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REVIEW ON THE USE OF NANOFLUID IN HEAT EXCHANGERS

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Abstract. *This paper presents a review of studies on the use of nanoparticles in suspension as the working fluids of compact mini-split heat exchangers. There are several studies indicating the feasibility of applying nanoparticles in refrigeration systems and resulting in increased efficiency. The physical properties of nano refrigerants, mainly viscosity and thermal conductivity, are fundamental parameters for analyzing heat transfer and drag coefficients when designing a climatization system. This review presents recent experimental and theoretical research on thermal conductivity and viscosity of nanofluids. Results reveal that viscosity and thermal conductivity are function of base fluid and particle's shape, size, temperature, and concentration. Particle concentration has a positive correlation with thermal conductivity, but the effects of particle size, shape, base fluid property, and temperature are not similar. In addition, the main difficulties and future challenges are reviewed in the literature and presented at the end of this article.*

Keywords: *nanorefrigerants, heat exchangers, air-condition, nanofluid*

1. INTRODUCTION

The high-performance cooling is a vital need for many industrial technologies. However, the thermal conductivity of refrigerants is low compared to metals, which is the main limitation in the development of heat transfer fluids with greater energy efficiency (Das et al., 2008). The nanofluid arose with the purpose of improving this limitation of the thermal fluid, so that the nanofluid is a dispersion of nanoparticles (metallic and non-metallic particles with sizes between 1 to 100 nm) in conventional thermal fluids, with the purpose of improving the thermal performance of the base fluid. The nanoparticles being studied for this purpose are commonly metals or their oxides, or carbon-based particles of which must be less than 100 nm in at least two dimensions (Akhavan-Behabadi et al., 2015).

Numerous theoretical and experimental studies show the increase in thermal conductivity and the various factors that influence it. Types of nanofluids have developed and expanded greatly in recent decades. Most current models of thermal conductivity of nanofluids are influenced by the thermal conductivity of the nanoparticle (Yang et al., 2017). In addition, other factors such as type, concentration, size and temperature of the nanoparticles have also been extensively investigated. Thus, several theoretical research and calculation models on the thermal conductivity of nanofluids have been proposed considering these specific influencing factors.

Viscosity is an important property in a thermal system that must be determined, as it is directly linked to the coefficient of fluid friction, pressure drop and pumping power. Viscosity interferes with the speed of the nanofluid and is a determining factor in the temperature distribution and, thus, affecting heat transfer (Rashidi et al., 2014). Therefore, before designing a heat transfer system with nanofluids as the working fluid, viscosity must be determined by experimental or numerical measurements. As well as the thermal conductivity, parameters such as type, concentration, size, temperature of the nanoparticles, were studied by several researchers. This article reviews the current experimental and modeling studies conducted on the viscosity and thermal conductivity of nanofluids, considering the parameters mentioned above.

2. THERMAL CONDUCTIVITY

Thermal conductivity is the main exploitable factor in the use of nanofluids. Currently, there are several experimental and theoretical investigations on the thermal conductivity of various types of nanofluids and showing different results. Even for the same type of nanofluid, the measured values of thermal conductivity are quite different in different works. The manuscripts should be written in English, typed in A4 size pages, using font Times New Roman, size 10, except for the title, authors affiliation, abstract and keywords, for which particular formatting instructions are indicated above. Single space between lines is to be used throughout the text.

2.1 Experimental studies

2.1.1 Influence of the type of nanoparticles

In general, the increase in the thermal conductivity of nanofluids depends directly on the type of nanoparticle used. They can be classified into three groups: advanced materials and structures (such as graphene and carbon nanotubes), simple metals with high thermal conductivity (such as Au, Cu, Ag, Fe) and metallic and non-metallic oxides (such as CuO, Al_2O_3, TiO_2, ZnO, SiC). In the same nanoparticle load, the higher thermal conductivity of the nanoparticle corresponds to a greater increase in the thermal conductivity of the nanofluids. Purbia et al. (2019) studied graphene oxide nanofluids dispersed in water and compared them with nanofluids containing Al_2O_3 and TiO_2. The results showed that for the 0.1% concentration of nanoparticles, the thermal performance of the graphene-containing nanofluid increased in the range of 40% to 300 % in relation to pure fluid. For the Al_2O_3 and TiO_2 nanoparticles, an increase of about 27% and 25% was observed, respectively, Figure 1. shows the performance of the nanoparticles.

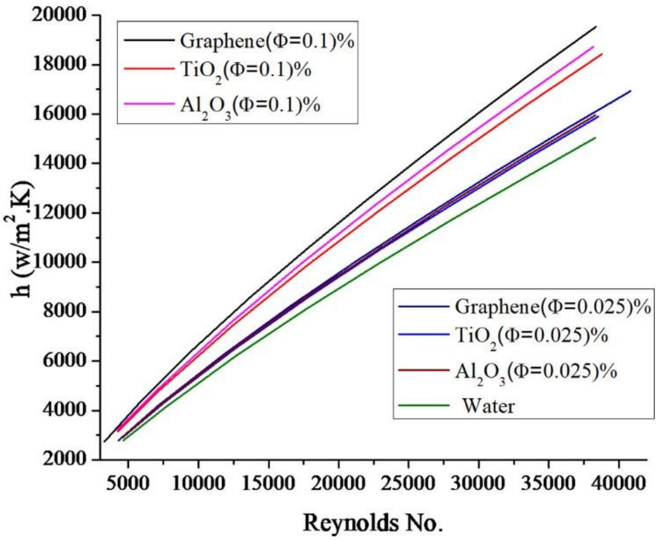

Figure 1. Performance of nanoparticles as a function of Reynolds number (Purbia et al. 2019)

2.1.2 Concentration of nanoparticles

Numerous experiments involving the concentration of nanoparticles were carried out, of which it was possible to observe the great influence of the concentration of the nanoparticles. Zheng et al. (2020) in their study found that the Fe_3O_4-water nanofluid with a 1.0 wt% nanofluid concentration showed a 21.9% increase in the convection heat transfer coefficient. However, the pressure drop rose by 10.1%. Zhong et al. (2020) experimentally investigated TiO_2 nanoparticles dispersed in water (with concentrations between 0.5% and 1%) and observed that the addition of nanoparticles not only increases the thermal conductivity by 4.2% on average, but also significantly increases the viscosity in 14.9% for the 1% nanofluid. Kang et al. (2006) found that, keeping constant parameters, nanofluids formed by Ag dispersed in water showed an increase in thermal conductivity from 3% to 11% with an increase from 0.1% to 0.39% in the concentration of nanoparticles. In their study Purbia et al. (2019) compared different concentrations of graphene oxide and observed that for higher concentrations there is an increase in the pressure drop Figure. 2. In general, the increase in the concentration of the nanoparticle increases the thermal conductivity of the nanofluids, however there is also an increase in the drop system pressure.

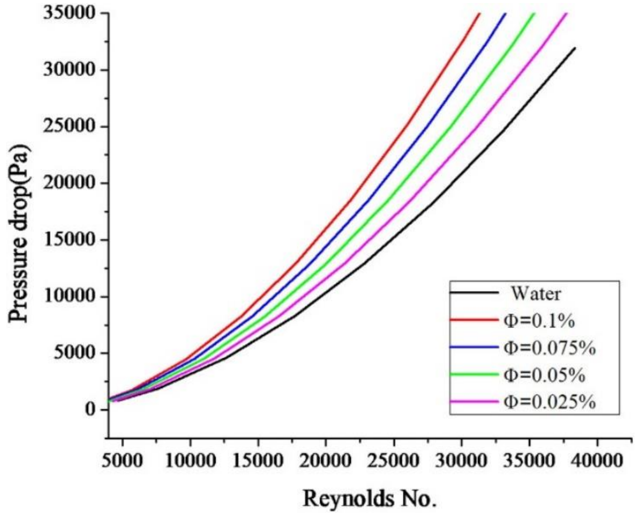

Figure 1. Performance of nanoparticles as a function of Reynolds number (Purbia et al. 2019)

2.1.3 Nanoparticle temperature

Arccording to Hasona et al. (2018) the temperature is directly linked to the Brownian movement and the clustering effect, consequently the thermal conductivity of the nanofluid. Even though a more drastic Brownian movement can increase the thermal conductivity of the nanofluids, the influence of the grouping effect is negative for the Brownian movement. Therefore, the increase in temperature does not always contribute to the improvement of thermal nanofluids and, sometimes, the results can be reversed.

Most of the results have positive effects on the thermal conductivity of the nanofluids, increasing the temperature. Abareshi et al. (2010) found that, for water nanofluids with a concentration of 1% Fe_3O_4, the temperature variation from 10 to 40ºC represented an increase in thermal conductivity from 2.8% to 8.9%. Ranjbarzadeh et al. (2019) analyzed the thermal conductivity of the SiO_2 nanofluid in the temperature range and volume fraction of 25 to 55 °C and 0.1 to 3.0%, respectively. The results revealed that for the volume fraction of 3.0%, the greatest increase in thermal conductivity of 33% is observed at a temperature of 55 °C. The positive effects were also found in Ijam et al. (2015), Huminic et al. (2015), Sabiha et al. (2016).

Negative effects of increased temperature can be seen in the study by Ignacio et al. (2015) prepared a water-based nanofluid by dispersing SiO_2 nanoparticles with particles in the 40 to 65 nm range. They determined the thermo-physical properties in the concentration and temperature range of 1 to 5% by volume and 30 to 70 °C, respectively. The amplification in the dynamic viscosity and thermal conductivity of the SiO_2 nanofluid of 5% concentration is 202% at 30 °C and 50% at 70 °C, respectively, compared to water.

2.1.4 Nanoparticle size

The effect of increasing the size of the nanoparticle generally tends to decrease the thermal conductivity of the nanofluids. Sharifpur et al. (2017) investigated the effect of the change in particle size and temperature variation on the thermal conductivity of the α-Al_2O_3 - glycerol nanofluid. The particle size used in this study was 31 nm, 55 nm and 134 nm. It was observed that the increase in the size of the nanoparticles decreases the thermal conductivity. Esfe et al. (2015) studied the effect of changing the concentration and size of the nanoparticle on the MgO/water nanofluid. The nanoparticle diameters used were 20, 40, 50 and 60 nm. The results showed a tendency to increase conductivity when there is a decrease in the size of the particles. Paul et al. (2010) studied the size effect of Au nanoparticles dispersed in water, their results confirm the decrease in thermal conductivity with the increase in the size of the nanoparticle.

2.2 Theoretical Models

There are many theoretical models created to determine the effective thermal conductivity of nanofluids, the most common models are based on the concentration of nanoparticles, thermal conductivity of the nanoparticle and the base fluid, type of nanoparticle. There are also theoretical models that consider the effect of heat exchange by convection caused by Brownian motion and the effect of the temperature of the nanofluid.

Maxwell's model (Maxwell 1873) is considered in the literature as the first mathematical model to determine the thermal conductivity of suspensions. The model is based on a suspension containing homogeneously dispersed hard spherical particles. Thus, Maxwell's model is defined in Eq. (1):

$$k_{ef} = k_{fb} + 3\varphi \frac{k_p - k_{fb}}{2k_{fb} + k_p - \varphi(k_{fb} - k_p)} k_{fb} \quad (1)$$

Where kef, k_{fb}, k_p are the effective thermal conductivities, base and particle fluid respectively and φ is the concentration of the particles.

Introducing an empirically obtained form factor, Hamilton & Crosser (1962) modified Maxwell's equation. Thus, the thermal conductivity of the fluid / particle system becomes a function of the volumetric concentration and the shape of the particle. The empirical form factor, that is, the sphericity ψ of the particle is defined as the ratio between the surface area of a sphere with a volume equal to that of the given particle and the surface area of that particle. Hamilton & Crosser found the following Eq. (2) for the effective thermal conductivity of a mixture:

$$k_{ef} = k_{fb} + 3\psi^{-1}\varphi_p \frac{k_p - k_{fb}}{(3\psi^{-1} - 1)k_{fb} + k_p - \varphi(k_{fb} - k_p)} k_{fb} \quad (2)$$

Where ψ is the particle sphericity.

Corsione (2011) proposed a model for the effective thermal conductivity of the nanofluid based on a variety of experimental data related to nanofluids that were carried out with nanoparticles of alumina, copper oxide, titanium or copper. His model focused on the Brownian movement of particles influenced by temperature and uses the freezing point of the base fluid as a reference point. The model is expressed by Eq. (3):

$$\frac{k_{ef}}{k_{fb}} = 1 + 4{,}4\mathrm{Re}^{0{,}4}\mathrm{Pr}_{fb}{}^{0{,}66} \left(\frac{T}{T_{fr}}\right)^{10} \left(\frac{k_p}{k_{fb}}\right)^{0{,}03} \varphi^{0{,}66} \quad (3)$$

Where Re is the Reynolds number of the particle, Pr is Prandtl number of the base fluid, T is the temperature of the nanofluid, T_{fr} is the solidification point of the liquid base.

Garoosi [22] proposed a new empirical correlation to estimate the thermal conductivity of nanofluids. The equation was developed from a variety of nanofluids with volume fractions ranging from 0% to 12%, nanoparticle size from 10 nm to 5 µm and nanoparticle type Ag, Cu, Fe, Al, AlN, $CaCO_3$ and several nanoparticles of metal oxide. The model agreed well with Corcione's correlation and demonstrated excellent agreement with the experimental data Eq. (4):

$$k_{ef} = k_{fb} \frac{k_p + 2k_{fb} + 2\varphi(k_p - k_{fb})}{k_p + 2k_{fb} - \omega\varphi(k_{fb} - k_p)} + 3{,}762 \left(\frac{T}{T_0}\right)^{8{,}661} \left(\frac{d_p}{d_{fb}}\right)^{-0{,}4351} \left(\frac{k_p}{k_{fb}}\right)^{0{,}08235} \varphi^{0{,}64} e^{(-5{,}742\varphi)} \quad (4)$$

Where d_{fb} is the equivalent diameter of the base fluid molecule and Eq. (5) ω is the correction factor Eq. (6) and are defined by:

$$d_{fb} = 0{,}1 \left(\frac{6M}{N\pi\rho_{fb}}\right)^{\frac{1}{3}} \quad (5)$$

$$\omega = 1 + 0{,}8946\varphi \quad (6)$$

Where M, N and T_0 are the molecular weight, Avogadro's number and the reference temperature respectively.

In their study Timofeeva et al. (2007) suggested an average effective thermal conductivity for nanofluid, which is expressed by Eq. (7):

$$k_{ef} = k_{fb}(1 - 3\varphi) \quad (7)$$

Xue (2005) created a thermal conductivity model aimed at nanofluids containing CNT, expressed by Eq. (8):

$$k_{ef} = k_{fb} \frac{1 - \varphi + 2\varphi \frac{k_p}{k_p - k_{fb}} \ln \frac{k_p + k_{fb}}{2k_{fb}}}{1 - \varphi + 2\varphi \frac{k_{fb}}{k_p - k_{fb}} \ln \frac{k_p + k_{fb}}{2k_{fb}}} \quad (8)$$

3. VISCOSITY

In general, studies of nanofluids are associated with the performance of heat or mass transfer. Therefore, determining the viscosity behavior of the nanofluid becomes essential for the analysis of flow resistance and pumping power, in order to identify its viability in an air conditioning system. As viscosity is linked to dimensionless numbers (Nusselt number and Reynolds number) it has, the flow speed, a great influence on heat transfer. This section presents experimental results and modeling investigations to show the progress of the research.

3.1 Experimental studies

Many experimental studies on the viscosity of nanofluids have resulted in an increase in viscosity associated directly with increased concentration of nanoparticles, however it is possible to observe the same result in experiments with different concentrations. Silambarasanet al. (2012) and Jarahnejad et al. (2015) in their studies with TiO_2 nanoparticles dispersed in water as the base fluid found that the absolute viscosity decreases with temperature growth, but the effective viscosity remains practically constant in addition to appearing to be independent of temperature. However, the research by Yapici et al. (2014) revealed that temperature has a large effect on the effective viscosity rate in the low shear rate condition, but has little effect in the high shear rate condition. Raj and Subudhi (2018) studied solar collectors using particles, they observed that the efficiency of the collector increased as the volume fraction increased. However, due to the excessive increase and due to the high viscosity of the fluid, the rate of heat transfer has decreased. Thus, they observed that there is an ideal way to choose this parameter. In addition, the use of carbon nanotubes had maximum thermal performance in the considered system.

Aravind et al. (2011) studied the viscosity of nanofluids containing CNT in a very low concentration of 0.005% and 0.03% with water and EG as the base fluid. As a result, it was possible to observe that the relative viscosity of CNT nanofluids is not influenced by the type of base fluid, however at 70 ºC the relative viscosity of the nanofluid was greater than 30 ºC. Phuoc et al. (2011) studied nanofluids of water with a concentration of 0.5% CNT, they observed that the nanofluids of CNT had lower viscosity than distilled water. From this observation, they concluded that this lower viscosity is caused by the lubricating character of nanoparticles. Aladag et al. (2012) studied water nanofluids with Al_2O_3 nanoparticles and water with CNT at low temperatures (from 2 ºC to 10 ºC) and low concentrations. Experiments showed that nanofluid suspensions indicated Newtonian or non-Newtonian behavior, depending on the shear rate. In addition, the water-based nanofluid and CNT behave like Newtonian fluid at high shear speeds, while the water-based nanofluid and Al_2O_3 nanoparticles are non-Newtonian within the range of investigated low temperatures. According to reported studies, the use of nanofluids does not guarantee an improvement in the overall performance of the heat exchanger. The increase in thermal conductivity and density leads to increased heat transfer.

3.2 Experimental studies

Theoretical formulas have been proposed to determine the viscosity of nanofluids. They are based on Einstein's pioneering model (Einstein A. 1956). The model assumes a viscous fluid with a concentration of less than 1% of rigid spherical particles and does not consider the interactions between them. The model is expressed by Eq. (9):

$$\mu_{ef} = \mu_{fb}(1 + 2{,}5\varphi) \tag{9}$$

Brinkman (1952) presented a viscosity correlation that extended the Einstein equation to suspensions with a particle concentration below 4%. The correlation is expressed by Eq. (10):

$$\mu_{ef} = \mu_{fb}\frac{1}{(1-\varphi)^{2,5}} \tag{10}$$

Batchelor's model (1977) considers the Brownian movement of nanoparticles and their interactions. The model is expressed by Eq. (11):

$$\mu_{ef} = \mu_{fb}(1 + 2{,}5\varphi + 6{,}5\varphi^2) \tag{11}$$

Guo et al. (2006) updated the Batchelor correlation to involve the particle size effect. They found that the small particle size induces a higher viscosity in nanofluids, then by Eq. (12):

$$\mu_{ef} = \mu_{fb}(1 + 2{,}5\varphi + 6{,}5\varphi^2)\left(1 + 350\,\frac{\varphi}{d}\right) \tag{12}$$

Corsione (2011) proposed another model to define the viscosity of nanofluids. Based on experimental results, Corsione applied linear regression, obtaining the best fit with a standard deviation of error of 1.84%, resulting in Eq. (13):

$$\mu_{ef} = \mu_{fb} \frac{1}{1 - 34{,}87\left(d_p / d_{fb}\right)^{-0{,}3} \varphi^{1{,}03}} \tag{13}$$

In his study, Garoosi (2020) defined the Eq. (14) to determine the viscosity of nanofluid applied to various types of nanoparticles:

$$\frac{\mu_{ef}}{\mu_{fb}} = 1 + 49{,}6\left(\frac{d_p}{d_{fb}}\right)^{-0{,}414} \varphi^{0{,}908} e^{(10{,}8\varphi)} \tag{14}$$

Although there have been many viscosity models for nanofluids, none are sufficiently accurate due to the various types of nanofluids. Therefore, to deal with different types of nanofluids, there are also many models of semi-empirical viscosity targeted at certain types of nanofluids.

4. CONCLUSION

This article presents a review of experimental and theoretical studies on the thermal conductivity and viscosity of nanofluids, in order to demonstrate the feasibility of the application in mini-split type air conditioning systems. The type of nanoparticles has a great effect on thermal conductivity so that NTC and metal nanoparticles show a greater increase than oxide and non-metal nanoparticles. The type of material has little effect on the viscosity of the nanofluids with the exception of the NTC which have a lubricating character, and thus, decreasing the viscosity of the base fluid. Most results show that viscosity and thermal conductivity increase with increasing particle load. And the rise in temperature can reduce absolute viscosity, but with no effect on relative viscosity. The experimental results, in general, demonstrate Newtonian behavior of nanofluids with a concentration below 4%. Although the factors described in this review are studied in many modeling researches, the main flaw in theoretical research is associated with a lack of predictability and application to determine thermal conductivity and viscosity in different types of nanofluids. In general, the theoretical model presented by Garoosi to determine the thermal conductivity and viscosity of the nanofluids showed better application for a wide variety of nanoparticles and base fluids.

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