U.P.B. Sci. Bull., Series D, Vol. 81, Iss. 4, 2019 ISSN 1454-2358

INVESTIGATION OF THE EFFECT OF ROUGHNESS ELEMENTS ON LAMINAR FLOW IN MICROCHANNELS

Zoubir BELKACEMI[1], Azeddine SOUDANI[2]

Understanding the behavior of laminar flow within microchannels is gaining more importance with the recent interest in microfluidics devices. In the current work, a numerical model was developed to evaluate the effect of surface roughness on hydrodynamic characteristics. In this model, the rough surface is configured with rectangular and triangular elements, respectively. Basing on the entropy production, an equation was developed to study the effect of the fluid flow on the Poiseuille number within valleys and within the reduced cross sections, separately. Also, the calculation of the entropy generation was used to understand the effect of roughness elements on Poiseuille number, and to predict a tendency to their variation with Reynolds number. As a result, a significant increase in Poiseuille number is detected for all configurations. It was detected that the Poiseuille number increases linearly with Reynolds, and this variation is mainly due to the fluid recirculation.

Keywords: Roughness, Microchannel, roughness elements, Entropy production, numerical analysis.

Nomenclature

- A: Cross section area (m^2).
- D_h: Hydraulic diameter, (m).
- f : Friction factor.
- K: Thermal conductivity (W/m^2 K).
- $\dot{m}$: Mass flow rate (kg/s).
- Po: Poiseuille number.
- Re: Reynolds number.
- $\dot{S}$: Entropy generation.
- T: Temperature (K).
- U: Mean velocity (m/s).

Greek Symbols

- μ: Dynamic viscosity (Pa s).
- ρ: Density (Kg/m^3)

[1] PhD., LPEA Laboratory, University of Batna 1, Batna, Algeria, e-mail: z.belkacemi@yahoo.fr
[2] Prof., Dept. of Physics, Faculty of matter sciences, University of Batna 1, Batna, Algeria, e-mail: azeddine.soudani@univ-batna.dz

1. Introduction

In recent decades, flows in micro-pipes are well present in the scientific literature, many numerical and experimental studies have been carried out to verify the classical laws and understand the behaviour of these flows, as well as to improve their thermal performance.

The concept of micro-channels is not new since it was introduced around 1980 by researchers Tuckerman and Pease [1]. In their work, they were able to demonstrate the cooling potential of these structures, with the manufacture of a 1 x 1cm² exchanger. And since, considerable researches have been conducted to study the fluid flow and heat transfer in microchannels.

For example, Schmitt and Kandlikar [2] studied rough rectangular microchannels of hydraulic diameter ranging from 325 to 819µm. An early transition to turbulence was observed with values of the friction coefficient greater than those predicted by classical laws.

Lelea et al [3] experimentally studied the flow in stainless steel micro-tubes with a diameter of 100-500µm for Re = 50-800. The results obtained for the Poiseuille number are in good agreement with the classical theoretical value $Po = 64$.

Brackbill and Kandlikar [4] investigated the effect of the roughness on the friction factor for a rectangular microchannel with roughness height that is ranging from 107 to 117µm. The results predicted an early transition to turbulence.

Qu et al [5] have studied the characteristics of a water flow through rough silicon micro-channels of trapezoidal sections, for a hydraulic diameter ranging from 51µm to 169µm and Reynolds numbers between 0 and 1500. They indicated that the friction coefficient of the flow was 8-38% higher than those predicted by classical theory.

Celeta et al [6] conducted an experimental study of the friction coefficient in a rough capillary tube. The experiments indicated that the Poiseuille number, for a laminar flow was in good agreement with the classical theory.

Kandlikar et al [7] investigated heat transfer and pressure drop of laminar flow in smooth and rough circular tubes with diameters of 1.067µm and 0.62µm. The effect of changing the relative roughness on the pressure drop was minimal, but the heat transfer in the entrance region showed a distinct dependence on roughness. Wu and Cheng [8] have experimentally studied the flow characteristics of de-ionized water in a silicon micro-channel with triangular and trapezoidal cross sections. The channel surfaces were smooth. Their experimental results confirmed the validity of the Navier-Stokes equations for laminar de-ionized water flows in smooth micro-tubes.

Li et al [9] examined the dynamic characteristics of de-ionized water in glass. They showed the consistent of their friction coefficient with classical values. While the friction coefficient in the rough stainless steel microtubes was higher than that predicted by the classical theory for relative roughness ranging from 3 to 4%, the difference reached the proportion of 35%.

Pfund et al [10] measured the pressure drop for a de-ionized water flow through rough rectangular microchannels. They found a normalized Poiseuille number of 1.26 for an average relative roughness of 1.5%.

Groce and Paola D'agaro [11, 12] studied numerically the effect, of 2D and 3D modelled roughness, on the friction factor and heat transfer with a finite element CFD code. The results showed significant effect of roughness on the pressure drop and a weaker one on the Nusselt number.

Kandlikar et al [13, 15] proposed a new set of roughness parameters. The use of their constricted flow model in the classical flow theory gives good results with their own experimental data. The deviation error between experimental results and those based on their model reached a 5%.

In their experiments on micro-channels of different roughness, Yangpeng Liu et al [14], showed the remarkable effect of roughness on the friction factor and the heat transfer coefficient compared to classical results.

In order to study the effect of roughness on laminar flow through rough micro-channels, Rawool et al [16] performed a three-dimensional numerical simulation of flow through serpentine microchannels with a roughness designed in the form of obstructions placed along the wall of the channels. The results showed that, the friction coefficient increases non-linearly with the increase in the height of the obstacle.

The main goal of most of these works was the understanding of the microfluidics flow, and the clarification of the effects of some parameters neglected during the classical flow studies, such as roughness. The development of a model that predicts the friction coefficient as well as that of heat transfer has been one of the major concerns of so many of this works. One of these models, quite used, was that of Kandlikar [13, 15] (constricted flow model), which takes into account the detachment of fluids during fluid flow in rough microchannels. This model develops a new definition of the hydraulic diameter which takes into account the constriction of the cross section due to the detachment of the fluid. Despite the importance of this model, it remains incapable to predict the variation of the Poiseuille number as a function of the Reynolds one, and gives no information on the fluid interactions in the detachment zones or those close to the rough walls. Our work aims to study the effect of roughness on microfluidic flows and to quantify the effects of fluid interactions in the near-roughness zones (neglected by the Kandlikar model [13, 15]) and that localized between the elements modeling the roughness, on the variation of the Poiseuille number with Reynolds, and tries to clarify the applicability limits of Kandlikar's model [15].

2. Mathematical model

In order to analyze the effect of roughness on pressure drop in a microchannel, a 2D laminar flow and heat transfer in microchannel with rough surface that was explicitly configured by different shapes of roughness elements (triangular, rectangular) is investigated in this paper, Fig (1). As shown in Fig (1), ε represents the roughness height and s represents the spacing between the adjacent peaks. For our model $s = 5\varepsilon$.

The following assumptions are applied to the mathematical model:

1- Steady laminar flow.

2- Constant fluid properties.

He was chosen to calculate the entropy production due to fluid friction. The volumetric rate of entropy generation for two- dimensional Cartesian system can be state like [17]:

$$\dot{S} = \frac{\mu}{T}\left\{2\left[\left(\frac{dv_x}{dx}\right)^2 + \left(\frac{dv_y}{dy}\right)^2\right] + \left(\frac{dv_x}{dy} + \frac{dv_y}{dx}\right)^2\right\} + \frac{K}{T^2}\left[\left(\frac{dT}{dx}\right)^2 + \left(\frac{dT}{dy}\right)^2\right] \tag{1}$$

In order to study and quantify, separately, the effect of each zone on the Poiseuille number and its variation as a Reynolds function, an equation, based on entropy production, was developed.

For a tube, the overall entropy generate rate due to fluid friction is calculated as [17]:

$$\dot{S} = \frac{\dot{m}}{\rho T}\Delta P \tag{2}$$

Where the friction factor for laminar fluid flow in smooth tube:

$$f = \frac{C}{R_e} \tag{3}$$

The friction factor is given by the relation:

$$f = \frac{2\Delta P}{L}\frac{D_h}{\rho U^2} \tag{4}$$

From Eq. (2) and Eq. (4):

$$f = \frac{2\rho T}{L\dot{m}}\dot{S}\frac{1}{\rho U^2} \tag{5}$$

From Eq. (3) and Eq. (5) we will have:

$$R_e f = \frac{2T}{\rho L}\left(\frac{D_h}{A}\right)\dot{S}\,\frac{R_e}{U^3} = P_0 \tag{6}$$

Assuming that the channel geometry and fluid properties are constant (as already mentioned during the assumption), Eq. (6) becomes for a smooth canal:

$$P_0 = C_1\,\dot{S}\,\frac{R_e}{U^3} = C \tag{7}$$

According to the literature review, the Poiseuille number of rough microchannel is no longer constant with the Reynolds number, in contrast to that of smooth microchannels and that predicted by the classical theory for laminar regimes. In order to find a tendency to this variation, Eq. (7) becomes:

$$P_0 = C_1\,\dot{S}\,\frac{R_e}{U^3} = P_0(R_e) \tag{8}$$

From our model, the total produced entropy was divided in two parts. The first corresponds to that produced within the reduced cross sections, and the second corresponds to that produced within valleys (inter-elements zones). Thus Eq. (8) becomes:

$$P_0 = C_1\left(\dot{S}_{RS} + \dot{S}_V\right)\frac{R_e}{U^3} = P_0(R_e) \tag{9}$$

We can put:

$$S_{RS} = \dot{S}_{RS}\,\frac{R_e}{U^3} \tag{10}$$

And:

$$S_V = \dot{S}_V\,\frac{R_e}{U^3} \tag{11}$$

Where $\dot{S}_{RS}$ is the total entropy produced within the reduced cross sections and $\dot{S}_V$ is that produced within valleys.

2.1 Constricted flow model

Kandlikar et al [11, 15] proposed a new definition to the hydraulic diameter, which takes into account the constriction of the cross section due to the fluid detachment, new geometric parameters were proposed.

According to this model, the effective diameter of the flow is not the reel diameter of the channel, but is reduced by the height of the roughness elements.

For roughness on two opposite sides of a rectangular microchannel the constricted parameters can be defined as follows:

$$H_{Cf} = H - 2RH \tag{12}$$

Where the H_{Cf} represents the constricted channel height and H represents the reel channel height.

$$A_{Cf} = bH_{Cf} \tag{13}$$

Where A_{Cf} represents the constricted cross section. Therefore, the constricted hydraulic diameter can be defined as follows:

$$D_{Cf} = \frac{4A_{Cf}}{2(b + H_{Cf})} \tag{14}$$

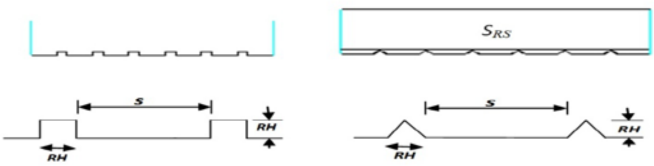
The friction factors are calculated by using the constricted parameters with the classical theory (used for smooth channels). It was reported that the use of the constricted hydraulic diameter in the classical theory results in good agreement (within 5 to 7%) with experimental data [11].

According to literature review, the constricted model remains incapable to predict the variation of the Poiseuille number as a Reynolds function and neglect completely the fluid interactions in the zones S_V for any roughness values.

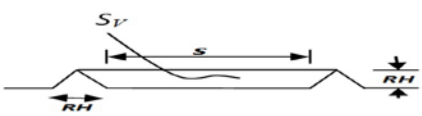
3. Numerical model

3.1 Description of the numerical model

In order to fully understand the effect of the roughness on the behavior of a laminar flow within microchannels, a numerical model was developed. In this model the surface roughness is explicitly modeled through a number of peaks on opposed channel walls. As shown in Fig (1), we consider two different configurations; triangular one and rectangular one. Relative roughness ε is defined as the ratio between the peak heights and the hydraulic diameter, and the values of the relative roughness are ranging from ε =0.0% to 1.26%. The hydraulic diameter was taken 0.4 µm for all relative roughness values.



(a)



(b)

Fig .1. Problem geometries.

3.2 Boundary conditions

Since the roughness is distributed in a regular manner on the smooth wall and is roughly repetitive along the tube and the flow is considered to be fully developed. Thus, we consider a relatively short tube segment, imposing mass flow periodic boundary conditions at the inlet and outlet sections with a fixed heat flux boundary condition at the walls. No slip boundary condition is considered at the surfaces, and the temperature of the fluid at the inlet was kept constant (300°K). Air is chosen as the working fluid.

3.3 Grid generation

We opted for a triangular mesh with non-uniform grid arrangement. A large number of grid points near the channel walls was arranged to resolve fluid flow and heat transfer with a consideration of the boundary layer flow and irregularities caused by roughness elements. The grid independence test is conducted using several mesh sizes. Three grids with a number of cells listed in table.1 are considered. The relative error between two grids was estimated by the following formula.

$$e(\%) = \left| \frac{Po_1 - Po_2}{Po_2} \right| \times 100 \quad (15)$$

Where, Po_1 represents the Poiseuille number at the first grid.

Table 1

Estimation of the relative error

Number of cells	7521	16321	23986
Po	99,21	101	104,04
Error	3%	1,8%	0

The equations of continuity and momentum are solved by the finite volume method, using Fluent CFD code. The SIMPLE algorithm was used for introducing pressure into the continuity equation. The flow equations were solved with a second-order upwind scheme. The convergence criteria for velocities, continuity and energy equation in the two models were kept as 1E-6.

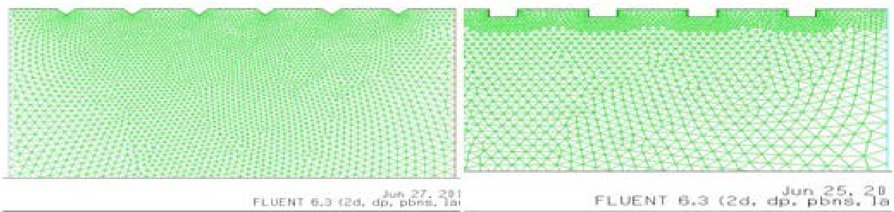


Fig.2. Mesh used for simulation.

4. Results and discussion

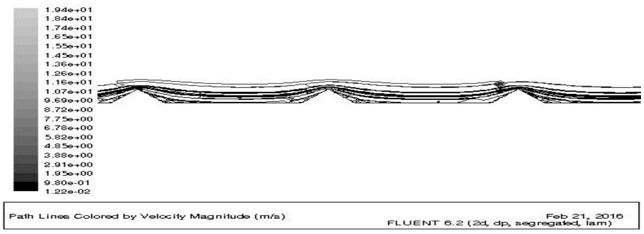
4.1 Pressure drop

4.1.1 Effect of the roughness height

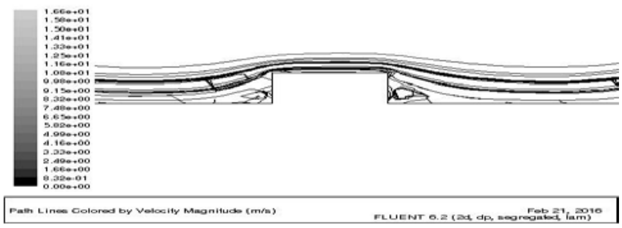
In order to understand the effect of the roughness on the pressure drop, the effect of the roughness height, as an important aspect characterizing the roughness elements, will be discussed and clarified.

Fig (3) shows the velocity distribution in near-wall region, the local near–wall streamlines can clarify the effect of roughness elements on fluid flow. As shown, the presence of roughness elements obviously perturbs the local flow near the channel walls and contributes to the creation of recirculation zones at the back of roughness elements. We notice also a decrease in the contact surface between the fluid and the wall within valleys.

From (Fig (3) (b)), it’s clear that the recirculation zones caused by the rectangular shape of roughness element is higher than that caused by triangular one. Both fluid recirculation and boundary layer regeneration increase friction losses. It’s clear that the augmentation of the height of roughness elements contributes to the creation of recirculation zones which increase the pressure drop added to that increased by the constriction of the cross section. Fig (4) shows the Poiseuille number for the channel flow. It’s clear that the roughness height leads to an increase in friction losses. Furthermore, we can see that Poiseuille number is no longer constant with Reynolds number.



(a)



(b)

Fig. 3. *Re* =700; ε = 0.82%; Streamlines: (a) Triangular obstructions, (b) Rectangular obstructions.

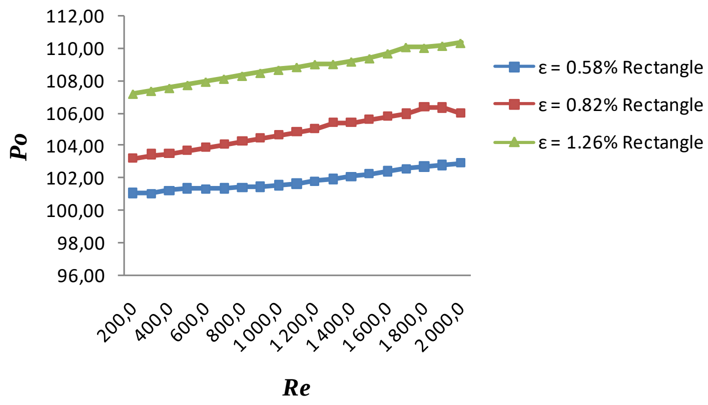


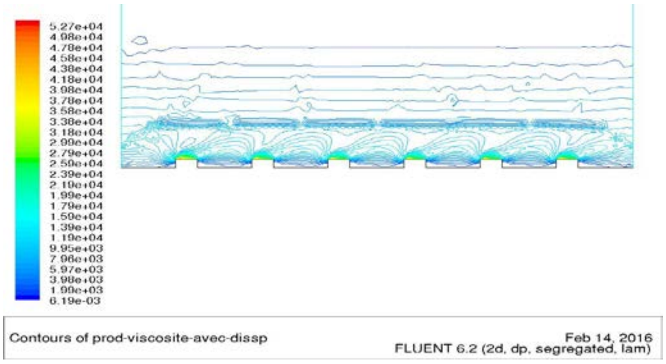
Fig.4. Variation of Poiseuille number at different Reynolds.

To understand this dependence, the entropy production appeared a very useful tool. By calculating the overall entropy generation due to friction and use of Eq (12), we try to better understand the effect of roughness elements and find a pattern for this variation.

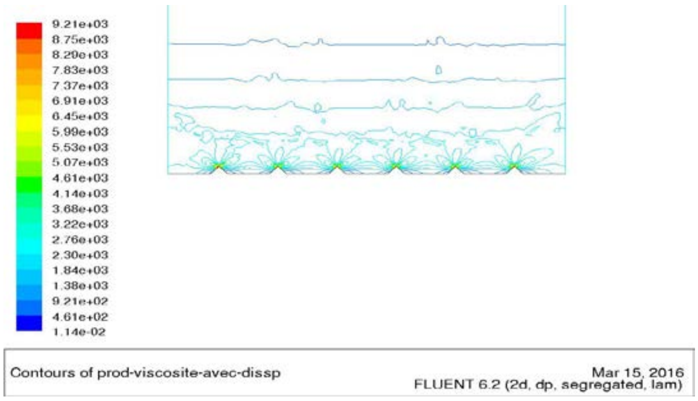
4.1.2 Entropy production and friction losses

Fig (5) shows the distribution of the local entropy generation along the rough channel wall. On the top of the peaks, the reduced cross sections induce higher velocities and lead to more entropy generation. We know that the lost available work is directly proportional to the entropy production [16].Thus; this increase of entropy production is proportional to the pressure drop per unit length. The reduced cross section induces more entropy production to keep the flow rate constant. As shown, the reduced cross sections induce more entropy production compared to recirculation zones for the same roughness value. We notice that the local entropy production within valleys represents 6% of that produced at the top of elements or in the zone S_{RS}.

Fig (5) shows that the reduced cross sections of rectangular elements produce more entropy than those of triangular elements; the reduced cross sections produce large velocity gradients. These velocity gradients increase the entropy production. The low percentage (6%) of entropy production within valleys makes the constricted flow model of Kandlikar [15] a useful tool to predict the friction factor with an error percentage which reached a maximum of 6% for the two forms in the range of studied roughness values.



(a)



(b)

Fig.5. Local entropy production along a rough microchannel wall, ε=0.82%;
(a): Rectangular elements; (b):Triangular elements.

By calculating the entire produced entropy within reduced cross sections and valleys, and the use of the Eq (9), which allows with its two functions (S_{RS}, S_V) to quantify the effect of the fluid flow on the Poiseuille number within valleys and within the reduced cross sections, separately, Fig (6, 7) shows the entropy generation functions S_V and S_{RS} plotted as a function of Reynolds. As shown, we notice that the Poiseuille number remains constant when we take only the entire produced entropy within the reduced cross sections, Fig (7). In contrast, the Poiseuille number varies linearly with Reynolds when we take the produced entropy within valleys, Fig (6). We notice that the Poiseuille number is less sensitive to Reynolds number for microchannels with triangular roughness elements than those with rectangular roughness ones. Thus, we can say that the variation of Poiseuille Number with Reynolds is mainly due to recirculation zones, created by the shape of roughness, and to the fluid interactions within valleys.

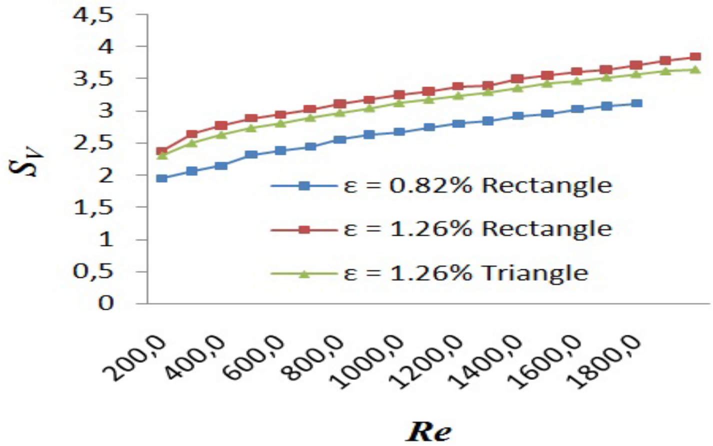


Fig .6. Variation of S_V at different Reynolds.

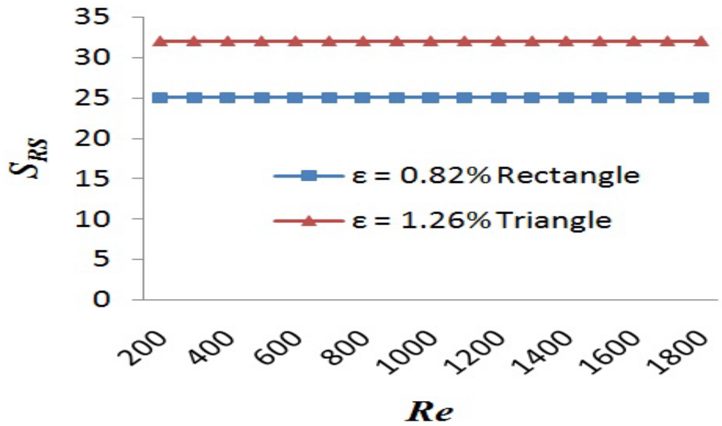


Fig .7. Variation of S_{RS} at different Reynolds.

4.1.3 Effect of roughness shape:

Comparing the results obtained from the two forms used in roughness modeling, we noticed the significant effect of the shape on the friction factor and Poiseuille number.

Fig (8) shows the Poiseulle number as a function of Reynolds for different shapes. There is an increase in Poiseuille number of the rectangular shape element comparing it to that of the triangular shape.

Fig (9) shows the local entropy produced along the channel wall of rectangular and triangular elements for the same roughness and for the same Reynolds values. It is clear that triangular rough elements produced more entropy within valleys than rectangular ones. It seems that the rectangular shape creates more recirculation than triangular shape. The decrease in velocity gradients and contact surface within valleys produce less entropy comparing it to that produced in a smooth channel. As shown, the recirculation zones and fluid detachment decrease the contact surface between the fluid and the wall within valleys. Thus, we can see that the rectangular shape produce more fluid recirculation zones which reduce the contact surface. These fluid recirculation zones produce less entropy than that produced by the constriction of the cross section caused by the fluid detachment. Thus, we understand the reason why the triangular shape produces more entropy than the rectangular shape within valleys.

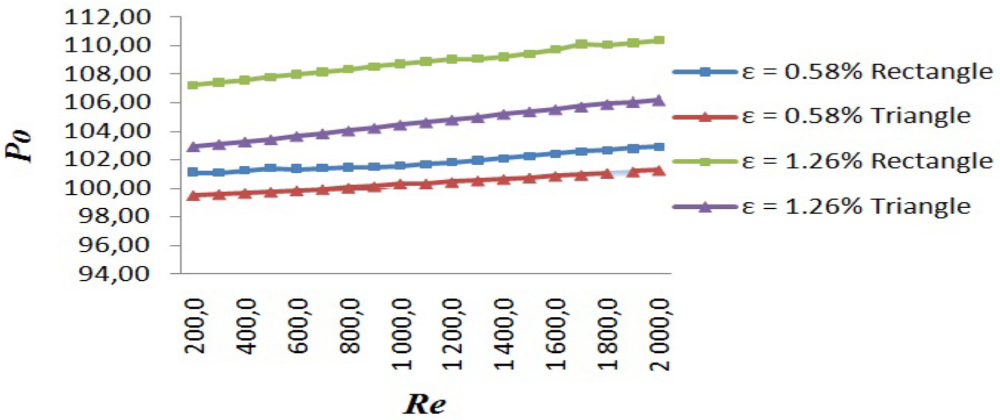


Fig .8. Variation of Poiseuille Number at different Reynolds.

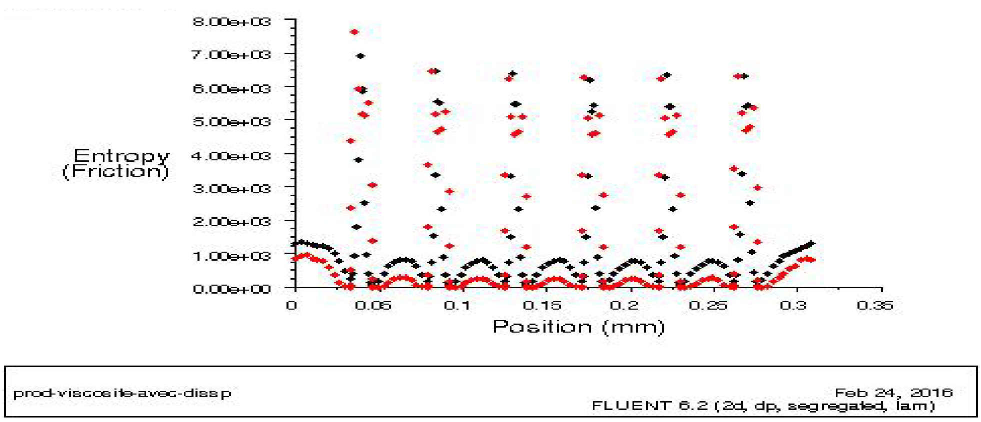


Fig .9. *Re*= 800, ε=0.82%, local entropy production along the rough microchannel walls.

5. Conclusion

The effect of the roughness on the pressure drop in microchannel has been investigated using the entropy generation. We have developed a numerical model where surface roughness was configured by triangular and rectangular roughness elements. The entropy production due to heat transfer and fluid friction was investigated to predict the behavior of the Poiseuille number with Reynolds number. The effects of the height and shape roughness on pressure drop was investigated and discussed. The conclusions can be summarized as follows:

- For both configurations, an increase in Poiseuille number was detected.
- The Poiseuille number increases with the relative roughness increase.
- By the calculation of the entropy production due to friction, it was observed for all studied roughness values and roughness elements that the Poiseuille number increases linearly with Reynolds.
- The variation of Poiseuille number with Reynolds was due to fluid recirculation zones.
- The constricted flow model can predict the friction factor within an error of about 6%.

REFERENCES

[1] *D.B.Tuckermane and R.F.W.Pease,* High performance heat sinking for VLSI; IEEE Electron Device Letters, Vol.EDL2, 5 May 1981, p.p 126-129

[2] *D.Lelea, K. Takano*, The experimental research on microtube heat transfer and fluid flow of distilled water, International journal of heat and mass transfer vol.74, no.12, pp. 2817-2830

[3] *G.P. Celata, M. Cumo, S. McPhail and G. Zummo,* Characterization of fluid dynamic behavior and channel wall effects in microtube, International Journal of Heat and Fluid Flow, vol27 ,no.1,2006,pp. 135 – 143

[4] *S.G. Kandlikar, S. Joshi and S. Tian,* Effect of channel roughness on heat transfer and fluid flow characteristics at low Reyunolds numbers in small diameter tubes, Heat Transfer Eng. Vol .23, 2003, pp. 4-16.

[5] *H.Y. Wu, Ping Cheng,* An experimental study of convective heat transfer in silicon microchannels with different surface conditions, International journal of heat and mass transfer. Vol. 46, no.14, 2003, pp. 2547-2556

[6] *Z.X. Li, D.X.Du and Z.Y. Guo,* Experimental study on flow characteristics of liquid in circular micro-tubes, Microscale Thermophysical Engineering, vol.7, 2003, pp. 253-265

[7] *D. J. Schmitt and S. G., Kandlikar,* Effects of Repeating Microstructures on Pressure Drop in Rectangular Mini-channels, Third International Conference on Micro-channels and Mini-channels(ICMM05),2005, no. ICMM2005-75111, ASME

[8]*Qu, W. Mohiuddin Gh. Mala and D. Li,* Pressure driven water flows in trapezoidal siliconmicro-channels, Int. J. of Heat and Mass Transfer, Vol.43, 2000, pp. 353-364

[9] *P.F. Hao, Z.H. Yao, F. He, K.O.Zhu*, Experimental investigation of water flow in smooth and rough silicon micro – channels, Journal of Micromechanics and microengineering, vol.16, no.7,2006,pp. 1397 – 1402

[10] *Z.Chengbin, C. Yongping and S. Mingheng*, Effects of roughness elements on laminar flow and heat transfer in microchannels, Chemical Engineering and Processing, vol. 49, 2010, pp.1188-1192

[11] *T. P. Brackbill and Satish G.Kandlikar,* Effect of Sawtooth Roughness on Pressure Drop and Turbulent Transition in Micro-channels, Heat Transfer Engineering, vol.28, no.0 9,2007,pp.662-669

[12] *Y. Liu, G. Xu, J. Sun, H. Li*, Investigation of the roughness effect on flow behavior and heat transfer characteristics in microchannels, International Journal of Heat and Mass transfer, vol. 83,2015,pp. 11-20

[13] *G. Croce, P. D'Agaro*, Numerical analysis of roughness effect on micro-tube heat transfer, Super lattices and Microstructures, vol. 35, 2004, pp. 601–616

[14] *Z.Chengbin, C. Yongping and S. Mingheng*, Effects of roughness elements on laminar flow and heat transfer in microchannels, Chemical Engineering and Processing, vol. 49, 2010, pp.1188-1192

[15] *V.V. Dharaiya, S.G. Kandlikar*, Numerical investigation of heat transfer in rectangular microchannels under H2 boundary condition during developing and fully developed laminar flow, Journal of heat transfer, vol.134, 2012, pp.190-201

[16] *A.S. Rawool, S.K. Mitra, S.G. Kandlikar*, Numerical simulation of flow through micro-channels with designed roughness, Micro-fluid. Nano-fluid.vol. 2, 2006, pp.215–221

[17] *A. Bejan*, Entropy Generation through Heat and Fluid Flow, New York, Wiley, Interscience, 1982