CFD SIMULATIONS OF THE STATIC AIRFLOW RESISTIVITY OF A PERFORATED SOLID: EFFECTS OF SIZE AND FLOW VELOCITY

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1 Introduction

For acoustic absorbers, the airflow resistivity is the parameter which has the greatest impact on their acoustic absorption coefficient. Therefore, its measurement according to standard ISO 9053-1 :2018 (or ASTM C522) should be done with care. This ISO standard gives specifications on the size and mounting of specimens, their location in the measuring cell, minimum and maximum flow velocities, calibration specimens and the measurement procedure. An important constraint is to ensure a stable linear flow so that the resistance is independent of the velocity. Additionally, it specifies the use of a calibration test specimen to ensure proper operation of hardware and software. The suggested calibration specimen consists of straight cylindrical pores whose value can be calculated theoretically. However, no other specification is given for designing the calibration specimen. Since the airflow resistivity of a perforated low porosity solid can behave nonlinearly with velocity, it is important to present some additional guidelines for their design. This work presents experimental results and CFD simulations on the flow resistivity of a cylindrical solid containing a single perforation subjected to an air flow velocity ranging from 0.5 mm/s to 10 mm/s. The simulations replicate a commercial airflow resistivity meter. The results of the simulations are compared with the theoretical formula and the experimental measurements. The results show the importance of the size of the perforation and the flow velocity so that the measurement corresponds to the theoretical value.

2 Materials and methods

The material considered here is a calibrated test specimen (CTS) as specified in the ISO standard to "ensure the proper functioning of the hardware and software of the measurement system". A CTS may consist of a solid cylinder containing straight circular perforations. The value measured on the CTS must not deviate by more than 10% from the theoretical value. ISO standard recalls the theoretical formula for the specific resistance to airflow (R_s) of a solid sample perforated with circular perforations : $R_s = 32L\eta/(\phi d^2)$, where L is the thickness of the material, η the dynamic viscosity of air, ϕ the perforation rate, and d the perforation diameter. ISO standard does not specify the number and rate of perforations, nor the thickness, nor the diameter of the CTS. However, it specifies that the lateral dimension of a porous sample must contain at least 10 pores, fibers or granules for respectively foams, fibrous materials and granular materials. Also, it specifies that the thickness must allow a measurement of the head loss. From these details, the simplest CTS is studied here. It is made of a perforated solid containing only one circular perforation. To better fulfill the criterion on the lateral dimension of the specimens, the CTS should contain at least 10 perforations. To the knowledge of the authors, this criterion aims only to ensure the statistical representativeness (homogenization) of the specimen. In the case of CTS, fine manufacturing tolerances are used and adding additional perforations would only lead to greater uncertainty effects. Therefore, as no other information is given in the standard, only one perforation is used. Two different diameters are tested : 2.10 mm for CTS#1, and 4.10 mm for CTS#2. Both CTS have a thickness of 30 mm. The fabrication tolerance is ±0.03 mm. Figure 1(a) presents the CAD of the CTS mounted on the measurement cell.

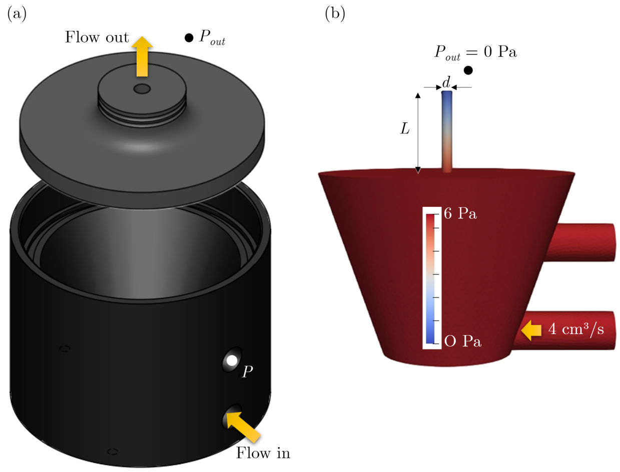

FIGURE 1 – (a) Calibrated test specimen on measurement cell. (b) CFD results on CTS#1.

The measurement procedure is applied according to the ISO standard using a Mecanum's Airflow Resistance Meter with Sigma-X software. Sigma-X adjusts flow velocity to ensure a measurable pressure drop. The first speed is always the lowest allowing a measurable pressure drop. Then the speed is increased step-wise. The measurement cell is shown

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in Figure 1(a). Its reference surface for velocity calculation is $D = 100$ mm in diameter. The CTS sits on the cell and an O-ring eliminates air leaks. The airflow comes through the lowest side inlet and is generated by a mass flow controller. The pressure before the specimen is measured at the upper side hole. A differential pressure gauge measures the pressure drop between this inlet point and the atmospheric pressure at the outlet of the sample. One condition imposed by the ISO standard is that the measurement must be made within a certain range of linear flow velocities. If pressure drop in this range is not measurable, the flow velocity can be increased step-wise without exceeding a velocity of 15 mm/s. In this case, we proceed to a second order regression on the pressure drop data (ΔP) versus velocity (U). The y-intercept is fixed at 0. The linear term is then the specific resistance.

To validate measurements with the hardware and software used, and further understand the results, CFD simulations are performed in the same conditions and geometry of the experimental measurement procedure. The mesh is generated with Salome on the air volume of the CAD shown in Figure 1(a). A RANS calculation is performed using OpenCFD OpenFOAM. A typical CFD model with results for CTS#1 is shown in Figure 1(b).

3 Results

Figure 2 shows the pressure drop in function of the volumetric flow rate for the small (CTS#1) and large (CTS#2) perforations. It is clear that both specimens have a non linear behavior. The small perforation is more resistive to airflow. This helps to have a measurable pressure drop at lower flow rates. On the contrary, the measuring equipment needs to increase the flow to have better measurements for the large perforation. ISO standard indicates that the flow velocity should not exceed 15 mm/s. It is not specified if this velocity is the macroscopic one (in front of the specimen) or the microscopic one (in the specimen). If the reference diameter is the one of the measurement cell ($\approx$ 100 mm), the velocity ranges from 0.5 mm/s to 1.5 mm/s for CTS#1, and from 0.5 mm/s to 10 mm/s. For conventional porous material, since porosity ϕ is close to one, the velocities at macro and micro-scales are similar. However, for perforated samples, the microscopic velocity can be much larger. For the studied CTS, the microscopic velocity ranges from 1130 to 3401 mm/s for CTS#1, and 296 to 5747 mm/s for CTS#2.

To be more related to flow conditions, it would be better to add a limit in terms of Reynolds number (Re) instead of flow velocity. Since the ISO standard states that the specific resistance can be obtained from second-order regression, the standard indirectly assumes the existence of nonlinear behavior. Therefore, why limit the flow velocity to 15 mm/s. The authors understand that this limit is more related to the nonlinear acoustic response of certain materials (notably microperforated plates) typically starting at 110 dB-re20μPa (which corresponds to an acoustic velocity of 15 mm/s). Since in a pipe the transition from laminar to turbulent flow takes place at Reynolds numbers around 2300, one could imagine that the approach would work for $Re < 2300$.

If we perform a regression of order 2 on the points of the figure, our results on the 30-mm thick specimens show that we obtain a good correspondence with the theoretical value if the regression is limited to $Re < 500$, see Table 1. If all points are taken for CTS#2, the obtained resistance is near 50% away from the theoretical one. We believe that in addition to the laminar/turbulent transition, the entrance length to establish developed flow in the perforation reduces this limit. This entrance length is proportional to the Reynolds number.

Further analyses are ongoing with CFD to better establish a flow criterion that could complement the ISO standard and to give additional recommendations for the calibration specimen. Some of these additional developments will be presented at the conference.

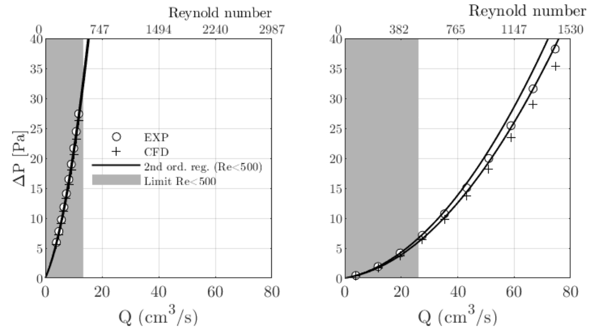

FIGURE 2 – Pressure drop versus volumetric flow rate of (a) CTS#1 and (b) CTS#2

TABLE 1 – Results of specific airflow resistance of two CTS. Values are scaled to the perforation ($\phi = 1$). Values in parentheses represent absolute deviations from theoretical values. Calculations on the regression is limited to data points with $Re < 500$.

CTS#	Theoretical (Pa*s/m)	Experimental (Pa*s/m)	CFD (Pa*s/m)
1	4.02 ± 0.23	$4.00(0.48\%)$	$3.61(7.67\%)$
2	1.05 ± 0.03	$1.13(6.03\%)$	$1.01(3.22\%)$

Conclusion

CFD and experimental results were obtained on perforated solids to emphasize limits of the ISO 9053 standard when measuring on a calibration sample. It has been shown that the speed limit of 15 mm/s specified by the standard can be misunderstood and constraining for the design and validation of a calibration specimen. It has been suggested that the limitation should be in terms of the Reynolds number. Preliminary tests have shown that the second-order extrapolation of specific resistance should be limited to Reynolds numbers less than 500 in the perforation of a 30 mm thick specimen. Further tests are needed to validate this proposition and give additional details to help in the design of the calibration specimen.

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