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NUMERICAL EVALUATION OF THE APPLICATION OF MWCNT NANOFLUIDS IN AUTOMOTIVE FLAT TUBE RADIATORS

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Abstract. *Heat dissipation and high performance cooling are some of the most important needs in the industry and are closely linked to the energy efficiency of cooling systems. In the automotive industry, engines need radiators with a highly efficient cooling system, in addition to having lower fuel consumption and emission of harmful gases to the environment. In this work, a numerical study was carried out to evaluate the application of MWCNT nanofluids in a flat tube automotive radiator. The influence of the Reynolds number and the concentration of nanoparticles in a flat tube under the action of a constant convective air flow of 50 W/(m^2 ·K) in a laminar regime was investigated. It is also noteworthy that in this work the thermophysical properties (thermal conductivity, specific heat, density and dynamic viscosity) of the analyzed fluids are considered temperature dependent along the flow implemented by a user-defined function (UDF). The governing equations (continuity, momentum and energy) were solved using the finite volume method implemented in the Ansys Fluent program with the SIMPLE pressure-velocity coupling method. Numerical convergence was given when the residual of the equations of continuity and momentum were less than 10$^-$6 and energy less than 10^{-9}. For nanofluids with nanoparticles concentration of 0.05, 0.1 and 0.2 vol.%, simulation was performed for the Reynolds numbers of 250, 750 and 1500 at an inlet temperature of 353.15 K From the results obtained, it was observed that the insertion of nanoparticles and the increase in the Reynolds number, increases the average heat transfer rate by up to 15.05 % and 80.70%, respectively, in relation to to the base fluid. Despite the increases in the convective heat transfer coefficient for all concentrations, the Nusselt number showed a decrease of up to 5.40 % with the insertion of nanoparticles. Therefore, the analyzed MWCNT nanofluids showed promising thermal performances for applications in automotive radiators.*

Keywords: *heat transfer, nanofluids, automotive radiator, computational fluid dynamics (CFD).*

1. INTRODUCTION

Currently, in the automotive industry, the miniaturization of components and increasing their efficiency, such as automotive radiators, has been sought. The most used refrigerants, such as water, ethylene glycol (EG) and EG-water mixture, have low thermal conductivity. From this problem, nanofluids emerged that constitute colloidal suspensions of nanoparticles to increase the conductivity of the base fluids and consequently increase the convective heat transfer coefficient, although this type of fluid presents an increase in the pressure drop due to presence of nanoparticles (Ba *et al.* (2022)).

One of the most studied nanoparticles is the multiwalled carbon nanotubes (MWCNT) due to its high thermal conductivity (600 - 6000 W/(m· K)) compared to other nanoparticles (Nan *et al.* (2003)). Contreras and Bandarra Filho (2022) carried out an investigation on the thermal performance of nanofluids with MWCNT nanoparticles (0.025 - 0.1 vol.%) and EG-water as base fluid for high operating temperature ranges (80 - 105 °C) in laminar regime. Increases in heat transfer rate and overall heat transfer coefficient of 4.6 and 4.4 %, respectively, were observed.

Gupta *et al.* (2016) evaluated the effect of inserting MWCNT nanoparticles (0.05 - 0.5 wt.%) in water on convective heat transfer from a copper pipe under the action of a heat flux. An increase in the convective heat transfer coefficient was observed with the concentration of nanoparticles (compared to the base fluid) and with the increase in the inlet velocity, with a maximum increase of 77.60%.

M'hamed *et al.* (2016) carried out the experimental study to improve the heat transfer of MWCNT/EG-water nanofluids (50:50) for concentrations of 0.01, 0.25 and 0.5 vol.% for flow rates of 2 - 6 l/min. It was possible to detect that the convective heat transfer coefficient is directly proportional to the concentration and the Reynolds number, in addition to the increase of 196.3 % for the highest concentration of nanoparticles.

Thus, this work aims to numerically evaluate the thermohydraulic performance of MWCNT/EG-water (50:50 vol.%) nanofluids with nanoparticles concentrations of 0.05 - 0.2 vol.% and temperature of input of 353.15 K in a flat tube in laminar regime under the action of a convective flow for applications in automotive radiators.

2. MATHEMATICAL MODELING

In the Fig. 1, the model of the simulated flat tube automotive radiator is illustrated. This geometry was obtained in the work of Hussein *et al.* (2014) whose dimensions correspond to 345 mm in length, 9 mm in width and 3 mm in height, thus, we have a hydraulic diameter of 4.68 mm.

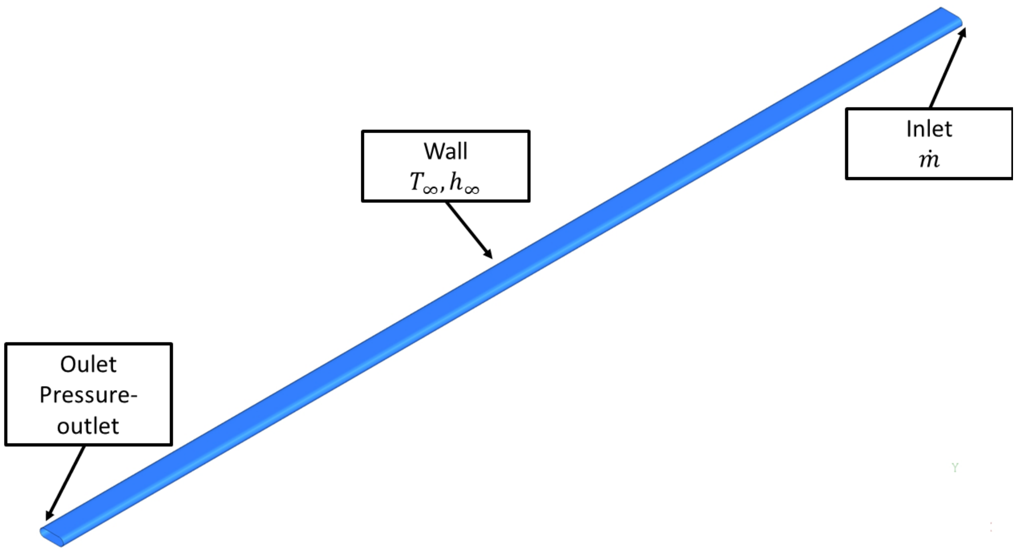

Figure 1. Schematic of the flat tube of radiator and boundary conditions

The evaluation of MWCNT nanofluids is performed considering a laminar flow with different nanoparticle volumetric concentrations and Reynolds numbers. In Tab. 1 the conditions used in this work are displayed. At the inlet of the tube, the mass flow was considered constant, while the outlet region was configured as pressure-outlet. In the wall region, the convective heat transfer coefficient of the air side of 50 W/m^2 ·K and temperature of 303 K was applied, similarly to that performed by Elsebay *et al.* (2016). These values adopted for the air side were obtained through the work of Park and Pak (2002) and correspond to the case of a vehicle traveling at 72 km/h.

Table 1. Flow conditions

Parameter	Value
Air temperature [K]	303
Outside heat transfer coefficient [W/m^2 · K]	50
Liquid inlet temperature [K]	353
MWCNT volumetric concentration [%]	0,05 - 0,2
Reynolds number [-]	250 - 1500

The simulations of this work were carried out by solving the continuity (Eq. (1)), momentum (Eq. (2)) and energy (Eq. (3)) equations implemented in the Ansys Fluent program using the finite volume method. To carry out the simulations, the fluid was considered as incompressible, laminar and, given the low concentrations adopted, the fluid was considered as single-phase.

$$\frac{\partial}{\partial x_i}\left(\rho_{ef} U_i\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_i}\left(\rho_{ef} U_j U_i\right) = \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i}\left(\mu_{ef}\left(\frac{\partial U_j}{\partial x_i}\right)\right) \tag{2}$$

$$\frac{\partial}{\partial x_i}\left(\rho_{ef} C_{p_{ef}} U_i T\right) = \frac{\partial}{\partial x_i}\left(k_{ef}\left(\frac{\partial T}{\partial x_i}\right)\right) \tag{3}$$

where ρ_{ef} is fluid density U_i refers to velocity vector component, p is pressure, μ_{ef} is dynamic viscosity, $C_{p_{ef}}$ is the specific heat, k_{ef} is the thermal conductivity of the fluid, and T is the temperature (Elsebay *et al.* (2016)).

2.1 Thermophysical properties of the coolants

Throughout the flow the thermophysical properties of the base fluid are considered to be temperature dependent. To carry out this configuration, a user-defined function (UDF) was implemented in Ansys Fluent for each property obtained by a curve fit performed from the ASHRAE (2013) tables.

Considering that the MWCNT nanoparticles are sufficiently dispersed in the base fluid and uniformly throughout the flow, the effective thermophysical properties can be considered through correlations. The equations used for density (Eq. 4), dynamic viscosity (Eq. 5), thermal conductivity (Eq. 6) and specific heat (Eq . 7) were proposed by Pak and Cho (1998), Brinkman (1952), Nan *et al.* (2003) and Xuan and Roetzel (2000), respectively.

$$\rho_{ef}\left(T\right) = \phi\rho_{np} + \left(1-\phi\right)\rho_{bf}\left(T\right) \tag{4}$$

$$\mu_{ef}\left(T\right) = \frac{\mu_{bf}\left(T\right)}{\left(1-\phi\right)^{2.5}} \tag{5}$$

$$k_{ef}\left(T\right) = k_{bf}\left(T\right)\left(\frac{3+\phi k_{np}/k_{bf}\left(T\right)}{3-2\phi}\right) \tag{6}$$

$$\left(\rho C_p\right)_{ef}\left(T\right) = \phi\left(\rho C_p\right)_{np} + \left(1-\phi\right)\left(\rho C_p\right)_{bf}\left(T\right) \tag{7}$$

where the subscripts ef, np and bf refer to effective, nanoparticle and base fluid, respectively.

2.2 Data reduction

The Reynolds number is given by Eq. (8).

$$Re = \frac{\rho_{ef}U_{in}D_h}{u_{ef}} \tag{8}$$

where U_{in} refers to the average velocity at the inlet of the pipe and D_h is the hydraulic diameter, defined through Eq. (9).

$$D_h = \frac{4\left[\frac{\pi}{4}H^2 + \left(W-H\right)H\right]}{\pi H + 2\left(W-H\right)} \tag{9}$$

where W and H refer to the height and width of the tube, respectively.

The local and average heat transfer coefficients are calculated using the equations (10) and (11), respectively.

$$h_z = \frac{q''}{T\left(z\right)_w - T\left(z\right)_b} \tag{10}$$

$$h_{avg} = \frac{1}{L}\int_0^L h(z)dz \tag{11}$$

where L refers to the length of the tube, $T\left(z\right)_w$ is the wall temperature, and $T\left(z\right)_b$ is the fluid temperature.

The local and average Nusselt number were defined through the equations (12) and (13), respectively.

$$Nu_z = \frac{h \cdot D_h}{k_{ef}} \tag{12}$$

$$Nu_{avg} = \frac{1}{L}\int_0^L Nu(z)dz \tag{13}$$

3. RESULTS AND DISCUSSIONS

The continuity, momentum and energy equations were solved using the finite volume method implemented in the Ansys Fluent program. The second-order upwind scheme was applied to discretize the convective and diffusive terms. For the pressure-velocity coupling, the SIMPLE method was used.

3.1 Mesh convergence

The mesh convergence study was carried out with three different structured meshes varying the number of elements. As illustrated in Fig. 2 and similarly to what was done by Ebrahimnia-Bajestan *et al.* (2011), the behavior of the local heat transfer convective coefficient for the base fluid was plotted in the Reynolds of 1500 for the three meshes cited. As can be seen, the mesh with 74520 elements showed a considerable difference in the estimation of h_z compared to the other two more refined ones, while meshes with 165600 and 379500 present identical behavior. In this way, the second mesh was selected for the numerical analysis to reduce the computational cost (when compared to mesh 3) with accurate results (when compared to mesh 1).

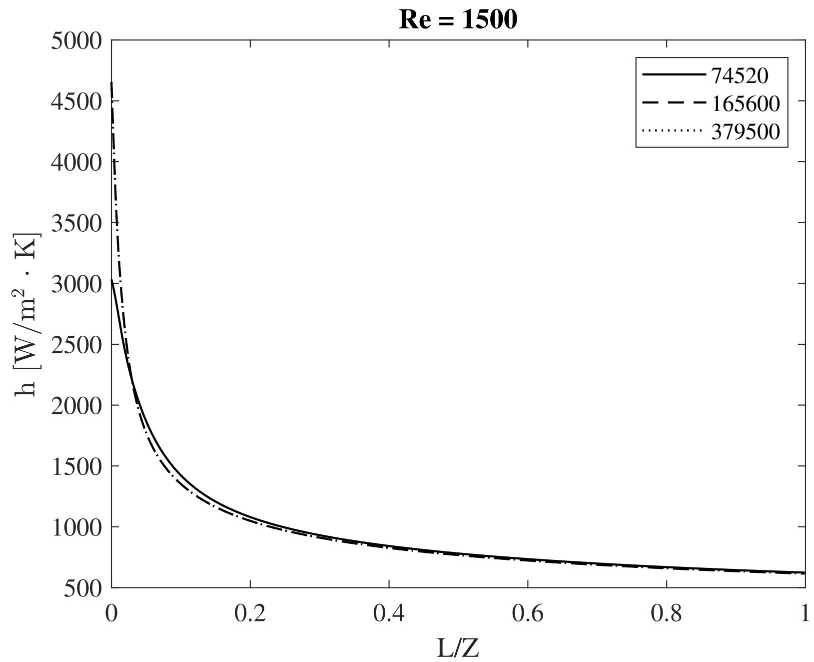

Figure 2. Axial temperature profile at center line of the pipe for base fluid.

The mesh used in this work has the quality parameters described in Tab. 2. According to ANSYS (2015) this mesh has a "very good" quality for the skewness parameter and "excelent" for the orthogonal quality.

Table 2. Quality of the mesh

	Skewness	Orthogonal quality
Minimum	$1.38058 \cdot 10^{-10}$	0.80297
Maximum	0.4473	1
Average	0.078907	0.98631
Standard deviation	0.090073	0.028231

3.2 Effect of Reynolds number and volumetric concentration on local heat transfer coefficient

Figures 3, 4 and 5 show the behavior of the convective coefficient of local heat transfer along the tube for the Reynolds numbers of 250, 750 and 1500, respectively. This length comprises both the developed and developing regions. The average increase of h_z was observed with the increase of the Reynolds number up to 80.70%. Furthermore, the convective coefficient of local heat transfer showed greater increases in the tube inlet region for all Reynolds number values (250 - 1500) as observed by Sajjad *et al.* (2018), while for next developed region it reaches almost constant values that are only dependent on the concentration of nanoparticles, whose behavior can be better observed for the Reynolds number of 250.

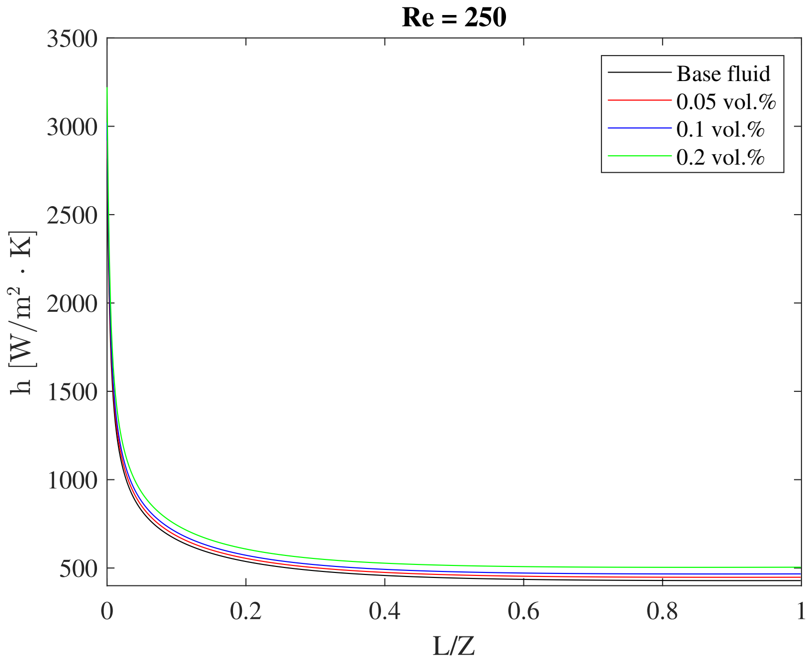

Figure 3. Effect of volumetric concentration of nanoparticles on the local heat transfer coefficient at Re = 250

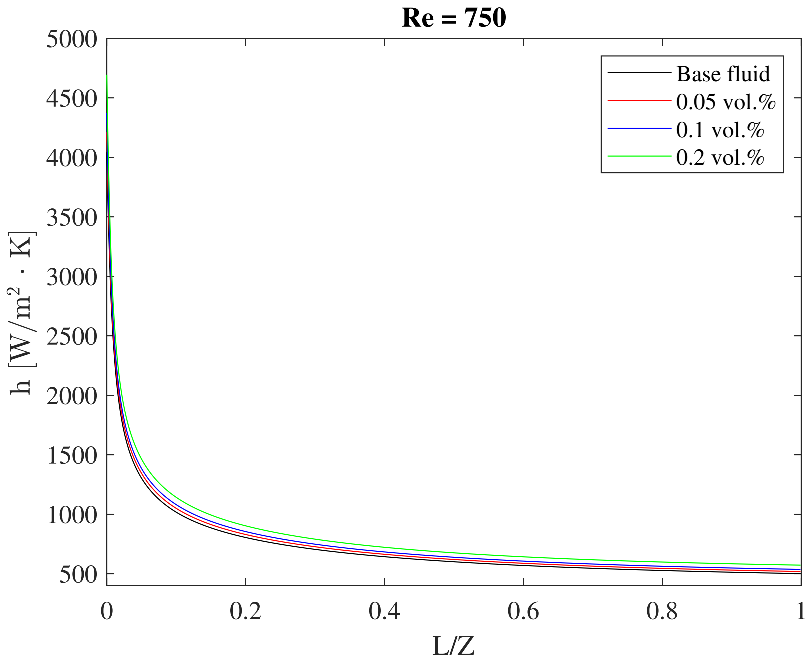

Figure 4. Effect of volumetric concentration of nanoparticles on the local heat transfer coefficient at Re = 750

For the fixed Reynolds number, the average convective coefficient increased up to 15.07% with the increment of MWCNT nanoparticles. It should be noted that this increase is also due to the increase in flow rates to compensate for the increase in density and dynamic viscosity by the increment of nanoparticles, as mentioned by Purohit *et al.* (2016), Oliveira (2016) and Nascimento *et al.* (2021) .

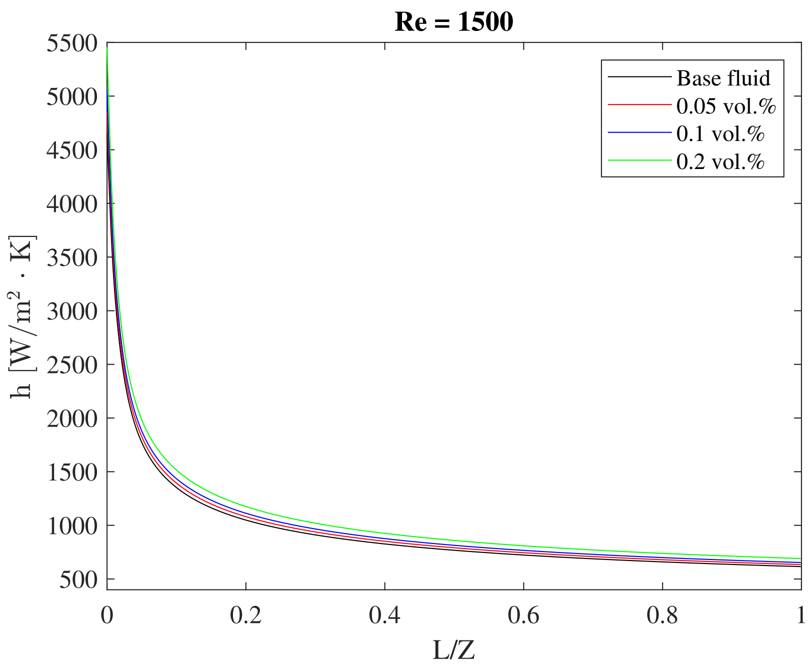

Figure 5. Effect of volumetric concentration of nanoparticles on the local heat transfer coefficient at Re = 1500

3.3 Effect of Reynolds number and volumetric concentration on average Nusselt number

Fig. 6 shows the effects of the variation of the Reynolds number and the concentration of nanoparticles on the Nusselt number. The Nusselt number showed a trend of maximum decrease of 5.40% with increasing concentration of nanoparticles, due to the increase in thermal conductivity being higher than the gains obtained by the convective heat transfer coefficient, as was observed in the work of Teng and Yu (2013).

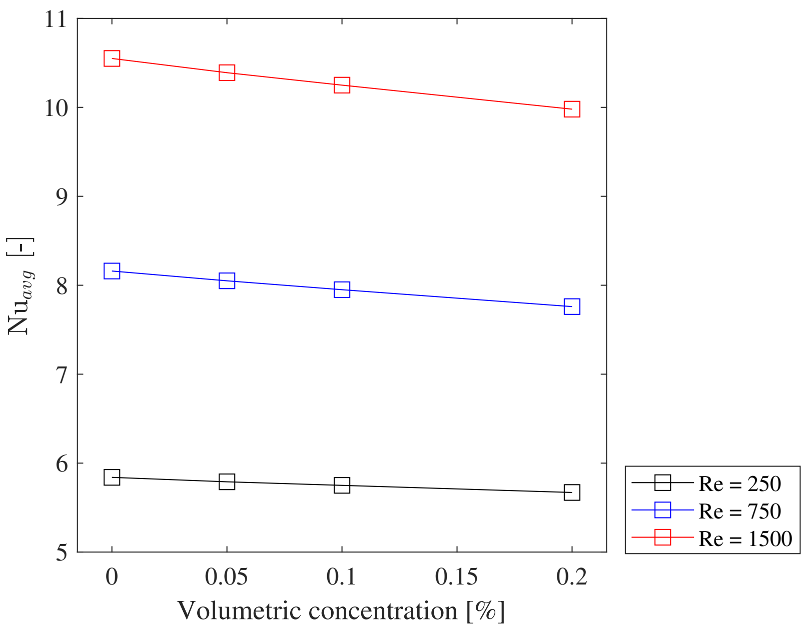

Figure 6. The Nusselt average number at various concentrations and Reynolds number

It was also observed that as the Reynolds number increases, the Nusselt number increases by up to 80.65 %. This can be explained by the reduction of the boundary layer thickness.

3.4 Pressure drop

As can be seen in Tab. 3 the increases in pressure drop that occurred are negligible, with a maximum increase of 0.9% for the highest concentration. This fact can be explained by the use of Brinkman (1952) correlation for dynamic viscosity which, despite being valid for CNT nanofluids (according to Rashmi *et al.* (2014)) underestimates the values, as described by Godson *et al.* (2010) and based on the values obtained from measurements performed by Contreras and Bandarra Filho (2022) and Contreras *et al.* (2017). Thus, there is a lack of correlations for dynamic viscosity of MWCNT nanofluids at high temperatures that show satisfactory agreement with the increment observed experimentally.

Table 3. Pressure drop

Reynolds\Fluid	Base fluid	0.05 vol.%	0.1 vol.%	0.2 vol%
250	21.774	21.8031	21.8337	21.9226
750	67.139	67.333	67.450	67.744
1500	144.721	144.963	145.239	145.926

4. CONCLUSIONS

The thermohydraulic performance by laminar convection was evaluated for three nanofluids and the base fluid flowing in a straight flat tube under the condition of constant convective flow was numerically investigated. The temperature variation of the base fluid along the flow, nanoparticles concentration and Reynolds number were taken into account. The main conclusions that could be made can be summarized as follows:

- The convective heat transfer coefficient increases with increasing concentration of MWCNT nanoparticles (maximum of 15.07%) and with the Reynolds number (maximum of 80.70%) when compared to the base fluid (EG-Water).
- The addition of MWCNT nanoparticles caused an increase in the pressure drop, although thee values are less than 1%. This can be explained by the use of the Brinkman correlation which underestimates the dynamic viscosity values. It was also observed that the pressure drop increased with the Reynolds number.
- Decrease in the Nusselt number (5.40%) with the increase in the volumetric concentration of MWCNT nanoparticles, which can be explained by the increase in thermal conductivity being higher than the gains obtained by the convective heat transfer coefficient. However, it was observed that the increase in the Reynolds number added the Nusselt number up to 80.65%.

Therefore, from a thermal point of view, MWCNT/EG-water nanofluids show promising results for automotive radiator applications.

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