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Effect of Nanofluids on Heat Transfer Enhancement in Automotive Cooling Circuits

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Abstract. Continuous technological development in automotive industries has increased the demand for high efficiency engines. Optimizing design and size of a radiator in order to reduce a vehicle weight is a requirement for making the world green. Using of fins is one of the techniques to increase the cooling rate of the radiator. However, traditional approach of enhancing the cooling rate by using fins and microchannels has already showed to their limit. Furthermore, heat transfer fluids such as water and ethylene glycol have very low thermal conductivity. As result there is an urgency for new and innovative heat transfer fluids for increasing heat transfer rate in an automotive cooling circuit. Nanofluids represent potential substitute of conventional coolants in engine cooling system. In this paper a cooling circuit is modelled in TRNSYS (version 17) and investigated in transient regime. The circuit is composed by a heating system, a pump and a heat exchanger. The heat exchanger represents a car radiator in the circuit. The nanofluid is a mixture of water and Al2O3 nanoparticles. The study is conducted for three different engine operating conditions (Low, Medium and High) and different volume concentrations of nanoparticles.

INTRODUCTION

Continuous technological development in automotive industries has increased the demand for high efficiency engines. Optimizing design and size of a radiator in order to reduce a vehicle weight is a requirement for making the world green. Using of fins is one of the techniques to increase the cooling rate of the radiator. However, traditional approach of enhancing the cooling rate by using fins and microchannels has already showed to their limit [1].

Furthermore, heat transfer fluids such as water and ethylene glycol have very low thermal conductivity. As a result there is an urgency for new and innovative heat transfer fluids for increasing heat transfer rate in an automotive cooling circuit. Nanofluids represent potential substitute of conventional coolants in engine cooling system. Recently different studies have demonstrated superior heat transfer performances of nanofluids [1-5].

Leong et al. [1] used copper nanofluids and ethylene glycol as base fluid in an automotive cooling system. They observed an increase in the heat transfer coefficient compared to the base fluid. Their results showed that with 2% volume concentration the heat transfer increases of 3.8% considering the Reynolds number of 6000 and 5000 for air and coolant, respectively. They have also given some indications on the reduction of the frontal surface. Hussein et al. [2] examined the increase of heat transfer by using nanoparticles of TiO_2 and SiO_2 in pure water under laminar flow conditions. The volumetric flow rate, the inlet temperature and the volume concentration of the nanofluids are between 2-8 LPM, 60-80 °C and 1-2% respectively. It was observed that the Nusselt number increased significantly with the flow velocity and slightly with the inlet temperature and the volumetric concentration of the particles. In the experimental work of Subhedar [3] focused on the global heat transfer coefficient of Al_2O_3 nanoparticles and water-monoethylene glycol (MEG), used as refrigerant in a car radiator under laminar flow conditions. The experimental setup developed is similar to the automotive cooling system. The nanofluid used was prepared by a two-step method, using ultrasound for the correct dispersion of Al_2O_3 nanoparticles, with a diameter of 20 nm, in the mixture of water and MEG (with volumetric proportion of 50:50). The experimental study showed that the use of nanofluid improves

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the global heat transfer coefficient compared to the base fluid. It has been observed that the increase of the volumetric concentration of nanoparticles from 0% to 8%, also increases the overall heat transfer coefficient. The increase of the inlet temperature from 65 °C to 85 °C. Finally, it was found that the nanofluid with a volumetric concentration of 2% of Al_2O_3 allows a reduction of the heat exchanger surface of the 36.69%.

Bozorgan et al. [6] carried out a numerical analysis on an application of CuO-water nanofluid in automotive diesel engine radiator. The results showed that for the nanofluid at 2% volume concentration circulating through the flat tubes while the automotive speed is 70 km/hr, the overall heat transfer coefficient and pumping power are approximately 10% and 23.8% more than that of base fluid for given conditions, respectively. An experimental study was accomplished by Hwa Ming Nieh [7]. An alumina (Al_2O_3) and titania (TiO_2) nano-coolant (NC) were used to enhance the heat dissipation performance of an air-cooled radiator. The experimental results showed that the heat dissipation capacity and the efficiency factor of the nanofluid are higher than ethylene glycol, and that the nanofluid with TiO2 is more efficient than one with Al2O3 according to most of the experimental data.

Gulhane and Chincholkar [8] carried out an experimental study on the application of water based Al_2O_3 nanofluid at lower concentrations in a car radiator. The results showed that the heat transfer coefficient enhances with an increase in particle concentration, flow rate, and inlet temperature of coolant and the maximum increase in heat transfer coefficient is 45.87 % compared to pure water. Ray and Das [9] compared three different nanofluids containing aluminum oxide nanoparticles, copper oxide and silicon oxide in the same base fluid, a mixture of ethylene glycol and water with a mass ratio of 60:40, used as a refrigerant in the car radiator. They observed that a nanofluid with a volumetric concentration of 1% of nanoparticles has better properties than those with higher concentrations: there was a 35.3% reduction of the pumping power and 7.4% of the heat transfer surface using an Al_2O_3 nanofluid. CuO nanofluid showed a slightly lower improvement, with a reduction of the pumping power and heat transfer surface of 33.1% and 7.2%, respectively. Finally, the SiO_2 nanofluid showed lower performance, but still allowed to reduce the pumping power of 26.2% and the surface of 5.2%.

Ali et al. [10] added ZnO nanoparticles in the base fluid with different volumetric concentrations (1%, 8%, 2% and 3%). The flow rate of the fluid was varied in a range between 7 and 11 LPM (liters per minute), the Reynolds number range was 17,500-27,600. The nanofluids showed an increase in heat transfer compared to the base fluid for all the concentrations examined. The maximum increase observed was 46% compared to the base fluid with a volumetric concentration of 2%. Increasing the volumetric concentration to 3%, it is noted that the heat transfer decreased. Besides, by varying the inlet temperature from 45 °C to 55 °C showed an increase in heat transfer velocity up to 4%. Moghaieb et al. [11] carried out an experimental analysis on the Al_2O_3 nanofluid and water, used in a cooling system of a car engine. The authors studied the convective heat transfer of the nanofluid with different diameters of nanoparticles (21-37 nm). The results showed that the convective heat transfer coefficient is directly proportional to the flow velocity and inversely proportional to its temperature. The heat transfer is 78.67% higher compared the traditional fluid in a car radiator, considering a volumetric concentration of nanoparticles of 1%.

In the study of Elbadawy [12] two nanofluids (Al_2O_3/water and CuO/water) flowing in a flat tube of radiator investigated numerically to evaluate thermal and flow performance. They achieved a significant reduction in the radiator volume due to marked improvement in the heat transfer performance, while the required pumping power is found to be a function of Reynolds number and naofluid concentration ratio. The increase in the heat transfer coefficient reached 45% and 38% for Al_2O_3/water and CuO, respectively compared to the values of pure water. The optimum nanoparticle volume concentration which gives a moderate heat transfer enhancement with moderate pumping power increase is investigated an approximately found to be 4.5% for both noanofluids. Harsh et al. [13] presented an experimental work on heat transfer using nanofluid as coolants in engine. Ethylene-glycol water solution was taken as a base fluid for nanoparticle dispersion. The analysis carried out with flow rate of 4,6,7 LPM and the air flow rate inside the duct was kept constant at 4.9 m/s. Results shows that there is an improvement of 24.5% in the overall heat transfer coefficient and there was also an increase of 13.9% in the heat transfer rate compared to the base fluid (80:20 Water:EG solution).

The application of Al_2O_3 nanoparticles in pure water with dimensions 45 nm and volumetric concentrations from 2-6% into a car radiator, is presented in this work. The analysis carried out considering three different car operation regimes (Low, Medium and High). The study focused on the evaluation of pumping power, heat transfer rate and temperatures at the radiator outlet. The results were compared with EG/water as coolant.

PROBLEM DESCRIPTION AND MATHEMATICAL REFERENCE

A heating system, a hydraulic pump and a heat exchanger are considered for the simulation of the cooling circuit. The heat exchanger represents the car radiator in the circuit. The nanofluid consisted of water containing 0 – 2 - 3 - 4 – 5 - 6 vol % Al_2O_3 nanoparticles. flows into the circuit. The studies are conducted for three different engine operating conditions (Low, Medium and High). Physical properties of the Al_2O_3 nanoparticles and water such as thermal conductivity, specific heat capacity, density and dynamic viscosity are evaluated by means equations (1-4). The described automotive cooling system is fully modelled in TRNSYS (version 17) as presented in figure 1.

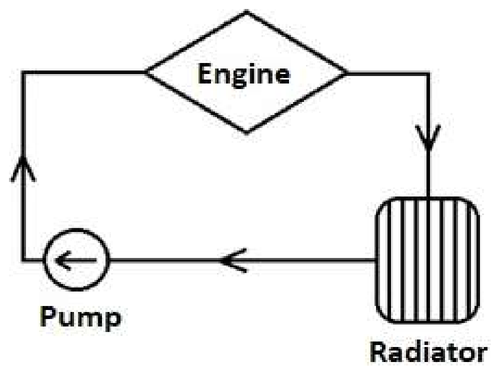

FIGURE 1. 1-D Sketch of the cooling system

Input Data and Operating Characteristics

Necessary input data were taken from literature to perform the analysis in this study. The characteristics of the radiator considered in this study are obtained from Vasu et al. [14] and Kays and London [15] and summarized in table 1.

TABLE 1. Operating characteristics of the heat exchanger

Parameters	Symbol	Unit	Value
Core geometry	L_r - H_r - D_r	m	0.673 - 0.406 - 0.0163
Number of ducts	N	-	52
Thickness of the wall ducts	a	mm	0.3302
External dimension of ducts	L_{ot}, H_{ot}	m	0.0144 – 0.0241
Internal dimension of ducts	L_{it}, H_{it}	m	0.0138 – 0.0175
Distance duct-plate	b_c	m	1.753
Material	-	-	Aluminum
Fin pitch	p	m	0.106
Distance plate-fin	b_a	m	0.00635
Fin thickness	δ	mm	0.152
Thermal conductivity fin and ducts	k_f	W/mK	177
Fin length	L_f	m	0.00318
Heat transfer area/total volume	β	m^2/m^3	2466
Fin area/total area	A_{ft}	-	0.887
Hydraulic diameter	D_h	mm	1.423

Nanoparticles aluminum oxide with water as the base fluid are considered. Thermo-physical properties are shown in table 2. The calculation of the nanofluid density at different volumetric concentrations of the nanoparticles is presented by Pak and Cho [16] and validated by the experimental study of Vajjha et al. [17]:

TABLE 2. Thermo-physical properties of nanoparticles

Parameters	Symbol	Unit	Value
Density	ρ_p	kg/m^3	3600
Heat specific	$c_{p,p}$	J/kgK	765
Thermal conductivity	k_p	W/mK	36
Diameter	d_p	nm	45

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

Where ρ_p is the density of nanoparticles, ρ_{bf} is the density of water (base fluid) and φ is the volumetric concentrations of nanoparticles.

The heat specific of nanofluid it is evaluated from Xuan and Roetzel [18]:

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

Thermal conductivity of nanofluid it is calculated with the equation proposed by Koo and Kleinstreuer [19]:

$$k_{nf} = \frac{k_p + 2k_{bf} - 2(k_{bf} - k_p)\phi}{k_p + 2k_{bf} + (k_{bf} - k_p)\phi} k_{bf} + 5\cdot 10^4 \beta\phi\rho_{bf} c_{p,bf} \sqrt{\frac{\kappa T}{\rho_p d_p}} f(T,\phi) \tag{3}$$

Where f(T,φ) is:

$$f(T,\phi) = (2.8217\cdot 10^{-2}\phi + 3.917\cdot 10^{-3})\cdot\left(\frac{T}{T_0}\right) + (-3.06669\cdot 10^{-2}\phi - 3.911\cdot 10^{-3}) \tag{4}$$

κ is the Boltzmann constant and β is equal to $8.4407(100\varphi)^{-1.07304}$.

The analysis of the cooling system carried out considering the parameters ethylene glycol-water (EG/W), corresponding to three different operating parameters of the car radiator (Table 3). Furthermore, the study takes into account the conditions of three different engine rotation speeds.

The analysis carried out in this way made it possible to evaluate the results of the cooling circuit corresponding to three different operating scenarios: Low, Medium and High performance (Table 4).

TABLE 3. Operating parameters

Parameters	Unit	Low	Medium	High
Inlet Temperature – air side	K	293	293	293
Reynolds number - air side	-	500	1000	2000
Velocity – air side	m/s	5.82	12.02	24.04
Volume flow rate – air side	m^3/s	1.01	2.09	4.18
Mass flow rate – air side	kg/s	1.16	2.35	4.69
Reynolds number – coolant	-	4500	5500	6500
Velocity – coolant	m/s	2.79	1.67	1.46
Mass flow rate – coolant	kg/s	$3.41\cdot 10^{-3}$	$2.04\cdot 10^{-3}$	$1.78\cdot 10^{-3}$
Efficiency of car radiator	-	0.51	0.38	0.27
Pressure drop - Coolant	kPa	10	10	10
Motor speed	rpm	1500	2000	2500
Engine power	kW		72	

Performance Calculation

Effectiveness for crossflow heat exchanger with both fluids unmixed is given by [20]:

$$\varepsilon = 1 - \exp\left[\frac{NTU^{0.22}}{C^*}\exp\left(-C^* NTU^{0.78} - 1\right)\right] \tag{5}$$

The total heat transfer rate has been calculated by:

$$\dot{Q} = \varepsilon \cdot C_{\min} \cdot (T_{nf,i} - T_{a,i}) \tag{6}$$

The pumping power is estimated by the following equation:

$$\dot{W}_{pumping} = \frac{\Delta P \cdot \dot{m}}{\rho_f} \tag{7}$$

Finally, performance index in according with [21] is expressed as:

$$PI = \frac{\dot{Q}}{\dot{W}} \tag{8}$$

RESULTS AND DISCUSSION

Simulations are performed for six different volume concentration values of nanoparticles, from 0% to 6%, in water. The investigation is carried out in order to evaluate the energy consumption by the pump, the outlet and inlet temperatures of the radiator and the heat transfer rate. The analysis has been carried out considering the engine power equal to 72 kW.

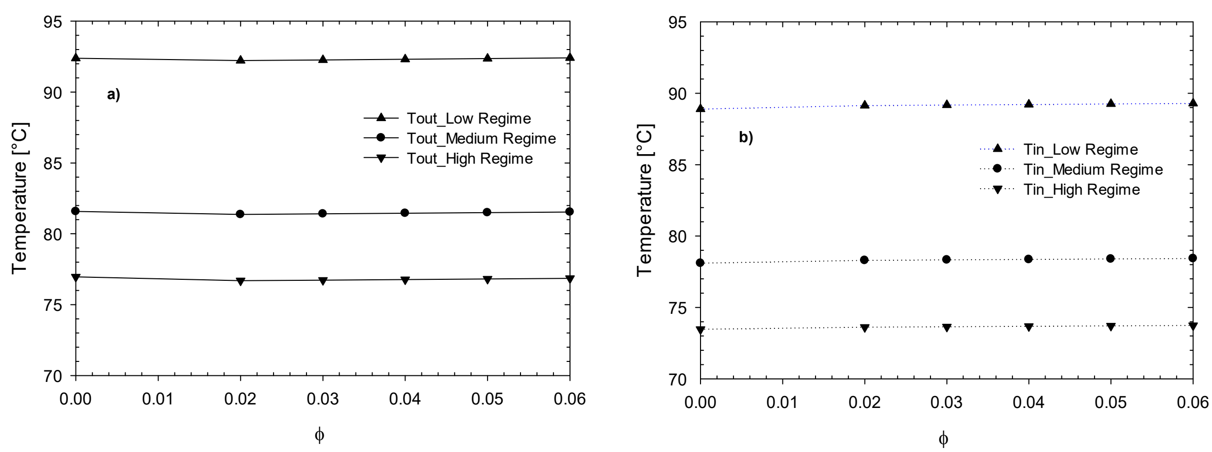

FIGURE 2. Temperature of the car radiator as a function of nanoparticles concentration: a) outlet temperature; b) inlet temperature

The temperatures at the outlet of the engine car a decreasing trend with the increase in the volumetric concentration of the nanoparticles in the base as shown in figure 2 (a-b). Besides, the temperature depends on the engine speed. Figure 3 shows the results of simulating the effects of using Al_2O_3 nanofluid coolant with different volume fractions flowing in the tubes in three range of the automotive speed and Reynolds number of the nanofluid on the heat transfer rate. The results of this study show that nanofluid enhances the heat transfer in the radiator and therefore the total heat transfer area of the radiator could be reduced.

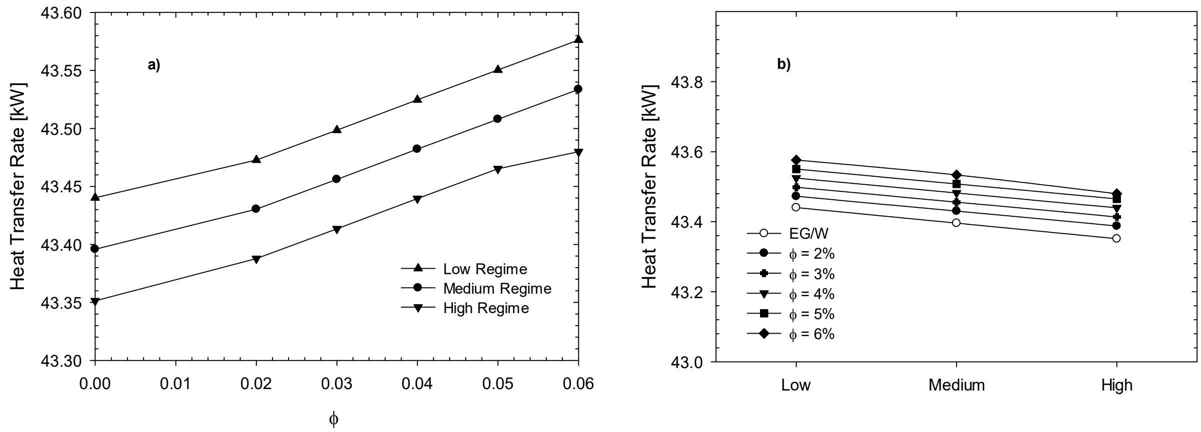

FIGURE 3. Heat transfer rate of the car radiator as a function of nanoparticles concentration a) and as a function of engine speed b).

About 1.5% of the heat transfer improvement can be achieved with addition of 6% aluminum particles at 500 and 4500 Reynolds number for air and coolant respectively. The nanofluids exhibit better thermal performance at higher temperatures.

In order to apply the nanofluids for practical application, in addition to the heat transfer performance it is necessary to study their flow features. Generally, nanofluids require the greater pumping power than their base fluid. The increase of the volumetric concentration of nanoparticles ϕ in the working fluid leads to an increase in its density with respect to the pure water, which implies an increase in energy consumption. Furthermore, a reduction of pumping consumption occurs as the operating conditions increase, due to the reduction of the mass flow of the refrigerant, necessary for the cooling of the engine (Figure 4). It was observed that the coolant pressure drops with the addiction of aluminum nanoparticles due to its higher density. Due to this extra pressure drop, a higher coolant pumping power is needed.

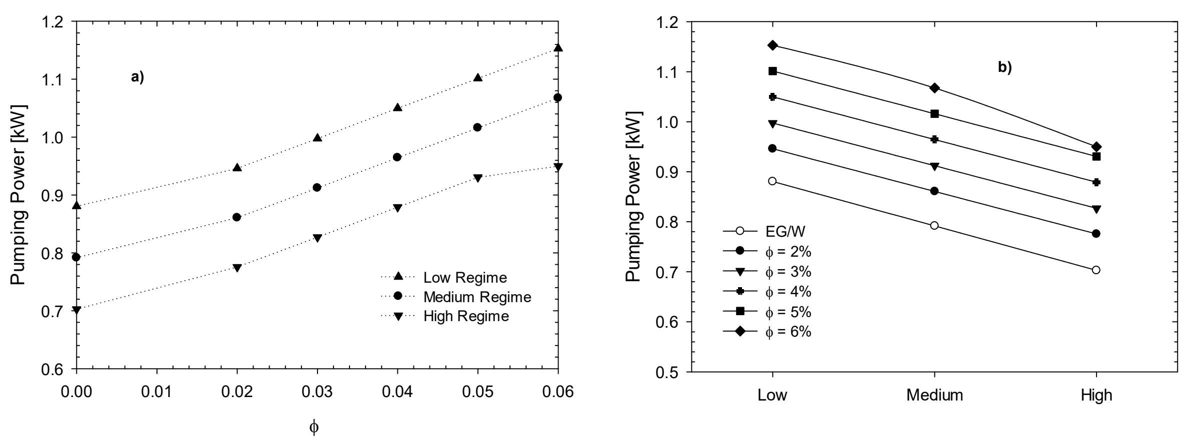

FIGURE 4. Pumping power of the car radiator as a function of nanoparticles concentration a) and as a function of engine speed b).

CONCLUSIONS

The heat transfer and performance analysis of an automotive radiator have been done using aluminum nanofluids as coolant. The better performances of nanofluids are achieved at low engine speed. Based on the results and discussions, the following conclusions can be made:

- The temperature is depending from the engine speed and from volumetric concentrations of nanoparticles, however, the difference between with nanofluid and EG/W is rather similar;
- In all cases studied, aluminum nanofluid has higher heat transfer of 2% with comparison to EG/W. The maximum value of heat transfer rate is equal to 43.58 kW for φ=6% and low engine speed;
- The same scenario it is possible to note for the pumping power trend. The maximum value of the pumping power is equal to 1.15 kW for φ=6% and low engine speed;
- Cause the higher pumping power needed to pump nanofluids, the performance index of nanofluids has values smaller than performance index of EG/W as shown in figure 5.

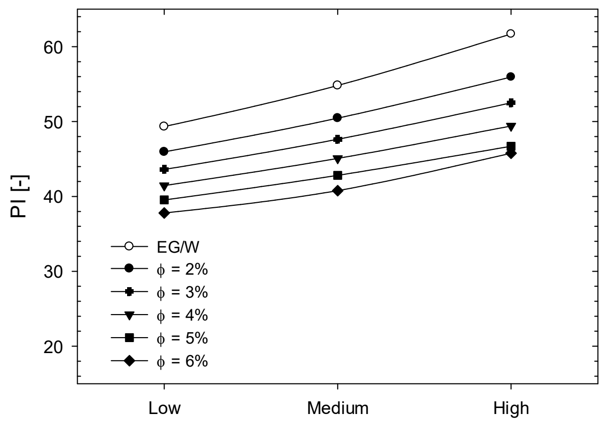

FIGURE 5. Performance index as a function of engine speed

NOMENCLATURE

a	tube wall thickness	mm
c_p	heat specific	J/kgK
k	thermal conductivity	W/mK
d_p	particle diameter	m
D_h	hydraulic diameter	m
C*	capacity ratio	
C_{min}	minimum heat capacity rate	W/K
$\dot{Q}$	heat transfer rate	W
$\dot{W}$	pumping power	W
T	temperature	°C
$\dot{m}$	mass flow rate	kg/h
PI	performance index	-
L	length	m
H	height	m
D_r	depth	m
N	number of tubes	-
NTU	number transfer units	
b	plate spacing	m

p	fin pitch	m
P	pressure	Pa
A_{ft}	fin area/total area	m^2

Greek symbols

α	total transfer area/total exchanger volume	m^2/m^3
β	total transfer area/volume between plates	m^2/m^3
δ	fin thickness	m
ρ	density	kg/m^3
ϕ	volumetric concentration	-
ε	heat exchanger effectiveness	-
κ	Boltzmann constant	1.38×10^{-23} J/K
ΔP	pressure drop	Pa

Subscripts

0	properties at reference temperature (273 K)
a	air side
f	fluid
nf	nanofluid
i	inlet
o	outlet
p	particle
bf	base fluid

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