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Temperature gradient effects on acoustic and streaming velocities in standing acoustic waves resonator

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ABSTRACT

This paper experimentally investigates the effects of an imposed axial temperature gradient in a cylindrical resonant cavity. The consequences on the acoustic velocity and acoustic streaming velocity are explored. The synchronised PIV (stands for Particle Image Velocimetry) technique was used in a 7 m long-standing wave air-filled acoustic resonator for the measurements. This method enabled the quantification of the changes in the velocity amplitudes due to the temperature gradient and highlighted the formation of one sole vortex in place of two Rayleigh vortices usually observed when acoustic streaming occurs.

1. Introduction

Nonlinear phenomena can occur in a standing wave acoustic resonator if the system delivers high amplitude acoustic waves. These phenomena may distort originally harmonic waves and transform acoustic energy into higher harmonic components, which increase the dissipation of acoustic energy. They may also lead to the formation of a system of rotational cells that originates from within the boundary layers [1]. In this particular case, the interaction of the high amplitude acoustic waves with the walls of the resonator creates this flow, which is called Rayleigh streaming [2]. It appears as two symmetrical torus-shaped cells extending generally along a length of a quarter wavelength in the central part of the acoustic guide. While the acoustic wave is an oscillating wave, the Rayleigh streaming is a second-order non-oscillatory mean flow induced by the nonlinearities of the acoustic propagation inside the resonator. It is quasi-stationary and will be superimposed on the main acoustic wave.

In recent years, studies on acoustic streaming found a revival with works related to thermoacoustics (whose works from Rott [3] and Swift [4] are considered as reference). In thermoacoustic processes, the reverse conversion between the thermal and acoustic energy is featured within an acoustic resonator. The systems use an environmentally friendly working medium (noble gas) to carry out a thermodynamic cycle, which facilitates the generation or spending of acoustic energy [5]. The interaction between a temperature gradient set locally in the resonator, inside a porous medium, and the acoustic waves allow us to distinguish two operating functions in thermoacoustic machines: the receiver (heat pump or refrigerator) or prime-mover (motor).

Nevertheless, this new technology, which is actually booming requires further development. New architectures machines (whose size is still important), a more detailed description of the temperature field established along the porous medium or a description of heat transfer within the machine are all subjects of study and improvement, where experimentation remains important. This remains true for this next point which is the subject of much attention from the scientific community in the thermoacoustic field.

Various sources of energy dissipation [6] due to nonlinear effects are presently the leading cause of degradation in the machine performances of thermoacoustic systems. An important class of these non-linear effects is streaming flow [7]. Although already known and studied by the acoustic community [8,9], these effects and their interaction with the temperature gradient yet need further analysis through various observations.

Despite several theoretical studies in this area, they sometimes lack detailed information since the evaluations of these effects, which among other things are characterised by the appearance of Rayleigh streaming, is not elementary, as these second-order phenomena generally lead to tricky situations where interactions with a temperature gradient and couplings between the different effects encountered are prominent. Hence the importance of experimental studies.

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Numerous experimental studies of Rayleigh-type streaming have been performed recently.

However few experimental studies on nonlinear acoustic phenomena and the influence of an imposed temperature gradient have been published. Thompson et al. [10] studied the influence of an axial thermal gradient imposed on the entire resonator via measurements made with Laser Doppler Velocimetry (LDV) in a standing wave resonator. Increasing the temperature gradient (the maximum value is up to 8 K/m) distorts the Rayleigh cells, although the results do not match any existing theories. These researchers had previously analysed the acoustic velocity and streaming velocity within the same setup and showed that changes in the viscosity as a result of temperature in the fluid influence the amplitude of the streaming [11].

Nabavi et al. [12,13] were one of the first to observe the effects of a locally set transverse temperature gradient on acoustic Rayleigh wind via PIV measurements. They followed the disappearance of one of two vortices of the Rayleigh cell and the dominance of the second as the gradient increased, which led to the formation of a single vortex. Aktas and Ozgumus [14] numerically investigated the same subject and particularly studied the effects of acoustic streaming on thermal convection in an acoustic enclosure with differentially heated horizontal walls. Once again, the transverse temperature gradient strongly affected the acoustic streaming structures and velocities. They found that acoustic streaming enhanced the heat transfer, a conclusion also reached by Tajik et al. [15] from their experiments on a closed cylindrical enclosure filled with water.

Daru et al. [16] numerically investigated the mean temperature evolution associated with the streaming motion for high intensity waves in the nonlinear streaming regime.

In this paper, the influence of an axial temperature gradient on Rayleigh streaming flows in a standing acoustic wave resonator was first considered and is investigated via synchronised PIV measurements. The objective was to observe the behaviour of streaming when a temperature gradient is locally imposed in the resonator, where a high level of sound wave propagates. The measurements were focused in the area in which the temperature gradient is set.

Section 2 of this paper presents the experimental PIV setup along with the associated PIV methodology and processing. Section 3 shows results for the study of the evolution of streaming with the drive ratio and the consequences on the acoustic streaming of the establishment of a temperature gradient inside the standing wave resonator.

2. Experimental setup and methodology

2.1. Experimental apparatus

In this section, the experimental setup used to investigate the influence of an axial temperature gradient on the acoustic Rayleigh streaming is developed. The whole system (acoustic resonator and PIV instrumentation) was previously used in [17] where more details can be found.

The experimental investigation was performed on an air-filled cylindrical resonator that was 7 m in length ($L = 7.03$ m), made of stainless steel closed at one of its ends and equipped with an acoustic driver at the other. The inner diameter of the resonator was $d = 56.3$ mm. A transparent square section, which fits the resonator without modifying the cross section area, facilitated the optical measurements (see again [17] for its description and how it fits the resonator). Two heat exchangers were inserted in the resonator on either side of the PIV cell (i.e., the transparent section), thereby establishing a temperature gradient in the measuring cell, as shown in Fig. 1. These liquid–gas heat exchangers (water/air) are based on the shell and tube heat exchanger technology. More specifically, they are 1-pass straight-tube heat exchangers. The temperature gradient set between both exchangers is 86 °C/m: the hot heat exchanger, within which water circulates at 63 °C, was situated approximately 1.4 m from the resonator's end. The cold heat exchanger is cooled by cold water flowing at 3 °C.

A shaker (LDS – Ling Dynamic Systems – V450/1 – PA 500L) equipped with a piston whose diameter matched the internal diameter of the resonator was used as the acoustic source. It was chosen because of its ability to reach high amplitudes. Besides its working conditions maximise the possible single-frequency and thus do not affect the measurements via parasitical acoustic effects (i.e., harmonic frequencies). The superior harmonics amplitude reaches only 6% of that of the resonance frequency and therefore can be neglected.

To vary the drive ratio (Dr), which is defined as the ratio of the maximum amplitude of the acoustic pressure to the mean pressure, the piston stroke is changed while the frequency remains the same. The system is tuned at a frequency of $f = 24.4$ Hz, which is the resonance frequency, the first mode of the system. This frequency was calculated for our experimental conditions and experimentally verified.

An Nd YAG laser of 200 mJ pulse (PIV 190 PS1/TwinsBSL Quantel) at a wavelength of 532 nm combined with spherical and cylindrical optical components was used to generate the laser sheet. A prism was used to deflect the laser sheet into the vertical *xy* plane of the PIV cell. The image was then acquired with a CCD (Charge Couple Device) camera (TSI PIvCam 13-8) of 1024 × 1248 pixels. The camera was connected to a synchroniser (LASERPULSE Synchroniser – TSI Model 610034), which allowed the image acquisition to be triggered with the control signal of the shaker at a rate of 3.63 Hz. An aerosol generator (TOPAS ATM 210) was used to generate the seeding mist. The passive tracers are particles of DEHS (Di-2-Ethylhexyl-Sebacat). These particles have relaxation time of about 0.3 µs, which set the Stokes number to about 2×10^{-5}.

$$St = \frac{\tau \cdot u}{d} \quad (1)$$

where τ is the particle relaxation time; u is the fluid velocity; and d is the resonator diameter.

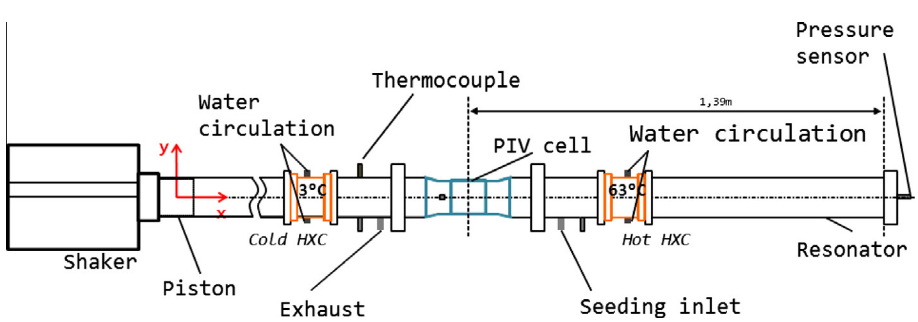

Fig. 1. Zoom in: measurements configurations and setup.