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Fanno flows in micro-channels: an enhanced quasi-2D laminar numerical model for gas flow

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In micro-flows surface friction dominates over the inertial effects so that the fluid compressibility cannot be neglected when dealing with gas flows. The Fanno theory presents a mathematical model for computing the stationary adiabatic fluid flow characteristics in constant cross-section channels. The model is based on three first-order differential equations (conservation of mass, momentum, and energy) and a constitutive equation (*e.g.* ideal gas state equation), and requires three boundary conditions (upstream and downstream stagnation pressures, and stagnation temperature). From these, 1D models are easily built where all the flow characteristics are computed as a function of the local Mach number and friction factor.

While the evaluation of the Mach number can be derived iteratively from the boundary conditions, the friction factor in case of compressible flow poses a number of issues[1]. For simplicity, it is often accepted that friction is constant when the flow is laminar, in line with the canonical fluid dynamics formulas for incompressible flows. However, this leads to large errors in the model predictions as the Mach number grows and compressibility cannot be neglected. In fact, assuming the flow is laminar, the velocity profile is no longer parabolic but becomes more and more flat with growing Mach numbers. Consequently, the velocity derivative at the wall is larger. A similar behaviour is also encountered in compressible turbulent flows. Proper correlations are thus needed for the correct evaluation of the friction factor. For the case of laminar flow these will depend on the channel cross-section type and the Mach number alone.

Similarly, the numerical model that can be built from the Fanno theory inherently suffers from the limitations of 1D models. For instance, correct values for the average dynamic pressure and the bulk temperature over a section cannot be derived from a single velocity value having no knowledge over the velocity profile. Also in this case, proper correlations derived from the analysis of the velocity profiles are needed if the predictive capability of the model is to be improved in a quasi-2D fashion. Once again, these correlations depend on the cross-section type and the Mach number.

Considering the small channel size required, an accurate experimental study in order to collect the information needed for the correlations would almost be impossible. In the present study it was decided to proceed numerically by collecting a large amount of data (*e.g.* velocity profiles, pressures, temperatures, thermophysical properties, wall shear stresses) over 1638 cross-sections from a set of 40 CFD analyses for two channel cross-sections types (circular and parallel-plates). All the correlations are derived by analysing, plotting and fitting this data.

The predictive capability of the 1D Fanno flow numerical model has been shown to improve after implementing the correlations proposed and validating against additional CFD simulations.

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[1] Cavazzuti and Corticelli, *Therm. Sci. Eng. Prog.* **2**, 43 (2017)