiO_2/R134a nanorefrigerant mixture, the nanoparticles could settle down without the aid of surface activators to form a layer of agglomerated particles, which subsequently increase the resistance to heat transfer. Nevertheless, with CuO nanoparticles and POE oil, the flow boiling heat transfer performance of R134a seemingly improved. They reported that 0.04% and 0.08% volume fractions of CuO nanoparticles in the mixture of CuO/R134a/POE oil enhanced the flow boiling heat transfer coefficient of R134a as much as 82% and 101%, respectively, compared to that of pure refrigerant. The clear physical mechanism behind this enhancement is not explained, except reasoning an increase in thermal conductivity of the nanorefrigerant than that of the pure refrigerant.

Sun et al. [55], in 2013, experimentally examined the heat transfer performance of four nanorefrigerants during its flow inside an internal threaded copper tube. The four nanoparticles Cu, CuO, Al, and Al_2O_3 are added with refrigerant R141b at different mass fractions, varying the range of vapor qualities from 0.3 to 0.8 and at different mass fluxes. They showed that at a fixed mass flow rate of nanorefrigerant in the copper tube, the flow boiling heat transfer coefficient of nanorefrigerant increases with increase in the mass fraction of nanoparticles. This is analogous with the experimental observations made by others [33, 77]. Additionally, increase in the mass flux from 120 $kgm^{-2}{\cdot}s^{-1}$ to 330 $kgm^{-2}{\cdot}s^{-1}$, resulted in decreasing the heat transfer enhancement of nanorefrigerant for the same mass fraction of nanoparticles also found from their experiments. The reduction in the enhancement of flow boiling heat transfer coefficient of nanorefrigerant at high mass flux is attributed to the effect of insufficient time of interaction of the nanorefrigerant with the heating wall. Nevertheless, the physical mechanism behind this nature is to be found. The influence of nanoparticles' mass fraction on the heat transfer coefficient of nanorefrigerant agrees with other research results [56, 60]. They claimed that the mass fraction of nanoparticles is having stronger effect in enhancing the heat transfer coefficient of a refrigerant compare to the effect produced by the types of metal or metal oxide particles on the enhancement.

In 2015, Akhavan-Behabadi et al. [61] conducted experiments to characterize the heat transfer performance of R600a with CuO nanoparticles and POE oil during the condensation process. They showed that the condensation heat transfer coefficient increases with mass flux and vapor quality. According to their claim, at high vapor quality, the enhancement of heat transfer coefficient decreases due to increased oil concentration towards the high vapor region. The oil with relatively higher viscosity increases the average viscosity of mixture in the high vapor quality region, which leads to decrease in the Reynolds number and hence the rate of convection heat transfer coefficient. To understand this effect, the dominant factor which influences the heat transfer rate with the variation of vapor quality is to be found and explained.

Mahbubul et al. [77] conducted an analysis on the flow boiling heat transfer performance of Al2O3-R141b nanorefrigerant for the experimental conditions of 100 $kgm^{-2}{\cdot}s^{-1}$ mass flux, 0.2–0.7 vapor qualities, at 25°C, and 0.078535 MPa pressure. The heat transfer performance of nanorefrigerant was investigated for 1 to 5 volume fraction of nanoparticles, and they concluded that the flow boiling heat transfer coefficient of nanorefrigerant increases with increase in the nanoparticles volume fraction, which agrees with the experimental observation made by Peng et al. [33]. The influence of vapor quality on the performance enhancement showed that the enhancement of flow boiling heat transfer coefficient at low vapor quality is higher than that of the enhancement at high vapor quality, with a trend of reduced enhancement at a medium vapor quality. Also, they estimated the frictional pressure drop during the flow boiling of refrigerant R141b with addition of nanoparticles. Their calculations showed that at 0.7 vapor quality, a pressure drop of 464.27 kPa is obtained with 5 vol% of nanoparticles in the nanorefrigerant mixture, while at a vapor quality of 0.2, the obtained value of pressure drops to 3.34 kPa for 1 vol% of nanoparticles. Their study cleared that the addition of nanoparticles in refrigerant will induce pressure drop during its flow in tubes as claimed by Alawi et al. [64] through their investigation. Intensified experiments have to be performed to be aware of the exact influence of fraction of nanoparticles on the pressure drop of nanorefrigerants compared to that of the pure refrigerants.

In a similar work, Yang et al. [89] experimentally studied the heat transfer behavior of R141b with four different nanoparticles (Cu, CuO, Al, and Al_2O_3) suspended in it during its flow in a smooth tube and in a threaded tube. Under different experimental flow flux conditions, the authors found that the suspended nanoparticles enhanced the heat transfer coefficient of the refrigerant in both flow conditions, and the enhancement is found to be larger with threaded tube. The addition of nanoscale particles in refrigerant in optimal volume fraction results improvement in its heat transfer coefficient whereas any further increment would cause reduction in the enhancement [75].

In a different study, Seo et al. [90] investigated the effects of nanoparticles' deposition on critical heat flux of refrigerant during its flow. Al_2O_3 based nanofluid was made to flow inside a boiling test section (600–650°C) at a rate of 3 cm/s. The boiling process induces coating of nanoparticles where the adhesion force is significant for the particles' deposition in the wall for prolonged time. Their established results claim that at constant mass flux of the refrigerant R113, the heat transfer coefficient is found increased with Al_2O_3 nanoparticles coated tube compare to that of the flow with bare tube. The Al_2O_3 nanoparticles deposited in the inner side of the tube (test section) increased the porosity, which further increases the wettability of the test (inner) surface with the refrigerant. This can be attributed to the enhanced flow boiling heat transfer coefficient of R113 with nanoparticles coated tube. During flow condition, the refrigerants form an annular region at low vapor qualities in the evaporator region, and the chance of augmenting the boiling heat transfer of the refrigerant falls a bit [91].

Dey and Mandal [91] developed mathematical models and henceforth optimized the nanoparticles addition and the flow pipe diameter to have enhancement in flow boiling heat transfer coefficient of refrigerant with minimum pressure drop during its flow in the evaporator. Lin et al. [92] performed experimental work to understand the migration of TiO_2 nanoparticles from the refrigerant-oil mixture to oil excess layers, during the dry-out condition of refrigerants in the evaporator region. The authors observed that the particles which migrate from refrigerant to oil during the dry out condition of the refrigerant will adhere to the oil-excess layer. The more the amount of oil mixed in refrigerant, the more the thickness of the excess layer and the more the migration tendency of particles in to the excess layers. However, lesser would be the particles' agglomeration in the layer, whereas the authors conclude that the particle migration in to oil layer reduced with increase in heat flux owing to more nucleate site formations under such conditions.

Deokar and Cremaschi [93] conducted flow boiling studies of R410A refrigerant/polyolester lubricant mixture with separately Al_2O_3 and ZnO nanoparticles. The authors found that the added two different nanoparticles on the lubricant, during its flow in the evaporator tube, got deposited sparingly. Henceforth, the heat transfer performance of R410A-nanolubricants is found to be reduced from that of the R410A-polyolester. The authors quoted the reason for such degradation of performance is mainly due to the diffusion of particles in the turbulent layer (as it gets deposited on the flow tube) and hence thickening the laminar sublayer as per the previous studies reported by Bigi and Cremaschi [94].

6. Reports on Size and Morphology

Harvesting the benefits of size dependent characteristics from nanoscale particles gives way for their industrial usage. Furthermore, the size of the particles and its morphology are considered to be significant to achieve their prolonged usage in industrial applications. At higher concentrations, exclusively the high aspect ratio nanoelements (nanorods/nanowires/nanotubes that possess large length to effective diameter ratio) would result very viscous nanofluid [95] and henceforth find less useful for cooling purpose. High aspect ratio nanoelements can easily be entangled when optimum fractions are not maintained in the dispersion, which could lead to agglomeration quickly, and this effect depends on the type of nanotubes too [19]. CNTs are found to have higher thermal conductivity than silver nanotubes; however, the easy entanglement nature of CNTs when dispersed in base fluids finds it less effective when compared to nanofluids containing silver nanotubes. Jeong et al. [23] have interestingly found that the near to rectangular shape Zinc oxide nanoparticles provided more viscous to the base fluid than their spherical counter parts. The inability of rectangular shape to rotate freely in the base fluid and further causing more resistance to flow property is attributed as the reason for viscous nature according to the authors. Not alone the concentration of particles, yet, the particle size also could significantly influence the viscosity of the nanofluids. Al_2O_3 particles of 47 nm average size could contribute more viscosity to the base fluid compared with the same particles of size 36 nm [24]. The larger particles could directly increase the intermolecular attractions and henceforth would pave way for increasing the viscous force. In a similar work, Peng et al. [32] found that copper nanoparticles of lesser in size contributed much enhancement for the heat transfer in the nucleate boiling regime, when compared with the same particles of larger in size. In general, the particles in reduced size would find its more interactions with the heater surface and favor more secondary nucleation sites at the surface, which could boost the heat transfer rate.

Apart from shape and size factors, it is equally significant to focus on the surface structures of nanoscale particles since it controls the performance of any engineering fluids/materials in applications. The morphology of nanostructured elements can be studied in electron and force probing microscopes. On the other kind, nanoparticles, owing to its agglomeration, might deposit on the heater surface which in further would change the morphology of the heating surface. Particle types directly can contribute for the morphological change of the surface and consequently, the bubble formation and departure mechanism, the perturbations in the running speed of fluid can be resulted. Furthermore, the morphological changes will cause poor heat transfer performance of the fluids. Yao and Teng [96] claim that the addition of nanoparticles in base fluid will alter the surface structure, raise the capillary force, increase the bubble departure, and favor quick replenishment of liquid molecules at the heater surface. The authors noted reduction in critical heat flux and boiling heat transfer rate of base fluids at higher concentration of nanoparticles; however, no clear suggestion was given about the concentration level. Kim et al. [97] explained the physics behind the increase in wettability of heating surface while nanoparticles are seeded in base fluids, with modified young's equation as given by

$$\cos\theta = \frac{(\gamma_{SV} - \gamma_{SL})}{\sigma} * r. \quad (5)$$

The contact angle of the wetting liquid molecule depends on adhesion tension ($\gamma_{SV} - \gamma_{SL}$), surface tension ($\sigma$), and the effective surface area ratio (r). The authors found that in the increasing adhesion tension, the effective contact area of the heater surface due to nanoparticle addition caused reduction in the contact angle, henceforth increasing the wettability of the surface to result increase in boiling heat transfer performance. In the similar fashion, Jaikumar et al. [98] proved that the surface irregularities of the heater created by the addition of graphene oxide nanoelements in the colloids improved its thermal conductivity. The authors postulated that the hysteresis aroused with the contact angles due to the particles addition would be the key mechanism behind the enhancement of boiling heat transfer characteristics of the base liquid.

7. Conclusion and Future Scope

The present study covers most of the works about the nanorefrigerants available in the literature. It is categorized to review the nanorefrigerants about the following: basic interactions between the particles and refrigerants, thermophysical properties, pool boiling mechanisms, and flow boiling studies. Nanorefrigerants are expected to have better performance in the systems with efficient energy consumption [99]. From the present study, the following concluding remarks are arrived.

(1) Performance of refrigeration systems can be enhanced using nanorefrigerants

(2) Metal nanoparticles like Al, Cu, Ti, and metal oxide nanoparticles of Al_2O_3, CuO, TiO_2, SiO_2, diamond nanoparticles, and CNTs are investigated for the thermal performance enhancement of refrigerants

(3) The influential parameters on the performance of nanorefrigerants include size, shape, and types of nanoparticles along with the mass and heat fluxes

(4) Increase in the mass fraction of nanoparticles and decreasing the lubricant concentration enhances the heat transfer performance but with an associated pressure drop in flow conditions

(5) Surfactants play a vital role in the stabile suspension of nanoparticles with refrigerant, an essential criterion to benefit the advantage of nanorefrigerants for long run

(6) Heat transfer characteristics of nanorefrigerants during pool boiling conditions can be used to depict the thermal performance of the nanorefrigerants in flow boiling conditions

(7) Morphology of the heating surface is found to be modified by the nanoscale particles, and it is attributed as the reason for the enhancement of thermophysical properties and heat flux nature of the nanofluids

The research about the mixture of nanoparticles in refrigerant has believed to have a potential future scope and the following points can be considered to progress further in this research field.

(1) More combination of studies involving metal and metal oxide nanoparticles in various refrigerants is needed to have common conclusion about the influence of various parameters on the performance of nanorefrigerants in the systems

(2) Many studies related to thermal conductivity and viscosity of nanorefrigerants are available in the literature, but the studies related to other thermophysical properties are not sufficient in numbers

(3) The exact physical mechanisms and their sequence during boiling of nanorefrigerants are not identified

(4) The pool boiling studies on the nanorefrigerants are to be correlated to its flow boiling with adequate parameters to have a better understanding about the flow characteristics in one variable

(5) Numerical investigations in proposing correlations to estimate the physical properties and heat transfer coefficients are to be extended further for a wide range of nanoparticles' volume fraction and various experimental conditions

(6) Simulation of nanorefrigerants flow process and mapping the flow regime across the evaporator region are to be carried out

(7) To make the existence of nanorefrigerants in the systems, studies related to long term stability, trade-off between the thermal performance enhancement, and the pumping power loss suitable nanoparticles to retrofit the existing refrigerants are to be carried out

(8) Studies on refrigerants used for systems operating other than vapor compression principle are less available in the literature

(9) Studies examining the potential of nanoparticles in the new generation refrigerants like HFO1234yf are to be carried out

(10) Limited studies are found with the particle morphological effects on the heat transfer characteristics of nanofluids, and the research gap needs to be addressed

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

"G.N. and V.T. were responsible with the conceptualization. F.M., T.M., and Y.K. were responsible with the methodology. G.N., V.T., and F.M. conducted the formal analysis. G.N. and V.T. were responsible with the investigation. N.M.A., S.A., and A.S.A. were responsible with the resources. G.N.

and V.T. contributed to the writing—original draft preparation. T.M., Y.K., S.A., N.M.A., and A.S.A. contributed to the writing—review and editing. T.M., Y.K., S.A., N.M.A., and A.S.A. were responsible with the project administration. T.M., Y.K., S.A., N.M.A., and A.S.A. were responsible with the funding acquisition. All authors have read and agreed to the published version of the manuscript."

Acknowledgments

The author extend his appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through research groups program under grant number (R.G.P 1/222/41).

References

[1] S. U. S. Choi and J. A. Eastman, "Enhancing Thermal Conductivity of Fluids with Nanoparticles," in *1995 International mechanical engineering congress and exhibition*, San Francisco, CA (United States), 1995.

[2] O. A. Alawi and N. A. C. Sidik, "Influence of particle concentration and temperature on the thermophysical properties of CuO/R134a nanorefrigerant," *International Communications in Heat and Mass Transfer*, vol. 58, pp. 79–84, 2014.

[3] X. Wang, X. Xu, and S. U. S. Choi, "Thermal conductivity of nanoparticle-fluid mixture," *Journal of Thermophysics and Heat Transfer*, vol. 13, no. 4, pp. 474–480, 1999.

[4] W. Yu and S. U. S. Choi, "The role of interfacial layers in the enhanced thermal conductivity of nanofluids: a renovated Maxwell model," *Journal of Nanoparticle Research*, vol. 5, no. 1/2, pp. 167–171, 2003.

[5] R. S. Khedkar, S. S. Sonawane, and K. L. Wasewar, "Influence of CuO nanoparticles in enhancing the thermal conductivity of water and monoethylene glycol based nanofluids," *International Communications in Heat and Mass Transfer*, vol. 39, no. 5, pp. 665–669, 2012.

[6] M. Ghanbarpour, E. B. Haghigi, and R. Khodabandeh, "Thermal properties and rheological behavior of water based Al2O3 nanofluid as a heat transfer fluid," *Experimental Thermal and Fluid Science*, vol. 53, pp. 227–235, 2014.

[7] C. Pang, J. W. Lee, and Y. T. Kang, "Review on combined heat and mass transfer characteristics in nanofluids," *International Journal of Thermal Sciences*, vol. 87, pp. 49–67, 2015.

[8] K. Wang, G. Ding, and W. Jiang, "Development of Nanorefrigerant and Its Rudiment Property," in *In Proceedings of the 8th International Symposium on Fluid Control, Measurement and Visualization*, Chengdu, China, 2005.

[9] S. Bi, L. Shi, and L. L. Zhang, "Application of nanoparticles in domestic refrigerators," *Applied Thermal Engineering*, vol. 28, no. 14-15, pp. 1834–1843, 2008.

[10] S. Bi, K. Guo, Z. Liu, and J. Wu, "Performance of a domestic refrigerator using TiO2-R600a nano-refrigerant as working fluid," *Energy Conversion and Management*, vol. 52, no. 1, pp. 733–737, 2011.

[11] O. A. Alawi, N. A. C. Sidik, and H. A. Mohammed, "A comprehensive review of fundamentals, preparation and applications of nanorefrigerants," *International Communications in Heat and Mass Transfer*, vol. 54, pp. 81–95, 2014.

[12] S. Rahman, S. Issa, Z. Said, M. El Haj Assad, R. Zadeh, and Y. Barani, "Performance enhancement of a solar powered air conditioning system using passive techniques and SWCNT /R-407c nano refrigerant," *Case Studies in Thermal Engineering*, vol. 16, p. 100565, 2019.

[13] G. Kosmadakis and P. Neofytou, "Investigating the performance and cost effects of nanorefrigerants in a low- temperature ORC unit for waste heat recovery," *Energy*, vol. 204, p. 117966, 2020.

[14] G. Kosmadakis and P. Neofytou, "Investigating the effect of nanorefrigerants on a heat pump performance and cost-effectiveness," *Thermal Science and Engineering Progress*, vol. 13, p. 100371, 2019.

[15] W. Jiang, G. Ding, H. Peng, Y. Gao, and K. Wang, "Experimental and model research on nanorefrigerant thermal conductivity," *HVAC&R Research*, vol. 15, pp. 651–669, 2009.

[16] I. M. Mahbubul, R. Saidur, and M. A. Amalina, "Thermal conductivity, viscosity and density of R141b refrigerant based nanofluid," *Procedia Engineering*, vol. 56, pp. 310–315, 2013.

[17] I. M. Mahbubul, S. A. Fadhilah, R. Saidur, K. Y. Leong, and M. A. Amalina, "Thermophysical properties and heat transfer performance of Al_2O_3/R-134a nanorefrigerants," *International Journal of Heat and Mass Transfer*, vol. 57, no. 1, pp. 100–108, 2013.

[18] A. Nasiri, M. Shariaty-Niasar, A. M. Rashidi, and R. Khodafarin, "Effect of CNT structures on thermal conductivity and stability of Nanofluid," *International Journal of Heat and Mass Transfer*, vol. 55, no. 5-6, pp. 1529–1535, 2012.

[19] B. Gu, B. Hou, Z. Lu, Z. Wang, and S. Chen, "Thermal conductivity of nanofluids containing high aspect ratio fillers," *International Journal of Heat and Mass Transfer*, vol. 64, pp. 108–114, 2013.

[20] A. Ghadimi and I. H. Metselaar, "The influence of surfactant and ultrasonic processing on improvement of stability, thermal conductivity and viscosity of titania nanofluid," *Experimental Thermal and Fluid Science*, vol. 51, pp. 1–9, 2013.

[21] R. X. Wang, B. Hao, G. Z. Xie, and H. Q. Li, "A refrigerating system using HFC134a and mineral lubricant appended with N-TiO2 (R) as working fluids," in *In Proceedings of the Proceedings of the 4th international symposium on HAVC*, Beijing, China, 2003.

[22] I. M. Mahbubul, R. Saidur, and M. A. Amalina, "Influence of particle concentration and temperature on thermal conductivity and viscosity of Al_2O_3/R141b nanorefrigerant," *International Communications in Heat and Mass Transfer*, vol. 43, pp. 100–104, 2013.

[23] J. Jeong, C. Li, Y. Kwon, J. Lee, S. H. Kim, and R. Yun, "Effet de forme de particules sur la viscosite et la conductivite thermique de nanofrigorigenes ZnO," *International Journal of Refrigeration*, vol. 36, no. 8, pp. 2233–2241, 2013.

[24] C. T. Nguyen, F. Desgranges, G. Roy et al., "Temperature and particle-size dependent viscosity data for water-based nanofluids–hysteresis phenomenon," *International journal of heat and fluid flow*, vol. 28, pp. 1492–1506, 2007.

[25] M. A. Kedzierski and M. Gong, "Effet de l'oxyde de cuivre utilise comme nanolubrifiant sur l'echange de chaleur lors de l'ebullition libre du R134a," *International Journal of Refrigeration*, vol. 32, no. 5, pp. 791–799, 2009.

[26] H. Peng, G. Ding, H. Hu, W. Jiang, D. Zhuang, and K. Wang, "Caracteristiques du transfert de chaleur lors de l'ebullition libre nucleee d'un melange frigorigene/huile aux nanoparticules de diamant," *International Journal of Refrigeration*, vol. 33, no. 2, pp. 347–358, 2010.

[27] Y. H. Diao, C. Z. Li, Y. H. Zhao, Y. Liu, and S. Wang, "Experimental investigation on the pool boiling characteristics and critical heat flux of cu-R141b nanorefrigerant under atmospheric pressure," *International Journal of Heat and Mass Transfer*, vol. 89, pp. 110–115, 2015.

[28] K. J. Park and D. Jung, "Boiling heat transfer enhancement with carbon nanotubes for refrigerants used in building air-conditioning," *Energy and Buildings*, vol. 39, no. 9, pp. 1061–1064, 2007.

[29] W. U. Xiao-Min, L. I. Peng, L. I. Hui, and W. Wei-Cheng, "Investigation of pool boiling heat transfer of R11 with TiO2 nanoparticle," *Journal of Engineering*, vol. 28, 2008.

[30] P. Naphon and C. Thongjing, "Pool boiling heat transfer characteristics of refrigerant-nanoparticle mixtures," *International Communications in Heat and Mass Transfer*, vol. 52, pp. 84–89, 2014.

[31] V. Trisaksri and S. Wongwises, "Nucleate pool boiling heat transfer of TiO_2-R141b nanofluids," *International Journal of Heat and Mass Transfer*, vol. 52, no. 5-6, pp. 1582–1588, 2009.

[32] H. Peng, G. Ding, H. Hu, and W. Jiang, "Effect of nanoparticle size on nucleate pool boiling heat transfer of refrigerant/oil mixture with nanoparticles," *International Journal of Heat and Mass Transfer*, vol. 54, no. 9-10, pp. 1839–1850, 2011.

[33] H. Peng, G. Ding, W. Jiang, H. Hu, and Y. Gao, "Caracteristiques du transfert de chaleur d'un frigorigene aux nanoparticules lors de l'ebullition en ecoulement a l'interieur d'un tube horizontal lisse," *International Journal of Refrigeration*, vol. 32, no. 6, pp. 1259–1270, 2009.

[34] K. Henderson, Y. G. Park, L. Liu, and A. M. Jacobi, "Flow-boiling heat transfer of R-134a-based nanofluids in a horizontal tube," *International Journal of Heat and Mass Transfer*, vol. 53, no. 5-6, pp. 944–951, 2010.

[35] Y. Li, S. Tung, E. Schneider, and S. Xi, "A review on development of nanofluid preparation and characterization," *Powder Technology*, vol. 196, pp. 89–101, 2009.

[36] A. Ghadimi, R. Saidur, and H. S. C. Metselaar, "A review of nanofluid stability properties and characterization in stationary conditions," *International Journal of Heat and Mass Transfer*, vol. 54, no. 17-18, pp. 4051–4068, 2011.

[37] W. Yu and H. Xie, "A review on nanofluids: preparation, stability mechanisms, and applications," *Journal of Nanomaterials*, vol. 2012, 17 pages, 2012.

[38] Z. Haddad, C. Abid, H. F. Oztop, and A. Mataoui, "A review on how the researchers prepare their nanofluids," *International Journal of Thermal Sciences*, vol. 76, pp. 168–189, 2014.

[39] A. Celen, A. Çebi, M. Aktas, O. Mahian, A. S. Dalkilic, and S. Wongwises, "Un passage en revue des nanofrigorigenes: caracteristiques d'ecoulement et applications," *International Journal of Refrigeration*, vol. 44, pp. 125–140, 2014.

[40] D.-W. Liu and C.-Y. Yang, "Effect of nano-particles on pool boiling heat transfer of refrigerant 141b," in *In Proceedings of the International Conference on Nanochannels, Microchannels, and Minichannels*, pp. 789–793, Puebla, Mexico, 2007.

[41] K. J. Park and D. Jung, "Enhancement of nucleate boiling heat transfer using carbon nanotubes," *International Journal of Heat and Mass Transfer*, vol. 50, no. 21-22, pp. 4499–4502, 2007.

[42] K. Bartelt, Y. Park, L. Liu, A. Jacobi, Y.-G. Park, and A. M. Jacobi, "Purdue E-Pubs Flow-boiling of R-134a/POE/CuO nanofluids in a horizontal tube," in *International Refrigeration and Air Conditioning Conference*, pp. 244–6534, Purdue University, 2008.

[43] G. Ding, H. Peng, W. Jiang, and Y. Gao, "Caracteristiques de la migration des nanoparticules lors de l'ebullition libre d'un nanofrigorigene et d'un melange nanofrigorigene/huile," *International Journal of Refrigeration*, vol. 32, no. 1, pp. 114–123, 2009.

[44] W. Jiang, G. Ding, and H. Peng, "Measurement and model on thermal conductivities of carbon nanotube nanorefrigerants," *International Journal of Thermal Sciences*, vol. 48, no. 6, pp. 1108–1115, 2009.

[45] H. Peng, G. Ding, H. Hu, and W. Jiang, "Influence of carbon nanotubes on nucleate Pool boiling heat transfer characteristics of refrigerant-oil mixture," *International Journal of Thermal Sciences*, vol. 49, no. 12, pp. 2428–2438, 2010.

[46] S. Bobbo, L. Fedele, M. Fabrizio, S. Barison, S. Battiston, and C. Pagura, "Influence de la dispersion des nanoparticules dans les huiles POE sur la lubricite et la solubilite de R134a," *International Journal of Refrigeration*, vol. 33, no. 6, pp. 1180–1186, 2010.

[47] M. A. Kedzierski, "L'effet du nanolubrifiant Al_2O_3 sur le transfert de chaleur lors de l'ebullition libre de R134a," *International Journal of Refrigeration*, vol. 34, no. 2, pp. 498–508, 2011.

[48] H. Peng, G. Ding, and H. Hu, "Effect of surfactant additives on nucleate pool boiling heat transfer of refrigerant-based nanofluid," *Experimental Thermal and Fluid Science*, vol. 35, no. 6, pp. 960–970, 2011.

[49] H. Peng, G. Ding, and H. Hu, "Influences de la composition et le chauffage d'un nanofluide sur la migration des nanoparticules lors de l'ebullition libre. Partie I : mesures experimentales," *International Journal of Refrigeration*, vol. 34, no. 8, pp. 1823–1832, 2011.

[50] E. A.-H. Abdel-Hadi, S. H. Taher, A. H. M. Torki, and S. S. Hamad, "Heat transfer analysis of vapor compression system using nano CuO-R134a," *Ipcsit*, vol. 15, pp. 80–84, 2011.

[51] I. M. Mahbubul, R. Saidur, and M. A. Amalina, "Pressure drop characteristics of TiO2–R123 nanorefrigerant in a circular tube," *Engineering E-Transaction*, vol. 6, pp. 124–130, 2011.

[52] N. Subramani and M. Prakash, "Experimental studies on a vapour compression system using nanorefrigerants," *International Journal of Engineering, Science and Technology*, vol. 3, pp. 95–102, 2012.

[53] D. S. Kumar and R. Elansezhian, "Experimental study on Al2O3-R134a nano refrigerant in refrigeration system," *International Journal of Modern Engineering Research*, vol. 2, pp. 3927–3929, 2012.

[54] H. Hu, H. Peng, and G. Ding, "Caracteristiques du transfert de chaleur lors de l'ebullition libre nucleee d'un melange frigorigene / nanolubrifiant contenant un agent tensio-actif," *International Journal of Refrigeration*, vol. 36, no. 3, pp. 1045–1055, 2013.

[55] B. Sun and D. Yang, "Experimental study on the heat transfer characteristics of nanorefrigerants in an internal thread copper tube," *International Journal of Heat and Mass Transfer*, vol. 64, pp. 559–566, 2013.

[56] B. Sun and D. Yang, "Caracteristiques du transfert de chaleur d'ecoulement en ebullition de nano- frigorigenes dans un tube horizontal," *International Journal of Refrigeration*, vol. 38, pp. 206–214, 2014.

[57] X. Tang, Y. H. Zhao, and Y. Diao, "Experimental investigation of the nucleate pool boiling heat transfer characteristics of δ-Al_2O_3-R141b nanofluids on a horizontal plate," *Experimental Thermal and Fluid Science*, vol. 52, pp. 88–96, 2014.

[58] S. Baqeri, M. A. Akhavan-Behabadi, and B. Ghadimi, "Experimental investigation of the forced convective boiling heat transfer of R-600a/oil/nanoparticle," *International Communications in Heat and Mass Transfer*, vol. 55, pp. 71–76, 2014.

[59] I. M. Mahbubul, S. S. Khaleduzzaman, R. Saidur, and M. A. Amalina, "Rheological behavior of Al_2O_3/R141b nanorefrigerant," *International Journal of Heat and Mass Transfer*, vol. 73, pp. 118–123, 2014.

[60] M. A. Akhavan-Behabadi, M. Nasr, and S. Baqeri, "Experimental investigation of flow boiling heat transfer of R-600a/oil/CuO in a plain horizontal tube," *Experimental Thermal and Fluid Science*, vol. 58, pp. 105–111, 2014.

[61] M. A. Akhavan-Behabadi, M. K. Sadoughi, M. Darzi, and M. Fakoor-Pakdaman, "Experimental study on heat transfer characteristics of R600a/POE/CuO nano- refrigerant flow condensation," *Experimental Thermal and Fluid Science*, vol. 66, pp. 46–52, 2015.

[62] D. Yang, B. Sun, H. Li, and X. Fan, "Etude experimentale sur le transfert de chaleur et les caracteristiques d'ecoulement de nanofrigorigenes a l'interieur d'un tube ondule," *International Journal of Refrigeration*, vol. 56, pp. 213–223, 2015.

[63] M. A. Kedzierski, "Effet de la concentration sur des melanges de R134a et de nanolubrifiant Al_2O_3 sur la surface d'une cavite de retour," *International Journal of Refrigeration*, vol. 49, pp. 36–48, 2015.

[64] O. A. Alawi, N. A. C. Sidik, and A. S. Kherbeet, "Measurements and correlations of frictional pressure drop of TiO2/R123 flow boiling inside a horizontal smooth tube," *International Communications in Heat and Mass Transfer*, vol. 61, pp. 42–48, 2015.

[65] Y. Xuan and Q. Li, "Heat transfer enhancement of nanofluids," *International Journal of Heat and Fluid Flow*, vol. 21, no. 1, pp. 58–64, 2000.

[66] Q. Li and Y. Xuan, "A preliminary analysis of the intensified thermal-conductivity mechanism of nano-fluids," *Journal of Engineering for Thermal Energy and Power*, vol. 17, pp. 568–571, 2002.

[67] H. Xie, M. Fujii, and X. Zhang, "Effect of interfacial nanolayer on the effective thermal conductivity of nanoparticle-fluid mixture," *International Journal of Heat and Mass Transfer*, vol. 48, no. 14, pp. 2926–2932, 2005.

[68] Q. Z. Xue, "Model for the effective thermal conductivity of carbon nanotube composites," *Nanotechnology*, vol. 17, no. 6, p. 1655, 2006.

[69] R. L. Hamilton and O. K. Crosser, "Thermal conductivity of heterogeneous two-component systems," *Chem. Fundam.*, vol. 1, no. 3, pp. 187–191, 1962.

[70] N. Pelević and T. H. Van Der Meer, "Numerical investigation of the effective thermal conductivity of nano-fluids using the lattice Boltzmann model," *International Journal of Thermal Sciences*, vol. 62, pp. 154–159, 2012.

[71] C. Sitprasert, P. Dechaumphai, and V. Juntasaro, "A thermal conductivity model for nanofluids including effect of the temperature-dependent interfacial layer," *Journal of Nanoparticle Research*, vol. 11, no. 6, pp. 1465–1476, 2009.

[72] R. Mondragón, C. Segarra, R. Martínez-Cuenca, J. E. Juliá, and J. C. Jarque, "Experimental characterization and modeling of thermophysical properties of nanofluids at high temperature conditions for heat transfer applications," *Powder Technology*, vol. 249, pp. 516–529, 2013.

[73] B. Lamas, B. Abreu, A. Fonseca, N. Martins, and M. Oliveira, "Critical analysis of the thermal conductivity models for CNT based nanofluids," *International Journal of Thermal Sciences*, vol. 78, pp. 65–76, 2014.

[74] N. Nikkam, E. B. Haghighi, M. Saleemi et al., "Experimental study on preparation and base liquid effect on thermo-physical and heat transport characteristics of α-SiC nanofluids," *International Communications in Heat and Mass Transfer*, vol. 55, pp. 38–44, 2014.

[75] F. Jiang, J. Zhu, and G. Xin, "Experimental investigation on Al2O3-R123 nanorefrigerant heat transfer performances in evaporator based on organic Rankine cycle," *International Journal of Heat and Mass Transfer*, vol. 127, pp. 145–153, 2018.

[76] R. K. Sabareesh, N. Gobinath, V. Sajith, S. Das, and C. B. Sobhan, "Application des nanoparticules de TiO_2 en tant que lubrifiant et additif dans les systemes frigorifiques a compression de vapeur - une etude experimentale," *International Journal of Refrigeration*, vol. 35, no. 7, pp. 1989–1996, 2012.

[77] I. M. Mahbubul, R. Saidur, and M. A. Amalina, "Heat transfer and pressure drop characteristics of Al2O3-R141b nanorefrigerant in horizontal smooth circular tube," *Procedia Engineering*, vol. 56, pp. 323–329, 2013.

[78] D. Madhesh, R. Parameshwaran, and S. Kalaiselvam, "Experimental investigation on convective heat transfer and rheological characteristics of Cu-TiO2 hybrid nanofluids," *Experimental Thermal and Fluid Science*, vol. 52, pp. 104–115, 2014.

[79] S. S. Khaleduzzaman, I. M. Mahbubul, I. M. Shahrul, and R. Saidur, "Effect of particle concentration, temperature and surfactant on surface tension of nanofluids," *International Communications in Heat and Mass Transfer*, vol. 49, pp. 110–114, 2013.

[80] I. M. Mahbubul, A. Saadah, R. Saidur, M. A. Khairul, and A. Kamyar, "Thermal performance analysis of Al_2O_3/R-134a nanorefrigerant," *International Journal of Heat and Mass Transfer*, vol. 85, pp. 1034–1040, 2015.

[81] V. P. Zhelezny, N. N. Lukianov, O. Y. Khliyeva, A. S. Nikulina, and A. V. Melnyk, "Une etude complexe des proprietes thermophysiques des nanofluides R600a-huile minerale-Al_2O_3 et R600a-huile minerale-TiO_2," *International Journal of Refrigeration*, vol. 74, pp. 488–504, 2017.

[82] M. A. Kedzierski, "Un modele semi-theorique de calcul des coefficients de transfert de chaleur en cas d'ebullition de melange frigorigene/lubrifiant," *International Journal of Refrigeration*, vol. 26, no. 3, pp. 337–348, 2003.

[83] M. A. Kedzierski, "R134a/Al2O3 nanolubricant mixture boiling on a rectangular finned surface," *ASME J. Heat Transf*, vol. 134, p. 121501, 2012.

[84] L. Lin, H. Peng, and G. Ding, "Model for predicting particle size evolution during nanoparticle aggregation in refrigerant-oil mixture," *International Journal of Heat and Mass Transfer*, vol. 119, pp. 91–104, 2018.

[85] V. Umesh and B. Raja, "A study on nucleate boiling heat transfer characteristics of pentane and CuO- pentane nanofluid on smooth and milled surfaces," *Experimental Thermal and Fluid Science*, vol. 64, pp. 23–29, 2015.

[86] H. Kim, H. S. Ahn, and M. H. Kim, "On the mechanism of Pool boiling critical heat flux enhancement in nanofluids," *Journal of Heat Transfer*, vol. 132, no. 6, 2010.

[87] E. I. Eid, R. A. Khalaf-Allah, and M. Tolan, "Amelioration des caracteristiques de l'ebullition libre par adjonction de nano

oxyde d'aluminium a du R-141b sur un element chauffant circulaire horizontal en acier," *International Journal of Refrigeration*, vol. 98, pp. 311–322, 2019.

[88] A. Zendehboudi and A. Tatar, "Utilization of the RBF network to model the nucleate pool boiling heat transfer properties of refrigerant-oil mixtures with nanoparticles," *Journal of Molecular Liquids*, vol. 247, pp. 304–312, 2017.

[89] D. Yang, B. Sun, H. Li, C. Zhang, and Y. Liu, "Comparative study on the heat transfer characteristics of nano-refrigerants inside a smooth tube and internal thread tube," *International Journal of Heat and Mass Transfer*, vol. 113, pp. 538–543, 2017.

[90] S. B. Seo and I. C. Bang, "Effects of AL2O3 nanoparticles deposition on critical heat flux of R-123 in flow boiling heat transfer," *Nuclear Engineering and Technology*, vol. 47, pp. 398–406, 2015.

[91] P. Dey and B. K. Mandal, "Performance enhancement of a Shell-and-tube evaporator using Al_2O_3/R600a nanorefrigerant," *International Journal of Heat and Mass Transfer*, vol. 170, p. 121015, 2021.

[92] L. Lin, H. Peng, Z. Chang, and G. Ding, "Étude experimentale sur la migration des nanoparticules de TiO_2 depuis un melange frigorigene-huile vers une huile lubrifiante durant le dessechement du frigorigene," *International Journal of Refrigeration*, vol. 77, pp. 75–86, 2017.

[93] P. S. Deokar and L. Cremaschi, "Effet des additifs a base de nanoparticules sur le coefficient de transfert de chaleur des melanges de frigorigenes et de lubrifiants lors du chauffage monophasique dans le tube et de l'ebullition en ecoulement diphasique," *International Journal of Refrigeration*, vol. 110, pp. 142–152, 2020.

[94] A. A. M. Bigi and L. Cremaschi, "Theoretical investigation of Al2O3 nanoparticle slip mechanisms in high-viscosity two-component mixture in two-phase flow," *Journal of Heat Transfer*, vol. 141, no. 7, 2019.

[95] H. Hong, X. Luan, M. Horton, C. Li, and G. P. Peterson, "Alignment of carbon nanotubes comprising magnetically sensitive metal oxides in heat transfer nanofluids," *Thermochimica Acta*, vol. 525, no. 1-2, pp. 87–92, 2011.

[96] S. Yao and Z. Teng, "Effect of nanofluids on boiling heat transfer performance," *Applied Sciences*, vol. 9, no. 14, p. 2818, 2019.

[97] S. J. Kim, I. C. Bang, J. Buongiorno, and L. W. Hu, "Surface wettability change during pool boiling of nanofluids and its effect on critical heat flux," *International Journal of Heat and Mass Transfer*, vol. 50, no. 19-20, pp. 4105–4116, 2007.

[98] A. Jaikumar, A. Gupta, S. G. Kandlikar, C.-Y. Yang, and C.-Y. Su, "Scale effects of graphene and graphene oxide coatings on pool boiling enhancement mechanisms," *International Journal of Heat and Mass Transfer*, vol. 109, pp. 357–366, 2017.

[99] V. Nair, P. R. Tailor, and A. D. Parekh, "Les nanofrigorigenes: une synthese complete de leur passe, present et futur," *Present and Future. Int. J. Refrig.*, vol. 67, pp. 290–307, 2016.