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Nanorefrigerants: A Review on Thermophysical Properties and Their Heat Transfer Performance

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ABSTRACT

The last decade has seen the rapid enhancement of nanofluid in several ways. Nanofluid with refrigerant base have been introduced as nanorefrigerant in recent years due to their significant effects on the efficiency of heat transfer. A brief review of past studies on nanorefrigerants and their performance in thermodynamics and heat transfer area are reported in this paper. Some current challenges and future prospect of nanorefrigerant will also be highlighted.

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1. Introduction

Refrigerant is a material used during heat cycle to transfer heat from one region and remove it to another. There are four main groups of refrigerants and they are determined by their chemical constituents but are generally classified as Chlorofluorocarbons (CFCs), Hydro chlorofluorocarbons (HCFCs), Hydro fluorocarbons (HFCs) and natural refrigerants [1]. Refrigerants play an essential position in refrigeration and air conditioning systems which regularly consumes a significant proportion of energy generated, particularly in the more advanced countries for industries, commercial buildings and automotive.

Each refrigerant has different physical properties. Previous researchers used refrigerant R113 (Formula: CI2FC-CCIF2; CAS Number: 76-13-1) since it is in liquid state at room temperature and atmospheric pressure, and so it is easy to prepare a nanorefrigerant [9]. However, there are difficulties to mix nanoparticles with gas phase of refrigerant at room temperature since nanoparticles can only be added in a liquid.

With the advancement in nanotechnology, nanoparticles (particles with size less than 100 nanometers) have been introduced by Maxwell for dispersing in fluid to enhance the thermal physical properties [2, 4]. Metal, metal oxide or carbon are some popular examples of nanoparticles. In 1995,

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Choi introduced a new idea called nanofluid where nanoparticles are dispersed into base fluid [5]. The improvement of heat transfer performance is the main motivation behind the development of nanofluids and recently, the research has widened to the refrigerant as well.

Nanorefrigerant is formed when refrigerant is mixed with small amount of nanoparticles, usually less than 4% of total volume of the mixture. Results from previous researches have shown that nanorefrigerant would achieve more than 10% better thermal conductivity compared to pure refrigerant [5]. Number of studies regarding nanorefrigerant increases over the years and it has been proven that the performance of refrigeration system will increase by adding nanoparticles into the system. The three main benefits of using refrigerants with nanoparticles are [6]: 1) Solubility between refrigerant and the lubricant can be enhanced. 2) Thermal conductivity and heat transfer characteristics of the refrigerant can be improved. 3) The friction coefficient and wear rate reduces when nanoparticles are dispersed into the refrigerant.

Numerous amount of work has been performed using refrigerant- nanoparticles pair. Nanoparticles CuO, TiO2, Cu, CNT were dispersed in refrigerants R113, R141b and R134a and all results show enhancement in the thermal properties [7, 8]. However, there are still many high pressure refrigerants that have not been prepared and investigated as nanorefrigerant due to lack of suitable preparation method. Therefore, in this paper, we will briefly discuss some current researches on nanorefrigerant, and their performance in thermodynamics and heat transfer area. Some current challenges and future prospect of nanorefrigerant will be highlighted.

2. Recent Researches on Nanorefrigerants

Research on nanorefrigerants have been conducted in several ways. Alawi *et al* [12], Mahbubul *et al* [13] and Alawi *et al* [14] performed numerical analysis by using suitable mathematical models from existing studies to determine the thermal conductivity, viscosity and density of the nanorefrigerant. Thermal conductivity models that are used are Maxwell, Sitprasert, Koo and Kleinstreuer and empirical correlation. Alawi and Sidik [15] performed numerical analysis by using suitable mathematical model to determine thermal conductivity and viscosity of the nanorefrigerant.

Coumaressin and Palaniradja [16] performed simulation CFD heat transfer analysis by using FLUENT software to investigate the heat transfer coefficient of the refrigeration system. Hernandez *et al* [17] also performed simulation in ANSYS FLUENT software to investigate the thermal efficiency of a refrigeration system. During simulation, the nanorefrigerant flowing through a horizontal tube with a constant wall temperature.

Tashtoush *et al* [18] performed parametric analysis to investigate relation of heat transfer coefficient (HTC) with variation of temperature, nanoparticle types, size and mass fraction. Ajayi *et al* [19] performed a CFD flow analysis by using CFD simulation/solver to investigate the flow of nanorefrigerants through adiabatic capillary tubus of vapour compression refrigeration systems. Mishra and Jaiswal [20] performed thermal modelling and numerical analysis to investigate the coefficient of performance (COP) of refrigeration system with different nanorefrigerant.

In an experimental research by Subramani and Prakash [21], they added nanoparticles into mineral oil which act as lubricant before being released in R134a refrigeration system. Bartelt *et al* [22] added nanoparticles into polyester lubricant (RL68H) before being released in R134a refrigeration system. The heat transfer coefficient is then measured when nanorefrigerant flowing through a horizontal tube. Henderson *et al* [8] added nanoparticles into polyester oil which act as lubricant before being released in R134a refrigeration system. Bi *et al* [23] added nanoparticles into mineral oil which act as lubricant before being released in R134a refrigeration system. The performance is then investigated by using energy consumption test and freeze capacity test.

Mahbubul *et al* [24] added nanoparticles into POE oil which act as lubricant before being released in R134a refrigeration system.

In a different study, Park and Jung [25] added nanoparticles into long plain tube with nucleate boiling heat transfer of R134a and R132. Sun and Yang [7] performed experimental work to investigate the heat transfer and flow characteristic of nanorefrigerant. Nanoparticles was added directly into refrigerant R141b by using two-step method. The researchers chose to mix nanoparticles directly with refrigerant since R141b is a low pressure refrigerant. Jiang *et al* [9] also dispersed nanoparticles directly into refrigerant R113. This method is chosen since refrigerant R113 is in the liquid state at room temperature and atmospheric pressure.

3. Thermo-physical Properties of Nanorefrigerant

Measurement of nanorefrigerant thermophysical properties, such as thermal conductivity, viscosity and density is critical for estimating heat transfer and pressure drop of thermal engineering systems. A summary of some studies on the thermophysical properties and heat transfer performance of nanorefrigerants is performed. Alawi *et al* [12] investigated thermal conductivity and viscosity of refrigerant R134a with four nanoparticles which are CuO, ZnO, SiO_2 and Al_2O_3. The size and concentration of nanoparticles used are varied from 20 nm to 100 nm and 1% to 5% respectively. The results showed that higher volume fraction and smaller size of the nanoparticles increase the thermal conductivity ratio of nanorefrigerant. Dynamic viscosity of the nanorefrigerant also increase. Nanorefrigerant CuO/R134a with nanoparticles of 5% volume fraction showed the highest thermal conductivity ratio. Meanwhile, nanorefrigerant SiO_2/R134a gave the lowest and slowest thermal conductivity ratio.

Mahbubul *et al.,* [13] investigated thermophysical properties and heat transfer performance of nanorefrigerant Al_2O_3/R134a. The thermal conductivity ratio of nanorefrigerant with nanoparticles volume fraction of 5% showed the highest value. It can also be observed that heat transfer coefficient is directly proportional to volume fraction of nanoparticles. Alawi *et al*., [14] investigated thermophysical properties and heat transfer performance of refrigerant R134a with nanoparticles Single Walled Carbon Nanotube (SWCNT). The thermal conductivity of nanorefrigerant SWCNT/R134a increases with the increase of nanoparticle volume fraction and temperature. Viscosity and density of the nanorefrigerant also increase when nanoparticle volume fraction.

Coumaressin and Palaniradja [16] investigated heat transfer coefficient of nanorefrigerant CuO/R134a. The nanoparticles concentration varied from 0% to 0.8%. Heat transfer coefficient of nanorefrigerant increased and showed the highest value at concentration 0.55%. However, the heat transfer coefficient decreased after concentration 0.55%. Hernandez *et al*., [17] investigated heat transfer coefficient and thermal conductivity of nanorefrigerant Al_2O_3/R113, Al_2O_3/R123 and Al_2O_3/R134a. The volume fraction of nanoparticles is varied from 1% to 5%. Nanorefrigerant Al_2O_3/R134a gave the highest heat transfer coefficient and thermal conductivity compared to other nanorefrigerants. The highest results are observed when the nanoparticles concentration is 5%.

Tashtoush *et al*., [18] investigated coefficient of performance (COP) of the ejector refrigeration cycle of refrigerants R134a and R141b with nanoparticles CuO and Al_2O_3. The augmentation in COP reached 24.7% for nanorefrigerant CuO/R134a and 12.61% for Al_2O_3/R134a. Both volume concentration of nanoparticles were 2%. COP for refrigerant R141b also increased after nanoparticles have been added. However, the value of COP observed is lower compared to refrigerant R134a with nanoparticles. Ajayi *et al*., [19] investigated heat transfer properties of nanorefrigerant Cu/R134a and Cu/R600a. It is observed that refrigerant R600a is less thermally efficient than refrigerant R134a. However, after addition of copper nanoparticles, its thermophysical properties improved greatly that it can readily replace R134a. R600a is considered as replacement for R134a due to its low global warning and zero ozone depletion.

Mishra and Jaiswal [20] investigated COP of three refrigerants which are R134a, R407c and R404a. All refrigerants are added with nanoparticles CuO, TiO_2 and Al_2O_3. Nanorefrigerant Al_2O_3/R134a showed the highest COP followed by CuO/R134a and TiO_2. For refrigerant R407c and R404a, addition of nanoparticle CuO showed the highest COP followed by Al_2O_3 and TiO_2. Kumar and Elansezhian [26] investigated COP of refrigerant R134a with nanoparticle Al_2O_3 in refrigeration system. It is observed that addition of 0.2% volume concentration of nanoparticles showed improvement in the COP of refrigeration system. Subramani and Prakash [21] investigated COP of refrigerant R134a with 0.06% mass fraction of nanoparticle Al_2O_3in refrigeration system. It is observed that COP of the refrigeration system increased by 33% with the addition of nanoparticles. Bartelt *et al.*, [22] investigated the heat transfer coefficient of refrigerant R134a with nanoparticle CuO. It is observed that addition of nanoparticle into the refrigeration system increase the heat transfer coefficient.

Henderson *et al.,* [8] investigated heat transfer enhancement of refrigerant R134a and nanoparticle CuO. An average heat transfer enhancement of 52% is measured for a 0.04% volume fraction of CuO and 76% heat transfer enhancement for a 0.08% volume fraction of CuO. Bi *et al.*, [23] investigated refrigeration performance of refrigerant R134a and nanoparticle TiO_2. 26.1% less energy consumption used in the refrigeration system with 0.1% mass fraction TiO_2 nanoparticles. Park and Jung [25] investigated the heat transfer enhancement of refrigerants R134a and R123 with nanoparticle carbon nanotubes (CNTs). Nanorefrigerant CNTs/R134a showed greater heat transfer enhancement compared to CNTs/R123. The heat transfer enhancement of CNTs/R134a and CNT/R123 are 36.6% and 28.6% respectively. Mahbubul *et al.*, [24] investigated the thermal conductivity and viscosity of refrigerant R141b and nanoparticle Al_2O_3. The nanoparticle concentration is varied from 0.5% to 2%. Thermal conductivity of nanorefrigerant Al_2O_3/R141b increases with the increase of nanoparticle concentration and temperature. However, the viscosity of the nanorefrigerant decreases with the increase of temperature.

Mahbubul *et al.*, [27] once again investigated the thermal conductivity, viscosity and density of refrigerant R141b and nanoparticle Al_2O_3. The nanoparticle concentration is varied from 0.1% to 0.4%. Thermal conductivity of nanorefrigerant increased with the increase of nanoparticle concentration. The thermal conductivity of nanorefrigerant with concentration 2% is higher compared to 0.4% volume concentration. Density of the nanorefrigerant decreases with the increase of temperature. Sun and Yang [7] investigated heat transfer coefficient of refrigerant R141b and four nanoparticles which are Cu, Al, Al_2O_3 and CuO. Nanorefrigerant Cu/R141b gave the highest heat transfer coefficient followed by Al/R141b, Al_2O_3/R141b and CuO/R141b. Mahbubul *et al.*, [28] investigated pressure drop of refrigerant R123 and nanoparticle TiO_2. It was observed that pressure drop increases with the increase of nanoparticle volume fraction. 4% volume fraction of nanoparticle showed the highest pressure drop value in the refrigeration system. Jiang *et al.*, [9] investigated the thermal conductivity of refrigerant R113 and four kinds of nanoparticle CNTs. Each nanoparticle has different value of aspect ratio which are 100.0, 666.7, 18.8 and 125.0. The volume fraction of nanoparticle is varied from 0% to 1%. CNTs/R113 with 666.7 aspect ratio of CNTs showed the highest thermal conductivity enhancement which is 104%.

Table 1 shows the summary of previous studies of nanorefrigerant according to refrigerant type.

Table 1
Past studies on nanorefrigerants

Researchers	Nanoparticles	Nanoparticles size (nm)	Nanoparticles concentration (%)	Research Method
Refrigerant R134a				
Alawi *et al.*, [12]	CuO, ZnO, SiO_2, Al_2O_3	20-100	1-5	Numerical method
	Findings: Thermal conductivity of nanorefrigerant decrease when the particle size increase.			
Alawi *et al.* [14]	SWCNT	20	1-5	Numerical method
	Findings: Viscosity and density of nanorefrigerant increase with the increase of volume fractions but these parameters decrease with the increment of temperature.			
Mahbubul *et al.* [13]	Al_2O_3	5-25	1-5	Numerical method
	Findings: The convective heat transfer coefficient and flow boiling heat transfer coefficient increase significantly with nanoparticle concentration.			
Coumaressin and Palaniradja [16]	CuO	10-70	0-0.8	Numerical method
	Findings: The addition of CuO nanoparticles in refrigerant increase the evaporating heat transfer coefficient result.			
Hernandez *et al.*, [17]	Al_2O_3	20-50	1-5	Numerical method (Simulation in ANSYS FLUENT 15.0.)
	Findings: R134a/Al_2O_3 with nanoparticle size of 30nm and 1% volume fraction shows the best thermal efficiency.			
Tashtoush *et al.* [18]	CuO, Al_2O_3	10-100	0.5-4.0wt %	Numerical method
	Findings: The effect of nanoparticles on pressure drop is proportional to the nanoparticle density and diameter			
Alawi and Sidik [15]	CuO	20	1-5 vol. %	Numerical method
	Findings: Viscosity and density of nanorefrigerant increase when volume fraction increase			
Ajayi *et al.* [19]	Cu, Al	-	0-0.1	Numerical method (CFD analysis)
	Findings: The use of nanorefrigeran t significantly reduce in the power requirement of refrigerators			
Mishra and Jaiswal [20]	Cu, CuO, TiO_2, Al_2O_3	-	0.01- 0.05	Numerical method
	Findings: The use of nanoparticles enhances thermal performance of vapour compression refrigeration system from 8% to 35 % using nanorefrigerant in primary circuit.			
Kumar and Elansezhian [26]	Al_2O_3	40-50	0.2	Experimental method (Nanoparticles and lubricant were ultrasonically mixed)
	Findings: 10.32% less energy consumption in the refrigeration system and Coefficient of Performance (COP) increased.			
Subramani and Prakash [21]	Al_2O_3	<50	0.06	Experimental method (Nanoparticles and lubricant were ultrasonically mixed)
	Findings: 25% less energy consumption in the refrigeration system			
Bartelt *et al.*, [22]	CuO	30	4	Experimental method. (Nanoparticles and

				lubricant were ultrasonically mixed)
	Findings: The nanoparticles produced an increase in heat transfer between 42% and 82% for a 1% nanolubricant mass fraction, and an increase of between 50% and 101% was calculated for a 2% nanolubricant mass fraction			
Henderson *et al.* [8]	CuO	30	4	Experimental method. (Nanoparticles and lubricant were ultrasonically mixed)
	Findings: Average of 76% heat transfer enhancement			
Bi *et al.* [23]	TiO_2	50	0.06 and 0.1	Experimental method. (Nanoparticle s and lubricant were ultrasonically mixed)
	Findings: 26.1% less energy consumption in refrigeration system with 0.1% TiO_2 nanoparticles			
Park and Jung [25]	Carbon Nanotube s (CNT)	20	1.0	Experimental method
	Findings: At low heat flow, heat transfer when using CNT/R134a increased to 36.6%.			
Refrigerant R141b				
Tashtoush *et al.* [18]	CuO Al_2O_3	10-100	0.5 – 4.0 wt%	Numerical method
	Findings: COP increased slightly with decreasing evaporating saturation temperature for refrigerant R141b			
Mahbubul *et al.* [24]	Al_2O_3	13	0.5 – 2.0	Experimental method
	Findings: Thermal conductivity of nanorefrigerant was 1.626 times greater than base refrigerant for 2% of nanoparticles concentration			
Mahbubul *et al.* [27]	Al_2O_3	13	0.1 - 0.4	Experimental method
	Findings: Thermal conductivity of nanorefrigerant increased with the increase of temperature and nanoparticle volume fraction			
Sun Yang [29]	Cu, Al, CuO, Al_2O_3	40	0.1 - 0.3	Experimental method
	Findings: Heat Transfer coefficient of Cu/R141b increased by 25%			
Refrigerant R600a				
Ajayi *et al.* [19]	CuO Al_2O_3	-	0 - 0.1	Numerical method
	Findings: The thermophysical properties of nanorefrigerant CuO/R600a have been greatly enhanced that it is able to substitute R134a.			
Refrigerant R123				
Mahbubul *et al.* [28]	TiO_2	21	0-5	Numerical method
	Findings: Pressure drop increased tremendously for >1% nanoparticle			
Hernandez *et al.* [17]	Al_2O_3	20-50	1-5	Numerical method
	Findings: Al_2O_3/R123 showed an increase of 31.62% in heat transfer coefficient with 5% of Al_2O_3			

	concentration			
Park and Jung [25]	Carbon Nanotubes (CNT)	20	1	Experimental method
	Findings: At low heat flow, heat transfer when using CNT/123 increased to 28.6%			
Refrigerant R113				
Hernandez *et al.* [17]	Al_2O_3	20-50	1-5	Numerical method
	Findings: Al_2O_3/R113 showed an increase of 21.16% in heat transfer coefficient with 5% of Al_2O_3 concentration			
Jiang *et al.* [9]	CNT	15 & 80	0.2-1	Experimental method
	Findings: CNT/R113 nanorefrigerants have higher thermal conductivity enhancements than CNT/water nanofluids and spherical nanoparticles/ R113 nanorefrigerants with the same volume fraction of nanoparticles			
Refrigerant R407c				
Mishra and Jaiswal [20]	Cu, CuO, TiO_2, Al_2O_3	-	0.01-0.05	Numerical method
	Findings: R407 with different nanoparticle showed enhancement in COP for about 3% to 12%			
Refrigerant R404a				
Mishra and Jaiswal [20]	Cu, CuO, TiO_2, Al_2O_3	-	0.01-0.05	Numerical method
	R404a with different nanoparticle showed enhancement in COP for about 3% to 14%			

4. Conclusion

This paper reviewed past researches on nanorefrigerants and their performance in refrigeration system. Based from the above brief review, we found that most of the researchers mix nanoparticles into lubricant first before being released and tested with refrigerant in refrigeration system. This is because most refrigerant exist at high pressure and in gas condition at room temperature. Hence, it is difficult to add nanoparticles directly into refrigerant since nanoparticles cannot be mixed with a gas and should only be added into a liquid base fluid. The weakness of adding nanoparticles into lubricant is resulting in difficulties to investigate the properties of nanorefrigerant. Therefore, usually researchers will observe or measure the overall performance of the system to see the effectiveness of the nanoparticles. The sedimentation and aggregation of nanoparticles in refrigerant also has not been well studied by previous researchers albeit these two phenomena may reduce the stability of nanorefrigerant and limit the application of nanorefrigerant.

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