Thermophysical properties of Copper/Water nanofluid for automotive cooling system – Mathematical modeling

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ABSTRACT

Nanofluid is an advanced fluid with enhanced thermophysical properties that has been introduced in many applications for better heat transfer process. In automotive cooling system, conventional coolants such as water and ethylene glycol could have superior thermophysical properties of thermal conductivity, viscosity, density and heat transfer coefficient by introducing nanoparticles suspension. This study investigated the thermophysical properties of Copper/Water nanofluid by using mathematical modeling approach to come out with a new coolant for Louvered-fins and flat tube of a radiator. The nanofluid showed enhanced thermophysical properties with nanoparticles suspension of 2 vol.% to 10 vol.%. By offering 10 % of copper nanoparticles concentration, the heat transfer coefficient of the nanofluid was increased up to 26000 $W.m^{-2}K^{-1}$ with enhancement of 92 %. Consequently, it also enhanced the heat transfer rate in the cooling system. The different particles sizes of 10 nm, 50 nm, and 100 nm showed different heat transfer coefficients but the heat transfer rate in the radiator is similar, up to 64400 W with 10 % of nanoparticle volume fraction. The nanofluids showed better heat transfer characteristics as a new alternative coolant for the radiator.

KEYWORDS:*Nanofluid, mathematical modeling, automotive radiator, thermophyscal properties.*

1.0 INTRODUCTION OF NANOFLUIDS AND RADIATOR

Nanofluids have been a new research area for the past years as an approach to enhance the heat transfer rate in many applications. Many investigations through experimental works, mathematical modeling and simulation have been done to begin with massive implementation of nanofluids in important modern equipments and systems like air-conditioner, automotive cooling system, electronics, and medical equipment. Nanofluids is a potential fluid with superior properties to replace conventional fluids such as water, deionised water, refrigerant, coolant, lubricant, etc. The term of "nanofluids" has been introduced by Choi in 1995 at Argonne Research Laboratory as an advanced fluid that showed superior heat transfer properties with nanoparticle suspensions (Choi, 1995).

The nanofluids have been grouped based on their applications which occasionally called as nanolubricant or nanorefrigerant, which is also one kind of nanofluids which depends on the type of conventional fluids. Nanofluids studies mainly involved thermal conductivity and heat transfer

coefficient of the nanofluids since the thermophysical properties show a very significant influence in heat transfer processes. Murshed et al. (2007) stated that the thermal conductivity of nanofluids varies with three attributes; size, shape and material of nanoparticles. Other properties such as viscosity, density and surface tension of nanofluids have also been explored to obtain reliable results for massive implementation in future. The nanofluids have superior thermophysical properties which have been proved since past decades by many researchers due to the suspension of nanoparticles. The nanoparticles could be metal, non-metal or carbon nanotubes (CNTs) which must be dispersed in conventional fluids to produce nanofluids.

Eastman et al. (1997) proved that the thermal conductivity of nanofluids that contains CuO, Al_2O_3 and Cu nanoparticles with two different base fluids; water and HE 200 oil showed 60% improvement for the thermal conductivity as compared to the corresponding base fluids for only 5 vol% of nanoparticles suspension. Nanoparticles suspended into the refrigerant (nanorefrigerant) also has higher thermal conductivity than conventional pure refrigerant (Jiang et al., 2007). The superior of nanofluids thermophysical properties in consequence of the nanoparticles dispersion have been demonstrated to the world. Nowadays, the stage of research is changing from investigating the thermophysical properties based on the nanoparticles types and nanoparticles volume fraction to the development of nanofluids in diverse industries to make it useful as a new energy-efficient heat transfer fluid in real world application.

The superior properties and stability of nanofluids are considered as main research areas as it challenges the significance of nanofluids implementation in existing application such as radiator and air-conditioners. Suitable material of nanoparticle is crucial to be identified in order to be suspended in different types of base fluids. The size of nanoparticles, temperature, and optimum concentration of nanoparticles must be considered carefully. These factors are important to be considered so that high thermal conductivity and heat transfer coefficient of nanofluids could be obtained without causing agglomeration, instability, corrosion, high pressure drop and pumping power (Saidur et al., 2011; Leong et al., 2010; Han, 2008)

An automotive cooling system usually consists of radiator, water pump, thermostat, radiator pressure cap, and electric cooling fan (Maple, 2008). The radiator is the main component as it was designed to remove heat from an engine block by using specified coolants. Generally, the coolant of the radiator is either water or water and ethylene glycol (anti-freezing fluid), which flows inside the tubes. In fact, the coolants have poor heat transfer properties in nature. Another type of coolant is outside air which flows through the fins to cool down the temperature of water. Nowadays, the researchers and engineers from automotive industries have been applying green technology concept and desiring for a compact engine system with low fuel consumption. Consequently, the study of nanofluids as an application in the automotive industries has developed throughly. By introducing nanofluids with superior thermophysical properties, the radiator size can be reduced but at the same time, it is offering identical heat transfer rate. The frontal area of a car could be redesigned to reduce aerodynamic drag so that less fuel consumption is required (Leong et al., 2010; Wong et al., 2010).

Argonne researchers proved that despite nanofluids thermal conductivity depends on temperature and particle volume fraction, it still showing high thermal conductivity than conventional radiator coolants (Choi, 2011). The heat transfer rate and thermal performance of Cu/EG coolant in an automotive radiator can be enhanced by increasing the particle volume fraction from 0 % to 2 % (Leong et al., 2010). The enhancement of heat transfer depends on air and coolant Reynolds number (*Re*) which is increasing with nanoparticle concentration. Mare et al. (2011), experimentally proved that the convective heat transfer coefficient of CNTs nanofluid increased about 50 % in comparison to water for the same Reynolds number. Basically, there are five factors that can enhance the heat transfer; Brownian motion, layering at the solid/liquid interface, Ballistic

phonon transport through the particles, nanoparticles clustering, and friction between the nanoparticles and fluid (Wang and Mujumdar, 2007). Meanwhile, Xuan and Li (2003) agreed dispersed phase of nanoparticles caused pressure drop slightly but the nanoparticles dispersion is stable either with surfactant or conventional fluid only. Razi et al. (2011) investigated the heat transfer and pressure drop of CuO-base oil nanofluid flow inside horizontal flattened tubes under constant heat flux of 2600 W/m^2 and proved that the pressure drop of nanofluids increased with nanoparticle concentration. There is also a withdrawn investigation of nanofluids natural convective heat transfer since the suspension of nanoparticles caused higher viscosity and pressure drop as compared to conventional fluid (Calvin & Peterson, 2010).

Therefore, there are a lot of factors that need to be considered when deciding to introduce specified nanofluid as a new alternative for heat transfer enhancement.This study aims to improve the heat transfer rate in an automotive cooling system by introducing copper/water nanofluids as a new coolant in the system. The mathematical modeling approach is used to investigate the effects of nanoparticles volume fraction on the nanofluids thermal conductivity and the heat transfer coefficient. The thermal properties are used to determine overall total heat transfer rate of a car radiator.

2.0 METHODOLOGY

Three different sizes of copper nanoparticles; 10 nm, 50 nm and 100 nm are used to identify the effect of nanoparticle size on nanofluid thermal conductivity. The thermal conductivities of the nanofluids from the diverse nanoparticles sizes are used to determine the heat transfer rate of a louvered-fin flat tube radiator as shown in Figure 1. The heat transfer rate in the radiator considered only the conventional coolant; water (0% copper nanoparticle suspension) is 64.354 kW based on the mathematical modeling and radiator specification shown in Table 2.

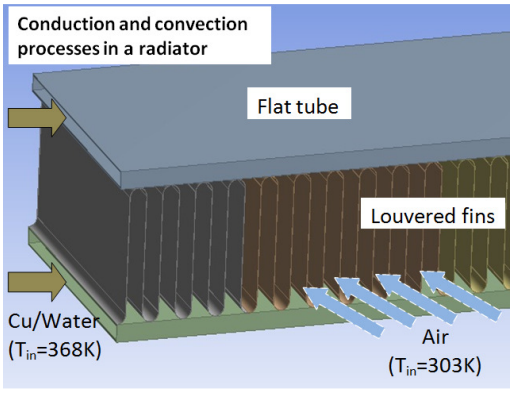

FIGURE 1
Louvered-fins and flat tube of a radiator

The effects of nanoparticles concentration; 2 vol.% to 10 vol.% on thermal conductivity and heat transfer coefficient are investigated by using mathematical modeling from other studies (Maple, 2008; Leong et al., 2010). In advance, the properties of water, air and copper are identified and tabulated as shown in Table 1. From Table 1, it shows that the thermal conductivity of copper (nanoparticles) is significant higher than water (conventional fluid). For this reason, the main basis of suspending the copper nanoparticles is to enhance the thermal conductivity of the conventional fluid (coolant).

TABLE 1
Properties of coolants and nanoparticle (Yunus, 2004)

Properties	Water (368 K)	Air (303 K)	Cu (300K)
Density, ρ [kg.m^{-3}]	962	1.15	8933
Thermal Conductivity, k [W.m^{-1}K^{-1}]	0.678	0.0263	401
Specific heat, C_p [Jkg^{-1}.K]	4212	1007.12	385
Dynamic viscosity, μ [kgm^{-1}s^{-1}]	2.96 x 10^{-4}	1.86 x 10^{-5}	-

Table 2 shows a geometry description of a car radiator that has been used to calculate the overall heat transfer rate by introducing Copper/Water nanofluid to replace the coolant. The coolant volumetric flow in the radiator is 0.11 m^3.min^{-1}, meanwhile the air volumetric flow and air velocity are 66.5 m^3.min^{-1} and 4.47 m.s^{-1}. This study used exact working condition and radiator specification (Maple, 2008) except the coolant (water) is changed to nanofluid with various nanoparticles concentration. Some analyses have been done by using mathematical modeling and Microsoft Office Excel 2007 by considering the inlet temperature of the coolant is 368 K, and the outside air is 303 K.

TABLE 2
Geometry description of automotive radiator (Maple, 2008)

Radiator Dimension	**Unit**	
Radiator length, *rL*	meters	0.4572
Radiator width, *rW*		0.4318
Radiator height, *rH*		0.0246
Tube width, *tW*		0.0246
Tube height, *tH*		1.56 x 10^{-3}
Fin width, *fW*		0.0246
Fin height, *fH*		0.0119
Fin thickness, *fT*		2.54 x 10^{-5}
Distance between fins, *fD*		1.59 x 10^{-3}
No. of tubes		33

3.0 MATHEMATICAL MODELING

The effective thermal conductivity of nanofluid k_{eff}, considered the effect of interfacial layers which have been developed around the nanoparticles as suspending metallic particles in the coolant. The effective thermal conductivity has been calculated by using Equation (1) with diverse nanoparticles concentration and sizes (Leong et al., 2006),

$$k_{\text{eff}} = \frac{\left(k_{\text{p}} - k_{\text{lr}}\right)\phi_1 k_{\text{lr}}\left[2\beta_1^3 - \beta^3 + 1\right] + \left(k_{\text{p}} + 2k_{\text{lr}}\right)\beta_1^3\left[\phi_1\beta^3\left(k_{\text{lr}} - k_{\text{f}}\right) + k_{\text{f}}\right]}{\beta_1^3\left(k_{\text{p}} + 2k_{\text{lr}}\right) - \left(k_{\text{p}} - k_{\text{lr}}\right)\phi_1\left[\beta_1^3 + \beta^3 - 1\right]} \tag{1}$$

where k_p is the thermal conductivity of nanoparticle, k_{lr} is the thermal conductivity of interfacial layer, k_f is the thermal conductivity of coolant, ø is the particle volume fraction, $\beta = 1 + \gamma$, $\beta_1 = 1 + \gamma/2$, and $\gamma = h/a$ is the interfacial layer thickness over the radius of nanoparticle. The enhancement of nanofluids thermal conductivity, $k_{eh} = (k_{eff} - k_f)/k_f \times 100$ is calculated to observe the significane of nanoparticles concentration in the conventional coolant. The dynamic viscosity of nanofluid, μ_{nf} is obtained from Brinkman model (Leong et al.,2010) which considered only two parameters: a) the conventional coolant viscosity, μ_f and b) the nanoparticles concentration, ø.

$$\mu_{nf} = \mu_f \frac{1}{(1-\phi)^{2.5}} \tag{2}$$

The density, ρ_{nf} and specific heat, $C_{p,nf}$ of the nanofluid have been calculated from Equation (3) and Equation (4) as following,

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p \tag{3}$$

$$C_{p,nf} = \frac{(1-\phi)\rho_f C_{p,f} + \phi\rho_p C_{p,p}}{\rho_{nf}} \tag{4}$$

where ρ_f and ρ_p are the densities of coolant and nanoparticle, meanwhile $C_{p,f}$ and $C_{p,p}$ are the specific heat of coolant and nanoparticle. To determine the heat transfer rate, the universal heat transfer equation from Maple, (2008) is used as shown in Equation (5),

$$\frac{1}{UA} = \frac{1}{h_c A_c} + \frac{1}{h_a A_a} \tag{5}$$

where h_c is the heat transfer coefficient of the coolant ($W.m^{-2}K^{-1}$), h_a is the heat transfer coefficient of air meanwhile A_c and A_a are the coolant surface area and air surface area (m^2). To determine the heat transfer coefficent, Nusselt number (*Nu*) must be identified. The Dittus Boelter equation is used since the flow inside the tubes is turbulent based on the calculated Reynolds number, *Re*. The Dittus Boelter equation, Reynolds number and Prandtl number, *Pr* as well as the heat transfer coefficient are calculated as following (Leong et al., 2010),

$$h_c = \frac{Nu\, k_{eff}}{D_H} \tag{6}$$

$$Nu = 0.023 Re^{0.8} Pr^{0.3} \tag{7}$$

$$Pr = \frac{C_{p,nf}\mu_{nf}}{k_{eff}} \tag{8}$$

$$Re = \frac{\rho_{nf} v D_H}{\mu_{nf}} \tag{9}$$

where v is the velocity of the nanofluid, (ms^{-1}), and D_H is the hydraulic diameter. The hydraulic diameter is determined by using the following equations (Maple, 2008),

$$D_H = \frac{4A_{min}}{WP} \tag{10}$$

$$A_{min} = tW.tH \tag{11}$$

$$WP = 2(tW + tH) \tag{12}$$

The universal heat transfer coefficient, UA of the nanofluid is determined by using NTU, a dimensionless modules which defined the number of transferred units shown in Equation (13). NTU is determined by considering the air surface area, the nanofluid surface area and the heat transfer coefficient of the conventional coolant.

$$NTU = \frac{UA}{C_{min}} \tag{13}$$

C_{min} in Equation (13) is obtained by comparing the thermal capacity rate of both coolants; the nanofluid and the air. The thermal capacity rate of the nanofluid, CR_{nf} or thermal capacity rate of the air, CR_a is calculated by using a general equation of thermal capacity rate, CR in Equation (14). The higher calculated value of CR is considered as C_{max} and the lower value is C_{min}.

$$CR = C_p\, \mu\rho \tag{14}$$

The heat exchanger (radiator) effectiveness is determined by applying Equation (15),

$$\varepsilon = 1 - e^{-\frac{C_{max}(1-e^{-C_{ratio}Ntu})}{C_{min}}} \tag{15}$$

where $C_{ratio} = C_{min}/C_{max}$ (Maple, 2008). To find the total transfer rate Q (W), the different between the nanofluid temperature, $T_{nf,in}$ and air temperature, $T_{a,in}$ must be identified and substituted into Equation (16) based on Leong et al., (2010) and Yunus (2004) studies.

$$Q = \varepsilon C_{min} (T_{nf,in} - T_{air,in}) \tag{16}$$

4.0 RESULTS AND DISCUSSION

Figure 1 shows the enhancement of nanofluid thermal conductivity with particle volume fraction. By suspending 10 % of copper nanoparticles into the water, the thermal conductivity of the nanofluid can be enhanced more than 100 % for nanoparticles size of 10 nm. The other particle sizes of 50 nm and 100 nm show quite similar enhancement of thermal conductivity up to 100 %. The result proved that the particle size contributed significant effects on thermal properties and the thermal conductivity of nanofluid is increasing significantly with nanoparticles concentrations. The increasing size of nanoparticles has decreased the thermal conductivity of nanofluids.

The localized convection in the coolant because of nanoparticles Brownian motion is one of the reasons that enhance the thermal conductivity. Besides, the formation of interfacial layer between the copper nanoparticles and basefluid (water) is also contributing to the percentage of enhancement. The interfacial layer thermal conductivity (k_l) is two times higher as compared to the basefluid (Leong et al., 2006). Therefore, instead of depending on the nanoparticles concentrations and particle sizes, the formation of interfacial layers around the nanoparticles is also contributing to improve the overall thermal conductivity of nanofluids. By using different nanoparticle volume fraction of 2 vol.% to 10 vol.%, the viscosity of nanofluids is also increasing and influencing the values of Reynolds number. The viscosity of nanofluids solely depends on nanoparticle volume fraction according to Brinkman model. By increasing the viscosity, the Reynolds number should be smaller. However, another important thermophysical property that need to be considered in determining the Reynolds number is the density of nanofluids. The effects of nanoparticles suspension on nanofluid density has increased the Reynolds number in this study.

In this study, the nanoparticle volume fraction has more significant effects on density rather than viscosity of the nanofluid. Therefore, the Reynolds number is increasing with nanoparticles concentration. The Reynolds number is important to be used in identifying the type of flow in the tubes. As the Reynolds number is increasing from 15000 to 21000, it shows that the turbulence flow inside the radiator rectangular tubes becomes more "chaos". Since the advanced coolant consists of nanoparticles, the turbulence flow increases conduction and convection processes since there are more contacts occurred between the nanoparticles and the tubes wall. This contributes to better heat transfer rate in the cooling process.

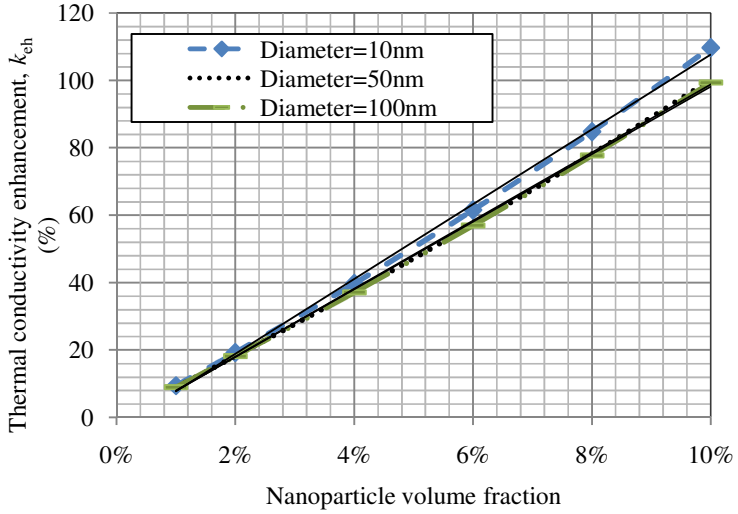

FIGURE 2
Nanofluid thermal conductivity as a function of nanoparticle volume fraction

In Figure 3, the overall heat transfer coefficient of nanofluid of different nanoparticle sizes are increasing with nanoparticle volume fraction. The coefficient of 10 nm nanoparticles increased about 9 % of percentage enhancement with 2 % of volume fraction, and constantly increasing up to 92 % with 10 % of volume fraction, respectively. The heat transfer rate of the radiator is also increasing from 64356 W to 64376 W for 10 nm nanoparticles suspension as shown in Figure 4. The overall heat transfer rate enhancement shows insignificant value which is about 0.03 %. In Figure 4, the results of heat transfer rate for three different particle size are similar eventhough the

heat transfer coefficients quite varies as compared to each other. There are many factors that influence the results. One important factor is the flow rate of the outside air. This study assumed that the air flow rate is constant by focusing the influence of nanoparticles concentration on the thermal conductivity and heat transfer coefficient of nanofluid. The temperature of coolants should be varied due to operating temperature and air flow. High temperature different between two surfaces and air flow tend to increase the heat transfer rate. The fins construction is also one of the important factors that could influence the heat transfer rate by extending the surface area and choosing high conductive material. This study showed that copper/water nanofluid as the advanced coolant has increased the heat transfer rate of the radiator. Therefore, the combination of the major factors that influence the heat transfer characteristics of the radiator will produce high energy-efficiency automotive cooling system.

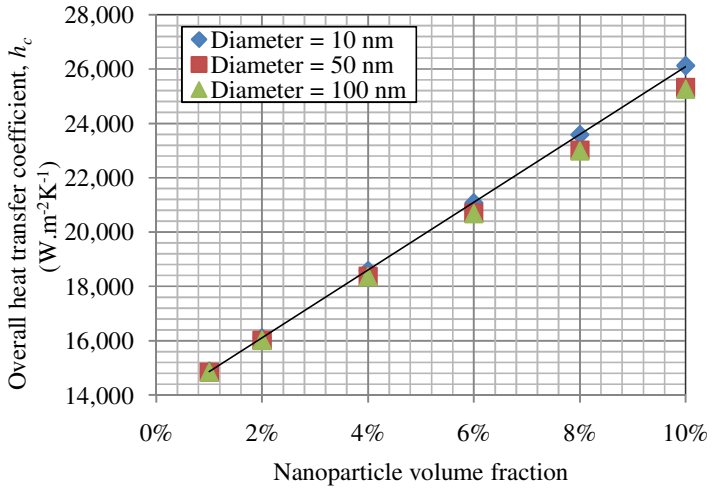

FIGURE 3
Overall heat transfer coefficient as a function of nanoparticle volume fraction

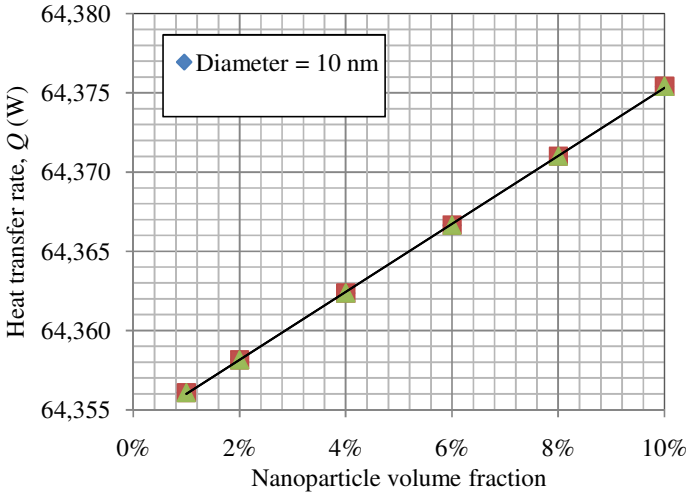

FIGURE 4
Heat transfer rate of a louvered-fin and flat tube radiator

5.0 RECOMMENDATION FOR FUTURE WORK

In automotive cooling system, the radiator is a main component that linking to other components such as water pump and hoses. By using nanofluid as the new coolant, there are possibilities of nanoparticles agglomeration and sedimentation inside the tubes, hoses and clogging the water pump. The corrosion issue in the cooling system cannot be neglected as adding metallic particle could damage the efficiency of the existing system.This problem might lead to parts wear, pressure drop increment, and higher energy consumption. Therefore, more investigations on other parts need to be proceed in order to introduce nanofluid as the advanced-coolant in the cooling system. It is important to have practical knowledge of nanofluids performance in real world cooling system so that the important aspects such as fuel consumption, construction cost, quality and safety can be identified before high-volume production of nanofluids-radiator.

6.0 CONCLUSION

Based on the mathematical modeling approach, the thermal conductivity of Cu/Water nanofluid is increasing significantly with nanoparticle volume fraction of 2 % to 10 % but decreasing with the increment of particle size. The suspension of nanoparticles into the conventional coolant has increased the heat transfer coefficient significantly up to 26000 $W.m^{-2}K^{-1}$ with the percentage enhancement is about 92 % for smallest nanoparticles size of 10 nm. Eventhough with different nanoparticle sizes, the enhancement of heat transfer rate is similar and depending significantly on nanoparticle volume fraction. The overall heat transfer rate of louvered-fin and flat tube radiator shows approximately up to 0.03 % enhancement as considering both types of coolants; the nanofluids and air.

7.0 ACKNOWLEDGMENT

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