NUMERICAL SIMULATION OF FLOW THROUGH MICROCHANNELS OF TECHNICAL EQUIPMENT WITH TRIANGULAR AND RECTANGULAR ELEMENTS OF ROUGHNESS

Symulacje numeryczne przepływu przez mikrokanały urządzeń technicznych z trójkątnymi i prostokątnymi elementami chropowatości

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A b s t r a c t: This paper presents a computational study on an influence of a rough surface on the fluid flow in a microchannel used in various technical microdevices of complex products. Two-dimensional axially symmetrical microchannels with a circular cross-section were considered. The fluid flow were simulated as simple geometric figures, i.e. a triangle and a rectangle with different height h and different distance s between each other. The flow equations were solved with Ansys / Fluent software. A streamline analysis is performed to investigate the flows in the recirculation zone behind the roughness elements. It was found that the friction factor increases with increasing height of rough elements. The coefficient of friction factor is greater for rectangular elements than for triangular elements, and decreases as the geometry of the element changes. Friction factor decreases as the Reynolds number increases. The authors indicate that in the production of microchannels of complex products, it is recommended to use triangular elements to model roughness.
K e y w o r d s: natural mechanical engineering, roughness, microchannels, Ansys, friction factor

S t r e s z c z e n i e: Celem pracy jest określenie wpływu chropowatej powierzchni na przepływ płynu w mikrokanałach stosowanych w różnych mikrourządzeniach technicznych złożonych wyrobów. Rozpatrywano dwuwymiarowy osiowo-symetryczne mikrokanały o przekroju kołowym. Chropowatość została zasymulowana jako proste figury geometryczne tj. trójkąt i prostokąt o różnej wysokości *h* i różnej odległości s między sobą. Równania przepływowe zostały rozwiązane za pomocą oprogramowania Ansys/Fluent. Przeprowadzana jest analiza linii prądu w celu zbadania przepływów w strefie recyrkulacji za elementami chropowatości. Stwierdzono, że współczynnik tarcia wzrasta wraz ze wzrostem wysokości elementów chropowatych. Współczynnik tarcia jest większy dla elementów prostokątnych niż trójkątnych i zmniejsza się wraz ze zmianą geometrii elementu. Straty tarcia maleją wraz ze wzrostem liczby Reynoldsa. Autorzy wskazują, że w produkcji mikrokanałów złożonych wyrobów do modelowania chropowatości zaleca się używać elementów trójkątnych.
S ł o w a k l u c z o w e: inżynieria mechaniczna, chropowatość, mikrokanały, Ansys, straty tarcia

Introduction

The miniaturization of devices, especially electronic devices, resulted in the miniaturization of mechanical parts and machines, which allowed for the development of production processes for very small machines, e.g. microengines, micropumps, and microreactors. Microcomponents and microdevices are increasingly used in many industries: from energy generation, fuel cells to biomedical devices, as well as cooling systems. Due to the intensive development of more complex systems in small scales, microchannels have become an inseparable part of most microfluidic devices, hence the necessity to use small cross-sections, therefore the requirements and requests related to the use of mini and microchannels are increasing. The flow and heat transfer models developed and tested for macrochannels do not take into account the significant phenomena in the microchannels, and the difference increases with the reduction of the dimension characterizing the flow and the surface treatment method. As the channel size decreases, the effect of roughness on fluid flow also increases. A surface roughness is a set of irregularities, i.e. peaks and pits on the real surface of an object with relatively small intervals between the vertices [2, 4, 8].

At the macro scale, the material from which the element was made, the type of processing and processing parameters undoubtedly have the greatest influence of the surface roughness. The surface can most often be characterized as a combination of two profiles – waviness and roughness (some surfaces also show a shape error). Surface roughness is the result of the simultaneous interaction of many independent factors, both random and determined, and as a result it has a very complex microgeometry. The roughness is influenced by many factors, such as: decohesion processes, plastic deformation in the cutting zone and the formation of chip segments, friction of the tool contact surface against the machined surface, metal crystalline structure, chip friction against the machined surface, etc. [2, 8].

During the surface treatment of the micro-scale surface roughness is unavoidable. There are many types of micromachining methods, such as EDM (electrical discharge machining), ECM (electrochemical machining), etching, micro-milling, and so on; the precision of processing of these methods ranges from 10^{-2}μm to 5 μm. Depending on the manufacturing process channels they may, however, even have a surface roughness comparable to the dimensions of the channel. To properly design a microdevice, it is necessary to establish the physical laws that govern fluid flow and heat transfer in micro-geometry to taking into account performance of the microdevice, thus it involves identification of the surface of microchannels [4].

Although the flows in rough macrochannels are very well known, the micro scale has not been fully researched yet. Therefore, in the last few decades, many experimental studies have been conducted on the microchannels of different hydraulic diameter. Some studies show that there are no significant differences in the time of transition from laminar to turbulent flow, and no differences in the flow between the macro and micro scale. In contrast, other studies indicate a change in the character of flow below the critical value of the Reynolds number (2300) and a higher coefficient of roughness that occurs in channels with small hydraulic diameter. It is suggested by the increase of the roughness effect together with the decrease of the channel size [1, 9].

At the microscale level, it is impossible to obtain a completely smooth wall surface. According to the knowledge of macrosystems, when the relative roughness is less than 5%, its influence on the coefficient of friction is negligible [4].

For microscale channels, experimental and numerical results showed that surface roughness has a significant effect on heat transfer and heat transfer. For example, the experiment of Kandlikar et al. indicated that for a 0.62 mm pipe with a relative roughness height of 0.355%, the influence of roughness on the friction factor and heat transfer was significant [3].

A very extensive literature study is shown in [2]. The main goal was to investigate the effect of roughness on the friction coefficient and the critical Reynolds number. The study was based on 33 scientific articles (a total of 5569 data were collected) for flows in micro- and mini-channels with different wall roughness. The authors concluded that if the relative roughness height is <1%, it has little effect on the friction coefficient and the critical Reynolds number. The value of 1% is suggested as a threshold to distinguish smooth and rough micro- and mini-channels. However, it is not easy to obtain a perfectly smooth surface using this criterion in real applications [1].

However, while a large pool of experimental data is available, there is not yet a complete understanding of all aspects of microscale flow behaviour, therefore numerical methods are used to model flows at this scale. The computational approach can therefore be useful for understanding the basic physics of the problem on a micro-scale, because it is possible to analyze several aspects difficult to grasp in an experiment at the same time, but also indicate the direction of surface technology in micro-devices and microchannels.

Most often in the literature, the surface roughness is modeled with simple geometric shapes, e.g. triangles, rectangles, squares, ellipses, trapeziums [6, 9]. In the paper [6], the authors simulate the flow in microchannels, where the roughness is modeled, inter alia, by means of triangles and rectangles. The tested relative roughness ranged from 2.5 to 15%. The analysis shows that the roughness influences on the streamline distribution. This increases the friction and the pressure differences between the inlet and outlet. With a high roughness value, this can keep the flow breaking off near the wall and the formation of recirculation zones. The detachment and recirculation flow is probably the main cause of increased friction and pressure drop [9].

Research methodology

The aim of the study is an estimation of the effect of roughness on the laminar flow of fluid in microchannels, as well as to select an appropriate method of roughness modelling (so that it best reflects the actual phenomenon) and to compare it with the literature.

Two-dimensional axially symmetric micro channels with a circular cross-section were considered. Elements of the rectangular or triangular shape are placed on the

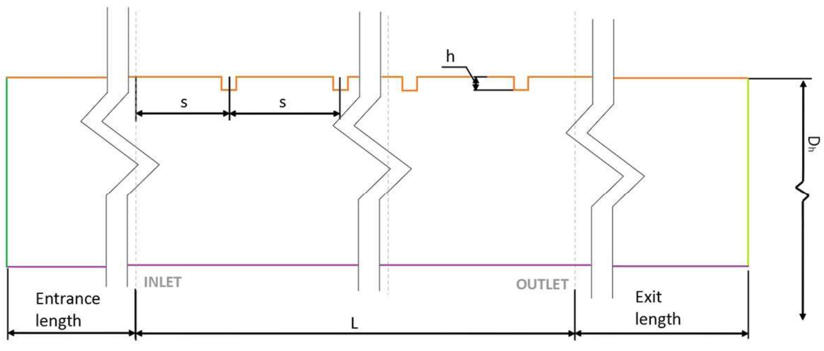

Fig. 1. The geometry of the microchannel

walls (simulating the roughness of the channel). Elements simulating roughness with a constant width w and different heights h are placed in different distances s. The microchannel geometry is shown in Fig. 1.

The flow was assumed to be two-dimensional, axisymmetric, incompressible and steady (the influence of gravity is neglect). A characteristic dimension of the Reynolds number is the diameter of the channel. The working medium is water (fluid density $\rho = 998\frac{kg}{m^3}$, dynamic viscosity $\mu = 0{,}001\ Pa \cdot s$).

The parameters used in the calculations are presented in Table 1, and the dimensionless parameter values are presented in Table 2.

Table 1. Parameters used for calculations

Characteristic	Symbol	Value	Unit
microchannel length	L	1	mm
microchannel diameter	D_h	50	μm
element height	h	1/1,75/2,5	μm
element width	w	2	μm
distance between elements	s	10/15/20	μm
inlet velocity	V_{in}	2,01 – 42,12	m/s

Table 2. Dimensionless height and distance between roughness elements

h	h/D_h	s	s/D_h
1	0,02	10	0,2
1,75	0,035	15	0,3
2,5	0,05	20	0,4

The flow realized in the micro channel results from the principles of conservation of mass and , momentum [4]:

1. The conservation of mass:

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \bar{V}) = 0 \qquad (1)$$

2. The conservation of momentum:

$$\rho \frac{\partial \bar{V}}{\partial t} = \rho \bar{F} - \mathrm{grad}\ p + \mu \Delta \bar{V} \qquad (2)$$

where: $\bar{V}\left[\frac{m}{s}\right]$ – velocity vector, $\rho\left[\frac{kg}{m^3}\right]$ – fluid density, $\bar{F}\ [N]$– vector of mass forces, $P\ [Pa]$ – fluid pressure.

The system of equations adopted for modelling can be written in the form of equations [4]:

- Equations of continuity:

$$\frac{1}{r}\frac{\partial (r u_r)}{\partial r} + \frac{\partial (u_z)}{\partial z} = 0 \qquad (3)$$

- Momentumequations (Navier - Stokes):

$$\rho\left(V_r\frac{\partial V_r}{\partial r} + V_z\frac{\partial V_r}{\partial z}\right) = -\frac{\partial p}{\partial r} + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V_r}{\partial r}\right) - \frac{V_r}{r^2} + \frac{\partial^2 V_r}{\partial z^2}\right]$$
$$\rho\left(V_r\frac{\partial V_z}{\partial r} + V_z\frac{\partial V_z}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V_z}{\partial r}\right) + \frac{\partial^2 V_z}{\partial z^2}\right] \qquad (4)$$

The commercial ANSYS software was used to solve the equations – the Fluent module, using the finite volume method.The boundary conditions adopted for the analysis are:

- at the inlet to the channel outlet profile established reference pressure (Pout = 0 Pa),
- zero tangential velocity on the channel walls (also impenetrability of the walls),
- axial symmetry.

When determining the type of flow, a dimensionless similarity number is defined - the Reynolds number given by the formula [4]:

$$Re = \frac{\rho V D_L}{\mu} \qquad 5)$$

where: $D_L[m]$ – characteristic dimension, $\mu\left[\frac{kg}{m\cdot s}\right]$ – dynamic viscosity, $V\left[\frac{m}{s}\right]$– flow velocity

To determine the effect of roughness on the flow in the microchannel, the formulas used in macrochannels and milichannels are used, and the dimensionless coefficient of friction (Fanning or Dracy) can be used to determine the pressure drop [3]. The Fanning friction coefficient (f_F) is defined as:

$$f_F = \frac{\tau_w}{\frac{1}{2}\rho u_m^2} \qquad (6)$$

where: $\tau_w[Pa]$ – shear stresses, $u_m\left[\frac{m}{s}\right]$– average velocity in the channel.

The Dracy coefficient of friction (f_D), related to the Fanning coefficient of friction, is expressed as:

$$f_D = 4 f_F \qquad (7)$$

The Dracy coefficient is also defined as the ratio of the Poiseuille number P_o to the number R_e as in the formula [6]:

$$f_D = \frac{P_o}{R_e} \qquad (8)$$

The Poiseuille number assumes a constant value, in the case of developed laminar flow it differs depending on the shape of the channel cross-section. For the channel with a circular cross-section, the Poiseuille number is assumed to be constant at 64.

Formula for pressure drop taking into account frictional losses:

$$\Delta p = \frac{2 f_D \rho u_m^2 L}{D} \quad (9)$$

where: $D[m]$ – microchannel diameter or hydraulic diameter if the channel cross-section is other than circular, $L[m]$ – channel length.

The Dracy coefficient of friction depends on: the type of flow, wall roughness, channel geometry (length, diameter) and is most often determined using the Moody diagram. The Dracy coefficient of friction for laminar flow is based on the Hagen-Poiseuille law [3]:

$$f_D = \frac{64}{Re} \quad (10)$$

In macro and microscale in laminar flow, the friction loss coefficient depends on the Reynolds number and not on the roughness [3].

In the construction of the microchannel geometry an entrance length was included. The entrance length was calculated from the formula [4]:

$$\mathrm{h/D} \cong 0{,}05\, Re \quad (11)$$

The value of the entrance length was adopted at 6 mm for R_e = 2100. The value of the exit length was set at 0.5 mm.

To investigate the effect of mesh density on the results, 4 types of mesh were generated (Fig. 2) for the same Reynolds number (R_e = 1100; h = 1.75 μm; s = 15 μm). When comparing the results, the Grid Convergence Index (GCI) was used, related to the average velocity in the cross-section located in the middle of the canal length [5]:

$$CGI = F_s * \frac{\left|\frac{u_{h2} - u_{h1}}{u_{h1}}\right|}{a^p - 1} * 100 \quad (12)$$

where: $F_s[-]$ – safety factor, $u_{h1}, u_{h2} \left[\frac{m}{s}\right]$ – selected parameter (velocity was assumed in the middle of the channel length, 12.5 μm from the axis of symmetry $h_1, h_2\ [-]$ – number of finite elements, $p = \frac{h_2}{h_1}\ [-]$ – mesh compaction factor, $a[-]$ – calculation approximation order (assumed value is 2).

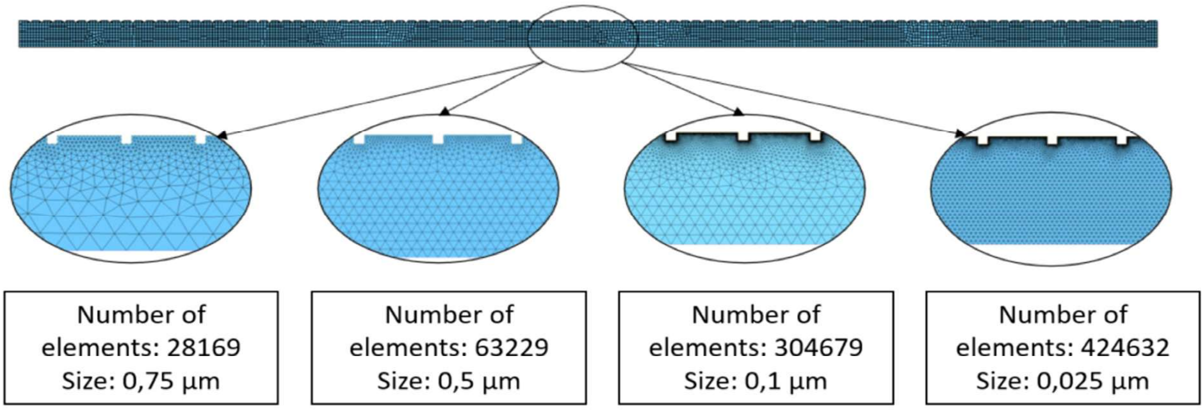

Fig. 2. The grids used to check the recommended length of the element

To optimize the mesh, a study of the GCI coefficient was performed. These studies have indicated, the GCI coefficient is less than 0.4% with an element size of 0.1 μm.

Results

To investigate the influence of roughness on the flow in the microchannel, calculations of the flow system were performed. The changes were analysed:

1) the shape of the roughness element - rectangle or triangle,
2) the height of the roughness element h in relation to the diameter of the microchannel *D* – parameter *h/D*,
3) the distance between the roughness elements s in relation to the diameter of the microchannel *D* – parameter *s/D,*
4) Reynolds number (flow velocity), where R_e = 100-2100.

The influence of the shape (rectangle, triangle) and height of the roughness element, i.e. the value of the

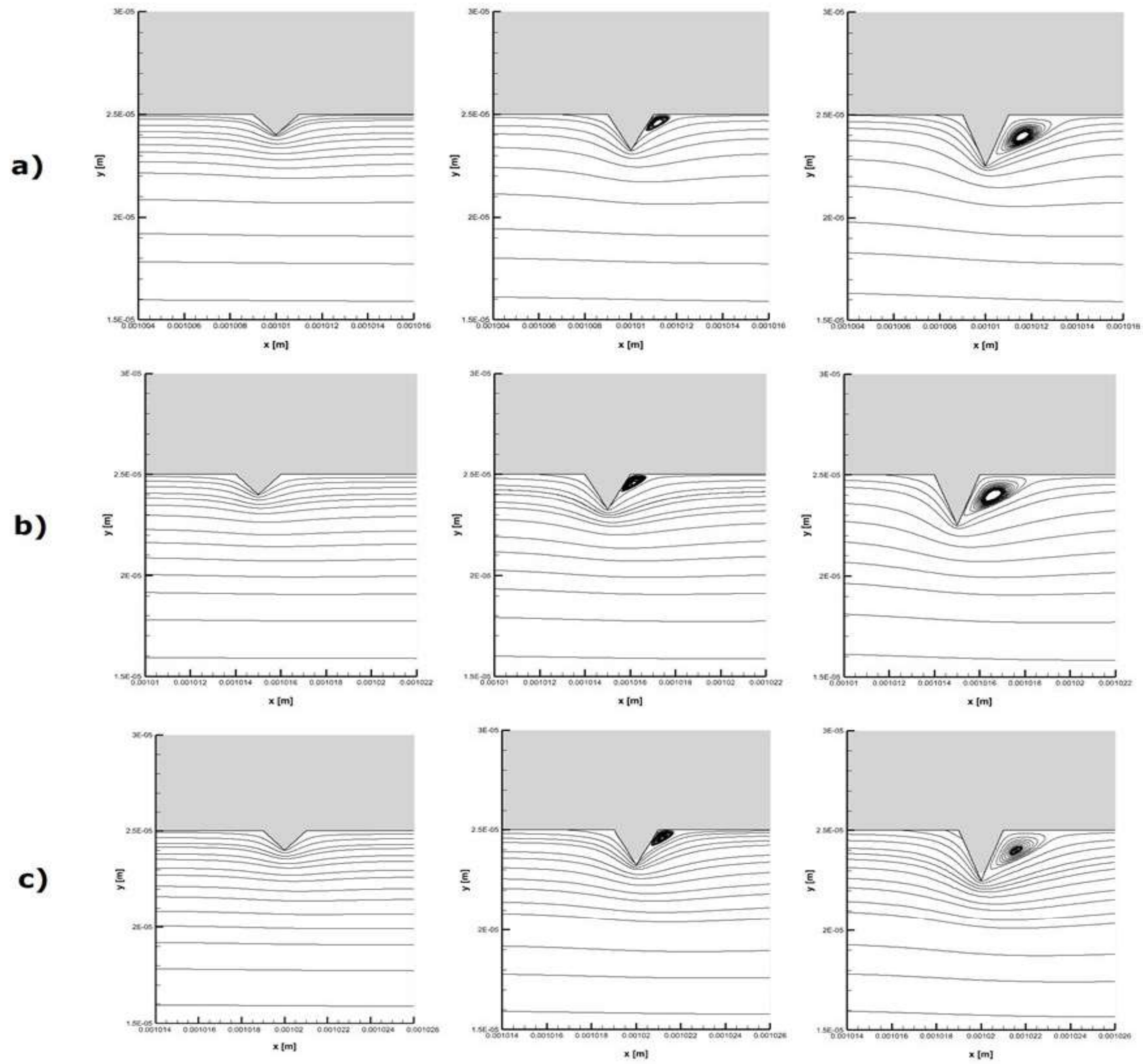

Fig. 3. Distribution of the streamline in the microchannel when *s/D* = 0.3 with triangular roughness elements a) *h/D* =0.02; b) *h/D* = 0.035; c) *h/D* =0.05

h/D parameter, on the flow in the microchannel was investigated, and on the basis of the obtained numerical results, stream lines were drawn, which was shown in Figs. 3 and 4. The parameter describing the change in the height of the roughness element is *h/D*, with the following values were analyzed *h/*D = 0.02; b) *h/D* = 0.035; c) *h/D* = 0.05; with constant parameter *s/D* = 0.3. The flow was carried out at the velocity of *V* = 2.01 m/s, which corresponds to the number R_e = 100. The results of flows in microchannels with roughness in the form of triangular and rectangular elements are presented in Figs. 3 and 4. The deformation of the flow image was shown. The analysis of the test results shows the formation of circulation zones behind the elements (in some cases, circulation also occurs before the element). The flow was not disturbed only in the case of triangular elements with *h/D* = 0.02. On the basis of the analysis of the length of the vortices, it can be concluded that the height of the element is the main parameter determining the length of the vortex. For *h/D* = 0.035 and *h/D* = 0.05, of the vortex length increases by 140% and 393.3%, respectively, against *h/D* = 0.02. The second parameter is the element type – rectangular elements disturb the flow more.

The distance between the roughness elements, i.e. the influence of the parameter *s/D* was investigated. It was observed that for the height of the triangular element, when *h/D* = 0.02, there is no vortex zone, and for rectangular elements, increasing the distance does not change the length of the vortex or the length of the vortex is slightly colder. In other cases, when the vortices do not interact, a slight decrease in the length of the vortex, on average 2.85% for rectangular elements, 1.13% for triangular elements, is noticeable, so the influence of the spacing of the roughness elements is marginal.

In order to compare the friction factor calculated on the basis of numerical simulations in microchannels with

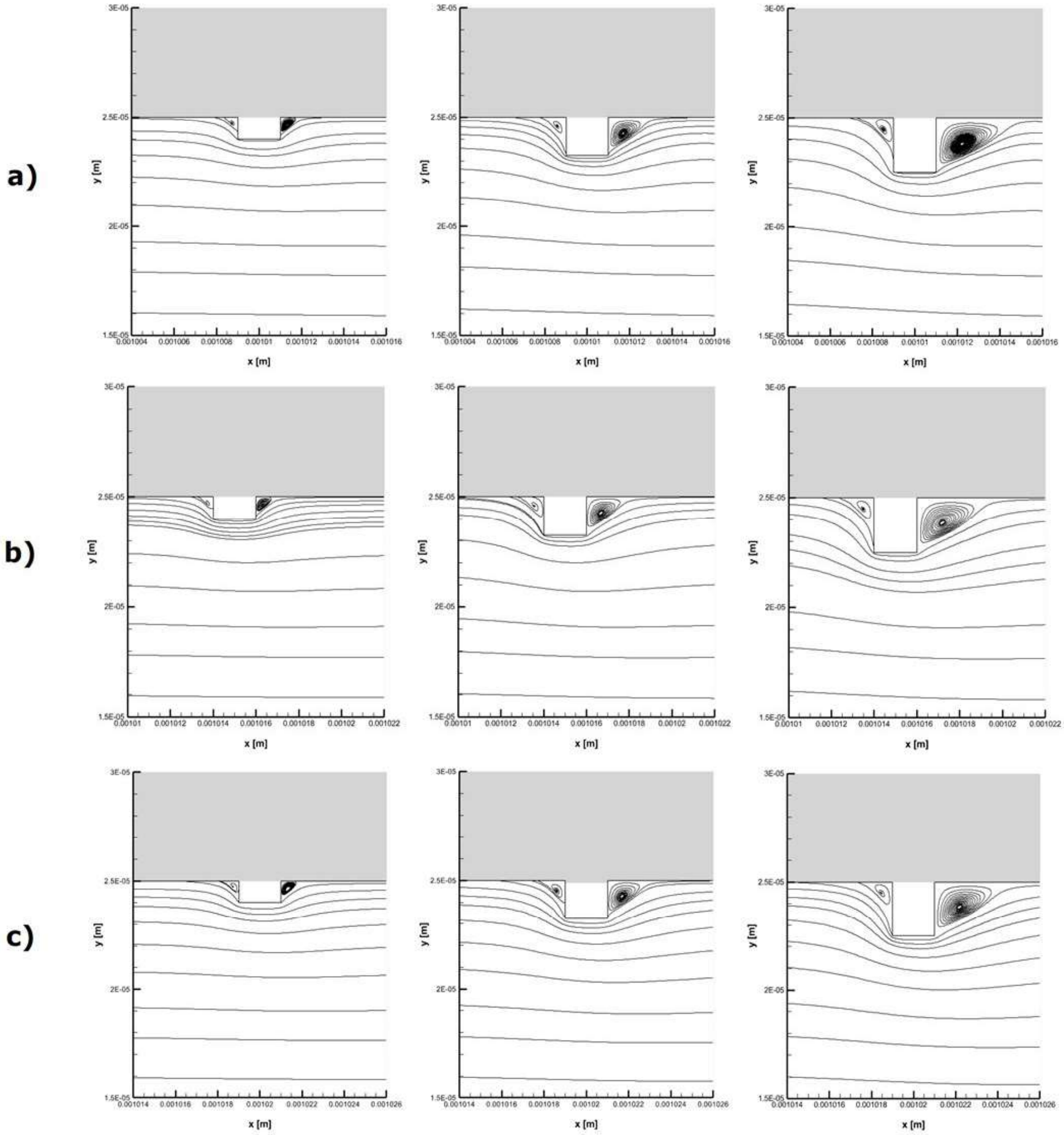

Fig. 4. Distribution of the streamline in the microchannel when *s/D* = 0.3 with rectangular roughness elements a) *h/D* =0,02; b) *h/D* = 0,035; c) *h/D* =0,05

the roughness simulated with simple geometric elements in the form of triangles and rectangles. The calculation results are presented in Fig. 5 and compared with the results resulting from the Hagen-Poiseuille law (formula 10).

The results obtained from the simulation presented in Fig. 5 show that the value of the friction factor increases with the increase of the roughness height. This is a characteristic trend for both the model with triangular and rectangular elements. There is also a reduction in the coefficient as the distance between the elements simulating roughness increases (for both cases). Rectangular obstacles have a much higher friction factor than triangular obstacles (5% higher on average). The greater the roughness, the greater the difference between rectangular elements compared to triangular elements. The obtained values of the coefficients on the basis of calculations are higher than in the case of the friction factor obtained by analytical calculations, both for rough elements modelled by means of triangles and rectangles. Rough triangular elements have a smaller discrepancy between the friction factor and the literature data (maximum discrepancy of 21% for triangular elements compared to 30% for rectangular obstacles).

In order to investigate the effect of the Reynolds number on of the friction factor value, a comparison was made of the flows in rough microchannels with triangular, rectangular elements, when *s/D* = 0.4 (selected on

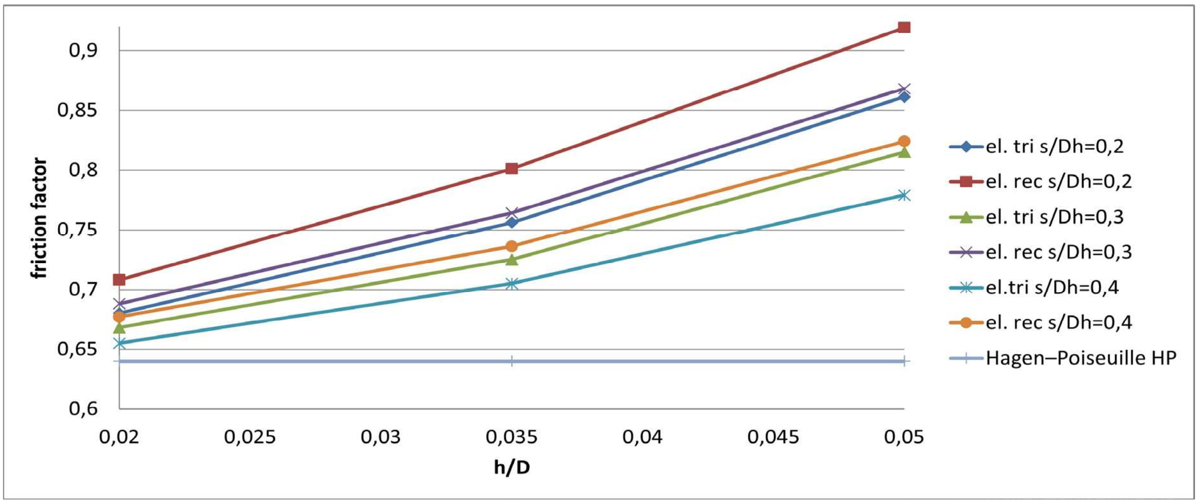

Fig. 5. Comparison of the friction factor values calculated on the basis of the simulation and the Hagen-Poiseuille law

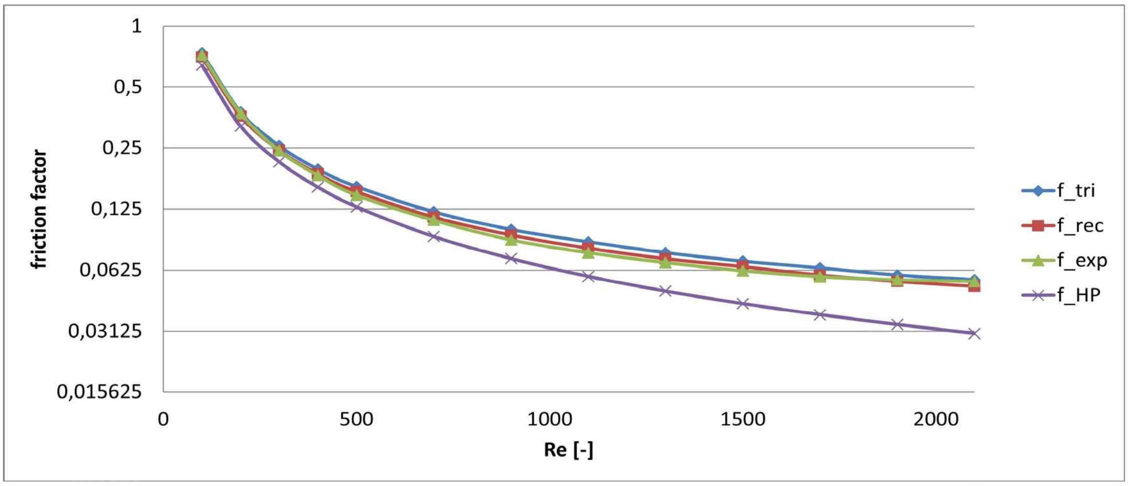

Fig. 6. Comparison of the friction factor values calculated on the basis of the simulation, experimental data [7] and the Hagen-Poiseuille law

the basis of the previous analysis), *h/D* = 0.035 and the experimental data contained in [7] for a microchannel with a diameter of 50 µm and a roughness measured at the level of 1.75 µm, which corresponds to *h/D* = 0.035, and the results were compared to the Hagen-Poiseuille law (Fig. 6).

The results show that the friction factor decreases as the Reynolds number increases. The greatest discrepancies with the experimental data occur for the Re numbers in the range 500-1150. For rectangular elements, all relative differences in this range exceed 10%. On the other hand, triangular elements generate 3.9-5.8% of the relative error in the given range. Triangular elements simulate the real surface condition much better.

Conclusion

Along with the development of miniaturized technologies, microchannels have found wide application in cooling systems of various technical devices, especially electronic devices. However, the flow behaviour in rough microchannels still needs to be investigated. In the article, the influence of roughness modelled with triangular and rectangular elements on the flow and friction factor in microchannels was examined numerically. The analysis of the numerical obtained results showed a significant influence of the roughness on the flow in the microchannel. The conclusions based on the results are as follows:

- The main mechanism to influence fluid flow is the creation of recirculation zones downstream of the roughness elements.
- The length of the recirculation zones increases with the height of the rectangular and triangular elements.
- The main parameters affecting the length of the recirculation zones are the roughness height as well as the element type - this effect is less visible for the triangular elements with the smallest height.
- The higher the roughness height, the greater the pressure difference between rectangular elements in relation to triangular elements.
- As the roughness of rectangular and triangular elements increases, the value of the pressure loss coefficient increases.
- There is also a reduction in the loss factor as the distance between the roughness simulators increases (for both cases).
- The friction factor decreases as the Reynolds number increases (for both).
- Triangular elements achieve a much lower friction factor than rectangular elements.

In the production of microchannels of complex products taking into account roughness, it is recommended to use triangular elements for modelling it as a simple figure - they show greater convergence with experimental and literature data.

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