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Rigid-Frame Porous Material Acoustic Attenuation on Compressor Discharge

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ABSTRACT

Standards have limited the allowable noise levels in different situations, requiring the study of solutions at the source, in the path or the receiver. Muffler is the major factor influencing the noise of rotary compressor. Control and analyze the acoustic characteristics of muffler is essential. Porous materials have been studied and widely applied to reduce aircraft and vehicular noise or industrial problems in general. Generally, designers use absorbing materials available on the market, however they are not always adequate to the problem when there is the presence of another gas, for example in hermetic compressors. Thus it is proposed to model the propagation in rigid porous material, characterize and develop the porous metal optimizing your acoustical absorption performance, when applied in a cavity. Direct techniques for measuring the material properties such as resistivity, porosity, tortuosity and characteristic thermal and viscous length will be studied.

1. INTRODUCTION

Compressor is the main noise source of the refrigerator. With the increasing demands for quiet environment and quiet refrigerator, it's becoming important to reduce the compressor`s noise. The main contributor of noise from the rotary compressor is the acoustically amplified pressure pulsation in the discharge manifold of the compressor. As an important method to control pressure pulsation, the discharge muffler is a crucial part influencing the compressor`s noise. The objective is to find the best rigid porous absorber to attenuate the acoustic resonances from the same compressor`s discharge chamber. In this paper, a standing wave tube experimental set up with two-microphone is (it´s referring just to the wave tube) developed to analyze absorption coefficient, and its results are compared with a numerical calculation using a FEM model.

The use of porous materials has a large attenuation over a wide frequency range, and if the porous material has a robust structure, it will not easily damaged along years of operation. So this kind of material will be the object of the study. In the automotive and aviation cavities and compartments noise is often controlled through the use of a wide range of porous materials such as foams, rock wool, glass wool, reticulated, fibrous, materials such as aluminium rigid frame porous material, ceramics and polymers. After choose the appropriate type of passive noise control, we have to characterize it, find the best model and parameters, and optimize it according to the application. In rigid porous materials, the determination of physical parameters is very important to predict the behavior of its acoustical propagation. Some of these quantities as airflow resistivity, open porosity, tortuosity and viscous and thermal characteristic lengths have been chosen by numerous authors to model the porous media (Allard, 1993).

Direct measurement of all parameters requires a set of test-rigs to be used and could be however complicated. As an alternative, inverse identification methods can be used to evaluate these parameters from acoustical measurements in a standing wave tube. In the next section, we can find the appropriate five parameters model to describe the acoustical propagation in this type of porous material.

2. FLUID EQUIVALENT MODEL

Consider an isotropic homogeneous medium, presenting a rigid porous structure of high density. It is also assumed that the acoustic wavelength in the fluid is much larger than the pore size, and that an element of the macroscopic material response is considered where the fluid is relevant. The viscous and thermal effects are treated separately independently deriving the dependence of the frequency function of the compressibility modulus and density dynamics. Following the model of Zwikker and Kosten (1949), for simplicity, is a one-dimensional harmonic pressure gradient $-\partial p/\partial x$ with a time dependency $e^{i\omega t}$ applied to the medium, being p the complex amplitude of sound pressure at any point and ω the angular frequency. The amount v_{in} is introduced in a similar way to represent the complex velocity of the fluid in the direction x inside the porous medium. The equation of motion can be written as follows:

$$-\frac{\partial p}{\partial x} = i\omega\tilde{\rho}_{ef}(\omega)v_{in} \,, \tag{1}$$

where $\tilde{\rho}_{ef}(\omega)$ is the dynamic effective density dependent on frequency. Based on the continuity equation and the equation of state and assuming a noise disturbance for a given frequency, one can write:

$$\rho_o\frac{\partial v_{in}}{\partial x} + i\omega\delta p = 0 \,, \tag{2}$$

$$\frac{\delta\rho}{\rho_o} = \frac{p}{\widetilde{K}_{ef}(\omega)}, \tag{3}$$

where ρ_o is the density of static equilibrium, $\delta\rho$ is the density fluid variation, $\widetilde{K}_{ef}(\omega)$ é o is the dynamics modulus of compressibility of the fluid or bulk modulus. This last function takes into account the fact that the density variations in the pore spaces are neither a purely isothermal nor adiabatic. Note that the compressibility $\beta(\omega)$ is proportional to the inverse of the compressibility modulus $\beta(\omega) = \gamma P_o/\widetilde{K}_{ef}(\omega)$, where γ is the ratio of specific heats and P_o is the static pressure of the medium. From Eqs. (2) and (3), we have that:

$$-\frac{\partial v_{in}}{\partial x} = \frac{i\omega p}{K_{ef}(\omega)}. \tag{4}$$

Combining the partial derivative of Eq. (1) of v_{in} in relation of X and Eq. (4), leads to the following Helmholtz equation:

$$\frac{\partial^2 p}{\partial x^2} + \omega^2\frac{\tilde{\rho}_{ef}(\omega)}{\widetilde{K}_{ef}(\omega)}p = 0. \tag{5}$$

Assuming an acoustic pressure in the form $p = Ae^{-\widetilde{m}_c(\omega)x}$, where $\widetilde{m}_c$ is the complex constant propagation $\widetilde{m}_c(\omega) = \alpha^* + i\beta^*$ where we have that α^* is the amplitude attenuation and β^* is the wave number of sound wave propagation in the porous material. From Eq. (5), $\widetilde{m}_c(\omega)$ is given by:

$$\widetilde{m}_c(\omega) \ = i\omega\left[\tilde{\rho}_{ef}/\widetilde{K}_{ef}\ \right]^{1/2}. \tag{6}$$

Assuming a similar expression for v_{in} as the same used for p, $v_{in} = Be^{-\widetilde{m}_c(\omega)x}$, the Eq. (4) can be written as:

$$\widetilde{m}_c(\omega)v_{in} = \left[i\omega/\widetilde{K}_{ef}(\omega)\right]p. \tag{7}$$

The average velocity v_x in the x direction, under a unit cross section of the pores in the surface boundary, but outside of the porous media is given by $v_x = \phi v_{in}$, where ϕ is the porosity of the material. The characteristic impedance of the medium will be $\tilde{Z}_c(\omega) = p/v_x = R + iX$, where R represents the resistive part and X reactive portion, and can be expressed in terms of $\tilde{\rho}_{ef}(\omega)$ and $\widetilde{K}_{ef}(\omega)$, is given by:

$$\tilde{Z}_c(\omega) = \left[\tilde{\rho}_{ef}\widetilde{K}_{ef}\right]^{1/2}. \tag{8}$$

This is the basic form of the equations used in most models of sound propagation in porous materials in rigid structure.

To eliminate the effects of the elasticity of the structure of porous material, the acoustic excitations are considered in a frequency range where the coating behaves rigidly acoustically, for frequencies below the frequency of fluid-structure coupling. From the moment that the structure of the material is still considered only longitudinal waves propagate in the fluid phase. Under this consideration, the fluid that saturates the interconnected pores of the porous material can be described macroscopically as a homogeneous fluid density equivalent effective $\tilde{\rho}_{ef}(\omega)$ and modulus of compressibility $\widetilde{K}_{ef}(\omega)$, as previously described. In this case, following the model of equivalent fluid based on the work of Johnson *et* al (1987) and Allard (1992), effective density and compressibility modulus are respectively given by:

$$\tilde{\rho}_{ef}(\omega) = \rho_o \alpha_\infty \left(1 + \frac{\phi\sigma}{j\omega\rho_o\alpha_\infty}\left(1 + j\,\frac{4\omega\rho_o\eta\alpha_\infty^2}{\sigma^2\phi^2\Lambda^2}\right)^{\frac{1}{2}}\right), \tag{9}$$

$$\widetilde{K}_{ef}(\omega) = \frac{\gamma P_o}{\gamma - (\gamma-1)\left(1 + \frac{8\eta}{j\omega \Pr \Lambda'^2 \rho_o}\left(1 + j\frac{\omega \Pr \rho_o \Lambda'^2}{16\eta}\right)^{1/2}\right)^{-1}}, \tag{10}$$

where η is the cinematic viscosity, Pr is the prandtl number, and c_o is the sound velocity. In this model, the five non-acoustic parameters considered important to describe the complexity of inter-connectivity of the pores is the flow resistivity, σ, porosity, ϕ, tortuosity, α_∞ and the characteristic viscous length, Λ and characteristic thermal length Λ'.

The surface impedance of the porous material backed on a rigid wall can be calculated as:

$$\tilde{Z}_s(\omega) = \frac{\tilde{Z}_c}{\phi}\coth(\widetilde{m}_c d) = -i\,\frac{\tilde{Z}_c}{\phi}\cot(\tilde{k}_c d)\,, \tag{11}$$

where d is the porous material thickness and $\tilde{k}_c(\omega) = \omega\left[\tilde{\rho}_{ef}/\widetilde{K}_{ef}\right]^{1/2}$ is the complex wave number. The normal incidence absorption coefficient is given by $\alpha = 1 - \left|(\tilde{Z}_s - 1)/(\tilde{Z}_s + 1)\right|^2$.

3. POROUS MATERIAL CHARACTERIZATION

The characterization of porous materials can be done basically by two different ways. The first is measuring the non-acoustic parameters one by one separately which is required as input data for the analytical model, and of course it's possible to compare to impedance tube measurements for normal incidence. This way is called Direct Methods. Another way is using impedance tube measurements of the surface impedance according ISO 10534-2 (1998), and the analytical model with unknown parameters (flow resistivity, porosity, tortuosity, and the characteristic lengths). From an optimization algorithm we can find the best adjust of the real and imaginary parts of the model surface impedance, estimating the non-acoustic parameters. In this paper we tackle just the first way. The most important parameter in the porous material characterization is possibly the flow resistivity, which the SI unit is given by $[Ns/m^4]$. The ISO 9053 (1991) standard also reports a method for the measurement of the air-flow resistance with an oscillating flow. It is based on the measurement of the sound pressure in a small chamber having rigid walls except the one constituted by the sample to be tested. A piston, oscillating at a very low frequency about 2 Hz and connected to the chamber, acts as a constant and known volume-velocity generator. The test condition ensures that the volume velocity of the generator is the volume flow rate through the porous sample.

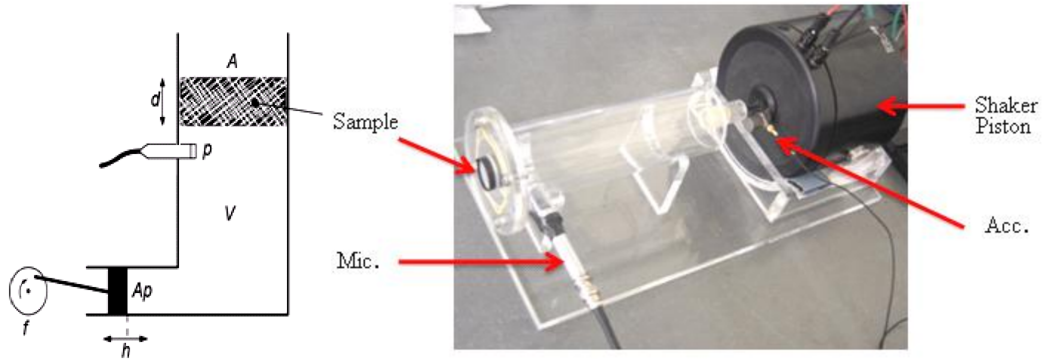


Figure 1: Flow resistivity apparatus.

Considering the volume compression of the chamber, the calculation of the flow resistivity is given by:

$$\sigma = \frac{A.p_o.10^{L/20}}{2.\pi.d.f.\frac{Ap.h}{2\sqrt{2}}\sqrt{1-\left(\frac{V.p_o.10^{L/20}}{P_o.\gamma.\frac{Ap.h}{2\sqrt{2}}}\right)^2}}, \tag{12}$$

where A is the porous sample area, p_o is the threshold of hearing $(2.10^{-5}\,Pa)$, L is the sound pressure level on microphone at frequency $f = 2Hz$, A_p is the piston area, h is the peak to peak displacement, V is the volume of the chamber. One accelerometer close to the piston is used to find the peak to peak displacement or the RMS value. It is known that microphones and accelerometers typically have poor sensitivity at very low frequencies. Therefore, frequencies near 20 Hz can be used in this experiment, where the responses of the transducers are flat.

The open porosity (ratio of pore volume to total sample volume) is directly measured by the method of water evaporation, where the pore volume is the weight of saturated sample minus the weight of dry sample divided by the density of water.

Tortuosities as well as the thermal and viscous characteristic lengths are the basic physical parameters used in the description of acoustic propagation in porous structures in models of fluid equivalent rigid structure (Allard, 1992). These parameters can be measured by several methods; however, the use of ultrasound techniques is definitely faster and more efficient for this purpose, and has been described for the last 15 years. For example, the spread in different gases (Leclaire *et al*, 1996), or air to various static pressures has been used to determine both the tortuosity and characteristic lengths (Ayrault *et al*, 1999). To simplify these measurements in industrial applications is very convenient to consider the ratio of viscous and thermal characteristic lengths, for a given value, generally being 1 and 3. The study conducted by Fohr *et al* (2008), simplified these two procedures. Instead of using ultrasonic transducers for broadband, to cover a significant portion of the dispersion curve, we used ultrasonic sensors narrow band around 40 kHz, producing a pulse of pure burst tone. This frequency is high enough to use so-called asymptotic approximation for high frequency and is low enough to have a wavelength much larger than the pore sizes. Using cheap ultrasonic sensors of narrow band around 40 kHz, the apparatus can be seen on Figure 2.

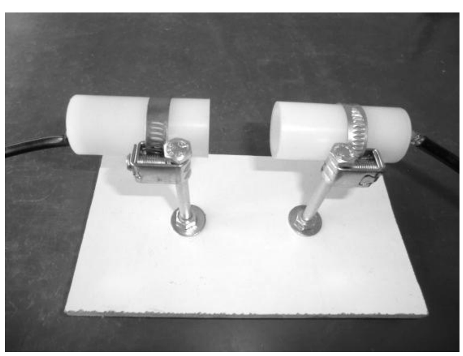


Figure 2: Tortuosity and characteristic lengths apparatus.

From the time delay τ and the attenuation ratio amplitude T with/without sample of the signal time, it's possible to find the tortuosity and the characteristic lengths considering the ratio between them as $\mathrm{N} = \Lambda'/\Lambda = 2$. The formulation for the tortuosity and the characteristic viscous length are (Fohr *et al,*2008):

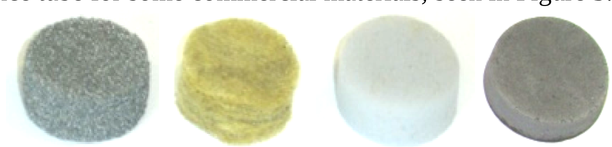
$$\alpha_\infty = \left[\left(\frac{|\ln(T)|c_o}{d\omega}\right) - \sqrt{\left(\frac{|\ln(T)|c_o}{d\omega}\right)^2 + \left(1 + \frac{c_o\tau}{d}\right)^2}\right], \tag{13}$$

$$\Lambda = -\frac{\delta}{2}\left[\frac{\mathrm{N}\sqrt{\mathrm{Pr}} + \gamma - 1}{\mathrm{N}\sqrt{\mathrm{Pr}}}\right]\left[1 - \sqrt{1 + \left(1 + \frac{c_o\tau}{d}\right)^2\left(\frac{\omega d}{c_o|\ln(T)|}\right)^2}\right]. \tag{14}$$

where $\delta = \sqrt{2\eta/\omega\rho_o}$ is the viscous skin depth and Pr is the Prandtl number. The units of the characteristic lengths generally are in μm.

4. MEASUREMENTS AND APPLICATION RESULTS

The first step of characterization measurement is related to the absorption coefficients and surface impedance, considering the air normal condition of temperature and pressure. Therefore, we carried out absorption measurements on the impedance tube for some commercial materials, seen in Figure 3.



(a) (b) (c) (d)

Figure 3: Porous aluminum (a), rockwool (b) melamine (c) and Labmat process (d).

Knowing that the materials present near 10mm thickness, they can be compared acoustically from each other according to Figure 4, considering the absence of air cavity behind the sample. The samples MP-10 and CP-01 are metallic porous materials produced by powder metallurgy. They use iron oxide (Fe_2O_3) and graphite, which were pressed and sintered by the Materials Laboratory (LabMat), from the Mechanical Engineer Department (EMC) of the Federal University of Santa Catarina (UFSC).

It´s known that the sound absorption caused by heat exchange and viscous losses through the pores of the material are related to the properties of the gas and the parameters which characterize the porous material. However, parameters such as porosity, tortuosity and characteristics lengths depends only on the microstructure of the porous material, and are independent of fluid properties. But the impedance and the sound absorption depend from the the fluid properties.

It can be observed on Table 1 the comparison of the results for the five parameters of rockwool, melamine, porous aluminum, MP-10 and CP-01 samples.

Table 1: Comparison of resistivity and tortuosity of samples.

	Aluminium	Melamine	Rockwool	CP-01	MP-10
Thickness [mm]	12.6	11	10	10	9.8
Resistivity [kNs/m^4]	4.7	10.3	20.6	202	364
Porosity [%]	84	99	98	68	60
Tortuosity [$-$]	1.08	1.0	1.01	2.2	2.3
Char.Thermall Lenght [μm]	348	128	90	54	40
Char. Viscous Lenght [μm]	175	120	85	33	26

Looking at Figure 4, we note that the absorption coefficient is directly related to the flow resistivity. Considering only the flow resistivity and knowing that the porosity of the sample are high (above 80%, except for MP-10 and CP-01), there is an increase on absorption coefficient in accordance with the increase on airflow resistivity. For a sample thickness of 10 to 12mm and considering the optimum Rayleigh condition $\phi\sigma L/\rho_o c_o \approx 2$, we note the maximum absorption for flow resistivities between $70kNs/m^4$ and $90kNs/m^4$ in the air. For the gas case, we need higher flow resistivity and maximum porosity always. That´s it, the increase of absorption coefficient in accordance with the increase on resistivity until to find the optimum. The characteristic lengths were found by fitting Johnson-Allard inverse model, and using a genetic method as optimization algorithm. For a better fit between the model and the experimental, it was necessary to reduce the characteristic lengths given by the micro geometry factors of c = 0.7 and N = 1.5, because the powder used in the sintering process has reduced diameters (order of 10 to 40μm) . The comparison for the samples between the analytical Johnson-Allard model and the experimental absorption are observed on Figure 4.

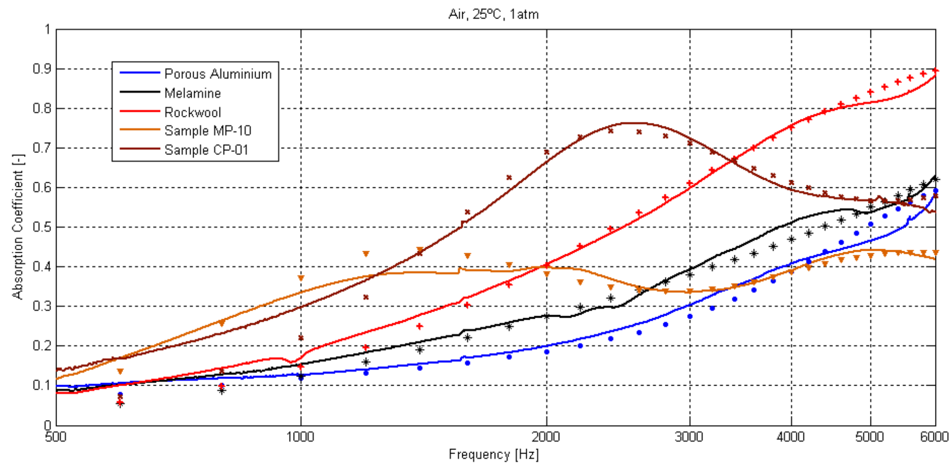


Figure 4: Analytical adjusted model (points) and experimental results (lines).

After the measurement and parameters adjustment for a given porous material, we can find the absorption coefficient for any fluid by adjusting the resistivity values, that is proportional to the fluid viscosity. Thus, we carried out this analysis for a discharge compressor cavity condition using R134a. The interest is observing the absorption on the discharge of an generic compressor, changing the properties for R134a according to Table 2.

Considering a 10 mm thick sample for each of the materials evaluated, it can be observed the comparison of absorption in the discharge condition on Figure 5. Note that for R134a, under such conditions, the rockwool, melamine and the porous aluminum materials have lower absorption coefficients compared with the impedance tube measurements for air on the Figure 4. The major fluid differences are related to the static pressure, sound velocity and density. The R134a properties can be observed on Table 2.

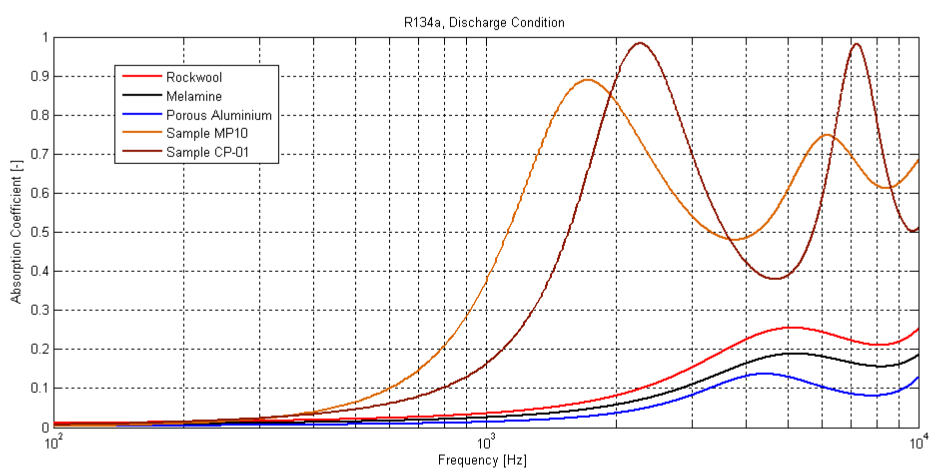


Figure 5: Absorption for the compressor discharge condition.

Table 2: Gas Compressor Properties.

R134a	Temp. [ºC]	Pressure [Mpa]	Density [kg/m^3]	Cv [kJ/K-kg]	Cp [kJ/K-kg]	Sound Speed [m/s]	Viscosity [uPa-s]	Therm Cond. [W/m-K]
Discharge	60	1.49	72.8	0.92	1.24	138.3	13.64	0.0176

Due to high airflow resistivity, the sample MP-10 and the sample CP-01 presents much higher absorption coefficient in comparison with the porous aluminum or rockwool on Figure 5, whereas R134a saturates the sample.

All the viscous characteristics and thermal boundary layer are altered by gas changing and their thermodynamic conditions, and consequently the heat exchange characteristics and viscous losses will also be changed. So we need a new material that is suitable for a given particular environment. Therefore, optimization tools (designed to maximize absorption) are required. From the characterization reverse process it´s possible to obtain the optimal parameters that should construct the material. Thus one can evaluate the attenuation caused by the porous material, applied on compressor discharge cavity, using the finite element model. The analysis complex geometric shapes and thickness variations become quite limited for some impedance surface application.

Nevertheless, it´s possible to model the porous material volume attached to a rigid acoustic cavity, by considering an equivalent fluid. We only need the effective density $\tilde{\rho}_{ef}(\omega)$ and the complex velocity propagation $\tilde{c}(\omega)$ of the porous material, both frequency dependent from an analytical appropriate model, for example Allard-Biot or Johnson-Allard. The elements that represent the porous material will have these two complex acoustic properties, and therefore a new characteristic impedance of the porous material. The modeled geometry FEM mesh can be seen on Figure 6.

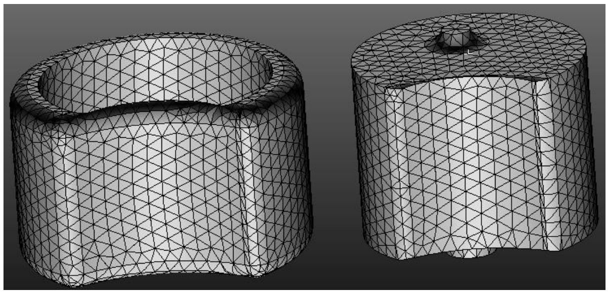


Figure 6: FEM Porous material mesh (left) and generic discharge muffler cavity mesh (right).

The excitation is a particle velocy on the discharge valve face of 1E-4 m/s and a anecoic termination impedance $\rho_o c_o$ for R134a. In this case, we used an 1% speed of sound damping. There are 31% porous material volume and the output discharge sound pressure level can be seen on Figure 7 for the tested materials.

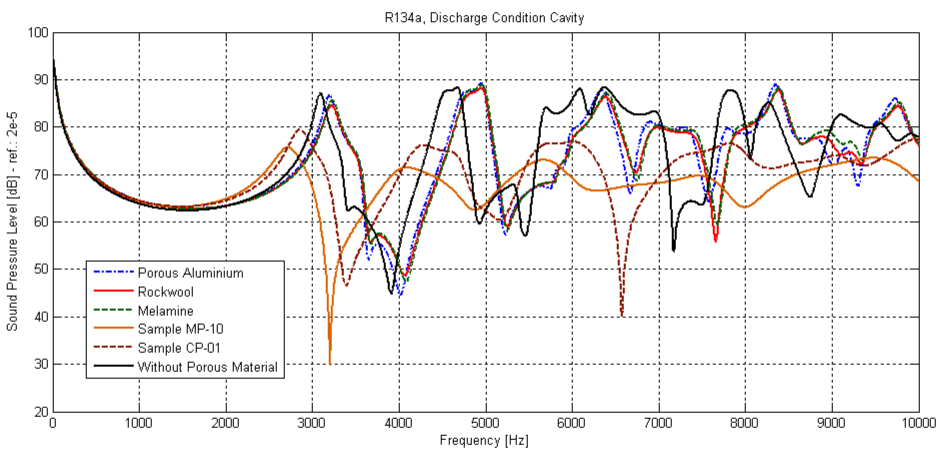


Figure 7: Sound pressure level for numerical application of different porous materials.

Varying the porous material thickness we can compare the output cavity sound pressure level, by observing the increase on the attenuation of acoustic resonances according of the thickness increasing. This can be observed on Figure 8.

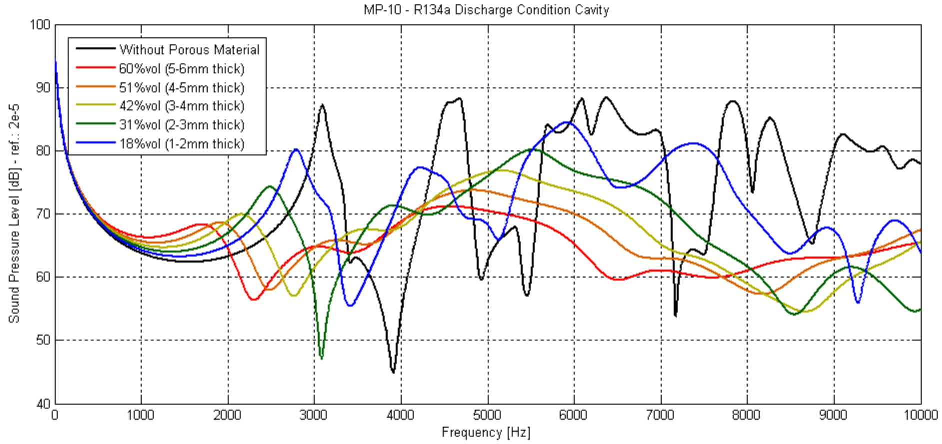


Figure 8: Sound pressure level with numerical application of diferent porous material thickness.

6. CONCLUSIONS

In summary, the following observations have been made:

- The characterization of the porous materials have been successfully done;
- Validation of the rigid frame porous material model, that presents good agreement with the impedance tube measurement of the absorption coefficient, considering the air.
- It´s important to know the gas thermodynamic properties where need to apply the porous material. The absorption coefficient is strongly dependent of these properties.
- The metallic porous material fabricated presents good absorption coefficient for R134a discharge condition, due to the high flow resistivity.
- The application of the porous material on the discharge cavity presents good damping resonance for the proposed porous metallic material, but not for the commercial materials (Rockwool, melamine, porous aluminum.). The attenuation depends on the thickness of the material, but we cannot really strangling the cavity due some pulsations problems.
- We expect 2dB in the global noise reduction of the compressor, but some more experiments must be performed.

NOMENCLATURE

p	complex pressure amplitude	(Pa)
$\partial p/\partial x$	pressure gradient	(Pa/m)
ω	angular frequency	(rad/s)
t	time	(s)
$\tilde{\rho}_{ef}$	complex effective density	(kg/m^3)
ρ_o	fluid density	(kg/m^3)
c_o	fluid speed of sound	(m/s)
$\tilde{K}_{ef}$	compressibility modulus	(Pa)
γ	ratio of specific heats	(Pa)
P_o	Static medium pressure	(Pa)
x	longitudinal axis	(m)
$\tilde{m}_c$	complex propagation constant	(m^{-1})
$\delta\rho$	density fluid variation	(kg/m^3)
v_{in}	velocity inside the pores	(m/s)

Subscripts

o	medium
ef	effective
c	characteristic
in	inside

v_x	velocity in *x*-direction	(m/s)
A	pressure amplitude	(Pa)
B	velocity amplitude	(m/s)
ϕ	material porosity	(-)
$\tilde{Z}_c$	characteristic impedance	(Rayls)
α_∞	tortuosity	(-)
σ	airflow resistivity	(Ns/m^4)
η	viscosity	(Pa.s)
Λ	characteristic viscous length	(m)
Λ'	characteristic thermal length	(m)
Pr	Prandtl number	(-)
d	porous material thickness	(m)
$\tilde{k}_c$	complex wave number	(m^{-1})
$\tilde{Z}_s$	surface impedance	(Rayls)
α	absorption coefficient	(-)
p_o	threshold of hearing	(Pa)
τ	time delay	(s)
δ	viscous skin death	(m)
T	amplitude attenuation	(-)

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