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CHARACTERISTIC FLOW DIMENSIONS OF POROUS MEDIA

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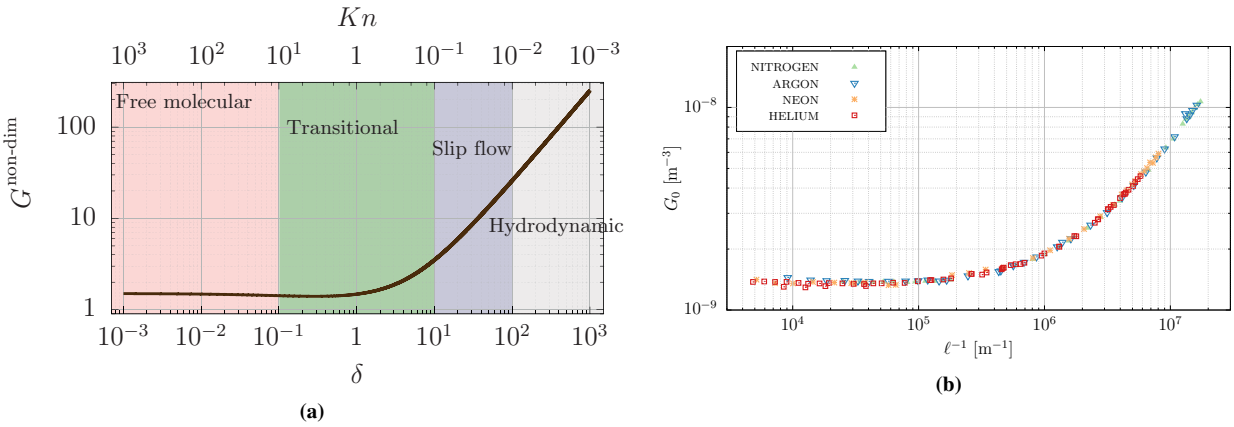
KEY WORDS

Transient method, porous media, permeability, mass flow rate, pressure gradient, constant volume technique, free molecular regime, transitional regime, slip flow regime, characteristic flow dimension.

ABSTRACT

The morphology of the porous structure dominates the fluid flow through a porous medium. Therefore, it is important to characterise the geometrical properties of a porous medium quantitatively. Different methods exist for the measurements of the average pore size and pore size distribution. The choice of the most appropriate method depends on the application of the porous solid, its chemical and physical nature and the range of pore size. The most commonly used methods are [3]: mercury porosimetry, where the pores are filled with mercury under pressure. This method is suitable for many materials with pores in the appropriate diameter range of 0.005 µm to 300 µm. From mesopore to micropore size analysis, BET method [1], can be done by gas adsorption, usually nitrogen, at liquid nitrogen temperature. This method can be used for pores in the approximate diameter range from 1 nm to 0.1 µm. The pore size diameter can also be determined via direct observation methods: scanning electron microscopy (SEM), field-emission scanning electron microscopy (FESEM), environmental scanning electron microscopy (ESEM), and atomic force microscopy (AFM). The tomography analysis of a porous structure can allow the determination of the internal structure of a sample limited by the characteristics of their spatial resolution [2]. All these methods require either preliminary sample preparation or lead to the complete sample destruction, furthermore, they only use a small part of the sample for analysis. We propose here a simple approach for the non-destructive porous sample characterization by measuring the pressure variation in the inlet and outlet tanks (or just the pressure difference between them). The experimental methodology, based on the constant volume technique, was initially developed for the isothermal and non-isothermal measurements of the mass flow rate through the microchannels [4] and has been adapted for the analysis of porous samples. The gas permeability of the porous sample can be easily obtained directly from the pressure evolution in time without calculation of the mass flow rate. Also, the characteristic pore size dimension can be derived from the analytical expression of the mass flow rates for the hydrodynamic, slip and free molecular flow regimes.



(a) **(b)**

Figure 1: a) Normalised mass flow rate for a circular tube Eq. 3. **b)** G_0 Eq. 5. as a function of inverse smean free path.

Measurements of the pressure evolutions in time

The experimental setup is a high vacuum system capable of measuring 5 decades of pressure ranging from $1,3$ Pa up to 133 kPa. The reservoirs are connected only by a porous sample fixed with vacuum epoxy glue. Different types of porous samples were tested. Pressure evolution in time in the high and low-pressure tanks are recorded and then fitted to the exponential function with a single fitting parameter, pressure relaxation time. From this experimental data, the mass flow rate through porous structure is extracted and analysed.

Modeling of a gas flows through a porous sample

The primary objective of this analysis is to find out information about initially unknown complex porous structure from the pressure evolution in time measurements. Therefore, we have to develop a model which allows us to use the available from the measurement data and to derive the quantities which we are looking for. First, we present the experimental data on the mass flow rate, $\dot{M}$, but normalised by the known quantities (G-normalized mass flow rate):

$$G_0 = \dot{M} \times v_0/\Delta p, \qquad v_0 = \sqrt{2\mathcal{R}T} \tag{1}$$

is the most probable molecular speed, $\mathcal{R}$ is the specific gas constant, T is the gas temperature, Δp is the pressure difference between two tanks. The normalized according to Eq. (1) mass flow through the porous simple for four different gases is presented in Fig. 1 b) as a function of the inverse molecular mean free path

$$\ell = v_0 \frac{\mu}{p_{\text{m}}} \tag{2}$$

where μ is the gas viscosity, all gases overlap, Fig. 1b). We note that the curves of the normalised mass flow rate have a similar shape to that of the mass flow rate through a single tube, see Fig. 1 a). This dimensionless mass flow rate G through a capillary of a radius a and the length L_c, which covers all flow regimes, was proposed in [5]:

$$G^{non-dim}(\delta) = \dot{M}/M_G = \frac{8}{3\sqrt{\pi}} \frac{1 + 0.04\,\delta^{0.7} \ln \delta}{1 + 0.78\,\delta^{0.8}} + \left(\frac{\delta}{4} + \sigma_p\right) \frac{\delta}{1+\delta}, \qquad M_G := \frac{\pi a^3 \Delta p}{v_0 L}, \qquad \delta := \frac{a}{\ell} \tag{3}$$

where L is a tube length, and the rarefaction parameter δ is defined as a/ℓ.

Assuming that the flow through the porous medium behaves similarly to the flow through a pipe, we expect in the hydrodynamic regime that

$$\dot{M} \propto \frac{\Delta p p_m}{\mu v_0^2}, \qquad \dot{M} \frac{\mu v_0^2}{\Delta p p_m} =: S_0, \tag{4}$$

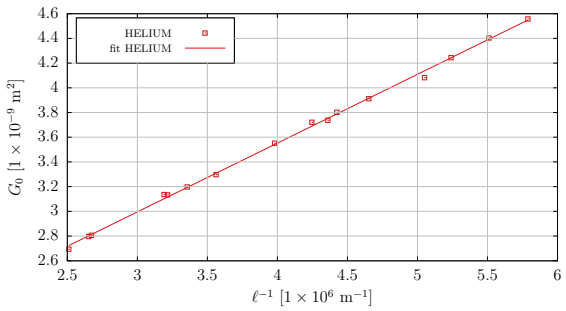
in hydrodynamic regime $S_0 \propto$ Constant. Similarly, in the free molecular regime, we expect

$$\dot{M} \propto \frac{\Delta p}{v_0}, \qquad \dot{M}\frac{v_0}{\Delta p} =: G_0 \tag{5}$$

and in the free molecular regime $G_0 \propto$ Constant. We can let the shape of the $G^{\text{non-dim}}$ on Fig. 1a) help us identify the slip flow and transitional flow regimes. Quantitatively, we define the slip flow regime by using the inverse mean free path ranges $\ell^{-1} > 2.0\times10^6$. However, the single tube model is too simple to extract any useful information. Instead, we suggest the *N-straight tubes* model.

$$\begin{gathered}\dot{M} = \frac{N\pi a^4}{L_c}\frac{p_m}{\mu}\frac{\Delta p}{v_0}\left(\frac{1}{4}+\sigma_p\frac{\mu v_0}{a p_m}\right) = \frac{\Delta p}{v_0}\left(A_G\frac{1}{\ell}+B_G\right) \\ A_G := \frac{N\pi a^4}{4L_c} \qquad \text{and} \qquad B_G := \sigma_p\frac{N\pi a^3}{L_c} \qquad \rightarrow \qquad a = 4\sigma_p\frac{A_G}{B_G},\end{gathered} \tag{6}$$

we assume a is related to the characteristic flow dimension as $2\,a =: D$. σ_p is the slip flow coefficient. We assume fully diffusive scattering, that is $\sigma_p = 1.018$. This assumption is motivated by looking at the relative difference between the fitting coefficients of the gases. We find that this variation is negligible within experimental uncertainty. We assume that L_c is the sample length, it is worth to note that a is independent of L_c.



(a)

GAS	A_G [10^{-16} m^2]	B_G [10^{-9} m^2]
He	5.57 ± 0.1	1.33 ± 0.1
Ne	5.58 ± 0.1	1.36 ± 0.1
N_2	5.44 ± 0.1	1.30 ± 0.1
Ar	5.51 ± 0.1	1.28 ± 0.1
AVR	5.51 ± 0.1	1.32 ± 0.1

(b)

Figure 2: On the left, **a)** we have a linear fit of the G_0 mass flow in slip flow regime. On the right **b)** we have the corresponding fitting coefficients.

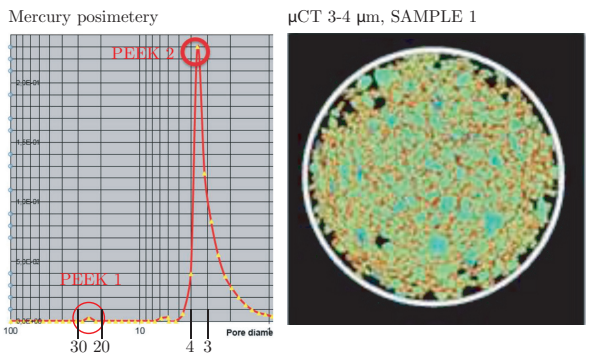
With the flow regimes identified, we may analyse the measurements in the frame of these models. Simply, by fitting a linear function to the measurements restricted to hydrodynamic and slip flow regime.

GAS	$2\,a$ [μm]	N [10^3]
He	24.60	0.92
N_2	19.08	2.51
Ar	23.23	1.18
AVR	21.16	1.85

(a)

GAS	$2\,a$ [μm]	N [10^5]
He	3.42	1.90
Ne	3.33	2.11
N_2	3.41	1.90
Ar	3.50	1.72
AVR	3.41	1.91

(b)



(c)

Figure 3: On left, tables for extracted flow dimenison First table **a)** is the sample no.1, 2nd table **b)** sample no.2. On the right the we the porsimitery pore distribution and micro-computed tomography for sample no.1 **c)**.

CONCLUSION

With the simple N-*straight tubes* model we may find the *characteristic flow dimension* D, this value is interesting it itself for predicting the flow behavior for the porous media. In addition, it is interesting to consider if the extracted flow dimension have any physical interpretation. Therefore, we complemented with porsimitery and μCT measurements. To interpret the result of the of the flow dimension and porsimitery distribution we need further explanation of the samples. We have measured two seemingly identical samples with manufacture specified pore size around 3.5 micro meter. In the pore distribution we can clearly see the peek specified by manufacturer (PEEK no.2 in Fig. 3c)) around 3-4 μm. However, the flow dimension we find for the first sample is around 25 μm and by having a closer look at the pore size distribution we also find this small peek (PEEK no.1). The PEEK no.1 is considered a manufacturer defect and has a significantly smaller number than the dimension specified by manufacturer. Still, for the gas flow this larger dimension is more important. Theoretically, it is expected that a large flow dimension in a small number will be more significant than a small dimension with a huge number of flow channels. This is because the mass flow rate in hydrodynamic regime is scaled by N and a^4. For the sample no.2 we find directly the manufacturer specified flow dimension and can conclude that this sample did not have the same defect. In summary, from pressure measurements we may can determine the characteristic flow dimension with high accuracy and highlight some advantages with this method in comparison to the previously mentioned methods. This method based on gas flow does not require any contamination or destruction of a porous sample.

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