COMPUTATIONAL MECHANICS 2019
35th conference with international participation
Srní
November 4 - 6, 2019

Numerical and experimental investigation of compressible viscous fluid flow in minichannels

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1. Introduction

The work deals with compressible viscous fluid flow in narrow channels with rectangular cross-section with high aspect ratio. The characteristic dimension is the height of the channel which is varied from 0.5 to 10 mm. The issue of fluid flow in a straight channel may appear very easy thanks to the simplicity of the geometry and many commonly known facts. The opposite is true in case of narrow channels and compressible fluid. The study is focused on the value of critical Reynolds number Re_c and also on suitable approaches to the measuring and modelling of such flows. The usually known value of $Re_c \approx 2\,300$ is derived for channels of ordinary dimensions. In microchannels (height to 200 μm) the laminar flow can be stable to the values of $Re_c \approx 10^4$. The study aims mostly at minichannels (height between 200 μm and 3 mm), where the situation is very poorly explored, especially in case of a compressible fluid. Fluid flow in narrow channels and gaps of various cross-sections is a phenomenon occuring in many technical applications, such as clearance gap flow in control valves of steam turbines, tip leakage flow in gas and steam turbines, clearance gaps in screw compressors etc., and it is therefore important to further develop knowledge in this area.

The experimental part of the study is taking place in the Institute of Thermomechanics of the CAS, v.v.i., where properties of air flow through the channels were measured. The air is sucked in the channel through the shaped inlet area, then it is accelerated thanks to the selected pressure drop and behind the channel the air flows into the free space represented by a settling chamber. The appropriate pressure is maintained in the settling chamber. Distribution of static and total pressure was measured in the channel axis together with wall shear stress. Interferograms were also obtained in several cases. Experiments are performed in a calibration channel of height 10 mm and sufficient length for the flow to get fully developed. This channel serves for calibration of mesurement techniques and for validation of numerical solver for this type of flow. Experiments and numerical simulations in minichannels are then carried out for heights from 0.5 to 4 mm and conclusions concerning critical Reynolds number are drawn from them.

2. Numerical discretization using discontinuous Galerkin method

Laminar and fully turbulent numerical simulations were performed to examine compressible fluid behaviour in minichannels. The in-house numerical solver based on the discontinuous Galerkin finite element method [1, 2] is used. Mathematical model of laminar compressible viscous fluid flow is formed by the system of Navier-Stokes equations in 2D. In case of turbulent simulations the system is Favre averaged and closed by the two-equation k-ω turbulence model of Wilcox [4]. Spatial discretization of the mathematical model is accomplished by the discontinuous Galerkin method (DGM), using second order of accuracy and Langrange basis functions. Time discretization is realized with first order of accuracy using an implicit scheme and GMRES method.

Despite of many advantages of the discontinuous Galerkin method, discretization of the two-equation turbulence model by DGM causes serious problems with stability of numerical simulations. Modifications of the turbulence model are employed for this reason, namely the logarithmic formulation of the transport equation for specific dissipation rate ω [3] and restriction of turbulent kinetic energy k.

3. Validation of experimental and numerical methods in calibration channel

Geometry of the calibration channel computational domain and appropriate boundary conditions are shown in Fig. 1. The real channel is the thin middle part of length 1526 mm and the small inlet area of length 114 mm. The large added inlet and outlet areas are necessary to prevent boundary conditions to influence natural intake of air into the channel and free outflow into the settling chamber. The computational domain is discretized by a structured computational grid properly refined near the walls and in the outflow area, where shock waves occur in case of an over-critical pressure ratio. Considering the dimensions of the channel and velocity of the flow, the numerical simulation is performed as fully turbulent. There is a distribution of static and total pressure in channel axis for pressure ratio 0.3 shown in Fig. 2, numerical results are compared to the experimental ones. Similar results are obtained for two under-critical pressure ratios 0.6 and 0.8. Wall shear stress distribution for all pressure ratios is show in Fig. 3. Experimental and numerical values of the wall shear stress are in very good agreement except for the first three measured points, where the flow is not yet fully developed and the used measuring technique (sublayer fence probe) gives not quite reliable values. Despite small disagreement in the total pressure we consider the numerical solver suitable for use in minichannels.

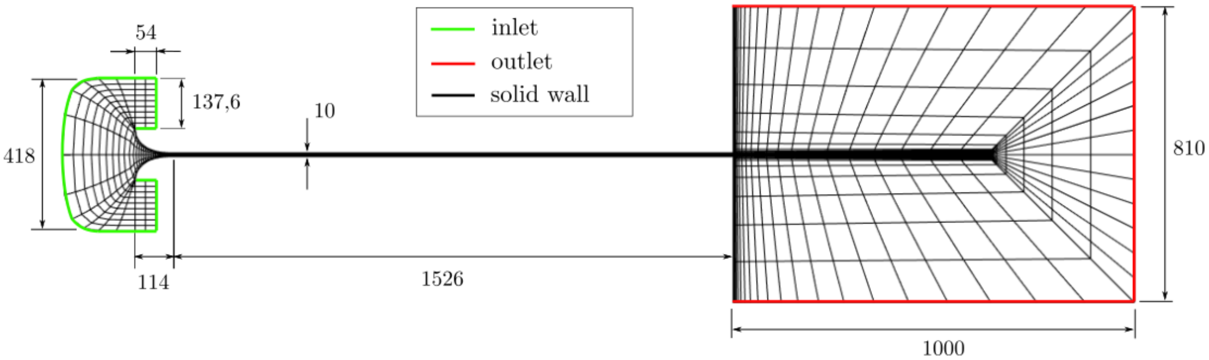

Fig. 1. Geometry of computational domain for the calibration channel with highlighted boundary conditions; dimensions are in millimetres, grid density is only illustrative

4. Compressible fluid flow in minichannels of height 0.5 to 4 mm

Geometry of the computational domain for minichannels is very similar to the one of the calibration channel. The height is set to 0.5, 2, 3 and 4 mm and the length is 92 mm. Only static pressure is measured in minichannels because of the small dimensions of the channel. Estimated Reynolds numbers for all minichannels lie above commonly recognized critical value,

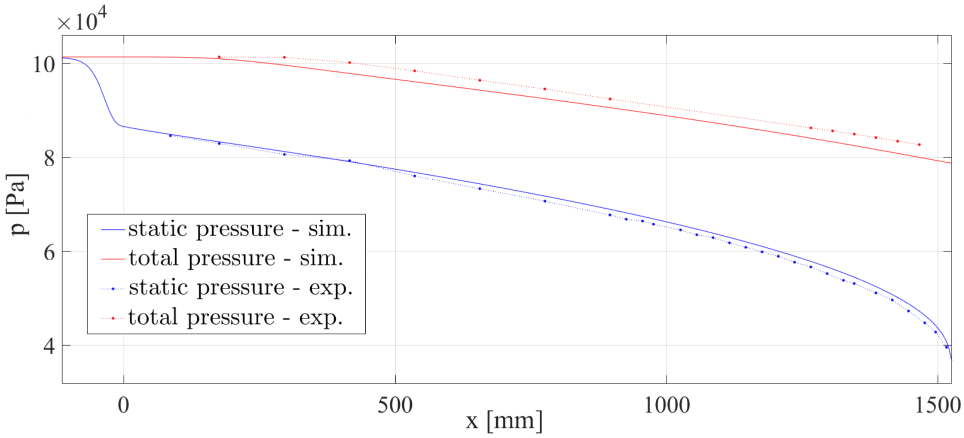

Fig. 2. Distribution of static and total pressure in calibration channel axis for pressure ratio 0.3

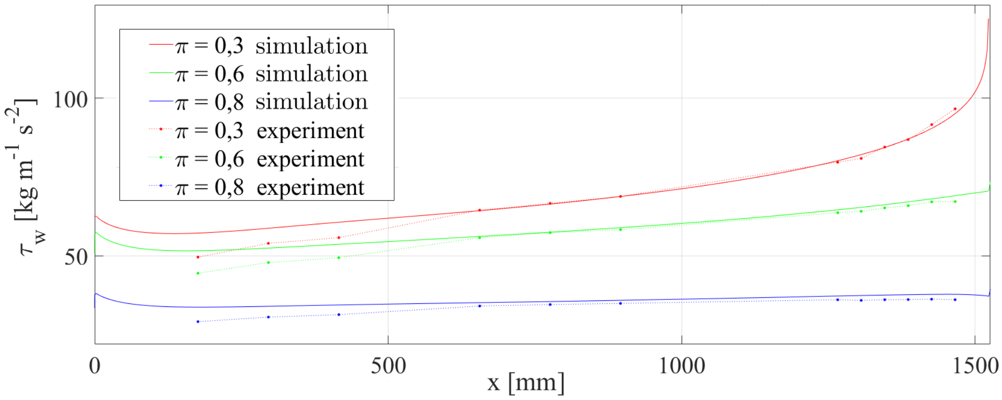

Fig. 3. Distribution of wall shear stress in calibration channel for all three pressure ratios

but due to many uncertainties in this area both laminar and fully turbulent simulations are performed. Numerical results in comparison with experimental data are shown in Fig. 4 for channel of height 3 mm. For all four channels we get similar numerical results. For channels of height up to 2 mm the experimental values fit very closely the laminar curve. From 3 mm we can observe clear deviation from laminar curve as in Fig. 4. Nevertheless the experimental values stay far from the turbulent curve. They come close to the turbulent curve only at the end of the channel. Reynolds number in the channel based on the height of the channel and approximate velocity in the vertical cross-section is at least $Re_c \approx 17\,000$ for the height 2 mm, which is far above the supposed critical values. In this case the flow turns out to be laminar in the whole channel.

5. Conclusions

The obtained results indicate that there starts a transition from laminar to turbulent flow in channel of height around 3 mm. An intermittent regime may occur in the channel. Where exactly in the channel and for which height the transition occures is a very difficult question. We must have a proper model of transition to answer this question. Since essentially almost all current models of transition are calibrated for flow around the body, there is a need to calibrate one of them for internal flows and broadly test it with help of experimental data.

The shift of the critical Reynolds number to the value of approximately $17\,000$ is an important result. It confirmes the assumption of the need to treat minichannels differently than

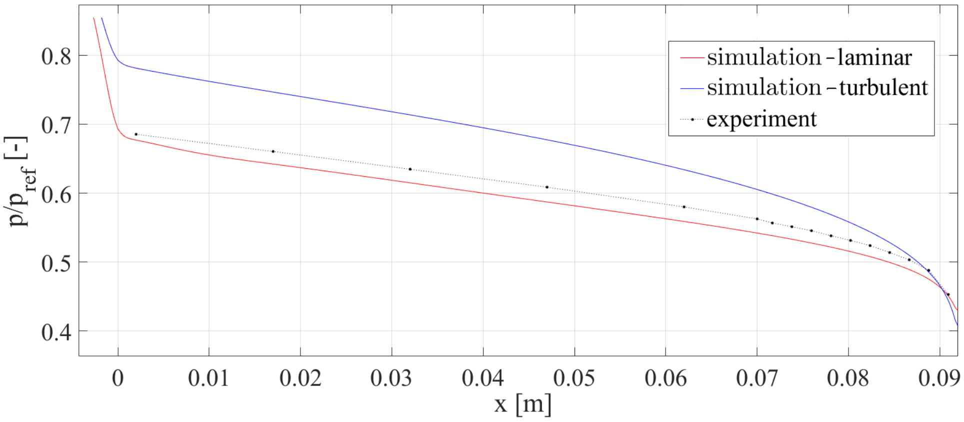

Fig. 4. Distribution of static pressure in channel of height 3 mm, pressure ratio 0.189

common channels or microchannels. The chosen approaches and numerical methods prove themselves to be suitable for investigation of the compressible viscous fluid flow in narrow channels and can be used for future research in this area.

Acknowledgements

This work was supported by the project LO1506 of the Czech Ministry of Education, Youth and Sports under the program NPU I, and by the project SGS-2019-009.

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