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An Update Review on Performance Enhancement of Refrigeration Systems Using Nano-Fluids

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Abstract: Considering the issues of energy saving and environment protection, the performance of refrigeration systems requires to be improved. In recent years, nano-fluids have attracted greatly attention from the researchers due to their outstanding thermal characteristics. In this work, the published investigations on the preparation and characterization of nano-fluids have been discussed at first. Furthermore, the key thermo-physical properties of nano-fluids, such as thermal conductivity, viscosity, specific heat and density have been summarized. Finally, the performance enhancements in different types of refrigeration systems by using nano-fluids have been reviewed. It is concluded that nano-fluids as refrigerant, lubricant or secondary fluid have wide potential application in refrigeration systems.

Keywords: nano-fluids, performance enhancement, nano-refrigerant, nano-lubricant, nano-secondary fluid, refrigeration

1. Introduction

Energy consumption of refrigeration and air conditioning could account for almost of the total urban electricity consumption in summer [1, 2]. In order to save energy, it is urgent to change the rising trend of energy consumption in refrigeration and air-conditioning. Furthermore, the refrigeration industries produce environmental impact-Ozone Depletion Potential (ODP). The other environmental effect is Global Warming Potential (GWP) that causes associate degree increase in international earth surface temperature. Specifically, Hydrochlorofluorocarbon (HCFC) and Chloro Fluoro Carbon (CFCs) refrigerants are banned by Montreal protocol due to chemical element Cl while hydrofluorocarbon (HFC) refrigerants are banned in 2010. Developing next generation refrigeration systems demand high efficient, energy saving and environmental working fluids and advanced technology.

Improving heat transfer properties of working fluids in the refrigeration system could enhance refrigeration system performance. According to Maxwell's mixing theory [3], adding solid particles into fluid can improve the thermal conductivity, which has been studied for hundreds of years. Researchers have used nanofluids for practical engineering applications [4, 5]. However, the larger particles will block the micro-channels and increase wear. Nanomaterials can effectively solve these

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problems due to small size effect. In 1995, Choi of Argonne National Laboratory first proposed the concept of nano-fluids [6]. Usually, the performance of refrigeration systems is enhanced by introducing nanoparticles into refrigerant or lubricant. Application of nano-fluids into refrigeration systems could improve the heat transfer performance and compressor energy efficiency. Thus, investigating these thermo-physical properties, mechanism of heat transport and tribological behavior of nano-fluids are necessary. Azmi et al. [7] reviewed the influence of nano-refrigerants or nano-lubricants on energy saving of refrigeration system. Sharif et al. [8] summarized the mechanism of improving the performance of vapor compression refrigeration system by using nano-refrigerants and nano-lubricants. Rasheed et al. [9] reviewed the research progress of graphene nano-fluids and lubricants. Bhattad et al. [10] reviewed the preparation and characterization of nano-fluids, the thermo-physical and electrical properties. Further, applications of nano-fluids as refrigerants, lubricants and secondary fluids in refrigeration systems are reviewed.

In summary, adding nanoparticles into refrigeration systems could enhance the heat transfer performance and tribology properties, and further enhance the characteristics of heat exchangers and compressors, finally increase the cooling capacity and Coefficient of Performance (COP). At present, the existing reviews mainly focus on the application of nano-fluids in vapor compression refrigeration system. With the development of nanotechnology, the nano-fluids have also been used in other refrigeration systems, such as absorption refrigeration and ejection refrigeration. Therefore, this review presents an overview of performance enhancement in all kinds of refrigeration systems by using nano-fluids. The preparation and characterization of nano-fluids are addressed. Furthermore, the key thermal physical properties like thermal conductivity, viscosity, specific heat and density et al. have been discussed. Finally, the performance enhancements in different types of refrigeration systems by using nano-fluids have been reviewed.

2. Nano-Fluids

2.1 Preparation

Nano-fluid is a kind of colloidal dispersion, in which nanomaterials (dispersed phase) are dispersed into base liquids (dispersed medium). At present, the preparation methods are one-step or two-step methods. One-step method refers to preparation of nanomaterials and nano-fluids at the same time by directly dispersing the particles into the base fluid. Two-step method is to prepare nano-materials first, and then disperse nanoparticles in the base fluid in an appropriate way to form nano-fluids. Specifically, the preparation of nanoparticles and nano-fluids is completed separately. The methods of producing the nanoparticles are various, e.g. laser ablation, ball milling etc. Besides, available dispersion methodologies such as thermal agitation, ultrasonication etc. are widely used when preparing nano-fluids. Fig. 1 shows the flowchart of nano-fluids preparation. The two-step method is widely used to prepare nano-fluids in engineering applications because of the advantages of convenience and low cost. However, there are some shortcomings in the two-step method, such as particle agglomeration and poor stability. The surfactant possessing hydrophobic and hydrophilic head groups has been extensively used for the higher dispersion stability of nano-fluids. For example, the hydrophobic groups of the surfactant could adsorb onto the surfaces of hydrophobic nanoparticles through hydrophobic inter-action, leaving the hydrophilic head groups facing the aqueous phase and thereby make the hydrophobic

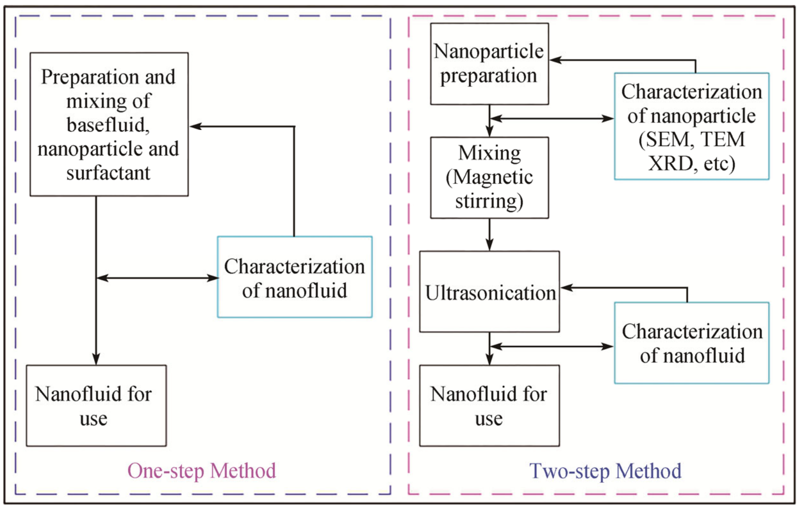


Fig. 1 Flowchart of nano-fluids preparation

nano-particles to be hydrophilic, and then improve the nano-particles stability in aqueous phase. The mechanism is opposite for the oil phase. Moreover, the dispersion stability of nano-fluids could be characterized by UV spectrometer, dynamic light scattering transmittance and absorbance.

There are three main ways to apply nano-fluids in refrigeration system: nano-refrigerant, nano-lubricant and nano-second refrigerant as shown in Table 1. The boiling point of most refrigerants used in refrigeration and air conditioning equipment is under the atmospheric temperature, so the refrigerants are in the gas phase under atmospheric environmental condition, which is not convenient for the preparation of nano-refrigerants [11–14]. So far, two kinds of refrigerants, R113 and R141b (boiling point at atmospheric pressure is 47.6°C and 32.1°C, respectively), are mainly used to prepare nano-refrigerants that are liquid phase at atmospheric condition. Peng et al. [11] added CuO nanoparticles into R113 refrigerant to form nano-refrigerant, and the stability would be kept more than 12 h. In 2010, they investigated diamond-oil mixture and R113 that was vibrated for 1 h, and the mixture shows stability for 12 h [12]. In 2011, Cu/R113 nano-refrigerant was prepared with the addition of surfactants, which could be stable for more than 24 h [13]. In 2015, TiO_2/R141b was studied by Peng et al. [14] using two-step method and sonic oscillation for 20 min. But the aggregation behavior is found. Trisaksri and Wongwises [15] prepared TiO_2/R141b nano-refrigerant through blending nanomaterials and refrigeration in the concentration range of 0.01%–0.05% (volume fraction), in which sonic oscillation was kept for 6 h. Lin et al. [16] prepared multi-walled carbon nanotubes (MWCNTs)/R141b nano-refrigerant with different concentration by the two-step method.

Nano-lubricant is another positive way to introduce nanomaterials in refrigeration system. Lee et al. [17] prepared the fullerene, MWCNT and CuO nano-lubricants in the mineral oil for refrigeration application. The ultraviolet-vis spectrophotometer was applied to measure the stability by the Lambert-Beer law that describes the proportional relationship between the intensity of light absorption and the concentration. The results exhibit fullerene nano-lubricants show the best dispersion stability, and the concentration was maintained at over 80% after 800 h. Zawawi et al. [18, 19] dispersed Al_2O_3-SiO_2, Al_2O_3-TiO_2 and TiO_2-SiO_2 composite nanoparticles into Polyalkylene Glycol (PAG 46) to prepare the composite nano-lubricant by two-step method. Each metal oxide nanoparticles were dispersed in PAG separately and then two nano-lubricants were mixed by 1:1 at volume. The stabilization of nano-lubrication was ensured by ultrasonic vibration and the result shows the stability of the composite nano-lubricant was obtained over 30 days. Sabareesh et al. [20] fabricated the TiO_2 mineral oil with 300 min sonic oscillation. It was indicated that the stability of prepared TiO_2/mineral oil system is observed after 800 h. Jatinder et al. [21] dispersed TiO_2 nanoparticles with 5–15 nm in mineral oil to form nano-lubricant based on the two-step method. There was a little settlement of the nanomaterials and further the deposition of nanoparticles was studied by analysis of UV-visible spectral absorption.

Table 1 Previous work on preparation of nano-fluids in refrigeration application

Author, Year	Nano/based fluid	Preparation method	Stability
Peng et al., 2009 [11]	CuO/R113	Two-step	more than 12 h
Peng et al., 2010 [12]	Diamond/R113/VG68	Two-step	more than 12 h
Peng et al., 2011 [13]	Cu/R113/SDS, CTAB, Span 80	Two-step	more than 24 h
Peng et al., 2015 [14]	TiO_2/R141b	Two-step	Checked aggregation behavior
Tazarv et al., 2016 [28]	TiO_2/R141b/CTAB	Two-step	one week
Yang et al., 2017 [29]	Cu, CuO, Al, Al_2O_3/R141b	Two-step	Stability test
Yang et al., 2017 [30]	TiO_2/Ammonia water	Two-step	Stable
Maheshwary et al., 2018 [31]	ZnO/R134a	Two-step	–
Lee et al., 2009 [32]	Fullerene, MWCNT, CuO/Mineral oil	Two-step	Fullerene sedimented 80% after 800 h; MWCNT sedimented 70% after 50 h; CuO sedimented 40% after 500 h
Sabareesh et al., 2012 [20]	TiO_2/Mineral oil	Two-step	more than 800 h
Zawawi et al., 2017 [18]	Al_2O_3-SiO_2/PAG	Two-step	more than 30 days
Zawawi et al., 2018 [19]	Al_2O_3-SiO_2, Al_2O_3-TiO_2, TiO_2-SiO_2/PAG	Two-step	more than 30 days
Sanukrishna and Prakash, 2018 [26]	TiO_2/PAG	Two-step	more than 120 h
Jatinder et al., 2019 [21]	TiO_2/Mineral oil	Two-step	more than 30 days
Vasconcelos et al., 2017 [22]	SWCNT/water	Two-step	–
Qi et al., 2017 [33]	Al_2O_3, TiO_2/water	Two-step	more than 3 days

Nano-fluids are also used as secondary fluid for refrigeration system. This can be prepared by adding metal, metal oxides and non-metallic nanoparticles into second refrigerant (water, brine mixture, etc.). Vasconcelos et al. [22] experimentally investigated the water based single wall carbon nanotubes (SWCNT) nano-fluid as a secondary fluid in indirect vapor compression refrigeration system, in which nano-fluid was prepared by the two-step method at volumetric concentrations of 0.035 33%, 0.053 46% and 0.2122%.

2.2 Thermo-physical properties

The thermo-physical properties of nano-fluids have an important influence on the performance of refrigeration equipment, and the previous studies can be summarized in Table 2. Thermal conductivity, viscosity, density, surface tension, specific heat and latent heat are most important thermo-physical properties of fluids. Alawi et al. [23] investigated the influence of thermal conductivity, viscosity, density and specific heat on the refrigeration cycle performance by applying Al_2O_3/R141b nano-refrigerant. The results show that the thermal conductivity, viscosity and density of nano-refrigerant increase by 28.88%, 12.63% and 11.54% when the volume fraction of nanomaterials is 4% and the temperature is 35°C compared with R141b. In addition, the COP values of Al_2O_3/R141b nano-refrigerant influenced by thermal conductivity, density and specific heat capacity were most significant, which increased 15.13%, 3.3% and 2.65% respectively comparing with R141b. Therefore, it is important to study the thermal parameters of nano-fluids for evaluating the efficiency of refrigeration cycles.

Mahbubul et al. [24] researched the influences of Al_2O_3 volume concentrations on thermal conductivity, viscosity and density of R141b based nano-fluids under different temperatures. It is observed that thermal conductivity of nano-fluids rises with increasing volume fraction and temperature. Compared with temperature increment, the increase of nanomaterial concentration makes it more obvious. However, viscosity and density increase as the increase in concentration and reduce as the increase in temperature. As the increase of thermal conductivity and decrease of pressure, the heat transfer characteristics also increases, and the pump power consumption arises as the increase of viscosity and density. As a result, choosing the optimal volume fraction of nano-fluids can enhance refrigeration cycle performance.

Jaffri et al. [25] assessed the thermo-physical properties of nano-refrigerants consisting of R290 and R600a mixed with nanoparticles using the fluid data provided in version 3.2.1 of NIST database standard 4 (SUPERTRAP®). The influence of nanomaterials concentration on thermal conductivity, viscosity, density and specific heat for the mixed refrigerant was further

Table 2 Summary of previous work on thermo-physical properties of nano-fluids in refrigeration application

Researcher, Year	Nanomaterial	Refrigerant	Lubricant	Concentration	Remarks
Jiang et al., 2009 [34]	CNT	R113		0 wt%–1 wt%	Enhanced thermal conductivity
Mahbubul et al., 2012 [35]	TiO_2	R123	–	0.5 vol%–2 vol%	Viscosity increases with concentration
Rashidi and Nikou, 2012 [36]	CNT	R113	–	–	Thermal conductivity model
Kedzierski, 2013 [37]	Al_2O_3	–	POE	5.6 wt%–25 wt%	Kinematic viscosity and density measurements A new correlation for viscosity
Mahbubul et al., 2013 [24]	Al_2O_3	R141b	–	0.5 vol%–2 vol%	Thermal conductivity, viscosity and density measurements
Cuenca et al., 2014 [38]	CNT	NH_3-$LiNO_3$	–	0.02 vol%–0.8 vol%	Enhanced Thermal conductivity
Alawi et al., 2014 [39]	CuO	R134a		0 vol%–0.4 vol%	Thermal conductivity, viscosity and density measurements
Alawi et al., 2015 [40]	SWCNT	R134a	–	1 vol%–5 vol%	Thermal conductivity, viscosity, specific heat and density
Zawawi et al., 2017 [18]	Al_2O_3-SiO_2	–	PAG 46	0.02 vol%–0.1 vol%	Thermal conductivity and viscosity measurements
Zawawi et al., 2018 [19]	Al_2O_3-SiO_2, Al_2O_3-TiO_2, TiO_2-SiO_2	–	PAG 46	0.02 vol%–0.2 vol%	Thermal conductivity and viscosity measurements
Sanukrishna and Prakash, 2018 [26]	TiO_2	–	PAG 46 PAG	0.02 vol%–0.2 vol% 0.07 vol%–0.8 vol%	Thermal conductivity and viscosity measurements Enhanced thermal conductivity, rheological properties
Jaffri et al., 2018 [25]	CuO	R290, R600a	–	1 vol%–5 vol%	Thermal conductivity, density, viscosity and specific heat
Alawi et al., 2019 [23]	Al_2O_3	R141b	–	1 vol%–4 vol%	Thermal conductivity, density, dynamic and viscosity

studied. The results exhibited density and thermal conductivity enhanced gradually with the increase of volume concentration. The density and thermal conductivity decrease with decline of the concentration percentage of R600a. However, the specific heat would decrease as the increase of the nanomaterials volume concentration. As the R290 concentration increases, the specific heat enhances. The viscosity of nano-fluid increases as the volume concentration increases.

Zawawi et al. [18] investigated the thermal conductivity and viscosity of Al_2O_3-SiO_2/PAG nano-fluids with a volume concentration of 0.02%–0.1% at temperature range of 30°C–80°C in 2017. Al_2O_3-SiO_2 nano-fluids were formed by two-step method and added in PAG 46 lubricants. The thermal conductivity and viscosity were evaluated by KD2 Pro Thermal Properties Analyzer and LVDV-III Rheometer. The results show that thermal conductivity and viscosity of the composites enhance as the increased volume fraction and decrease as the increased temperature. It is observed the composite nano-fluids are Newtonian fluids in the applied temperature and concentration ranges. The maximum thermal conductivity increase was 2.41% at the 0.1% concentration and the temperature of 30°C. At a temperature of 60°C, the maximum viscosity increment observed was 9.71% at the 0.1% concentration. The thermal conductivity of Al_2O_3-SiO_2/PAG composite nano-fluids was significantly higher than that of their single components Al_2O_3/PAG and SiO_2/PAG. At the same time, the viscosity of composite nano-fluids is also lower than that of their single component. Therefore, the composite nano-fluids show the better thermal conductivity and viscosity than single component. Finally, a novel model for predicting the performance of composite nano-fluids based on the application of refrigeration system is proposed.

In 2018, Zawawi et al. [19] studied the thermal conductivity and viscosity of three various metal oxide nanoparticle collocations for nano-lubricants at various volume factions (0.02 vol%–0.1 vol%) and various temperatures (30°C–80°C). Using two-step preparation method, the formed Al_2O_3-SiO_2, Al_2O_3-TiO_2 and TiO_2-SiO_2 composite nanomaterials were added in the PAG 46 lubricant. The maximum viscosity enhancement value of Al_2O_3-TiO_2/PAG nano-lubricant at the volume fraction of 0.1% and temperature of 30°C was 20.50%. At the 0.1% concentration and temperature of 30°C, the thermal conductivity of Al_2O_3-SiO_2/PAG nano-lubricant increased the most, with an improvement rate of 2.41%. A novel model is proposed to predict the viscosity and thermal conductivity. Sanukrishna and Prakash [26] investigated the thermal conductivity and rheological properties of TiO_2-PAG nano-lubricants with volume fractions of 0.07% to 0.8% in the temperature range of 20°C–90°C. The experimental results show that the thermal conductivity and viscosity of the oils enhance as the increase of the volume concentration and reduce as increasing temperature. The obtained conductivity and viscosity were compared to the traditional model, and the model failed to accurately calculate the thermal properties. The increase in the maximum thermal conductivity and viscosity was 1.38 and 10 times higher than that of basic lubricants when the volume fraction was 0.8% or 0.6%. The non-Newtonian shear thinning behavior of TiO_2-PAG nano-lubricant was demonstrated by calculating the power law and consistency index. The optimal concentration is 0.4 vol% for refrigeration system application.

A viscoelastic-fluid-based nano-fluid (VFBN) applying MWCNTs as nanomaterials were prepared for getting new thermal fluids with resistance reduction and heat transfer improvement [27]. The thermal conductivity and shear viscosity of the VFBNs were studied experimentally. The results show that thermal conductivity of VFBNs increases in comparison with the corresponding basic fluid, and increases as the increasing volume concentration and temperature. The thermal conductivity of VFBNs with MWCNTs was predicted by considering liquid stratification, particle agglomeration, particle shape, Brownian kinematics and basic viscosity. The shear viscosity increased as increasing concentration and the decline of temperature. Therefore, it can be expected that formed VFBNs might also have resistance reduction capabilities in turbulence.

In summary, for the nano-refrigerants, the thermal conductivity increases with the augmentation of nanoparticle concentration and temperature. The specific heat increases with the temperature and decreases with the concentration. In addition, the viscosity and density of the nano-refrigerant increase with the increase of concentration and decrease accordingly with the increment of temperature. However, thermal conductivity and viscosity of nano-lubricants increase with concentration and decrease with temperature. Moreover, nano-lubricant shows Non-Newtonian behavior under some certain circumstances.

3. Application in Vapor Compression Refrigeration

3.1 Nano-refrigerant

Nano-refrigeration is the mixture of nanomaterials and refrigerant. At present, nano-refrigerants have become an important application field of nano-fluids because of good heat transfer characteristics in refrigeration and air conditioning equipment. Coumaressin et al. [41] used FLUENT software and CFD heat transfer analysis to investigate the influence of CuO/R134a nano-refrigerant on evaporation Heat Transfer Coefficient (HTC) in vapor compression system. Further, a set of experimental equipment has been established based on the Indian national standards. The results show refrigeration cycle with nano-refrigerant works well. Fluent was applied to evaluate the HTC of CuO nano-refrigerant with 10–40 kW/m^2 heat flux, 0.05%–1% concentration and 10–70 nm particle size. The results show HTC of the evaporator increases as using CuO nano-refrigerant. Yang et al. [29] experimentally studied heat transfer properties of Cu/R141b, CuO/R141b, Al/R141b, and Al_2O_3/R141b nano-refrigerants in horizontal smooth tube and internal thread tube. The results show the heat transfer effect of nano-refrigerant in inner thread tube is more obvious in comparison with the smooth tube. The heat transfer performance of 0.2 wt% (mass fraction) Cu/R141b nano-refrigerant in smooth tube and inner screw tube was compared. The heat transfer improvement rate in inner thread tube increased by 4.50% at flow rate of 9.4 kg/s. Under the condition of 16.5 kg/s flow rate, the heat transfer enhancement rate of internal thread tube enhanced by 5.17%.

Kumar et al. [42] investigated the performance of ZrO_2 nano-refrigerant in vapor compression refrigeration cycle. The GWP of traditional refrigerant R134a is 1300, while that of R152a is 140. The results show ZrO_2 nano-refrigerant runs normally and safely in the refrigeration cycle. The concentration of zirconia nanoparticles shows an important role in enhancing heat transfer. Nano-refrigeration with particle diameter of 20 nm and concentration of 0.01%–0.06% was studied. It is indicated that the system performance coefficient increased by 33.45% using 0.06% volume concentration of zirconia R152A refrigerant. Alawi et al. [23] simulated the influence of Al_2O_3/R141b nano-refrigerant on thermo-physical parameters and discussed its influence on COP with the change of volume fraction and temperature. The results show thermal conductivity of Al_2O_3/R141b nano-refrigerant increases as increasing volume fraction and temperature. Compared with the base liquid, thermal conductivity of nano-refrigerant increases by 28.88%. In addition, the increase of thermal conductivity improves the COP by 15.13%. Compared with pure refrigerant, the viscosity and density of Al_2O_3/R141b nano-refrigerant also enhance by 12.63% and 11.54%, respectively. As the increasing temperature, the density and dynamic viscosity decrease, while as the increasing volume concentration, the density and dynamic viscosity increase. As the density increases, COP increases by 5%. The specific heat capacity of refrigerant and nano-refrigerant increase with an increase in temperature, but the specific heat of nano-refrigerant decreases with an increase in concentration. Furthermore, the specific heat value is slightly lower than that of basic refrigerant. But the COP improvement is 2.65% that can be owed to its specific heat capacity. Jaffri et al. [25] investigated the influence of the volume concentration of CuO nanomaterials added to R290/R600a refrigerant mixture on the density, thermal conductivity, viscosity and specific heat. Maheshwary et al. [31] researched the influence of zinc oxide shape on the thermo-physical and heat transfer characteristics of R134a nano-refrigerant. Spherical and cubic zinc oxide nanoparticles were added to refrigerants. The results show that the shape of ZnO has an important influence on the thermo-physical and heat transfer characteristics. The thermal conductivity of cubic ZnO nanomaterials is 42.5% bigger compared with the pure refrigerants. It was considered that ZnO /R134a nano-refrigerant was suitable for refrigeration and air conditioning equipment.

Furthermore, the aggregation and precipitation of nanomaterials might decrease the stability of nano-refrigerant and prevent the application in refrigeration cycles. For stabilizing nanomaterials in nano-refrigerants, surfactant addition is an effective method. Meanwhile, the addition of surfactants could change the thermo-physical properties of refrigerants, including surface tension and viscosity. Therefore, the adding of surfactants may affect the boiling heat transfer characteristics of evaporators. Nuclear pool boiling heat transfer is the fundamental phenomena of nano-refrigerant in evaporator. Therefore, for evaluating the overall property of the evaporator, that is important to understand the influence of surfactant addition on the boiling heat transfer. Peng et al. [13] studied the influences of surfactant addition on the boiling heat transfer of refrigerant based nano-fluids. Three surfactants, sodium dodecyl sulfate (SDS), cetyltrimethylammonium bromide (CTAB) and sorbitol anhydride monooleate (Span-80), were selected in the experiment. Nano-refrigerants were prepared from copper nanoparticles and refrigerant R113. The results show the application of surfactants can enhance the boiling heat transfer in most situations, but it will worsen the heat transfer when the concentration of surfactants is very high. The ratio of boiling heat transfer coefficients (SER) between surfactant-containing and surfactant-free nano-refrigerant is 1.12–1.67, 0.94–1.39 and 0.85–1.29 for SDS, CTAB and Span-80 surfactants, respectively. There is an optimal concentration of surfactant. For the constant concentration of surfactant, SER rises as the decline in nanomaterial mass. The nucleate pool boiling heat transfer correlation of nano-refrigerant with surfactant additives was given. The results show that 92% of the predicted results agree well with the experimental values, and the deviation was within ±25%.

3.2 Nano-refrigerant/oil mixture

Nanomaterials are dispersed into lubricating oil to achieve the purpose of applying nanomaterials to refrigeration system. Furthermore, the refrigerant and oil mixture is existed during the practical operation process of refrigeration system, so the nano-refrigerant/oil mixture also was investigated. Akhavan-Behabadi et al. [43] carried out an experimental study on heat transfer characteristics of R600a/POE/CuO nano-refrigerant flow during condensation inside a horizontal smooth tube. It is shown that significant heat transfer enhancement is achieved by adding nanoparticles to the baseline mixture and pure refrigerant. Dhamneya et al. [44] used nanoparticles in coolers to improve system performance. As increasing the concentration of nanomaterials (titanium dioxide) in refrigerant, the power consumption of compressor decreases and the heat transfer rate increases, thus enhancing system performance. The experimental results indicate in hot and dry climates, the maximum temperature increased by about 51% compared with the normal system. Hu et al. [45] investigated the nucleate pool boiling heat transfer characteristics of refrigerant/nano-lubricant mixture with surfactant. Furthermore, a nucleate pool boiling heat transfer correlation for refrigerant/nano-lubricant mixture was also proposed.

The migration characteristics of nano-refrigerant and nano-refrigerant/oil mixtures during pool boiling are the basic knowledge of the employment of nano-refrigerant in refrigeration cycles. Ding et al. [46] carried out experimental research and numerical simulation on the migration properties. Specifically, the migration characteristics of CuO/R113 nano-refrigerant and R113/CuO/RB68EP nano-refrigerant/oil compound at 0.0912%, 0.183% and 1.536% nanoparticles concentration were studied during pool boiling. The migration process of nanoparticles is exhibited in Fig. 2. The results show that the nanoparticle mass transfer has an increase in initial mass of nanomaterials and refrigerant mass, and the mobility reduces as the increasing concentration. The migration of nanomaterials in nano-refrigerant is greater than that in nano-refrigerant/oil compound. The numerical model was also established to calculate the migration mass of nanomaterials. The deviation between the prediction values and experimental results was 7.7%–38.4%.

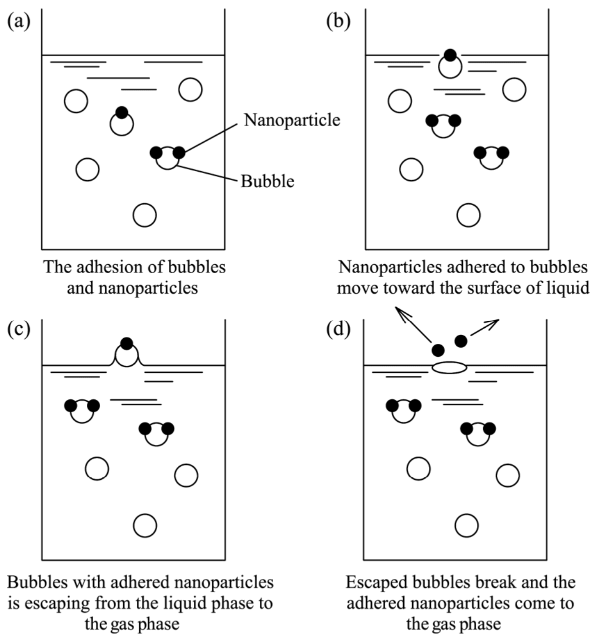


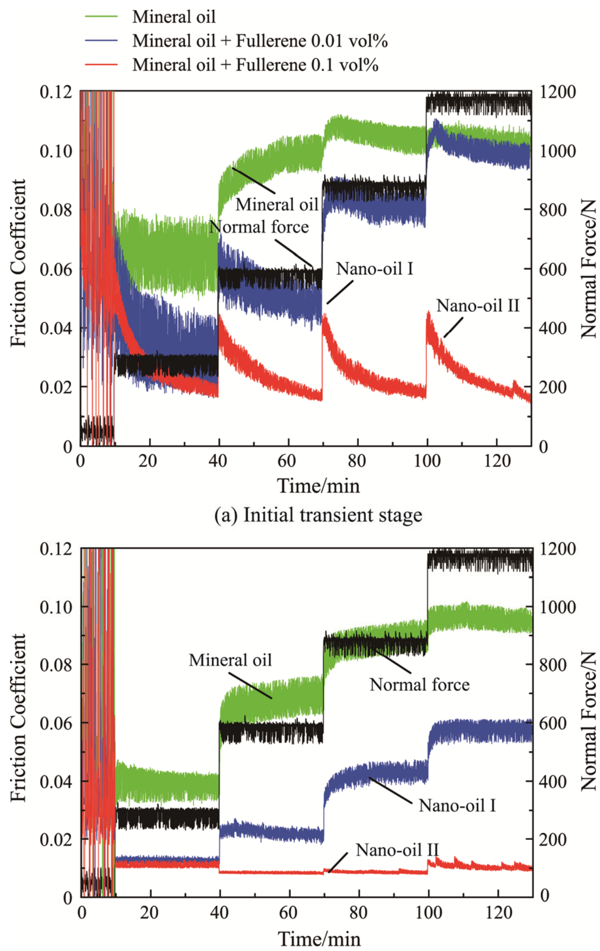
Fig. 2 Migration process of nanoparticles in boiling heat transfer [46]

3.3 Nano-lubricant

Lee et al. [17, 47] studied the lubrication properties of fullerene in refrigeration oils. In the lubrication process, the friction coefficient reduces as the decrease in the viscosity of oil. The wear rate increases with the decrease of lubricant viscosity because of the decline of lubricant bearing capacity. Researchers suggested nanomaterials dispersed in oil could reduce friction coefficient and wear rate. The lubricating oil with nanoparticles is applied to refrigerator compressor to reduce the friction coefficient under the equal or higher bearing capacity. Fullerene nanoparticles with volume fraction of 0.1% were mixed with 8 mm^2/s mineral oil. The lubrication characteristics of pure oil and two types of nano-oils with various concentrations were evaluated via disc lubrication tester. The results indicate friction coefficient is reduced by 90% in comparison with the crude oil as shown in Fig. 3. This is contributed to the polishing result of nanomaterials, that is, the interaction between nanomaterials and the roughness of sample surface. With the improvement of polishing result, the friction coefficient reduces. It declines the friction heat and therefore maintains a bigger viscosity than the crude oil. In a word, nano-lubrication could help to improve the efficiency and reliability of compressors as shown in Fig. 4.

Bobbo et al. [48] investigated the effects of TiO_2 and single-walled carbon nanohorns (SWCNH) on the tribological characteristics of POE lubricant (SW32). The results indicate addition of a small amount of nanomaterials has little effect on the tribological characteristic. TiO_2/SW32 nano-lubricant exhibits the optimal performance in comparison with SW32 and SWCNH/SW32 blends. Jwo et al. [49] researched the application of R12/Al_2O_3/mineral oil system instead of R134a/POE. Aluminum oxide nanomaterials with concentration of 0.05 wt%, 0.1 wt% and 0.2 wt% were added to mineral oils to enhance lubrication and heat transfer characteristics. The results show system using R12 refrigerant exhibits the smaller compression ratio than the cycle using refrigerant R134a. The results show that using hydrocarbon refrigerant instead of R134a refrigerant and dispersed Al_2O_3 nanomaterials in oil can greatly reduce energy consumption.

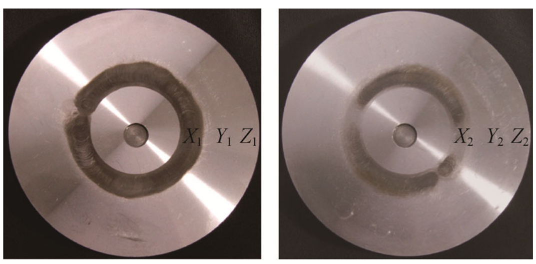
The performance enhancement of fullerene C_{60} nano-lubricant used to the domestic refrigerator compressors are investigated in our previous work [50]. The stability of C_{60} in the lubricant was studied firstly, and then the friction coefficients of prepared nano-lubricants were measured by the four-ball friction pair. The experimental results show that the fullerene C_{60} could steadily disperse in the lubricant at static conditions for a period of time. The friction coefficients greatly reduce as an increase in the concentration of fullerene in the lubricant. Compared to the pure mineral lubricant, the nano-lubricant friction coefficients are reduced 12.9%–19.6% when the concentration rises from 1 g/L to 3 g/L. Finally, the nano-lubricant at the 3 g/L concentration was applied into domestic refrigerator compressors. It is found that the COP of compressor was improved by 5.45%.



(a) Initial transient stage

(b) Steady state

Fig. 3 Friction coefficient [17]



(a) Pure oil (b) Nano-oil

Fig. 4 Wear and surface roughness of the orbiting plate [47]

3.4 Nano-secondary fluid

Adding nanomaterials in the basic fluids like water and salt water might be applied as secondary fluids in the refrigeration equipment. Ndoye et al. [51] established a mathematical model for predicting the performance of nano-fluids secondary circuit refrigeration system in cold chain refrigeration unit. The results show HTC significantly increases with increase in the nanoparticles concentration under laminar and turbulent conditions. But the pressure drop that interrelated with the pump power increases with the increment of the concentration in both flow states. The calculated Performance Evaluation Criterion (PEC) shows energy performance depends largely on the kind of nanomaterials: some nano-fluids (Al_2O_3, SiO_2, TiO_2) is inefficiency in comparison with base liquids, while the energy performance of other nano-fluids (Co, CuO, Fe) is outstanding, and the PEC value reaches 80%. The investigation shows the potential of nano-fluids as secondary fluids to enhance cooling capacity transfer efficiency.

Vasconcelos et al. [22] used water-based SWCNTs nano-fluids as the second refrigerant to test a 4–9 kW indirect vapor compression refrigeration cycle. The experiment was carried out in the range of various volume concentrations of nanomaterials (0–0.21%), inlet temperature (30°C–40°C) and mass flow rate (40–80 g/s). Generally speaking, the property of the cycle using nano-fluids as the second refrigerant is better than that of the basic fluids under the same condition. The improvement of thermal conductivity is considered to be the primary factor. Compared with basic fluids, SWCNTs/water nano-fluids exhibit superior refrigeration capacity and COP. It is concluded that nano-fluids can be applied as secondary fluids in refrigeration equipment.

Purohit et al. [52] theoretically analyzed the property of double pipe gas cooler in trans-critical carbon dioxide refrigeration system applying water-based alumina nano-fluids. Under turbulent conditions, the volume fractions of nano-fluids are 0.5%, 1.5% and 2.5%, respectively. The dramatic changes in thermal and transport characteristics of carbon dioxide near the quasi-critical temperature were studied by appropriate discretization techniques. The results indicate

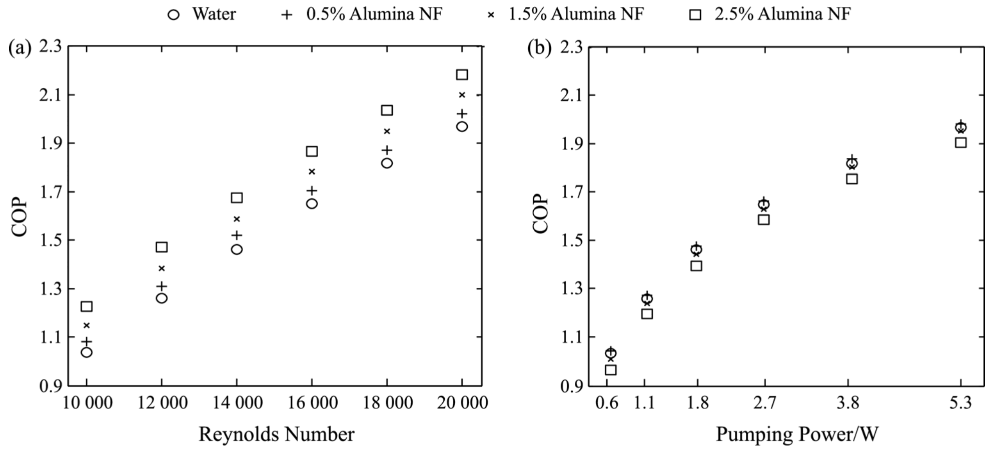


Fig. 5 Variation of COP for water and Alumina nano-fluid [52]

performance of alumina nano-fluid cooling cycle is better in comparison with the water cooling cycle under the same Reynolds number as shown in Fig. 5. On the other hand, the performance of water cooling cycle is better on the basis of equal pump power contrast. Even under the equal mass flow contrast criterion, the performance of nano-fluid cooling cycle will decrease as increasing in the nanomaterial concentration.

4. Application in Absorption and Adsorption Refrigeration

Nano-fluids could be used in absorption and adsorption refrigeration due to the improved heat and mass transfer performance. Yang et al. [30] studied the real working process of real-time disperser installed on NH_3-H_2O refrigeration cycle. The results show that the suspension stability of ammonia-water based nano-fluids can be greatly improved by dynamic cycling process. The influence of sodium dodecylbenzene sulfonate (SDBS) on suspension stability of nano-fluids was studied. The absorption ratio of nano-fluids containing SDBS decreases more quickly compared with nano-fluids without surfactants, and further tends to be flat or tiny increased, which has good long-term suspension stability. Ultrasound vibration makes the suspension stability increase suddenly, but this improvement is unsustainable. The results also show that the dynamic cycling process plays a slight role in the viscosity of nano-fluids, and the variation of surface tension is mainly contributed to the SBDS additive.

Babaei et al. [53] dispersed Fe, Al_2O_3 and SiO_2 three kinds of nanoparticles into LiB-H_2O solution for the efficiency improvement in a novel absorption-recompression refrigeration system. The simulation results show heat transfer is increased in the heat exchanger. Furthermore, the generator and absorber components became more efficient in the presence of nanoparticles, and especially Fe addition is most effective. Bellos and Tzivanidis [54] used a numerical model to study an absorption refrigeration system with LiBr-H_2O working pair driven by a solar collector with nano-fluids. Water and water-based Cu nano-fluids (2% volume fraction) were compared as working fluids in steady-state conditions and daily operations. The results show average thermal efficiency has an increase for nearly 2.5%. In addition, it is confirmed the higher evaporator temperature can improve energy efficiency, but reduce exergy efficiency. In the process of system optimization, it was found that under the optimum conditions of nano-fluids, the evaporation temperature was 7.5°C; the generator temperature was 75.64°C; the exergy efficiency was 0.019 76, and the COP of the system was 0.3995. Furthermore, under the optimum water condition, the evaporation temperature is 8°C; the generator temperature is 74.93°C; the exergy efficiency is 0.019 04, and the COP of the system is 0.3945. Exergy efficiency increased by 3.78% and COP increased by 1.27%. The optimized system was further studied with pure water and nano-fluids on a daily basis as shown in Fig. 6. The results show average daily exergy efficiency and the refrigeration production of the solar collector are increased by 3.99% and 0.84% respectively in the daily simulation of the system.

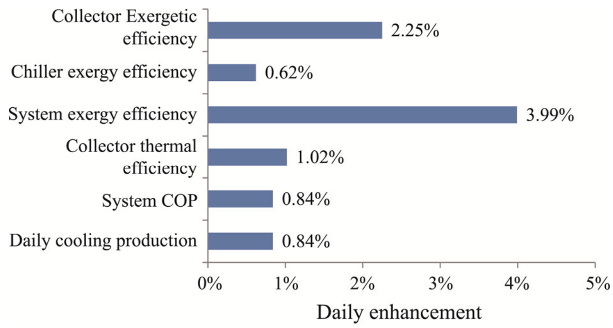


Fig. 6 Daily enhancement of different properties using nano-fluids [54]

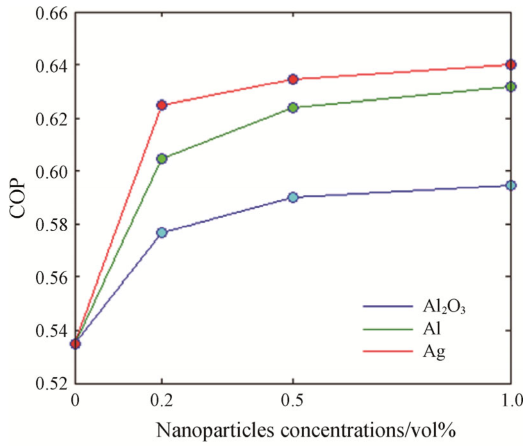
Pourfayaz et al. [55] developed a natural gas hydrogen-rich composite absorption chiller cycle composed of a high temperature polymer fuel cell and a fuel processing system. In this paper, water-based nano-fluids are used as absorbents to improve COP, and their influences on the overall property are evaluated. The specific heat capacity and density of nano-fluids were evaluated by normal mixing theory. The famous Einstein viscosity formula is used to calculate the viscosity of spherical particles with fraction under the 5.0 vol%. The thermal conductivity of nano-fluids is decided by the concentration, size and temperature of nano-materials. The effect of concentration, size and temperature on thermal conductivity can be obtained by using the formula. The types and thermo-physical properties of nano-fluids are shown in Table 3.

Table 3 Thermal properties of nano-fluids [55]

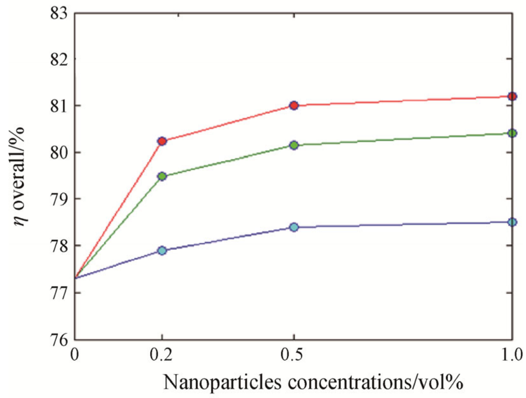
Metal	Atomic weight	ρ/ g·cm^{-3}	C_p/ J·g^{-1}·K^{-1}	K/ W·cm^{-1}·K^{-1}
Al	26.98	2.7	0.904	2.37
Ag	107.87	10.5	0.235	4.29
Al_2O_3	101.96	3.97	0.89	0.3

The steady-state simulation of the hybrid refrigeration cycle was carried out using Aspen HYSYS software. The influence of nanomaterials on the characteristics of refrigeration cycle and composite system is shown in Fig. 7. The electric efficiency and total efficiency of the hybrid cycle are 36% and 77.3%. With the application of silver nano-fluids, the total efficiency can be raised by 81%. Exergy analysis of the hybrid cycle shows that the exergy efficiency is 29%. Sensitivity analysis is used to evaluate important parameters of hybrid power system performance.

Hamrahi et al. [56] projected and manufactured a solar-powered continuous-running adsorption refrigerator using micro-nano activated carbon-methanol as working pair, as shown in Fig. 8. Unlike the traditional refrigerant system which only refrigerates at night, the proposed two-bed continuous refrigeration system can still refrigerate during the day. The main purpose is to study the influence of nano-activated carbon on the property of adsorption refrigerators. In the following experiments, nano-activated carbon with concentrations of 4.7 wt%, 11.1 wt% and 18.3 wt% was added to the bed, and the experiments were conducted under the temperature of 30°C or 34°C. The results indicate adsorption capacity of activated carbon nanoparticles at different concentrations was increased. Therefore, the adsorption capacity and the COP of the system increase at this time. Adding nano-activated carbon with concentrations of 4.7 wt%, 11.1 wt% and 18.3 wt% to the adsorption bed under 30°C and 34°C can increase COP by 11% and 21%, 33% and 17%, 23% and 25%, respectively.



(a) The COP of refrigeration system



(b) Hybrid system efficiency

Fig. 7 Effects of nano-fluids on system performance [55]

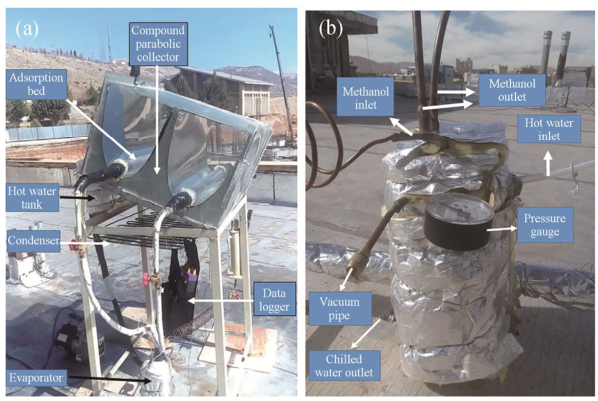


Fig. 8 (a) Solar adsorption chiller with two beds; (b) Evaporator [56]

5. Application in Ejector Refrigeration

Recently, the application of nano-fluids in the ejector refrigeration was also reported. Tashtoush et al. [57] studied the property of ejector refrigeration cycle applying nano-refrigerant. The variation of HTC as the temperature, nanomaterial type, particle size and concentration was studied by parameter analysis. Finally, the influence of nanomaterials on the performance coefficient of ejector refrigeration system was studied via simulating a 5 kW refrigeration system. For the advantages of applying nano-refrigerants, higher quality steam is obtained at the outlet of the evaporator, thus increasing the enthalpy difference of the evaporator in the refrigeration system as shown in Fig. 9. Therefore, the mass flow rate in the evaporator is lower when the same cooling capacity is obtained. The enhanced refrigerant side HTC increases the HTC of the whole evaporator, allowing the evaporator to work at smaller temperature difference and higher pressure, thus increasing the COP of the refrigeration cycle.

In addition, the quality of refrigerant vapor at the outlet of the evaporator increases, which leads to the increase of COP. When the mass fraction of CuO and Al_2O_3 is 2%, the COP of R134a system increases by 24.7% and 12.61%, respectively, while the vapor mass of refrigerant at evaporator exit increases from 0.7616 of refrigerant to 0.8212 of R134a/CuO nano-refrigerant. Nano-refrigerants enhance the heat transfer properties of pure refrigerants. At the same time, the presence of nanoparticles increases the pressure drop in the evaporator tube with increasing in the equal viscosity and density. In addition, the influence of nanomaterials on pressure drop varies directly as the density, concentration and diameter of nanoparticles, mass flow rate of refrigerant and inner diameter of evaporator tube. Therefore, to select nano-fluids as working fluids, the improvement of HTC and the increase of head loss in circulation must be taken into account.

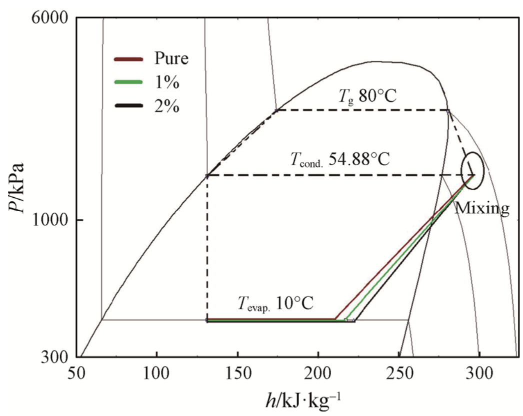


Fig. 9 Pressure-enthalpy chart [57]

6. Application in Other Refrigeration

According to the progressive nanotechnology, nano-fluids are applied in refrigeration and cooling systems. Boyaghchi et al. [58] modeled and optimized a new type of micro-cogeneration cycle powered by solar and geothermal energy in Fig. 10. The copper oxide nano-fluid dispersed in the water is used as heat transfer fluid of heat collection sub-system. The results of multi-objective optimization show the optimization effect of R134a is the best, which is 30.73% and 1.33% higher than the basic situation, respectively in consideration of energy and exergy. In addition, R423A shows the best refrigerant that has the smallest total heat transfer area. In this case, compared with other research fluids, the maximum collection area and the minimum concentration of nanoparticles are required.

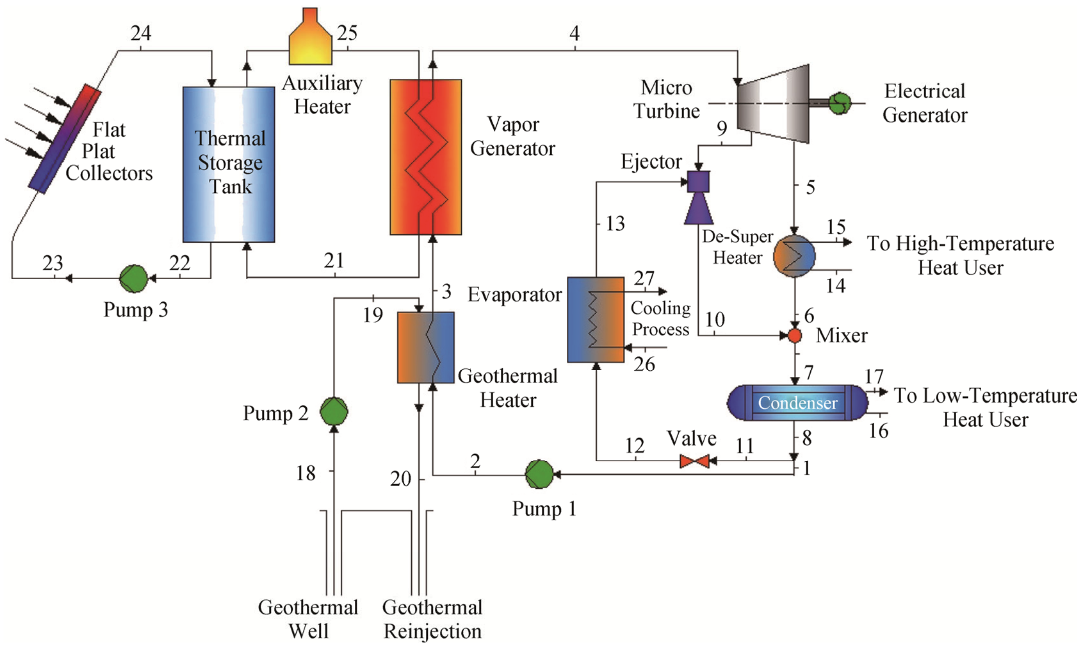


Fig. 10 System schematic diagram of Ref. [58]

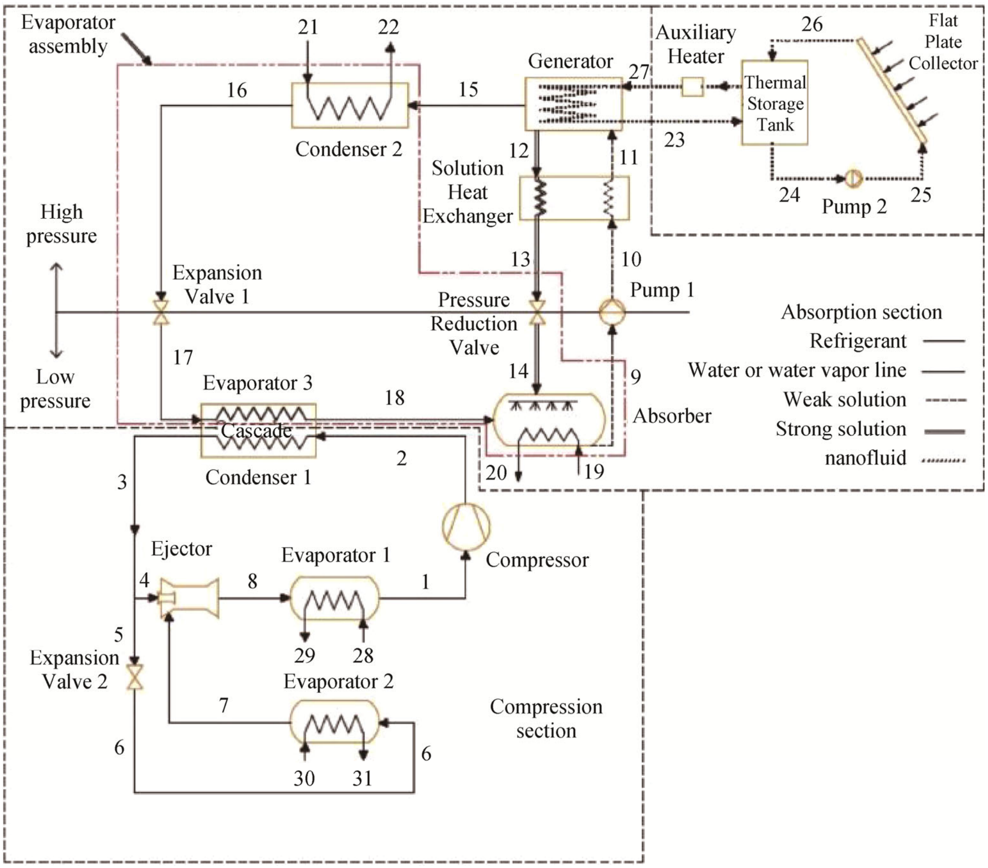


Fig. 11 The proposed DEVCACRS schematic [59]

In 2016, Boyaghchi et al. [59] modeled and optimized the new type vapor compression/absorption with flat panel solar collector cascade refrigeration system as shown in Fig. 11. LiBr/water is used as working pair in the absorption section of cascade system; R134a, R1234ze, R1234yf, R407C and R22 are used as refrigerants in vapor compression cycle, and water/cupric oxide nano-fluids are used as heat transfer fluid in solar collector sub-system. The results of model calculation show R134a is the optimal refrigerant in terms of energy and exergy. The daily energy and exergy efficiency are 9.340% and 0.5815%. The optimal results show daily energy and exergy efficiency of R134a are increased by 2.4% and 2% respectively. Moreover, the maximum nanoparticles and collecting area required for R1234ze with a 2.4% reduction in total product cost were 0.0141 vol% and 702.01 m^2, respectively.

Qi et al. [33] prepared stable water-based alumina and titanium dioxide nano-fluids. The experimental device for heat transfer properties of CPU cooled by nano-fluids was built, and the heat transfer and flow characteristics of nano-fluids in the CPU radiator were studied. The influences of concentration of nanoparticles (Al_2O_3: 0.1%–2%; TiO_2: 0.1%–1%) and Reynolds number on heat transfer and flow properties were investigated. Furthermore, the thermal and hydraulic properties of nano-fluids were evaluated comprehensively. It is found the higher mass fraction, the better heat transfer performance of nano-fluids. Nusselt number firstly rises and further reduces with the increase of concentration. For water-based alumina and titanium dioxide nano-fluids, the optimum mass fractions of nanoparticles are 1.0 wt% and 0.4 wt%, respectively. Compared with water, the CPU temperature of water-based Al_2O_3 and TiO_2 are decreased by 23.2% and 14.9%, respectively.

Wongcharee et al. [60] discussed the influences of CuO/H_2O nano-fluids concentration and swirl on jet impingement cooling. CuO/H_2O nano-fluids were employed to rotate impinging jet to enhance heat transfer. The results indicated Nusselt number of nano-fluids with volume fractions of 2.0% and 3.0% is higher than that of basic fluids, while the Nusselt number of nano-fluids at concentration of 4.0% is the opposite.

The research progress of nano-fluids in automotive engine cooling cycle was reviewed by Sidik et al [61]. The engine cooling cycle applying nano-fluids supplies the novel basis for technology combination and innovation. Because of its high thermal diffusivity, nano-fluids are considered potential coolants and can be used in any system requiring rapid response to thermal changes, such as automotive engines. For the cooling systems, nanomaterials could be added in the oil to improve its thermal conductivity. Besides, the nanomaterials could also enhance the lubricating property of oil and decrease friction. But the optimal content of nanomaterials in oil is still unclear. Another way to cool engine systems is to add nanomaterials into traditional cooling radiators. Compared with the original cooling liquid, the HTC could be increased by 50%, but the pressure drop restricts the efficiency of the cooling cycle. In the situation, most of researchers believe best cooling system characteristic could be obtained at the lower amount of nanomaterials (<1%). Meanwhile, there are still some problems and challenges in the mechanism and practical application of heat transfer enhancement. At present, the research of nano-fluids for engine cooling cycle is still in the infancy and requires growth.

7. Conclusions

Refrigeration systems are responsible for increasing energy consumption. Nano-fluids have shown significant potential in enhancing the performance of refrigeration cycles. The conclusions are shown as follows:

(1) Nano-fluids could be formed by one-step or two-step methods. The two-step method is broadly used for nano-fluids preparation in engineering applications because of advantages of convenience and low cost. Moreover, the thermo-physical properties like thermal conductivity, viscosity, density and specific heat are greatly influenced by the addition of nanoparticles.

(2) There are three ways to improve property of vapor compression refrigeration cycle by using nano-fluids as nano-refrigerant, nano-lubricant and nano-second refrigerant. Nano-fluids applied in the vapor compression refrigeration cycle could enhance heat transfer properties and compressor energy efficiency, further increases refrigeration capacity, reduces compressor power consumption and finally improves the performance of refrigeration system.

(3) Nano-fluids are applied to absorption and adsorption refrigeration systems by adding the nanoparticles into the working pair or secondary cycle driving fluids such as solar collectors. The absorbency ratio or adsorption capacity would be enhanced, and then the cooling performance would be improved.

(4) Applying nano-refrigerant in the ejection refrigeration system, the improved refrigerant side heat transfer enhances the overall heat transfer. At the same time, the quality of refrigerant vapor at the outlet of the evaporator increases, which leads to the increase of COP.

(5) Nano-fluids are also employed in some compound or cascade refrigeration systems. Nano-fluids improve the heat transfer characteristics of base fluids. However, the presence of nanoparticles increases pressure drop as increasing in viscosity and density. Thus, the improvement of HTC and the increase in head loss in circulation must be taken into account when using nano-fluids.

For choosing the appropriate nano-fluids in various refrigeration systems, there are some principles to follow. Firstly, it is worth noting that viscosity of nano-fluids deserves as much attention as thermal conductivity. Pumping power and pressure drop depends on viscosity. Moreover, extreme percentage of nanoparticles could create clogging in refrigeration system. Therefore, nano-fluids with low concentrations are suggested for better performance of a refrigeration system. As a result, optimal nanoparticle concentration is important to be considered in preparing nano-fluids that can enhance the performance of refrigeration systems. During last decade, different kinds of nanomaterials, such as metal, metal oxide, carbon etc., have been used to develop nano-fluids in refrigeration systems. However, the mechanism or reason is not clear yet. So more correlations, simulations and experiments are necessary to be studied in future work.

Acknowledgements

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