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The Performance Evaluation of Overall Heat Transfer and Pumping Power of γ-Al_2O_3/water Nanofluid as Coolant in Automotive Diesel Engine Radiator

The efficiency of γ-Al_2O_3/water nanofluid as coolant is investigated in the present study. γ-Al_2O_3 nanoparticles with diameters of 20 nm dispersed in water with volume concentrations up 2% are selected and their performance in a radiator of Chevrolet Suburban diesel engine under turbulent flow conditions are numerically studied. The performance of an automobile radiator is a function of overall heat transfer coefficient and total heat transfer area. The heat transfer relations between nanofluid and airflow have been investigated to evaluate the overall heat transfer and the pumping power of γ-Al_2O_3/water nanofluid in the radiator with a given heat exchange capacity. In the present paper, the effects of the automotive speed and Reynolds number of the nanofluid in the different volume concentrations on the radiator performance are also investigated. As an example, the results show that for 2% γ-Al_2O_3 nanoparticles in water with Re_{nf}=6000 in the radiator while the automotive speed is 50 mph, the overall heat transfer coefficient and pumping power are approximately 11.11% and 29.17% more than that of water for given conditions, respectively. These results confirm that γ-Al_2O_3/water nanofluid offers higher overall heat transfer performance than water and can be reduced the total heat transfer area of the radiator.

Keywords: *Automotive Diesel Engine Radiator, Nanofluid, Turbulent Flow, Overall Heat Transfer, Pumping Power.*

1. Introduction

Cooling is one of the top technical challenges to obtain the best automotive design in multiple aspects (performance, fuel consumption, aesthetics, safety, etc.). Automotive radiator is an important part of the engine cooling system. Due to limited space at the front of the engine, the size of the radiator is restricted and cannot be essentially increased. Therefore, it is necessary to increase the heat transfer capabilities of working fluids such as water and ethylene glycol in radiators because of their low thermal conductivity. A recent advancement in nanotechnology has been the introduction of nanofluids, i.e., colloidal suspense-ons of nanometer-sized solid particles instead of common working fluids. Nanofluids were first innovated by Choi [1] in 1995 at the Argonne National Laboratory, U.S.A. Compared with traditional solid-liquid suspensions containing millimeter or micrometer sized particles, nanofluids as coolants in the heat exchangers have shown better heat transfer performance because of small size of suspend solid particles. It causes that nanofluids have a behavior similar to base liquid molecules. Nanofluids have attracted attention as a new generation of heat transfer fluids in building heating, in heat exchangers, in chemical plants and in automotive cooling applications, because of their excellent thermal performance. Recently there have been considerable research findings highlighting superior heat transfer performances of nanofluids. Xuan and Li [2] investigated experimentally heat transfer performance of Cu/water nanofluid with concentration of 2% under turbulent flow conditions in a tube and observed more than 39% enhancement in the Nusselt number compared with pure water. Ollivier et al. [3] investigated the use of nanofluids as a jacket water coolant in a gas spark ignition engine. They numerically simulated the unsteady heat transfer through the cylinder and inside the coolant flow. Authors reported that because of higher thermal diffusivity of nanofluids, the thermal signal variations for knock detection increased by 15% over the predicted using water alone. Tzeng et al. [4] investigated experimentally the use of CuO and Al_2O_3 nanofluids into engine transmission oil to analyze the temperature distribution on the exterior of the rotary-blade-coupling transmission at four engine operating speeds (400, 800, 1200 and 1600 rpm). They reported that the use of nanofluids in the transmission has a clear advantage from the thermal performance viewpoint. In 2007, Nguyen et al. [5] used Al_2O_3/water nanofluid in an electronic cooling system and found a maximum of 40% enhancement in convective heat transfer coefficient at an added particle concentration of 6.8 vol%. Gherasim et al. [6] presented numerical simulations for a radial flow cooling system with an Al_2O_3/water nanofluid flow. The results indicate that the addition of nanoparticles to the base fluid enhances heat transfer performance. Also the numerical results show that the avrage Nusselt number and pumping power of nanofluid increase with increasing the particle volume concentration. Mohammed et al. [7] numerically studied the effects of using nanofluid on the performance of a square shaped microchannel heat exchanger (MCHE). Their results demonstrated that Al_2O_3 and Ag nanoparticles have the highest heat transfer coefficient and lowest pressure drop among all nanoparticles tested, respectively. They concluded that the benefits of nanofluids such as enhancement in heat transfer coefficient are dominant over the shortcomings such as increasing in pressure drop. Peyghambarzadeh et al. [8] investigated experimentally the convective heat transfer enhancement of water and EG based nanofluids consisting of Al_2O_3 nanoparticles up 1% volume concentration as the coolants inside flat aluminum tubes of the car radiator under laminar and turbulent flows. The results show that the heat transfer enhances about 40% compared with the base fluids in the best conditions. Vajjha et al. [9] numerically investigated the heat transfer augmentation by application of two different nanofluids consisting Al_2O_3 and CuO nanoparticles in an ethylene glycol and water mixture circulating through the flat tubes of an automobile radiator. The numerical results showed that at a Reynolds number of 2000, the percentage increase in the average heat transfer coefficient over the base fluid for a 10% Al_2O_3 nanofluid was 94% and that for a 6% CuO nanofluid was 89%. Also the average heat transfer coefficient increases with the Reynolds number and also with the particle volumetric concentration. Leong et al. [10] have studied the application of nanofluids as working fluids in shell and tube heat recovery exchangers in a biomass heating plant and showed that about 7.8% of the heat transfer enhancement could be achieved with the addition of 1% copper nanoparticles in ethylene glycol based fluid at 26.3 kg/s and 111.6 kg/s mass flow rate for flue gas and coolant, respectively. Ijam et al. [11] theoretically analyzed a minichannel heat sink with a 20 × 20 cm bottom for SiC-water and TiO_2-water nanofluids as the coolants through hydraulic diameters under turbulent flow. Their results showed a maximum enhancement of 12.44% in thermal conductivity for SiC-water and 9.99% for TiO_2-water at 4% of volume fraction. Also the maximum improvement in heat flux by using SiC-water and TiO_2-water nanofluids at 4% of volume fraction for inlet velocities of 2 and 6 m/s is calculated by~ 7.63%, 12.43% and 7.25%, 12.43%, respectively. In 2012 Saeedinia et al. [12] applied CuO-base oil particles varying in the range of 0.2-2% inside a circular tube and showed that the CuO nanoparticles suspended in base-oil increases the heat transfer coefficient even for a very low particle concentration of 0.2% volume concentration. They found a maximum heat transfer coefficient enhancement of 12.7% for 2% CuO nanofluid. Shafahi et al. [13] used a two-dimensional analysis to study the thermal performance of a cylindrical heat pipe utilizing Al_2O_3, CuO and TiO_2 nanofluids. Their results confirmed that the thermal performance of a heat pipe is improved and temperature gradient along the heat pipe and thermal resistance across the heat pipe are reduced and maximum capillary heat transfer of the heat pipe is observed when nanofluids are utilized as the working fluid. In the present paper, 20nm-γ-Al_2O_3/water nanofluid with concentration up 2 vol.% has been numerically studied as a coolant in a radiator of Chevrolet Suburban diesel engine with a given heat exchange capacity. It shall be noted that metal oxides such as γ-Al_2O_3 nanoparticles are chemically more stable than their metallic counterparts. In addition, Gamma irradiation offers many advantages for the preparation of metal nanoparticles because of large number of hydrated electrons produced during γ-ray irradiation can reduce the metal ions to zero valiant metal particles [14].

2. Methodology

In order to investigate the heat transfer performance of nanofluids and use them in practical applications, it is necessary first to study their thermophysical properties such as density, specific heat, viscosity and thermal conductivity. In this study, to validate the the numerical results, the methodology employed to determine the efficiency of γ-Al_2O_3/water nanofluid as coolant in a radiator of Chevrolet Suburban diesel engine with a given heat exchange capacity is based on new rheological and thermophysical properties correlations developed from experiments.

2.1 Prediction of thermophysical properties

At the first step, the heat characteristics of the nanofluid have been evaluated and at the next step the application of nanofluid coolant has been investigated to improve the heat transfer performance of the radiator. The type of the radiator core is shown in Fig. 1. This radiator consists of 644 brass flat tubes with six tube rows and 346 continuous copper fins. The main characteristics of radiator are listed in Table 1 that useful for assessing the radiator performance in this work [15,16]. However, following assumptions are made:

- The flow is an incompressible, steady state and turbulent.
- The effect of body force is neglected.
- The thermophysical properties of nanofluids are constant.

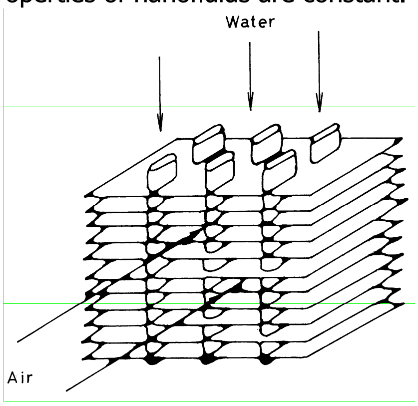

Figure 1. Schematic of the applied radiator flat tube.

The characteristics of nanoparticles and base fluid used in this study are summarized in Table 2. The necessary thermophysical properties in this paper are density, viscosity, specific heat and thermal conductivity.

Table 1. Radiator Specifications.

Description	Air	Coolant
Radiator frontal area, ($h\times w$)	0.5m×0.6m	
Fin thickness, t	0.01 cm	
Fin length for symmetric heating from primary to midpoint between plates, L	0.4 m	
Hydraulic diameter, D_h	0.351 cm	0.373 cm
Heat transfer area/total volume, α	886	138
Fin area/total area, (A_f/A)	0.845	

Table 2. Thermophysical properties of base fluid and nanoparticles.

Property	γ-Al_2O_3	Water
c_p [J $kg^{-1}K^{-1}$]	880	4197
ρ [kg m^{-3}]	3700	971
k [$Wm^{-1}K^{-1}$]	46	0.669
d_p (nm)	20	0.384

In this paper, density (ρ_{nf}) and special heat capacity ($c_{p,nf}$) of γ-Al_2O_3/water nanofluid have been calculated based on empirical correlations proposed by Pak [17] and Xuan [18] as follows:

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

$$c_{p,nf} = \frac{(1-\phi)\rho_{bf}c_{p,bf} + \phi\rho_p c_{p,p}}{\rho_{nf}} \tag{2}$$

where ϕ is nanoparticle volume concentration and ρ_p, ρ_{bf} and $c_{p,p}$, $c_{p,bf}$ are the densities and the specific heats of the nanoparticles and base fluid, respectively.

Also, thermal conductivity (k_{nf}) and viscosity (μ_{nf}) for nanofluid have been estimated based on two semi-empirical equations presented by Corcione [19] in 2011 on the basis of a wide variety of experimental date available in the literature as following equations:

$$\frac{k_{eff}}{k_{bf}} = 1 + 4.4Re^{0.4}Pr_{bf}^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{k_p}{k_{bf}}\right)^{0.03}\phi^{0.66} \tag{3}$$

$$\mu_{nf} = \frac{\mu_{bf}}{1-34.87(d_p/d_{bf})^{-0.3}\phi^{1.03}} \tag{4}$$

where k_{bf} is the thermal conductivity of the base fluid, Re is the nanoparticle Reynolds number, Pr_{bf} is the Prandtl number of the base fluid, T is the nanofluid temperature, T_{fr} is the freezing point of the base fluid, k_p is the thermal conductivity of the nanoparticles, μ_{bf} is the dynamic viscosity of the base fluid, d_p is the diameter of the nanoparticles and d_{bf} is the equivalent diameter of a base fluid molecule. The standard deviations of error of Eqs. (3) and (4) are 1.86% and 1.84%, respectively.

In more detail, the Reynolds number of the suspended nanoparticles can be calculated as follows [19]:

$$Re = \frac{2\rho_{bf} k_b T}{\pi \mu_{bf}^2 d_p} \tag{5}$$

wherein k_b=1.38066×10^{-23} J/K is the Boltzmann constant.

2.2 Heat transfer and pressure drop modeling

2.2.1 Heat transfer modeling

The rate of heat transferred between nanofluid coolant and airflow in the radiator can be written as follows:

$$Q = \dot{m}_{nf}\, c_{p,nf} (T_1 - T_2) \cong \dot{m}_{air}\, c_{p,air} (t_2 - t_1) \tag{6}$$

where *nf* and *air* denote the relevant parameters of nanofluid coolant and airflow. Here, T_1=110°C and T_2=49°C are the inlet and outlet temperatures of nanofluid coolant, t_1=32°C is the inlet air temperature and outlet air temperature (t_2) can be calculated as:

$$t_2 = t_1 + \frac{Q}{\dot{m}_{air}\, c_{p,air}} \tag{7}$$

The mass flowrates are calculated based on the pump flowrate for water and the speed and frontal area for the air as follows:

$$\dot{m}_{nf} = \rho_{nf} \eta_{vol.p} Q_p \tag{8}$$

$$\dot{m}_{air} = \rho_{air} V_{Automotive} (h \times W) \tag{9}$$

Here, the Bosch Cobra pump is used with flowrate of Q_p=317 gallons/hour and volumetric efficiency ($\eta_{vol.p}$) by 80%. In Eq. (9), $V_{Automotive}$ is the automotive speed.

The total heat transfer area of the radiator, A, is computed from the following equation:

$$A = \frac{Q}{U \times LMTD} \tag{10}$$

$$LMTD = \frac{(T_1 - t_1) - (T_2 - t_2)}{ln \frac{(T_1 - t_1)}{(T_2 - t_2)}} \tag{11}$$

In Eq. (10), U is the overall heat transfer coefficient which is expressed in the following form [15]:

$$U=\left(\frac{1}{\eta_o h_{air}}+\frac{1}{\left(\frac{\alpha_{nf}}{\alpha_{air}}\right)h_{nf}}+Rf\right)^{-1} \tag{12}$$

where h_{air} is the heat transfer coefficient of air, η_o *is* the total surface temperature effectiveness, h_{nf} is the heat transfer coefficient of nanofluid coolant and Rf is the fouling resistance that is assumed to be 5×10^{-4} m^2KW^{-1}. In the present study, the heat transfer coefficient of air is calculated as:

$$h_{air}=\frac{J_a Re_a \mu_a C_{p,a}}{Pr_a^{2/3} D_{h,a}}\left(\frac{\mu_{nf}}{\mu_{wnf}}\right)^{0.14} \tag{13}$$

In the above equation, $\left(\frac{\mu_{nf}}{\mu_{wnf}}\right)^{0.14}$ is the viscosity correction factor that is defined as the ratio of viscosity of the nanofluid at the mean temperature of inlet and outlet conditions to that one at the mean temperature of wall tube and also

$c_{p,air}$=1007Jkg^{-1}K^{-1}, Pr_a=0.7057, μ_a=0.00001889 (Nsm^{-2})

In Eq. (13), Reynolds number and Colburn factor for the air are calculated with considering the air properties as follows:

$$Re_a=\frac{G_a D_{h,a}}{\mu_a} \tag{14}$$

$$J_a=\frac{0.174}{Re_a^{0.383}} \tag{15}$$

where G_a is the mass flow rate of air. In Eq. (12), the total surface temperature effectiveness is expressed as:

$$\eta_o=1.0-(1.0-\eta_f)\times\frac{A_f}{A} \tag{16}$$

where η_f is the fin efficiency of plate fin which is defined as follows:

$$\eta_f=\frac{tanh\left(\sqrt{\frac{2h_{air}}{kt}}\times L\right)}{\sqrt{\frac{2h_{air}}{kt}}\times L} \tag{17}$$

Here, k=377 Wm^{-1}K^{-1} is thermal conductivity of copper fin.

The heat transfer coefficient of the nanofluid coolant (h_{nf}) flowing in the flat tubes can be calculated with considering the turbulent Nusselt number presented by Li and Xuan [20] as follows:

$$\frac{h_{nf} D_{h,nf}}{k_{nf}} = Nu_{nf} = 0.0059\left(1.0 + 7.6286\phi^{0.6886} Pe_d^{0.001}\right) \times Re_{nf}^{0.9238} Pr_{nf}^{0.4} \left(\frac{\mu_{nf}}{\mu_{wnf}}\right)^{0.14} \quad (18)$$

where Pe_d is the nanofluid Peclet number and is defined in the following form:

$$Pe_d = \frac{u_{nf} d_p}{\alpha_{nf}} \quad (19)$$

where α_{nf} is the nanofluid thermal diffusivity which is defined as follows:

$$\alpha_{nf} = \frac{k_{nf}}{\rho_{nf} c_{p,nf}} \quad (20)$$

The Reynolds and Prandtl numbers in Eq. (18) are calculated with considering the nanofluid properties as follows:

$$Re_{nf} = \frac{\rho_{nf} u_{nf} D_{h,nf}}{\mu_{nf}} \quad (21)$$

$$Pr_{nf} = \frac{c_{p,nf} \mu_{nf}}{k_{nf}} \quad (22)$$

2.2.2 Pressure Drop Modeling

In the present paper, the fanning friction factor (f_n), the pressure drop (Δp_{nf}) and pumping power (*PP*) for γ-Al_2O_3/water nanofluid coolant flowing in the flat tubes are calculated as follows [16]:

$$f_{nf} = 0.079 \times (Re_{nf})^{-0.25} \quad (23)$$

$$\Delta p_{nf} = 2\frac{G_{nf}^2 \times f_{nf} \times H}{\rho_{nf} \times D_{h,nf}} \left(\frac{\mu_{nf}}{\mu_{wnf}}\right)^{0.25} \quad (24)$$

$$PP = Q_p \times \Delta p_{nf} \quad (25)$$

In Eq. (24), H is the total nanofluid flow length which is obtained as:

$$A_t = A - A_f \quad (26)$$

$$A_t = \pi \times D_{h,nf} \times H \quad (27)$$

where A_t is the total heat transfer area of flat tubes.

3. Simulation results and discussion

3.1. Overall Heat Transfer

Figs. 2-4 show the results of simulating the effects of using γ-Al_2O_3/water nanofluid as coolant with different volume fractions flowing in the flat tubes in the various ranges of the automotive speed and Reynolds number of the nanofluid on the overall heat transfer coefficient. The results of this study show that nanofluid enhances the overall heat transfer coefficient in the radiator and therefore can be reduced the total heat transfer area of the radiator. Enhancement of heat transfer by the nanofluid may be resulted from the following two aspects: first is the suspended particles that increase the thermal conductivity of the mixture; the other one is that chaotic movement of ultrafine particles accelerates energy exchange process between the fluid and the wall.

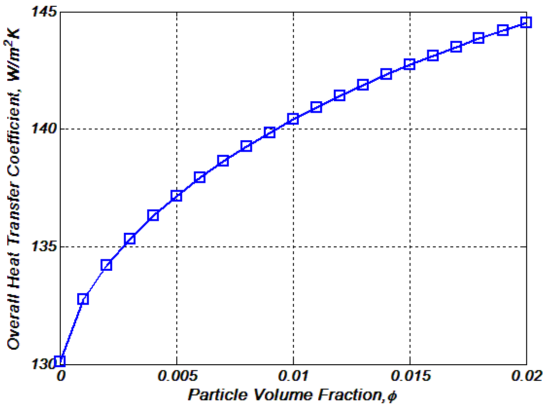

Figure 2. Variations of overall heat transfer coefficient for nanofluid at different volume fractions.

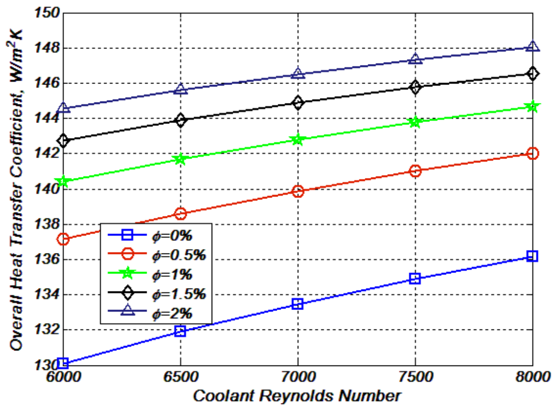

Figure 3. Effect of coolant Reynolds number on overall heat transfer coefficient in the radiator.

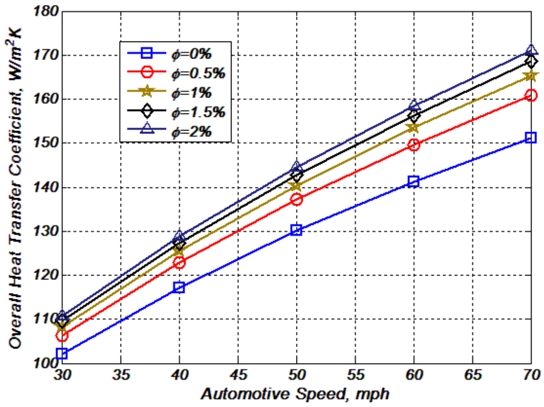

Figure 4. Effects of the automotive speed and γ-Al_2O_3 volume fraction on overall heat transfer coefficient in the radiator.

Fig. 2 shows the overall heat transfer coefficient for γ-Al_2O_3/water nanofluid coolant in an automotive radiator that has been calculated by Eq. (12). In this analysis, Reynolds number of the nanofluid is 6000 and the automotive speed is assumed to be 50 miles per hour (mph). As shown in this figure, the overall heat transfer coefficient is high when the probability of collision between nanoparticles and the wall of the flat tubes has increased under higher concentration conditions. It confirms that nanofluids have considerable potential to use in the automotive radiator. A further inspection of Fig. 2 shows that the overall heat transfer coefficient of the γ-Al_2O_3/water nanofluid for volume concentrations in the range of 0.1% to 2% increases by 2-11.11%.

The coolant Reynolds number has an important role in determining the radiator performance. The coolant Reynolds number must be properly controlled by thermostat pump because of engine might be overcooled or overheated. Therefore, the effect of the coolant Reynolds number on the radiator performance at an automotive speed of 50 mph has been studied in this paper. According to Fig. 3, the increase in the coolant Reynolds number increases the overall heat transfer coefficient that the magnitude of this property for γ-Al_2O_3/water nanofluid at higher concentration is more than that of a base fluid. For instance, the results show that the increase in overall heat transfer coefficient for 2% γ-Al_2O_3 nanoparticles in water at Re_{nf}=8000 compared with Re_{nf}=6000 is about 2.4%.

As well as, the automotive speed plays an important role on the radiator performance. As expected, the mass flowrate of the air increases with increasing the automotive speed and therefore Reynolds number and mass velocity for the air increase. Increasing the air Reynolds number raises the air mass velocity (refer to Eq. (14)) and decreases the air Colburn factor (refer to Eq. (15)). But the results shown in Fig. 4 indicate that increasing in automotive speed and air Reynolds number raises the overall heat transfer coefficient because of the increase in air heat transfer coefficient. Therefore, it can be concluded that the change in the air mass velocity is more than the change in Colburn factor with increasing the air Reynolds number. In the analysis shown in Fig. 4, the overall heat transfer coefficient of the radiator is calculated for the fixed coolant Reynolds number of 6000 at different volume fractions. For instance, the results show that the increase in overall heat transfer coefficient for 2% γ-Al_2O_3 nanoparticles in water at automotive speed of 60 mph compared with 40 mph is about 23%.

3.2. Pumping Power

In order to apply the nanofluids for practical application, in addition to the heat transfer performance it is necessary to study their flow features. With increasing nanoparticles loading in the base fluid, viscosity and density of the nanofluids increase and therefore must be increased the friction factor and the pressure drop. Hence, nanofluids generally require the greater pumping power than their base fluid. In the present paper, the pumping power for γ-Al_2O_3/water nanofluid coolant flowing in the flat tubes in the various ranges of the coolant Reynolds number (at $V_{Automotive}$=50 mph) and the automotive speed (at Re_{nf}=6000) calculated and shown in Figs. 5 and 6. For instance, Fig. 5 shows that the increase in pumping power for 2% γ-Al_2O_3 nanoparticles in water at Re_{nf}=8000 compared with Re_{nf}=6000 is about 61.3%. Also as an example, Fig. 6 shows that the decrease in pumping power for 2% γ-Al_2O_3/water nanofluid at the automotive speed of 60 mph compared with 40 mph is about 22%.

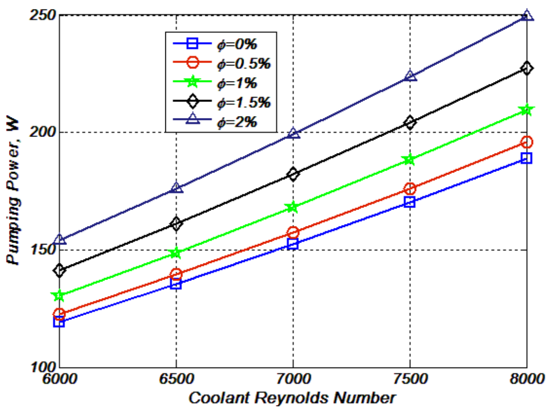

Figure 5. Effect of coolant Reynolds number on pumping power in the radiator.

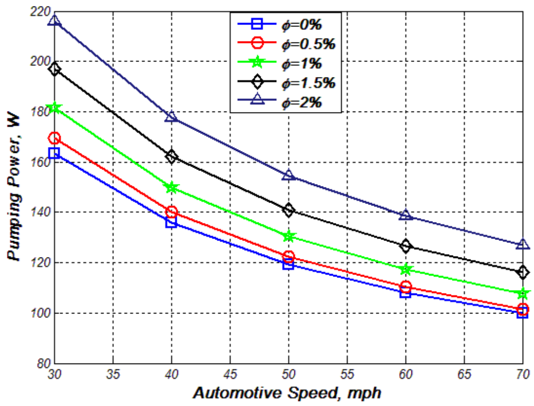

Figure 6. Effect of the automotive speed on pumping power for nanofluid with different volume fractions in the radiator.

4. Conclusions

This paper presented a numerical investigation of the use of γ-Al_2O_3/water nanofluid as a coolant flowing in a radiator of Chevrolet Suburban diesel engine with a given heat exchange capacity. The overall heat transfer coefficient and pumping power for nanofluid at different volume fractions (0.1-2%) was studied under turbulent flow conditions. Also, the effects of the coolant Reynolds number and the automotive speed on the radiator performance considered in this work. The simulation results indicate that the overall heat transfer coefficient of nanofluid is greater than that of water and therefore can be reduced the total heat transfer area of the radiator. However, the considerable increase in associated pumping power may impose some limitations on the efficient use of this type of nanofluid in automotive diesel engine radiators.

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