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Laminar, transitional and turbulent friction factors for gas flows in smooth and rough microtubes

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ABSTRACT

Theoretical and experimental works on microscale transport phenomena have been carried out in the past decade in the attempt to analyze possible new effects and to assess the influence of downscaling on the classical correlations which are used in macro-scale heat and fluid flow, following the need to supply engineers with reliable tools to be used in the design of micro-scale devices. These results were sometimes in mutual contrast, as is the case for the determination of the friction factor, which has been found to be lower, higher or comparable to that for macroscopic channels, depending on the researchers. In this work the compressible flow of nitrogen inside circular microchannels from 26 μm to 508 μm in diameter and with different surface roughness is investigated for the whole range of flow conditions: laminar, transitional and turbulent. Over 5000 experimental data have been collected and analysed. The data confirmed that in the laminar regime the agreement with the conventional theory is very good in terms of friction factors both for rough and smooth microtubes. For the smaller microchannels (<100 μm) when Re is greater than 1300 the friction factor tends to deviate from the Poiseuille law because the flow acceleration due to compressibility effects gains in importance. The transitional regime was found to start no earlier than at values of the Reynolds number around 1800. Both smooth and sudden changes in the flow regime have been found, as reported for conventional tubes. Fully developed turbulent flow was attained with both smooth and rough tubes, and the results for smooth tubes seem to confirm Blasius' relation, while for rough tubes the Colebrook–White correlation is found to be only partially in agreement with the experimental friction factors. In the turbulent regime the dependence of the friction factor on the Reynolds number is less pronounced for microtubes than the prediction of the Colebrook–White correlation and the friction factor depends only on the microtube "relative roughness".

1. Introduction

In the last years a large amount of experimental analyses have been addressed to the study of the frictional characteristics of liquid and gas flows in microchannels, with a chronologically decreasing discrepancy between experiments and theoretical results. This fact can be explained with the improvement of the techniques for microfabrication with a consequent more accurate control of surface roughness and channel geometry. However, it is the authors' opinion that some systemic studies are still needed, both to give the whole subject a coherent treatment and to further investigate some points, such as the laminar-to-turbulent transition and the reliability of conventional correlations in the developing and fully developed turbulent regime, since these are still controversial.

Recent reviews of the experimental results related to the laminar-to-turbulent transition published in the last years are due to Morini [1,2] and Hetsroni et al. [3]. These studies indicate that the transition from the laminar to the turbulent flow in micro-scale passages could take place at critical Reynolds numbers ranging from 70 (Peng and Peterson [4]) up to 10,000 (Stanley et al. [5]). This large spread of the critical Reynolds values has stimulated this work with the aim to experimentally add a contribution in terms of data and comments to the region and form of the onset of such a transition. The first work in which the friction factor through rectangular and trapezoidal glass and silicon microchannels was measured for different gases (N_2, H_2, Ar) is due to Wu and Little [6]; the measured values of the friction factor were larger (10%–30%) than those predicted by the conventional theory. The glass channels they employed had a rectangular cross section with two rounded corners and with a high "relative roughness" ($\epsilon/D = 0.2$–0.3) non uniformly distributed along the wetted perimeter. The silicon microchannels were chemically etched on a ⟨100⟩ oriented wafer; in this case the channels were trapezoidal and could be considered smooth.

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Nomenclature

A	cross-sectional area, m^2
C^*	Poiseuille numbers ratio, Eq. (3)
D	inner diameter, m
f	Darcy–Weisbach friction factor
FS	full scale
L	microtube length, m
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
p	pressure, Pa
Re	Reynolds number
Greek symbols	
Δ	difference
ε	absolute roughness, m
μ	dynamic viscosity, Pa s
ρ	gas density, $kg\,m^{-3}$
Subscripts	
c	critical
h	hydraulic
i	inlet
m	measured
n	net
no	nominal
o	outlet

Comparing the results of Wu and Little [6] for glass and silicon channels, the role of the "relative roughness" on transition was evidenced. Wu and Little concluded that transition occurred at Reynolds numbers ranging from 1000 to 3000. Acosta et al. [7] presented an analysis of the friction factors for isothermal gas flows in rectangular microchannels; the investigated channels had a very small aspect ratio. The tests evidenced trends which were very similar to those for conventional laminar-to-turbulent transition; the critical Reynolds number was about 2770, as quoted by Obot [8]. Choi et al. [9] measured the friction factor for the fully developed laminar flow of nitrogen through silica micropipes having a diameter of 3, 7, 10, 53, 81 μm with Reynolds numbers ranging between 30 and 20,000. Their data suggested that the critical Reynolds number decreased with the hydraulic diameter; in particular, the transition occurred at Reynolds equal to 2000 for a circular tube with a hydraulic diameter of 53 μm and at 500 for a hydraulic diameter of 9.7 μm. Yu et al. [10] tested nitrogen and water flows through silica microtubes having a diameter of 19, 52 and 102 μm for Reynolds numbers ranging between 250 and 20,000. They found that transition occurred for Reynolds numbers between 1700 and 6000, in line with the conventional theory for continuum flows. Stanley et al. [5] carried out experiments on liquid and gas flow in rectangular microchannels having a hydraulic diameter from 56 μm to 260 μm. Transition was reported for nitrogen flows at values of the Reynolds number between 1500 and 2000 when the hydraulic diameter was larger than 150 μm. Li et al. [11] deduced from their experimental results on the friction factors for circular microtubes that the transition in microtubes occurs at a Reynolds number equal to 2300. In a further work [12] the same authors concluded that the transition from laminar to turbulent occurred at Reynolds numbers between 1700 and 2000. Yang et al. [13] experienced that transition occurred when the Reynolds numbers varied from 1200 to 3800 for air, water and R-134a through microtubes. The range of critical Reynolds numbers increased with the decrease in tube diameter. This dimensional dependence was more marked for water flow than for air flow. Li et al. [14] observed that for smooth microtubes with a hydraulic diameter ranging between 79.9 and 166.3 μm transition occurred at Reynolds numbers equal to 2000–2300; this fact underlined that the conventional theory for incompressible laminar flow still worked for microtubes with diameters larger than 80 μm. They also observed that for rough stainless steel microtubes ($D_h = 136.5$–179.8 μm) having a "relative roughness" equal to 5% the flow transition occurred at lower Reynolds number (≈1700–1900). By analyzing their experimental data, the authors remarked that the conclusion of an early transition for flows in rough microtubes could not be drawn with certainty. Faghri and Turner [15] investigated the effect of relative surface roughness in microchannels etched in ⟨100⟩ (leading to trapezoidal cross sections) and ⟨101⟩ (leading to rectangular cross sections) silicon wafers. They fabricated various microchannels having different surface roughness and tested them with nitrogen and helium. They found that the effect of "relative roughness" on the friction factor was negligible for values lower than 6% and their results were in a good agreement with the conventional theory. Tang and He [16] measured friction factors for nitrogen flows in fused silica microtubes and square microchannels with diameters ranging from 50 μm to 201 μm. They concluded that the theoretical prediction for conventional tubes are in good agreement with the measured friction factor but for smaller microtubes the effects related to compressibility, roughness and rarefaction could not be neglected. The laminar-to-turbulent transition was experimentally evidenced for critical Reynolds numbers ranging between 1900 and 2500. Kohl et al. [17] studied the flow of water and air in rectangular silicon microchannels with a hydraulic diameter varying between 24.9 and 99.8 μm and performed internal pressure measurements. They could predict their data quite well using the classical correlations for laminar flows. None of their experimental results indicated an early transition to turbulence. However, they remarked that when the compressibility effects became significant the L/D (length-to-diameter) ratio could influence the critical Reynolds number. Their values of the critical Reynolds number obtained for air ranged between 2300 and 6000 as a function of the L/D ratio. The authors explained this behavior by invoking the large accelerations in the microtube, as theoretically predicted by Kurokawa and Morikawa [18] and Schwartz [19].

From the above analysis one can conclude that the flow behavior in the transitional region is still an open issue for microchannels: this flow regime is more frequent for gases at the microscale owing to the flow velocities and corresponding Reynolds numbers involved. Moreover, although it seems that there is a widespread agreement that the friction factor for the laminar regime is correctly predicted by traditional correlations, provided all effects are accounted for (and this is not always the case, even in very recent works like Dutkowski [20], where e.g. inlet and outlet losses and compressibility are not considered), the influence of surface finish, which can involve very high values of roughness as this term is understood in mechanical manufacturing, is still an interesting issue, which has been granted special attention by Kandlikar and co-workers [21,22], and data on rough tubes add elements to the discussion in this area. When it comes to turbulent flow, the matter becomes more involved as there is considerable misunderstanding and misuse in the notion of "relative roughness", which is normally taken as the ratio of the surface roughness as measured by a profilometer or equivalent instrument to the characteristic dimension of the tube or channel. This is unfortunately not the same as the parameter introduced by Colebrook in his paper on transitional friction factor [23], which makes comparison with this correlation very tricky. This work on the compressible flow of gaseous nitrogen within circular microchannels with both smooth and rough walls is meant to be a contribution to the subject.