A MISSING MASS METHOD TO MEASURE THE OPEN POROSITY OF POROUS SOLIDS

Emmanuelle Gros[1] and Raymond Panneton[2]
GAUS, Department of mechanical engineering, Université de Sherbrooke, Québec, Canada, J1K 2R1
[1]Emmanuelle.Gros@USherbrooke.ca , [2]Raymond.Panneton@USherbrooke.ca

1. INTRODUCTION

An air-saturated open cell porous material is a solid containing interconnected air cavities. In acoustics, one important physical property of such a material is indubitably its open porosity (ϕ). The open porosity is defined as the fraction of the interconnected air volume to the total volume of a porous aggregate. Sound propagation models for porous solids use the open porosity to relate the effective properties of the saturating air to the effective properties of the porous aggregate [1]. Consequently, from the measurements of the effective properties on a porous aggregate [2], this scaling is required to go back to the effective properties of the interstitial air, hence the importance of the open porosity.

In this paper, a non limitative method is proposed to evaluate the open porosity of air-saturated porous materials. The proposed method deduces the open porosity through the experimental determination of the volume of the solid phase of a porous aggregate. The method is based on the measurement of the apparent (in-air) and true (in-vacuum) masses of a porous aggregate, where an in-air "missing mass" is found and related to the volume of the solid phase through the Archimedes' principle. The originality of the method lies in its predictable accuracy, the simplicity of the experimentation, and in the fact that no isothermal process needs to be assumed.

2. THEORY

Let denote by V_s and V_f the volumes of the solid phase and interconnected air cavities, respectively, and by ρ_s and ρ_f the mass densities of the solid phase constituent and saturating air in a porous aggregate, respectively. While the mass density of the air may be determined from the ideal gas law, the mass density of the solid phase constituent as well as the solid phase and air-cavities volumes are usually unknown and not directly measurable. However, the total or bulk volume V_t of a porous aggregate and its vacuum mass M_1 are directly measurable with precision. The mass of solid per unit volume of porous aggregate is given by $\rho_1=(1-\phi)\rho_s$, where ϕ is the open porosity defined as $\phi = 1 - V_s / V_t$.

Since the mass density of the solid phase constituent is usually unknown, the mass density ρ_1 can be deduced from the measurable parameters following: $\rho_1 = M_1 / V_t$, where M_1 is measured with a balance under vacuum condition. Usually, a good estimate of M_1 may be obtained using a balance in air. Nevertheless, in cases where a high precision is required, the measurement in air is not appropriate since the measured apparent mass M_1' underestimates the true value of M_1. This underestimate is due to the Archimedes' principle [3] on the buoyancy. In air, the buoyancy is very small yet not negligible for the purpose of this work. Consequently, the difference M_1 - M_1' between the in-vacuum and in-air masses gives the "missing mass" error relative to any measurements performed on a balance in air. Following the Archimedes's principle, the "missing mass" of the porous aggregate measured in air is $\hat{M} = \rho_f V_s$, since the volume of air displaced by the solid phase of the aggregate is equal to V_s.

Following this observation, one can deduce a simple method for the measurement of the open porosity ϕ of the porous aggregate. This yields

$$\phi = 1 - \frac{\hat{M}}{\rho_f V_t} = 1 - \frac{M_1 - M_1'}{\rho_f V_t} \qquad (1)$$

The masses and the bulk volume in Eq. (1) can be measured with precision, and the density of dry air can be calculated from the ideal gas law equation.

3. PRECISION OF THE METHOD

Since the "missing mass" $\hat{M}$ is usually small compared to mass M_1', the accuracy of the balance, and the volume of the porous aggregate are important parameters to take into account in the measurement of the open porosity. An error analysis has been performed using a total differential method to predict the expected error on the open porosity due to the propagation of the errors relative to the measurement of the air density, bulk volume, and masses. The error predicted is valid only if the "missing mass" can be read by the balance. Figure 1 gives the minimum bulk volume per balance readability in function of the open porosity. Now, assuming $\hat{M}$ can be read by the balance, the absolute value of the expected error on the open porosity in function of the bulk volume of aggregate per balance readability is plotted in Figure 2.

4. EXPERIMENTAL TESTS

To validate the "missing mass" method and its precision, three experimental tests are studied.

4.1 Experimental set-up and measurement procedure

The experimental set-up includes a vacuum air pump, an analytical balance, and an airtight rigid chamber. A digital atmospheric station is used to measure ambient temperature, pressure and relative humidity.

The test procedure consists first in measuring the in-air mass M_1' of the test sample. Second, the empty chamber is pumped down to vacuum, and mass M_a is measured. Third, the test sample is placed in the chamber, the chamber is vacuumed, and mass M_b is measured. The true mass M_1 is deduced from the difference M_b - M_a. Finally, the open porosity and its expected error are obtained.

4.2 Air density test

The first test consists in measuring the "missing mass" of a solid sample of known solid phase volume V_s. Since the solid phase volume is known, the air density can be calculated, and compared to the air density predicted by the perfect gas law. The test samples are six cylindrical columns made from Delrin. Using the ambient conditions, the theoretical density of the humid ambient air is 1.146±0.001 kg/m^3. Following the test procedure described above, the "missing mass" $\hat{M}$ is deduced and is about 0.24 g. The statistics on the six measurements give an air density of 1.148±0.026 kg/m^3. This value compares well with the theoretical value calculated from the ideal gas law. To reduce the standard deviation, an optimal choice of volume and balance readability should be selected.

4.3 Low-porosity test

The second test consists of measuring the porosity of open-cell materials by mean of the "missing mass" method. In view of validating the method for low-porosity samples, eleven Delrin hollow cylinders of different bulk volumes have been machined. Their solid phase volume V_s and porosity ϕ are easily found. The results and the statistics are summarized in Figure 2 and Figure 3, where it is clearly observed that the precision on the measurements improves with the volume-to-readability ratio.

4.4 High-porosity test

In this third validation test, the "missing mass" method is applied on a high-porosity aluminum Duocel© foam. For the porosity tests, six samples of different bulk volumes have been used. Using the solid phase density ρ_s, the true mass M_1, and the bulk volume V_t, the theoretical open porosity of the sample can be found. The results and the statistics of the "missing mass" method are summarized in Figure 2 and Figure 3.

5. CONCLUSION

A simple method was proposed to measure the open porosity of open-cell porous solids. Contrary to existing methods, the "missing mass" method is not time consuming, and does not assume isothermal conditions for the test. Also, it only requires simple apparatuses: vacuum pump, small airtight container, analytical balance, thermometer, barometer, and humidity meter. The last three meters can be eliminated if the ambient air density is measured using the "missing mass" as per the first test.

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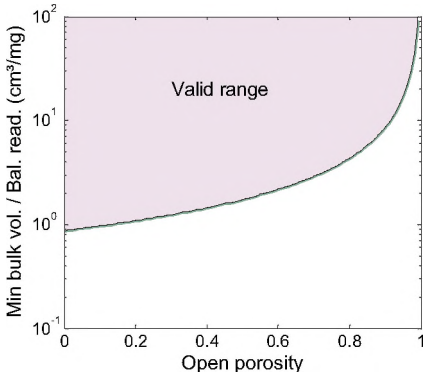

Fig.1 Minimum bulk volume of aggregate per balance readability in function of the open porosity.

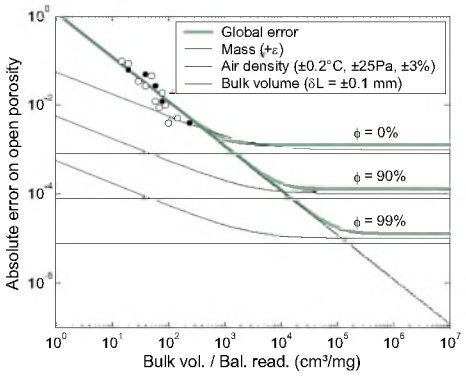

Fig. 2 Absolute error on the open porosity in function of the bulk volume per balance readability

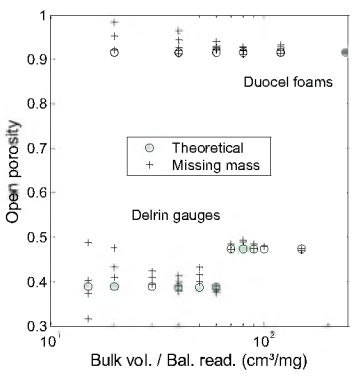

Fig. 3 Open porosity measured by the "missing mass" method compared to theoretical value