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Experimental analysis of the non isothermal rarefied gas flow through a packed bed of spheres

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ABSTRACT

We present the results of an experimental study concerning the gas flow through a packed bed of spheres located between two concentric cylinders, in non isothermal conditions. This problem is prototypal for more complex geometries which can be found in Micro Electro-Mechanical Systems (MEMS) where the heat transfer is a crucial issue. In these applications the characteristic lengths are such that the gas flow regime could fall in almost rarefied regime where the features of heat and mass flows can be markedly different with respect to the continuum regime. We investigated a wide range of regimes, spanning from the compressible continuum flow to rarefied conditions with a variation of the peculiar Knudsen number of about three orders of magnitude, i.e. from $Kn = 10^{-3}$, which corresponds to almost continuum regime, to $Kn \approx 1$ which falls in the transitional region. The heat transfer through the porous medium have been studied by the analysis of the temperature field and the heat flux as a function of the flow rate, the boundary conditions and the porous materials.

1. Introduction

The recent development of MEMS devices called the attention to efficient heat transfer mechanisms. In fact the advent of micro-system with high performances brings the important challenge of how to dissipate the heat fluxes produced by miniaturized devices of increasing power [1]. In this frame, gas flows through porous and/or fibrous media are particularly appealing due to their potentially high capability to transfer the heat. We observe that, when a gas flows through a porous medium, it is not unusual that the flow conditions correspond to the rarefied regime. In fact the size of the interstitial spaces inside the porous media can be on the order of the mean free path of the gas molecules, exhibiting a rarefied behavior, though the values of pressure are around the standard one.

The experience in the modeling of flows through porous media in this peculiar regime is actually quite poor and significant attention has to be paid to evaluate correctly the momentum and energy transport in these conditions. We observe that the gas flow through simple micro-devices geometries, like micro channels and micro tubes, has been widely investigated and quite well understood. The most important results are reported in [2–4], just to cite a few.

The extension of the results obtained in these simple geometries to the physics of rarefied gases through porous/fibrous matrices is still matter of discussion and the experiments reported in the present paper can be useful to improve the comprehension of how the most important parameters influence the fluid field with a particular attention to the heat transfer properties of the porous medium.

Although the literature on transport phenomena through porous media is very large the analysis of the temperature effects in porous media has been focused almost in the continuum and, for isothermal flows, the main influence of the compressibility of the gas can be re-conducted to the prediction of the Klinkenberg law for the permeability of the medium [5,6].

When the flow is rarefied both numerical and experimental results are quite few. Some efforts have been carried out to model the problem in Refs. [7,8] and the main numerical approaches were based on the DSMC (Direct Simulation Monte Carlo) technique adapted to take into account the presence of the porous medium by introducing a probability of interaction between the gas molecules and a spatially diffused solid phase. This method is sufficiently efficient when the porosity of the medium is very large and the typical velocity of the gas in the porous matrix is significantly higher than the thermal speed. When the porosity decreases to lower values, like those typical of a bed of spheres, the mean speed decreases to low values and, in these cases, the low signal to noise ratio leads to simulations highly time consuming and, in

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Nomenclature

d	gas molecule diameter
D_p	mean diameter of the pore of the bed of spheres
D_s	diameter of the spheres
k	thermal conductivity
k_B	Boltzmann constant
K	permeability of the porous medium
L	length of the test section
m	gas molecule mass
$\dot{m}$	mass flow rate
p_d	pressure in the downstream stagnation chamber
p_i	pressure at the inlet of the test section
q_w	heat flux at the cylindrical heater cartridge surface
R_i	radius of the internal cylindrical heater cartridge
R_o	radius of the cylindrical probe
T_a	ambient temperature
T_i	temperature at the inlet of the test section
T_{s_i}	temperature of the surface of the internal cylindrical cartridge
T_{s_o}	temperature of the surface of the cylindrical probe
z	dimensional longitudinal coordinate
Z	non dimensional longitudinal coordinate
Non dimensional characteristic numbers	
Kn	Knudsen number
Ma	mach number
Nu	Nusselt number
Re	Reynolds number
Greek letters	
γ	ratio of the specific heats
ϵ	porosity of the bed of spheres
η	non dimensional and normalized radial coordinate
λ	mean free path
μ	dynamic viscosity
ρ	mass density
Θ	non dimensional temperature

many circumstances, unfeasible. Furthermore the probability of interaction introduced in the method can be shown to be related to the local Knudsen number [7]. According to the DSMC method, in a simulation cell the molecules susceptible to be collided are chosen according to their positions, velocities and an intermolecular interaction model whose validity is typically validated through comparison with experimental results. Some possible solutions to reduce the statistical errors for the molecular Monte Carlo simulations have been proposed [9], but without the presence of a porous medium. Alternative and, in principle, more efficient approaches to simulate the gas dynamics near the equilibrium state are based on the solution of the kinetic equations, in particular by means of BGK, S or ES models[10,11]. Recently a formal extension of these methods to investigate the flows of rarefied gas through porous media has been proposed by Pavan et al. [12]. In this paper an additional contribution was added to the collisional term of the Boltzmann equation to model the interaction of the molecules against the solid phase of the porous medium. By means of the homogenization technique the authors have shown how the Klinkenberg effect and the Darcy contribution can be recovered in the hydrodynamic limit [13].

In this paper we present some experimental results concerning the gas flows through a porous medium made of a packet bed of spheres. The isothermal case, studied in [7] is here extended to a physical situation where the heat transfer plays a significant role. In particular the experimental results show how the heat transfer can be enhanced by the presence of a porous solid matrix.

2. Problem definition and experimental setup

Fig. 1 shows a sketch of the test section adopted in the experiment. It consists mainly of an instrumented cylindrical probe of radius $R_o = 0.019$ m where a coaxial cylindrical cartridge of radius $R_i = 0.0034$ m is internally located. The length of the test section is $L = 0.18$ m and the packed bed of spheres, with diameter D_s, is located in the annulus between the two cylinders. By means of an electric resistance and an electronic control unit it is possible to assign, at the surface of the internal cylinder, the temperature T_{s_i} or the heat flux q_w. The temperature of the wall of the external cylinder T_{s_o}, which is located in an ambient kept at constant temperature T_a, is a function of the boundary condition assigned at the inner wall, the mass flow rate through the probe, the operating pressure and the properties of the porous matrix. The probe is equipped with a series of 5 taps where temperature/pressure transducers can be introduced to measure the longitudinal and radial distributions. The radial distribution is obtained by changing the position of the transducers inside the probe. The taps are longitudinally distributed at distances from the inlet equal to $Z = z/L = (1/8, 2/8, 3/8, 4/8, 6/8)$. We run our experiments with spheres made of two different materials, glass and lead, with diameter $D_s = 0.002$ m. The spheres are produced by R.G.P. International S.r.l. and are provided with accuracy of $10^{-5} m$. The porosity of the system has been measured [7] and is $\epsilon = 0.33$.

A detailed scheme of the complete experimental set up is reported in Fig. 2 and the characteristics of all the instruments are provided in Table 1. When the experiment is running the test section is connected by a systems of valves to two stagnation chambers $C1$, $C2$, located upstream and downstream with respect to the test section probe, respectively. A bottle with compressed Nitrogen supplies the mass flow controller (MFC) that feeds the upstream chamber C_1 where the inlet temperature T_i and the pressure p_i are monitored. The valve $V1$ lets the gas flows in the probe through the porous medium and finally ends in the downstream chamber where the pressure p_d is kept constant to a low value by the system of pumps P located at its exit. We adopted either absolute capacitive MKS pressure transducers and differential pressure sensors. Each device has a range which covers four decades and redundancy was employed to improve the reliability of the measurements. The temperature has been measured by thermocouples type K located both in the porous medium and in the stagnation chambers. We took the opportunity of using three different mass flow meters to achieve the maximum accuracy all over the flow regimes studied.

The system of pumps is constituted by Roots and Turbo-molecular machines produced by Pffeifer and a high vacuum of about 10^{-6} Pa can be reached. The total uncertainty of the measurement chain is driven by the errors on the temperature and so estimated around 1% of the full scale of the thermocouples (see Table 1).

The experiments were carried out in two different conditions. A first set of data was obtained by imposing the heat flux q_w at the internal wall. The temperature field, in particular the T_{s_i} of the surface of the inner cylinder is measured as a function of the mass flow rate, the rarefaction level and the type of material adopted for the bed of spheres. The maximum heat flux that can be delivered from the surface of the internal cylinder is $q_{w_{max}} = 45000\ W/m^2$ but in our experiments, in the range of mass