Experimental and numerical characterization of the flow in slits: influence of the relative roughness and spacer inter-filaments distance

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Abstract

Despite the significant amount of studies about slit flows, certain phenomena remains to be fully quantified and physically interpreted, namely, the superficial roughness effects on open channel flows and the stability of spacer-filled channel flows. A cell was projected and constructed in order to permit channel height variations, different superficial roughness interposition, and spacer displacement. Through head loss measurements, it was inferred, qualitative and quantitatively, the type and interval of the superficial relative roughness influence. A correlation was proposed to characterize the Poiseuille number in slits flows. Nine spacer configurations were tested and friction factor vs. Reynolds number evolutions were described by numerical and experimental data. Transition quantification and localization and hydrodynamic entrance length were also analyzed by head loss measurements. Flow visualization was made through ink injection and high-resolution photography, supporting the conclusions derived from pressure drop evolutions for spacer-filled channels.

Keywords: relative roughness, spacer, inter-filaments distance, Poiseuille number.

1. Introduction

Miniaturized equipments have been widely applied in numerous areas of industry and investigation, as they can provide an improved global performance attaining very small dimensions. The successful design of equipments such as modern membrane modules requires a good knowledge of the hydrodynamic conditions occurring inside a representative channel. In this context, a slit can be used to study the flow through a great lot of apparatuses, and in particular, of the flow through spiral-wound membrane modules (Schock and Miquel, 1987), which tend to diminish their characteristic length to achieve an augmented total mass transfer. However, despite the significant amount of studies developed in the area of microfluidics, a consensus about the nature of the effects suggested by the published empirical data is far from achieved. As characteristic dimensions for these equipments reduce to and below the millimeter threshold, the continuum approach had to be validated in order to safely apply the Navier-Stokes equations (Pfahler et al., 1990). This macroscopic approach remains valid for this type of flows, especially when the fluid is a liquid (Bayraktar and Pidugu, 2006). Hetsroni et al. (2005) pointed out distinct pressure drop behaviors for different types of similar dimension microchannels, giving credit to the existence of phenomena irrelevant at macroscale. The main criterion for the distinction made by these investigators lied on the microchannels surface...
roughness, summarizing the published data for smooth walled channels and rough walled ones. As the former experiments exhibit at most cases a reasonable coadunation with the theoretical Poiseuille prevision, the latter ones show evident deviations to macroscale typical behavior (Hetroni et al. 2005). Nearly a decade ago, Mala and Li (1999) measured the pressure drop through minitubes with dimensions comprehended between 50 µm e 254 µm, denoting a global increase in the pressure drop for most studied cases, especially in the smaller diameters. Two different materials were used in the fabrication of these channels, fused silica and stainless steel, resulting in appreciable differences in the energy loss through both microtubes. The fused silica ones gave origin to augmented demarcations to Poiseuille flow, fact that was attributed to the different surface roughness values or configurations. Further, a βRe dependence on the Reynolds number was found for values grater than a thousand, maintaining a linear dependence for lower values. At Re<500, exp/lam presented values between 1.08 and 1.18. Papaitsky et al. (1999) measured the pressure drop in rectangular mini-pippettes and found values for the friction factors up to 20% greater than the theoretical ones. More recently, Magueijo et al. (2006) suggested the existence of effects at microscale that are irrelevant at macroscale in slits possessing heights between 700 and 1200 µm, with and without permeation on the bottom wall. Two membranes were used and each one had a distinct manufacturing process, with led to different surface topologies and, consequently, two different surface roughness values. Based on U-manometer pressure measurements, they verified dissimilar head losses and a divergence from the Hagen-Poiseuille solution. Pressure drops were greater for the higher surface roughness value, and a fictitious viscosity was defined as μrough= μapp - µ, varying from 0.516µ e 0.915µ in the experiments. In order to verify the wall roughness effect on microscale flows, Silva et al. (2008) applied the micro-PIV technique to the flow through a rough-walled microchannel, with a hydraulic diameter of 637 µm. The surface irregularities configured a relative roughness value of 1.6%. Through the measurement in 61 horizontal planes, the tridimensional profile was inferred and integrated to provide mass and momentum balances. In comparison with numerical simulation of a similar but smooth-walled microchannel, differences of about 11% on the Poiseuille number were found, demonstrating the need for taking the surface roughness in account at macroscale dimensions.

Retaking the specific case of the spiral wound membrane modules, different flow patterns can occur as parameters such as the Reynolds number and the channel height can vary for a given application or performance. Net-type spacers are widely used since they can promote mixture throughout the flow chamber as well as a periodic disruption of the concentration boundary layer, stopping the spatially growing mass transfer resistance. However, this type of advantages is counterbalanced by a significant raise of the pressure drops through the channel, configuring a trade-off between mass transfer efficiency and energy loss. Although diamond-shaped spacers can be optimized to achieve the most favorable solution for a great variety of flows, ladder-type spacers have their application on very viscous fluids flowing at low Reynolds numbers, due to their comparatively low head losses. Ladder-type spacers are comprised by an equally-spaced series of filaments displaced perpendicularly to the flow direction, supported by longitudinal filaments that provide mechanical support. As investigated in the past, the longitudinal filaments play a minor role on the mass transfer enhancement (Santos et al., 2007) and, besides their voidage effect on the flow, the hydrodynamic conditions remain similar in their absence. A study on the flow patterns and head loss was performed by Geraldes et al. (2002), using flow aligned cylindrical filaments in a slit with the height of 2 mm, 30 mm wide and 200 mm long. Effort was made to verify the flow bi-dimensionality through ink injection and visually determine the Reynolds numbers for which deviations to this trend occur. Supported by differential pressure measurements in a U manometer, transition to an unsteady flow was found in the interval Re (defined with the channel height and mean open channel velocity) of 150 – 300, depending on the inter-filament distance setting. Above critical Reynolds numbers, the flow couldn’t be classified either as laminar or bidimensional, since flow current lines were unidentifiable. CFD simulations were made and the experimental and numeric head loss results were matched to a margin of 15%.

Several investigators stressed the application of numerical simulations to spacer-filled channels, since CFD can be an accessible tool to investigate the flow patterns occurring in those conditions. Geraldes et al. (2002, 2004) used the control volume formulation to the description of the flow and mass transfer occurring in slits, concluding that the reversion of the flow, by means of a recirculation formed in the inter-filament region has the ability to disrupt the mass boundary layer and provide enhanced mass transfer coefficients. Cao et al. (2001) used the software FLUENT to extend these conclusions. Schwinge et al. (2002) used the software CFX to study the flow in similar conditions, comparing it to the flow through a single filament. It was found that the former case shows signals of transition to a transient state at critical Reynolds numbers of about half the same value for a single filament. As this stationary-transient transition phenomenon remains not fully-understood, further investigations are needed in both quantification and visualization of the flow states and patterns occurring in spacer-filled channels.
2. Experimental

In order to carry out the experiments in the context of the two studied phenomena, i.e. the surface roughness effect and the quantification and visualization of stationary-transient transition on a spacer-filled channel, a multi-purpose apparatus had to be projected and constructed. There were three variable parameters in the experiments. The characteristic length of the channel is the first of the imposed variable conditions in the experiments regarding the study of the two phenomena. A slit models an infinite parallel plate flow, which has a characteristic length equal to the channel height. To gauge correctly the influence of this parameter, five different channel heights were considered in the experiments: 0.7 mm, 1.0 mm, 1.2 mm, 1.5 mm and 2.0 mm.

As seen, the superficial roughness seems to have a significant role on the demarcations to theory, observed at microscale. As so, and concomitantly with the quantitative approach aimed in the experiments, five different surfaces for the bottom wall of the channel were constructed to provide, together with the five different channel heights, a great variety of relative wall roughness values. The quantification of the roughness parameter for each surface, the ε value, was made through the use of a contact profilometer. This equipment supplied measurements of the surface topology and a post-treatment to obtain the normalized ε value (half of the maximum distance peak-to-valley \( R_{\text{max}} \), \( R_{y} \) of the norm DIN 4762). Obtained results are presented in table 1.

The third variable parameter in the experiments was the configuration of the spacers. The spacers used in this work were cylindrical filaments transversally placed throughout the channel. As so, three inter-filament distances were implemented and, together with the variation of the height of the channel (three dimensions were used in these experiments: \( h=1.0 \text{ mm, } h=1.2 \text{ mm and } h=1.5 \text{ mm}, \) as they are standards in spiral wound modules), nine spacer configuration were subjected to head loss measurements. The projected and constructed apparatus which fulfills the above requirements is presented in fig. 2.

The possibility of visual access in both upper and lateral directions was granted through the construction of these surfaces in PMMA and further adaptation to microscope visualization is possible due to the lateral fit to standard microscope plates. A great care was taken in the project of the flow development region, since at the beginning of the slit, a total absence of perturbations caused by the standard thread connection and respective section change was intended. A smooth 8 cm-long ramp at the developing zone eliminated all significant perturbations. The studied slit channel was 30 mm wide and 200 mm long. The fluid path throughout the cell length is represented in fig. 3. The head loss measurements were took in multiple pressure taps along the top wall of the channel for the experiments regarding the influence of the \( x \) coordinate on pressure drops, and in two particular taps in the experiments regarding the global head loss evaluation through the channel. The pressure taps consisted on calibrated holes in specific positions on the top wall, linked to small tubes with standard connections.

Table 1 – Roughness values

<table>
<thead>
<tr>
<th>Base</th>
<th>Roughness ε (sample ( \bar{x} ))</th>
<th>( \sigma/\bar{x} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P40</td>
<td>108.8</td>
<td>19.27%</td>
</tr>
<tr>
<td>P80</td>
<td>45.6</td>
<td>31.60%</td>
</tr>
<tr>
<td>P240</td>
<td>17</td>
<td>33.46%</td>
</tr>
<tr>
<td>P600</td>
<td>6.5</td>
<td>54.28%</td>
</tr>
<tr>
<td>HL</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2 – Geometric characteristics of the studied spacer configurations

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h ) [mm]</td>
<td>9.89</td>
<td>5.04</td>
<td>2.54</td>
</tr>
<tr>
<td>( d ) [mm]</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( l/h )</td>
<td>0.40</td>
<td>0.58</td>
<td>0.70</td>
</tr>
<tr>
<td>( d/h )</td>
<td>0.47</td>
<td>0.58</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Fig. 1 – Dimensional parameters

Fig. 3 – Fluid path throughout the cell

Fig. 2 – The cell
In order to achieve precise head loss measurements, two distinct equipments were used: an U-manometer and differential pressure transmitters (Honeywell 24PCE and 24PCC). The differential pressure transmitters were used in the majority of the experiments, while the U-manometer was used to confirm punctually the results provided by the former equipment. Complementing the head loss measurements in the context of the spacer filled channel studies, a digital photographic camera equipped with a Macro 10X lens was used to photograph the patterns of the flow. The scheme of the experiments is represented in fig. 5. To trace the flow, a food colorant was pumped by a syringe pump into two different locations of the cell, at rates between 60 and 200 µl/min. For all the experiments, the Reynolds numbers were comprehended between 58 and 500, as this representative interval can provide the information needed for the study of the intended phenomena.

3. Numeric simulations

Numeric simulations have been widely used to study the flows in a great variety of equipments. As computational power increases, CFD simulations configure an accessible and time-saving technology for predicting flow properties and patterns. The numeric calculations of the present work were made using the commercial software package FLUENT®, which uses the finite volume formulation to solve the continuity and momentum equations (eqs. 1, 2, 3 and 4)

\[
\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  
\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = \frac{\partial P}{\partial x}
\]  
\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}
\]

simulation of the flow occurring in that zone can approximate the behavior throughout the entire geometry. However, this is only possible if adequate boundary conditions are applied to the problem, namely, the periodic boundary conditions. This can be attained by making:

\[
u(0, y, z) = u(l_f, y, z), v(0, y, z) = v(l_f, y, z), w(0, y, z) = w(l_f, y, z)
\]

where \(l_f\) is the length of the periodic geometry – inter-filament distance. No-slip boundary conditions were applied to all solid surfaces. The tridimensional grids used in this work totalized 501,618 hexahedral elements, spaced unequally throughout the geometry as a more refined mesh was placed in the vicinity of the boundary zones to capture the most intense gradients. Due to the unstable character of the studied flow in a broad range of Reynolds numbers, an unsteady approach had to be made in order to simulate the flow. To avoid numerical instability caused by too large time steps, resulting in a high Courant number \(Co = U \delta t / \delta x\), the implicit formulation was chosen. Thus, bigger time steps are successfully implemented as this formulation provides a solution based on spatial calculation at the same time instant, for a given node. In order to solve eqs. (1), (2), (3) and (4), a solution algorithm for the pressure-velocity coupling had to be chosen. The PISO (Pressure Implicit with Splitting of Operators) algorithm, developed by Issa and Gosman (1986) is advantageous in the simulation of instable flows, since it provides two pressure corrections based on mass and momentum balances, before obtaining a new velocity field in the subsequent iteration. Despite the need for augmented computational power for the realization of these extra operations, Issa e Gosman (1986) demonstrated an actual reduction by half in computational time at the study of the flow over a backward-facing step, a problem which exhibits important similarities with the studied case.
Discretization schemes are of the outmost importance to numerical simulations as well, since they quantify how much of the node vicinity information is used in the calculation of a given node. The QUICK (Quadratic Upstream Interpolation for Convective Kinetics) is a second order differentiation scheme that uses a three-point upstream-weighted quadratic interpolation for cell face values. Diminishing the Taylor series truncation error in the discretization – second order precision – more precise results are expected, therefore the QUICK scheme was applied in all present experiments.

The total simulation time varied between 0.1 s and 5 s, and the time step varied between 1e-3 s and 1e-5 s, following the demands of different convergence behaviors denoted in the various numeric calculations. Real simulation time was comprehended between 4 and 40 hours, depending on the used time step.

4. Results presentation and discussion

As referred in the introduction, surface roughness seems to have a significant effect on microscale flows, which traduce into distinct pressure drop behaviors when different surface topologies are tested. In this context, a quantification of these effects is needed, thus, a comprehensive number of surface conditions and channel heights had to be subjected to pressure drop measurements. The results are presented in fig. 7, in comparison with the theoretical values for rectangular channels given by eq. (6) (e.g. Zheng and Silber-Li, 2007)

$$\Delta P = \frac{12\mu^2 L \cdot \text{Re}_h}{\rho h} \left[ 1 - \sum_{n=1,3,5} \frac{1}{n^2} \frac{192}{\pi} \frac{b}{h} \tanh \left( n\pi \frac{b}{2h} \right) \right]$$

(6)

Limiting the result analysis to hydrodynamic smooth wall cases, it can be seen that the magnitude of the characteristic length is an influent parameter to describe the deviations to theoretical predictions. The smaller the channel height, the bigger the difference between the measured head losses and eq. (6) is. This evidence is in agreement with the conclusions of Papautski et al. (1999) and Magueijo et al. (2006): the pressure drop deviation to theory in smooth-walled channels (having a surface roughness at the nanometer scale) is in deep dependent of the characteristic length. It can be noticed in fig. 7 that this deviation occurs for channels having $h\leq1.2$ mm, marking the threshold for the significance of microscale effects, irrelevant to macroscale. Extending these conclusions to the superficial roughness effect, fig. 7 is quite elucidative, as the increase of that parameter leads to higher pressure drops. The dependence is monotonic. In engineering calculations, it’s usual to adimensionalize the pressure drop to the Darcy friction factor

![Fig. 7 – Head loss measurements for all tested channel heights and superficial roughness](image-url)
\[ f = \frac{\Delta P}{h} \sqrt{\frac{2\rho}{L}} \] for diverse experiments. In can be easily deduced that for Hagen-Poiseuille’s infinite and parallel plates flow solution, the friction factor is given by \( f = 24/Re \).

Commonly, the dependence of the friction factor on the Reynolds number is presented on a bi-logarithmic scale, as theoretical values fit into a straight line in such scale.

A linear behavior is showed by figs. 8 and 9, for all surface topologies, denoting a qualitative similarity to the theoretical evolutions. An inverse proportionality stays valid for all surface roughness values, and nonlinear effects caused by possible flow direction changes, recirculations and kinetic energy losses due to the geometry irregularities showed no significant influence on the results.

In order to quantify the exact contribution made by the surface roughness in each case and in an overall context, the Poiseuille number \( Po = Re \) is calculated for each case and related to the respective \( \epsilon/h \) value. Additionally, the height of the channel is adimensionalized as \( h/h_{ref} \), being \( h_{ref} \) the threshold for the influence of phenomena at microscale, previously inferred: \( h_{ref} = 1.2 \) mm.

![Fig. 9 - Friction factors for all tested surface roughness values](image)

(a) \( h=1.0 \) mm (b) \( h=1.2 \) mm (c) \( h=1.5 \) mm (d) \( h=2.0 \) mm

Figure 10 illustrates that plotting, and one conclusion can be readily taken: the experimental points do not align themselves on a common region or line, instead, they show that the relative roughness parameter \( \epsilon/h \) is insufficient to describe the Poiseuille number for each case. However, one other conclusion stands out: for each \( h/h_{ref} \) the Poiseuille number reveals a linear dependence with \( \epsilon/h \) which points out the importance of that parameter on head loss predictions. The slope of that dependence is highly dependent on \( h/h_{ref} \), so microscale flows are very sensible to the surface topologies.

![Fig. 10 - Poiseuille number dependence on relative surface roughness \( \epsilon/h \) and on the adimensionalized channel height \( h/h_{ref} \)](image)

Note that the influence of \( h/h_{ref} \) also affects the \( Po \) value for approximately null relative surface roughness values \( \epsilon/h \) and, therefore, phenomena occurring at microscale, irrelevant at macroscale, are present, whether related to nanoscopic surface roughness or not. The two-variable dependence denoted on fig. 10 can be correlated in a function \( Po/24 = f(\epsilon/h, h/h_{ref}) \). By visual analysis of fig. 10, it seems that a good approximating function belonging to the quadratic form function family can be obtained to match the experimental data.

\[ Po/24 = f(\epsilon/h, h/h_{ref}) = a \epsilon/h + b h/h_{ref} + c \epsilon/h h/h_{ref} + d \] (7)

As \( a, b, c, l_1, l_2 \) and \( d \) are unknown variables, an optimization approach may be made by the least squares method, which minimizes the squared residuals (difference between experimental and approximated points) for all data. A MATLAB® code was created to generate optimal values for the described variables, and the approximating function had a maximum residual of 14.7%, for two of the worst experimental error conditions. It was able to describe the experimental data with a mean residual of 5.4%, and therefore a good agreement between experimental and correlated values was achieved by eq. (8).

\[ Po/24 = f(\epsilon/h, h/h_{ref}) = a \epsilon/h + b h/h_{ref} + c \epsilon/h h/h_{ref} + d \]

\[ + [0.0875 - 4.285] \left[ \frac{\epsilon/h}{h_{ref}} \right] + 3.706 \] (8)

The second objective of this formulation is to confirm the previous conclusions about the linearity of the \( Po \) dependence on \( \epsilon/h \), as well as evaluate the dependence on \( h/h_{ref} \). In fact, comparing the values of \( a \) and \( l_1 \), coupled to \( \epsilon/h \), an almost two-order magnitude difference exists so the optimization...
The method is corroborant with the linear dependence, previously inferred. About the \( h/h_{ref} \) influence, \( c \) and \( l_2 \) terms are in the same order of magnitude and therefore linear and quadratic trends in the \( \text{Po} - h/h_{ref} \) dependence is present. The weak contribution of the \( b \) term suggests a non-significant coupling of the two variables. A similar plot to fig. 10 but with \( h/h_{ref} \) in the abscissa can confirm the dimensions for which the surface roughness effects are noticed – see fig. 11.

Herein is confirmed the existence of two regions, a region for \( h/h_{ref} \geq 1 \) where the \( \text{Po}/24 \) factor stays in the unity vicinity and a narrow band comprehends the experimental data, showing the neglecting influence of surface roughness and microscale effects, irrelevant at macroscale. For the complementary region \( h/h_{ref} < 1 \), a broad zone establishes and the department from the \( \text{Po}/24=1 \) zone is obvious, denoting the influence of both described phenomena.

The experiments made with spacer-filled channels intended to simulate the flow on the feed side of spiral-wound membrane modules. As such, nine spacer configurations were tested, corresponding to three inter-filament distances, and three cannel heights. The adimensionalization of the pressure drop was performed in the same way that in the previous case, by the Darcy friction factor. Pressure drops for each spacer configuration and channel height are represented in fig. 12, combining the experimental and numerical data. The dashed lines are the linear adjustments suggested by experimental data. Analyzing the results, two different regimes can be denoted, as the adjusted curves slope changes on a give Reynolds number – the critical Reynolds number. The transition phenomenon divides a regime where the molecular viscosity is dominant and no transient characteristics are present from a regime where the viscosity and inertial effects parallelize. The numerical predictions were made to infer the validity of the method for predicting head losses. Convergence of the numerical method took place for the four spacers.
presenting more verisimilar configurations, and divergence was found for most obstructed channels as well as for the bigger inter-filament distance. The periodic boundary conditions is therefore adequate for \( \text{d}/\text{h} < 0.58 \) and \( l/\text{h} < 4.2 \). Good agreement was found for S2 spacers, while under-predictions are observed for spacers S3. Transition considerations will be retaken ahead in this document.

Extrapolation of the previous results for spacer-filled channels typifying a spiral-wound module needs accountancy for channel entrance effects. Thus, it is important to estimate the hydrodynamic entrance length, defined as the distance from the entrance of the channel for which the flow presents cyclic behavior. A way to infer that parameter is to disturb the flow by fluid injection in the perpendicular direction of the main flow – in this particular case, the injection of ink – and verify the distance for which the flow becomes periodic. Fig. 13 illustrates the above-described technique and one can denote cyclic pattern establishment downstream of the third filament. For that case, \( \text{Re}=100 \), typical laminar patterns can be distinguished, with formation of current lines defining recirculating zones in the downstream vicinity of each filament, and also maximum velocity zones. These two regions are visible in weaker color due to low radial diffusion in the former case and to low fluid residence times in the latter.

It remains to be inferred the Reynolds number influence on the hydrodynamic entrance length. As stationary laminar regime occurs in a narrow Reynolds number interval, soon we lose definition in the current lines to visually determine that parameter as it was done through fig. 13. Another useful method for evaluating the hydrodynamic entrance length is to measure the pressure drops in various \( x \) locations, defining a pressure drop evolution for the longitudinal coordinate. It is known that the local friction factor assumes its bigger values at the channel entrance due to a plug-like velocity profile, thus, cyclic flow is achieved when the slope \( \gamma \) of the evolution \( \rho(x,y) = (\rho_0 - \rho) + \bar{\rho}(x,y) \) becomes a constant value. The pressure distribution is then formed by the addition of a mean term, related to the bulk pressure drop and a fluctuant term related to local friction factor variations on spacers inter-distance. Fig. 14 shows the longitudinal evolution of \( \Delta P \) in spacer S1, \( h=1.0 \text{ mm} \), for three different circulation velocities. The experimental data aligns onto a linear evolution from an almost fixed \( x \) location, to all tested Reynolds numbers. Fig. 15 extends that conclusion to the other spacer configurations, thus, it can be affirmed that the hydrodynamic entrance length does not depend significantly on the Reynolds number, but instead on the filament count from the channel entrance. Considering the figs. 14 and 15, and the inter-filament distances presented in table 2, one can infer that the entrance length corresponds to the displacement of 3 to 4 filaments. With the support of the pressure losses presented in fig. 14 and 15, fig. 13 can be validated as model-flow for the remaining Reynolds numbers, confirming the influence of spacer filaments count on the hydrodynamic entrance length.

In the study of spacer-filled channel, the flow behaves as a dampened non-linear system with one control parameter – the Reynolds number. Thus, after a given Reynolds number, a flow instability occurs, generating transient phenomena which eventually may lead – with the raise of this parameter – to turbulence transition. The instabilization of the pure viscous flow is denoted on fig. 12 by a slope
The change in the friction factor – in a bi-logarithmic representation with the Reynolds number – in a well-defined region. Table 3 resumes the data of linear adjustments, as well as the critical Reynolds number deduced in the intersection of those adjustments. The results are clear about the channel height and inter-filament distance effects on flow stability. Critical Reynolds number rise in broader channels: this stabilizer effect is due to a bigger volumetric portion of unperturbed flow, as a minor fluid mass experiences direction changes and pressure variations caused by a filament displacement. Influence of inter-filament distance is less immediate on its physical interpretation, but the filament number per length unit is concluded to stabilize the flow, as spacer S1 presents the minor $Re_c$ and S3, the major. This conclusion is in agreement with other investigators (Santos et al., 2007). Distinct behaviour is observed for channels with $h=1.0$ mm, where there is no evidence of transition as data adjusts onto a linear fit. Therefore, and with support of fig. 17(b), it is inferred that in channels where the obstruction level is very high, transient regime occurs in the entire $Re$ studied interval. Through destabilization considerations is useful to have a visual access to the flow patterns, in order to study the evolution of those as the Reynolds number increase towards $Re_c$. The apparatus represented in fig. 5 was used to provide a flow trace method capable to reveal flow current lines and therefore, the formed patterns. The results for spacer S2, $h=1.5$ mm is presented in fig. 16.

For $h=1.2$ mm - fig. 17(a) – well defined laminar patterns can be observed up to $Re=125$. From $Re=150$ to $Re=175$ occurs a similar phenomenon for that of fig. 16, i.e. the current lines fade to time-dependent configurations. Again from table 3, $Re_c=159$ is in agreement with the visual analysis. For $h=1.0$ mm, despite the presence of recirculations, these structures do not repeat themselves along the channel in a similar form, nor did present stationary characteristics in the laboratory experiments. The conclusion of transient regime for this channel height is then suggested as well on visual experiments. Other question may be posed regarding the instability study: does transition to transient flow depend on the longitudinal coordinate $x$? Fig. 18 shows a top view of a spacer-filled channel.
flow, for spacer S2 and \( h=1.5 \text{ mm} \) and three distinct regimes can be deduced. The first one corresponds to a purely viscous laminar flow, for which the flow can dampen the spacer-induced perturbations and the \( x \) coordinate has no influence on the flow stability. A second regime, in the vicinity of \( \text{Re}_c \), has both stationary and transient regimes separated by a well-defined point in space, which moves upstream as the Reynolds number rise. A third regime is established when the transition point installs itself on the entrance of the cell, for which the \( x \) coordinate cannot describe the flow stability once more.

5. Conclusions

Superficial roughness was found to have a significant influence on pressure drops of slit channel flows as the characteristic heights reduce to \( h \leq 1.2 \text{ mm} \). A two variable dependence for the Poiseuille number was concluded, since the relative roughness parameter \( \varepsilon/h \) was unable to describe the \( \text{Po} \) behaviour for all experimental data. However, \( \text{Po} \) vs. \( \varepsilon/h \) plotting showed a linear dependence between these two variables, despite the apparent random character of the roughness topology. The channel height seems to have also influence on the Poiseuille number, and a correlation for \( \varepsilon/h<16\% \) and \( 0.58<h/h_{\text{ref}}<1.67 \):

\[
\text{Po} = \frac{1}{24} \left( e/h, h/h_{\text{ref}} \right) = \begin{bmatrix} 0.00180 & 0.0299 \\ -0.0299 & 1.629 \end{bmatrix} \left( e/h \right) + \begin{bmatrix} 0.0875 \\ -4.285 \end{bmatrix} \frac{e/h}{h/h_{\text{ref}}} + 3.706
\]

In spacer-filled channel flows, pressure drops are higher for lower channel heights and lower inter-filament distances. Numerical and experimental data are in agreement for spacer S2 but not for spacer S3. Periodic boundary condition could not be applied with success to all spacer configurations. Regarding the hydrodynamic entrance length, by flow visualization and pressure drop measurements, a spacer count of 3 to 4 filaments was found to establish periodic flow, quite independently of the Reynolds number. A transition phenomenon was inferred for most of the studied spacer configurations, as it was found that higher channel heights and lower inter-filament distances have a stabilizer effect on the flow, delaying the instability occurrence. Through ink injection, flow patterns were photographed in a lateral section view. Viscous laminar regime, with well defined current lines and recirculations were observed for low Reynolds numbers, while for \( \text{Re} \) in the vicinity of \( \text{Re}_c \) transient patterns appear, before the fading of the flow trace due to improved flow mixing capacity. The appearance of transient structures in concomitant with critical Reynolds numbers derived from friction factor representations. The instability of the flow was found to have three distinct regimes: a stationary laminar regime for lower \( \text{Re} \) values, an \( x \)-dependent transition in the vicinity of \( \text{Re}_c \) and a fully transient flow for higher Reynolds numbers.

References


