



COB-2021-0279

NUMERICAL ANALYSIS OF THE THERMAL PERFORMANCE OF AN AUTOMOTIVE RADIATOR USING GRAPHENE NANOFUIDS

Erick Oliveira do Nascimento
Edwin Martin Cardenas Contreras
Enio Pendone Bandarra Filho

Federal University of Uberlandia, Av. Joao Naves de Ávila, 2121, Santa Mônica, Uberlândia, Minas Gerais, Brazil
erick.nascimento@ufu.br
emcardenas.1989@gmail.com
bandarra@ufu.br

Abstract. *The conventional coolant fluids used in automotive radiators present low heat transfer rate for the new needs of the automobile industry. Therefore, this work aims to analyze the convective heat transfer of graphene nanofluids/water-Ethylene glycol (50:50 by volume) flowing in an elliptical automotive radiator, in laminar, through the computational fluid dynamics. This flow was simulated numerically for three different nanoparticles concentration (0.01, 0.05 and 0.1 vol.%), in addition to the base fluid, under the condition that the solid particles are sufficiently dispersed to consider the fluid as single-phase and incompressible, for the mass flow of 0.09 kg/s and inlet temperature of the nanofluids from 55 °C to 85 °C, while the air velocity and temperature were maintained constant 25 °C. The results were compared with those available in the literature and it was observed that the studied nanofluids, can increase the heat transfer rate related to the base fluid. In addition, the volumetric concentration of the nanoparticles and the nanofluid temperature have directly influence in the results. It was also observed a tendency to increase considerably the average Nusselt number with the inlet temperature of the nanofluid. Finally, it is important to highlight that the graphene/water-EG nanofluids evaluated numerically in this work showed promising thermal performances for automotive applications.*

Keywords: *heat transfer, nanofluids, automotive radiator, computational fluid dynamics*

1. INTRODUCTION

Radiators are used in automobiles to efficiently transfer heat from the engine's coolant to the environment. The conventional approaches used to increase the heat transfer rate of the system, such as the use of fins and microchannels have reached a technical limit. Combined with this situation, the low thermal conductivity of conventional coolant fluids have sparked the interest of some researchers in dispersing nano-sized solid particles in base fluids that are commonly used in automotive cooling systems (water, ethylene glycol (EG), oil, and the H₂O/EG mixture) to increase their thermal conductivity. Thermal fluids also act as antifreeze in colder components or even in hotter parts depending on the climatic conditions, in addition, these fluids act as lubricants (Abbas et al., 2020).

To perform the evaluation of the thermal performance of nanofluids, it is necessary that the parameters of these substances are well defined, because these properties depend directly on other variables such as thermal conductivity, viscosity, specific heat, density, in addition to the heat transfer rate, and these properties also vary, either by the shape, size and concentration of the nanoparticles, the presence of surfactants and among others (Gupta et al., 2018). Tafakhori et al. (2020) synthesized Fe₃O₄ nanoparticles with water with volumetric concentrations ranging from 0 to 0.9% and performed tests to evaluate their thermohydraulic performance in an automotive radiator. Through this study, it was observed that with 0.1 vol.% the heat exchange increased by 21% on average over the base fluid for the temperature range of 72 to 88 °C, furthermore, concentrations above this, nanoparticle agglomeration and Reynolds number can reduce the heat transfer rate. When analyzing the influence of the radiator fan speed, it was noticed that the coolant temperature decreases with increasing speed from 1000 to 2500 rpm, having its effect attenuated for temperatures above 80 °C and speeds between 2000 and 2500 rpm.

Contreras et al. (2019) prepared graphene and silver nanofluids with base fluid H₂O/EG, by the high pressure homogenization method, whose thermal conductivities showed an increase of 9.2% and 4.7% compared to the base fluid at 25 °C. The experimental results obtained in wind tunnel indicated that the heat transfer of these nanofluids in an automotive radiator for laminar flow regime, strongly depends on the concentration and temperature. Selvam et al., (2017) detected an increase in thermal conductivity and convective heat transfer coefficient by up to 29% for nanofluids with 0.5% volume of graphene and H₂O/EG nanoplates in a radiator. Furthermore, it was observed that this fluid has promising results for automotive cooling applications with laminar flows at 45 °C. However, the authors point out that tests should be conducted for higher mass flow rates and temperatures to observe the behavior of this fluid. Kılınç et al., (2020) observed that for graphene and H₂O/EG nanofluids, the efficiency of an automotive radiator increased with nanoplate

concentration. Furthermore, it was observed that increasing the overall heat transfer coefficient allows the same amount of heat to be transferred in smaller radiators.

In recent years, a vast number of studies have proven that nanofluids have improved thermal conductivity compared to base fluids. With this improvement, it opens up the possibility of using smaller radiators with the same thermal load, as well as reducing the drag produced by the larger frontal area of the heat exchanger (Vajjha et al., 2010). The circular tube is the most conventional for applications in heat exchangers, such as automotive radiators, for this reason, there is a vast literature highlighting the positive results in the heat transfer of nanofluids in this type of structure.

Oliveira et al. (2021) analyzed the thermal conductivity and dynamic viscosity of multi-walled carbon nanotube and graphene nanofluids for concentrations of 0.025 - 0.15% for automotive applications. The samples with graphene showed an increase in thermal conductivity of 5.9% for the 0.1% volumetric concentration, similar to the carbon nanotube sample. Furthermore, they were able to observe that this increase, coupled with viscosity similar to that of the base fluid, indicates that nanofluids are promising for applications as coolants.

Ho et al. (2021) analyzed alumina/water nanofluids with concentrations between 0 to 10%, in a copper tube with constant heat flux, for Reynolds number between 168 and 2031. They observed an increase in the inner wall and decrease in the total temperature as a result of increasing Reynolds number, in addition, the use of nanoparticles can reduce the temperature of the inner part of the tube, heat flux did not show considerable effect on the inner wall temperature. Ho et al. (2018) experimentally and numerically investigated the thermohydraulic contributions of Al_2O_3 /water nanofluids in a circular tube. The authors could see that the insertion of the nanoparticles leads to the reduction of the wall temperature and the increase of the Nusselt number, however, for the same condition, the increase of the pressure drop along the tube occurs.

She and Fan (2018) conducted the study of CuO-water nanofluids in a tube for Reynolds number from 6000 to 10000. As a result, the authors observed that the insertion of the nanoparticles increases the heat transfer coefficient and the viscosity of the fluid, moreover, it is highlighted that the nanofluid shows improvement in heat transfer compared to the circular tube. Arya et al. (2018) experimentally analyzed the use of carbon nanotube/water nanofluids, in the cooling system of an aluminum heater, and identified the increase in heat transfer coefficient of up to 40% compared to the base fluid.

Sharma et al. (2020) analyzed the performance of a flat tube with copper oxide nanofluids and could highlight the increase of heat transfer with nanoparticle concentration, temperature and Reynolds number, while the increase of pressure drop is linked to nanoparticle volumetric concentration and Reynolds number. Kaska et al., (2019) studied the enhancement of hybrid nanofluids of aluminum nitride and alumina, and water in a flat tube by means of computational fluid dynamics, adopting the finite volume method and SIMPLE algorithm. From the simulations of these fluids with volumetric concentrations of 1, 2, 3 and 4%, Reynolds number from 5000 to 17000, it was identified that the pressure drop increases with concentration and Reynolds number, moreover, there is an improvement in heat transfer. Sokhal et al. (2018) experimentally studied the effect of copper oxide nanofluids (0.1 - 0.5% v/v) on the thermal and hydraulic performance in flat tubes of an automotive radiator, and could observe that the Nusselt number increased with nanoparticle concentration, coolant inlet temperature, and Reynolds number. From the hydraulic point of view, the increase in pressure drop is linked to the Reynolds number and the concentration of the nanofluids.

Alosious et al. (2017) conducted an experimental and numerical study of the heat transfer of Al_2O_3 and CuO nanofluids in an automotive radiator, for inlet temperatures up to 90 °C and Reynolds numbers ranging from 136 to 816. The results showed the increase in internal heat transfer of up to 13.2% and 16.4% for CuO and Al_2O_3 nanofluids, respectively. Elsebay et al. (2016) also analyzed Al_2O_3 and CuO nanofluids in an automotive radiator, however, for Reynolds numbers from 250 to 1750, and could observe the increase in heat transfer coefficient of up to 45% and 38% for Al_2O_3 and CuO nanofluids, respectively, compared to pure water. Hussein et al. (2016) analyzed the heat transfer and friction factor of TiO_2 nanofluids in an elliptical tube using Ansys Fluent program in turbulent regime. The results presented indicated the transfer of the elliptical tube is higher than that of the circular tube.

Thus, this work aims to analyze the heat transfer of graphene/EG-W nanofluids flowing in an elliptical tube automotive radiator for volumetric concentrations of 0.01, 0.5 and 0.1%, and inlet temperature from 55 to 85 °C in laminar regime, through computational fluid dynamics. It is highlighted that the experimental data used in this work was obtained through the work of Contreras et al. (2019).

2. MATHEMATICAL MODELING

2.1 Problem geometry

As can be seen in Figure 1, the geometry of the problem analyzed consists of an elliptical tube of an automotive radiator with fins, for the cooling of fluids, based on the dimensions of the work by Contreras et al. (2019). In this work, the fins are considered by increasing the convective heat transfer, as performed by Alosious et al. (2017) and Elsebay et al. (2016).

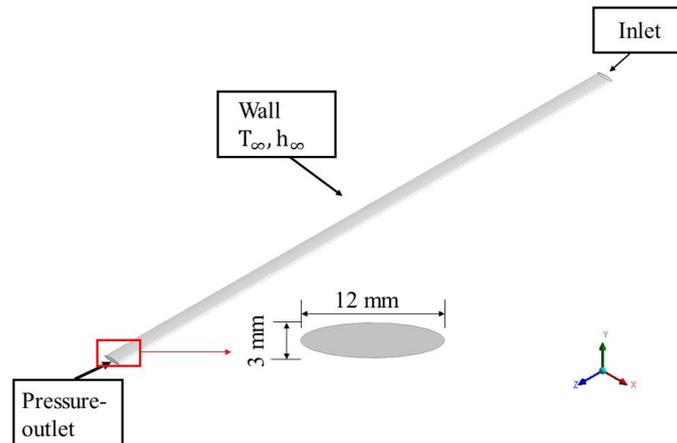


Figure 1. Schematic of the elliptical tube radiator

The analyzed radiator is of the two-pass type; therefore, the equipment will have the inlet and the outlet on the same side. Thus, two tubes with a length of 429 mm, described in Figure 1, were needed to evaluate the thermal performance of the equipment.

2.2 Governing equations

The radiator coolant was an ethylene glycol/water mixture in a 50:50, in addition to the nanofluids, which had the nanoparticles dispersed in volumetric concentrations of 0.01 to 0.1%. For these considerations, generally, the flow of fluids (including nanofluids) in automotive radiators are considered incompressible. It is noteworthy that for all simulations, the fluid was considered as laminar, single-phase, given the low concentrations of nanoparticles, as per the works of Vajjha et al. (2010) and Ting and Hou (2015). Thus, the numerical solution of this problem is obtained by means of the conservation equations, using the Ansys Fluent 16.0 software.

Continuity:

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

Momentum:

$$\rho(\nabla \cdot \vec{V})\vec{V} = -\nabla p + \mu \nabla^2 \vec{V} \quad (2)$$

Energy:

$$\rho C_p (\nabla \cdot \vec{V})T = \nabla^2 (kT) \quad (3)$$

where \vec{V} represents the velocity vector (m/s), ρ is the density of the fluid, p is the pressure (Pa), μ is the viscosity (kg/m·s), C_p is the specific heat (J/kg·K), T is the temperature, and k is the thermal conductivity of the fluid (W/(m·K)) (Alosious et al., 2017).

2.3 Numerical method

Equations (1-3) were solved using the finite volume method using the Ansys Fluent 16.0 software. Double precision was adopted for all calculations. A second-order upwind scheme was used to discretize the advection, diffusion, and other terms of the governing equations. The SIMPLE algorithm was adopted to perform the pressure-velocity coupling scheme. For all simulations performed in this work, it was considered that the convergence of the solution is obtained when the values of the residuals of the conservation equations were less than 10^{-6} .

The average Nusselt number (Nu_{avg}) is defined by equation (4)

$$Nu_{avg} = \frac{h_{avg} D_h}{k} \quad (4)$$

where $h_{avg} = (\frac{1}{L} \int_0^L h_l dz)$ represents the average convective heat transfer coefficient, where h_l obtained through post-processing in the Ansys Fluent program and L is the total length of the tube.

2.4 Boundary conditions

To reduce the computational cost, it was decided to carry out the simulations using $\frac{1}{4}$ of the domain described in Figure 1. In the radiator inlet region, the constant mass flow of 90 g/s and the temperature ranging between 55 and 85 °C were determined. In the tube outlet region, an outlet-pressure condition was considered, since the tube length is smaller than the thermal inlet length. Along the entire tube, wall regions have been set up as the no-slip condition. To reproduce the effects of the externally flowing air, in addition to the influence of the fins, the heat transfer coefficient was set at 903 W/m²·K and an ambient temperature of 25 °C.

2.5 Thermophysical properties of nanofluids

As described earlier, this work is based on the experimental data of Contreras et al. (2019), which obtained the properties of the base fluids from ASHRAE (2013) data, as shown in Table 1. The properties of the nanofluids were obtained partially by direct measurements and others by correlations. In this work, it is assumed that the nanoparticles are uniformly dispersed.

Table 1. Thermophysical properties of base fluid. Source: ASHRAE (2013).

Temperature (K)	Viscosity (kg/m·s)	Thermal conductivity (W/(m·K))	Specific heat (J/kg·K)	Density (kg/m ³)
328.15	0.00159	0.402	3416.00	1055.13
338.15	0.00129	0.406	3454.00	1048.83
348.15	0.00107	0.410	3493.00	1042.04
358.15	0.00089	0.413	3532.00	1034.77

The thermal conductivity and viscosity of nanofluids were measured using a LINSEIS THB-1 sensor and an Anton Paar rotational viscometer, respectively. Specific heat and density were defined through the correlations of Pak Cho (1998) and Xuan and Roetzel (2000), according to equations (4) and (5). In this work, the dynamic viscosity and thermal conductivity were determined using the Einstein and Maxwell equations, respectively, according to equations (6) and (7).

$$\rho_{nf} = \phi \cdot \rho_{np} + (1 - \phi) \cdot \rho_{bf} \quad (4)$$

$$(\rho \cdot C_p)_{nf} = \phi \cdot (\rho \cdot C_p)_{np} + (1 - \phi) \cdot (\rho \cdot C_p)_{bf} \quad (5)$$

$$\mu_{nf} = (1 + 2.5\phi)\mu_f \quad (6)$$

$$\frac{k_{nf}}{k_{bf}} = \frac{(k_p + 2k_{bf} + 2\phi(k_p - k_{bf}))}{(k_p + 2k_{bf} - \phi(k_p - k_{bf}))} \quad (7)$$

where, the superscripts bf, nf and np refer to the base fluid, the nanofluid and the nanoparticle, respectively.

Table 2. Thermophysical properties of nanofluids.

Temperature (K)	Volumetric concentration (%)	Viscosity (kg/m·s)	Thermal conductivity (W/(m·K))	Specific heat (J/kg·K)	Density (kg/m ³)
328.15	0.01	0.0015900	0.402	3412.87	1056.06
	0.05	0.0015920	0.403	3400.39	1059.80
	0.10	0.0015940	0.403	3384.91	1064.47
338.15	0.01	0.0012900	0.406	3450.81	1049.77
	0.05	0.0012920	0.407	3438.11	1053.51
	0.10	0.0012930	0.407	3422.35	1058.18
348.15	0.01	0.0010700	0.410	3489.75	1042.98
	0.05	0.0010710	0.411	3476.81	1046.72
	0.10	0.0010730	0.411	3460.76	1051.40

358.15	0.01	0.0008902	0.413	3528.69	1035.71
	0.05	0.0008911	0.414	3515.50	1039.45
	0.10	0.0008922	0.414	3499.15	1044.14

3. NUMERICAL COMPUTATION

3.1 Grid Independence study

A three-dimensional mesh was used, as shown in the Figure 2. To achieve mesh independence and obtain the mesh with the best relationship between accurate results and the lowest number of volumes, three different mesh configurations were configured to discretize the computational domain, mesh 1 ($N_X = 40$, $N_Y = 20$ and $N_Z = 100$), mesh 2 ($N_X = 60$, $N_Y = 30$ and $N_Z = 200$) and mesh 3 ($N_X = 60$, $N_Y = 30$ and $N_Z = 300$). As was done by Elsebay et al. (2016), in order to carry out this procedure, it was decided to analyze the temperature at the outlet of the tube, for the base fluid (water-ethylene glycol) with an inlet temperature of 55 °C. It is noteworthy that for all meshes the convergence of the requested solution was obtained.

Table 3. Grid Independence

Grid	Temperature (°C)
Mesh 1	48.441
Mesh 2	48.499
Mesh 3	48.499

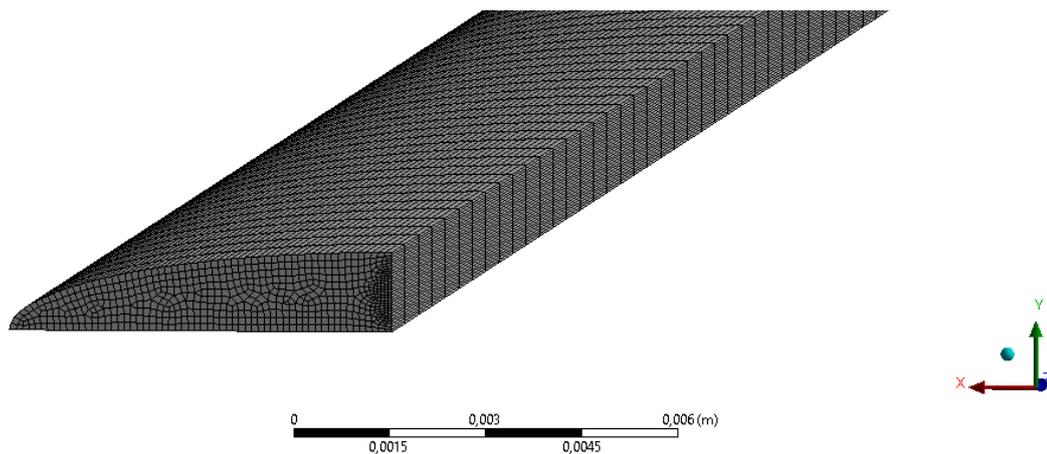


Figure 2. Grid layout used in the present analysis

It can be seen in Table 2 that the temperatures obtained for the more refined meshes (2 and 3) are identical, while mesh 1 presents considerable divergence when compared to the other meshes. In this way, all the simulations carried out in this work were using the configuration of mesh 2, as it presents the same result as mesh 3, but with a smaller amount of volumes, reducing the computational cost.

4. RESULTS AND DISCUSSION

4.1 Outlet temperature

Figure 3 shows the average temperature at the radiator outlet as a function of the base fluid inlet temperature (Figure 3 (a)) and nanofluids (Figure 3 (b-d)). It can be observed that the numerical results obtained in this work show satisfactory agreement in relation to the experimental results of Contreras et al. (2019), with a maximum difference of 0.83% for the nanofluid with a concentration of 0.05% and an inlet temperature of 85 °C.

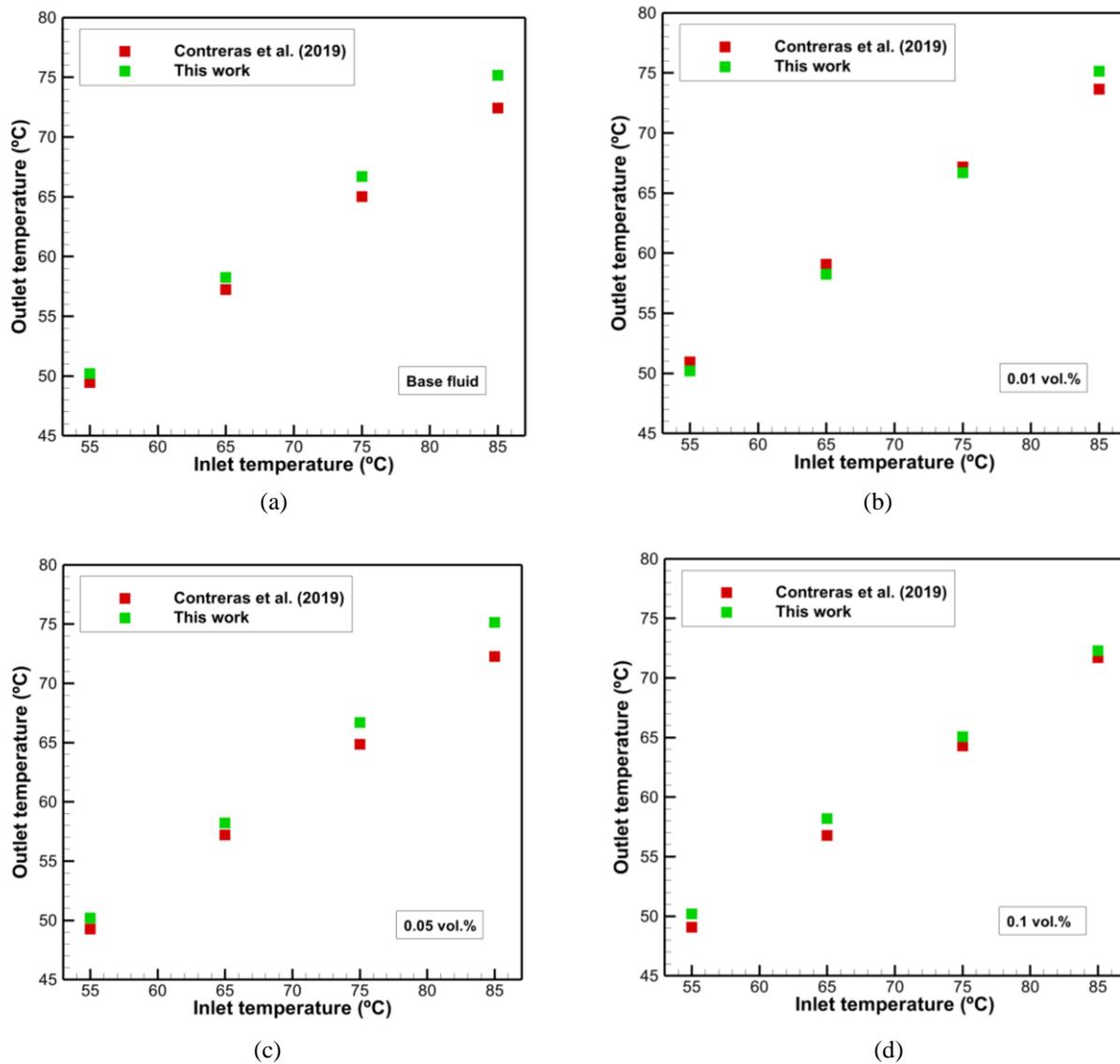


Figure 3. Average coolant temperature at the radiator outlet.

4.2 Effect of concentration and inlet temperature on average Nusselt number

Figure 4 illustrates the average Nusselt number as a function of the volumetric concentration of the coolant for the first and second radiator tubes for different inlet temperatures. It can be seen that in both tubes there was a decrease in the average Nusselt number for all samples, except for the concentration of 0.1% at the inlet temperature of 75 °C and 85 °C, which had maximum increases of 0.57% and 2.68%.

When you compare this behavior with the experimental heat transfer rate data from Contreras et al. (2019), it can be seen that the results obtained in this work have similar behavior, in where is a decrease in the heat transfer rate for the nanofluid samples, except for the sample with a concentration of 0.1%. Estellé et al. (2017) also had similar results when analyzing carbon nanostructured nanofluids at volumetric concentrations of 0.0055–0.418% in a rectangular cavity, in which the decay of the Nusselt number occurred at low temperatures.

However, these results show a relative discrepancy in relation to the majority of experimental works already carried out, where the Nusselt number increases as a function of volumetric concentration, as in the work of Ting and Hou (2015). However, this fact can be explained by Oliveira (2016) that most works that present increased heat transfer as a function of the fixed Reynolds number (thus, it is necessary to increase the mass flow to compensate for the increase in viscosity), directly affecting the increase in heat transfer, and by the use of correlations that underestimate or overestimate the thermophysical properties of nanofluids as described by Sajjad et al. (2018). Trinavee et al. (2016) presents results that show the underestimation of the Nusselt number when considering that the properties of nanofluids are constant in relation to temperature, which corroborates the results obtained.

Furthermore, according to Huang et al. (2015), heat transfer may be being deteriorated by increased viscosity (caused by the addition of nanoparticles) and increased thermal conductivity. It should be noted that the increase in convective heat transfer does not depend solely on the increase in the thermal conductivity of the cooling fluid, but also on dispersion, Brownian motion, thermophoresis, etc., as described by Ting and Hou (2015).

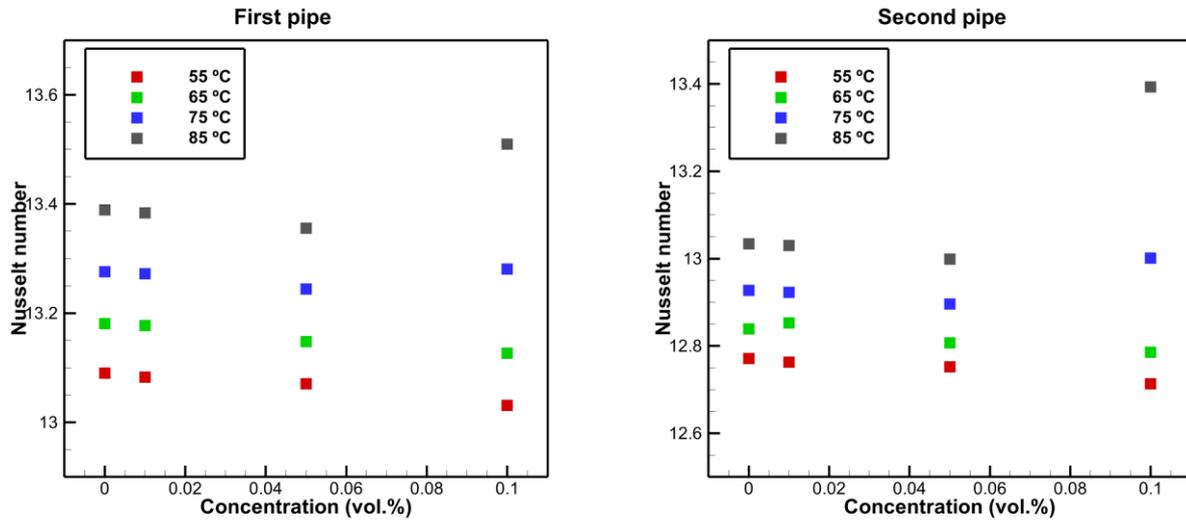


Figure 4. Variation of average Nusselt number with volumetric concentration.

On the other hand, it is noteworthy that the increase in the coolant inlet temperature tends to increase the average Nusselt number for all samples. The maximum increases were 2.23% for the base fluid, 2.25% for the sample with 0.01 vol.%, 2.13% for the nanofluid with 0.05% and 3.55% for the concentration sample of 0.1%. These results are in agreement with experimental results available in the literature, such as those by Kiliç et al. (2019) and Contreras et al. (2019). However, it is noteworthy that the indiscriminate increase in the temperature of the coolant fluid can cause the deterioration of thermophysical properties, which may lead to a phase change and agglomeration of nanoparticles.

Figure 5 illustrates the temperature contours of graphene nanofluid with a concentration of 0.1% for the inlet temperature of 85 °C in a plan view. As expected, the fluid temperature decreased due to the release of heat from the tube walls. Therefore, the coolant that leaves the radiator returns to the engine at lower temperatures than the tube inlet.

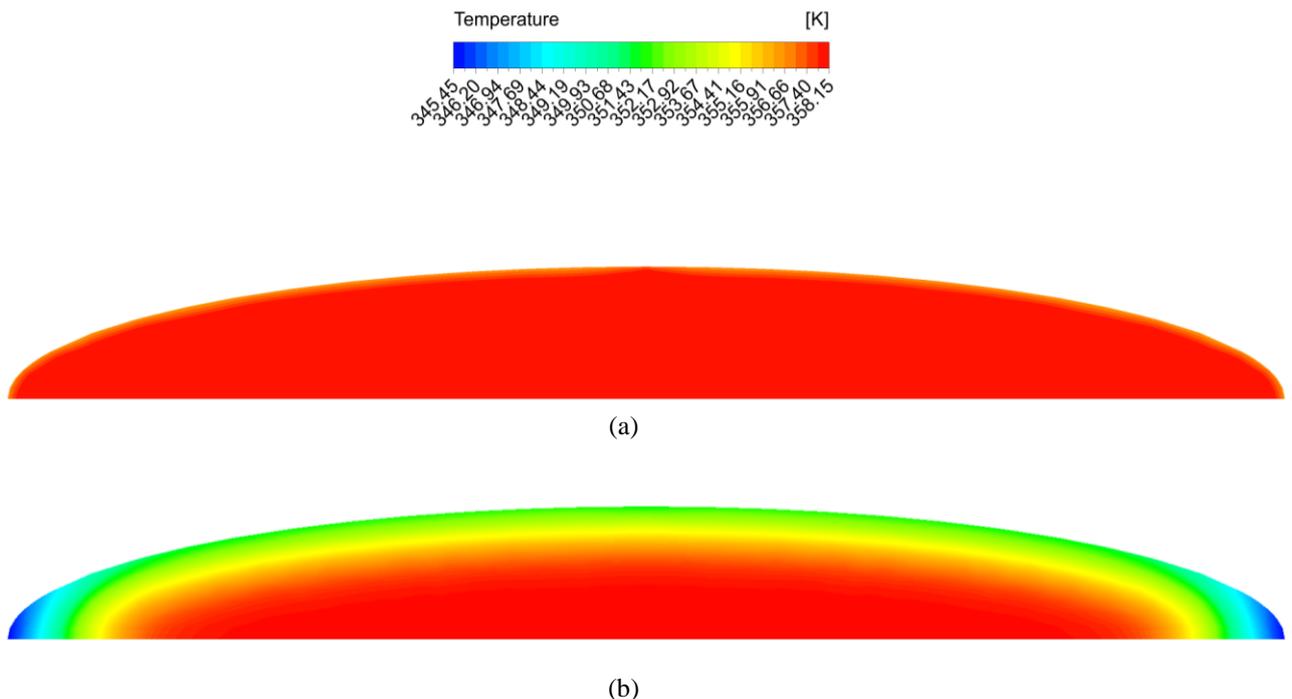


Figure 5. Contour plot for temperature distributions in the flow domain.

5. CONCLUSIONS

In this work, we analyzed the heat transfer performance in an elliptical tube of an automotive radiator through computational fluid dynamics for four different fluids: the water-ethylene glycol base fluid (50:50), and three graphene nanofluids at different concentrations and inlet temperatures.

Due to the dispersion of graphene nanoparticles in the base fluid, there was an increase in the thermal conductivity of the cooling fluid, increasing the Nusselt number for the nanofluid with the highest volumetric concentration in relation to the base fluid, however, for lower concentrations, it was observed the decrease, which can be justified by the use of correlations that can underestimate or overestimate the thermophysical properties of nanofluids.

Therefore, it is necessary more experimental and numerical tests to evaluate the correlations of graphene nanofluids, as it could be observed for the highest concentration, it presented promising results for the application of nanofluids in cooling systems.

6. ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided for this research by CAPES, CNPq and FAPEMIG. The authors also wish to extend their gratitude to FCA, FIAT CHRYSLER AUTOMOVEIS BRASIL LTDA.

7. REFERENCES

- Abbas, F.; Ali, H.M.; Shah, T.R.; Babar, H.; Janjua, M.M.; Sajjad, U.; Amer, M., 2020. "Nanofluid: potential evaluation in automotive radiator". *Journal of Molecular Liquids*, Vol. 297, pp. 112014.
- Alosious, S.; R, Sarath S; Nair, A. R; Krishnakumar, K., 2017. "Experimental and numerical study on heat transfer enhancement of flat tube radiator using Al₂O₃ and CuO nanofluids". *Heat and Mass Transfer*, Vol. 53, No. 12, pp. 3545-3563.
- Arya, A.; Sarafraz, M.M.; Shahmiri, S.; Madani, S.A.H.; Nikkhah, V.; Nakhjavani, S.M., 2017. "Thermal performance analysis of a flat heat pipe working with carbon nanotube-water nanofluid for cooling of a high heat flux heater". *Heat and Mass Transfer*, Vol. 54, No. 4, pp. 985-997.
- ASHRAE, 2013. *Handbook Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- Contreras, E.M.C.; Oliveira, G.A.; Bandarra Filho, E.P., 2019. "Experimental analysis of the thermohydraulic performance of graphene and silver nanofluids in automotive cooling systems". *International Journal of Heat and Mass Transfer*, Vol. 132, pp. 375-387.
- Elsebay, M.; Elbadawy, I.; Shedid, M.H.; Fatouh, M., 2016. "Numerical resizing study of Al₂O₃ and CuO nanofluids in the flat tubes of a radiator". *Applied Mathematical Modelling*, Vol. 40, No. 13-14, pp. 6437-6450.
- Estellé, P.; Mahian, O.; Maré T. Öztop, H. F., 2017. "Natural convection of CNT water-based nanofluids in a differentially heated square cavity". *Journal of Thermal Analysis and Calorimetry*. Vol. 128, pp. 1765-1770.
- Gupta, M.; Singh, V.; Kumar, S.; Kumar, S.; Dilbaghi, N.; Said, Z., 2018. "Up to date review on the synthesis and thermophysical properties of hybrid nanofluids". *Journal of Cleaner Production*, Vol. 190, pp. 169-192.
- Ho, C.J.; Chen, W.; Yan, W.; Amani, P., 2018. "Contribution of hybrid Al₂O₃-water nanofluid and PCM suspension to augment thermal performance of coolant in a minichannel heat sink". *International Journal of Heat and Mass Transfer*, Vol. 122, pp. 651-659.
- Ho, C.J.; Cheng, C.; Yang, T.; Rashidi, S.; Yan, W., 2021. "Experimental study on cooling performance of nanofluid flow in a horizontal circular tube". *International Journal of Heat and Mass Transfer*, Vol. 169, pp. 120961.
- Huang, D.; Wu, Z.; Sunden, B., 2015. "Pressure drop and convective heat transfer of Al₂O₃/water and MWCNT/water nanofluids in a chevron plate heat exchanger". *International Journal of Heat and Mass Transfer*, Vol. 89, pp. 620-626.
- Hussein, A.; Bakar, R.A.; Kadirgama, K.; Sharma, K.V., 2016. "Heat transfer enhancement with elliptical tube under turbulent flow TiO₂-water nanofluid". *Thermal Science*, Vol. 20, No. 1, pp. 89-97.
- Karabulut, K.; Buyruk, E.; Kilinc, F., 2020. "Experimental and numerical investigation of convection heat transfer in a circular copper tube using graphene oxide nanofluid". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 42, No. 5.
- Kaska, S.A.; Khalefa, R.A.; Hussein, A.M., 2019. "Hybrid nanofluid to enhance heat transfer under turbulent flow in a flat tube". *Case Studies in Thermal Engineering*, Vol. 13, pp. 100398.
- Kilinç, F.; Buyruk, E.; Karabulut, K., 2019. "Experimental investigation of cooling performance with graphene based nano-fluids in a vehicle radiator". *Heat And Mass Transfer*, Vol. 56, No. 2, pp. 521-530.
- Oliveira, G.A., 2016. "Experimental analysis of thermal performance of nanofluids in automotive radiators", Ph.D. Thesis (in portuguese), Federal University of Uberlândia.

Oliveira, G.A.; Contreras, E.M.C.; Bandarra Filho, E.P., 2021. "Experimental study of thermophysical properties of MWCNT and graphene coolant nanofluids for automotive application". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 43, No. 3.

Pak, B.C.; Cho, Y.I., 1998. "Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles". *Experimental Heat Transfer*, Vol. 11, No. 2, pp. 151-170.

Sajjad, M.; Kamran, M.S.; Shaukat, R.; Zeinelabdeen, M.I.M., 2018. "Numerical investigation of laminar convective heat transfer of graphene oxide/ethylene glycol-water nanofluids in a horizontal tube". *Engineering Science And Technology, An International Journal*, Vol. 21, pp.727-735.

Sarafraz M.; Safaei, M.; Tian, Z.; Goodarzi, M.; Bandarra Filho, E.P.; Arjomandi, M., 2019. "Thermal Assessment of Nano-Particulate Graphene-Water/Ethylene Glycol (WEG 60:40) nano-suspension in a compact heat exchanger". *Energies*, Vol. 12, No. 10, pp. 1929.

Selvam, C.; Lal, D. M.; Harish, S., 2017. "Enhanced heat transfer performance of an automobile radiator with graphene based suspensions". *Applied Thermal Engineering*, Vol. 123, pp. 50-60.

Sharma, P.; Kumar, V.; Sokhal, G.S.; Dasaroju, G.; Bulasara, Vijaya K., 2020. "Numerical Study on Performance of Flat Tube with Water Based Copper Oxide Nanofluids". *Materials Today: Proceedings*, Vol. 21, pp. 1800-1808.

She, L.; Fan, G., 2018. "Numerical Simulation of Flow and Heat Transfer Characteristics of CuO-Water Nanofluids in a Flat Tube". *Frontiers in Energy Research*, Vol. 6.

Sokhal, G.S.; Gangacharyulu, D.; Bulasara, V.K., 2018. "Influence of copper oxide nanoparticles on the thermophysical properties and performance of flat tube of vehicle cooling system". *Vacuum*, Vol. 157, pp. 268-276.

Tafakhori, M.; Kalantari, D.; Biparva, P.; Peyghambarzadeh, S.M., 2020. "Assessment of Fe₃O₄-water nanofluid for enhancing laminar convective heat transfer in a car radiator". *Journal of Thermal Analysis and Calorimetry*.

Ting, H.; Hou, S., 2015. "Numerical Study of Laminar Flow Forced Convection of Water-Al₂O₃ Nanofluids under Constant Wall Temperature Condition". *Mathematical Problems in Engineering*, Vol. 2015, pp. 1-8.

Toh, L.K.L.; Ting, T.W. "Thermal performance of automotive radiator with graphene nanoplatelets suspension". *Aip Conference Proceedings*.

Trinavee, K.; Gogoi, T. K.; Pandey, M., 2016. "Laminar convective heat transfer characteristic of Al₂O₃/water nanofluid in a circular microchannel". *Journal Of Physics: Conference Series* v. 759, p. 012088.

Vajjha, R.S.; Das, D.K.; Namburu, P.K., 2010. "Numerical study of fluid dynamic and heat transfer performance of Al₂O₃ and CuO nanofluids in the flat tubes of a radiator". *International Journal of Heat and Fluid Flow*, Vol. 31, No. 4, pp. 613-621.

Xuan, Y.; Roetzel, W. "Conceptions for heat transfer correlation of nanofluids". *International Journal of Heat and Mass Transfer*, Vol. 43, No. 19, pp. 3701-3707.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.