



REGULAR ARTICLE

The Effect of Nanofluid Concentration and Flow Profile on Heat Transfer

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In order to assess the profitability of an energy system, various factors such as fluid nature, geometry shape, and operating conditions must be considered. This study focuses on the impact of sinusoidal rib shapes, with different values of space ratio (e/b) ranging from 0 to 1, on heat transfer in nanofluid flow. The channel's upper surface is subject to a uniform heat flux, with Al_2O_3 Nanofluid as the working fluid and Reynolds numbers ranging from 5000 to 20000. The effect of the volume fraction of aluminum nanoparticle, ranging from 0 to 6 %, is also analyzed. The simulation results demonstrate that the performance of the channel's corrugated surface is greatly influenced by rib shapes and their geometrical parameters. The highest Performance Evaluation Criteria index (PEC) is obtained for ribs with a space ratio (e/b) of 0 at $\text{Re} = 5000$ and at 6 % volume fraction. Furthermore, the average Nusselt number increases with an increase in particle volume fraction and Reynolds.

Keywords: Nanofluid, Geometric factor, Turbulent flow regime, Nanoparticle volume fraction, Heat convective transfer.

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1. INTRODUCTION

Energy systems used for thermal applications, such as heating water systems, solar air conditioning, drying agro-alimentary products, and refrigeration machines, require materials that optimize their efficiency [1-3]. In particular, the area that limits fluid flow in heat exchangers plays a crucial role in their performance. To improve this performance, coefficients of convective transfer between the absorber layer and fluid must be optimized while reducing the load loss among heat exchanger components [4, 5]. Over the years, various energetic systems have been developed in the industry, which rely on introducing solid particles of high thermophysical properties, such as aluminum oxide (Al_2O_3), to the basic fluid, and modifying the internal surface of the fluid channel, to achieve high heat transfer [4, 5].

The aim of this numerical investigation is to analyze turbulent flow of Al_2O_3 nanofluid in a mini-channel with a sinusoidal rib-shaped wall. The study examines the effects of nanoparticle concentration and Reynolds number, ranging from 5000 to 20000, on critical factors such as the mean Nusselt number, coefficient of friction, and performance index for both water and nanofluid.

2. GEOMETRY AND THERMOPHYSICAL PROPERTIES OF NANOFLUIDS

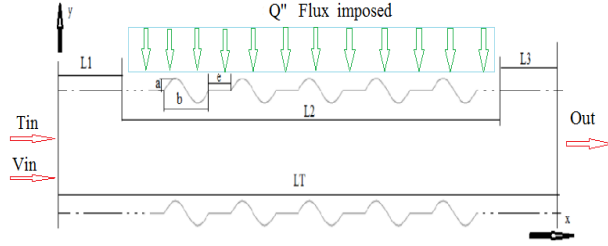
The geometry represented in Fig. 1 is the field of study of this numerical research, it considered as horizontal tube with inner hydraulic diameter $D_h = 10$ mm and a total length $L_T = 340$ mm. In the purpose of enhancing the heat transfer and flow behavior of water/ Al_2O_3 nanofluid in the studied geometrics, the sinusoidal shapes of rib of the inner surface of the wall had been used. The uniform heat flux (Q'') equal to 10^4 W/m^2 parallel to the Y axis is imposed on the channel wall of the test section which has a length $L_2 = 108$ mm, the channel inlet length $L_1 = 200$ mm, and the exit section has the length of $L_3 = 32$ mm. The space ratio (e/b) equal to 0, 0.25, 0.5 and 1 mm are studied. The inlet temperature of working fluid is $T_{in} = 300$ K, and inlet velocity changes based on varying Reynolds number ranging from 5000 to 20000, with a volume fraction of aluminum nanoparticle ranging from 0 to 6 %. The sinusoidal function used for drawing the corrugate shape of the wall of the ribs is written as following:

$$y = a \sin(2\pi(x/b)) \quad (1)$$

where $a = 1$ (mm) and $b = 6$ (mm).

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**Fig. 1** – Studied configuration

We take note that:

- If the ratio ($e/b = 1$) it means that $e = b$.
- If the ratio ($e/b = 0.5$) it means that $e = b/2$.

This work analyzes a new displacement model for sandwich plates on an elastic foundation under various thermal loads. Analytical solutions are presented using a New High Order Theory (HSDT).

A simply to calculate the thermophysical properties of nanofluid such as density, specific heat, dynamic viscosity and thermal conductivity by considering the effects of nanoparticles and base fluid, the following equations are used [6].

Density:

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_{np} \quad (2)$$

Specific heat:

$$(\rho C_p)_{nf} = (1 - \phi)(\rho C_p)_f + \phi(\rho C_p)_{np} \quad (3)$$

Where $(\rho C_p)_f$ and $(\rho C_p)_{np}$ are heat capacities of the based fluid and the solid nanoparticles, respectively

Dynamic viscosity:

$$\mu_{nf} = \mu_f (123\phi^2 + 7.3\phi + 1) \quad (4)$$

Thermal conductivity:

$$k_{nf} = k_f (4.97\phi^2 + 2.72\phi + 1) \quad (5)$$

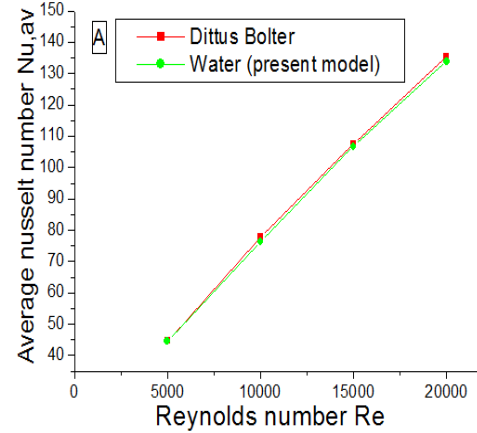
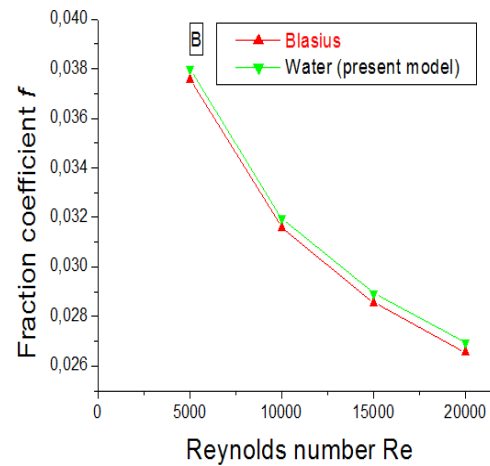
Table 1 below present properties of the nanofluid used in this study.

Table 1 – The properties of nanofluids [7]

	ϕ	ρ	μ	C_p	k
Type of fluid	%	Kg/m ³	MPa.s	J/Kg.K	W/m.K
Pure water	0	997.7	0.949	4178.90	0.600
Al ₂ O ₃ /water	1	1027.4	1.020	4046.96	0.617
	2	1057.2	1.130	3922.46	0.635
	4	1116.6	1.410	3695.36	0.671
	6	1176	1.780	3487.42	0.709

3. CODE VALIDATION

The numerical results have been validated with correlations of Dittus–Boelter and Blasius, respectively in terms of average Nusselt number and friction coefficients. The results are plotted in Fig. 2(a) and Fig. 2 (b).

**a****b****Fig. 2** – Comparison of present results with equations of (a) Dittus–Boelter and (b) Blasius. (Working fluid is the Water)

Dittus–Boelter correlation: [8].

$$Nu_s = 0.023 Re^{0.8} Pr^{0.4} \quad (6)$$

Correlations of Blasius

$$f = 0.316 Re^{-0.25} \quad (7)$$

For ($3 \times 10^3 < Re < 2 \times 10^4$)

The comparison between the results of this study and previous works shows that the present numerical simulation is accurate because the results are in good agreement with the previous studies.

4. RESULTS AND DISCUSSION

The results reported in terms of average Nusselt number, friction coefficient, performance evaluation criteria index, as a function of Reynolds number ranging from 5000 to 20000, roughness pitch values from $e/b = 0$ to 1, and particle volume concentrations of 1 %, 2 %, 4 % and 6 %.

4.1 Results of Water Working Fluid

The variation of the Nusselt number profiles as a function of Reynolds number and space ratio e/b is presented in Fig. 3, the water is used as working fluid. It can be seen that the Nusselt number increases with the increase in Reynolds number for all values of space ratio e/b in comparison with the smooth channel.

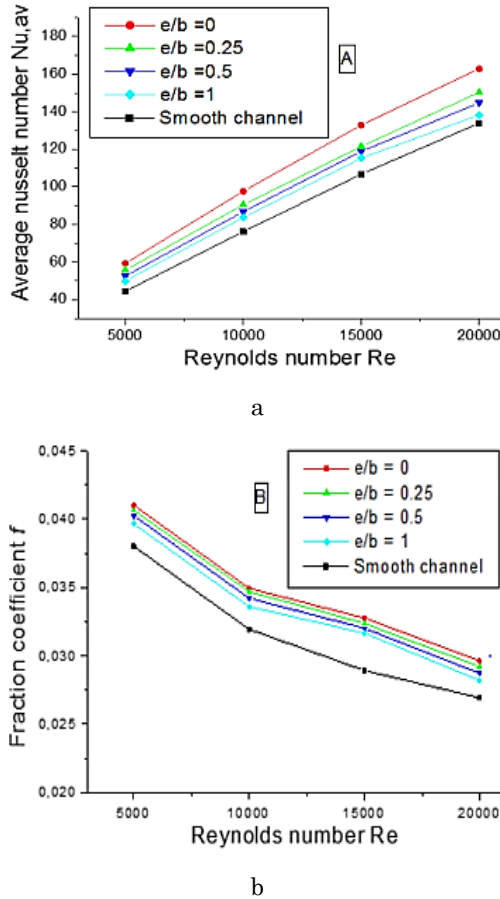


Fig. 3 – Effect of space ratio on Average Nusselt number (a), friction factor (b), (Working fluid is the Water)

In Fig. 3 (a) the results show that the Nusselt number increases with 48,65 % in case the space ratio $e/b = 0$ and 31,21 %, 24,86 %, 18,68 %, in cases $e/b = 0.25$, $e/b = 0.5$, $e/b = 1$ respectively. Thus, in Fig. 3 (b) we notice that there is an inverse relationship between friction coefficient and Reynolds number, the increase of the latter leads to the reduction in the coefficient of friction, the maximum values of the friction coefficient are noted for the space ratio case $e/b = 0$, where $f = 0,041$ for Reynolds number $Re = 5000$.

4.2 Results of Al_2O_3 -Water Mixture (Nanofluid) Working Fluid

Case Smooth Channel

Fig. 4 shows the evaluation of the average Nusselt number in smooth channel with different volume fraction

of nanoparticles, and Reynolds number.

In influenced by the presence of Aluminum particles in the water with different concentrations. It is clearly shown that the heat transfer mechanism improves by increasing volume fraction of nanoparticles.

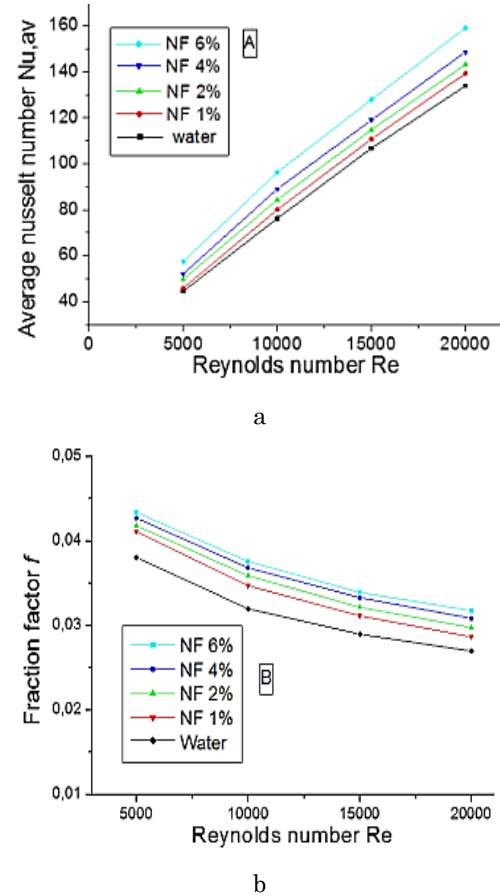
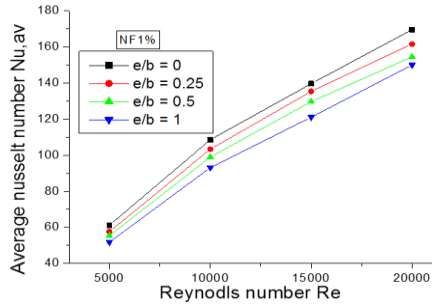


Fig. 4 – Effect of different volume fraction nanoparticles with different Reynolds numbers on average. (a) Nusselt number, (b) friction factor (Case smooth channel Al_2O_3 -water mixture)

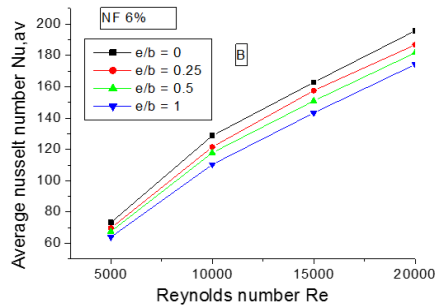
In Fig. 4(a), the average Nusselt number increases as Reynolds number increases, also that this quantity influenced by the presence of Aluminum particles in the water with different concentrations. It is clearly shown that the heat transfer mechanism improves by increasing volume fraction of nanoparticles. The Fig. 4(b) shows the variation of friction factor with Reynolds number for different volume fraction of nanoparticles. It is seen that the particle volume concentrations of $\phi = 0.06$ has the highest effect on friction factor and it is followed by $\phi = 0.04$, 0.02 and 0.01 respectively, and it is high at lower Reynolds number $Re = 5000$. The results of this investigation study also shows that the average Nusselt number increases with 21.54 % in case $\phi = 0.06$ in comparison with $\phi = 0.04$, 0.02 and 0.01 where the height of values of Nusselt number is 21.54 %, 16.16 %, 10.18 % and 8.86 % respectively.

Case Channel with Ribs

The combined effect of space ratio of ribs, ϕ values on the average Nusselt number, and friction factor are presented in Fig. 5 and Fig. 6.

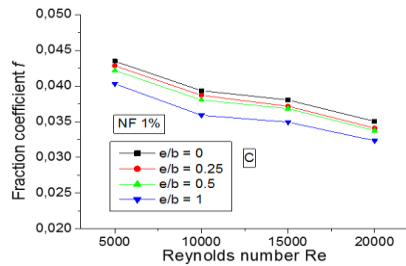


a

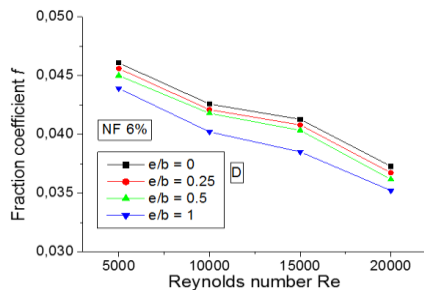


b

Fig. 5 – Effect of space ratio with different Reynolds numbers on average Nusselt number (a) NF 1 %, (b) NF 6 %



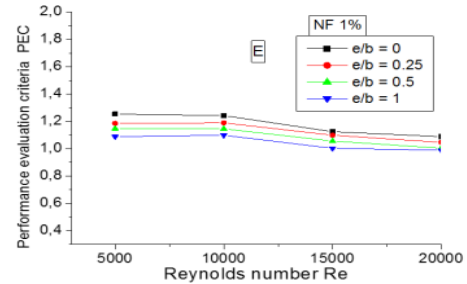
a



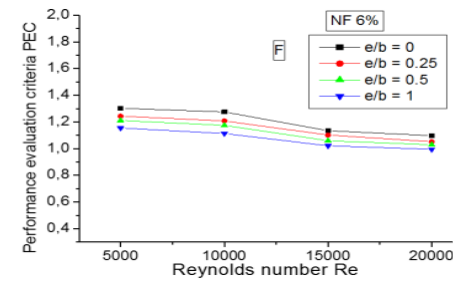
b

Fig. 6 – Effect of space ratio with different Reynolds numbers on fraction factor, (a) NF 1 %, (b) NF 6 %

It is observed that the distance between the undulations of ribs of the wall contributed to the reduction of the coefficient of friction. However, the average Nusselt numbers result enhanced by the employment of ribssurfaces and nanofluids. Also, it is observed that the space ratio $e/b = 0$ has the best heat transfer compared with other space ratios $e/b = 0.25, 0.5$ and 1 respectively.

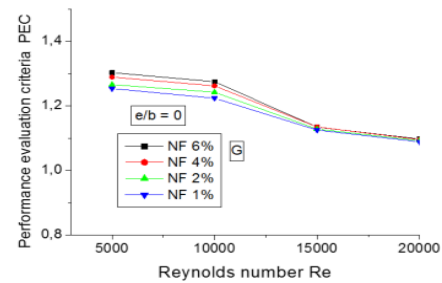


a

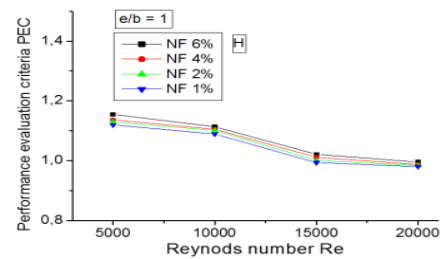


b

Fig. 7 – Effect of space ratio with different Reynolds numbers PEC. (a) NF 1 %, (b) NF 6 %



a



b

Fig. 8 – Effect of volume fraction nanoparticles with different Reynolds numbers PEC, (a) $e/b = 0$, (b) $e/b = 1$

The same indication for the PEC results was noticed in Fig. 7 and Fig. 8. The continuity of undulation ribs of the wall gave optimum performance in terms of thermal and hydraulic behavior. It is noted that the increase in the Reynolds number lead to the lowering of the PFC, as well as the profiles of the variation of PFC are almost identical for the two cases. We noted that the performance evaluation criteria index PEC can be written as following [9].

$$PEC = \frac{(Nu/Nu_0)}{(f/f_0)^{1/3}} \quad (8)$$

Profile of Velocity

In Fig. 9, the axial velocity profile it's plotted for different position of x , 0.218, 0.236, 0.254 and 0.272 (m) respectively, these calculation positions are located in the same test section (L_2). It is observed that there is an increase in the axial velocity values each time the fluid goes deeper into the test channel, it is clear that the fluid flow acceleration is due to the effect of the presence of the wall ribs.

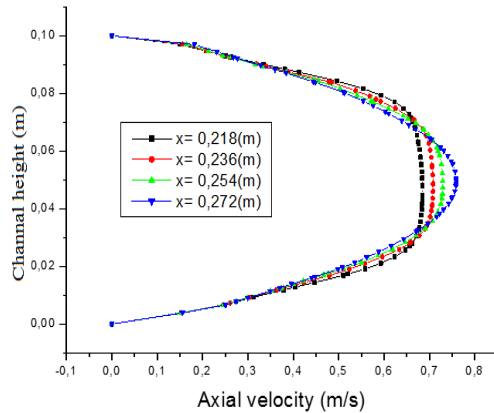


Fig.9 – Axial velocity profile of different position of (x) at $Re = 5000$ for same test section (L_2)

The profiles of static temperature are shown in Fig. 10 for different values of Reynolds number ranging from 5000 to 20000 and fraction volume of thermal en-

hancement factor are found when the Al_2O_3 nanofluid is used in comparison with water as the working fluid. In comparison with the smooth channel the increase in Nusselt number results and pressure drop are obtained by using the ribs wall.

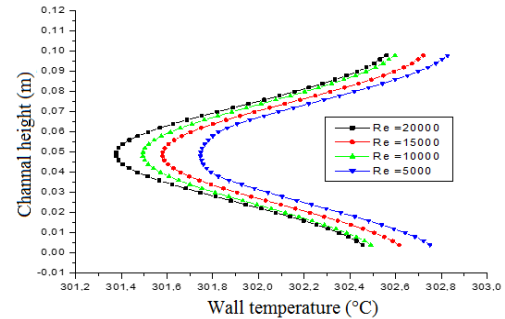


Fig.10 – Profiles of static temperature as function Reynolds number

5. CONCLUSION

In this study, turbulent flows in forced convection within a channel with a ribbed wall and uniformed heat flow were simulated using the finite volume method with the SIMPLE algorithm. The results indicate that utilizing sinusoidal micro-channels with nanoparticles is a more efficient approach for enhancing heat transfer compared to using nanoparticles with the base fluid in smooth micro-channels. The highest Nusselt number values were observed for nanofluid with a concentration of 1 %, with the minimum temperature at the side surfaces of the channel walls and higher values at the channel center, indicating that heat exchange can be intense in areas close to the wall. Furthermore, the friction factor decreases as Reynolds number increases for all channel cases, but increases with higher nanofluid particle concentrations. Lastly, ribbed channels with a rib distance of 0 mm ($e/b = 0$) produced the highest average Nusselt number for all Reynolds numbers.

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Вплив концентрації нанорідин та профілю потоку на теплопередачуB. Litouche¹, B. Rebai², K. Mansouri³, M.L. Cherrad⁴¹ *University Center Abdelhafid Boussouf, Mechanic and ElectroMechanic Department, 43000 Mila, Algeria*² *University of Abbes Laghrour, Civil Engineering Department, 40000 Khenchela, Algeria*³ *University of Abbes Laghrour, Mechanical Engineering Department, 40000 Khenchela, Algeria*⁴ *National Mechanical Research Laboratory, 25000 Constantine, Algeria*

Для оцінки рентабельності енергетичної системи необхідно враховувати різні фактори, такі як природа рідини, геометрична форма та умови експлуатації. Це дослідження зосереджено на впливі синусоїдальних форм ребер з різними значеннями просторового співвідношення (e/b) від 0 до 1 на теплопередачу в потоці нанорідини. Верхня поверхня каналу піддається рівномірному тепловому потоку з нанорідиною Al_2O_3 як робочою рідиною та числами Рейнольдса від 5000 до 20000. Також аналізується вплив об'ємної частки наночастинок алюмінію в діапазоні від 0 до 6 %. Результати моделювання показують, що на характеристики гофрованої поверхні каналу значно впливають форми ребер та їх геометричні параметри. Найвищий індекс критеріїв оцінки продуктивності (PEC) отримано для ребер з просторовим співвідношенням (e/b) 0 при $\text{Re} \leq 5000$ та при об'ємній частці 6 %. Крім того, середнє число Нуссельта збільшується зі збільшенням об'ємної частки частинок та числа Рейнольдса.

Ключові слова: Нанорідина, Геометричний фактор, Турбулентний режим течії, Об'ємна частка наночастинок, Теплоконвективний перенос.