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Computational Analysis of Automobile Radiator Roughened with Rib Roughness

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ABSTRACT

Heat transfer enhancement in a car radiator using different nano fluids has been performed very often, but use of artificial roughness has been seldom done. In the present work, artificial roughness in the form of ribs has been incorporated in car radiator. A numerical comparative study has been performed between the ribbed automobile radiator and conventional radiator (flat tube). The nanofluid (Al_2O_3/Pure Water) has been used as a coolant in the car radiator configuration. The pitch is kept 15 mm (constant) for all the studies performed. The Reynolds number of the flow is selected in the turbulent regime i.e. ranging from 9350 to 23000 and the concentration of the nanofluid is taken from 0.1 to 1.0 %. It has been observed that the heat transfer rate improved with the ribbed roughness as compared to conventional configuration, but the pumping power has also increased. Furthermore, heat transfer rate also increased with increase in nano-particle concentration. The maximum heat transfer enhancement of 79% reported at nanofluid concentration of 1.0% and Reynolds number of 9350 for ribbed configuration.

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1. Introduction

In the automotive market, there is a huge demand for more powerful engines with aesthetic car design. The design department has to go through multiple challenges in doing so. One of the major problems is the dissipation of the waste heat produced by the engines (about one third of total heat) through cooling system. The waste heat should be rejected very effectively otherwise it may lead to various problems like increase in pollution, increase in fuel consumption and may even damage the engine components. With the increase in engine power, the radiator size also increases to dissipate extra waste heat. However, increasing the size of the radiator will lead to major design changes. This problem can be resolved by increasing the efficiency of cooling systems without changing the radiator size. The efficiency of the cooling system can be enhanced by using active and passive methods. However, active method required external power. An efficient cooling system can decrease fuel consumption and helps to improve the engine performance [1].

The performance of the cooling system can be enhanced by using various heat transfer enhancement techniques viz. effective geometry, modified coolant, increased surface area etc. Apart from that use of fins and various designs of micro-channels are other ways to improve the performance [2]. Initially, Water was used as a working fluid to extract heat. However, due to its freezing point limitation, water has been mixed with freezing point depressants for its application. Weight fraction of freezing point depressant in the working fluid depends upon the local weather conditions.

However, use of freezing point depressant also affects the thermal conductivity of the working fluid [3]. The thermal characteristics of working fluid can be

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augmented by introducing nano particles. The use of nanofluids as a working fluid in engine cooling system has gain huge attention of researchers [4].

Choi and Eastman [5] were the first to show the use of nanofluids by using metal and metals oxides as suspended nanoparticles in base fluid. Afterwards, various researchers have used nanofluids to enhance the thermal performance of the car radiator. Ahmed et al. [6] investigated the thermal performance of the car radiator with TiO_2-water nanofluids for the laminar flow regime. They concluded that the performance of the car radiator is optimal with 0.2% concentration of TiO_2-water nanofluid. Naraki et al. [7] investigated the effect of CuO-water nanofluid on heat transfer in a car radiator and concluded that, heat transfer significantly increased with the use of nanofluid. Apart from that, they also reported heat transfer rate increased with increase in nano particle concentration and decreases with temperature. Heris et al. [8] also investigated thermal performance of CuO nanoparticles with water and ethylene glycol mixture and reported that Nusselt number increased with increase of Reynolds number and nano particle concentration. SiO_2 based nanofluid was also used in car radiator, and it was found that heat transfer enhanced by using nanofluid and significantly affected with particle concentration, flow rate and inlet temperature [9]. Various researchers have also used Al_2O_3 based nanofluids in automobile radiator to enhance the thermal performance [10-12]. Senthilraja et al. [13] compared the performance of a radiator using CuO and Al_2O_3 based nanofluids and concluded that CuO based nanofluid has performed better than Al_2O_3 based nanofluids. Furthermore, researchers also studied the effect of various types of inserts along with nanofluids on the thermal performance of radiator. Chougule et al. [14] experimentally investigated effect of wire coil insert with nanofluid in a circular tube. They observe augmented thermal performance for low volume concentration of CNT/water nanofluid. Recently, Singh et al. [15-16] had proposed dimple and protrusion in conical insert inside of heat exchanger for enhancing the performance.

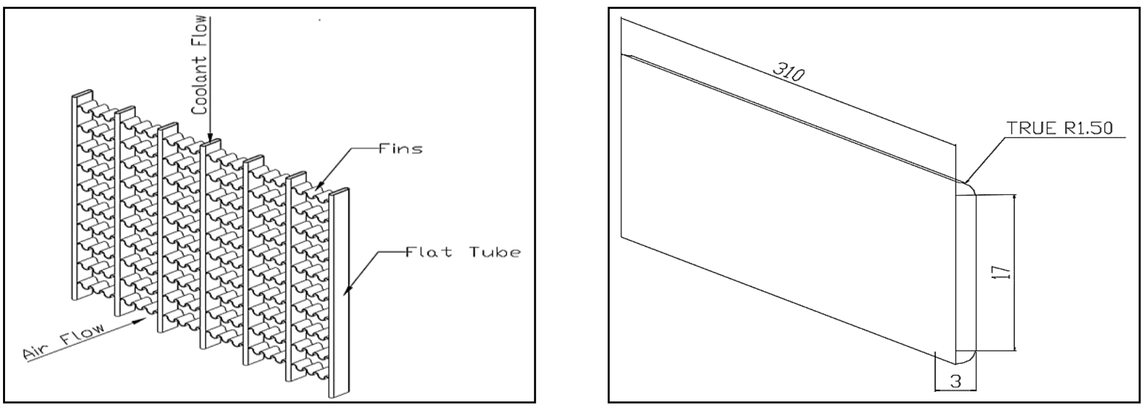
In internal combustion engines, about 65% of the heat energy generated is wasted. About half of this total waste heat is dissipated through the cooling systems and the rest of the waste heat is lost through the tail pipes in exhaust gases. If cooling systems do not work effectively, then the performance of engine is strongly affected. Most of the studies have been focused on passive techniques and uses various inserts and different nanofluids. However, heat transfer augmentation in conventional car radiator using different nanofluids has been performed very often. Apart from that, use of artificial roughness has been seldom done. Therefore, in the present work computational study of roughened automobile radiator tubes with Al_2O_3 based nanofluid has been performed.

2. CFD Modelling

Fig. 1(a) shows the actual geometry of the car radiator which is considered for the present problem. It consists of the flat tubes since they offer low resistance to the surrounding air in comparison circular cross-section tubes. The horizontal fins are present between the vertical flat tubes. However, to reduce the computational cost and time, in the present work, only the single flat tube is considered and furthermore simulation has been performed for vertically halved portion to take the advantage of symmetry in the model as shown in figure.

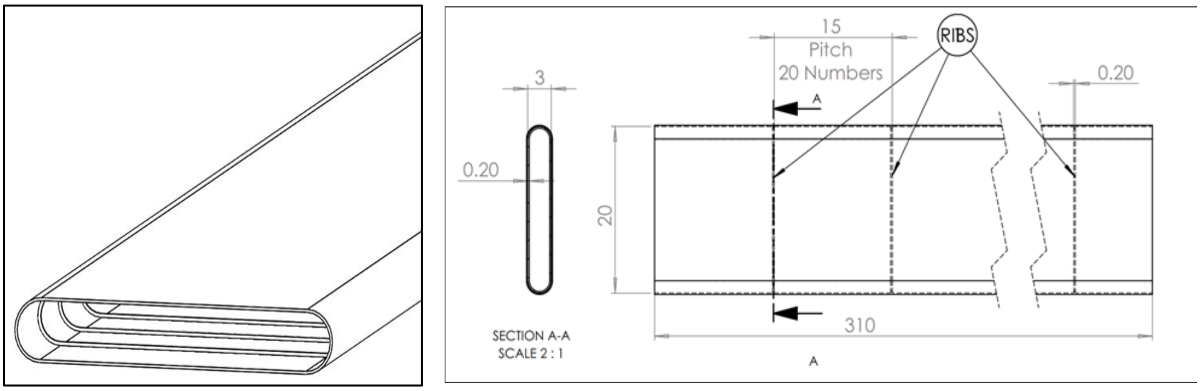
Fig. 1(b) shows half of the single flat tube simulated in this study with specifications. The length of the flat tube is 310 mm. The width and height of the flat tube's cross-section are 3 mm and 20 mm respectively. The ribs were wrapped all around the inside wetted face of the flat tube.

Total of 20 ribs were placed in the radiator tube along its length and ribs are having a pitch of 15 mm as depicted in Fig. 2. The isometric view and specifications of the ribbed geometry is depicted in Fig. 2(a) and Fig. 2(b), respectively.



(a) (b)

Fig. 1. (a) Actual model of the car radiator (b) Computational domain of single flat radiator tube (axis symmetric view)



(a) (b)

Fig. 2. Ribbed flat tube configuration (a) isometric view (b) Side and top view with specification

The continuity, momentum and energy equations for single phase flow are shown below:

Conservation of mass:

$$\nabla.\left(\rho_{eff}\vec{u}\right) = 0 \tag{1}$$

Conservation of momentum:

$$\nabla.\left(\rho_{eff}\vec{u}\vec{u}\right) = -\nabla P + \nabla.\left(\mu_{eff}\nabla\vec{u}\right) - (\rho\beta)_{eff}(T - T_0)g \tag{2}$$

Conservation of energy:

$$\nabla.\left((\rho C_p)_{eff}\vec{u}T\right) = \nabla.\left(k_{eff}\nabla \mathrm{T}\right) \tag{3}$$

where, ρ, C_p, k, μ shows fluid density, specific heat, thermal conductivity and dynamic viscosity, respectively. While, the subscript eff is used for denoting effective value of nano fluid. $\vec{u}$ is the velocity vector.

The heat transfer coefficient (CFD) and the corresponding Nusselt number can be calculated using the expressions shown below:

$$h_{nf}(CFD) = \frac{\rho_{nf}(A_t V_t)C_{p,nf}(T_{in} - T_{out})}{A_p(T_b - T_w)} \tag{4}$$

$$Nu_{nf}(CFD) = \frac{h_{nf}(CFD)d_h}{k_{nf}} \tag{5}$$

where, T_w is the weighted average temperature of the solid surface of tube which in interacting with the working fluid and is calculated directly from the FLUENT module of ANSYS. T_b is the bulk temperature and is calculated as

$$T_b = \frac{T_{in} + T_{out}}{2} \tag{6}$$

where, T_{in} and T_{out} *is* inlet and outlet temperature of the working fluid.

Nusselt number enhancement for ribbed radiator tube has also been calculated with respect to the flat or plain radiator tube for different nano particle concentrations. It has been calculated as:

$$Nu\ enhancement = \frac{Nu(ribbed\ \ tube) - Nu(flat\ tube)}{Nu(flat\ tube)} \times 100\% \tag{7}$$

Pressure drop has been calculated as the difference of pressure values at inlet and outlet of the tube. Further, pumping power required for the fluid circulation in the flat/ribbed tube is calculated as product of mass flow rate with pressure drop.

The thermo-physical properties of nano fluid i.e. density, specific heat, thermal conductivity, and viscosity were obtained using following expressions:

Density of nano fluid has been calculated by the expression given by Pak and Cho [17]

$$\rho_{nf} = \varphi\rho_p + (1 - \varphi)\rho_{bf} \tag{8}$$

where, subscript p, bf and nf represents nano particles, base fluid and nano fluids. φ denotes the particle concentration.

Specific heat capacity of nanofluid was evaluated from the expression by Xuan and Roetzel [18]

$$Cp_{nf} = \frac{\emptyset\rho_p Cp_p + (1 - \varphi)\rho_{bf}Cp_{bf}}{\rho_{nf}} \tag{9}$$

While, thermal conductivity has been calculated by Hamilton model [19]

$$k_{nf} = \frac{k_p + (\Phi{-}1)k_{bf} - \varphi(\Phi - 1)(k_{bf} - k_p)}{k_p + (\Phi{-}1)k_{bf} + \varphi(k_{bf} - k_p)} \tag{10}$$

where, $\emptyset$ is empirical shape factor given by $\Phi = 3/\Psi$. Ψ is the particle sphericity of nano-particle which is measured as the ratio of surface area of a sphere that has same volume as the nano-particle to the actual surface area of the nano-particle. Since the shape of the particle considered in this study is spherical therefore the particle sphericity will come out to be 1. Hence the empirical shape factor considered in this study is 3.

The effective viscosity of nanofluid has been determined by Masoumi et al. [20]

$$\mu_{nf} = \mu_{bf} + \frac{\rho_p V_B d_p^2}{72C\delta} \tag{11}$$

where V_B is the Brownian motion velocity

The thermo-physical properties considered for the base fluid and nano particles are tabulated in Table.1 For *turbulence* modelling, the k-epsilon turbulence model with enhanced wall treatment has been employed. SIMPLE algorithm was applied to resolve the pressure-velocity coupling while all the equations are discretized using second order formulations.

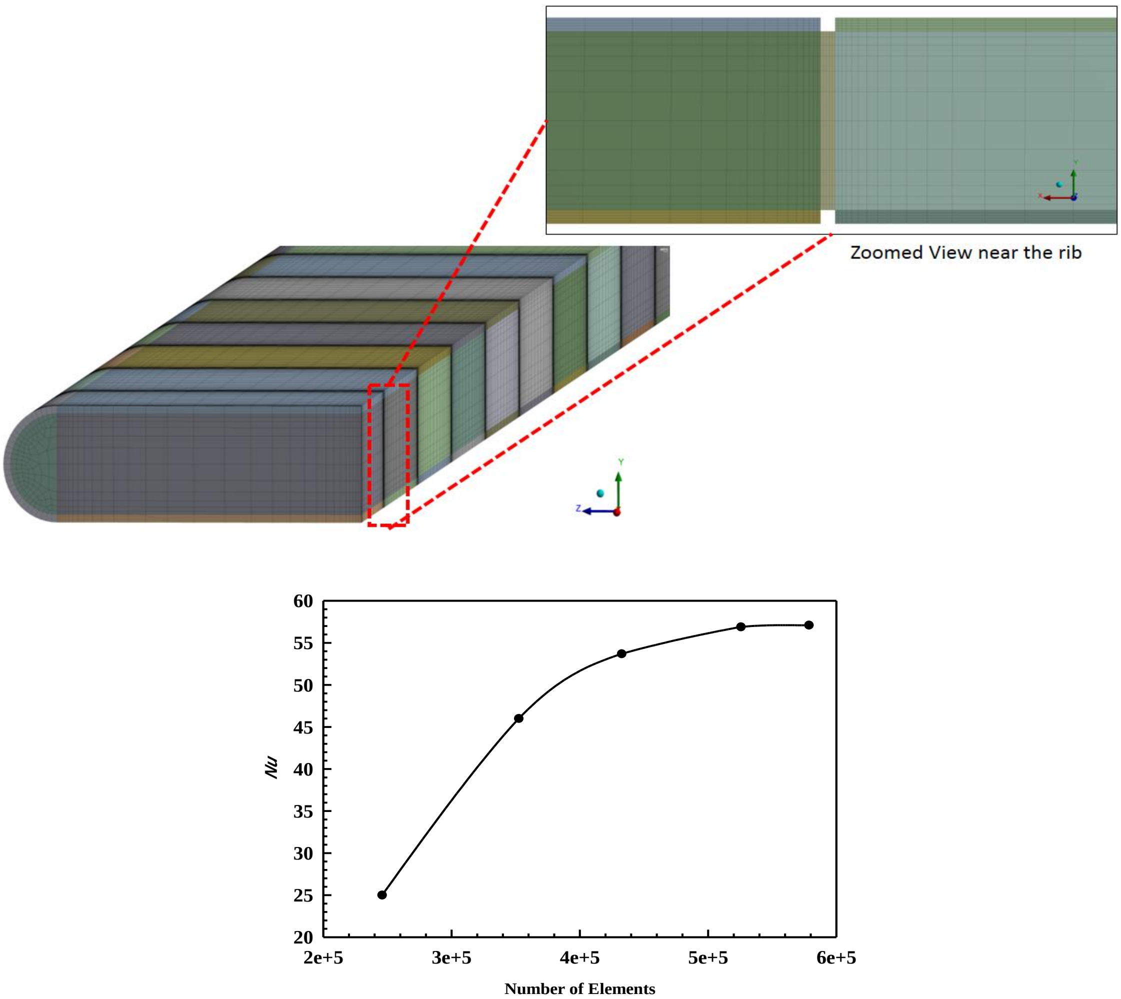
Table 1. Thermo-physical properties of base fluid (Water) and nano particles (Al_2O_3)

Properties	**Base fluid (Water)**	**nano particles (Al_2O_3)**
Density (kg/m^3)	988	3970
Dynamic Viscosity (kg/m-s)	0.0005468	-
Thermal Conductivity (W/m-k)	0.6436	40
Specific Heat (J/kg-k)	4179.55	765

For both the configurations, a high-quality grid was generated using the slicing technique in ANSYS meshing application. The generated mesh for the ribbed configurations is shown in Fig. 3(a). The orthogonal quality has been maintained above 0.3 and the skewness below 0.77. Small sized elements are created in the region of high gradients i.e. near the walls and ribs.

The grid comprised of hexahedral and wedge shaped elements. Inflation layer also generated around the walls to capture the boundary layer and important feature of the flow. The cell wall distance, y is calculated as 0.0185 mm for y+ of 5. It is the distance of the cell centre of the first layer of elements from the wall. Therefore, the thickness of first layer of inflation layer is taken as 0.04 mm to achieve y+ of 5 at the wall.

Fig. 3(b) shows the variation of Nusselt number with number of elements for *Re* = 9350 for conventional radiator tube configuration. Total of five different cases has been considered in the grid independence test. It has been observed that last two grids has shown less than 1% variation in Nusselt number, so grid size having 525605 number of elements has been used in further study.



(a)

(b)

Fig. 3. (a) Grid generated for the ribbed flat tube configuration (b) Variation of Nusselt number in conventional radiator tube configuration with number of elements for Re = 9350

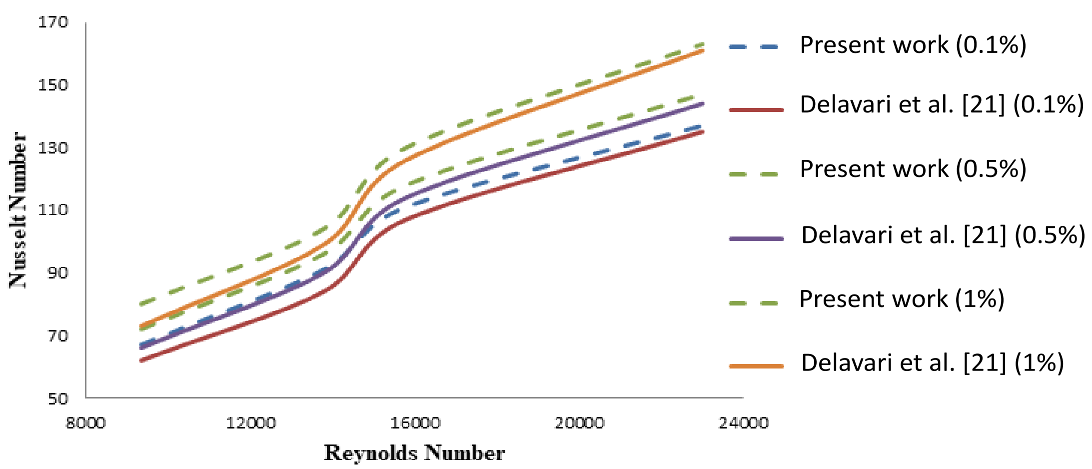
3. Validation

The present CFD model has been validated by comparing the results with published results of Delavari et al. [21] as depicted in Fig. 4(a). The validation has been performed under turbulent regime (Reynolds 9000-23000) for Al_2O_3 based nanofluid with different particle concentrations (0.1, 0.5 and 1%). From the comparison, it is found that results obtained though CFD model has good agreement with publish results and the variation is not more than 8%. Furthermore, present work was also validated with the Nusselt number correlations provided by Dittus-Boelter and Gnielinski. The comparisons of Nusselt number value calculated from present study and correlations were shown in Fig. 4(b). It was observed that average percentage error between the present results and Dittus-Boelter correlations is 13.53%, while for Gnielinski correlation, the deviation of 3.1% was observed.

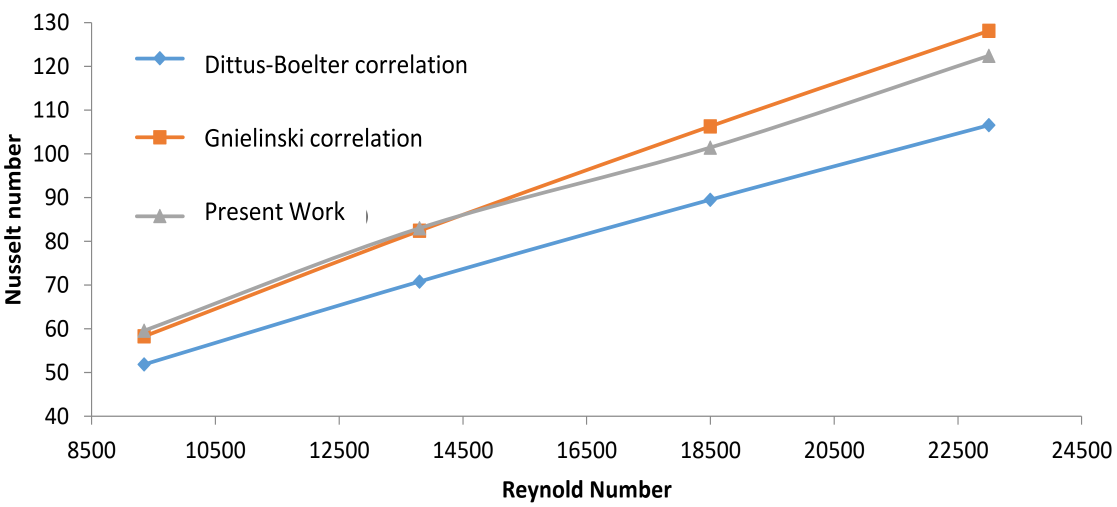
4. Result & Discussion

Fig. 5 (a & b) shows the velocity contours in the radiator tube with artificial roughness in the form of ribs. Fig. 5 (a) represents the results for the Reynold number of 9350 and Fig. 5 (b) represents the results for the Reynold number of 23000. Two extreme values of *Re* was considered for better understanding of flow physics. It can be observed that the artificial roughness has broken the laminar sub-layer region of the boundary layer at the walls and created a recirculation zone behind the ribs. This has helped to increase the heat transfer rate in the ribbed radiator tube configurations.

Fig. 6 (a & b) shows the contours of turbulent kinetic energy (TKE) in the ribbed radiator tube. Fig. 6 (a) represents the TKE contour for the Reynold number 9350 and Fig. 6 (b) represents the TKE results for the Reynold number 23000.

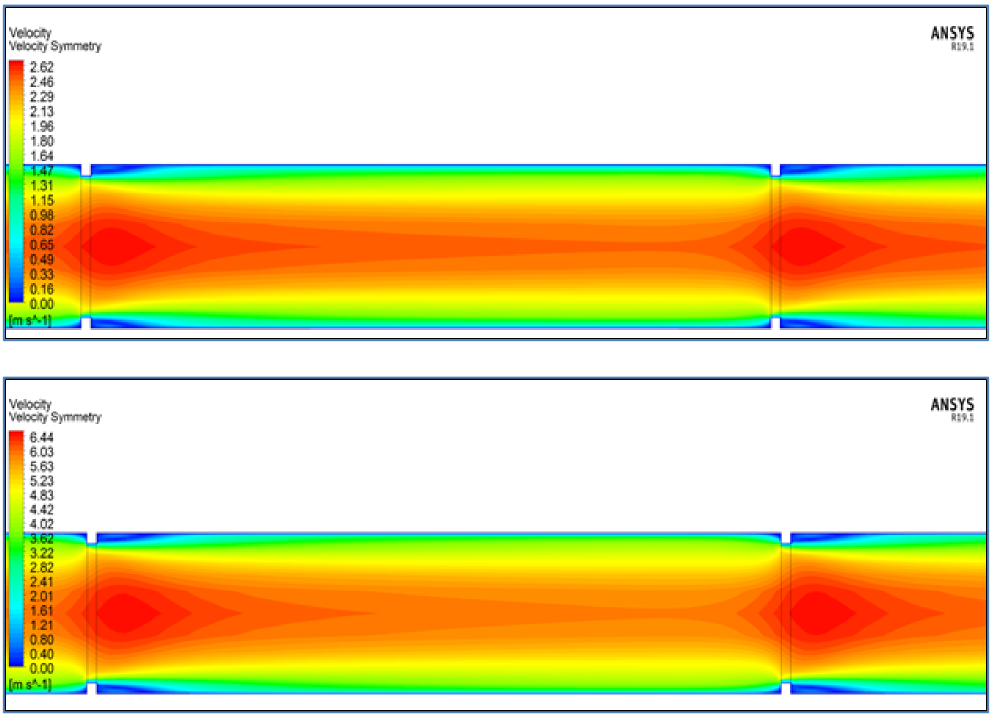


(a)



(b)

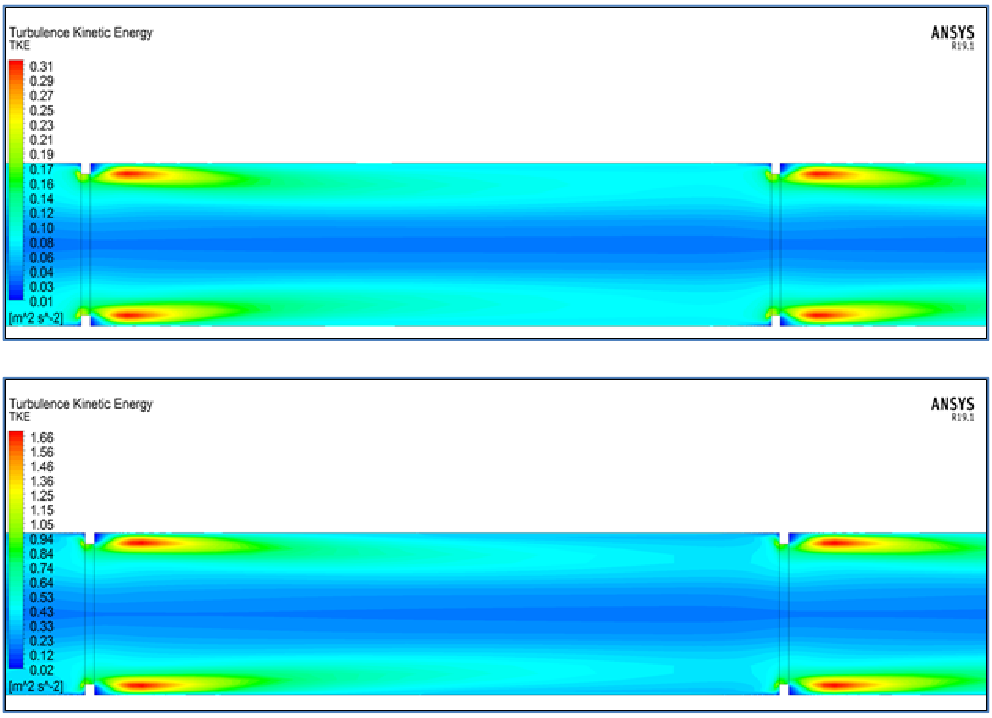
Fig. 4. (a) Comparison of present work with Delavari et al. [21] (b) Comparison of the Nusselt numbers calculated using correlations and from present work



(a)
Re = 9350

(b)
Re= 23000

Fig. 5. Velocity contours at 1% nano-fluid concentration for (a) *Re* = 9350 (b) *Re* =23000



(a)
Re = 9350

(b)
Re= 23000

Fig. 6. Turbulent Kinetic Energy contours at 1% nano-fluid concentration for (a) *Re* = 9350 (b) *Re* =23000

Fig. 7 shows the variation of the Nusselt number with Reynold number in a conventional radiator tube and radiator tube with artificial roughness. The results are shown for different concentration of nanofluids (0.1 to 1%) for the turbulent flow regime (Reynolds number ranging from 9350 to 23000).

It can be observed from the figure that Nusselt no. increases with the Reynold number in both conventional radiator tube and ribbed radiator tube configurations. It is also clear from the figure that the heat transfer significantly improved with the use of artificial roughness. Similar observation was reported by Yadav and his group [22-24] in case of solar air heaters. Apart from that, the effect of nanofluid concentration on Nusselt number can be seen.

Fig. 8 represents variation of percentage enhancement of Nusselt number with Reynold number for ribbed radiator tube. The results are shown for different concentration of nanofluids (0.1 to 1%) for the turbulent flow regime (Reynolds number ranging from 9350 to 23000). It can be observed from figure that percentage enhancement in Nusselt number is more at lower Reynolds and then it decreases with increase in Reynolds number. For 1 % nanofluid, the heat transfer enhancement at Reynolds 9350 is about 79% and at Reynolds 23000 it is around 18 % which is lowest. At Reynolds 15500, all the three curves (0.1, 0.5 and 1.0%) intersect each other which indicates same enhancement at that location.

The hydraulic performances for both radiator configurations are evaluated with the help of pressure drop and pumping power requirement. Fig. 9 shows the variation of the pressure drop with Reynold number in a flat radiator tube with and without artificial roughness. The results are shown for different concentration of nanofluids (0.1 to 1%) for the turbulent flow regime (Reynolds number ranging from 9350 to 23000). It can be observed from the plot that ribbed tube has higher pressure drop compared to flat plat tube. This is attributed to increase in flow obstruction. Moreover, it can also be pointed that with increase in nano particle concentration, the pressure drop increases. Similar trend was observed for pumping power in Fig. 10.

To assess the overall thermal performance of all configurations, various parameters has been used. It is commonly observed that with increase in heat transfer characteristics, pressure drop penalty also increases. Therefore, to evaluate the overall performance the parameter thermo-hydraulic performance factor (*TPF*) has been evaluated [25-28]. Fig. 11 shows the variation of *TPF* with *Re* for all configurations. The base case considered for evaluation of *TPF* is flat radiator tube with 0.1% nano fluid concentration. Among all the cases, ribbed radiator tube with 0.1% nano particle concentration has yielded best performance.

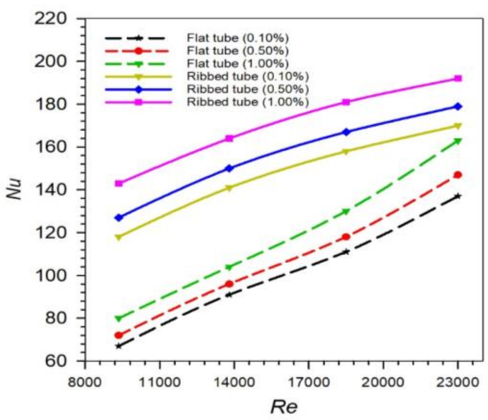


Fig. 7. Nusselt number variation for radiator tube with and without roughness

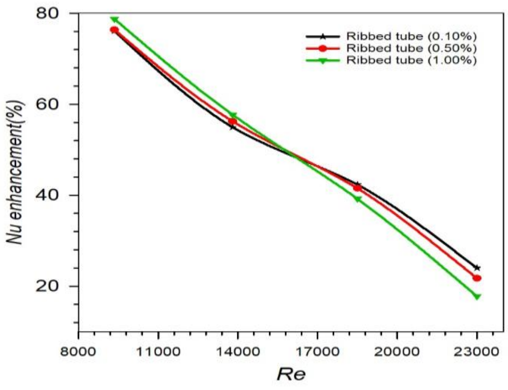


Fig. 8. Nusselt number enhancement percentage for ribbed flat tube configurations

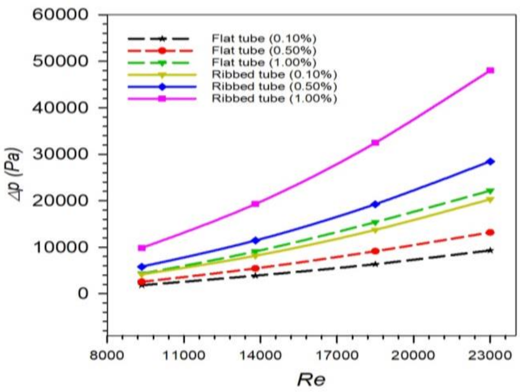


Fig. 9. Variation of pressure drop with Reynold number

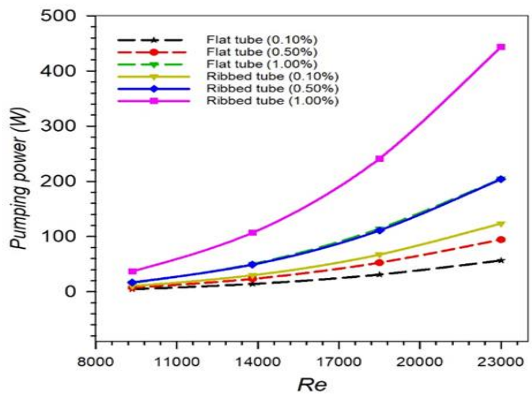


Fig. 10. Variation of pumping power with Reynold number

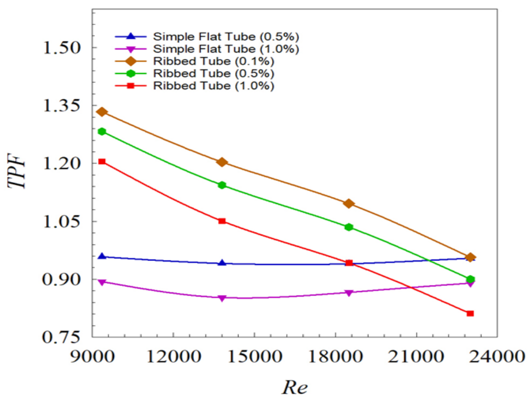


Fig. 11. Variation of TPF with Re for all configurations

Conclusion

In the present work, artificial roughness in the form of ribs has been provided in the simple flat tube of the car radiator. The water and Al_2O_3 nano-particles based nanofluid is used as a coolant for the study, with particle concentration varied between 0.1 - 1.0 %. The Reynolds number of the flow has been simulated in the range of 9350-23000. The Nusselt number and pumping power for all the configurations were studied in details. Following conclusions were drawn from the study:

1. For any configuration of the flat radiator tube (simple, or ribbed), the heat transfer coefficient increases with the increase in Reynolds number.
2. The heat transfer rate also increases with increase in nano-particle concentration from 0.1 to 1.0%.
3. On increasing the Reynolds number or nano-particle concentration the pumping power also increases significantly.
4. The application of artificial roughness in the form of ribs can increase the heat transfer coefficient as compared to that of simple flat tube for a particular Reynolds number.
5. For ribbed flat tube, the heat transfer enhancement is highest (79%) at *Re* = 9350 and lowest (18%) at *Re* = 23000 for nanofluid concentration of 1%.
6. For a constant heat flux, the required pumping power can be increased by up to 67% if ribs are employed in the conventional radiator tube at nano-fluid concentration of 1%.

Nomenclature

At	Cross sectional area of flat tube [mm^2]
Ap	Heat transfer area [mm^2]
Cp	Heat capacity [J/kgK]
C	Correction factor
dh	Hydraulic diameter [mm]
dp	Particle diameter [mm]
hnf	Heat transfer coefficient [W/m^2K]
K	Thermal conductivity [W/mK]
Nu	Nusselt number
Tw	Average wall temperature of flat tube [K]
Tb	bulk temperature [K]
Tin	Inlet temperature [K]
Tout	Outlet temperature [K]
$\vec{u}$	Velocity vector [m/s]
Vt	Velocity at the inlet of flat tube [m/s]
Δp	Pressure drop [N/m^2]

Greek symbols

ρ	Density [kg/m^3]
μ	Dynamic viscosity [kg/ms]
∅	Empirical shape factor
Ψ	Particle sphericity of nano-particle
δ	Distance between the nano particles [nm]

Subscript

nf	Nano fluid
bf	Base fluid
p	Nano particle

References

[1] Goudarzi, K. and Jamali, H., 2017. Heat transfer enhancement of Al_2O_3-EG nanofluid in a car radiator with wire coil inserts. *Applied Thermal Engineering*. 118, pp.510-517.

[2] Arora, N. and Gupta, M., 2020. An updated review on application of nanofluids in flat tubes radiators for improving cooling performance. *Renewable and Sustainable Energy Reviews*. 134, pp.110242.

[3] Naddaf, A., Heris, S.Z. and Pouladi, B., 2019. An experimental study on heat transfer performance and pressure drop of nanofluids using graphene and multi-walled carbon nanotubes based on diesel oil. *Powder Technology*, 352, pp.369-380.

[4] Pak, B. C. and Cho, Y. I., 1998. Hydrodynamic and heat transfer study of dispersed fluid with sub-micron metallic oxide particles. *Experimental Heat Transfer*, 11, pp.151-170.

[5] Choi, S. U. and Eastman, J. A., 1995. Enhancing thermal conductivity of fluids with nanoparticles. Argonne National Lab., IL (United States).

[6] Ahmed, S. A., Ozkaymak, M., Sözen, A., Menlik, T. and Fahed, A., 2018. Improving car radiator performance by using TiO2-water nanofluid. *Engineering science and technology an international journal*. 21(5), pp.996-1005.

[7] Naraki, M., Peyghambarzadeh, S. M., Hashemabadi, S. H. and Vermahmoudi, Y., 2013. Parametric study of overall heat transfer coefficient of CuO/water nanofluids in a car radiator. *International Journal of Thermal Sciences.* 66, pp.82-90.

[8] Heris, S. Z., Shokrgozar, M., Poorpharhang, S., Shanbedi, M. and Noie S. H., 2014. Experimental study of heat transfer of a car radiator with CuO/ethylene glycol-water as a coolant. *Journal of dispersion science and technology*, 35(5), pp.677-684.

[9] Naraki, M., Peyghambarzadeh, S. M., Hashemabadi, S. H. and Vermahmoudi, Y., 2013. Parametric study of overall heat transfer coefficient of CuO/water nanofluids in a car radiator. *International Journal of Thermal Sciences*. 66, pp.82-90.

[10] Bhogare, R. A. and Kothawale, B. S., 2014. Performance investigation of automobile radiator operated with Al_2O_3 based nanofluid. IOSR Journal of Mechanical and Civil Engineering. 11(3), pp.23-30.

[11] Nambeesan, K. P., Parthiban, R., Kumar, K. R., Athul, U. R., Vivek, M. and Thirumalini, S., 2015. Experimental study of heat transfer enhancement in automobile radiator using Al_2O_3/water-ethylene glycol nanofluid coolants. *International Journal of Automotive & Mechanical Engineering*. 12, pp. 2857-2865.

[12] Dhale, L. P., Wadhave, P. B., Kanade, D. V. and Sable, Y. S., 2015. Effect of nanofluid on cooling system of engine. *International Journal of Engineering and Applied Sciences.* 2(10), pp.257815.

[13] Senthilraja, S., Vijayakumar, K. C. and Gangadevi, R., 2015. Experimental investigation of Heat transfer performance of different nanofluids using automobile radiator. In: Applied mechanics and materials, vol. 787, Trans Tech Publications Ltd, pp. 212–216.

[14] Chougule, S. S., Nirgude, V. V., Gharge, P. D., Mayank, M. and Sahu, S. K., 2016. Heat transfer enhancements of low volume concentration CNT/water nanofluid and wire coil inserts in a circular tube. *Energy Procedia.* 90, pp.552-558.

[15] Singh, B. P., Bisht, V. S., Bhandari, P. and Rawat, K. Thermo-Fluidic Modelling of a Heat Exchanger Tube with Conical Shaped Insert having Protrusion and Dimple Roughness. *Aptisi Transactions on Technopreneurship*. 3(2), pp.13–29.

[16] Singh, B. P., Bisht, V. S. and Bhandari, P., 2021. Numerical Study of Heat Exchanger Having Protrusion and Dimple Roughened Conical Ring Inserts In Advances in Fluid and Thermal Engineering, Lecture Notes in Mechanical Engineering. pp. 151-161.

[17] Pak, B. C. and Cho, Y. I., 1998. Hydrodynamic and Heat Transfer Study of Dispersed Fluids with Submicron Metallic Oxide Particles. *Experimental heat transfer*. 11(2), pp. 151–170.

[18] Xuan, Y. and Roetzel, W., 2000. Conceptions for Heat Transfer Correlation of Nanofluids. *International journal of heat and mass transfer.* 43(19), pp. 3701–3707.

[19] Hamilton, R. L. and Crosser, O. K., 1962. Thermal conductivity of heterogeneous two-component systems. *Industrial and Engineering Chemistry Fundamentals*. 1(3), pp. 187–191.

[20] Masoumi, N., Sohrabi, N. and Behzadmehr, A., 2009. A new model for calculating the effective viscosity of nanofluids. *Journal of Physics D: Applied Physics,* 42(5), pp.055501.

[21] Delavari, V. and Hashemabadi, S. H., 2014. CFD simulation of heat transfer enhancement of Al_2O_3/water and Al_2O_3/ethylene glycol nanofluids in a car radiator. *Applied Thermal Engineering.* 73, pp.378-388.

[22] Yadav, A. S., Shukla, O. P. and Bhadoria, R. S., 2022. Recent advances in modelling and simulation techniques used in analysis of solar air heater having ribs. *Materials Today: Proceedings*. 62(3), pp.1375-1382.

[23] Yadav, A. S. and Gattani, A., 2022. Revisiting the influence of artificial roughness shapes on heat transfer enhancement, *Materials Today: Proceedings*. 62(3), pp. 1383-1391.

[24] Yadav, A. S., Agrawal, A., Sharma, A., Sharma, S., Maithani, R. and Kumar, A., 2022. Augmented artificially roughened solar air heaters, *Materials Today: Proceedings*. 63, pp. 226-239.

[25] Bhandari, P., 2022. Numerical investigations on the effect of multi-dimensional stepness in open micro pin fin heat sink using single phase liquid fluid flow. *International Communications in Heat and Mass Transfer*. 138, pp.106392.

[26] Bhandari, P. and Prajapati, Y. K., 2021. Fluid flow and heat transfer behaviour in distinct array of stepped micro pin fin heat sink. *Journal of Enhanced heat transfer*. 28(4), pp. 31-61.

[27] Bhandari, P., Prajapati, Y. K. and Uniyal, A., 2022, Influence of three dimensionality effects on thermal hydraulic performance for stepped micro pin fin heat sink. *Meccanica*. 2022.

[28] Bhandari, P. and Prajapati, Y. K., 2022. Influences of tip clearance on flow and heat transfer characteristics of open type micro pin fin heat sink. *International Journal of Thermal Sciences*. 179, pp.107714.