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Numerical Simulation of Graphene-Nanoplatelet Nanofluid Convection in Millimeter-Sized Automotive Radiator

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ABSTRACT

The depletion of fossil fuels and environmental considerations in transportation sector motivate the researchers to enhance the efficiency and performance of the automotive systems. However, the poor thermal performance of conventional coolant poses a limitation in the development of energy-efficient vehicle due to the cooling constraint. In the present study, a comprehensive numerical study is conducted to scrutinize the convective performance of graphene nanoplatelets (GnP) nanofluid in millimeter-sized automotive radiator, aiming to enhance the understandings on the underlying physical significance of the suspension of graphene-based nanoparticle in water for the performance enhancement of automotive radiator. The temperature-dependent thermophysical properties of GnP-water nanofluid is predicted via existing correlations, while a modified viscosity correlation is developed. ANSYS Fluent is employed in the present numerical simulation to investigate the effects of various pertinent parameters such as Reynolds number, nanoparticles aspect ratio, tube aspect ratio and tube hydraulic diameter on the heat transfer performance of the radiator. Double precision and second-order upwind scheme with inclusion of viscous heating, and convergent criteria of 10^{-6} are adopted for the present simulation. It is observed that the convective performance of the radiator is significantly enhanced by increasing Reynolds number and nanoparticle volume fraction while decreasing the aspect ratios of nanoparticle and radiator tube, with an enhancement rate as much as 1816%. Therefore, it is evident that the suspension of GnP intensifies the heat transfer performance of millimeter-sized automotive radiator, which could possibly lead to a more efficient radiator that is smaller and lighter.

1. Introduction

Gasoline and diesel fuelled vehicles are widely used in rural and urban transportation around the world [1]. The global transportation sector consumes around 51-million-barrel oil per day and it is expected to increase up to 70-million-barrel oil per day in year 2040 [2]. The increasing in energy demand coupled with the depletion of fossil fuels and the resulting environmental considerations are urging the need to develop energy-efficient vehicle with better fuel efficiency. However, issue like engine overheating poses a limitation on the efficiency of the automotive engine. Therefore, it is of

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vital importance to improve the engine cooling system by enhancing the convective performance of the automotive radiator [3].

In view of the low-thermal-conductivity characteristic of conventional coolant which constraints the cooling performance of radiator, an innovative method is adopted by suspending ultrafine solid particles in fluid to enhance the heat transfer characteristic of radiator coolant [4]. This novel type of engineered colloids, which contains nanoparticles with diameter less than 100 nanometer suspended in conventional fluid, is coined as nanofluid [5]. Nanofluids show great potential in enhancing the heat transfer performance of heat transfer devices [6] attributable to the large specific surface area [7]. Besides, the ultrafine nanoparticles do not impose clogging issue in macro- or milli-sized channel, making the nanofluid a suitable candidate coolant to enhance the thermal efficiency of radiators [8].

However, the presence of nanoparticles increases the density of nanofluids which could increase the friction factor and pumping power. In addition to that, the stability issue of nanofluids, due to the interaction among nanoparticles and fluid molecules, is posing a challenge to the commercialization of this novel type of fluid.

Numerous studies have been performed to investigate various effects related to the hydrodynamic and thermal characteristics of the nanofluids. By using Euler-Lagrange approach, Bahiraei *et al.,* [9] studied the heat transfer characteristics of CuO–water nanofluid in a straight tube under laminar flow regime. It is reported that the convective heat transfer coefficient of nanofluid is intensified as much as 14%, with the effects of thermophoretic and Brownian forces become more prominent at higher particle concentration and at greater distances from the tube inlet. Artificial neural network is also applied to nanofluid study for the prediction of water productivity [10] and energy efficiency [11] of solar still enhanced with Cu_2O-water nanofluid. Aswarthanarayana *et al.,* [12] performed a numerical study on the thermal properties of graphene-silicone oil nanofluid and reported a maximum increase of 21.19% in the thermal conductivity. A study on the hydrothermal attribute of a functionalized GnP nanofluid in micro liquid blocks revealed that by increasing either flow velocity or nanoparticle concentration, the cooling performance is augmented and the temperature of heating surface reduces, with the possibility of lowering the hot spot formation [13]. Jamshidmofid *et al.,* [14] performed thermohydraulic assessment of water-based rGO-Co_3O_4 nanofluid in a microchannel heat sink with sinusoidal cavities and rectangular ribs. It is noticed that the use of nanofluid weakens the vortices created by the cavities and ribs, while the convective heat transfer coefficient is intensified by 14%. However, Ting *et al.,* [15] showed that the presence of nanoparticles could deteriorate the performance of microchannel due to the presence of viscous dissipation effect, causing the reduction of heat transfer coefficient by 69%. This contradictory finding indicate the importance to consider the viscous dissipation term to avoid overestimation in the heat transfer performance of nanofluids flow.

In the earlier stage of research on the usage of nanoparticle in enhancing the heat transfer performance of automotive radiator, extensive research has been conducted on the usage of metal-based nanoparticle in enhancing the heat transfer performance of automotive radiator [16]. Shah *et al.,* [17] performed a potential evaluation of low concentration Fe_2O_3-H_2O nanocoolant for automotive cooling and reported an enhancement of 21.9% in the heat transfer rate of nanofluid as compared to the basefluid. The presence of a very small extent of nanoparticles can excessively lift the performance of the radiators [17]. Besides, the heat transfer coefficient enhancement intensifies with the increase of nanoparticle concentration and Reynolds number [18]. In an experimental work on heavy vehicle radiator, the suspension of TiO_2 nanoparticle enhances the heat transfer coefficient of the radiator by 48.2% when compared to pure water. Kumar *et al.,* [19] investigated the thermal performance of automobile radiator with CuO and SiO_2 nanoparticles suspended in ethylene glycol (EG) based coolant. By employing nanofluid in radiator, thermal conductivity is enhanced by 6.5%, but Nusselt number is significantly increased by 48.24% [19]. Arbak *et al.,* [20] performed an experimental investigation on bimetallic nanoparticles heat transfer characteristics in automotive radiator by using CuO and ZnO nanoparticles. It has been observed that bimetallic additives, significantly increase the heat transfer performance up to 40% [20], paving way to the reductions of automotive radiator size and fuel consumption.

In recent years, carbon-based nanoparticle such as graphene, a thin layer of pure carbon, has much higher thermal conductivity as compared to metal nanoparticle [21]. Therefore, it is conjectured that graphene-based nanoparticle could intensify the cooling performance of automotive radiator. Naveen *et al.,* [22] experimentally scrutinized the effect of employing graphene nanofluid in the cooling of automotive system as compared to the conventional EG/water coolant. The study shows that graphene nanocoolant enhances the heat transfer rate of radiator by 68% [22]. In another experimental study which investigated the automobile cooling system suspended with GnP and cellulose nanocrystals (CNC) nanoparticles, Yaw *et al.,* [23] reported that the presence of GnP and CNC nanoparticles intensifies the convective heat transfer coefficient of radiator by 51.9%. Similar enhancement rate is also reported by Selvam *et al.,* [24] which showed that GnP-EG/water nanofluid increases the convection heat transfer coefficient of automotive radiator by 51% [24]. Ponangi *et al.,* [25] studied the suspension of carboxyl graphene (CG) and graphene oxide (GO) in EG/water and showed that Nusselt number of the radiator is increased up to 11 times. An experimental investigation on the performance of GnP and multi-walled carbon nanotubes (MWCNT) suspended in radiator coolant oil showed that the thermal conductivity of the hybrid nanofluid is intensified up to 59% while improving the radiator overall heat transfer coefficient by 124% [26]. These existing studies revealed that automotive radiator performance can be greatly enhanced by suspending graphene-based nanoparticle in the radiator, implying the great potential of utilizing graphene-based nanofluid as a coolant in automotive cooling.

In the up-to-date literature, most of the studies on graphene-based nanofluid flow in automotive radiator employ the mixture of water and EG as the basefluids [22-25]. Numerical investigations on the convective performance of water-based GnP nanofluids in radiator for improving the cooling of automotive engine is relatively scarce. Besides, the lack of understanding of thermal enhancement mechanism of nanofluid in the automotive radiator forms a barrier to the commercialization the nano-coolant [27]. To bridge the information gap, the present study is conducted to perform a comprehensive numerical analysis on the thermal performance of millimeter-sized automotive radiator with GnP suspension in water. The temperature-dependent thermophysical properties of GnP-water nanofluid is predicted via existing correlations, while a modified viscosity correlation is developed. With the inclusion of viscous heating effect in ANSYS Fluent, the effects of various pertinent parameters such as Reynolds number, nanoparticles aspect ratio, tube aspect ratio and tube hydraulic diameter on the heat transfer performance of the radiator are scrutinized. The temperature contours of the nanofluid flows are analyzed to enhance the understandings on the underlying physical significance of the suspension of graphene-based nanoparticle in water for the performance enhancement of automotive radiator.

2. Methodology

2.1 Numerical Simulation

In the present study, ANSYS Fluent is utilized to simulate the thermal performance of a millimeter-sized automotive radiator with GnP suspension. Figure 1 shows a typical automotive radiator geometry that is formed by several tubes with plate fins for the transfer of heat between the coolant and air.

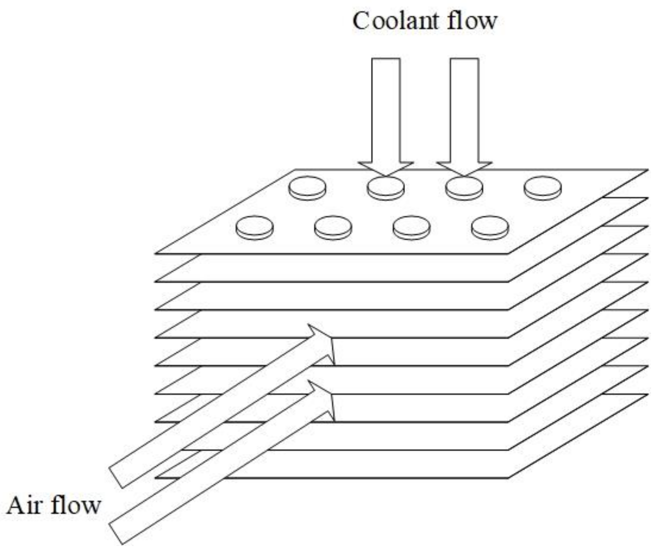

Fig. 1. The geometry of automotive radiator

The flow of nanofluid in the tube is assumed to be an incompressible laminar flow and the radiation heat transfer is assumed to be negligible. The single-phase fluid approach is employed as the low nanoparticles concentration in the basefluid can be considered as a continuous media [28-30]. Figure 2 depicts the dimension of the present millimeter-sized radiator with a hydraulic diameter of D_h = 3.6044 mm and tube length of L = 394 mm.

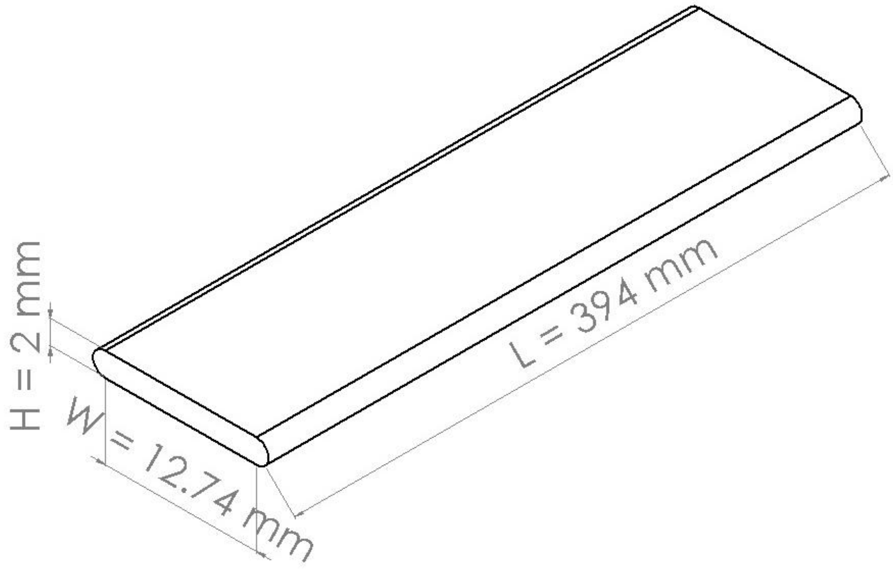

Fig. 2. The dimension of millimeter-sized radiator

The three governing equations of continuity, momentum and energy are solved by using ANSYS Fluent under a three-dimensional flow field. The continuity equation [31] can be written as

$$(\nabla \cdot V) = 0 \tag{1}$$

The momentum equation [31] can be expressed as

$$\rho(\nabla \cdot V)V = -\nabla P + \mu\nabla^2 V \tag{2}$$

The energy equation [31] can be defined as

$$\rho C_p(\nabla \cdot V)T = k\nabla^2 T + \mu\Phi \tag{3}$$

2.2 Thermophysical Properties Correlations

The thermophysical properties of GnP-based nanofluid are predicted by using mathematical approach. The density, specific heat capacity, thermal conductivity and viscosity of nanofluid can be determined by assuming the nanoparticles are well dispersed in basefluid with constant concentration [32]. The density for nanofluid can be determined by using equation presented by Pak and Cho [33] based on the basis of volume average.

$$\rho_{nf} = \phi\rho_p + (1 - \phi)\rho_{bf} \tag{4}$$

Where ϕ is the nanoparticle volume fraction. The specific heat capacity can be calculated by using equation reported by Xuan and Roetzel [34] based on the basis of mass average.

$$C_{p,nf} = \frac{\phi\rho_p C_{pp} + (1 - \phi)\rho_{bf} C_{pbf}}{\rho_{nf}} \tag{5}$$

These two equations are commonly used to determine the density and the specific heat capacity in the studies of nanofluid [18, 32, 35]. The thermal conductivity of the GnP-based nanofluid can be determined by using Nan's model [36]. Several studies have been conducted by using Nan's Model to determine the thermal conductivity of GnP nanofluid [37, 38]. The Nan's model are

$$k_{nf} = C_k k_{bf} \tag{6}$$

where the coefficient of thermal conductivity is expressed as

$$C_k = \frac{3 + \phi[2\gamma_{11}(1 - \ell_{11}) + \gamma_{33}(1 - \ell_{33})]}{3 - \phi(2\gamma_{11}\ell_{11} + \gamma_{33}\ell_{33})} \tag{7}$$

The geometrical factors ℓ_{11} and ℓ_{33} in Eq. (7) are defined by

$$\ell_{11} = \frac{\xi_p^{\ 2}}{2(\xi_p^{\ 2} - 1)} + \frac{\xi_p}{2(1 - \xi_p^{\ 2})^{3/2}}\cos^{-1}\xi_p \quad \text{for} \quad \xi_p < 1 \tag{8}$$

$$\ell_{33} = 1 - 2\ell_{11} \tag{9}$$

The nanoparticles aspect ratio ξ_p in Eq. (8) can be written as

$$\xi_p = \frac{t_p}{D_p} \tag{10}$$

In Eq. (7), γ_{11} and γ_{33} is expressed as

$$\gamma_{11} = \frac{k_{11} - k_{bf}}{k_{bf} + \ell_{11}(k_{11} - k_{bf})} \tag{11}$$

$$\gamma_{33} = \frac{k_{33} - k_{bf}}{k_{bf} + \ell_{33}(k_{33} - k_{bf})} \tag{12}$$

Where k_{11} and k_{33} represent the equivalent thermal conductivities along the x-axis and z-axis and can be defined as

$$k_{11} = \frac{k_{par}}{1 + \delta \ell_{11} k_{par} / k_{bf}} \tag{13}$$

$$k_{33} = \frac{k_{per}}{1 + \delta \ell_{33} k_{per} / k_{bf}} \tag{14}$$

The dimensionless parameter δ is expressed as

$$\delta = (1 + 2\xi_p)\frac{2K_r}{t_p} \quad \text{for} \quad \xi_p < 1 \tag{15}$$

Where K_r represents Kapitza radius which can be defined as

$$K_r = R_i k_{bf} \tag{16}$$

In Eq. (16), R_i is the interfacial thermal resistance which is depicted as

$$K_r = R_i k_{bf} \tag{17}$$

In the up-to-date literature, various studies have been conducted to determine the viscosity of nanofluid by using equation from Brinkman [39], Einstein [40], Brenner *et al.,* [41], Batchelor [42] and Sarsam *et al.,* [37]. These viscosity correlations [37, 39-42] are found to generate significant deviations when compared to the experimental study [43] as shown in Figure 3. Therefore, a modified correlation is employed to determine the viscosity of GnP nanofluid in the present study. The modified correlation equation is developed by using the equation reported by Brenner *et al.,* [41] and can be expressed as

$$\mu_{nf} = (1 + \sigma^{1.675}\phi)\mu_{bf} \tag{18}$$

Where $\sigma = \{0.312\beta / [\ln(2\beta - 1.5)]\} + 2 - \{0.5 / [\ln(2\beta - 1.5)]\} - (1.872 / \beta)$ is the intrinsic viscosities and $\beta = D_p / t_p$ is the axis ratio.

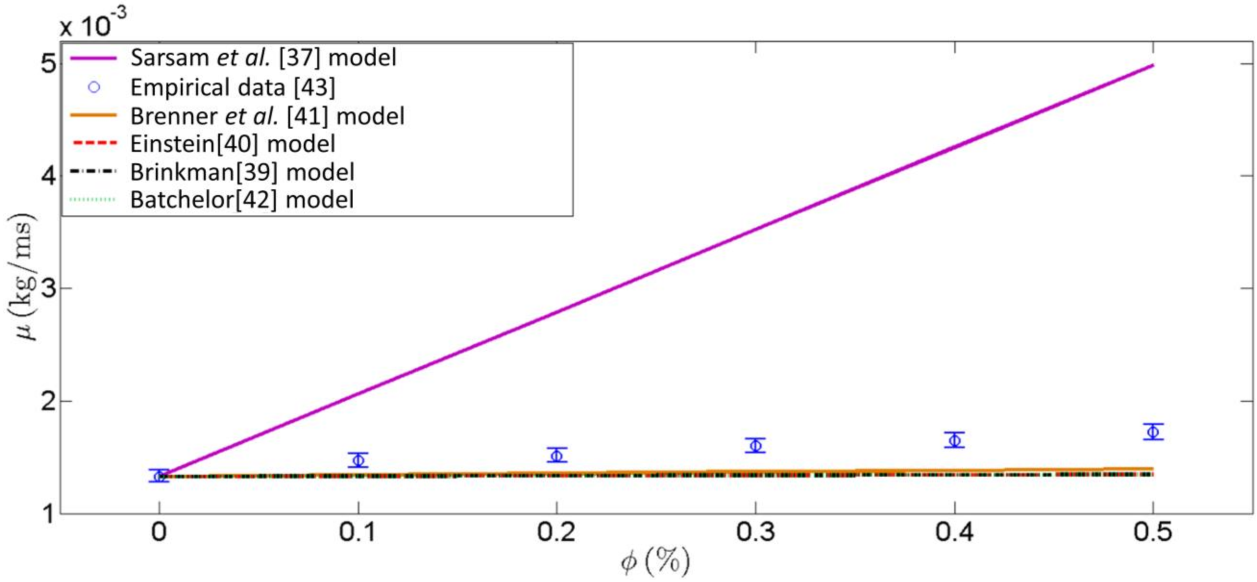

Fig. 3. Comparison of viscosity correlations [37, 39-42] with the empirical data from Selvam *et al.,* [43]

The modified viscosity correlation for GnP-based nanofluid as expressed by Eq. (18) is validated with several existing studies [43-45] as depicted in Figure 4. The results show a good agreement with the reference studies [43-45] with the error ranges between 0.00778% and 5.57%. This indicates that the present viscosity correlation is capable to predict the viscosity of GnP-based nanofluid with various GnP nanoparticles thickness and diameter.

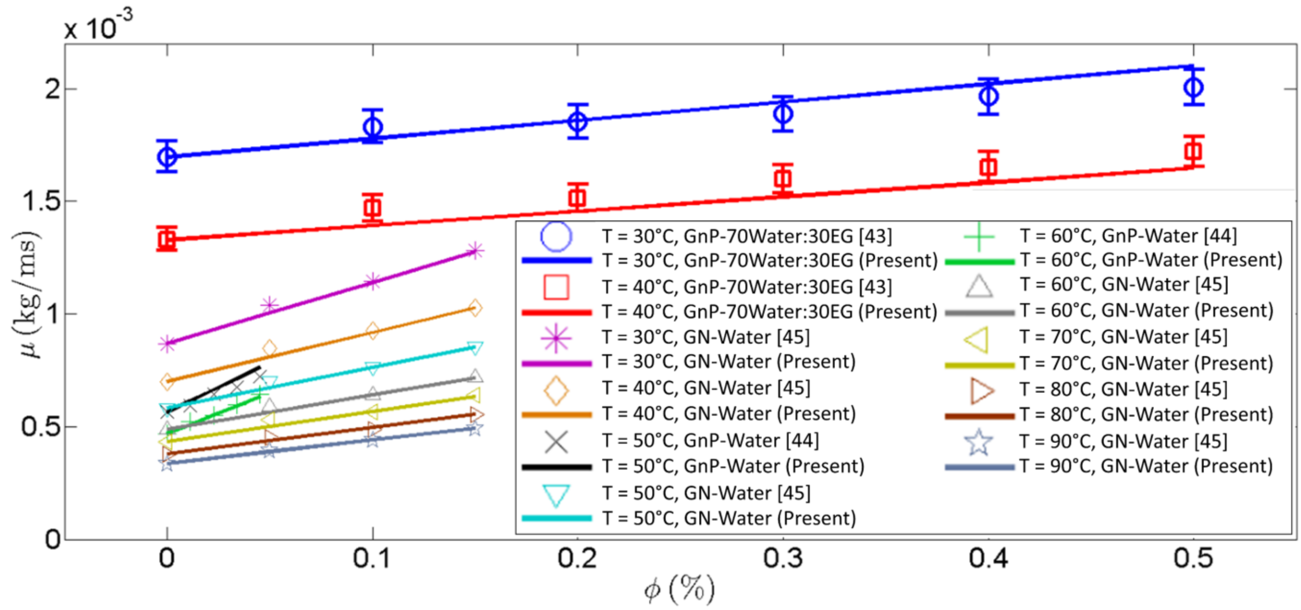

Fig. 4. Comparison of the modified viscosity correlation with several existing studies [43-45]

2.3 Boundary Conditions

ANSYS Fluent is utilized to scrutinize the thermal performance of GnP-water nanofluid in millimeter-sized radiator. Double precision and second-order upwind scheme with inclusion of viscous heating, and convergent criteria of 10^{-6} are adopted for the simulation. The velocity, V, temperature, T, and pressure, P, are solved throughout the interior computational domain of the geometry. The wall temperature, T_W, wall heat flux, q'', and bulk mean temperature, T_b, are recorded in the data post-processing for the calculations of heat transfer coefficient. The boundary conditions of the present simulation as illustrated in Figure 5. The uniform axial inlet velocity and pressure outlet condition are adopted and are assumed to be an idealization of the actual flow pattern [18]. As referred to Park *et al.,* [46], the convection heat transfer coefficient for tube wall and temperature are imposed with h_o = 50 W/m^{2}K and T_o = 303 K respectively, which is corresponding to an automotive vehicle moving with a speed of 72 km/h. The symmetry boundary condition is applied to reduce the meshing size. No-slip boundary condition is adopted at the wall. This study is conducted in the laminar flow regime and Reynolds number is determined by the inlet velocity. The temperature-dependent thermophysical properties of GnP-based nanofluids, that are determined by Eq. (4) - (18) , are used in ANSYS Fluent. Various pertinent parameters such as volumetric concentration ϕ , Reynolds number Re, nanoparticle aspect ratio ξ_p , tube aspect ratio ξ_T and flat tube hydraulic diameter D_h, are investigated in the convection flow of the millimeter-sized radiator with GnP suspension.

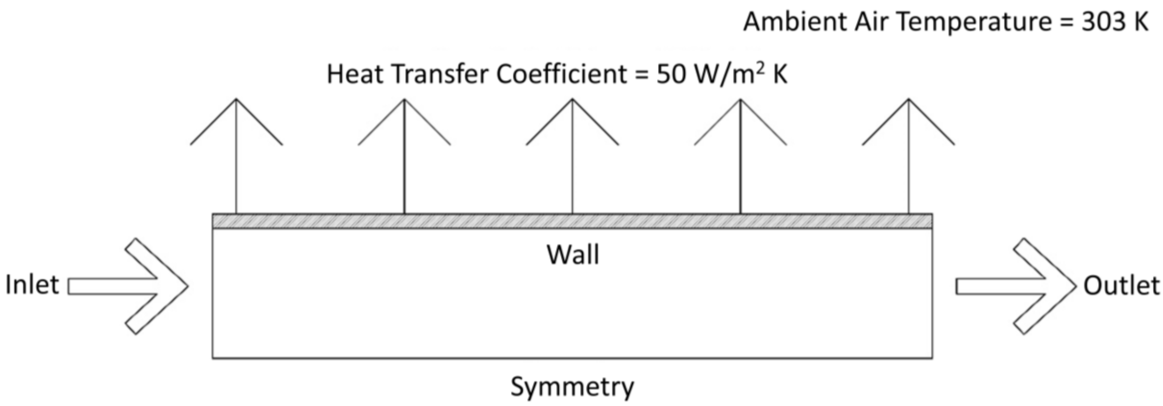

Fig. 5. Boundary conditions of the simulation

2.4 Data Reduction

In the present study, Reynolds number of GnP-based nanofluid is defined as

$$\mathrm{Re} = \frac{\rho V D_h}{\mu} \tag{19}$$

Where D_h represents the hydraulic diameter of the tube, $D_h = 4A / L_c$. The local heat transfer coefficient, h_l along the circumference of the tube can be calculated from

$$h_l = \frac{q''}{(T_W - T_b)} \tag{20}$$

The average local heat transfer coefficient, $\bar{h}_z = \sum h_l \; / \; n$ where *n* represents number of points. The average local Nusselt number, $\overline{Nu}_z$ along the tube length can be defined as

$$\overline{Nu}_z = \frac{\bar{h}_z D_h}{k_{bf}} \tag{21}$$

The average heat transfer coefficient of the entire tube length, $\bar{h}$ can be written as

$$\bar{h} = \frac{1}{L}\int_0^L \bar{h}_z dz \tag{22}$$

The average Nusselt number over the entire tube length, $\overline{Nu}$ can be expressed as

$$\overline{Nu} = \frac{1}{L}\int_0^L \overline{Nu}_z dz \tag{23}$$

The percentage enhancement of the average Nusselt number, Δ can be defined as

$$\Delta = \frac{\overline{Nu}_{nf} - \overline{Nu}_{bf}}{\overline{Nu}_{bf}} \tag{24}$$

2.5 Validation

Validations are conducted to verify the numerical model before data collection. The flat tube temperature and velocity profile of coolant with 40% water and 60% ethylene glycol at Re = 100 is compared with that reported by Vajjha *et al.,* [18] as shown in Figure 6. Based on flat-tube radiator dimension of 2.54 mm × 16.18 mm × 500 mm, the results show a good agreement between the two studies with the maximum errors of 2.97% and 0.13% for velocity and temperature, respectively.

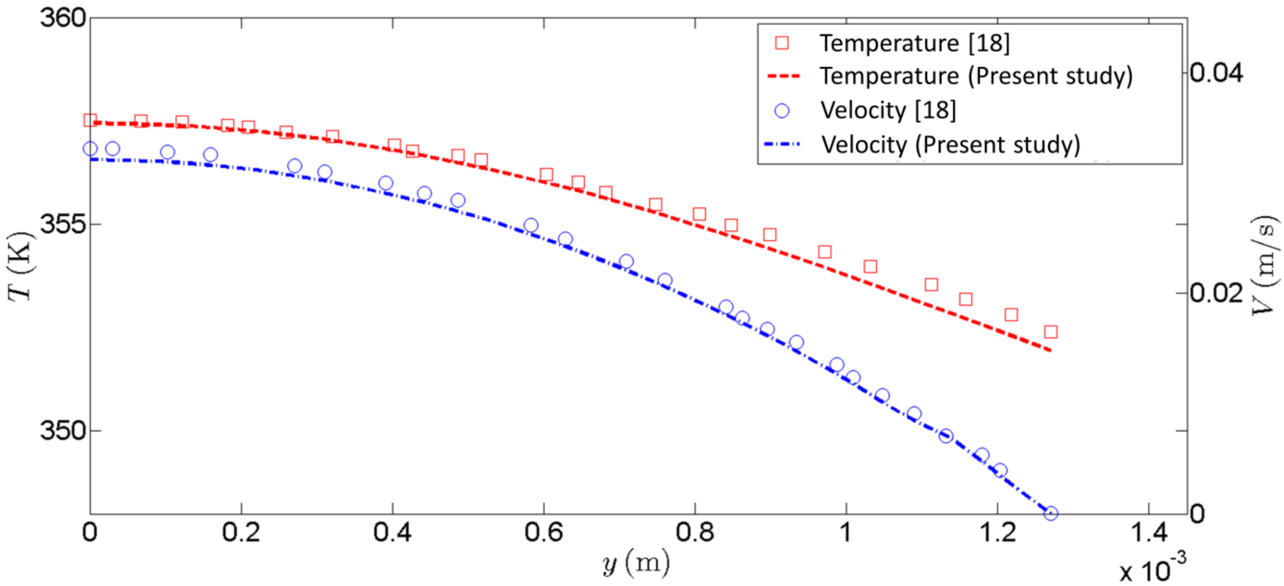

Fig. 6. Comparison of temperature and velocity profiles of the present study with Vajjha *et al.,* [18]

Moreover, validation works for the average local Nusselt number, $\overline{Nu_z}$ is performed using water at Re = 1750 along the tube length as shown in Figure 7. Based on flat-tube radiator dimension of 3 mm × 9 mm × 345 mm, the results demonstrate a good agreement between the present study and Elsebay *et al.,* [32]. The deviations between the two studies are in the range of 0.51% to 3.51%. This provides a sound validation of the accuracy of the numerical modelling approach employed in this study.

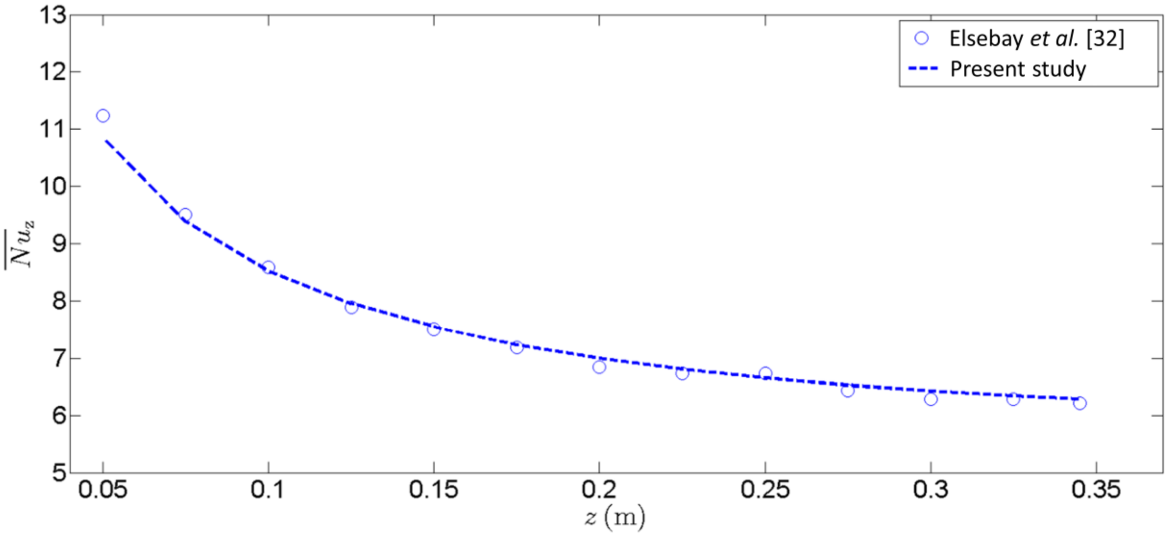

Fig. 7. Comparison of average local Nusselt number of the present study with Elsebay *et al.,* [32]

In addition, Figure 8 shows the simulation results of GnP-water nanofluids flow in a cylindrical tube with constant heat flux of 8231 W/m^2 and Reynolds number of 4583. The thermophysical properties of GnP-water based nanofluids are calculated based on the Eq. (4) – (18). The present study are compared to the experimental and the numerical results reported by Sadeghinezhad *et al.,* [44]. The results demonstrate a good agreement with the referred study, particularly with the experimental results, with the maximum error of 0.27%. The errors are diminished with the increase of the GnP weight concentration. This provides a sound validation of the accuracy of the nanofluid modeling approach employed in this study.

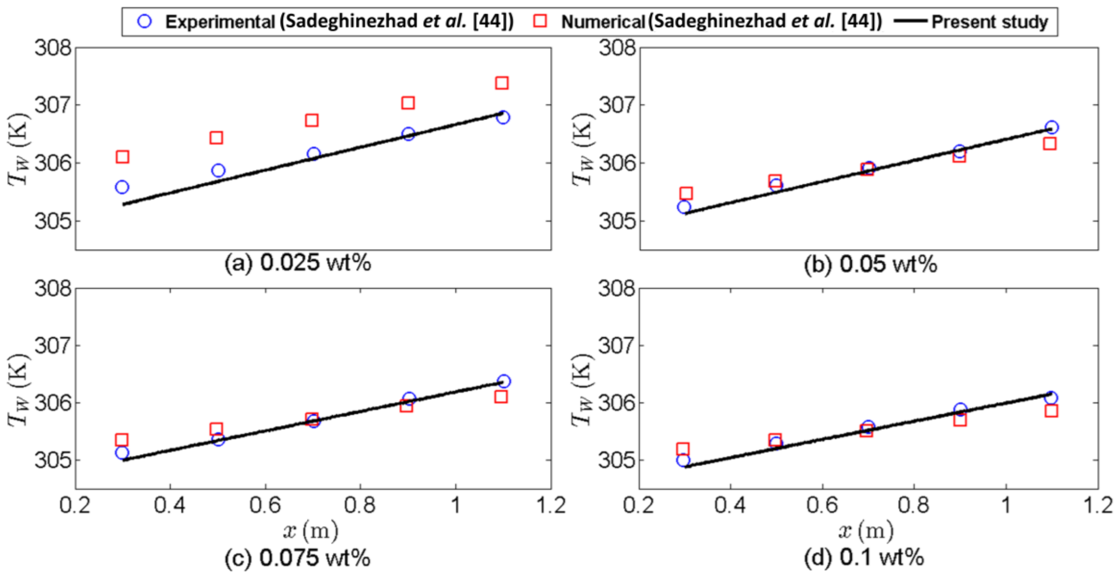

Fig. 8. Comparison of tube wall temperature of the present study with Sadeghinezhad *et al.,* [44]

3. Result and Discussion

3.1 Thermophysical Properties of Nanofluid

The nanofluid of the present study consists of graphene nanoplatelets (GnP) which is suspended in basefluid of water. The thermal performance of millimeter-sized radiator is investigated by using GnP with $t_p = 10$ nm and $D_p = 2$ um. The thermophysical properties of water as reported in Bergman *et al.,* [47] and the properties of GnP nanoparticles as shown in Table 1 are used to determine the properties of GnP-water nanofluid by employing Eq. (4) – (18).

Table 1
Thermophysical properties of GnP nanoparticles

Property	Thermophysical properties for GnP nanoparticles	Reference
ρ	2200 kg/m^3	[21]
C_p	643 J/kgK	[38]
k_{par}	3000 W/mK	[21]
k_{pen}	6 W/mK	[21]

In the present study, the thermophysical properties of GnP-water nanofluids are temperature dependence. This is of vital importance to ensure the accuracy of the simulated heat transfer characteristic of nanofluid along the radiator tube which has varying streamwise temperature. As illustrated in Figure 9, the density of GnP-water nanofluid increases with the increase of ϕ. This is due to higher density characteristic of GnP nanoparticles as compared to basefluid. The density of GnP-water nanofluid decreases when temperature increases due to the reduction of the density of basefluid at higher temperature. For GnP-water nanofluid with $\phi = 1.0\%$ and T = 363 K, the density intensifies by 1.28% as compared to basefluid.

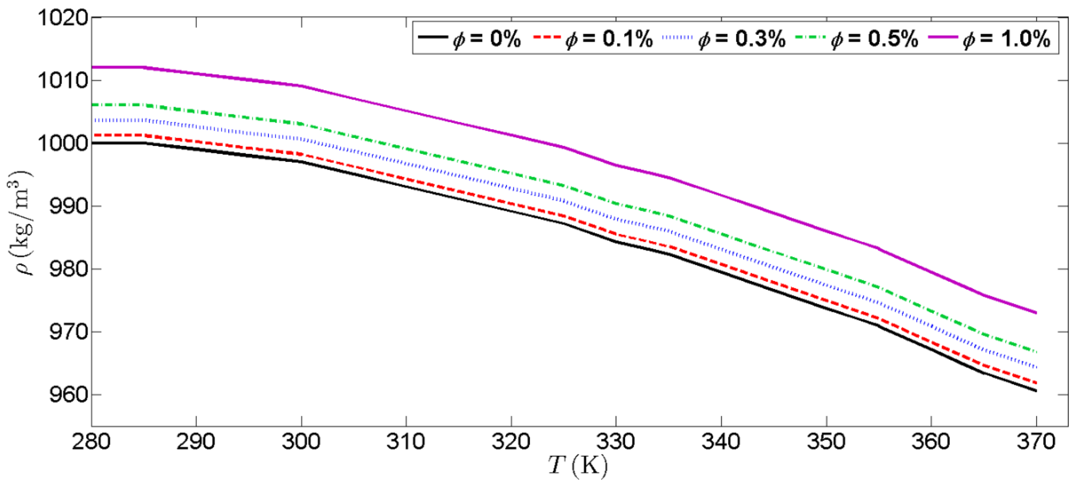

Fig. 9. Density of GnP-water nanofluid with respect to temperature for various ϕ

Figure 10 shows the variation of specific heat capacity of GnP-water nanofluid with respect to temperature. It is observed that the specific heat capacity of GnP-water nanofluid decreases with the increase of ϕ. This is because the specific heat capacity of GnP nanoparticles is lower than the basefluid. For GnP-water nanofluid with $\phi = 1.0\%$ and T = 363 K, the specific heat capacity decreases by 1.91% as compared to basefluid.

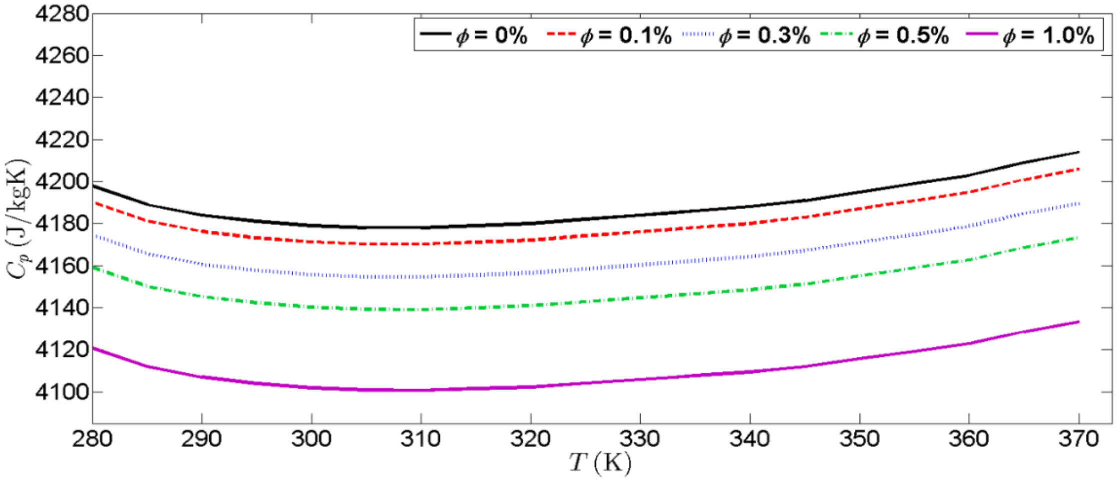

Fig. 10. Specific heat capacity of GnP-water nanofluid with respect to temperature for various ϕ

The thermal conductivity enhancement of GnP-water nanofluid is highly affected by the interfacial thermal resistance [36]. In the present study, the thermal conductivity for GnP-water nanofluid is calculated by assuming the perfect interface characteristic, with Kapitza radius equals to zero [36, 37]. The thermal conductivity of GnP-water nanofluid enhances with respect to GnP loadings and temperature as displayed in Figure 11. This is due to the increase of particle movements associated with Brownian motion within the fluid [24, 48]. The effect of Brownian motion becomes more significant at higher temperatures due to the micro- convection induced by such motion, causing a significant intensification of the thermal conductivity of nanofluid. Moreover, the enhancement of thermal conductivity at higher nanoparticle concentrations is attributable to the high-thermal-conductivity characteristics of GnP. For GnP-water nanofluid with $\phi = 1.0\%$ and T = 363 K, the thermal conductivity intensifies by 161.77% as compared to basefluid.

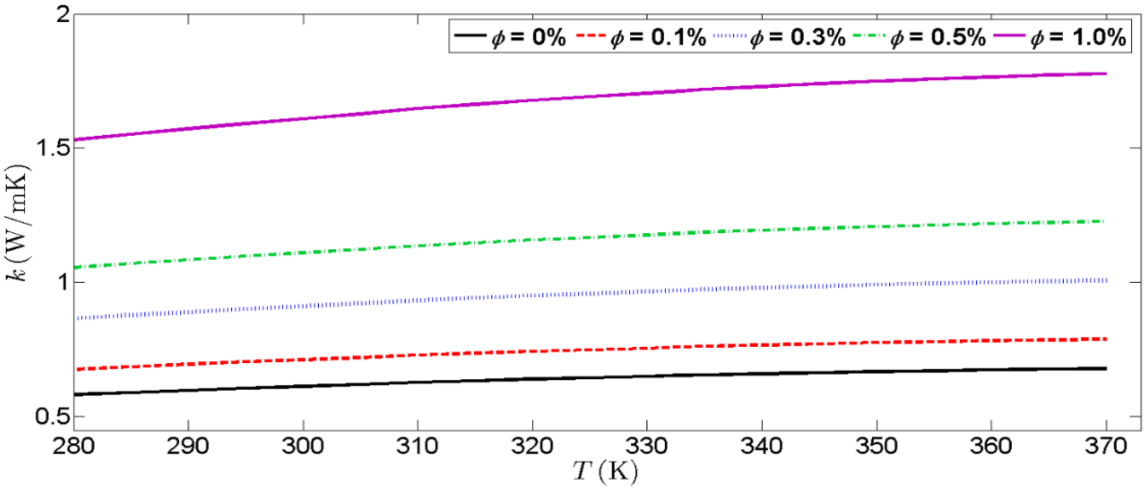

Fig. 11. Thermal conductivity of GnP-water nanofluid with respect to temperature for various ϕ

Figure 12 illustrates the variation of viscosity of GnP-water nanofluid with respect to temperature for various particle concentration. Based on Figure 12, it is noticed that the viscosity of GnP-water nanofluid increases with the increase of GnP suspensions and the decrease of temperature. As temperature decreases, the intermolecular interactions within the particles reduces, inducing a higher viscosity [24]. For GnP-water nanofluid with $\phi = 1.0\%$ and T = 363 K, the viscosity increases by 101.5% as compared to basefluid.

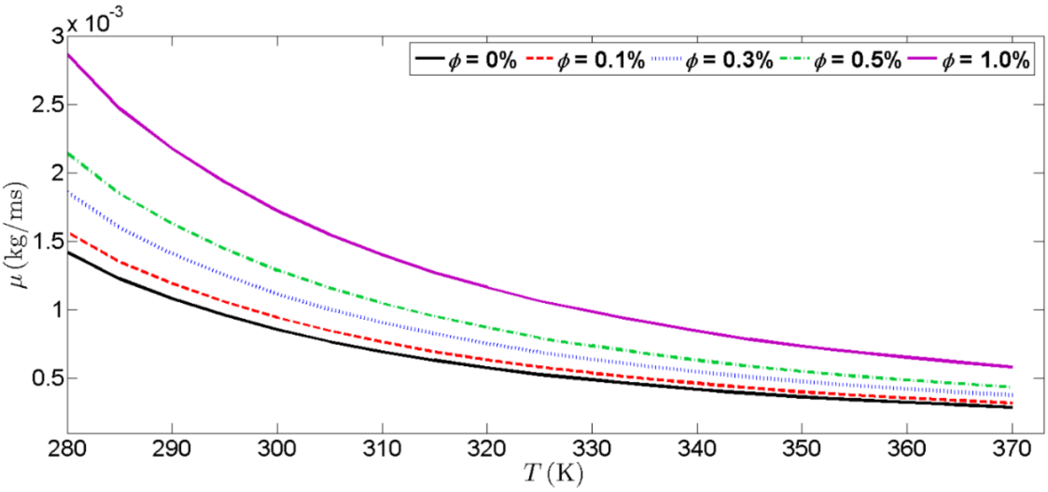

Fig. 12. Viscosity of GnP-water nanofluid with respect to temperature for various ϕ

3.2 Grid Independence Study

The grid independence studies are conducted to determine the appropriate mesh size of the present numerical simulation. The mesh is created by using ANSYS Fluent Meshing function. Six different mesh sizes are generated to determine the average Nusselt number over an entire tube, $\overline{Nu}$ for the $\phi = 0\%$ (basefluid) and GnP-water nanofluid with $\phi = 0.5\%$ at Re = 1000 and T_{in} = 363 K in the millimeter-sized radiator as illustrated in Figure 13. The mesh sizes are listed in Table 2. Based on Figure 13, the difference of $\overline{Nu}$ between mesh 5 and 6, are 1.14% and 1.09%, respectively, for basefluid and GnP-water nanofluid with $\phi = 0.5\%$. Therefore, mesh 5 is grid independent and used for the present simulation of nanofluid conection in the automotive radiator.

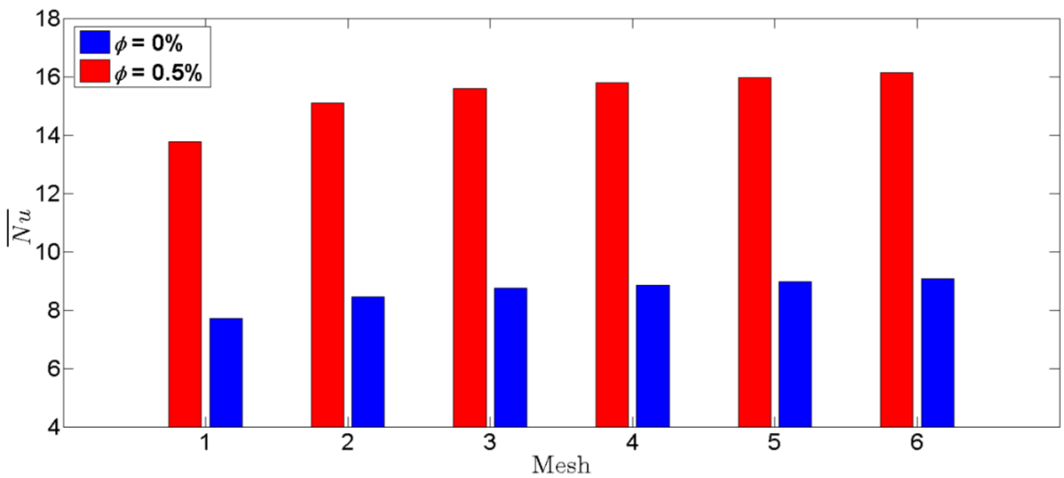

Fig. 13. Average Nusselt number of various mesh sizes for ϕ =0% and ϕ =0.5%

Table 2
Mesh sizes for millimeter-sized radiator

Grid	Nodes	Elements
Mesh 1	6716	4930
Mesh 2	32144	27300
Mesh 3	80196	71295
Mesh 4	170200	155760
Mesh 5	309324	288075
Mesh 6	508068	478740

3.3 Effect of Reynolds Number in Millimeter-sized Radiator

Figure 14 illustrates the temperature contour of basefluid and GnP-water nanofluid with $\phi = 1.0\%$ along the radiator channel for Re = 1000 and Re = 1750 at T_{in} = 363 K. By comparing Figure 13(a) and Figure 14(b), basefluid at Re = 1750 have a smaller streamwise temperature difference along the channel as compared to that with Re = 1000. Therefore, the heat transfer coefficient is elevated due to the reduction of T_w - T_b as depicted by Eq. (20). On the other hand, GnP-water nanofluid with $\phi =$ 1.0% at Re = 1000 portrays a smaller streamwise temperature difference as compared to the basefluid with Re = 1000. This is due to the enhancement of the thermal conductivity in GnP-water nanofluid. As Re increases, the streamwise temperature difference along the channel with the nanofluid flow is further reduced as illustrated in Figure 14.

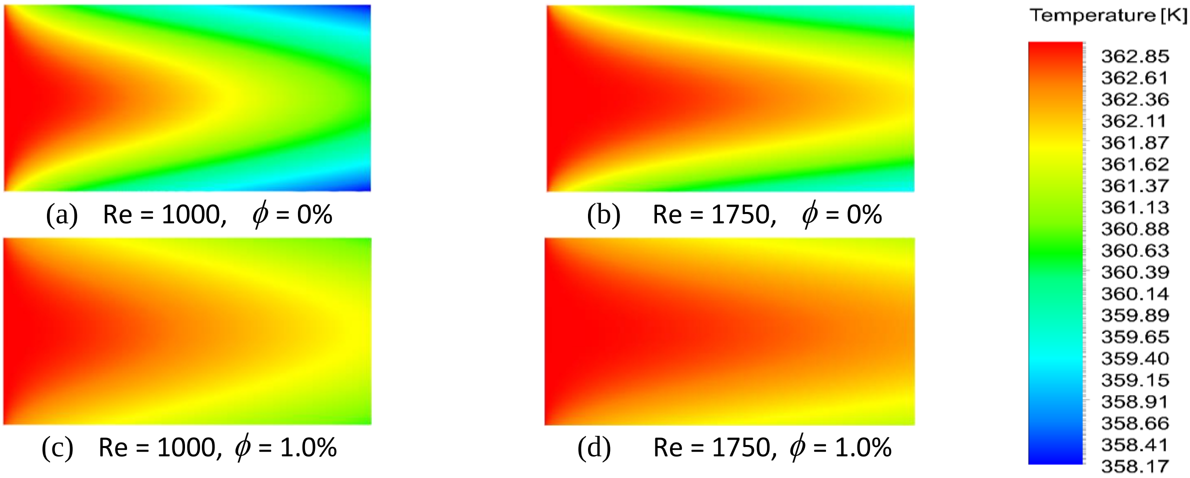

Fig. 14. Temperature contour of basefluid and GnP nanofluid in millimeter-sized radiator

Figure 15 shows the average Nusselt number over the entire tube length, $\overline{Nu}$ and Δ with various Re and ϕ. The present study shows an increase of $\overline{Nu}$ with respect to ϕ and Re. This concurs with Figure 14, which shows a smaller temperature difference of T_w - T_b in nanofluid at higher ϕ and Re. The highest Δ is 163.48% for GnP-water nanofluid with $\phi = 1.0\%$ at Re = 750. Δ Intensifies with the increase of ϕ and the decrease of Re. The maximum $\overline{Nu}$ =25.48 for GnP-water nanofluid with $\phi =$ 1.0% at Re = 2000. The heat transfer performance of the automotive radiator improves with the increase of ϕ and Re [49]. Based on Vajjha *et al.,* [18], the enhancement of the average heat transfer coefficient of Al_2O_3-based nanofluid with $\phi = 1.0\%$ and Re=2000 is 94%. This indicates that the thermal performance enhancement of the present study is higher than that of Vajjha *et al.,* [18] even with a smaller amount of GnP nanoparticles suspension. This is attributable to the thermophysical properties enhancement of GnP-water nanofluid. The increment of $\overline{Nu}$ for GnP-water nanofluid with $\phi = 1.0\%$ is 11.05 % as Re increases from 750 to 2000. Therefore, the present study shows that the effect of ϕ in enhancing $\overline{Nu}$ is more significant as compared to the effect of Re. This is in contrary to that reported by Vajjha *et al.,* [18] due to the superior thermophysical properties of GnP-water nanofluid. Based on Figure 14 and Figure 15, it is observed that the nanofluid demonstrate a higher thermal conductivity and a higher Reynolds number give rise to a greater mixing of flow, resulting in the enhancement of the radiator performance [50] which could possibly lead to a smaller and lighter radiator [35]. However, for the commercialization of nanocoolant for automotive application, the stability issue of nanoparticles in the coolant has to be addressed. The method to overcome large van der Waals agglomeration of nanoparticles, i.e. surface treatment or particle coating, has to be established. Besides, large-scale single-step and two-step nanofluid preparation techniques have to be developed. This is essential to achieve economies of scale for nanocoolant synthesis with good stability and low production cost.

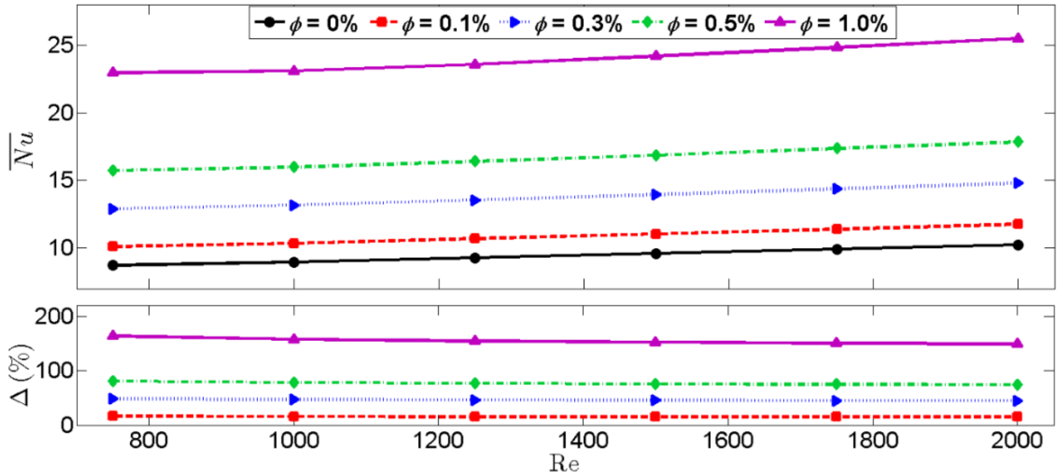

Fig. 15. Variation of $\overline{Nu}$ and Δ with ϕ for different Re in millimeter-sized radiator

3.4 Effect of Nanoparticles Aspect Ratio in Millimeter-sized Radiator

By varying the value of ξ_p, the shape of GnP is different with respect to particle thickness and diameter based on Eq. (10). The effects of ξ_p on GnP-water nanofluid flow in millimeter-sized radiator are conducted at Re = 1750 and T_{in} = 363 K. The plots of $\overline{Nu}$ and Δ with various ξ_p are displayed in Figure 16. The present study demonstrates that $\overline{Nu}$ increases with the decrease of ξ_p and the increase of ϕ. The maximum $\overline{Nu}$=190.16 and Δ=1816.53% is observed for GnP-water nanofluid with ϕ=1.0% and $\xi_p = 0.0004$ due to the significant intensification of thermal conductivity at low ξ_p, promoting energy exchange process between the nanofluid and tube wall [24]. As ξ_p decreases from 0.005 to 0.0004, the enhancement of the thermal conductivity is up to 412% while the intensifications of $\overline{Nu}$ are as much as 119.46% and 666.28% for ϕ= 0.1% and ϕ= 1.0%, respectively. Besides, Δ increases with the decrease of ξ_p and the increase of ϕ.

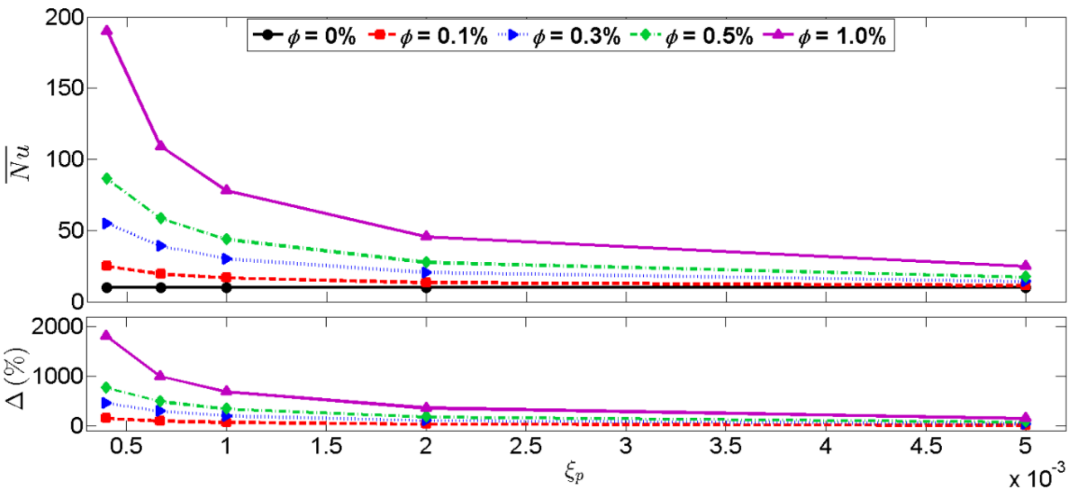

Fig. 16. Variation of $\overline{Nu}$ and Δ with ξ_p for different ϕ in millimeter-sized radiator

3.5 Effect of Tube Aspect Ratio in Millimeter-sized Radiator

Figure 17 portrays the variations of $\overline{Nu}$ and Δ with respect to ξ_T =2*H*/2(*W*+*H*) at Re = 1750, T_{in} = 363 K, D_h = 3.6044 mm and *L* = 0.394 m. It is observed that $\overline{Nu}$ increases with the decrease of ξ_T and the increase of ϕ. When $\phi = 1.0\%$ and $\xi_T = 0.0681$, the average Nusselt number is the maximum with $\overline{Nu}$ = 25.25. When ξ_T decreases from 1 to 0.0681, $\overline{Nu}$ intensifies by 19.30% and 22.56%, respectively, for $\phi = 0\%$ and $\phi = 1.0\%$. In addition, Δ intensifies with the increase of ϕ. With the reduction of ξ_T, the tube profile is more flatten and the thermal performance enhancement is achieved owing to the changes of the temperature and velocity distribution along the tube cross section [51]. Based on Figure 17, it is noticed that the increase of ϕ intensifies the effect of the tube aspect ratio, concurring with that reported by Huminic and Huminic [51] and Safikhani and Abbassi [52] which state that the increase of the tube flattening enhances the heat transfer coefficient of nanofluid. Figure 18 illustrates the temperature contour for GnP-water nanofluid with $\phi = 0.5\%$ at different ξ_T. By comparing Figure 18(a) and 18(b), GnP-water nanofluid with $\xi_T = 0.0681$ shows a smaller streamwise temperature difference along the tube as compared to $\xi_T = 1$. Therefore, based on Eq. (20), the reduction in T_w - T_b enhances the heat transfer coefficient of tube with low ξ_T.

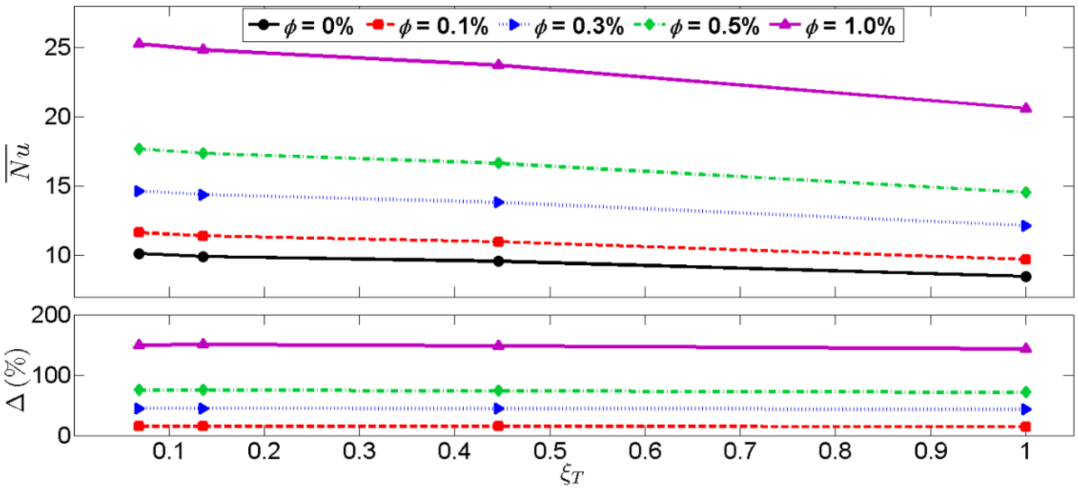

Fig. 17. Variation of $\overline{Nu}$ and Δ with ξ_T for different ϕ in millimeter-sized radiator

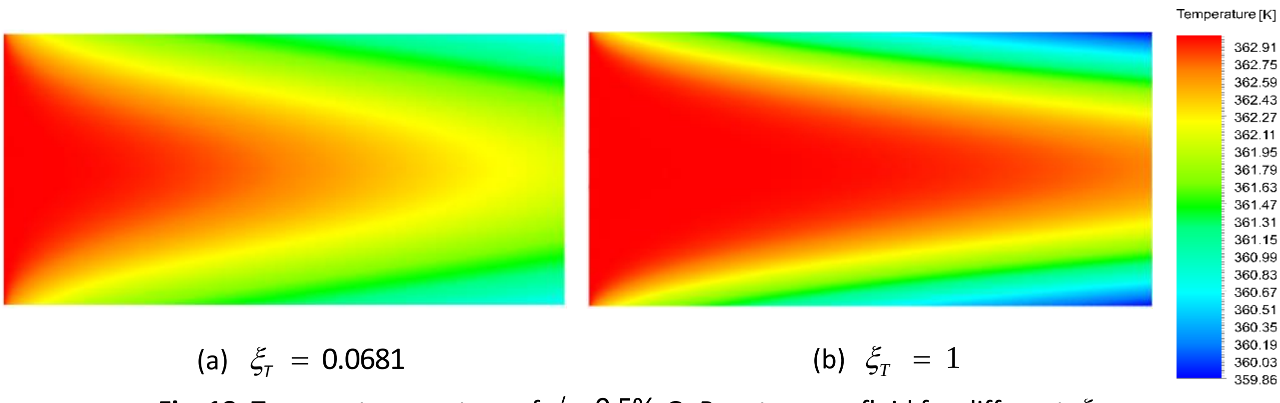

Fig. 18. Temperature contour of $\phi = 0.5\%$ GnP-water nanofluid for different ξ_T

3.6 Effect of Tube Hydraulic Diameter in Millimeter-sized Radiator

Figure 19 shows the plot of $\bar{h}$ with various D_h at Re = 1750, T_{in} = 333 K, $\xi_T = 0.1357$ and L = 0.394 m. It is observed that $\bar{h}$ increases with the decrease of D_h and the increase of ϕ when $D_h \geq 0.72$ mm. When D_h decreases from 7.2 mm to 0.72 mm, $\bar{h}$ intensifies by 534.36% and 656.38%, respectively, for $\phi = 0\%$ and $\phi = 1.0\%$. This is attributable to the increase of inlet velocity with a constant volume flow rate when the channel diameter is decreased, resulting in the increase of $\bar{h}$ [53]. The maximum $\bar{h}$ enhancement is up to 188.79% when GnP-water nanofluid is at $\phi = 1.0\%$ and D_h = 0.72 mm. However, when $D_h \leq 0.72$ mm, $\bar{h}$ deteriorates as D_h reduces. This is due to the effect of viscous dissipation as it has been reported that the thermal performance of nanofluid deteriorates in the microchannel when the viscous dissipation is significant [54]. Based on Figure 19, it is noticed that the promising performance of nanofluid in automotive radiator reverses as the tube hydraulic diameter decreases, inviting further study on this phenomenon to analyse the underlying physical significance of the suspension of nanoparticle in smaller-sized automotive radiator.

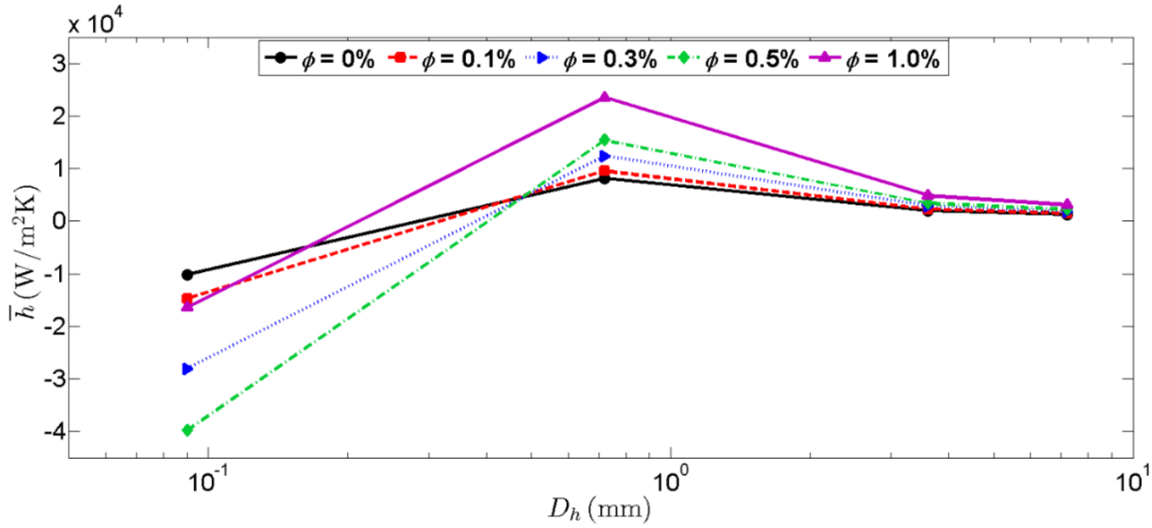

Fig. 19. Variation of $\bar{h}$ with D_h for different ϕ in millimeter-sized radiator

4. Conclusions

In the present study, a comprehensive numerical analysis is conducted to investigate the convection performance of millimeter-sized automotive radiator with the suspension of GnP nanoparticles. The temperature-dependent thermophysical properties of GnP-water nanofluid are predicted by using mathematical approach. A modified viscosity correlation for GnP-based nanofluid is developed and validated. It is observed that the thermal conductivity of GnP-water nanofluid intensifies with respect to GnP suspension and temperature, with an enhancement up to 161.8%. On the other hand, the viscosity of GnP-water nanofluid increases with the increase of GnP loading and the decrease of temperature. The present study shows that GnP-water nanofluid demonstrates a greater heat transfer performance in the radiator at high-Reynolds-number and high-nanaoparticle-concentration flow. Besides, $\overline{Nu}$ is enhanced up to 1816% when the aspect ratios of particle and tube are decreased. When $D_h \geq 0.72$ mm, $\bar{h}$ increases with the decrease of D_h and the increase of ϕ. However, when $D_h \leq 0.72$ mm, GnP-water nanofluid deteriorates the thermal performance of the radiator, which is worth further investigation. Based on the present work, it is evident that GnP-water nanofluid intensifies the heat transfer performance of the millimeter-sized radiator, which could lead to a smaller and a more effective automotive radiator. For future work, it is recommended to include the effects of nanofinned surface, turbulent flow, pulsating flow and hybrid nanoparticle suspension on the heat transfer performance of nanofluid convection in automotive radiator. Besides, experimental validation and multi-objective optimization can be conducted to identify the optimal combination of nanofluid and radiator parameters for heat transfer optimization of nanofluid performance in automotive radiator.

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