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Experimental Study on Convective Heat Transfer Enhancement of Automotive Radiator with Graphene-Nanoplatelet Suspension

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ABSTRACT

In the present work, an experimental investigation has been conducted to analyse the effects of graphene-nanoplatelet (GnP) suspension on the thermal performance of automotive radiator. GnP nanofluids are prepared by dispersing the nanoparticles in distilled water with a concentration of 0-0.3 vol.%. The thermophysical properties of water-GnP nanofluid have been studied with different volumetric concentrations and temperatures. The present study shows that convective heat transfer performance of the automotive radiator could be enhanced by increasing the nanoparticle suspension, heating power, air flow and Reynolds number. The maximum thermal performance enhancement of 275% is achieved for 0.3 vol.% GnP nanofluid at the highest rated heating power. It is also evident that the suspension of nanoparticle has the most significant effect in enhancing the convective heat transfer of automotive radiator, followed by the effects of heating power, air velocity and Reynolds number.

1. Introduction

The increasing demand of energy resources has become a critical issue [1]. In recent decades, the diesel and gasoline automotive are widely used in urban or rural areas [2]. As reported by World Energy Council [3], the global transportation sector has consumed more than 60% of oil which around fifty-one million barrels per day. Based on U.S. Energy Information Administration [4], in year 2040 the oil consumed by global transportation sector will approximately increase up to seventy million barrels per day. Therefore, the fuel efficiency of automotive becomes one of the important design factor for manufacturers to produce energy efficient engines in order to meet market demands [1]. By improving the design and reducing the size of automotive radiator, the weight of the vehicle can be decreased, leading to a better fuel consumption efficiency. Radiator, a vital component in the engine cooling system, is used to transmit heat generated in the engine through cooling fins. However, issues like engine overheating and low thermal conductivity of radiator coolant impose limitations on automotive manufacturers to reduce the size of radiator [5].

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With the advances of nanotechnology, engineers and researchers are enhancing the thermal efficiency of radiator through the application of nanoparticle [5-7]. In 1995, Choi and Eastman [8] proposed a novel kind of high-thermal-conductivity engineered fluid that can be produced by the dispersion of nanometre-sized metallic particle in conventional fluid. The newly engineered fluid was later coined as nanofluids [8]. Nanofluids are heat transfer fluid that contains nanoparticles with diameter less than 100 nanometres suspended in conventional fluid [6]. Nanofluids have superior heat transfer performance as compared to conventional fluid and fluid containing micrometre-sized particles [6, 7, 9-13]. Superior heat transfer performance of nanofluid is contributed by the large surface area of particle as heat transfer occurs at particle surface [7, 14]. Nanoparticles have larger surface area than millimetre and micrometre-sized particles and hence, ideal for heat transfer applications. Moreover, nanofluid eliminate the clogging problem that is commonly encountered in micrometre-sized particle fluids. Thus, nanofluids can be used to enhance the thermal efficiency of automotive radiator [5].

In the earlier stage of research on the usage of nanoparticle in enhancing the heat transfer performance of automotive radiator, the focus is on metal-based nanofluid such as copper oxide [6, 15-17] and aluminium oxide [6, 18-21]. Vajjha *et al.,* [6] numerically investigated the effect of the copper oxide and aluminium oxide nanoparticle suspension in a mixture of ethylene glycol (EG) and water in automotive radiator. It is reported that the presence of copper oxide nanoparticle intensifies the heat transfer coefficient of radiator by 89%, while aluminium oxide nanoparticle enhances the thermal performance by 94%. Besides, the heat transfer coefficient enhancement intensifies with the increase of nanoparticle concentration and Reynolds number [6]. On contrary to the significant enhancement as reported by Vajjha *et al.,* [6], an experimental investigation on the overall heat transfer coefficient of CuO/water nanofluids in a car radiator reported a mere enhancement of 6-8%. The contradictory conclusions denoted about the effect of nanoparticle suspension on Nusselt number in a car radiator system is also reported by Lotfi *et al.,* [22].

In recent years, the effect of carbon-based nanoparticle suspension in automotive radiator starts to garner the attention of research community. M'hamed *et al.,* [5] experimentally investigated the effect of suspending multi-walled carbon nanotubes (MWCNT) in EG/water for the cooling of automotive system. The study shows that the MWCNT nano-coolant significantly enhances the radiator thermal performance by 196.3% [5]. They attributed this significant enhancement to the much higher thermal conductivity, aspect ratio, larger specific surface area and lower specific gravity and thermal resistance than water and EG. Graphene, a thin layer of pure carbon arranged in honeycomb lattice, has a very high thermal conductivity value of 3,000 W/m K [23]. Hence, it is conjecture that graphene-based nanoparticle could also enhance the thermal performance of automotive radiator. Several studies have been conducted to study the thermal properties of graphene nanoplatelets (GnP) with difference types of basefluid through experimental study. Selvam *et al.,* [24] analyzed the performance of automotive radiator by using GnP-EG/water nanofluids. The maximum enhancement of Nusselt number is 90% while the overall heat transfer coefficient enhancement is 104% [24]. In another study, Selvam *et al.,* [7] investigated the performance of GnP-EG/water nanofluids in automotive radiator and show that the maximum enhancement of convection heat transfer coefficient and Nusselt number are, respectively, 51% and 21% [7]. Naveen and Kishore [25] reported that the graphene/water-EG coolant could intensifies the heat transfer rate by 68.04% at higher flow rate and volume concentrations. Besides, it is concluded that nanofluids shows a promising feature in automobile industry because of its superior heat transfer properties when compared with conventional coolant [25].

The number of studies on convective heat transfer of nanofluids in automotive radiator is relatively scarce as compared to the other heat transfer applications [22]. In up-to-date literature, most of the study of graphene-based nanofluid in automotive radiator employs the mixture of water and EG as the basefluid [7, 24, 25]. Experimental investigations on the performance of water-based GnP nanofluids in radiator for improving the cooling of automotive engine is very limited. Thus, the aim of the present study is to investigate the thermal performance of automotive radiator with GnP suspension in water. The study could enhance the understandings on the underlying physical significance of the suspension of graphene-based nanoparticle in water for the thermal performance enhancement of automotive radiator.

2. Methodology

2.1 Experimental Setup

In the present study, nanofluid is prepared using graphene nanoplatelets (GnP) from XG Sciences with average thickness of 7 nm and average particle diameter of 15 µm. Graphene-based nanofluids are prepared by dispersing GnPs into distilled water (DW) that acts as a basefluid. GnP nanofluids are prepared with GnP volume concentration of 0%, 0.15 and 0.3%. The GnP-DW nanofluids are subjected to ultrasonication for 120 minutes to prevent particle aggregation and to improve the stability of the fluid.

The experiment set up of the present study is shown in Figure 1, and the schematic layout of the equipment used to investigate the thermal performance of nanofluids in the automotive radiator is illustrated in Figure 2. The experimental setup consists of two fluid circulations, namely the main circulation loop and the recycle loop. The inlet temperature of nanofluid is controlled by coil heaters with different wattage. Two thermocouples are fixed at the inlet and outlet of the radiator to monitor the temperatures at the locations. The tube wall temperatures at nine different locations are measured by thermocouples that are fixed on the radiator tubes. The inlet, outlet and tube wall temperatures are recorded by a digital thermometer. All pipes are insulated to avoid additional heat gain or loss during the experiment. The flow rate of nanofluid is measured by a flow meter and controlled by ball valves. Radiator fan speed is controlled by regulating voltage supply from an AC-to-DC converter.

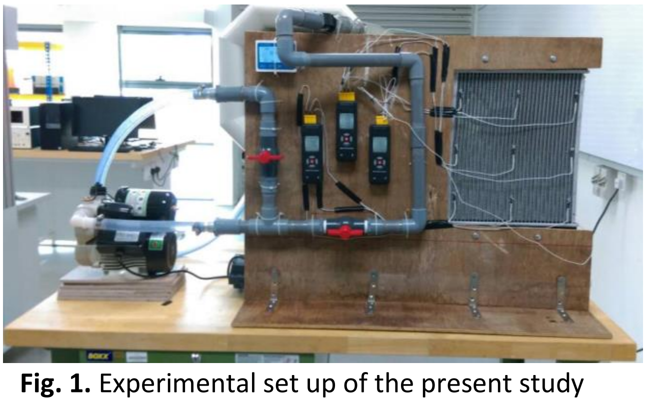


Fig. 1. Experimental set up of the present study

The thermal performance of nanofluids in an automotive radiator is investigated under the effects of various pertinent parameters such as nanoparticle volume concentration, heating power, Reynolds number and radiator fan speed. The equipment is left running until the change in temperature is less than 0.1°C to attain the heat transfer steady state. The heating power at inlet is varied by using coil heaters with different wattage and the outlet temperatures of nanofluids are recorded throughout the experiment to determine the convective heat transfer coefficient of the fluid. Nanofluid flow rate is varied by manipulating the ball valve.

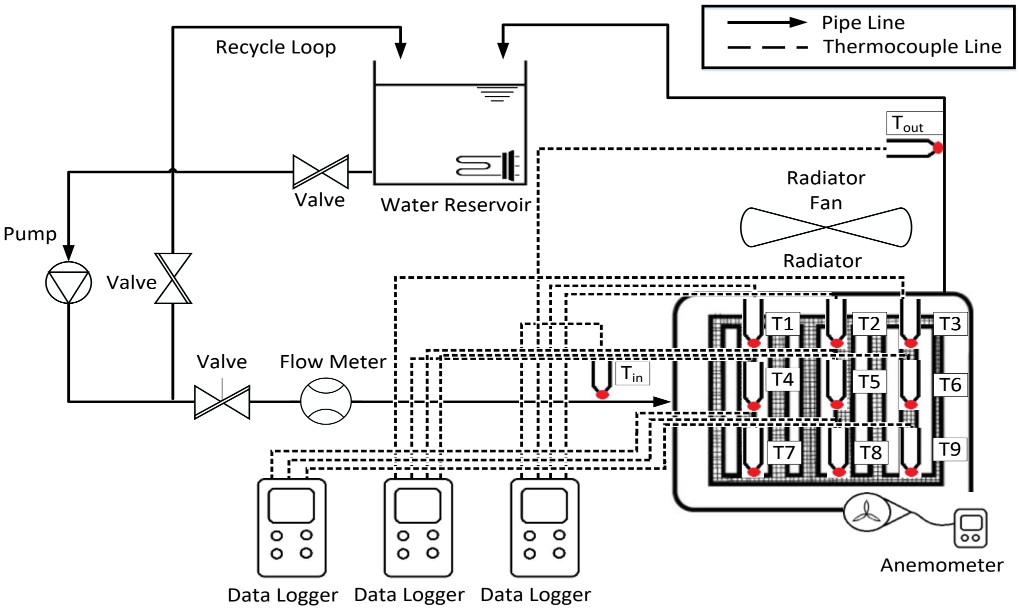


Fig. 2. Schematic diagram of the experimental set up

2.2 Thermophysical Properties Correlations

The density of nanofluid can be expressed by [15,18-20,26,27]

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

where ρ and ϕ are density and nanoparticle volume concentration, respectively. The subscript nf, bf and p represent nanofluid, basefluid and nanoparticle, respectively. The specific heat capacity of nanofluid can be computed by [18-20,28,29]

$$C_{p,\text{nf}} = \frac{\phi(\rho C_p)_{\text{p}} + (1-\phi)(\rho C_p)_{\text{bf}}}{\rho_{\text{nf}}} \tag{2}$$

where specific heat capacity is denoted by C_{p}. The dynamic viscosity of GnP nanofluids are evaluated using a modified empirical correlation which can be expressed by [30]

$$C_\mu = (1+\sigma^{1.675}\phi) \tag{3}$$

The thermal conductivity of GnP nanofluid is computed using Nan's model [31,32] as defined as

$$\frac{k_{\text{nf}}}{k_{\text{bf}}} = \frac{3+\phi[2\alpha_{11}(1-G_{11})+\alpha_{33}(1-G_{33})]}{3-\phi(2\alpha_{11}G_{11}+\alpha_{33}G_{33})} \tag{4}$$

where G_{11} and G_{33} are geometrical factors which can be expressed as

$$G_{11} = \frac{\sigma^2}{2(\sigma^2-1)} + \frac{\sigma}{2(1-\sigma^2)^{3/2}}\cos^{-1}\sigma \ \text{ for } \sigma<1 \tag{5}$$

$$G_{33} = 1 - 2G_{11} \tag{6}$$

The parameter σ represents the aspect ratio of GnP, σ = t/D. Dimensionless parameters α11 and α33 are defined as

$$\alpha_{11} = \frac{k_{11} - k_{\text{bf}}}{k_{\text{bf}} + G_{11}(k_{11} - k_{\text{bf}})} \tag{7}$$

$$\alpha_{33} = \frac{k_{33} - k_{\text{bf}}}{k_{\text{bf}} + G_{33}(k_{33} - k_{\text{bf}})} \tag{8}$$

where k_{11} and k_{33} are the equivalent thermal conductivity at x-axis and z-axis, respectively. k_{11} and k_{33} are defined as

$$k_{11} = \frac{k_{\text{p,x}}}{1 + \beta G_{11} k_{\text{p}} / k_{\text{bf}}} \tag{9}$$

$$k_{33} = \frac{k_{\text{p,z}}}{1 + \beta G_{33} k_{\text{p}} / k_{\text{bf}}} \tag{10}$$

where β is a dimensionless parameter and defined as follow

$$\beta = (1 + 2\sigma)\frac{K_{\text{r}}}{t/2} \text{ for } \sigma < 1 \tag{11}$$

In Eq. (11), K_r is Kapitza radius and defined as $K_{\text{r}} = R_i k_{\text{bf}}$ where Ri is the interfacial resistance and represented as $R_i = t_i / k_i$.

2.3 Data Reduction

According to Newton's law of cooling, the heat transfer rate between the nanofluid and tube wall can be expressed as

$$Q = h_{\text{nf}} A\left(T_{\text{b}} - T_{\text{w}}\right) \tag{12}$$

The inner surface area of tube, bulk fluid temperature and tube wall temperature are denoted by A, Tb and Tw, respectively. Tw is the average wall temperature measured by nine thermocouples. The heat transfer rate of nanofluid within the radiator can be calculated by

$$Q = \dot{m} c_{p,\text{nf}}\left(T_{\text{in}} - T_{\text{out}}\right) \tag{13}$$

where mass flow rate, inlet and outlet temperature of nanofluid are denoted by $\dot{m}$, T_{in} and T_{out} respectively. The convective heat transfer coefficient (CHTC) of GnP nanofluid can be determined by correlating Eq. (12) and Eq. (13) to yield

$$h_{nf} = \frac{\dot{m} c_{p,nf} \left(T_{in} - T_{out} \right)}{A \left(T_b - T_w \right)} \tag{14}$$

3. Results and Discussion

3.1 Thermophysical Properties of Nanofluid

Thermophysical properties of GnP nanofluid such as density, specific heat capacity, viscosity and thermal conductivity are evaluated using correlations which are presented in Eq. (1) – Eq. (4). The density of GnP nanofluid is found to decrease with respect to temperature and increase with respect to nanoparticle concentration as illustrated in Figure 3(a). As the temperature increases from 40°C to 60.5°C, the density of 0.15 vol.% and 0.30 vol.% GnP nanofluid decreases by 0.901% and 0.898%, respectively, whereas the density of basefluid decreases by 0.936%. The density ratio (ρ_{nf}/ρ_{bf}) at fluid temperature of 60.5°C increases from 1.00184 to 1.00369 when nanoparticle concentration increases from 0.15 vol.% to 0.30 vol.%. As fluid temperature increases, the Van der Waals forces between the fluid molecules become weaker, resulting in increasing fluid volume and thus, decreasing fluid density [18]. The increment of nanofluid density with respect to nanoplatelet loading can be attributed to the dispersion of high density nanoparticles in the fluid [33].

The specific heat capacity of nanofluid is found to increase with respect to temperature and decrease with respect to nanoparticle concentration, as illustrated in Figure 3(b). As the temperature rise from 40°C to 60.5°C, the specific capacity of 0.15 vol.% and 0.30 vol.% GnP nanofluid increases by 0.160% and 0.157%, respectively, whereas the specific heat of basefluid increases by 0.181%. The specific heat ratio ($C_{p,nf}/C_{p,bf}$) at fluid temperature of 60.5°C decreases from 0.99722 to 0.99439 when nanoplatelet loading increases from 0.15 vol.% to 0.30 vol.%. The decrease of specific heat capacity in nanofluids with respect to nanoparticle concentration can be attributed to the lower specific heat of graphene nanoplatelet, at 0.643 kJ/(kg. K) [34]. Due to the fact that graphene nanoplatlets have comparatively lower specific heat, the addition of more nanoparticles into the fluid further decreases nanofluid's specific heat capacity.

The thermal conductivity of GnP nanofluid is found to increase with respect to temperature and nanoparticle concentration as shown in Figure 3(c). Nanofluid of 0.15 vol.% and 0.30 vol.% exhibit enhancements in thermal conductivity by 2.73% and 2.54%, respectively, when fluid temperature increases from 40°C to 60.5°C. Basefluid exhibits similar trend in thermal conductivity enhancement when temperature increases. When comparing to the basefluid, 0.15 vol.% and 0.30 vol.% nanofluid exhibit enhancement in thermal conductivity by 171.3% and 342.7%, respectively, at fluid temperature of 60.5°C. Enhancement of thermal conductivity at higher temperature is due to the increase of particle movements associated with Brownian motion within the fluid [7, 18, 35]. The effect of Brownian motion becomes more significant at higher temperatures due to the micro-convection induced by such motion. On the other hand, the enhancement of thermal conductivity at higher nanoparticle concentrations is attributable to the high-thermal-conductivity characteristics of graphene nanoplatelet. In the present study, the thermal conductivity is evaluated by assuming that the interfacial thermal resistance is zero and thus, there is no resistive layer between the nanoparticles and fluid.

The viscosity of GnP nanofluid is observed to decrease with respect to temperature and increases with respect to nanoparticle concentration, as illustrated in Figure 3(d). The viscosity of 0.15 vol.%

and 0.30 vol.% GnP nanofluid decreases by 29.36% when temperature increases from 40°C to 60.5°C, whereas the viscosity of basefluid decreases by 29.42%. As nanoparticle concentration increases from 0.15 vol.% to 0.30 vol.%, the viscosity ratio (μ_{nf}/μ_{bf}) increase from 4.36 to 7.71 at fluid temperature of 60.5°C. It can be explained that the rise in temperature weakens the intermolecular forces of nanofluid, increasing molecule movements within the medium and reducing fluid viscosity [7]. At higher nanoparticle concentration, there are more nanoparticles within the fluid and the intermolecular forces between nanoparticles are higher [28]. Due to the strong bonding between molecules, particle mobility decreases, resulting in greater flow resistance. Thus, nanofluid with higher GnP concentration exhibits higher fluid viscosity.

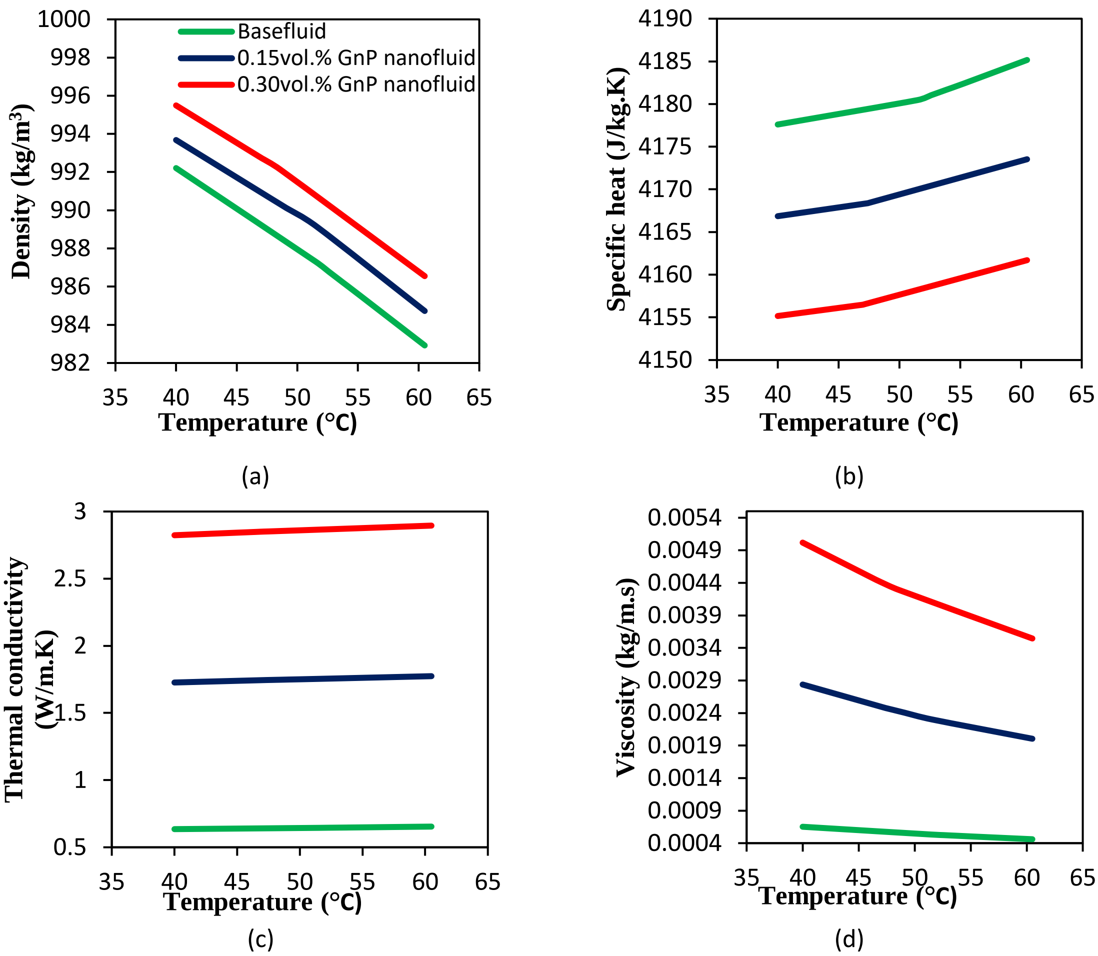


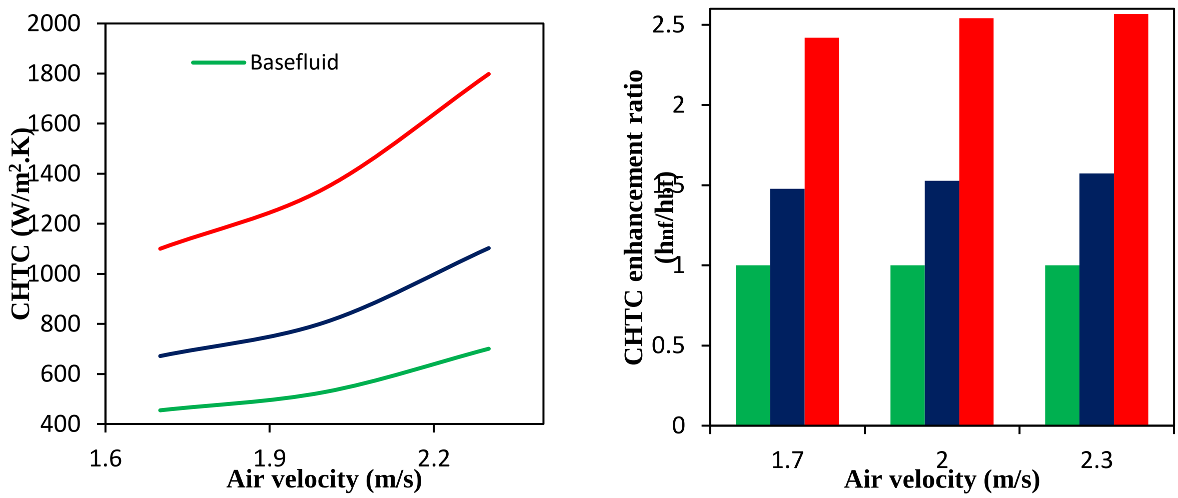
Fig. 3. Relationship between nanofluid (a) density, (b) specific heat capacity, (c) thermal conductivity and (d) viscosity with respect to the temperature for various particle concentration

3.2 Heat Transfer Enhancement Effects of Graphene-Nanoplatelet Suspension

In the present study, four pertinent variables, i.e. nanoparticle concentration, air velocity, heating power and Reynolds number are studied to analyse their effects on the heat transfer performance of an automobile radiator. Figure 4(a) shows that the heat transfer performance of radiator increases with respect to air velocity and nanoparticle concentration. When air velocity increases from 1.7 m/s to 2.3 m/s, nanofluid of 0.15 vol.% and 0.30 vol.% exhibit enhancements in CHTC by 64.2% and 63.4%, respectively. Similar trend is observed in basefluid, with a lower enhancement rate of 54.1%. It can be inferred that increasing air velocity would increase air mass flow rate, $\dot{m}_{air}$, leading to the enhancement of air side heat transfer rate, Q_{air}, as depicted by Eq. (17)

$$Q_{air} = \dot{m}_{air} c_{p,air} \left(T_{in} - T_{out} \right) \tag{15}$$

CHTC enhancement ratio (h_{nf}/h_{bf}) increases with respect to air velocity and nanoparticle concentration as illustrated in Figure 4(b). Maximum heat transfer enhancement of 256.6% is achieved by 0.30 vol.% nanofluid at air velocity of 2.3 m/s. As CHTC can be explained through the relationship between thermal conductivity (k) and thermal boundary layer thickness (δt) as k/δt [9, 36], the better CHTC enhancement of higher concentration GnP as depicted in Figure 4(b) could be attributed to the presence of more highly thermal conductive nanoparticles. The abundance of high-thermal-conductivity GnP particles and high air side heat transfer rate greatly enhances thermal performance of automotive radiator as compared to the basefluid. Besides, it is evident that the effect of GnP particles suspension could enhance the CHTC of automotive radiator by a greater extent as compared to the effect of air velocity through the radiator.



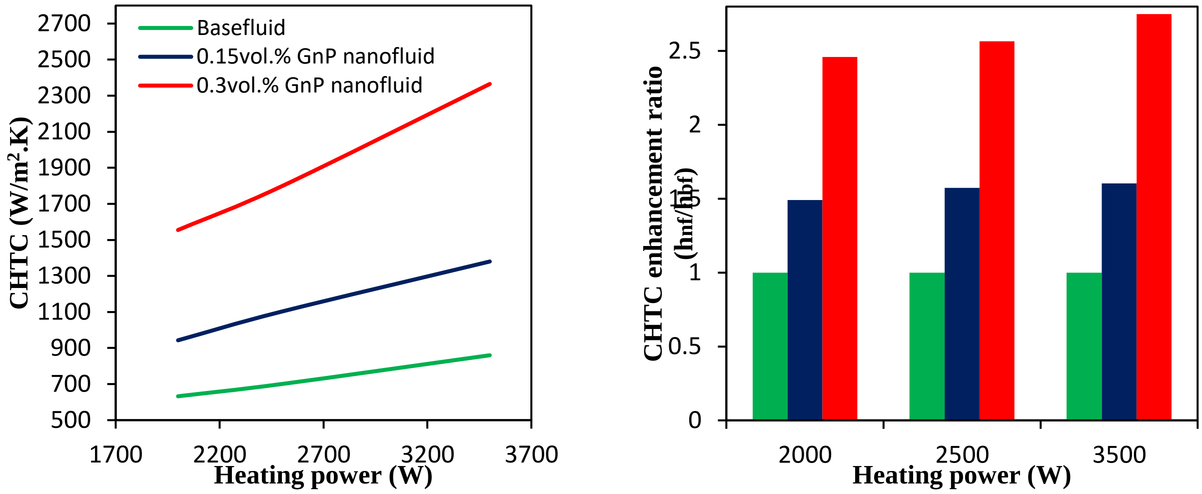
(a) (b)

Fig. 4. (a) CHTC and (b) CHTC enhancement ratio with respect to air velocity for various nanoparticle concentration

Figure 5(a) shows that the thermal performance of nanofluid increases with respect to the increase of heating power and nanoparticle concentration. Heat transfer performance of 0.15 vol.% and 0.30 vol.% nanofluid are enhanced by 46.3% and 52.1%, respectively, when the heating power increases from 2000 W to 3500 W. Basefluid exhibits similar trends with an enhancement of 36%. As the heating power increases, the inlet temperature of the nanofluid flow in the radiator increases, leading to the reduction of fluid viscosity and resulting in thinning of thermal boundary layer [26, 36]. Besides, the effects of Brownian motion are more prominent at higher temperatures as the particles gain more kinetic energy, resulting in more particle random motions and thus, reducing the thickness of boundary layer [35]. Accordingly, the reduction in thermal boundary layer thickness could lead to the enhancement of heat transfer performance in nanofluid flow in automotive radiator.

CHTC enhancement ratio increases with respect to the increase of heating power and nanoparticle concentration as shown in Figure 5(b). The maximum heat transfer enhancement of 275% is attained for 0.30 vol.% nanofluid at 3500 W heating power. It is observed that the enhancement of 0.30 vol.% nanofluid over 0.15 vol.% nanofluid is higher than that of 0.15 vol.%

nanofluid over basefluid. The abundance of highly thermal conductive and random motion of nanoparticles at high temperature greatly enhances the thermal performance of automotive radiator. Therefore, highly nanoparticle-concentrated nanofluid demonstrates better heat transfer performance at high temperatures. Besides, the effect of GnP particles suspension on the enhancement of CHTC of automotive radiator is more significant as compared to the effect of the heating power.

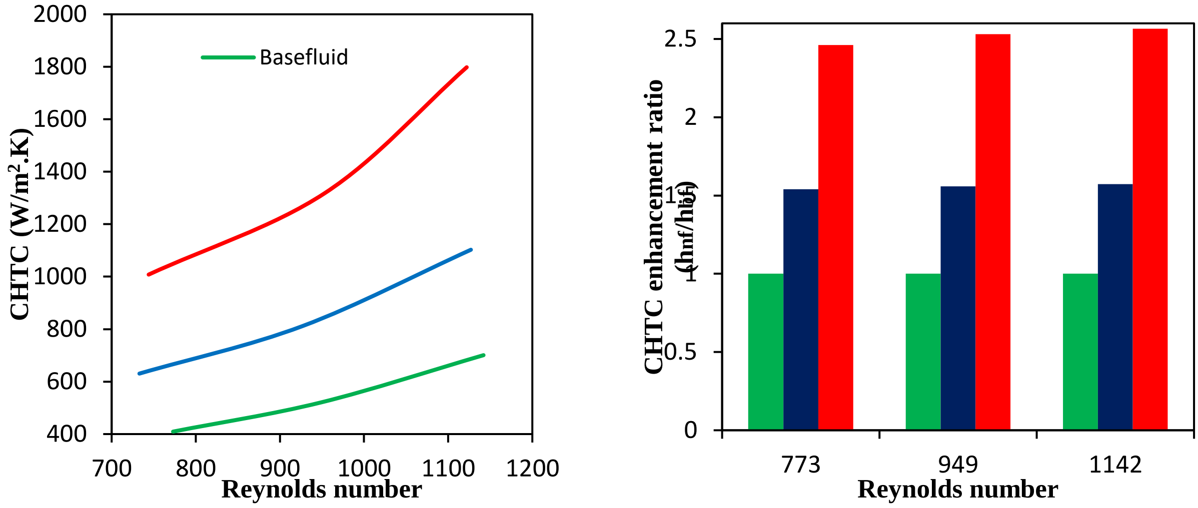


(a) (b)

Fig. 5. (a) CHTC and (b) CHTC enhancement ratio with respect to heating power for various nanoparticle concentration

Figure 6(a) illustrates that the convective heat transfer coefficient of GnP nanofluid increases with the intensification of Reynolds number and nanoparticle concentration. When Reynolds number increases from 773 to 1142, the thermal performance of 0.15 vol.% and 0.30 vol.% nanofluid enhances by 74.9% and 78.4%, respectively, while the basefluid exhibits a lower enhancement of 71.2%. With the increase of Reynolds number, the volumetric flow rate in the radiator increases, causing a better nanoparticle dispersion due to the presence of eddies in the flow [26]. The formation of eddies in the flow intensifies random motion of nanoparticles, leading to narrower thermal boundary layer and hence leading to the improved heat transfer of the radiator.

Figure 6(b) illustrates CHTC enhancement ratio against Reynolds number at various GnP concentration. It is observed that the maximum heat transfer enhancement of 256.6% is achieved at nanoparticle concentration of 0.30 vol.% and Reynolds number of 1142. Similar to Figure 4(b) and Figure 5(b), the enhancement of 0.30 vol.% nanofluid over 0.15 vol.% nanofluid is higher than that of 0.15 vol.% over basefluid. This shows that increase in nanoparticle concentration can significantly affect the thermal performance of nanofluid due to the addition of highly thermal conductive particles. Besides, the intensification of nanoparticle random motions at high Reynolds number results in greater heat transfer performance. Therefore, highly nanoparticle-concentrated nanofluid exhibits better thermal performance enhancement at high Reynolds number. It is worth noting that the effect of increasing Reynolds number to enhance the CHTC of the radiator is less significant as compared to the effect of suspending GnP in the radiator.



(a) (b)

Fig. 6. (a) CHTC and (b) CHTC enhancement ratio with respect to Reynolds number for various nanoparticle concentration

Figure 7 depicts the maximum CHTC enhancement ratio obtained by varying the air velocity, heating power and Reynolds number. It is observed that the maximum enhancement is achieved by increasing heating power, followed by the effects of air velocity and Reynolds number. By increasing the heating power, the inlet temperature of the radiator is intensified. This reduces the nanofluid viscosity due to the weakened intermolecular forces of nanofluid, allowing molecules to move more freely within the medium and hence reduces thermal boundary layer thickness. As a result, the convection heat transfer performance of the automotive radiator can be enhanced. Moreover, the effect of Brownian motion becomes more significant at higher temperatures due to the increase of particle kinetic energy with respect to temperature. Hence, the chance of molecule collision increases due to the intensification of nanoparticle movement and thus, better heat transfer performance can be achieved.

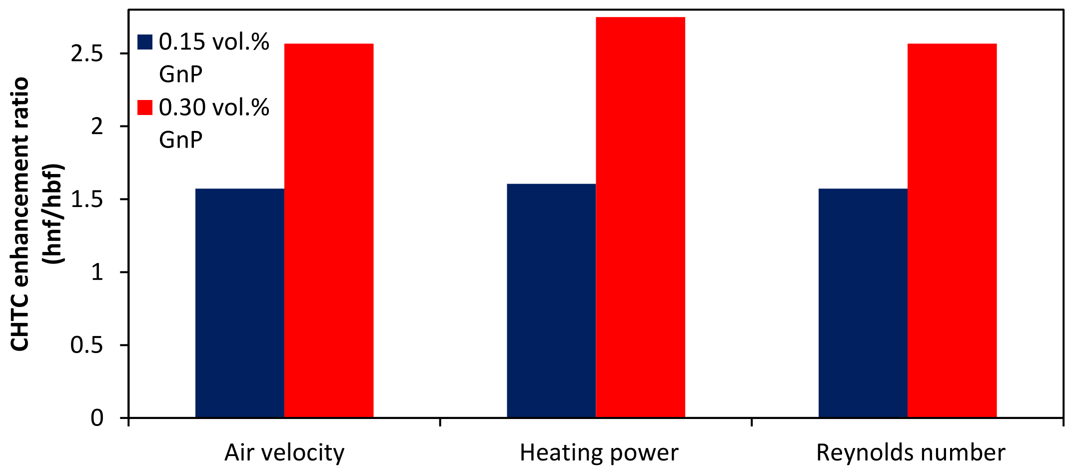


Fig. 7. CHTC enhancement ratio with respect to pertinent parameters for various nanoparticle concentration

4. Conclusions

In the present study, experimental investigations are carried out to study the heat transfer performance enhancement of an automotive radiator with GnP suspension. By increasing the nanoparticle concentration, the heat transfer performance of the radiator is enhanced due to the dispersion of high-thermal-conductivity particles in the radiator. Besides, the thermal performance of automotive radiator also increases with respect to air velocity, heating power and Reynolds number. The maximum CHTC enhancement of 275% is achieved in high-heating-power region when GnP is suspended in the radiator. On the other hand, the maximum CHTC enhancement of 256.6% is observed when increasing the air velocity and the Reynolds number of the nanofluid flow. Based on the present investigation, it is evident that the suspension of nanoparticle suspension induces the most prominent effect in enhancing the convective heat transfer of automotive radiator, followed by the effects of heating power, air velocity and Reynolds number. Therefore, it is beneficial to suspend GnP in the radiator to improve the automotive cooling system.

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