NUMERICAL ANALYSIS OF THE INFLUENCE OF VARIATIONS IN THE CROSS-SECTION OF MICROCHANNELS IN LAMINAR FLOW

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Abstract: *In the last decades, a lot of experimental investigations performed to the hydrodynamics and heat transfer in microscale, indicated divergences to the Darcy friction factor and the Poiseuille and Nusselt numbers, when the results were compared to the ones provided by classical theory. There are reports of deviations to the Darcy friction factor and Poiseuille number attributed to cross-section variations of microchannels. The aim of this numerical study is to analyze how the hydrodynamics and heat transfer characteristics can be affected by cross-section variations of microchannels, for the single-phase laminar flow of water. Results to imperfect microchannels are compared to the perfect ones through Poiseuille and local Nusselt numbers. Deviations to Poiseuille and local Nusselt numbers through cross-section variations of microchannels were verified. These deviations were also dependent on the Reynolds number range only for the Poiseuille number, and not for the local Nusselt number. The results presented were obtained by computational fluid dynamics (CFD), through conservation equations.*

Keywords: *microchannels, Poiseuille, Nusselt, CFD.*

1. NOMENCLATURE

A_{st}	cross-section area [m^2]
c_v	specific heat at constant volume [J/kg K]
D	tube diameter [m]
ε	error [%]
f	Darcy friction factor [-]
h	local heat transfer coefficient [W/m² K]
k	thermal conductivity [W/m K]
L	tube length [m]
$\dot{m}$	mass flow rate [kg/s]
Nu	local Nusselt number [-]
p	pressure [Pa]
Po	Poiseuille number [-]
q''_{sup}	superficial heat flux [W/m^2]
Re	Reynolds number [-]
T	fluid temperature [K]
u	*x*-direction velocity [m/s]
v	*y*-direction velocity [m/s]
w	*z*-direction velocity [m/s]
w_m	average velocity of fluid [m/s]
x, y, z	rectangular coordinates [m]
z^*	dimensionless axial position [-]

Greek symbols

α	thermal diffusivity [m^2/s]
Δp	drop pressure [Pa]
η	variation fraction in diameter [%]
μ	dynamic viscosity [Pa s]
υ	kinematic viscosity [m^2/s]
ρ	specific mass [kg/m^3]

Subscripts

dh	hydrodynamically developed
m	average
max	maximum
min	minimum
Nu	Nusselt
Po	Poiseuille
st	cross-section
sup	superficial
v	constant volume

2. INTRODUCTION

In the last decades, the reduction of electronic devices in several aplication fields, such as biomedicine, chemistry and computer technology, for example, has been providing high eficiency related to the space in equipments. At the same time, this reduction in physical space is counterweighted by the high performance required at the refrigeration systems in such equipments. Therefore, the thermal control is one of the most critical areas for the development of modern microelectronic devices (Celata et al., 2004, 2006a, 2006c; Rosa et al., 2009; Chiu et al., 2011).

A lot of experimental studies (Wu and Little, 1984; Pfahler et al., 1990, 1991; Choi et al., 1991, Yu et al., 1995; Pfund et al., 1998; Mala and Li, 1999; Xu et al., 1999, 2000; Li et al., 2000; Tunc and Bayazitoglu, 2001; Judy et al., 2000, 2002; Wu and Cheng, 2003; Niklas and Favre-Marinet, 2003; Celata et al., 2002, 2004, 2006a, 2006b, 2006c; Steinke and Kandlikar, 2006; Chiu et al., 2011), as well as theoretical studies (Mala et al., 1997, Yang et al., 1998; Tso and Mahulikar, 1998) and numerical studies (Toh et al., 2002; Niklas and Favre-Marinet, 2003; Koo and Kleinstreuer, 2004, 2005; Gamrat et al., 2004; Chiu et al., 2011), were carried out in the last decades, to investigate the hydrodynamics and heat transfer in microscale, especially in microchannels with rectangular or circular cross-section (microtubes). The results from these studies show divergences among them. In general, the reported divergences can be viewed through analysis of the Darcy friction factor, or the Poiseuille and Nusselt numbers, when they are compared to results predicted through conventional theory (Celata et al., 2004, 2006a, 2006b; Steinke and Kandlikar, 2006).

There are reports of friction factors higher than expected by classical theory (Wu and Little, 1984; Yang et al., 1998; Mala and Li, 1999; Judy et al., 2000; Koo and Kleinstreuer, 2004; Celata et al., 2006a), lower than expected for classical theory (Pfahler et al., 1990, 1991; Choi et al., 1991; Yu et al., 1995; Judy et al., 2000; Gamrat et al., 2004) and in good agreement with this one (Pfund et al., 1998; Mala and Li, 1999; Xu et al., 2000; Li et al., 2000; Judy et al., 2002; Celata et al., 2002, 2006a; Niklas and Favre-Marinet, 2003). Some of these deviations are attributed to variations in cross-section area of the microchannels, due to surface roughness (Wu and Little, 1984; Mala and Li, 1999; Li et al., 2000, Wu and Cheng, 2003), due to geometric imperfections at the cross-section of microchannels and microtubes considered, which can vary throughout its length (Celata et al., 2006a; Steinke and Kandlikar, 2006), due to aspect ratio of the channels (Pfahler et al., 1991; Wu and Cheng, 2003; Celata et al., 2006a; Chiu et al., 2011) and due to scaling effects, such as viscous dissipation (Koo and Kleinstreuer, 2004; Celata et al., 2006b) and electrokinetic effect (Mala et al., 1997; Yang et al., 1998; Judy et al., 2000), for example. Furthermore, there are reports (Pfahler et al., 1991; Celata et al., 2002) of deviations for the friction factor that showed dependence with the Reynolds number range considered. Thereby, the presence of various possible scaling effects, at once, difficults the identification of experimental errors sources in studies in this application area. Therefore, the use of numerical techniques can be advantageous in the study of flow in microscale. Thus, significant effects in this field, such as surface roughness, viscous dissipation and electrokinetic effect, for example, can be considered separately in the numerical model.

The aim of this numerical study is to analyze how the hydrodynamic and heat transfer characteristics of flow in microscale are influenced through cross-section variations in microchannels. Other scaling effects, such as surface roughness, viscous dissipation and electrokinetic effect, for example, are not considered. The results of Poiseuille and local Nusselt numbers for the single-phase laminar flow of water in microchannels, with variable cross-section, are compared to the ones obtained for geometrically perfect microchannels. These results were obtained through computational fluid dynamics (CFD).

3. COMPUTATIONAL DOMAIN

The Figure 1 shows the computational domain used in this study. It consists of a microtube with length L and circular cross-section with diameter D. The cross-section variation of the microtube consists of an expansion of the diameter D until a maximum value D_{max}, or a contraction of the diameter D until a minimum value D_{min}.

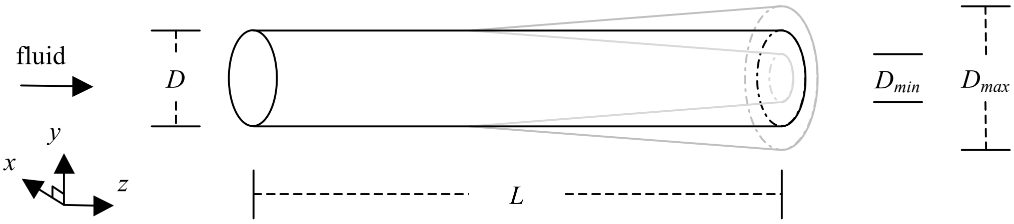


Figure 1. Schematic diagram of the computational domain.

Based on the works of Celata et al. (2002, 2004) and Steinke and Kandlikar (2006), a microtube with diameter D of 130 μm was selected. The length L used was 0.13 m, to ensure hydrodynamically and thermally developed flow conditions at the tube exit (since L/D = 1000). Six cases of variations for the diameter D were considered: ±1 %, ±3 % and ±5 %, from z = 0.04 m. In this position, approximately, the flow is thermally developed for higher Reynolds number (800) used in the simulations, which provides the greatest thermal entry length. All simulations consider the entry region under simultaneous development of thermal and hydrodynamic boundary layers. The Reynolds numbers 200, 400, 600 and 800 were considered. Water was the selected work fluid.

4. MATHEMATICAL MODEL

The fluid used is incompressible and with constant properties. The flow regime is laminar and permanent. Thus, the mathematical model consists of mass conservation, Eq. (1), Navier-Stokes, Eqs. (2-4) and energy, Eq. (5), equations, in rectangular coordinates. These ones (Incropera and DeWitt, 1998) are described below, in sequence:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\upsilon\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

where u, v and w are the velocity components in the x, y and z directions, respectively, ρ is the specific mass, υ is the kinematic viscosity, α is the thermal diffusivity, p is the pressure and T is the temperature.

For tubes with circular cross-section, in the considered conditions, the Darcy friction factor (f) is

$$f=\frac{\pi^2}{8}\frac{\rho D^5 \Delta p}{\dot{m}^2 L_{dh}}, \tag{6}$$

where Δp is the drop pressure, L_{dh} is the length of tube in hydrodynamically developed laminar flow and $\dot{m}$ is the mass flow rate, which is defined by

$$\dot{m}=\rho w_m A_{st}, \tag{7}$$

where w_m is the average velocity of fluid and A_{st} is the cross-section area of the channel. The Poiseuille number (Po) is

$$Po=f\,Re, \tag{8}$$

where Re is the Reynolds number, which is defined by

$$Re=\frac{\rho w_m D}{\mu}, \tag{9}$$

where μ is the dynamic viscosity of the fluid. The local Nusselt number (Nu) is

$$Nu=\frac{hD}{k}, \tag{10}$$

where k is the thermal conductivity of fluid, and h is the local heat transfer coefficient, which is determined by

$$h=\frac{q''_{sup}}{T_{sup}-T_m}, \tag{11}$$

where q''_{sup} is the superficial heat flux, T_{sup} is the temperature on the tube surface and T_m is the average temperature in cross-section, obtained by

$$T_m = \frac{\int_{A_{st}} \rho w c_v T dA_{st}}{\dot{m} c_v}, \tag{12}$$

where w is the local velocity of fluid in the flow direction and c_v is the specific heat at constant volume. The magnitude of deviation to the Poiseuille number, with respect the theoretical value for circular tubes (Incropera and DeWitt, 1998), in the conditions specified, is given by

$$\varepsilon_{Po} = \frac{|Po - 64|}{64} \times 100\% . \tag{13}$$

The magnitude of deviation to the local Nusselt number, with respect the theoretical value for circular tubes (Incropera and DeWitt, 1998), in the same conditions, with constant heat flux applied on the surface of the tube, is given by

$$\varepsilon_{Nu} = \frac{|Nu - 4.36|}{4.36} \times 100\% . \tag{14}$$

The fraction η of variation of the diameter of the cross-section ΔD in the output of imperfect microtubes, $D(L)$, with respect to the diameter D of homogeneous cross-section of them, is given by

$$\eta = \frac{\Delta D}{D} \times 100\%, \tag{15}$$

where $\Delta D = D(L) - D$. The dimensionless axial position along the length L of the microtubes is given by

$$z^* = \frac{z}{L}. \tag{16}$$

5. NUMERICAL SOLUTION AND GRID INDEPENDENCE TEST

The commercial software Ansys CFX-12 was used to analyze the problem. In this one, the differential equations, Eqs. (1-5), were discretized and numerically solved for each point at the computational domain. As a boundary condition to hydrodynamic problem, a static pressure of 0 Pa was taken at the exits of tubes. A uniform temperature and velocity profile was used at the entry of tubes. The entry temperature used was 293.15 K. The entry velocity was computed according to the value of Reynolds number. The boundary condition on the walls is with no slip and with a constant heat flux applied of 2,000 W/m^2. The temperature and the entry velocity were used as initial field of these ones. The mesh used was hexahedral, with refinement next to the walls and also to the inlet and outlet sections of tubes.

The number of elements was determined by analysis of the local Nusselt number for the flow with Reynolds number of 800, which provides the greatest thermal entry length. The local Nusselt number for different meshes is shown in Tab. 1.

Table 1. Number of elements versus local Nusselt number for different meshes.

Mesh	Number of Elements	Nu [-]	ε_{Nu} [%]
1	24,300	4.38920	0.66964
2	120,540	4.37576	0.36137
3	447,640	4.37271	0.29156
4	673,265	4.37246	0.28575
5	898,890	4.37231	0.28227

According to Tab. 1, the error analysis for the local Nusselt number, according to Eq. (14), shows the result obtained by mesh 3 showed better agreement with respect to the results obtained by meshes 1 and 2. However, the results obtained by meshes 4 and 5 showed no significant change compared that one obtained by mesh 3. Therefore, the refinement applied to mesh 3 was considered appropriate for this study. In Tab. 1, Nu is the average of the numerical values to the local Nusselt number in the thermally developed region.

6. RESULTS AND DISCUSSION

This section presents the results to Poiseuille and local Nusselt numbers to the imperfect microtubes, according to the considered cases. In all graphs, these microtubes are represented by the fraction of maximum expansion (+) or maximum contraction (–) in the diameter of the cross-section, with respect to the diameter *D* of the homogeneous cross-section of these tubes (which is equal to the cross-section of the ideal microtube, where $\eta = 0\%$).

6.1. Poiseuille Number

The Figure 2 shows the results for the Poiseuille number with respect to Reynolds number in considered range.

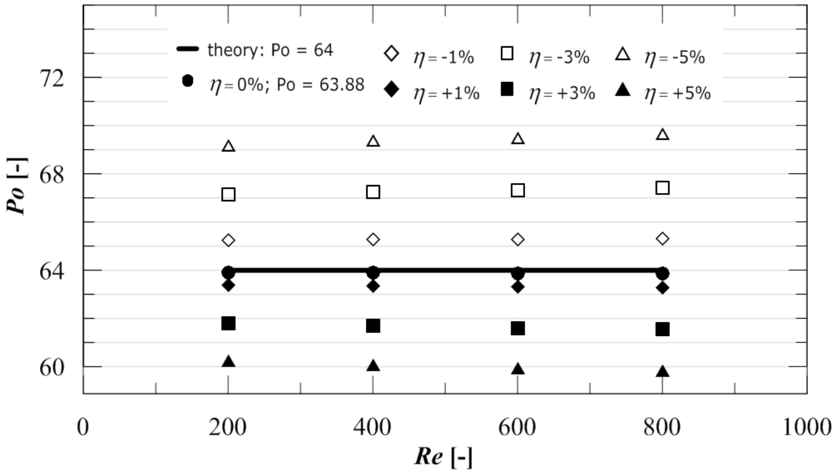


Figure 2. Poiseuille number (*Po*) versus Reynolds number (*Re*).

For microtubes with contraction at the cross-section, the results for the Poiseuille number exceeds the theoretical value expected for circular tubes. As the cross-section of these microtubes is contracted, the average flow velocity increases, to conserve the mass flow rate. Thus, a greater pressure drop occurs in this region, and a greater friction factor is obtained, which leads to a greater Poiseuille number. The opposite occurs for microtubes with expansion at the cross-section. It is observed that the Poiseuille number is also dependent on the Reynolds number considered, which is consistent with reports of Pfahler et al. (1991) and Celata et al. (2002), becoming greater as it increases.

The Figure 3 presents the results of the deviation to the Poiseuille number, with respect to the theoretical value for circular tubes, in according to the range of Reynolds number considered.

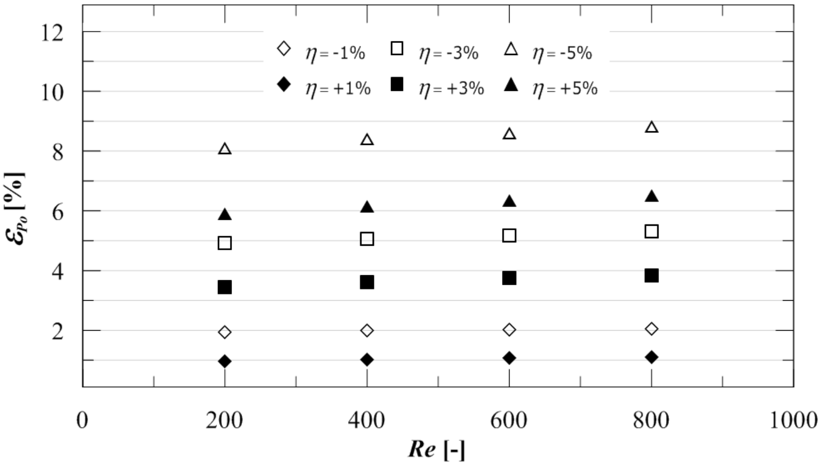
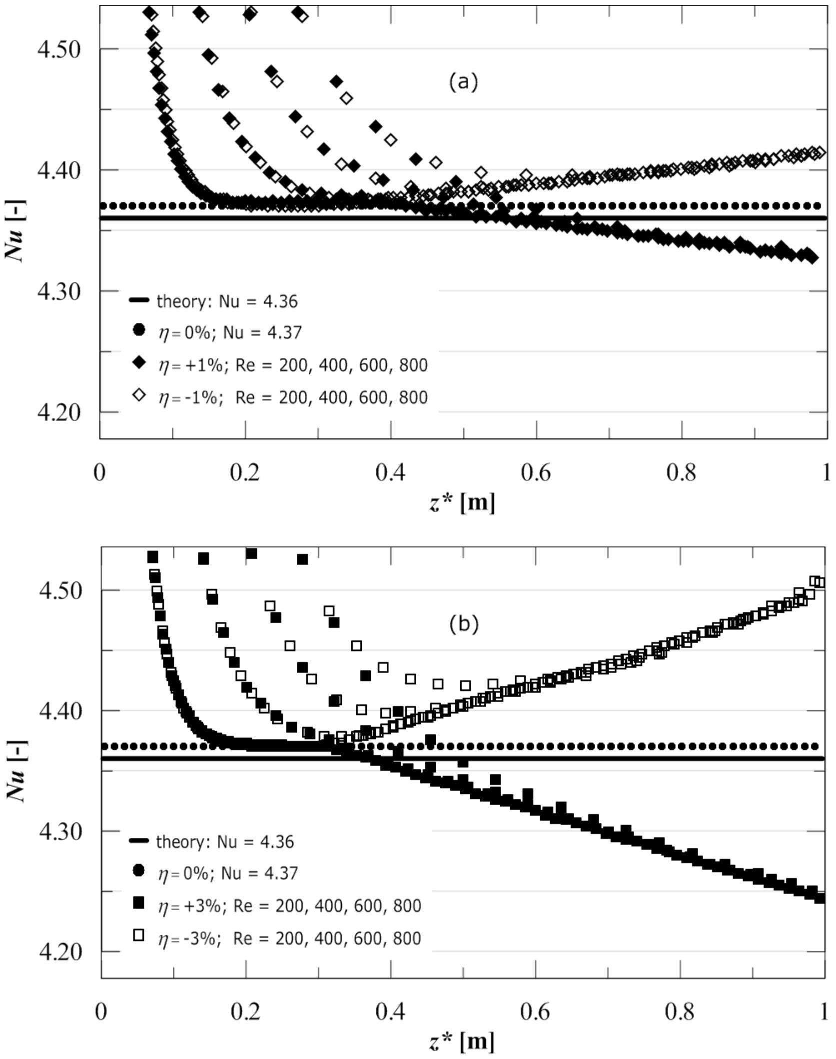


Figure 3. Deviation to the Poiseuille number (ε_{Po}) versus Reynolds number (*Re*) for the analyzed cases.

The deviations for the Poiseuille number were higher in microtubes with contraction at the cross-section, in agreement with accounts of Celata et al. (2006a). According to the Hagen-Poiseuille law (Bruus, 2008), the pressure drop between the ends of the tubes is equal to the product of hydrodynamic resistance of the flow with the volumetric flow rate of fluid (Bruus, 2008). As the mass flow rate is constant at the inlet and outlet pipes, the hydrodynamic resistance is proportional only to the friction factor. In microtubes with contraction in cross-section, the hydrodynamic resistance increases because the area available for flow is reduced, in the region where the cross-section varies. Therefore, occurs an average flow velocity increases, and also in the velocity gradient along the wall, in this region. This increases the shear stress, causing a greater pressure drop than expected. Therefore, a higher friction factor is obtained, which leads to a greater Poiseuille number. In microtubes with expansion at the cross-section, the opposite occurs.

6.2. Local Nusselt Number

The Figures 4(a-c) show the results for the local Nusselt number, along the dimensionless axial position of the analyzed microtubes, for the Reynolds number range considered.



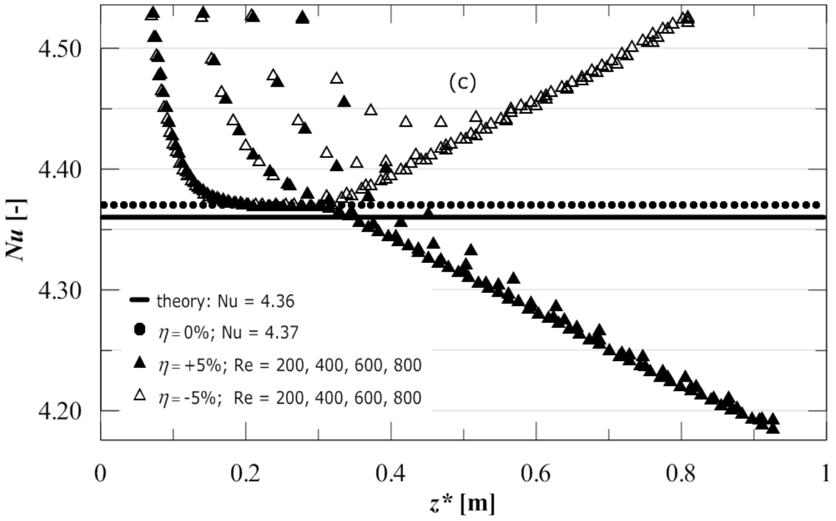


Figure 4. Local Nusselt number (*Nu*) versus dimensionless axial position of the tubes: η = (a) ±1%, (b) ±3%, (c) ±5%.

According to Figures 4(a-c), the Reynolds number range didn't cause influences on the divergences for the local Nusselt number, after thermal development of flow, in contrast with reports of Choi et al. (1991) and in agreement with accounts of Koo e Kleinstreuer (2005). The variations the local Nusselt number, with respect the theoretical value for the thermal condition considered on the surface of the tubes, are due only to variations at the cross-section of the tubes, which is consistent with reports of Chiu et al. (2011). This can be observed by the symbols regarding each one of the microtubes indicated in the figures's subtitle, which show the same trend in the cross-section variation region, for each one of the Reynolds number considered. The divergences for the local Nusselt number, with respect to variations in cross-section, in the thermally developed region, can be explained by variation of the average velocity in this region. For microtubes with contraction at the cross-section, the average flow velocity increases along the region of contraction in cross-section. Thus, the local heat transfer coefficient increases in this region, resulting in a larger local Nusselt number. The opposite occurs for microtubes with expansion at the cross-section.

7. CONCLUSIONS

This numerical study analyzed how the hydrodynamics and heat transfer characteristics are influenced by cross-section variations in microchannels subjected to single-phase laminar flow of incompressible fluid with constant properties. Others scaling effects, such as surface roughness, viscous dissipation and electrokinetic effect, for example, were not considered.

The results obtained in this study showed that cross-section variations in the microtubes considered can lead to divergences to the Darcy friction factor, which were visualized through deviations for the Poiseuille number. Divergences for the local Nusselt number through cross-section variations were also observed, according to reports of Chiu et al. (2011). These divergences showed dependence with the Reynolds number range only for the Poiseuille number in agreement with reports of Pfahler et al. (1991) and Celata et al. (2002), and not for the local Nusselt number, unlike reports of Choi et al. (1991). In the case of microtubes with contraction at the cross-section, the deviations for the Poiseuille number were higher than those obtained for microtubes with expansion at the cross-section, in agreement with reports of Celata et al. (2006a). These results indicate that divergences reported in the literature to measurements the Darcy friction factor, as well as the Poiseuille and local Nusselt numbers, in the flow at microscale, can be related to variations of cross-section in microchannels. Therefore, it is suggested to do a more systematic numerical study, which considers other models of variations of cross-section in microchannels.

8. ACKNOWLEDGEMENTS

The authors acknowledges the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Universidade do Vale do Rio dos Sinos (UNISINOS) for financial support for this work.

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10. RESPONSIBILITY NOTICE

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