DOI: 10.61782/fa.2025.0902

FORUM ACUSTICUM EURONOISE 2025

TOWARDS A UNIFIED APPROACH TO CHARACTERIZE VENTILATED ACOUSTIC METAMATERIALS

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ABSTRACT

Ventilated acoustic metamaterials have become increasingly popular among researchers given their ability to combine contrasting needs like sound insulation and air change, contributing to improved indoor environment quality. However, being a topic where contributions come from different disciplines, a literature review pointed out significant discrepancies in measuring (or more often simulating) approaches, used to both characterize acoustic and ventilation performances. Thus, published results are often difficult to compare. Starting from a preliminary subdivision of the metamaterial-based solutions into micro and macro-scale approaches and taking into account existing standardized procedures in use in acoustics and (more broadly) in building regulations, the present work investigates which might be the most reliable and appropriate techniques. This might represent a first important step towards defining consensus procedures and metrics to be used in acoustic metamaterial research, allowing for fully comparable results.

Keywords: ventilation, acoustic metamaterials, windows

1. INTRODUCTION

In recent years, ventilated acoustic metamaterials have emerged as promising candidates for novel window structures that attenuate transmitted sound waves while ensuring ventilation [1]. In urban areas, integrating metamaterials into window frames or glass can absorb or redirect traffic noise, enhancing indoor environmental quality by reducing sound transmission.

However, the design of acoustic metamaterials can be fine-tuned to balance noise control and airflow, ensuring proper air circulation. To this purpose, their ventilation performance should be carefully evaluated. A literature review [2] highlighted a critical lack of consistent metrics for assessing the ventilation properties of acoustic metamaterials. Additionally, the limited number of researchers studying ventilation performance resulted in further complicating comparisons among published results.

The real difficulty is to quantitatively determine the ventilation performance of the metamaterial unit. Most studies simply report open area or airflow resistance, without a consistent framework that defines how and where to measure the pressure difference, its magnitude, or how to evaluate the airflow rate.

A common method for evaluating the ventilation performance of metamaterials is to analyze the pressure drop across the material when an airflow occurs. The general idea is that, according to Bernoulli's equation, a change in velocity implies a change in pressure. In this way it is possible to evaluate the air flow resistance of the material. Higher-pressure drop indicates higher resistance offered by the material, reducing the efficiency of the ventilation system. Kumar et al. [3] showed the pressure drop versus flow rate characteristics for different opening percentages, registering an increase in the required pressure drop with increasing in airflow rate. A similar approach is followed by Fusaro et al. [4] and Kumar et al. [5] who analyzed the required pressure drop across the opening by varying the inlet airflow velocity. However, all authors studied the pressure drop resulting from modifying the opening percentage verifying that smaller openings offer high air flow resistance, establishing a high air pressure

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drop across the window by wind and buoyancy forces. Dong et al [6] and Xiang et al [7] generated the air flow by an electric fan installed at the inlet of a tube containing the metamaterial in the middle section. The sample, obstructing the movement of air, reduces its velocity which is measured by an anemometer placed at the outlet of the tube.
To overcome the limitations related to the lack of a defined approach, this research aims to propose a methodology for testing the ventilation properties of metamaterials at the laboratory scale.

2. EXISTING STANDARDIZED METHODS

A survey of existing standards identifies three key metrics for characterizing and comparing ventilated metamaterials: airflow resistance *Rs*, discharge coefficient *Cd*, and air change rate *ACR*. *Rs* value evaluates pressure drop across a porous material, *Cd* value assesses efficiency through openings under varying pressures, and *ACR* value expresses basically the same concept but with reference to the room volume and under well defined pressure drop. Despite their different purposes, each test relies on measured pressure differences and air flow rate to calculate the figures of merit.
Specific airflow resistance is a key parameter in determining the acoustic properties of a material, as it measures how easily air can pass through it. According to ISO 9053-1 [8], *Rs* is defined as the ratio between the pressure drop Δp and the linear flow velocity w of air inside the testing rig:

$$Rs = \frac{\Delta p}{w} \quad (1)$$

A steady air source generates unidirectional laminar airflow through a cylindrical sample at velocities as low as 0.5 mm/s. A differential manometer, measuring down to 0.1 Pa, records the pressure drop to determine specific airflow resistance.
Standard EN 13141-1 [9] proposes a method to calculate the air flow rate value by gradually increasing the pressure difference across the device. The method involves the application of various static pressure differences (1–100 Pa) to an air transfer device, while measuring the corresponding volume flow rates and defining the flow rate vs pressure characteristic curve. Depending on the device type, 8 to 12 pressure measurement points are taken. The *Cd* can be obtained by regressing the measured values according to a generalized flow equation:

$$q = C \cdot \Delta p^{n} \quad (2)$$

where q is the volume airflow rate, Δp is the pressure difference, n is the flow exponent (n = 1 for laminar flow, n = 0.5 for turbulent flow) and C is the airflow coefficient.
The discharge coefficient is a dimensionless coefficient commonly used to characterize openings by quantifying the reduced flow resulting from the formation of the so called “vena contracta”. It reflects the deviation of the actual flow rate from the ideal flow rate, accounting for factors like the geometry of the window opening, surface roughness, and turbulence. By analyzing the pressure difference across the opening and measuring the airflow, it is possible to calculate the coefficient *Cd*, which gives insight into how effectively air passes through the opening under specific conditions.
Mathematically, it is expressed as:

$$Cd = \frac{q_{actual}}{A} \cdot \sqrt{\frac{\rho}{2\Delta P}} \quad (3)$$

ISO 9972 [10] evaluates building infiltration rates through the measurement of the *ACR* value. The test is based on pressurizing or depressurizing the building using a fan to force airflow through the envelope. Airflow is measured at pressure from 50 Pa to 100 Pa. *ACR* is calculated by dividing the air leakage rate at 50 Pa $q50$ by building volume V:

$$ACR = \frac{q_{50}}{V} \quad (4)$$

3. TOWARDS A UNIFIED APPROACH

Standardized methods previously analysed measures the same quantities (pressure differences and volume flow rate or average air velocity across the opening section), but they derive different parameters. In order to characterize the air permeability of ventilated metamaterial units (i.e. devices individually tested in a small equipment like standing wave tubes but intended for use in planar or spatial arrays), none of the test procedures fits perfectly In fact, flow resistance tests are suitable for porous materials with low-velocity laminar flow (≤15 mm/s), but may fail to detect pressure variations in open structures. Conversely, EN 13141 [9] method can induce turbulence in small metamaterial openings. Considering that it is known from the theory [11] that the pressure variation can be expressed as a function of the volume airflow (q) (and consequently of the mean velocity w across the section) as the sum of a linear and a quadratic term respectively representing the laminar and the turbulent component:

$$\Delta p = a \cdot w + b \cdot w^2 \quad (5)$$

Some authors also express the above relationship taking into account that the linear term related to laminar flow

($Re < 1000$) is strongly influenced by viscous losses, equivalent to the airflow resistance and quantified using the Hagen-Poiseuille equation [12] that assumes, for a circular orifice having radius *r* and length *L* and resulting in an open fraction $\phi = A_{open} / A_{tube}$:

$$a = R_s = \frac{8\eta L}{r^2 \phi} \tag{6}$$

where η is the fluid viscosity.
On the other hand, the second term applies to turbulent flow ($Re > 2000$) and can be expressed as a function of the inertial losses depending on the opening geometry, flow separation, etc., whose combined effect is given by the loss factor ($\zeta = 1/Cd^2$) applied to the pressure variation resulting from the Bernoulli equation:

$$\Delta p = \frac{\zeta \rho w^2}{2} \rightarrow b = \frac{\zeta \rho}{2} \tag{7}$$

Thus, the equation can be rewritten as a function of *Rs* and *Cd* as follows:

$$\Delta p = R_s \cdot w + \frac{\rho}{2C_d^2} \cdot w^2 \tag{8}$$

The two terms could be consequently determined from a proper regression analysis performed over a sufficiently large interval of *w* values, capable of keeping into account different flow rates, and, consequently, different Reynolds numbers (Re). However, as turbulence needs space to fully develop, in short openings it is not obvious that this condition takes place even at higher *Re*. Conversely, presence of sharp edges may promote flow separation and turbulence even at lower *Re*.
It is worth noticing that the standard procedure to determine air flow resistance is based on plotting *Δp* as a function of *w* and then fitting the values with a quadratic equation. Subsequent calculation of *Rs* as $\Delta p / w$ and plotting as a function of *w* should consequently return a linear distribution where the constant term coincides with the *Rs* term in Eqn. 8 which, consequently, corresponds to flow resistance when flow tends to zero.
In a similar way, collected data about pressure drops and flow rate might be directly used to calculate *Cd* for each combination. It is known from the theory that *Cd* is generally dependent on *Re* (or *w*) and becomes independent when high *Re* values are reached, while at low values viscous and laminar effects tend to reduce the value. As a consequence the EN 13141 [9] suggests to plot the values and use a power law for interpolation, assuming that, in the most general case, under fully developed turbulent flow the previous equation may not apply. However, if Eqn. 5 is assumed to be valid, it is possible to replace *Δp* in the *Cd* equation, which yields, after some steps:

$$C_d = w \cdot \sqrt{\frac{\rho}{2\Delta p}} \rightarrow C_d^2 = \frac{1}{a + \frac{2b}{\rho w}} \tag{9}$$

From which it appears that the *Cd* value appearing in Eqn. 8, and obtainable from the regression analysis, is actually corresponding to the limiting value towards which *Cd* tends when *w* grows.
In other words, plotting data and calculating regression parameters is consequently the best way to understand whether the data can fit the model represented by Eqn. 8 or more complex turbulent flows appear.

4. NUMERICAL VALIDATION

In order to test whether the proposed approach could be conveniently applied in practice, a "virtual experiment" was carried out using Comsol 6.3 and, considering that most experiments on ventilated metamaterials are carried out on simple "units" that are tested in impedance tubes, a comparable setup was explored. A simple metamaterial employing a labyrinthine structure built around a square opening [13] was modelled. A 3D printed sample of the same design was tested according to the ISO 9053-1 method [8] without success due to the very low pressure drops that appeared. So the device was modelled in Comsol and, for the sake of simplicity, only the open square was modelled. Square dimensions were 14 mm by 14 mm and 8 mm height. Inlet and outlet tubes were modelled as 60 mm cylinders long enough to let the streamline as regular as possible (Fig. 1).

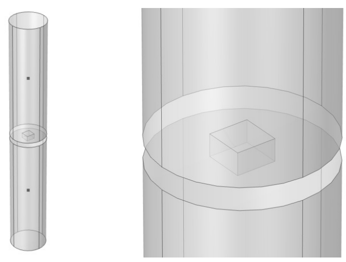

Figure 1. Schematic of the simulation set-up.

A pressure drop ranging from 0.1 Pa to 20 Pa was modelled obtaining the flow velocity distribution given in Fig. 2. Extraction of the parameters from the coefficients of the regression curve returns a Cd = 0.055 which is well aligned with analytical results given by Idelchick [16], while *Rs* shows bigger fluctuations compared to the theoretical value returned by Eqn. 4 and equal to 0.3 Pa.s/m. Extraction of values based only on the lowest *Δp* values and an increased number of simulation points in that range, significantly improved the accuracy.

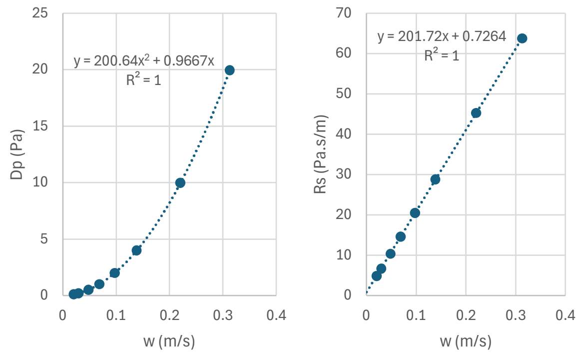

Figure 2. Velocity *w* versus Pressure drop *Δp* and air flow resistance *Rs*.

5. CONCLUSIONS

The method proposed by ISO 9053-1 can be considered, with the proposed amendments, a valid alternative for evaluating the ventilation performance of a metamaterial unit. In fact, the necessary adjustments to the velocity and pressure difference ranges make it suitable for applications with open structures and collected data can be interpreted obtaining representative parameters (Rs and Cd) that could ease comparisons among different devices.

6. ACKNOWLEDGMENTS

Project funded under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU– Project Title METAWAVE (New METAmaterial Window for simultaneous Acoustic, Ventilation and Energy performance) – Grant 2022RA785R-PE8-PRIN2022.

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