CFD Analysis of Thermal Performance Enhancement in Ribbed Microchannels Using Nanofluids

Simulation CFD de l'amélioration du refroidissement dans des microcanaux nervurés à base de nanofluides

Khadija Madani[1], Rejeb Ben Maad[1]

[1] Laboratoire d'Énergétique et des Transferts Thermique et Massique LETTM, Faculty of Sciences of Tunis, University of Tunis El Manar Tunis, Tunisia, khadijamadani88@gmail.com

ABSTRACT. A 2-D numerical investigation was carried out to study the nanofluid flow and heat transfer inside a horizontal ribbed micro-channel. The alumina oxide nanoparticles were suspended in water as based fluid at different volume fraction 0, 2 and 4%. The finite volume method was used to solve the continuity, momentum and energy equations. The effects of different parameters such as nanoparticles volume fraction, Reynolds number, and the larger of ribs has been reported. It was found that the heat transfer and the Poiseuille number increases with increasing nanoparticles volume fraction and Reynolds number. Using *a small* rib improves the heat transfer. Increasing ribs number enhances the heat transfer rate.

RÉSUMÉ. Une étude numérique bidimensionnelle a été menée afin d'analyser le comportement thermohydraulique d'un écoulement de nanofluide dans un microcanal horizontal nervuré. Des nanoparticules d'oxyde d'aluminium (Al_2O_3) ont été dispersées dans l'eau, utilisée comme fluide de base, pour des fractions volumiques de 0 %, 2 % et 4 %. Les équations de continuité, de quantité de mouvement et d'énergie ont été résolues à l'aide de la méthode des volumes finis. L'influence de plusieurs paramètres, notamment la fraction volumique de nanoparticules, le nombre de Reynolds et la géométrie des nervures, a été examinée. Les résultats ont montré que le transfert de chaleur ainsi que le nombre de Poiseuille augmentent avec la fraction volumique en nanoparticules et le nombre de Reynolds. Par ailleurs, l'ajout de petites nervures contribue à une amélioration notable du transfert thermique.

KEYWORDS. nanofluids, heat transfer coefficient, ribs larger.

MOTS-CLÉS. Nano-fluides coefficient de transfert de chaleur, largeur du nervures, nombre de Nusselt.

1. Introduction

Enhancing convective heat transfer can be reached by the passive or the active method [BER 00]. The passive one consists on enhancing thermal conductivity of the fluid, modifying the flow geometry or boundary conditions. Reduce the flow geometry could be primordial solution to lessen loss energy and raise heat transfer. In this area, it was affirmed the significant advantages of using microchannel in energy conservation and electronic equipment cooling. Tuckerman and Pease [TUC 81] studied the heat transfer in micro-channel. The results showed that using microchannel with 50µm width and 302 µm of depth could efficiency improves the high heat transfer rate of 800w/cm². With reference to the large application of microchannel, research has been carried out to improve the heat transfer mechanism in micro-channel. This improvement could be achieved by improving fluid proprieties because the usual worked fluid has a poor thermal conductivity. Thus, it failed to provide sufficiently the highest heat transfer enhancement requested. Using nanofluid which is a suspending solid particle with diameter less than 100 nm could enhance the thermal conductivity of fluid choi [CHO 95]. Numerous researchers have focused on studying the nanofluid effective thermal conductivity. Mainly, the studies ([YOO 07], [CHO 01]) affirmed that the measured thermal conductivity of nanofluid was higher compared to the classic theoretical predictions [HAM 62]. Experimentally, "MUR 05" found that the effective thermal conductivity of nanofluid increases as nanoparticles volume fraction increase.

Due to the advantage of increasing thermal conductivity, measureless works focused on studying the nanofluid flow and the heat transfer.

Otherwise, many researchers have proved that using rough surface could be a powerful technique to heighten convective heat transfer rate. "DAN 10" has highlighted that employing ribbed surface increases the convective heat transfer. Thereafter, numerous experimental and numerical investigations have explored the impact of using nanofluid as worked fluid in ribbed micro-channel. Laminar nanofluid flow and forced convection in ribbed micro-channel has been reported by Yari Ghale et al [YAR 15]. They found that the presence of ribs in the surface of microchannel led to increase the Nusslet number and the friction factor. "HUH 09" has conducted an experimental investigation to evaluate the impact of tooth height on heat transfer in rectangular channels. Their study revealed that increasing the blockage ratio enhanced the convective heat transfer. "KAR 05" have numerically investigated the nanofluid flow and heat transfer in micro channel. It was found that the heat transfer rate, the friction coefficient and the average nusselt number increase with increasing nanoparticles volume fraction and ribs heights. "AKB 16" conducted a numerical study on nanaofluid forced convection in microchannel. It was showed that increasing the Reynolds number and nanopartilces volume fraction enhances the heat transfer rate. Also, they concluded that the presence of ribs significantly affects of dimensionless temperature and velocity. "SHA 15" have numerically investigated nanofluid turbulent flow and heat transfer trough ribbed-grooved channel. Nanoparticles of Al2O3, CuO and SiO2 were dispersed in water as based fluid at different volume fraction. The finding showed that trapezoidal rib-groove using nanaofluid significantly enhances the heat transfer. Turbulent flow ad heat transfer in two dimensional ribbed channel was investigated by "MAN 12" nanoparticles of Al2O3 were dispersed in water. The results showed that the heat transfer enhancement increases with volume fraction and Reynolds number increase. "WAN 06" experimentally studied the shape impact on heat transfer and friction characteristics in a square roughened duct. They have highlighted that ribs shape strongly affects the local heat transfer. It was concluded that the trapezoidal shaped ribs provide the highest heat transfer enhancement. Numerical study of nanofluid forced convection flow in triangular ribbed microchannel has been carried out by "AND 16". They have exanimatedthe effect of ribs shapes on heat transfer. They found that the rectangular-trapezoidal rib shape provides the highest heat transfer enhancement.

The employment of ribbed micro-channel is widely developed. Nevertheless, few works have been interested to investigate nanofluid flow in ribbed micro channel. Different parameters related to enhancement heat transfer in ribbed micro-channel need to be more understood such as the effect of nanopartilces volume fraction and the spacing between ribs. Understanding the impact of these parameters could allow optimizing the micro-devices design. This was the main motivator for the present work. The current investigation attempted to numerically studied nanofluid laminar flow and heat transfer in ribbed rectangular micro-channel. The nanofluid used in this work consists on dispersing spherical alumina nanoparticles in water for different volume fractions 0-4%. The effect of spacing between the ribs is evaluated.

2. Physical model and mathematical formulation

The configuration analyzed in this study was presented in Figure 1. The microchannel studied by "KAR 05" has been adopted as based configuration. It consists of a horizontal rectangular microchannel with a length L=0.025 m and height of $H = 25\mu m$. The middle part of the lower wall is maintained at constant temperature $T_c = 293K$ and the rest was adiabatic. Two identical ribs with equal whit $\mathrm{h} = 0.3\mathrm{H}$ were placed in the lower wall. The position of the first rib was fixed at $x = 2a$ from the entrance of the channel. Different larger (c) of the ribs was examined (see Tabe1). Aluminum oxide nanoparticles were dispersed in water at different volume fraction of 0%, 2% and 4%. The nanofluid flow is assumed to be Newtonian, incompressible and laminar (Re=10 and Re=100) and hydro-dynamically fully developed with average inlet velocity U_o; and with constant temperature $T_h = 303K$.

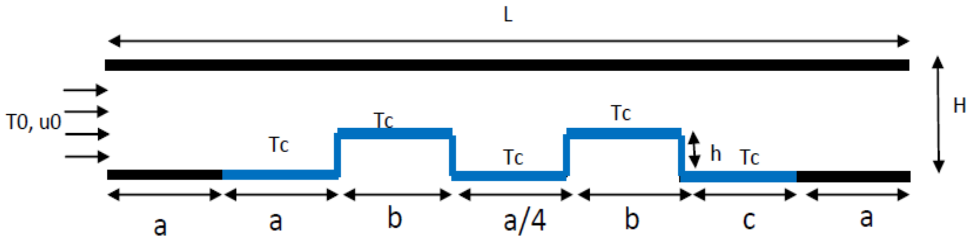

Figure 1. *Schematic of investigated microchannel.*

The single-phase model is used to describe the heat transfer characteristics of nanofluids through a micro channel under cooling condition. The following equations present the mathematical formulation of the single-phase model and two-dimensional [11]:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{1}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{\mu_{nf}}{\rho_{nf}\nu_f}\frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{2}$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{\mu_{nf}}{\rho_{nf}\nu_f}\frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{3}$$

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{\alpha_{nf}}{\alpha_f}\frac{1}{PrRe}\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right) \tag{4}$$

In the above equations, following dimensionless parameters are used

$$X = \frac{x}{H}\ Y = \frac{y}{H};\ U = \frac{u}{u_0};\ V = \frac{v}{v_0};\ Pr = \frac{\nu_f}{\alpha_f};\ H = \frac{H}{H} = 1;\ \theta = \frac{T - T_c}{T_h - T_c}\ Re = \frac{u_0 H}{\nu_f};$$

To calculate the local Nusselt number within the ribs width, we use the following equation:

$$Nu(Y) = -\frac{k_{eff}}{k_f}\left(\frac{\partial \theta}{\partial X}\right)_{X=0} \tag{5}$$

To calculate the local friction factor along the lower wall, the following relation is used:

$$c_f = \frac{\rho_f \frac{\partial u}{\partial u}}{\frac{1}{2}\rho_f u_c^2} \tag{6}$$

Physical proprieties of nanofluid:

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_s \tag{7}$$

$$(\rho Cp)_{nf} = (1-\varphi)(\rho Cp)_{bf} + (\rho Cp)_p \varphi \tag{8}$$

$$K_{nf} = K_{bf}(1.72\varphi + 1) \tag{9}$$

$$\mu_{nf} = \mu_{bf}(123\varphi^2 + 7.3\varphi + 1) \tag{10}$$

3. Results

The current study was carried out using Al_2O_3–water nanofluid, with nanoparticles volume fraction of 0, 2% and 4%. The results focused on the effect of volume fraction of nanoparticles, Reynolds number and ribs larger and number on fluid flow and heat transfer in microchannel. Then, two sets of numerical studies were conducted. The first set involved the investigation of the influence of larger of ribs on enhancement cooling microchannel. And, the second one involved the effect of number of ribs in enhancement heat transfer.

In order to evaluate the effect rib's larger on flow structures in the micro-channel, the velocity contours are presented in figure 2. As can be see, the fluid flow is fully developed in the entrance area. Getting closer the ribs, the flow development was perturbed and the velocity increases. This increasing is due to the presence of ribs which reduces the cross section of flow. With increasing the spacing between ribs, the hot fluid has more time to mix with the cooled fluid which explains the diminution of fluid temperature.

The isotherms within the microchannel for different ribs larger were presented in Figure 3. It shows that the fluid enters with hot temperature and it decreases with reaching the cold zone. The fluid temperature decreases with increasing rib's larger. The root cause behind this reduction is that the large ribs facilitate the fluid's contact with the cold zone for a longer time, enhancing the mixing between hot and cold fluid streams.

The effect of nanoparticles volume fractions and Reynolds numbers on the dimensionless temperature profiles at Y=0.5 were displayed in figure 4. The dimensionless temperatures oscillate periodically with the presence of ribs. As can be seen the dimensionless temperature rapidly decreases from the maximum value noted at X=0, and reaches its minimum at the outlet of micro-channel. Hence, for Re=100, the minimum temperature values were noted at ribs surfaces. For all the cases, the dimensionless temperature deceases with increasing nanoparticle volume fraction. This improvement is meanly do the fact that suspending nanoparticles in based fluid changes the thermo-physic proprieties of fluid and it increases the thermal conductivity which enhances the energy exchange process between the fluid and microchannel wall. Figure 5 depicts the influence of the rib's larger on dimensionless temperature at the center of microchannel. Increasing the distance (c) decreases the temperature under this section.

The variation of the axial dimensionless velocity of nanofluid for φ=4% at different Reynolds number 10 and 100 is displayed in Figure 6. The profile shows that after overshoot the entrance zone X=7.22, the nanofluid flow is fully. At the corners of the ribs, the velocity incurred a little peak which is mainly related to the adhesion condition. And then, it increases sharply reaching the ribs. This can be explained by the fact that the presence of ribs in the microchannel reduces the cross-sectional area available for nanofluid flow.

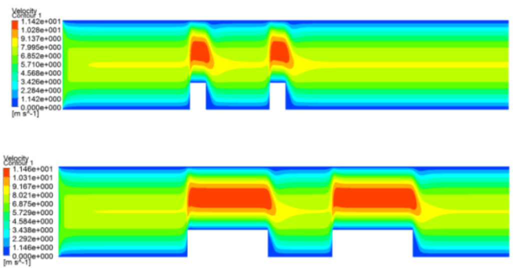

Figure 2. *velocity contours for φ= 4% and Re= 100*

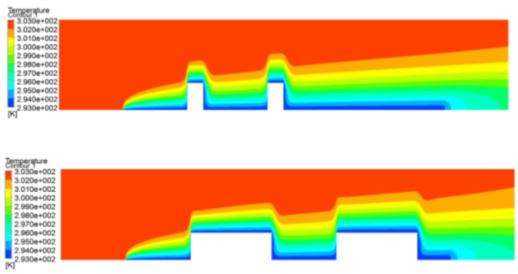

Figure 3. *Isotherms for φ= 4% and Re= 100*

Figure 7 displayed the effect of rib's larger ribs on dimensionless velocity for 4% nanoparticle volume fraction and at Reynolds number of 100. The velocity decreases after crossing the first rib surface. Thereafter, it increases again when the fluid enters on contact with the second ribs. It is noted that growing the rib's larger **increases** the nanofluid velocity. And the fluid is fully developed for greater value of c.

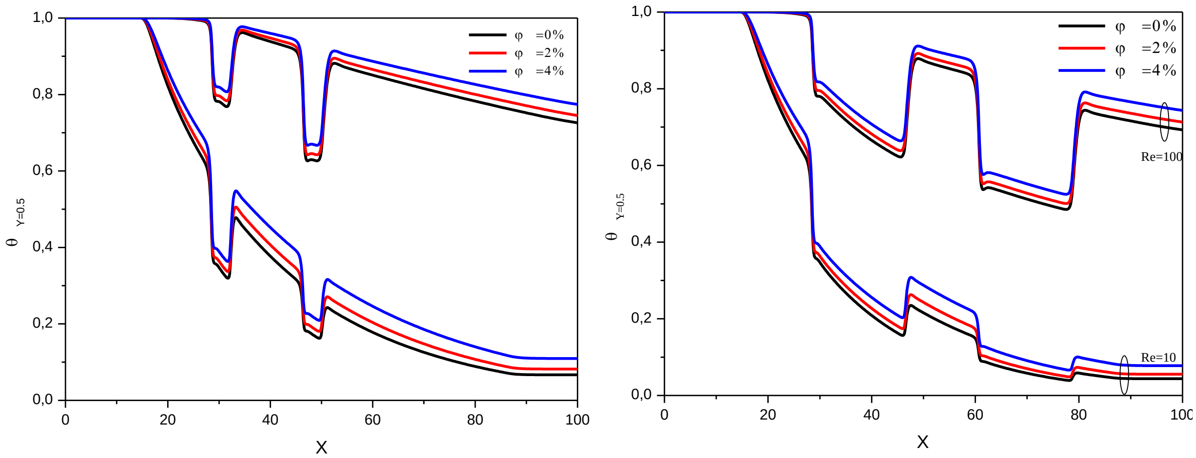

Figure 4. *Dimensionless temperature profiles at center line of microchannel for different volume fraction.*

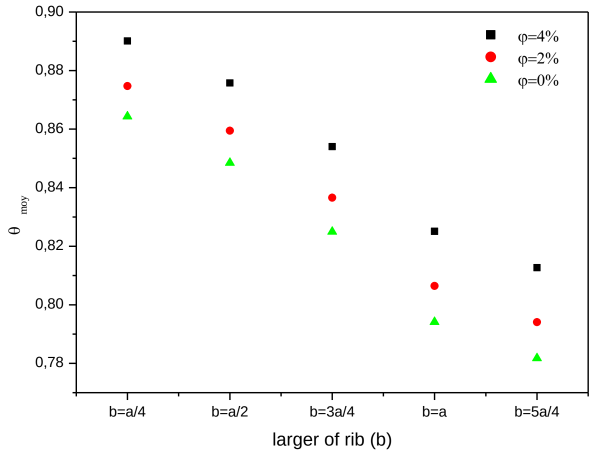

Figure 5. *Effect of lager's rib on temperature Re =100.*

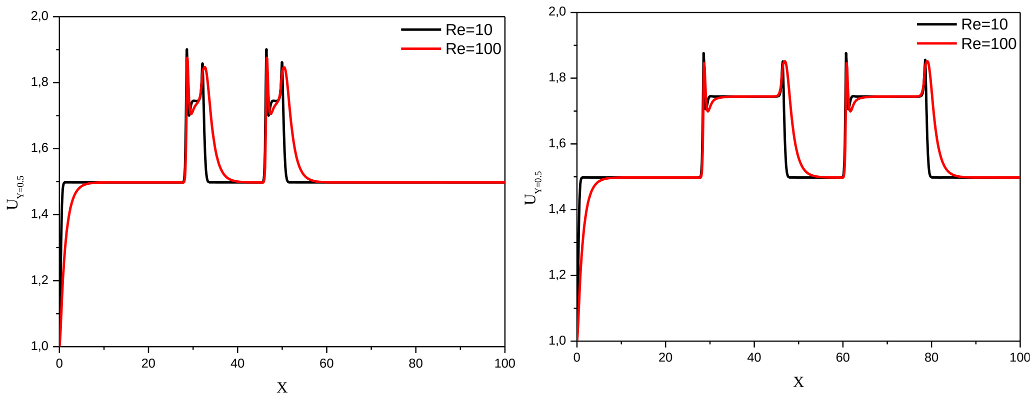

Figure 6. *Dimensionless velocity profiles at center line of micro-channel for Reynolds numbers of 10 and 100.*

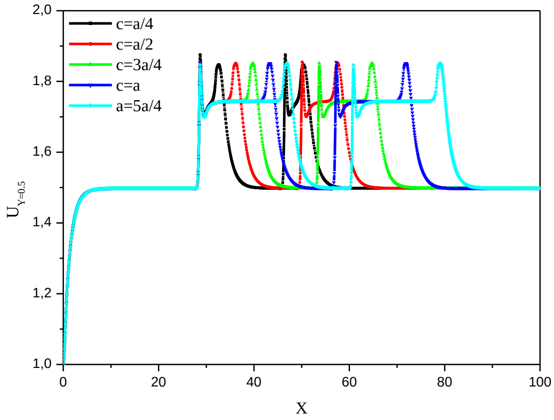

Figure 7. *Effect of lager’s rib on nanofluid velocity Re =100.*

The evolution of local Nusselt number on the lower wall of the microchannel for different volume fraction of nanoparticles in based fluid for all the cases and for Reynolds number of 100 is reported in figure 8. The results show that increasing nanoparticles volume fraction and Reynolds number improve Nusselt number of nanofluid. This could be due to the fact that adding nanoparticles with different volume fraction affects the physical proprieties of the mixture. Thus, nanofluid thermal conductivity was higher than those for based water which intensifies the heat transfer. Furthermore, heat transfer enhancement can be explaining by the fact that increasing the nanoparticle volume fraction leads to intensity the interactions and the collisions between nanoparticles and walls and thus cause a higher heat transfer and Nusselt number. Ribs are another factor that increases the Nusselt number. This increment is related to the fact that the presence of ribs interrupts the thermal boundary layer development which contributes to enhance the heat transfer.

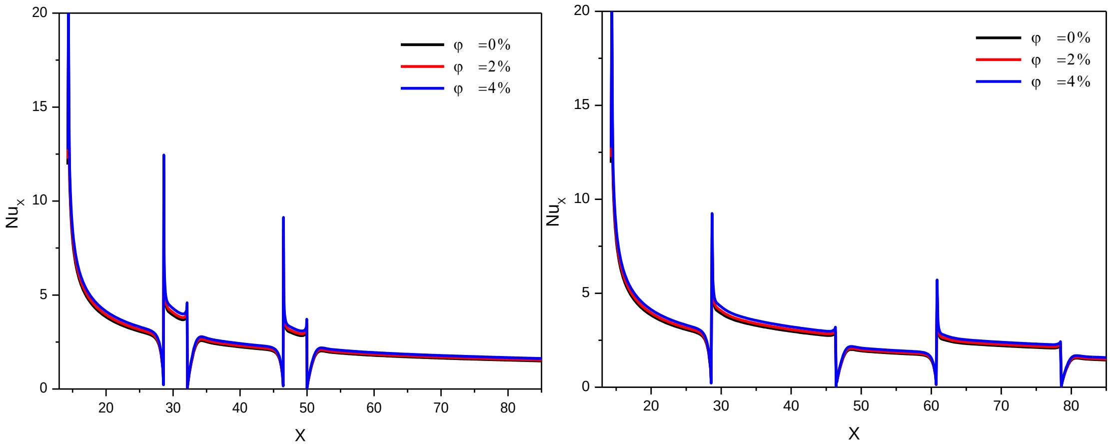

Figure 8. *Local Nusselt number on lower rib-roughened wall for Re = 100.*

Figure 9 represents the Poiseuille number along the upper wall of micro-channel for different volume fracion and at Re= 10. the poiseuilles number increases with nanaoparticle cencentration increases Poiseuille number .

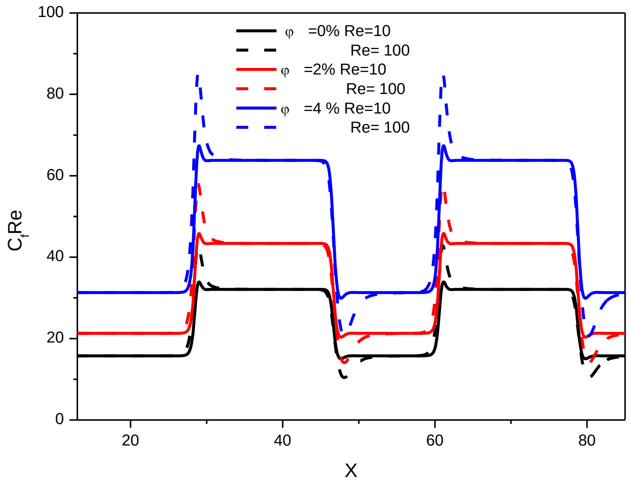

Figure 9. *Effect of volume fraction on Poiseuille number along the upper wall of micro-channel for Re= 100.*

Conclusion

This study presents a numerical analysis of the thermal and fluid flow characteristics of a nanofluid circulating through a microchannel equipped with ribs. The results indicate that both the nanoparticle concentration (ranging from 0% to 4%) and the Reynolds number (ranging from 10 to 100) play a significant role in enhancing heat transfer performance. An increase in either parameter leads to higher values of the Nusselt number and the Poiseuille number. Additionally, incorporating ribs along the microchannel walls contributes positively to heat transfer. However, when the rib size becomes too large, it negatively affects the Nusselt number, indicating a reduction in thermal efficiency.

Bibliographie

[AKB 16] O. A. Akbari , D Toghraie , A Karimipour , M R Safaei, M Goodarzi , H Alipour, M Dahari. Investigation of rib's height effect on heat transfer and flow parameters of laminar water–Al_2O_3 nanofluid in a rib-microchannel. Applied Mathematics and Computation, 2016.

[AND 16] A. Andreozzi, O. Manca, S. Nardini, D. Ricci. Forced convection enhancement in channels with transversal ribs and nanofluids. Applied Thermal Engineering, 2016.

[BER 00] A.E. Bergles, Some perspectives on enhanced heat transfer, second-generation heat transfer technology. Journal of Heat Transfer, 2000.

[CHO 95] S.U.-S. Choi, Enhancing Thermal Conductivity of Fluids with Nanoparticles FED-231/MD-66. American Society of Mechanical Engineers, Fluids Engineering Division (Publication) FED San Francisco, 1995.

[CHO 01] S. U. S Choi, Z. G. Zhang, W Yu, E. F.Lockwood, and A. E. Grulke. Anomalous thermal conductivity enhancement in nanotube suspension. Applied Physics Letters, 2001.

[DAN 10] A. Danish, H. Afzal, and K. Kwang-Yong Multiobjective Optimization of a Grooved Micro-Channel Heat Sink. IEEE Transactions on Components and Packaging Technologies , 2010.

[HAM 62] Hamilton, R. L. and Crosser, O. K, Thermal conductivity of heterogeneous twocomponent systems. Industrial & Engineering Chemistry Fundamentals, 1962.

[HUH 09] M.Huh, Y.H.Liu, and J.C. Han. Effect of Rib Height on Heat Transfer in a Two-Pass Rectangular Channel (AR=1:4) with a Sharp Entrance at High Rotation Numbers. International Journal of Heat and Mass Transfer, 2009.

[KAR 05] A.Karimipour, H. Alipour, O. Ali Akbari, D. T. Semiromi and M. H. Esfe., Vol 8 (15),2005. Studying the effect of Indentation on Flow Parameters and Slow Heat Transfer of Water-Silver, Nano-Fluid with Varying Volume Fraction in a Rectangular Two-Dimensional Micro Channel. Indian Journal of Science and Technology

[MAN 12] O. Manca, S. Nardini, D. Ricci. A numerical study of nanofluid forced convection in ribbed channels. Applied Thermal Engineering, 2012.

[MUR 05] S.M.S. Murshed , KC Leong , C.Yang . Enhanced thermal conductivity of TiO_2– water based nonofluids. International Journal of thermal Sciences, 2005.

[SHA 15] A. N. Al-Shamani, K. Sopian, H. A. Mohammed, S. Mat, M. H. Ruslan, A. M. Abed. Enhancement heat transfer characteristics in the channel with Trapezoidal rib-groove using nanofluids. Case Studies in Thermal Engineering, 2015.

[TUC 81] D. B. Tuckerman and R. F. W. Pease. High-Performance Heat Sinking for VLSI. IEEE Electron Device Letters, 1981.

[WAN 06] L. Wang, B. Sunden. Experimental investigation of local heat transfer in a square duct with various-shaped ribs. International Journal of Heat and Mass Transfer, 2006.

[YAR 15] Z. Yari Ghale, M. Haghshenasfard, M. Nasr Esfahany, Investigation of nanofluids heat transfer in a ribbed microchannel heat sink using single-phase and multiphase CFD models. International Communications in Heat and Mass Transfer, 2015.

[YOO 07] DH Yoo, KS Hong, HS Yang. Study of thermal conductivity of nanofluids for the application of heat transfer fluids. Thermochimica Acta, 2007.