Analytical investigation of energy performance in secondary loops of refrigeration systems using different nano materials additives

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Abstract: The energy performance in a secondary loop of refrigerating systems using nanomaterials additives was investigated analytically. In order to predict the performance of these systems an analytical model was developed. A combination of the Effectiveness-Number of Transfer Units method and traditional heat transfer and fluid dynamics correlations was used to develop this model. The Performance Evaluation Criterion (PEC: is the ratio between the heat transfer rate and the pumping power required) was used to evaluate the benefit of using nanofluids instead of pure fluids. The model was validated using the data find in the literature. model was done for a tubular heat exchanger with different Reynolds number (laminar and turbulent regimes), and for different types of nanoparticles (Al_2O_3, Ag, Au, TiO, TiO_2, Fe, Co, Cu, CuO, diamond and graphite) with different volume fractions. The results showed that the heat transfer rate significantly increased with the increase of nanoparticles concentration. But, the pumping power is also increased with the increase of nanoparticles concentration for laminar and turbulent flow regimes. PEC value results have shown that the energy performance is dependent on the type of nanoparticles: some of them (Al_2O_3, TiO, TiO_2, diamond and graphite) were less efficient than the pure fluid while the others (Ag, Cu, Au, Co, CuO, and Fe) were more efficient.

Keywords: Nano materials, Refrigeration, Secondary loop, Analytical, Energy.

1. INTRODUCTION

Recently, Egypt is facing an energy problem due to the increase in consumption. In the face of this problem there are two ways; first the world should be more interested in renewable energy resources and the second is the efficient use of energy. Thermal systems like refrigerators and air conditioners consume large amount of electric power. So, development of energy efficient refrigeration and air conditioning systems with lower electric consumption need to be explored. The rapid advances in nanotechnology have led to the emergence of new generation heat transfer fluids called nanofluids. Nanofluids are prepared by suspending nano sized particles (1-100nm) in conventional fluids to have higher thermal conductivity than the base fluids. Based on the applications, nanoparticles are currently made out of a very wide variety of materials, such as metal and metal oxide ceramics. (Macchi et al., 1999; Poggi et al., 2008; Wang et al., 2010) increase the heat transfer of the secondary loop system by using nano fluids with higher heat transfer properties. It can be used in secondary loop system throughout cold chain (Kumaresan et al., 2013). Choi and Eastman (1995) used nano particles instead of millimeter or micro meter particles for the first time in order to increase the thermal conductivity with avoiding stability and clogging problems (Vajjha et al., 2010; Ferrouillat et al., 2011, 2013; Mare' et al., 2011; Ferrouillat et al., 2013; Mahbubul et al., 2013a,b). Results showed that although nanofluids have higher thermal conductivity it also have higher pumping power and pressure drop due to viscosity increase (Kim et al., 2007; Jung et al., 2011; Saidur et al., 2011; Yang et al., 2012; Mahbubul et al., 2013a,b, Soliman et al. 2015). They have used nanoparticles additives to the traditional refrigerants and oils for different applications. Their results showed that energy consumption decreases by using nano particles additives due to the increase in heat transfer rate. Mare' et al. (2011) investigate the thermal performance of plate heat exchanger by using two nano fluids within temperature between 0 and 10°C. Their results showed that convective heat transfer increased by using nanofluids. Moreover, they referred to the connection between thermal performance and pressure drop. Sarkar (2011) and Kumaresan et al. (2013) investigated the use of nano fluids in secondary loop of refrigeration at temperatures above 0°C. They only studied the thermal performance of the system without taking into account the pressure drop.

The above literature shows that few studies have investigated the energy performances in a secondary loop of refrigerating systems using nano fluids of different nano material types. In the present study mathematical model developed to investigate the effect of using different types of nano material additives with wide variety of concentration on the heat transfer rate and pumping power through tubular heat exchanger. The model was validated with data given in the literature.

2. NUMERICAL MODEL

In order to calculate the heat transfer coefficient and the pressure drop in the system, thermophysical properties of nanofluids must be first calculated.

2.1. Thermophysical Properties of Nanofluids

2.1.1 Density

The density of nano fluid can be calculated by using the following equation (Vajjha et al., 2009):

$$\rho_{nf} = (1- \Phi_v)\, \rho_{bf} + \Phi_v \rho_p \qquad (1)$$

where Φ_v is the volume fraction of nano materials in the nanofluid, ρ_{bf} is the density of the base fluid and ρ_p is the density of nano materials . (Vajjha et al., 2009) had validated this equation through experiments for different nano material types.

2.1.2 Specific heat

The nanofluids specific heat can be calculated using the following equation (Murshed, 2011):

$$C_p = \frac{(1 - \Phi_v)\rho_{bf}\, Cp_{bf} + Cp_p}{\rho_{nf}} \qquad (2)$$

Where Cp_p , Cp_{bf} are the specific heat of nanomaterials and of the base fluid, respectively. This equation is derived from the mass fraction mixture rule. This equation had been validated by (Murshed, 2011) through experiments with a wide variety of nanomaterial and base fluid types.

2.1.3 Thermal conductivity

The nanofluids thermal conductivity can be calculated using the following equation (Hamilton and Crosser (1962):

$$k_{nf} = k_{bf}\left[\frac{k_p + (n-1)k_{bf} - (n-1)\Phi_v\,(k_{bf} - k_p)}{k_p + (n-1)k_{bf} + \Phi_v\,(k_{bf} - k_p)}\right] \qquad (3)$$

Where K_{bf} is the thermal conductivity of the base fluid, K_p thermal conductivity of the particles, $n=3/\psi$ and ψ is the particle sphericity. This equation is proposed by (Hamilton and Crosser (1962)) and it is used for spherical and no-spherical particle shape

2.1.4 Dynamic viscosity

The nanofluids viscosity can be calculated by using Thomas equation:

$$\mu_{nf} = \mu(1 + 2.5\Phi_v + 10.05\Phi_V^2 + 0.00273\ \exp(16.6\Phi_v)) \tag{4}$$

Where μ is the density of base fluid

2.2. Calculation of Heat Transfer Rate and Pumping Power

In order to calculate the PEC (Performance Evaluation Criterion), heat transfer rate and pressure drop must be calculated. First of all to calculate heat transfer coefficient inside the tubular heat exchanger equation (5) was used .Nu can be calculated using equations (6 and 7) depending on the flow regime, where Darcy coefficient (Λ) is also calculated with two different correlations depending on the type of flow (equations 8 and 9). After that pressure drop can be calculated using equation (10). Finally ε-NTU approach has been applied to calculate the nano fluid outside temperature using equations (11, 12, 13, 14, 15 and 16) respectively. Notice that cr is the ratio between the minimum and the maximum heat capacity equal zero because of the refrigerant flowing outside the tube is evaporating. PEC can be calculated now using equation (17).

$$h_i = \frac{Nu\,K}{d_i} \tag{5}$$

$$Nu = 3.66 \text{ For Laminar flow Re<2300} \tag{6}$$

$$Nu = \frac{(\Lambda/8)(Re - 1000)Pr}{1 + 12.7(\Lambda/8)^{1/2}(Pr^{2/3} - 1)} \quad \text{For turbulent flow Re>2300} \tag{7}$$

$$\Lambda = \frac{64}{Re} \quad \text{For Laminar flow Re<2300} \tag{8}$$

$$\Lambda = (1.82 \log_{10}(Re) - 1.64)^{-2} \quad \text{For turbulent flow Re>2300} \tag{9}$$

$$\Delta P = \Lambda \frac{L}{2d_h} \frac{m^{\cdot 2}}{\rho_{nf} s^2} \tag{10}$$

$$E = \frac{1 - \exp(-NTU(1 - C_r))}{1 - C_r \exp(-NTU(1 - C_r))} \tag{11}$$

$$E = \frac{T_{h,i} - T_{h,o}}{T_{h,i} - T_{c,i}} \tag{12}$$

$$E = 1 - \exp(-NTU) \tag{13}$$

$$NTU = \frac{UA}{m^{\cdot}\mathrm{Cp}} \tag{14}$$

$$\frac{1}{U} = \frac{1}{h_i} + R_w + \frac{1}{h_s} \tag{15}$$

$$R_w = \frac{d_i}{2k_w} \ln(\frac{d_s}{d_i}) \tag{16}$$

$$PEC = \frac{m^{\cdot} Cp(T_o - T_i)}{v^{\cdot} \Delta P} \tag{17}$$

3. RESULTS AND DISCUSSION

A copper tubular heat exchanger with tube having a length of 0.5 m, an inner diameter of 4 mm, a thickness of 1 mm and thermal conductivity of 400 W/mK. The inlet temperature of nanofluids was = -20°C and the evaporator temperature = -30°C. Laminar and in turbulent flow regimes were studied with different Reynolds number values of (100, 1500, 5000 and 8000). Different types of nano materials with different concentration were used (Al_2O_3, TiO_2, SiO_2, Co, Fe and CuO). The thermo-physical properties of the different nano materials are show in Table 1. Water was chosen as base fluid. The thermo-physical properties of water can be calculated through equations (18, 19, 20 and 21) by knowing its temperature.

Table 1: Thermophysical properties of different nano materials.

Nano material type	density (Kg/m^3)	Specific heat (J/Kg K)	Thermal conductivity (W/m K)
Al_2O_3	3960	773	40
diamond	3500	509	3300
Ag	10490	235	429
Au	19300	129	317
TiO	4930	711	330
Fe	7870	449	80.2
Co	8865	421	100
Cu	8940	385	401
CuO	6000	551	33
TiO_2	4230	692	8.4
graphite	2160	701	120

$$K(\mathrm{T}) = 1.5362\,(10)^{-8}\,\mathrm{T}^3 - 2.261\,(10)^{-5}\,\mathrm{T}^2 + 0.010879\mathrm{T} - 1.0294 \tag{18}$$

$$\rho(\mathrm{T}) = -1.5629\,(10)^{-5}\,\mathrm{T}^3 + 0.011778\,\mathrm{T}^2 - 3.0726\mathrm{T} + 1277.8 \tag{19}$$

$$\mathrm{Cp}(\mathrm{T}) = 1.1105\,(10)^{-5}\,\mathrm{T}^3 - 0.0031078\,\mathrm{T}^2 - 1.478\mathrm{T} + 4631.9 \tag{20}$$

$$\mu(\mathrm{t}) = 2.1897\,(10)^{-11}\,\mathrm{T}^4 - 3.055\,(10)^{-8}\,\mathrm{T}^3 + 1.6028\,(10)^{-5}\,\mathrm{T}^2 - 0.0037524\mathrm{T} + 0.33158 \tag{21}$$

3.1. Model Validation

Figure 1 shows the validation result with (Ferrouillat et al., 2011), they used water as a base fluid and three concentration of Sio_2 nano materials. It is clear that there were a strong agreement between experimental result of (Ferrouillat et al., 2011) and the results obtained from the present model.

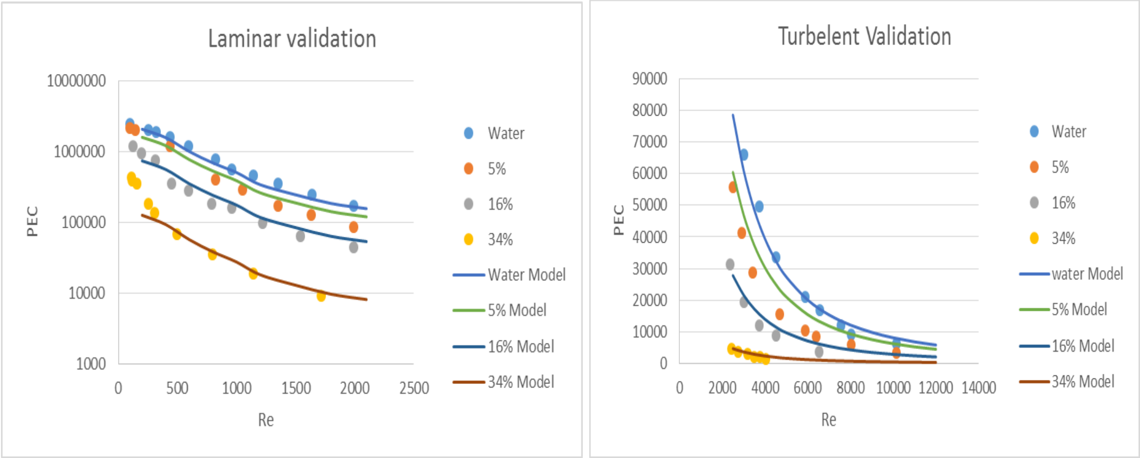
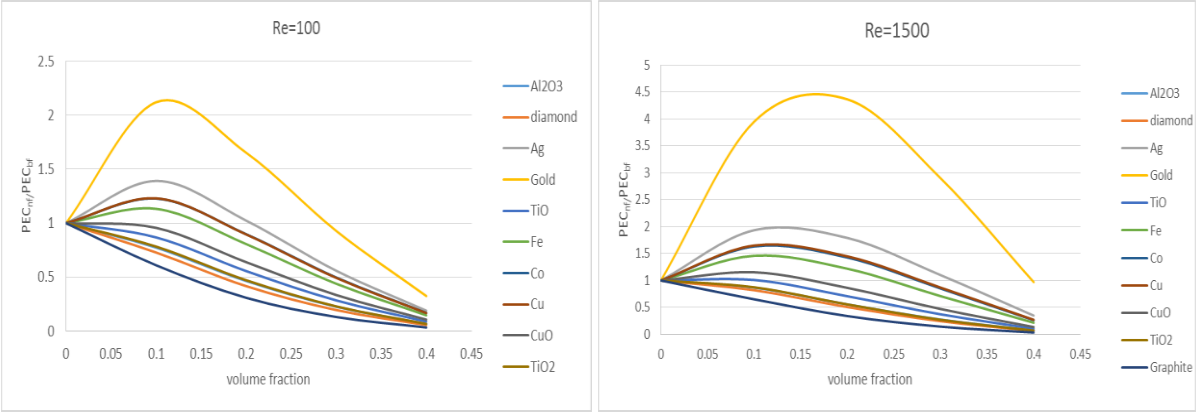


Figure 1: Laminar and turbulent flow regime validation results.

3.2. Energy Performance

Variation of the PEC ratio with nano materials volume fraction for different flow regime and different nano materials type are shown in Figure 2. It is clear that the PEC ratio strongly depend on the material type and the value of the Reynolds number. For example for Re = 100, we found that 4 nano particles types only show an increase in PEC ratio (Gold, Ag, Cu and Fe) while others types show decrease in PEC ratio. Moreover, for Re = 1500, 6 types shows an increase in PEC ratio (Ag, Cu, Au, Co, CuO, Fe) while the other types were less efficient. Figure 3 shows the Heat transfer enhancement as a function of the nanoparticles volume fraction for different types of nanoparticles and for different Reynolds numbers. The figure shows that the heat transfer coefficient increases with volume fraction of nanoparticles irrespective of the type of particles or the flow regime. Also the thermal conductivity increases with the increase of volume fraction of nano particles whatever it's nanoparticle type and its flow regime as shown in Figure 4. Figure 5 shows the variation of the pressure drop ratio with nano materials volume fraction for different nano materials type. It is also clear that pressure drop increases with the increase in volume fraction which means that the pumping power will increase and PEC value will decrease. Figure 6 and 7 shows the variations of the dynamic viscosity and density of nanofluids as a function of the nanoparticles volume fraction. Viscosity and density of nano fluids increases by the increase in volume fraction of nano particles.



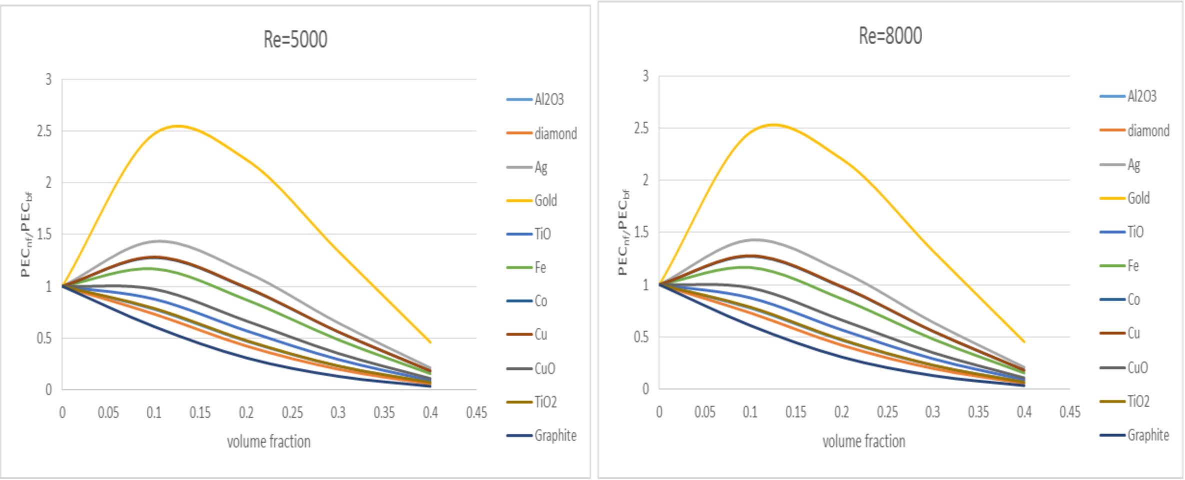


Figure 2: Effect of nanoparticles additives volume fraction increases on PEC ratio for different nano materials and different Reynolds numbers 100; 1500; 5000 and 8000.

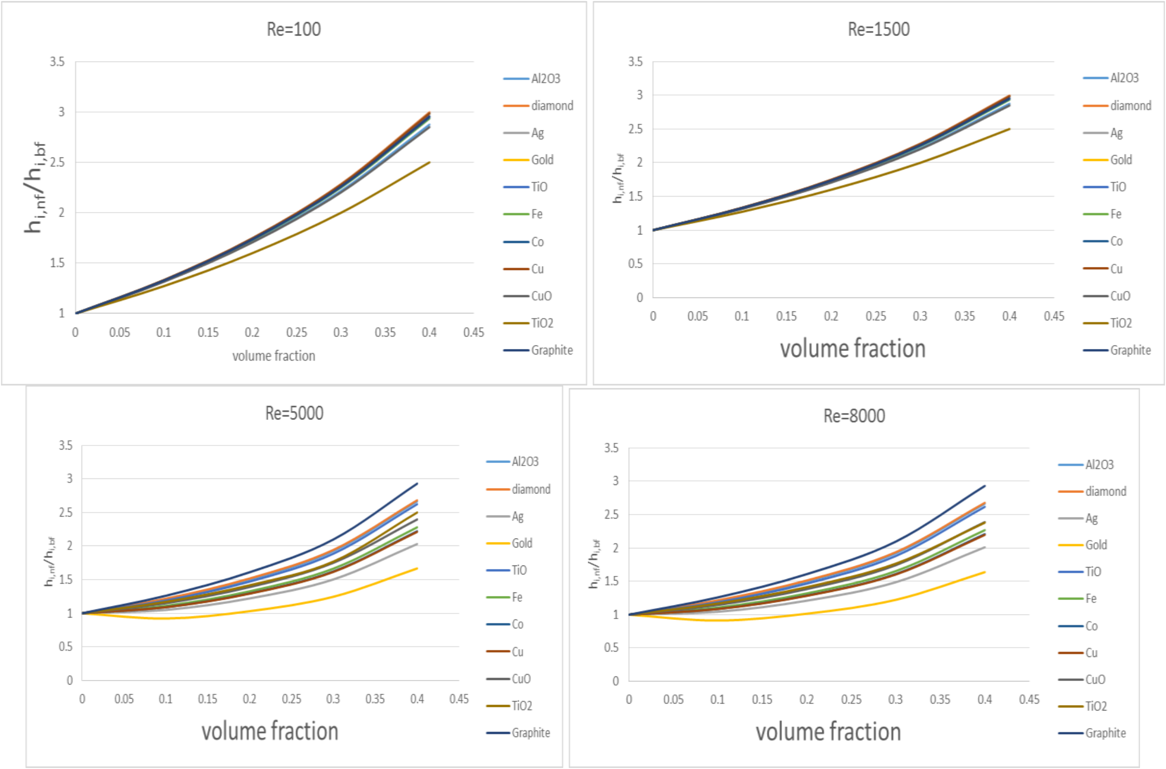


*Figure 3: **Variation of** Heat transfer enhancement with nanoparticles volume fraction for different nano materials and different Reynolds numbers 100; 1500; 5000 and 8000.*

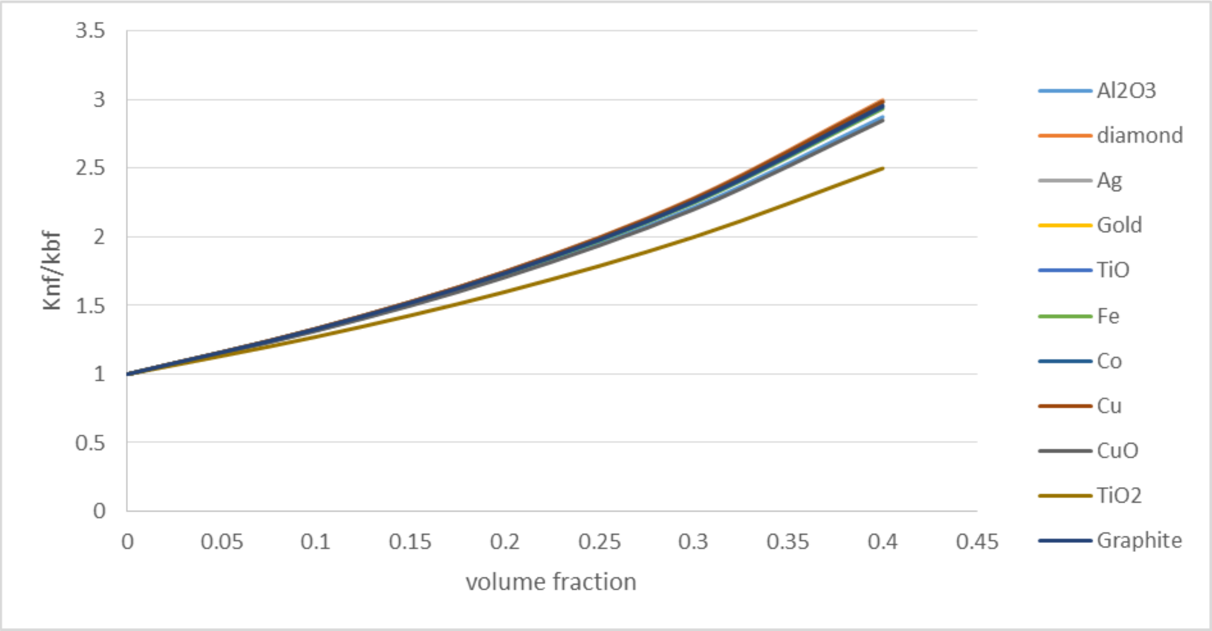


Figure 4: Variation of thermal conductivity ratio with nanoparticles volume fraction for different nano materials

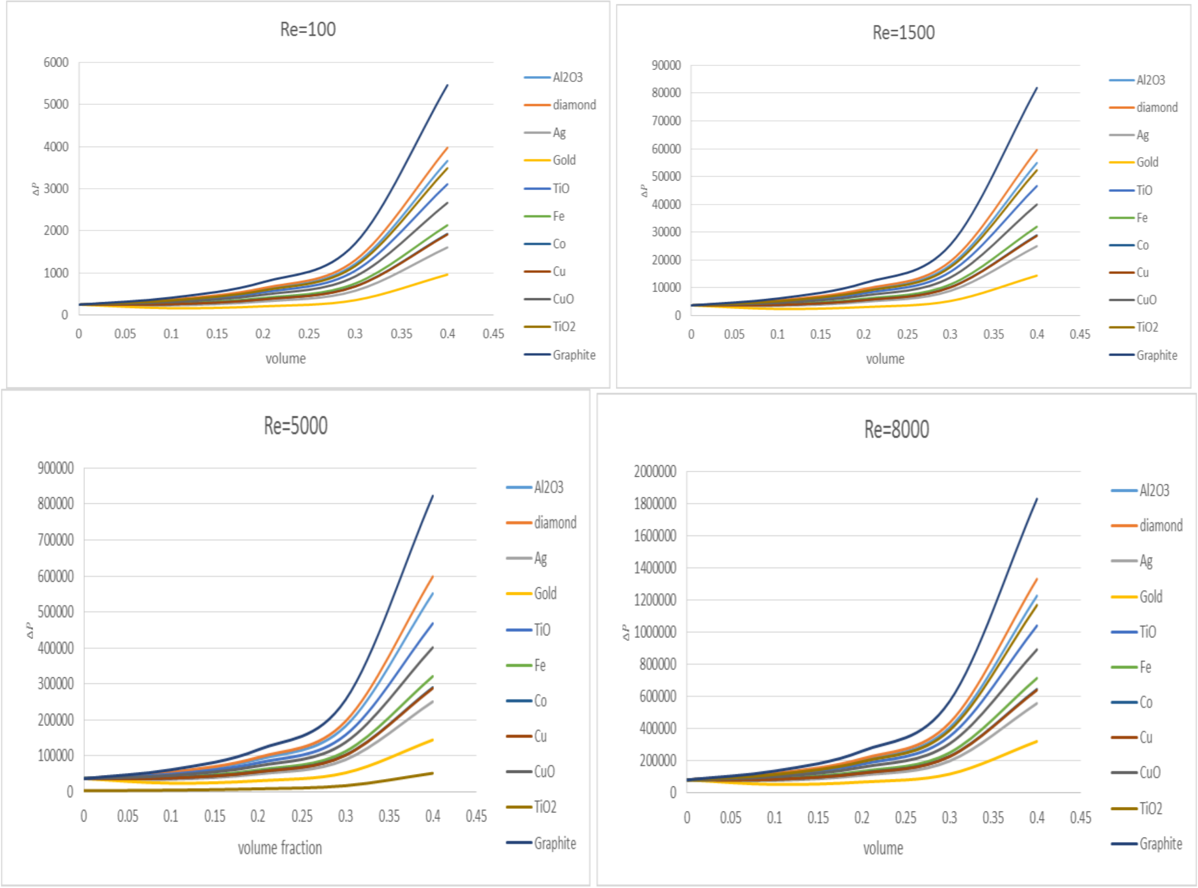


Figure 5: Effect of nanoparticles additives volume fraction increases on pressure drop ratio for different nano materials and different Reynolds numbers 100; 1500; 5000 and 8000.

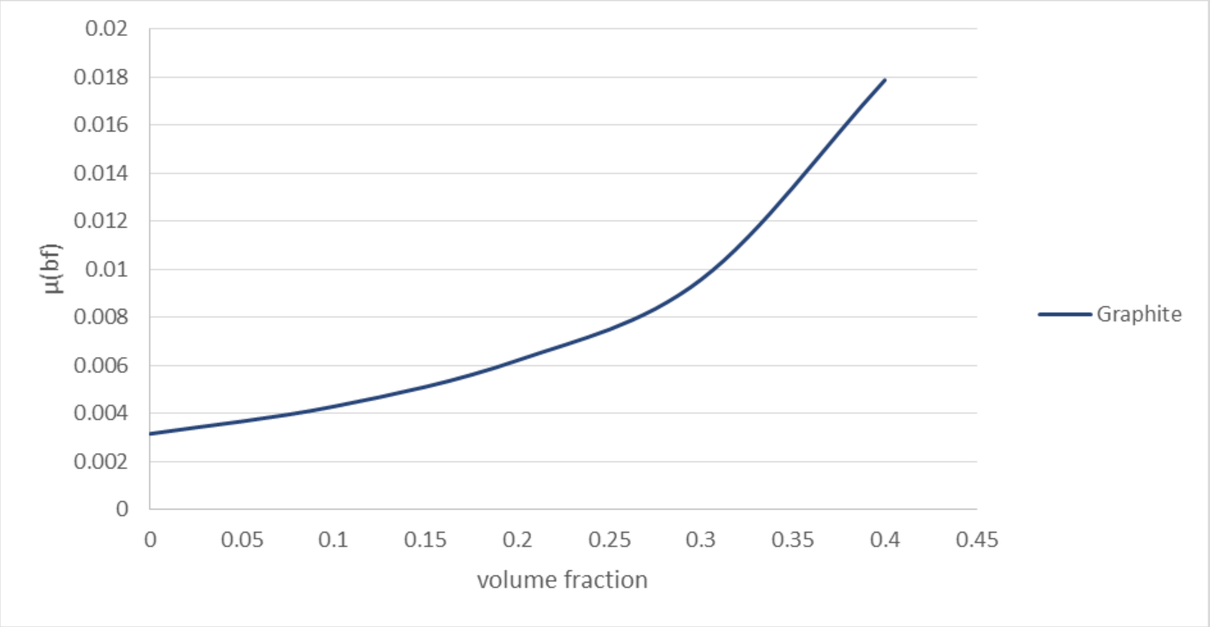


Figure 6: Variation of the dynamic viscosity of nanofluids with nanoparticles volume fraction

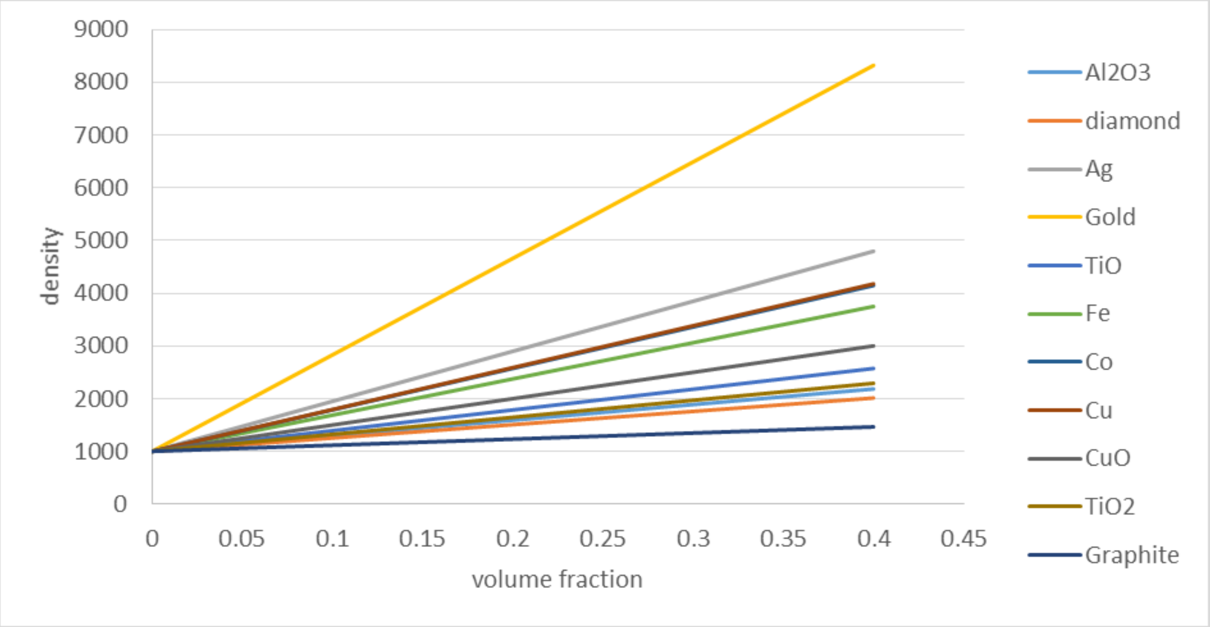


Figure 7: Variation of density of nanofluids with nanoparticles volume fraction for different nano material types

4. CONCLUSION

A model was developed to investigate the energy performances in a secondary loop of refrigerating systems using nanomaterials additives. Traditional heat transfer and fluid dynamics correlations develop in addition to Effectiveness-Number of Transfer Units method was used to this model. The Performance Evaluation Criterion (PEC) was used to evaluate the benefit of using nanofluids instead of pure fluids. PEC is the ratio between the heat transfer rate and the pumping power required. The results showed that the PEC value is strongly dependent of nano material type, gold nano material was the best efficient while graphite had the lowest figures. That is because the heat transfers coefficient and the pumping power increases with the increase in volume fraction. Sometimes the increase in heat transfer was bigger than the increase in pumping power and sometimes wasn't. The model was validated using the data find in the literature. Cooper tubular heat exchanger was used in model with different Reynolds number values (laminar and turbulent regimes), and for different types of nanoparticles (Al_2O_3, Ag, gold, TiO , TiO_2, Fe, Co , Cu, CuO , diamond and graphite) with different volume fractions. Thermal conductivity, density and dynamic viscosity of the nano fluids increases whatever the nano material type is.

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