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Research paper

Parameter estimation for the characterization of thermoacoustic stacks and regenerators

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HIGHLIGHTS

- A model for the propagation of acoustic waves in a thermoacoustic core is proposed.
- Geometrical and thermal parameters are adjusted by using an inverse method.
- Parameters are estimated for a ceramic catalyst, a stack of grids and a carbon foam.
- The values for geometrical parameters are close to manufacturers' data.
- The heat diffusion length is higher for the stainless-steel grids stack.

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ABSTRACT

This paper deals with the *in-situ* characterization of open-cell porous materials that might be used as a so-called stack (or regenerator) in a thermoacoustic engine. More precisely, the manuscript presents an inverse method aiming at estimating geometrical and thermal properties of various samples of porous media surrounded by heat exchangers and connected to a thermal buffer tube to form a ThermoAcoustic Core (TAC). This estimation is realized from acoustic measurements, and it is expressed as a minimization problem applied to the squared norm of the difference between experimental and theoretical transfer matrices of the TAC. Experimental data, obtained for different stacks (ceramic catalyst, pile of stainless steel wire meshes, carbon and metallic foams) under various heating conditions, are used in order to fit the theoretical *forward* model by adjusting geometrical properties of the sample and heat exchange coefficients. Common geometrical properties (porosity and average pore's radius) obtained with the present method are consistent with available data from manufacturers. Moreover, this method allows to estimate the tortuosity of the material which is not given by manufacturers. Estimation of heat coefficients (and their variations with heating) provides global information about anisotropic heat diffusion through the porous material employed as a thermoacoustic stack submitted to a temperature gradient. Among the four characterized samples, it appears that the carbon foam allows to get the highest temperature gradients and thus can be considered as the most efficient regenerator for energy conversion in a thermoacoustic prime mover.

1. Introduction

Thermoacoustic prime-movers are specific kinds of heat engines, which basically consist of a porous medium, referred to as a stack or a regenerator, inserted into an acoustic resonator. The operation of such a system consists in applying a steep temperature gradient along the stack, which leads to the onset of self-sustained acoustic oscillations at the frequency of the most unstable acoustic mode of the resonator. The resulting mechanical (acoustical) work can be used for the production of electricity [1] or for thermoacoustic refrigeration [2]. Thermoacoustic engines have fundamental advantages such as low maintenance costs, simplicity, and they are able to achieve good efficiency. Potential applications of thermoacoustic engines include refrigeration with low environmental impact [3], heat pumps [4] or engines [5] enabling to recover waste heat, as well as solar powered thermoacoustic engines [6,7].

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The operation of a thermoacoustic system – and especially the onset of self-sustained waves in thermoacoustic prime movers – depends mainly on the thermal exchanges involved in the stack and the heat exchangers. In the early versions of thermoacoustic engines built in the mid 90's, the thermal interaction between the fluid and the solid was realized by using porous materials of simple geometry such as stacks of parallel plates [8,9] or honeycombed materials [10]. However, recent research works have shown that the increase of efficiency of thermoacoustic systems may involve using more “exotic” materials, such as pin-array stacks [11], Reticulated Vitreous Carbon (RVC) foams [12] or Stainless Steel wire meshes [13], which are clearly anisotropic materials.

The theoretical description of the porous elements in the active thermoacoustic cell is essential for the design of thermoacoustic systems. The standard periodic frames such as parallel plates or uniformly-shaped channels networks may be described with the capillary-tube-based thermoacoustic theory [14–17]. In this theory, the viscous and thermal functions f_ν and f_κ – whose analytical expressions depend on the geometry of the channel – are introduced for taking into account the coupling between the oscillating fluid and the solid medium. In 1991, Roh et al. [18] notably validated with experiments Stinson's theoretical work for rectangular pores [17]. Numerous works have been made since then, in order to expand the theory to more complex porous frames. In a series of papers [19–21], Wilen and Petculescu measured the thermoviscous functions of different materials (notably RVC foams and aluminium foams), with and without temperature gradient. In 2005, Muehleisen et al. [22] used a 4-microphones method in order to measure the characteristic impedance and the complex wave number of RVC foams, and compared their results with those obtained with semi-analytical [23,24] and analytical [25] models of porous media. In recent works, Roh et al. developed a mathematical model for inhomogeneously heated porous materials [26], based on the capillary-based thermoacoustic theory, which showed good agreement with the experimental results obtained by Wilen and Petculescu [20,21], with an adjustment of shape factors n_ν and n_κ, together with the tortuosity q of the material.

However, as do the geometrical properties of the stack/regenerator, the temperature distribution strongly affects the operation of a thermoacoustic system [27]. Therefore, an accurate description of the onset and amplification processes governing the thermoacoustic instability should involve considering an accurate modelling of heat transfer in each element constituting the ThermoAcoustic Core (TAC). This accurate description remains arduous as it implies that the thermophysical properties – e.g. the axial and transverse thermal conductivities – of the anisotropic stacks or regenerators are known. In this context, our objective in this paper is to use an inverse method allowing to fit a theoretical model describing acoustic propagation in the inhomogeneously heated TAC with experiments, and to estimate geometrical and thermal parameters of the porous material.

In previous studies [28,29], we presented an experimental setup for the measurements of the acoustical transfer matrix of a TAC under various heating conditions, and we used the experimental data to predict the onset of self-sustained oscillations of any thermoacoustic device equipped with the TAC characterized beforehand. However, such a *black box* approach does not provide information about the inside of the thermoacoustic core, and therefore the main objective of this study is to evaluate an inverse method approach to get information about the acoustical and thermal properties of the stack/regenerator. More precisely, the purpose of the present paper is (1) to propose a theoretical description of the TAC and (2) to make use of the experimental results from Refs. [28,29] so as to adjust parameters which are generally hard to evaluate (tortuosity, heat exchange coefficient ...). In Section 2, a brief description of the TAC under study is presented. In Section 3, we describe the theoretical network modelling of the TAC with non-constant temperature gradients. The inverse method used to fit this model with experimental data obtained in the previous studies is presented in Section 4 and the results of the parameter estimation are presented and discussed in Section 5: this method allows notably to estimate the porosity and the tortuosity of the porous sample, as well as the average inner radius of the pores and the heat exchange coefficients with the walls.

2. Description of the thermoacoustic core and T-matrix measurements

The TAC under study is shown in Fig. 1. In the following, we give a brief description of this element and of the experimental procedure used for measuring its transfer matrix (for a complete description of the measurements methods, the reader can find more details in Refs. [28,29]). The TAC consists of a cylindrical waveguide (inner radius $R = 16.7$ mm) compounded of several aluminium and Stainless Steel pieces. Two honeycombed ambient exchangers are used to remove heat from the system. The hot exchanger is made of a piece of ceramic sample with squared pores of density 600 CPSI (*Cells Per Square Inch*). The heat power is supplied to the system by means of a Nickel–Chromium resistant wire which is regularly coiled across the whole cross section of the exchanger.

The acoustic properties of the TAC can be characterized by means of the so-called transfer matrix [30] (T-matrix), which gives a relationship between the complex amplitudes of acoustic pressure and acoustic velocity at both sides of the TAC. More precisely, the T-matrix of the TAC is here defined as

$$\begin{pmatrix} \tilde{p}(x_6) \\ \tilde{u}(x_6) \end{pmatrix} = \begin{pmatrix} \mathcal{T}_{pp} & \mathcal{T}_{pu} \\ \mathcal{T}_{up} & \mathcal{T}_{uu} \end{pmatrix} \times \begin{pmatrix} \tilde{p}(x_1) \\ \tilde{u}(x_1) \end{pmatrix}, \tag{1}$$

where $\tilde{p}(x_i)$ and $\tilde{u}(x_i)$ denote the complex amplitudes of acoustic pressure and acoustic volume velocity at position x_i (with $x_i = x_{1,6}$, see Fig. 1). These complex amplitudes are defined from the relation $\xi(x,t) = \Re(\tilde{\xi}(x)e^{-i\omega t})$, where $\xi(x,t)$ denotes the fluctuations of either acoustic pressure ($\xi \equiv p$) or acoustic volume velocity ($\xi \equiv u$), $\Re$ denotes the real part of a complex number, and where ω stands for the angular frequency of acoustic oscillations. Therefore, acoustic propagation through the TAC is only characterized by the four complex elements $\mathcal{T}_{ij}$ of its matrix, which depend on the frequency of acoustic oscillations, on the geometrical and thermophysical properties of the stack and heat exchangers, and on the assigned temperature distribution along the TAC. In previous works, we performed the measurements of the T-matrices of various TAC by means of two different methods, namely a classical two-load method [28] and another method based on the use of an acoustic impedance sensor [29]. As a result, experimental data for different kinds of TAC equipped with different stack materials (ceramic catalyst, stainless steel grids, RVC and NiCr foams) are now available, which are obtained for different values of heat power supply in the frequency range 30 Hz–500 Hz. These data can thus be used to fit a model for the acoustic propagation through the TAC and to estimate some of its physical parameters. In the following, we describe the model and the inverse method used for the estimation.

3. Theoretical description of the TAC – the forward problem

3.1. Acoustic propagation

The propagation of harmonic plane waves in the TAC is derived from the transfer matrices formalism, for which each element