

INLET AND OUTLET MINOR LOSSES IN PRESENCE OF COMPRESSIBLE GAS FLOWS IN A MICROTUBE

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1. INTRODUCTION

During the last decades a series of numerical and theoretical works have been addressed to the analysis of pressure drops in microchannels with inner dimensions lower than 0.5 mm. The results obtained by testing both liquid and gas flows have confirmed that a good agreement there exists between the correlations used for the prediction of the pressure drop in conventional channels and the experimental data obtained for microchannels if no significant scaling effects are present (Morini, and Yang, 2013). In fact, the reduction of the inner dimensions of the channels can introduce scaling effects which must be taken into account if a correct evaluation of the pressure drop is needed. As an example, when the inner diameter of the channel is reduced for a fixed value of the Reynolds number an increase of the average velocity is obtained. The increase of the average velocity can be very strong for gas flows through microchannels where values larger than 100 m/s can be reached at low Reynolds numbers. In this case the pressure drop can be affected by compressibility effects for Reynolds numbers lower than 2000 (laminar regime) which is not common for conventional tubes for which compressibility effects tend to become important for larger Reynolds numbers. In the cases in which the compressibility effects becomes predominant the conventional correlations used for the prediction of the minor losses linked to the inlet and outlet of the microchannel, validated in general for incompressible flows, are not still valid. The presence of the minor losses due to the entrance and to the outlet regions are very important in microdevices (Morini et al., 2007, Kandlikar et al., 2011) because in these regions a strong variation of the free cross section occurs and in many cases the geometry of these region is not optimized in order to reduce these minor losses. The role of these minor losses is extremely important in micro heat exchangers where the role played by the manifolds is very important on the distribution of gas flows among the parallel microchannels (Yang et al., 2013). The aim of this work is to study both experimentally and numerically in which way the minor losses linked to the entrance and to the outlet regions of a microtube must be evaluated in presence of a gas flow with strong compressibility effects at low Reynolds numbers ($Re < 2500$).

2. EXPERIMENTAL PROCEDURE

A series of experimental tests have been carried out by using as working fluid Nitrogen with the help of the test rig shown in Fig. 1. Nitrogen is stored in a high pressure flask (200 bar) (1) and is brought to approximately 11 bars and ambient temperature before entering a 7 μm particle filter (2, Hamlet) used to prevent possible impurities from clogging the microchannels or the flow meters. A three-way valve (3) directs the flow to the proper flow sensor, as the facility is equipped with three Bronkhorst EL-Flow E7000 operating in the 0-50 Nml/min (4a), 0-500 Nml/min (4b) and 0-5000 Nml/min (4c) ranges respectively. The flow sensors are able to impose the mass flow rate by means of a computer-steered valve: this allows an indirect regulation of the pressure at the inlet of the microtube. The gas enters then the test section (5), before which a pressure sensor is connected. The test section allows to test microtubes of varying length (1 to 100 cm) and variable inner diameter (from 100 μm to 300 μm), keeping the same external diameter, namely 1/16". After exiting the microtube, the gas is collected in a calm room and finally vented to the atmosphere. The total pressure drop between the inlet and the outlet of the microtube is measured by means of a differential pressure transducer (6, Validyne DP15) with an interchangeable sensing element, which allows accurate measurements over the whole range of encountered pressures. To measure the temperature at the entrance and at the exit of the microtube, two K-type, calibrated thermocouples are used (7): through these values and that of the pressure, the densities of the gas at the channel inlet and outlet can be calculated.

First, the microtube to be tested is mounted on the facility and the circuit is checked for leakages; then, measurements are performed by imposing a certain inlet Reynolds number (which can be related to the mass flow rate, the parameter which can be controlled) and recording for every measurement pressure drop, inlet and outlet temperatures and flow rate by means of a data acquisition system and a PC.

Three different stainless steel microtubes (Upchurch Inc.) have been tested in the experiment with internal diameters ranging between 300 and 100 μm . The minor losses at the inlet and at the outlet are due to the abrupt reduction of the cross section from an inner diameter of 4 mm to the inner diameter of the tested microtube.

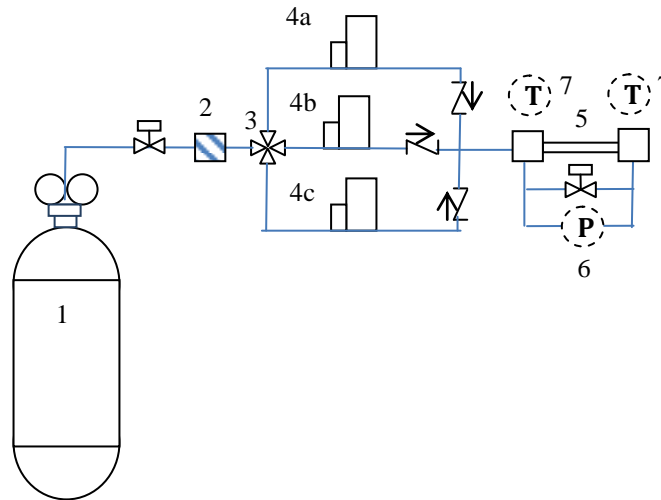


Figure 1 – Sketch of the test rig.

In order to gain a more detailed and complete set of physical data about the flow behavior through the microtube, the experimental analysis has been coupled to a numerical analysis of the compressible flow through the system in which the real geometry of the inlet and outlet regions has been modeled. The governing equations have been solved using the finite element method within the Comsol Multiphysics © environment with a relative tolerance for the main governing parameters set to 10^{-3} . The experimental data in terms of pressure, velocity and flow rate are used as boundary conditions for the numerical simulation; in this way the local trend of pressure, velocity and temperature can be calculated numerically along the tube.

3. RESULTS

The numerical results have been used to obtain a series of detailed information about the flow characteristics along the tube and close to the inlet and the outlet regions at different Reynolds numbers. The numerical code is able to calculate the outlet pressure by using the experimental value of the inlet pressure and of the flow rate imposed (i.e. Reynolds number). To analyze the grid independence of the numerical results, several mesh sizes have been considered. The grid resolution has been analyzed by monitoring the convergence of the pressure at both the channel inlet and outlet ($p_{in,ch}$ and $p_{out,ch}$).

Table 1. Comparison between experimental data and numerical results.

Re	Experimental		Numerical results	
	$p_{in,ch}$ [kPa]	$p_{out,ch}$ [kPa]	$p_{in,ch}$ [kPa]	$p_{out,ch}$ [kPa]
119.06	122.62	102.11	122.59	102.12
173.14	131.70	102.32	131.68	102.31
255.25	144.65	102.80	144.71	102.68
334.77	157.02	103.42	157.17	103.14
415.30	169.25	104.25	169.52	103.74
494.57	180.95	105.25	181.38	104.41
576.37	192.61	106.39	193.19	105.21
658.27	204.34	107.67	205.07	106.15
740.43	215.89	109.08	216.78	107.16
999.19	250.90	114.14	252.28	110.95
1088.45	262.78	116.00	264.29	112.48
1179.24	274.81	117.99	276.47	114.16
1274.88	287.05	119.96	288.77	116.01
1369.78	299.31	122.10	301.14	117.97
1468.64	311.71	124.32	313.62	120.09
1571.62	324.82	126.51	326.76	122.46
1681.00	337.95	128.89	339.91	124.97

For each analyzed mesh size, the *RMS error* between the predicted values and the experimental ones has been calculated. The comparison between the experimental data and the numerical results, in terms of outlet pressure, obtained for the finest mesh resolution highlighted a good agreement with the experimental data, as shown in Table 1.

The numerical code, calibrated with the help of the experimental data, have been used to estimate the values assumed by the minor losses coefficients (K_i and K_{out}) linked to the entrance and to the outlet regions as a function of the Reynolds number. In fact, these coefficients can be considered as constant (and linked to the geometry of the discontinuity) only for incompressible flow. In presence of compressible flows, like in this case, the minor losses becomes a function of the Reynolds number.

Moreover, several numerical runs have been performed in order to evaluate the influence of the edge shape and the manifolds diameter, at both the inlet and outlet regions, on the minor losses coefficients. The minor losses coefficients as a function of the Reynolds number are depicted in Figure 2 for different values of the manifold diameters and for both sharp edges and rounded edges. The numerical results have pointed out that the value of the minor losses coefficient depends on the value of the Reynolds number; therefore if constant values of the minor losses coefficients are considered the friction factor can be overestimated or underestimated, depending on the value of the Reynolds number.

In the paper a procedure for the right estimation of the pressure drop along a microchannel in presence of compressible flows will be described. It will be shown that the average Poiseuille number along the tube can be obtained starting from its value for incompressible flow and by introducing a correction factor which depends on the Mach number at the outlet section (which can be easily measured).

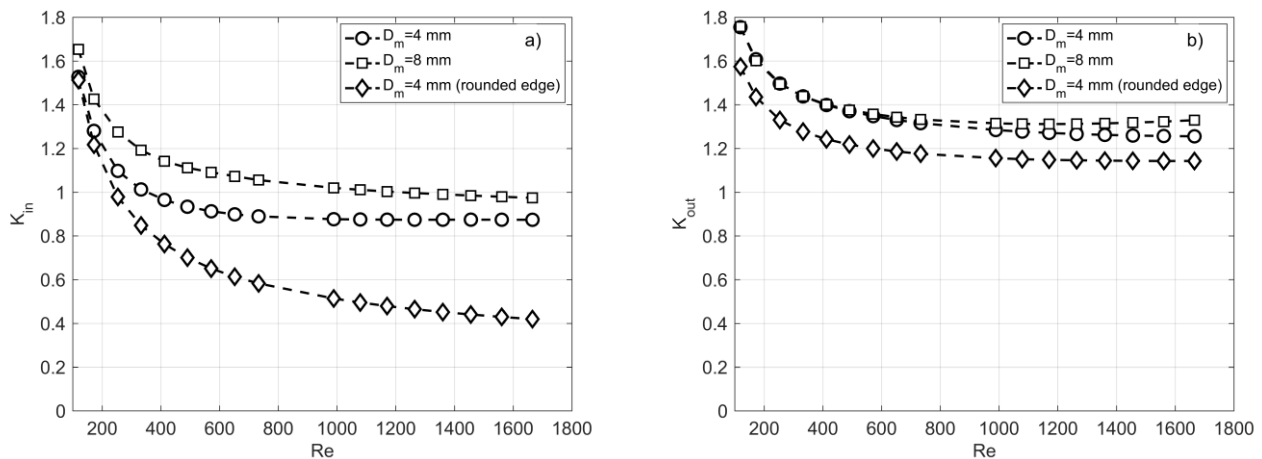


Figure 3. Minor losses coefficients linked to the entrance (a) and to the outlet (b) regions as a function of the Reynolds number. D_m is the inner diameter of the tube connected to the microtube ($D_h=133\mu\text{m}$) ends.

4. CONCLUSIONS

In this work a combined experimental and numerical analysis of pressure drop in microtubes in presence of compressible flows is described. The experimental data obtained at the ends of the microtube are used as boundary conditions for the numerical runs. In this way the local trend of the main flow parameters along the microtube can be obtained. By using the trend of the static and total pressure it is possible to predict the values of the minor losses coefficients linked to the inlet and outlet regions. A general procedure for the right estimation of the pressure drop along a microchannel in presence of compressible flows is finally described.

5. REFERENCES

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