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EFFECT OF FLOW CHOKING ON EXPERIMENTAL AVERAGE FRICTION FACTOR OF GAS MICROFLOWS

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KEY WORDS

Under expansion, Fanning friction, Adiabatic, Microchannel, Fanno Flow

ABSTRACT

Pressure drop experiments are performed for a rectangular channel having a hydraulic diameter of 295µm (w=360µm, h=250µm) up to Re 16000. A validated numerical model is used to gain insight of flow physics inside employed microchannel test assembly. Comparison of numerical and experimentally calculated flow properties considering two different data reduction methodologies show that adiabatic treatment of gas results in a better agreement of average friction factor values with conventional theory in turbulent regime. Minor loss coefficients available in literature are not valid for microflows as they change from one assembly to other. This necessitates an estimation of minor loss coefficients as a priori which can be established using a validated numerical model of the experimental test rig. However, such a treatment of minor loss coefficients adds an additional step of establishing a well posed numerical model before each experiment and hence is not convenient at all from experimentalist point of view. An adiabatic treatment of the gas along the length of the channel coupled with isentropic flow assumption from manifold to microchannel inlet results in a self-sustained experimental data reduction and therefore should be followed in consequent gas flow studies. Furthermore, assumption of perfect expansion and wrong estimation of average gas temperature between inlet and outlet results in an apparent increase of experimental friction factor in highly turbulent choked regime.

Literature has been divided into two main approaches for establishing experimental average frictional characteristics in micro channels (MCs). When a total pressure drop and inlet temperature are available, a classical methodology is to invoke minor loss coefficients and subtract pressure losses associated to inlet/outlet manifold. Resulting pressure difference is then utilized along with measured temperature at manifold inlet to calculate average isothermal fanning friction factor. Such a treatment is quite realistic when an incompressible liquid working fluid is utilized but has been applied to compressible flows as well in the past [1]. In reality, a gas microflow does not stay isothermal and shows a strong temperature decrease close to outlet for adiabatic walls. For an adiabatic flow, temperature estimation at MC outlet can be done using a quadratic equation proposed by [2]. Data reduction methodology where minor losses are utilized along with the temperature estimation at outlet, is referred to as ***M1*** in the subsequent text. An alternative methodology (***M2***), originally proposed by [2] is to estimate MC inlet flow properties by

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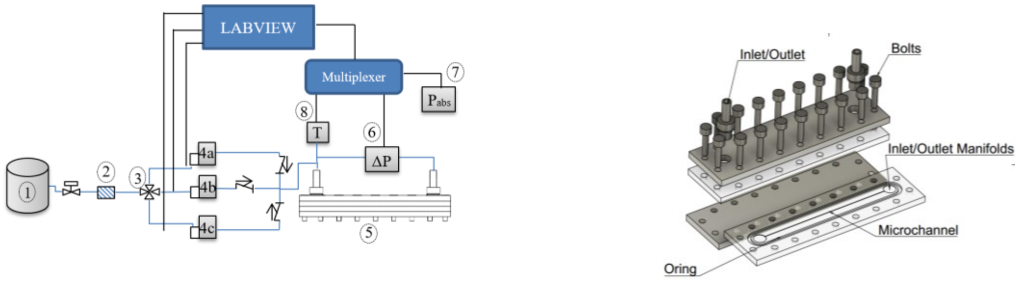
assuming isentropic flow between inlet manifold and MC inlet. This automatically caters for a reduction in MC inlet pressure and hence inlet coefficient is not required. Main aim of current study is to investigate underlying differences and their effects on experimental average friction factor between above stated methodologies in the presence of flow choking. An establishment of a unique methodology for future compressible gas experimentalists is also intended.

EXPERIMENTAL SETUP AND DATA REDUCTION

Schematic of test bench and MC assembly used in this work is shown in **Figure** 1. Nitrogen gas flows through the MC based upon the desired Re. Details of test rig and sensors can be found in [3] and are not repeated here.



(a) (b)

Figure 1: Experimental setup (a) and exploded view of microchannel assembly (b)

Considering ideal gas and adiabatic approximations for gas flow through MC and knowing the total pressure drop ($\Delta P_{MC}=P_{in}-P_{out}$), Fanning friction factor (f_f) for adiabatic flows can be calculated using Eq.(1) [2].

$$f_f = \left(\frac{D_h}{L}\right)\left[\frac{P_{in}{}^2 - P_{out}{}^2}{RT_{av}\left(\dot{m}/_{\Omega}\right)^2} - 2ln\left(\frac{P_{in}}{P_{out}}\right) + 2\ln(\frac{T_{in}}{T_{out}})\right] \tag{1}$$

where D_h and L are average hydraulic diameter and length of channel respectively. P_{in}/P_{out} and T_{in}/T_{out} represent the absolute pressures and temperatures at inlet and outlet of MC, $\dot{m}$ is the gas mass flow rate flowing through average cross-sectional area Ω of the channel, R is the gas constant and T_{av} is average bulk temperature of the fluid between inlet and outlet of MC. For an adiabatic flow, temperature at any cross section '*x*' of MC can be estimated using Eq. (2) obtained by total temperature balance between two given points [2]

$$\left(\frac{\rho_{in}{}^2 V_{in}{}^2 R^2}{2c_p P_x{}^2}\right)T_x{}^2 + T_x - \left(T_{in} + \frac{V_{in}{}^2}{2c_p}\right) = 0 \tag{2}$$

Where ρ_{in}, T_{in}, V_{in} denote cross sectional average density, temperature and velocity respectively at MC inlet. $C_p = \frac{\gamma R}{\gamma - 1}$ is specific heat of working fluid where γ is ratio of specific heat and is taken as 1.4 for diatomic gas like N_2.

RESULTS

Channel dimensions and surface roughness are measured by an optical profilometer. Measured average surface roughness (ε) is 0.7μm giving ε/D of 0.24% and therefore a smooth channel surface can be safely assumed. Temperature at inlet of MC is assumed to be same as measured in manifold for M1. Friction factor results obtained by employing M1 & M2 are shown in **Figure** 2. For adiabatic flow, an estimation of outlet pressure is required for calculation of T_{out} using Eq. (2). For a fully expanded flow in a duct, this pressure is equal to atmospheric pressure as outlet manifold is open to atmosphere in all the experiments. Comparison of inlet and outlet flow properties using both methodologies (M1 & M2) and assuming P_{atm} at the MC outlet is shown in **Figure** 3. MC inlet temperature is well predicted by isentropic flow expansion between manifold and MC inlet using M2 as shown in **Figure** 3a. Outlet experimental properties with both methodologies are in general deviant to the numerical trend because of an inherent error of perfect expansion assumption which is not the case in numerical results. Perfect assumption in experimental data reduction can be safely assumed up to Re~10000 after which P_{out} starts increasing rapidly above P_{atm} as shown in **Figure** 4. This is due to flow choking at outlet, evident in **Figure** 3c where numerical outlet Mach number has reached a maximum for Re>10000. An equal weighted average of temperature between inlet and outlet, assumed in M1&M2 results in a higher average temperature. Whereas gas temperature stays almost isothermal to the major part of the MC and then decreases steeply close to outlet as shown in **Figure** 4b. Therefore in the absence of numerical input a 80%-20% (in-out) temperature average results in an improvement of f_f in high turbulent choke regime as shown in **Figure** 5. Such an average is also close to numerically integrated temperature profiles.

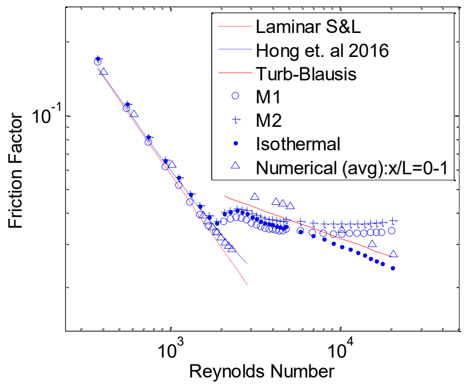
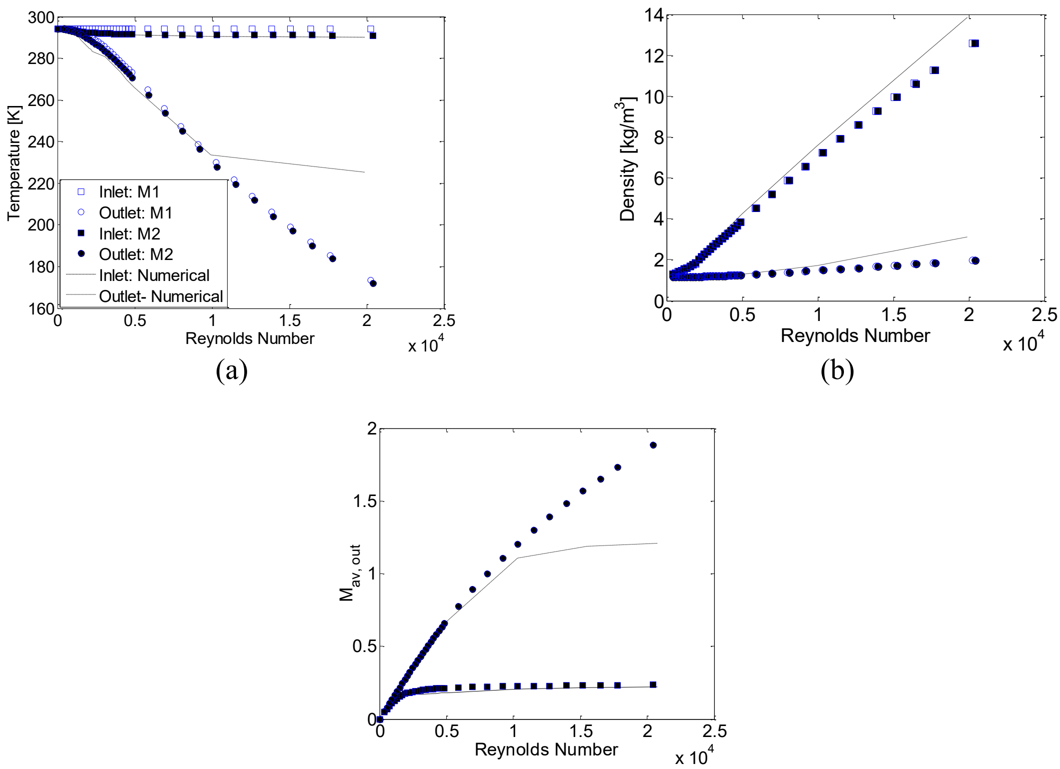


Figure 2: Friction factor using M1 & M2

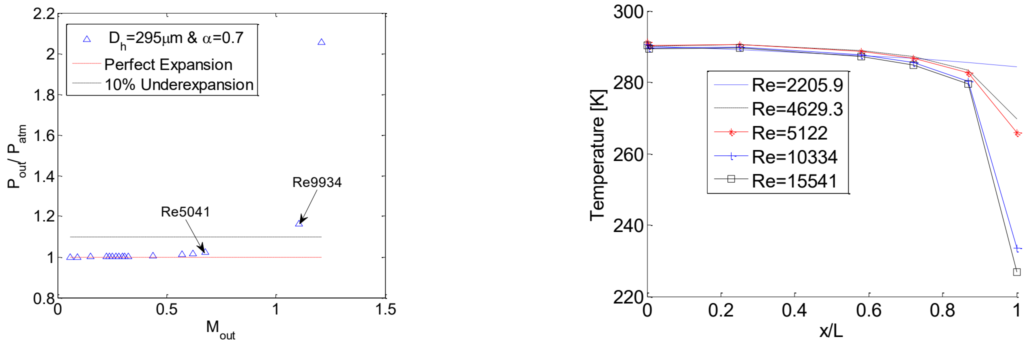


(a)

(b)

(c)

Figure 3: Comparison of experimentally deduced flow properties: temperature (a), density (b), and average Mach number at outlet (c)



a) (b)

Figure 4: Numerical results for the ratio of MC outlet to atmospheric pressures (a), temperature along the length of MC at various Re (b)

CONCLUSIONS AND FUTURE WORK

Flow choking at outlet cannot be ascertained correctly in both methodologies (M1 & M2) due to the absence of measured outlet static pressure and hence average friction factor results should be representative of reality until outlet flow starts to choke. After this limit, increase in outlet pressure (under-expansion) as well as wrong estimation of average temperature of gas cause an apparent increase in experimental average f_f while numerical results follow Blasius law. An improved data reduction methodology catering for integrated temperature variation between inlet and outlet instead of an equal weighted average, is the topic of future study.

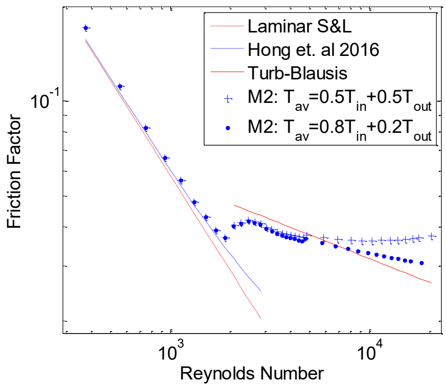


Figure 5: Friction factor when moving average of Tav is considered in M2

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