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Experimental and theoretical study of density fluctuations near the stack ends of a thermoacoustic prime mover

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ABSTRACT

This paper proposes the experimental and theoretical study of nonlinear heat transport processes generated by large amplitude acoustic oscillations at the ends of a stack of plates in the presence of a temperature gradient. These processes are notably involved in the operation of thermoacoustic engines. The measurement method, a time-resolved and full-field digital holography interferometry technique, enables to measure the density fluctuations from the optical phase difference between two laser beams. This technique is applied to the analysis of density fluctuations in the vicinity of a stack submitted to a temperature gradient, firstly for the case of (uncontrolled) self-sustained acoustic oscillations generated spontaneously in a standing wave thermoacoustic prime mover, and secondly for the case of an assigned acoustic field whose amplitude is controlled by an external sound source. A theoretical model describing the advective heat transport by sound at the ends of the heated stack is also presented, and numerical simulations are then carried out. The comparison between experimental data and numerical simulations is provided for several stack positions, several sound pressure levels, and several amounts of heat supplied to the stack, and the results show good agreement between the experiments and the model.

1. Introduction

Thermoacoustic engines are heat engines which involve the interaction of resonant gas oscillations with a porous medium (referred to as the "stack"), leading either to sound amplification (thermoacoustic prime mover) or to advective heat transport by sound (thermoacoustic heat pumps). This class of engines has been developed for about three decades [1] and has nowadays proved good performance [2] and potentiality for niche applications at moderate powers, notably for the recovery of waste heat [3]. The design of thermoacoustic engines is usually based on the linear theory derived by Rott [4] which does not account for several nonlinear saturation processes such as acoustic streaming [5,6], nonlinear propagation [7], as well as fluid separation [8] and/or complex heat exchange processes occurring at the ends of the stack and of the heat exchangers [9–12]. The latter effects are the ones investigated both experimentally and numerically in this paper.

The full-field and time-resolved digital holography interferometry technique (see Fig. 1) is chosen to analyze the processes occurring near the stack ends in a thermoacoustic prime mover. This method allows measuring the acoustic density fluctuations (averaged along the line-of-sight) from the optical phase difference between a reference beam and an object beam passing through the acoustic resonator. Previous works by some of the authors [13] has already shown that this experimental technique is adequate for measuring harmonic and mean (time-averaged) components of density fluctuations in the vicinity of the stack, which are generated locally as a result of the abrupt transition experienced by gas parcels going back and forth through the end of the stack. These previous works were related to the description of a single experiment performed during the transient regime of wave amplitude growth in a standing wave prime mover. In this paper, additional experimental data are provided, which are obtained on the same device but for two configurations. A first configuration is the same as the one used previously [13], which means that measurements are performed during the spontaneous onset of self-sustained acoustic oscillations, while for the second configuration the acoustic field is assigned by an external sound source (so that comparison with a model is easier). Moreover, this paper presents a theoretical model describing the advective heat transport by sound at the ends of the heated stack, which is compared to experimental data.

The paper is organized as follows. In Section 2, the experimental set-up and the measurement technique are briefly described. Experiments performed during the transient regime of wave

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Nomenclature

c_∞	speed of sound at room temperature	T_0	mean temperature of the fluid
C_p	isobaric heat capacity of the fluid ($C_p = 1003$ J kg^{-1} K^{-1})	T_∞	room temperature ($T_\infty = 293$ K)
d	distance between the stack and the rigid plug	T_c	characteristic amplitude of temperature fluctuations
d_s	length of the stack	$\overline{T'}$	average temperature fluctuations of the fluid over the cross-sectional area of a stack channel
D_i	inner diameter of the tube (D_i = 0.052 m)	u_c	characteristic gas parcel displacement
D_o	outer diameter of the tube (D_o = 0.06 m)	v'	acoustic velocity
f	frequency of acoustic oscillations	κ_0	thermal diffusivity of the fluid (at room temperature $\kappa_\infty = 2.2\ 10^{-5}$ m^2 s^{-1})
k_f	thermal conductivity of the fluid at room temperature ($k_f = 2.26\ 10^{-2}$ W m^{-1} K^{-1})	λ	acoustical wavelength
k_s	effective thermal conductivity of the stack ($k_s = 0.6$ W m^{-1} K^{-1})	ω	angular frequency, rad s^{-1}
L	tube length (L = 0.49 m)	ρ'	density fluctuations of the fluid
p'	acoustic pressure	$\langle\rho\rangle$	average of density through the line-of-sight
P_0	mean pressure of the fluid ($P_0 = 1.015\,10^5$ Pa)	ρ_0	mean density of the fluid
P_c	characteristic amplitude of acoustic pressure	ρ_∞	mean density of the fluid at room temperature
P_{mic}	peak amplitude of acoustic pressure at position $x = d$	τ	dimensionless time ($\tau = \omega t$)
Pe	Péclet number ($Pe = \omega u_c^2/\kappa_\infty$)	τ_R	thermal relaxation time
Q_{in}	heat power supplied to the stack	θ	dimensionless temperature fluctuations ($\theta = \overline{T'}/T_c$)
Q_{onset}	minimum of heat power to trigger self-sustained oscillations	θ_0	dimensionless mean temperature ($\theta_0 = \overline{T_0}/T_c$)
R	dimensionless relaxation time ($R = \omega\tau_R$)	ξ	dimensionless axial coordinate ($\xi = x/u_c$)
T'	temperature fluctuations of the fluid		

amplitude growth in a standing wave thermoacoustic prime mover are presented in Section 3. A model describing the generation of higher harmonics and time-averaged components of density fluctuations at the end of the stack is presented in Section 4. In Section 5, additional experimental data obtained for steady-state oscillations are shown and compared with numerical simulations, while conclusions are drawn in Section 6.

2. Experimental set-up

The digital holographic set-up and the thermoacoustic device are presented schematically in Fig. 1(a). The thermoacoustic engine has a very simple geometry: it includes a cylindrical glass tube (with length L = 49 cm, inner diameter D_i = 52 mm, outer diameter D_o = 60 mm) opened at one end and closed by a rigid plug at the other end. Inside the tube, a porous material made up of a ceramic catalyst (the 'stack') with a length d_s = 48 mm is installed. It is structured with many square channels of semi-width r_s = 0.45 mm and has the same diameter as the inner diameter of the resonator. The stack is the heart of the thermoacoustic device: it has a large surface of thermal contact with the gas, and therefore promotes the thermoacoustic amplification process which occurs within the acoustic thermal boundary layers [1]. The onset of thermoacoustic oscillations is generated thanks to the existence of a temperature gradient along the stack: this temperature gradient is obtained by means of a Nichrome wire (36 cm in length, 0.25 mm in diameter) which is used as a heating element and is coiled through the stack end facing the rigid plug. The distribution of the temperature produced is shown schematically in Fig. 1(c): thanks to the heat leaks through lateral walls (absence of any cold heat exchanger) a temperature gradient is obtained which highest amplitude is in the vicinity of the heating wire. The self-sustained oscillations are produced when the temperature gradient reaches a critical value, which depends on the stack position along the glass tube (see Ref. [14] for a marginal stability curve as a function of the stack position). The frequency of acoustic oscillations roughly corresponds to the quarter wavelength resonance, which can be calculated by $f \approx c_\infty/4L$, where $c_\infty \approx 343$ m/s stands for the adiabatic sound speed evaluated at room temperature $T_\infty \approx 293$ K. A microphone is flush-mounted through the plugged end of the resonator to measure the frequency and amplitude of acoustic pressure oscillations.

Although the thermoacoustic device has a simple geometry, it can exhibit complicated dynamics (e.g relaxation regime of spontaneous onset/damping) which are not reproduced by numerical simulations [15] and therefore appeal for further investigations (this is one of the motivations for this study). To that purpose, the measurement of density fluctuations is performed, with the aim of getting information about local effects in heat transfer due to the abrupt transition experienced by gas parcels going back and forth through the heated stack end. A schematic representation of the set-up used to measure density fluctuations is presented in Fig. 1(a): it basically consists of an interferometer which gives a map of the optical phase difference between a reference beam and a measurement beam passing through the acoustic resonator. In the following, only the main principles of the measurement technique are described, and further information (notably about signal processing) can be found in Ref. [13]. The light source is a continuous red laser (optical wavelength of 660 nm) which is separated into a reference beam and a probe beam by means of a polarizing cube. Both beams are then expanded and bundled to parallel rays by a collimating lens. The probe beam passes through the acoustic resonator next to the heated side of the stack, and the interference between the reference beam and the probe beam are captured by a high speed camera which is used for recording hologram sequences. The optical path length through the enlightened part of the tube may vary because of heating and/or acoustic oscillations, and this variation is captured by subtracting the instantaneous optical phase difference between the two beams with the one obtained for a reference state (e.g without sound). As a result, this measurement technique gives a map of refractive index variations which itself can be related to the density map of the fluid using the Gladstone–Dale relation. Note that the measured density map is actually a map of a density averaged through the line-of-sight, denoted as $\langle\rho\rangle$ (the notation $\langle\ldots\rangle$ refers to an average along the beam path through the waveguide). The size of the map, the spatial resolution and the time resolution of measurements are