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# **EXPERIMENTAL CHARACTERISATION AND OPTIMISATION OF 3D PRINTED STACKS FOR THERMOACOUSTIC REFRIGERATION**

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In light of the broadening use of refrigeration in the modern industrial era and considering that conventional refrigeration fluids such as HCFCs, CFCs and HFCs are among the major causes of increased global warming, it seems necessary to implement greener and more sustainable refrigeration solutions rather than continuing to use the ordinary refrigeration methods. Literature emphasizes the need to develop simple and inexpensive acoustic refrigerator prototypes, but one major difficulty results in finding robust and reproducible setups. The following study introduces the description of an experimental and inexpensive construction of a thermo-acoustic refrigerator (TAR), aimed to convert acoustic energy into thermal energy to be used as a heat source in a refrigeration cycle. TARs operate with inert non-polluting fluids such as air, present no frictional losses and require less maintenance costs than ordinary refrigerators, and can operate with either standing or traveling acoustic waves. This work focuses on the repeatability of the setup and the robustness of the results obtained, characterizing an innovative material for the stacks production and proposing a process of optimization of the stack itself. The aim of the study is to realize a simple and economic prototype, which is also robust, easily replicable and innovative from the point of view of the choice of materials, production techniques and their optimisation process. The results concerning the gradient of temperature obtained will be analysed in order to validate the success of the experiment in terms of optimization and reproducibility.

Keywords: Thermoacoustics, Stack optimisation, Thermoacoustic materials

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## **1. Introduction**

As stated in many studies [1-7], thermoacoustics is a technology that in recent years gained a particular interest within the scientific community. The conversion from acoustic energy deriving from fluid-

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dynamic processes in sound waves to heat or chemical energy is the fundamental principle characterising thermoacoustics. The advantages of this technology are multiple, since the machines that are based on it are mechanically simple, and usually do not have any moving parts; they are also reliable, not being interested by frictional and wear issues, economically advantageous and essentially non-polluting, since it is not necessary to use environmentally impacting refrigeration fluids. A standing wave acoustic refrigerator is an apparatus which converts the acoustic energy from standing sound waves produced by an acoustic driver, typically a loudspeaker, into thermal energy, obtaining a certain amount of temperature difference at the edges of a porous medium named stack. The stack should ideally have a low thermal conductivity and a high specific heat capacity. The duct containing the stack starting from the loudspeaker is called resonance tube, and its length is related to the frequency provided by the driver. The aim of the stack is to increase the surface area of the walls in contact with the gas in order to store a higher quantity of heat along the tube. The aim of this study is to build a simple, inexpensive and easily reproducible thermo-acoustic refrigerator. An optimisation of the stack in terms of geometry, dimensions and length is proposed in order to find the maximum temperature gradient obtainable from the tests conducted. A representation of the experimental setup used in the study is presented in Figure 1.

The prototype consists of a brass tube 29mm in diameter and 390mm long, with a resonance frequency of 193Hz, connected to a Visaton mid-range 8Omega loudspeaker. The excitation signal is a periodic sinusoidal type, and under these conditions an acoustic power of 0.229W and an internal pressure corresponding to 105dB are obtained. The resonator contains a stack placed at the pressure node of the configuration, i.e. close to the end of the tube opposite the acoustic source. Brüel & Kjær pressure-field microphones with a sensitivity of 3.72 mV/Pa are used for acoustic measurements, and Crouzet K-type thermocouples are appropriately placed at the ends of the stack to measure the temperature trend at the stack ends. The correct positioning of the thermocouples proved to be a major issue in the realisation of the setup, given the difficulty of ensuring stable positioning in the presence of a removable stack. A series of 95 tests was conducted, each under standard conditions.

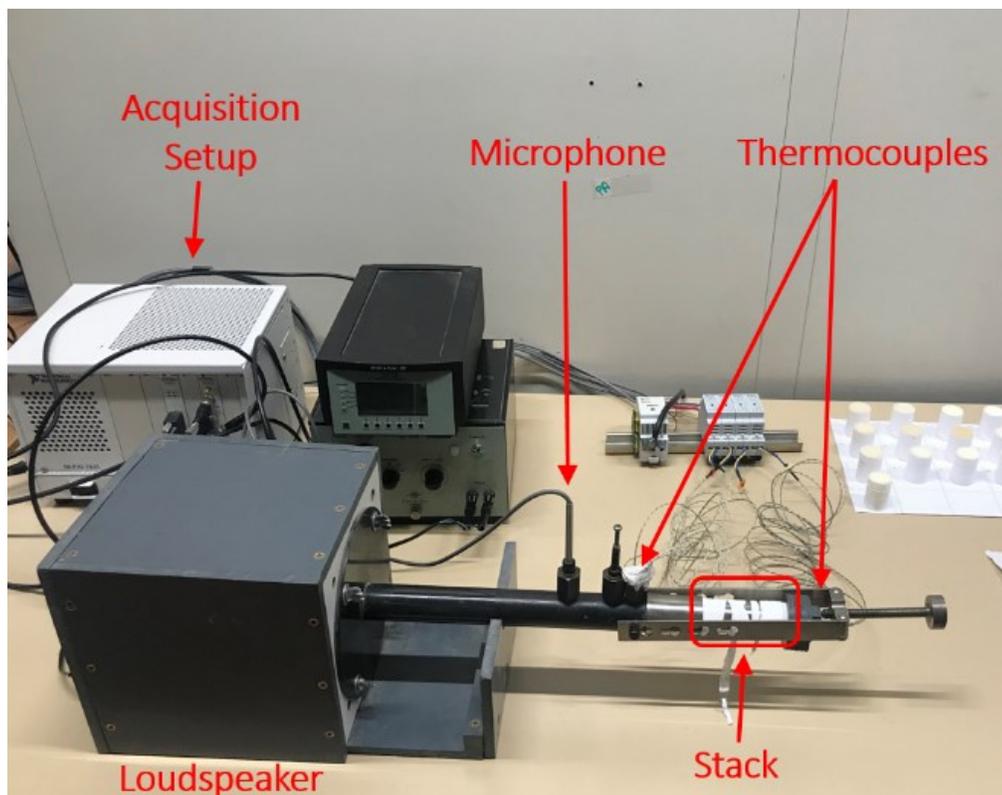


Figure 1: TAR and instrumentation setups.

Maintaining a constant sound level, the temperature difference reached at the edges of the different stacks was evaluated after a period of 1000s. With regards to the acquisition and post-processing of the results, a LabVIEW® interface was implemented for the output of the signal and the measurements acquisition, which were then post-processed using Matlab® and Excel® softwares.

## 2. Stacks design and implementation

The study and optimisation of the stack is one of the possibilities to increase the efficiency of a TAR. In this study, it was decided to implement 3D-printed stacks, both to be able to better manage the different geometric parameters of the stack and to be able to choose the most suitable type of material. The stacks produced in this research were first modelled in a CAD environment using the FreeCAD software, and then 3D printed using the Multi Jet Printing (MJP) technique, using a 3D Systems "ProJet 3510 SD" printer. This technique allows to achieve high resolution by means of a support material (a wax, removed in post processing) and depositing liquid photopolymers onto a build surface using inkjet technology. The material used for the printing process is the UV curable plastic "VisiJet® M3 Crystal", the characterisation of which is described in section 3. Once printed, the stacks are placed in a static oven to melt the wax backing and then coated with a layer of PTFE to ensure adhesion to the pipe walls and avoid any wall leaks. Figure 2 shows the different stages of stack design and realisation, from CAD modelling to a view of the front and side of the stack.

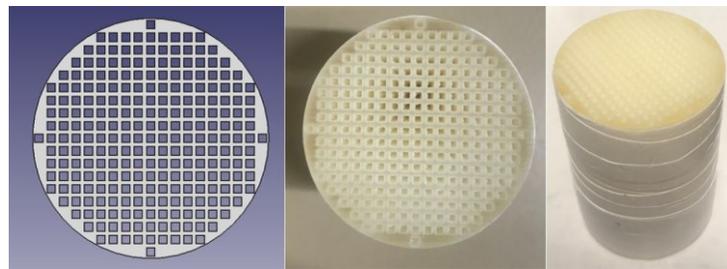


Figure 2: Design of the stack in CAD environment, front and side views of the printed stack.

## 3. Material characterisation

This section introduces the thermal characterisation of the material used to print the stacks and a description of the techniques used for this part of the study. While it is common in the literature to find the mechanical properties of materials similar to the one used in this study, it turned out to be necessary to characterise it from a thermal point of view. By printing rectangular specimens of material (Fig. 3a), it was possible to calculate the thermal conductivity through a hot-wire conductivity meter (Fig. 3b), resulting in  $0.167 \text{ W/mK}$ , and through a hot-plane effusivity meter (Fig. 3c), it was possible to calculate the effusivity and relatively a specific heat capacity of the material equal to  $1927.98 \text{ J/kgK}$ .

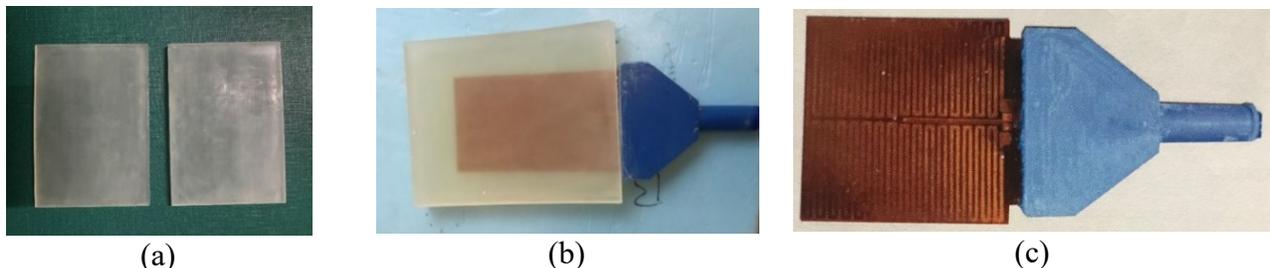


Figure 3: Visijet® M3 Crystal specimens (a), hot-wire conductivity meter between the specimens (b) and hot-plane effusivity meter (c).

By means of a high-precision balance, it was possible to find a material density of  $1170 \text{ kg/m}^3$ , corresponding to a material cube specimen of  $1 \text{ m}^3$ . Through the Eq. (1), a thermal penetration depth ( $\delta_t$ ) of the material equal to  $1.104 \cdot 10^{-5} \text{ m}$  can be found.

$$\delta_t = \sqrt{\frac{k}{\pi f \rho c_p}} \quad (1)$$

This quantity in fact turns out to be a fundamental thermoacoustic parameter as the distance that the heat is able to diffuse through a gas, being  $f$  the frequency of the sound wave,  $k$  the gas thermal conductivity,  $\rho$  the material density and  $c_p$  the material specific heat capacity. The material exhibits low thermal conductivity and a high specific heat, which are qualities that make it perfect for use in thermoacoustic refrigeration, as can be seen in literature [8]. A material specific heat higher than the working fluid aids the process of transferring heat from the source to the surface of the stack, while low thermal conductivity along the resonator prevents any useful heat from dissipating along the stack. From an economic point of view, an approximate cost for the production of a single stack is estimated at 1.70 € for the Visijet® M3 Crystal material and about 0.30 € for the wax backing.

#### 4. Stacks optimisation

Figure 4 shows the 20 different stacks tested in this study. Optimization involved three fundamental geometric parameters, namely the stack's pore geometry, the size of the air gap, i.e. the characteristic pore length, and the thickness of material between two adjacent pores. Once the ideal configuration of geometry and dimensions was found, the length of the chosen stack was optimized. In order to distinguish the different stacks, a designation of the type A-B-C-D was adopted. In the first step, only stacks of type A-B-C were considered, of a fixed length, where A is the pore geometry, B the pore size in mm and C the distance between two adjacent pores in mm. For the last optimisation step, the term D was added, indicating the length of the stacks in mm. Table 1 shows the stacks implemented in the firsts optimisation processes, with a fixed length of 40 mm with the corresponding temperature gradient obtained and the standard deviation from 5 different tests on each stack.



Figure 4: Representation and nomenclature of stacks produced in the study.

Name	Geometry	Material Thickness [mm]	Air Gap [mm]	Mean $\Delta T$ [ $^{\circ}C$ ]	1.96*Standard Deviation
Cr-0.25-1	Circle	0.25	1	6.04	0.38
Cr-0.1-1	Circle	0.1	1	9.91	0.75
Hc-0.25-1	Honeycomb	0.25	1	12.83	0.31
Hc-0.1-1	Honeycomb	0.1	1	16.87	0.52
Sq-0.5-1	Square	0.5	1	9.78	0.46
Sq-0.7-1.4	Square	0.7	1.4	7.57	0.70
Sq-1-1	Square	1	1	5.53	0.69
Sq-0.3-0.6	Square	0.3	0.6	8.18	0.40
Sq-1-2	Square	1	2	5.93	0.58
Sq-0.5-1.5	Square	0.5	1.5	10.24	0.74
Sq-0.25-1	Square	0.25	1	14.25	0.42
Sq-0.2-1	Square	0.2	1	14.88	0.70
Sq-0.1-1	Square	0.1	1	18.42	0.52
Sq-0.1-1.2	Square	0.1	1.2	17.45	0.42
Sq-0.1-1.4	Square	0.1	1.4	14.06	0.48

Table 1: Nomenclature and properties of the 40 mm length stacks.

The first step of the optimisation focused on the choice of the stack's pore geometry. Despite the fact that there are several kinds of geometry that can be implemented in the literature, and that some of them are considered to be optimal for the realisation of a stack, it was necessary to choose geometries that were not only satisfactory from the point of view of results, but that also allowed them to be realised by the 3D printing process used in this study. For this reason, the choice fell on the parameterisation of three geometries, one square, one circular and one hexagonal honeycomb. Two different configurations identical in characteristic dimensions but in the three geometries were printed, and the highest temperature gradient obtained was evaluated (Figure 5, blue-points part of the graphic). The square geometry was found to be the most effective, and as it is also the easiest to manufacture, it results in stacks with fewer manufacturing defects and inaccuracies. For this reason, once this geometry was chosen, the dimensions of the pores and the thickness of material between them were parameterised.

As could be seen from the previous parameterisation, at a given geometry, the temperature gradient varies considerably depending on the size of the chosen design. This optimisation step focuses on choosing the square pore size and the gap between two pores, and finally defining an ideal air/material ratio, as depicted in Figure 5, green-points part of the graphic. The choice of material gap size is limited by technical limitations. A material thickness of less than 0.1mm is not possible for structural reasons, as the inner walls of the stack are deformed and do not guarantee a perfect component realisation. Similarly, having air gaps that are too large (greater than 1.4 mm) means that the material discontinuities are too high, which means that the internal pore walls of the stack are not structurally dense.

After an analysis of 11 different configurations, the stack resulting in the best temperature gradient was the sq-0.1-1 stack, meaning a stack with square pores with a side dimension of 1mm and spaced by a material thickness of 0.1 mm, resulting in a temperature gradient at the sides of the stack of 18.42  $^{\circ}C$ .

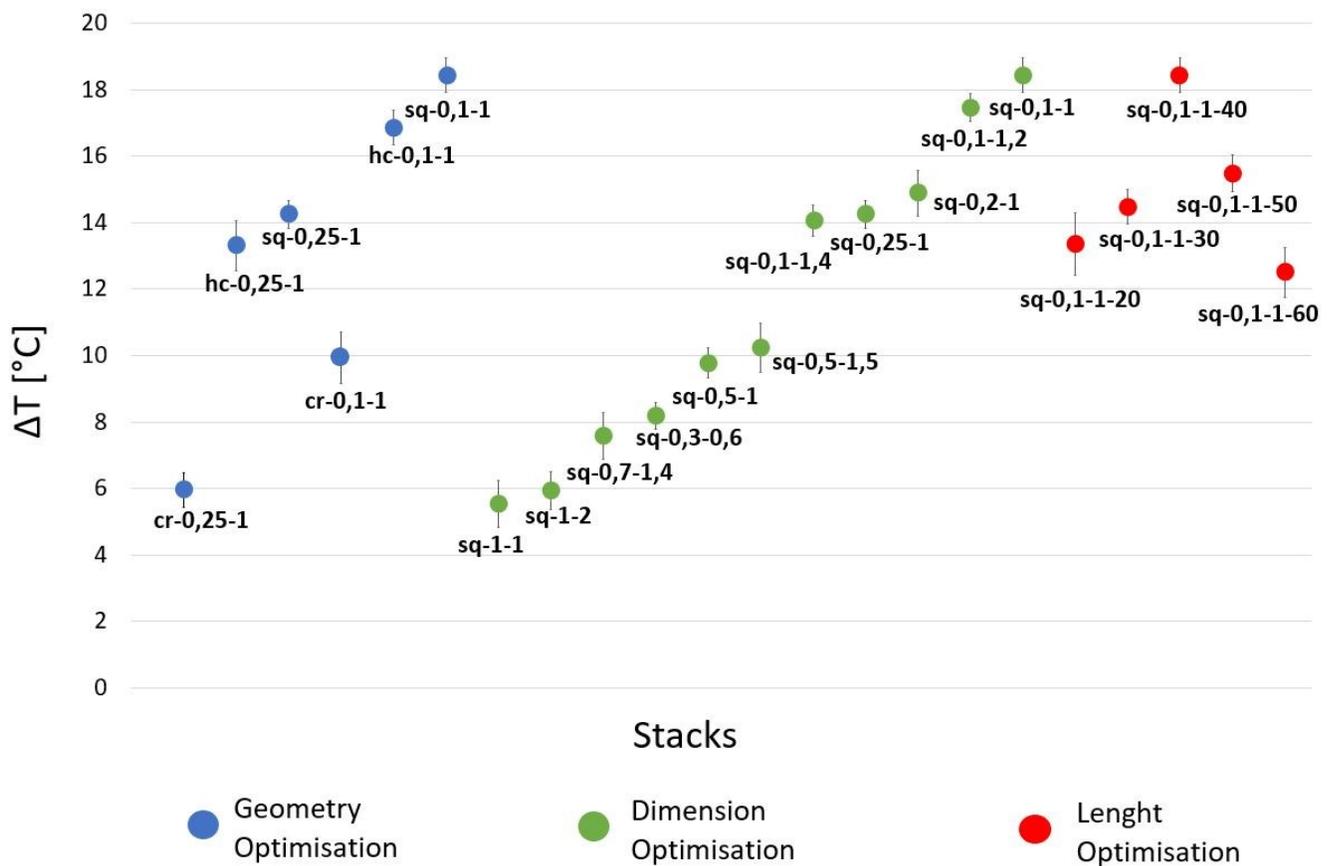


Figure 5:  $\Delta T$  obtained from the different stacks, divided by optimization and with the relative standard deviation.

The arbitrary length chosen for the stacks considered so far was 40mm, and once the ideal configuration of geometry and dimensions was found, a parameterisation of the optimal stack length was carried out. As shown in Figure 5 in the red-points part of the graphic, 5 different lengths were implemented, from 20 to 60 mm, and the length that allows for a higher temperature trend was 40mm. Considering the dimensions of the pipe used and the maximum pressure inside the pipe, this length allows for the best use of the thermo-acoustic conditions developed around the stack.

## 5. Conclusions

This paper presents the characterisation and optimisation study of 3D-printed stacks used in a prototype thermo-acoustic refrigerator. After characterising the innovative and inexpensive Visijet® material, and verifying its suitability for thermoacoustic applications, the geometric and dimensional parameters of the stack are optimised in order to obtain the greatest possible temperature difference at the ends of the stack. The optimisation is guided by the feasibility of the stacks considered, which places construction limits on the size of the stack holes and on the thickness of the material between adjacent pores. After analyzing different geometries and pore sizes, material thicknesses and stack lengths, an optimal stack configuration was achieved, characterized by square pores of 1mm side and material thickness of 0.1mm, 40mm long. This stack results in a temperature difference at the sides of the stack of 18.72 °C. As a future prospect, the authors aim to implement a numerical simulation of the prototype and to implement a complete setup with heat exchangers to be placed at the sides of the stack in order to emulate a real refrigeration cycle and to be able to analyze the machine's performance from an energetic point of view. Further clarification and more detailed information on the study and the setup can be found in the article recently published by the authors [9].

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