Numerical Simulation and Experimental Study of Water Flow Behavior in Minichannels

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This paper presents a contribution to the study of the pressure drop in rectangular mini-channels having hydraulic diameters of 0.099-1.923 mm. The test fluid was water, maintained at constant temperature of 20°C. Measurements of the pressure drops were done within the channels, far from the entrance and exit disturbances. We are particularly interested in the influence of dimensional characteristics of these mini-channels on the friction factor. We also report numerical simulation results (2D and 3D) of water flow under the same conditions. The Reynolds numbers were between 94 and 4912. The simulations were carried out using the FLUENT CFD software, which is based on the Finite Volume Method. These results are compared to experimental data resulting from tests.

The experimental apparatus consists of a pump driven by an electric motor. This pump ensures the circulation of the test fluid (water), pumping the required quantity from the reservoir and driving it toward the mini-channel. The channel, assembled in a sandwich configuration, consists of two plates of polycarbonate, which tighten a stainless steel spacer that defines the height of the channel. The thickness of the spacer was varied from 0.05 to 1 mm. The width of the channels was 25 mm for all the sections tested. We opted for 150 mm long mini-channels to take into account the length of developing boundary layers. The pressure taps were localised sufficiently far away from the entrance and exit to be sure that the flow was well established. Two measurements series were conducted to test the repeatability. Equipment calibration was done with particular attention.

The experimental data interpretation was based on the traditional results (Hagen-Poiseuille). The theoretical friction factor for the laminar flow in rectangular channels was calculated using Shah and London equation’s [1]. Finally, we used the Blasius equation to determine $C_f$ for turbulent flow.

The variation of the pressure drop vs. Reynolds number, for the first and the second series of measurements, shows a change in the friction behavior. This reveals a decrease in the critical Reynolds number of transition with the reduction of the channel’s height. In fact, it is an approximate critical Reynolds number around which the transition from the laminar flow towards the turbulent flow occurs.

The plot of the critical Reynolds number according to the height of the channel show that for the channel of 1 mm height, $Re_c$ is practically equal to 2200 (normal value). The 300 microns height channel indicates $Re_c \approx 1700$, whereas the transition appears round $Re_c \approx 700$ for the channel of 50 microns height. These Results are in good agreement with the results obtained by Peng et al. [2], Mala et al. [3], Yu et al. [4] and Harley et al. [5].

The evolution of $C_f$, according to the Reynolds number for the various heights of channels tested, shows that decreasing $D_h$ decreases $C_f$, and an overestimation produced both by the equation of Shah & London [1] for the laminar flow and the correlation of Blasius for the turbulent flow. The reduction in $C_f$ compared to the theory becomes more marked with high Reynolds numbers. Thus the difference with Blasius equation reaches more than 40%.

The measurement uncertainties were quantified to judge the relevance of our experimental results. An estimation of the relative error shows that most significant errors were: 0.10 % for $\Delta P$; 1.91 % for $\dot{Q}$; 4.84 % for $D_h$ and 14.40 % for $C_f$. The results of $C_f$ vs. the Reynolds number for the channel of 0.03 mm height, including the errors bars, indicate that the curves of experimental measurements remain distinct from the theoretical values and always fall below those, especially for higher Reynolds numbers.

The analysis of experimental data showed that transition from the laminar to turbulent regime appears rather than envisaged. With regard to $C_f$, the data were systematically lower compared to the
theoretical values, both in laminar and turbulent flow; and this occurs even after including the measurements uncertainties. This deviation increases as the Reynolds numbers increase, and also when the height of the channel decreases.

The results of the simulated friction factor were superimposed coarsely on the theoretical values, especially in the laminar region where the variation does not exceed a few percent. The results in the turbulent region are less accurate.

References