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EXPERIMENTAL INVESTIGATION OF ACOUSTIC STREAMING IN A SIMPLE THERMOACOUSTIC ENGINE

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Thermoacoustic engines suffer from many non-linearities that deteriorate the overall performance. Streaming phenomenon is one of these non-linearities which can affect the performance by convecting a certain amount of heat. In this study, the axial mean velocity distribution inside a basic standing-wave thermoacoustic engine is measured using Laser Doppler Velocimetry (LDV). A stack is positioned in a $\lambda/2$ resonator; the left end of the stack is electrically heated and the rest of the resonator is left uncontrolled. LDV measurements are performed from the right end of the stack up to the guide termination together with thermocouple measurements. Three different regions are distinguished and so called the "end-effects" region (very close to the stack), the hot streaming region (further away from the stack) and the cold streaming region (even further). In the cold streaming region at low acoustic level, there is a good agreement between the measured mean velocity and the Rayleigh streaming theoretical expectation. As the acoustic level is increased, results start to deviate from theoretical values, which agrees with the literature. In addition, the size of the cold region decreases. In the hot streaming region, the measured mean velocity distribution at all acoustic levels differs from Rayleigh streaming due to the effect of convection originated by the temperature distribution. Finally, the mean flow close to the stack is disturbed due to vortex shedding and this disturbance extends along a distance which defines the size of the last region (end-effects region). The balance between the three phenomena associated with the three regions is discussed for different experimental conditions.
Keywords: thermoacoustic engine, acoustic streaming, Laser Doppler Velocimetry

1. Introduction

Thermoacoustic engines convert any source of heat into acoustic waves which in turn can be converted into electricity. These types of engines have many advantages such as simple construction, very low number of moving parts; they use environmentally friendly working fluids and can also be powered by solar energy. On the other hand, thermoacoustic engines suffer from many non-linearities that affect the overall performance [1]. Thermoacoustic engines have been investigated for a long time, but many works are still required to deeply understand the effects of these non-linearities on their operation. In this work, we are concerned with streaming as one of these non-linearities.

Early observation of the acoustic streaming was recognized by Dvorak through the observation of a gas pattern motion in Kundt's tube. Rayleigh [2] was the first to demonstrate the physics behind this phenomenon. He elaborated that streaming is a second-order steady flow superimposed on the first-order oscillating flow and studied this phenomenon in the case of a standing wave in a large channel formed by two parallel plates. In addition, he formulated the mathematics to quantify this phenomenon which are considered as a base for further theoretical research. Many theoretical approaches have been developed concerning Rayleigh streaming. In the scope of thermoacoustic application some studies (i.e. [3], [4] and [5]) investigated the effects of a temperature gradient on Rayleigh streaming. More recently, Penelet *et al.* [6] developed a model in which Rayleigh streaming is considered to describe the non-linear processes that affects the steady-state operation of thermoacoustic engine. Reyt *et al.* [7] developed a numerical approach to model the Rayleigh streaming pattern at high non-linear Reynolds number:

$$\boldsymbol{Re_{NL}} = \left(\frac{\boldsymbol{U}}{\boldsymbol{c}}\right)^{2}\left(\frac{\boldsymbol{R}}{\boldsymbol{\delta_{v}}}\right)^{2} \tag{1}$$

where $\boldsymbol{U}$ is the acoustic amplitude at the velocity antinode, c is the speed of sound at the ambient conditions, R is the radius of the pipe and $\boldsymbol{\delta_v}$ is the viscous penetration depth ($\boldsymbol{\delta_v} = \sqrt{\nu/\pi f}$, where ν is the kinematic viscosity and f is the frequency of oscillation).

The first known trial to quantify the streaming velocity experimentally was done by Andrade [8]. He captured images for the smoke inside a glass tube where the flow is driven by an oscillator. After a long time, more experimental works have been devoted to measure the streaming in an empty wave guide and to understand the different parameters affecting the Rayleigh streaming patterns. Thompson and Atchley [9] used LDV to measure the Rayleigh streaming at low nonlinear Reynolds number. Their results show good agreement with theoretical expectations of Rayleigh streaming. Reyt *et al.* [10] used both PIV and LDV to measure the Rayleigh streaming for wide range of acoustic levels. They found that at high $\boldsymbol{Re_{NL}}$ the measured values deviate significantly from the theoretical expectations. Also, the maximum streaming velocity is shifted towards the velocity node.

To approach a geometry closer to real thermoacoustic devices, Moreau *et al.* [11] studied the effect of the stack on Rayleigh streaming patterns. They found that the effect of the stack on the Rayleigh streaming is limited to a certain zone around the stack and that the overall streaming pattern far from the stack remains the same even if the stack position is changed in a resonator. Also, Thompson *et al.* [12] investigated the effect of the wall temperature gradient on the Rayleigh streaming. They found that the measurements of streaming at high $\boldsymbol{Re_{NL}}$ are affected by the temperature gradient along the guide wall.

Pan *et al.* [13] measured the acoustic velocity in an empty pipe with a temperature gradient imposed by two heat exchangers and an acoustic wave generated by a loudspeaker. They noticed that the acoustic velocity is affected by convection velocity originated by the temperature gradient. Also, Saint Ellier *et al.* [14] measured the effect of the imposed temperature gradient on the axial velocity distribution in the radial direction only. However, their results do not agree with theoretical expectations. Finally, Debesse *et al.* [15] measured the acoustic streaming in a thermoacoustic engine. However, their measurements were done far from the thermoacoustic core (i.e. stack and heat exchangers) and at one axial location and hence the axial distribution of the acoustic streaming was not investigated.

In this paper, the axial streaming velocity distribution along the centreline of the resonator of a basic thermoacoustic engine is measured at different acoustic levels. Also, different regions for acoustic streaming are demonstrated and the contribution of both acoustic streaming and convection to the mean velocity are highlighted. In section 2, the experimental setup is explained and the signal processing method is described. In section 3, the results are presented and discussed. In section 4, the work is summarized and conclusions are drawn.

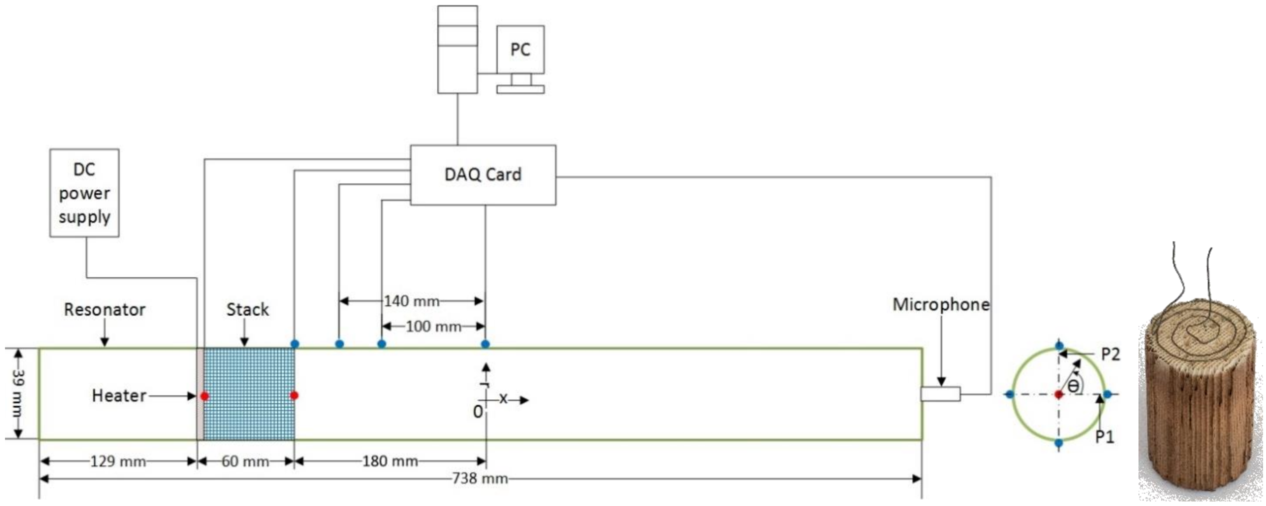
2. Experimental setup

2.1 Thermoacoustic engine

A basic standing-wave thermoacoustic engine is used to study the streaming phenomenon. As shown in Fig. 1, the wave guide is a glass tube with inner radius (R) of 19.5 mm, thickness of 2.5 mm and length (l) of 74 cm closed at both ends. A 6 cm long ceramic stack with radius just below

19.5 mm is placed inside the resonator. The stack mainly consists of square pores, 400 CPSI (Cell Per Square Inch). Each square pore has inner side length of 1.1 mm and the wall thickness is 0.18 mm. An electrical heater made of Ni-Cr wire with diameter of 0.6 mm and resistance of 2.1 ohm is formed into a spiral shape and attached to one end of the stack. The heater is powered by a DC-power supply (model: FI3610). The stack is placed in the resonator so that the heated side is at distance of 129 mm from left end of the tube. The rest of the resonator is left uncontrolled (i.e. no ambient heat exchanger). Two type-k thermocouples (indicated as red dots in Fig. 1) are attached to both sides of the stack to measure the fluid temperature. In addition, 4 type-k thermocouples (indicated by blue dots) are used to measure either the axial temperature distribution of the outside wall (at $x = 0, -100, -140\ and - 180\ \ mm$) or the azimuthal temperature distribution of the outside wall along two perpendicular axes ($P1\ (\Theta = 0)\ and\ P2\ (\Theta = \frac{\pi}{2})$) at two different axial locations (at $x = -140\ and - 180\ \ mm$). All thermocouples are connected to a data acquisition card (model: NI 9213) which is connected to a computer for data storage.

For high enough electrical power supply, the temperature gradient along the stack exceeds the critical value and a standing wave is generated in the guide. Measurements of the dynamic pressure oscillation, performed by a condenser microphone (manufacturer: GRAS – model: 40BP) placed at the right end of the engine, show that the standing wave verifies $f \approx c/2l$, and hence the $\lambda/2$ mode is excited by the thermoacoustic coupling. The microphone is connected to a data acquisition card (manufacturer: National instruments – model: NI 9234). The LDV measurements and the associated signal processing are discussed in the following section.



(a) (b)

Figure 1: (a) Schematic for the thermoacoustic engine and the instrumentations, (b) Close-up for the electric heater and the stack.

2.2 LDV measurements and signal processing

The LDV system, used in this work, is a 1-D LDV. It consists of a Dantec Dynamics beam splitter that receives the argon-krypton laser with wavelength of 514.5 nm provided by Spectra Physics laser (model: Stabilite 2017) and sends the split beams to the LDV transmitter. The intersection of the 2 beams, detected by the photomultiplier, forms the measurement volume which nearly has an elliptical shape with diameter of 0.047 mm and 0.4957 mm long. The fringe spacing is 2.694 µm. The transmitter and the receiver are configured to collect the forward-scattered light and hence achieve high sampling data rate. The LDV is mounted on a three-directional transverse mechanism enabling to perform the axial velocity measurements precisely in both axial and radial directions. A 10 mm step is set for the axial measurements at the centreline while a 2 mm step is set for the radial measurements. The axial velocity measurements are started from very close to the stack (i.e. x = -175 mm) up to near the right end of the resonator (i.e. x = 340 mm). After the engine is heated up for 10 minutes, coffee smoke is introduced into the resonator. The two terminations of the resonator have a hole that is generally closed by a plug. The plugs are removed either to introduce the smoke or to turn off the engine in some experiments as explained below. The measurements are started 5 minutes after seeding has been introduced. Preliminary test showed that this procedure ensures that the steady-state is reached when the measurements start.

The acquired signal by the LDV receiver is analysed by a burst spectrum analyser (Manufacturer: Dantec Dynamics – Model: BSA-F80) that provides the velocity of the seeding particles that cross the measurement volume along with the arrival time. The acquired data are post-processed using the processing technique presented in [16] to estimate the particle velocity at each location. The signal processing allows to access both the acoustic and the mean velocities.

For each velocity measurement, the acquisition is stopped after 10 seconds or acquiring 40,000 samples. As shown in Fig. 2, the estimation of the streaming velocity reaches for more than 30,000 samples.

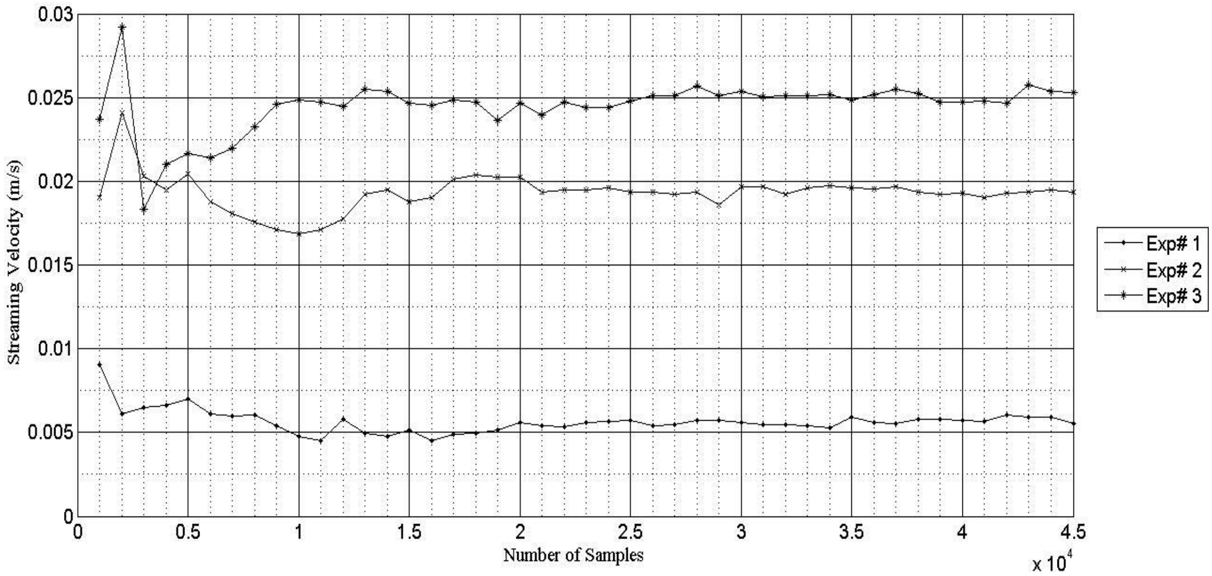


Figure 2: Axial streaming velocity at the center of the resonator as a function of number of acquired samples at three different acoustic levels (x = 180 mm).

3. Results and discussion

3.1 Experimental conditions and error analysis

In all experiments the resonator is filled with air at atmospheric pressure. We report 7 experiments with operating conditions shown in Table 1. Experiments number 1, 2 and 3 are performed to measure the steady-state axial mean velocity at the centre of the resonator (i.e. $r = 0$) along the axis from $x = -175\ mm$ to $x = 340\ mm$ while the engine is working for three different acoustic amplitudes. On the other hand, experiments number 4, 5 and 6 are performed for heating conditions as close as possible to experiments 1 to 3 but without acoustic oscillations. To reach this the plugs at both ends of the resonator are removed in order to cease the oscillations and hence the measured axial flow velocity distribution at the centre along the axis of the resonator is due to convection. Also, in these three experiments the engine is heated until reaching steady-state. Finally, the experiment number 7 is conducted at input power just below the critical input power. In this experiment the critical temperature gradient across the stack ends is not reached, therefore no sound wave is generated and thus no acoustic streaming. Accordingly, the measured velocity is only due to heat effects. Also, the obtained results by experiment 7 should be close to that given by experiment 4 to validate that the use of "open plug" condition does not affect the convection velocity.

The variations of the value of the electrical input power and the measured temperatures were estimated and presented in Table 1. Also, the errors in the measured values of both acoustic and mean velocities due to the variations of the temperatures were estimated by repeating the measurements at the same conditions and calculating the standard deviation of these repeated measurements. The error in the value of the acoustic velocity were estimated to be ± 1 %, ± 3.5 % and ± 2 % in experiments# 1, 2 and 3, respectively. The error in the measured mean velocity in experiments# 1, 2 and 3 were found to be ± 12 %, ± 5.8 % and ± 8.5 %, respectively.

Table 1: The operating conditions for experiments

Exp. #	Electrical input power (Watts)	Re_{NL}	Pressure Amplitude (Pa)	Oscillating Frequency (Hz)	Stack ends temperatures (^{O}C)		Plugs
					$x = -180\ mm$	$x = -240\ mm$	
1	32.2 ± 1%	0.87	820	234	42.5 ± 9.9%	254 ± 1.5%	Placed
2	59.0 ± 1%	3.59	1950	238	73.8 ± 5.6%	362.4 ± 1%	Placed
3	82.2 ± 1%	7.25	2600	241	119.7 ± 7.4%	439 ± 3.5%	Placed
4	32.2 ± 1%	-	-	-	40 ± 2%	255.2 ± 2%	Removed
5	59.0 ± 1%	-	-	-	50 ± 2%	363.5 ± 2%	Removed
6	82.2 ± 1%	-	-	-	50 ± 2%	439 ± 2%	Removed
7	28.1 ± 1%	-	-	-	39 ± 2%	201 ± 2%	Placed

3.2 Mean flow velocity at different acoustic levels

The amplitude of the axial acoustic velocity at the centre of the resonator along the axis is measured and compared with the theoretical values. As shown in Fig. 3, there is good agreement between the measured and the theoretical values at all acoustic levels. It was checked that the acoustic waveform keeps sinusoidal for all the cases studied. In Fig. 3c, results from previous study [10] are also shown, that was obtained in a waveguide of same radius and for a wave at nearly the same frequency but the latter being generated by the loudspeakers at each end of the guide.

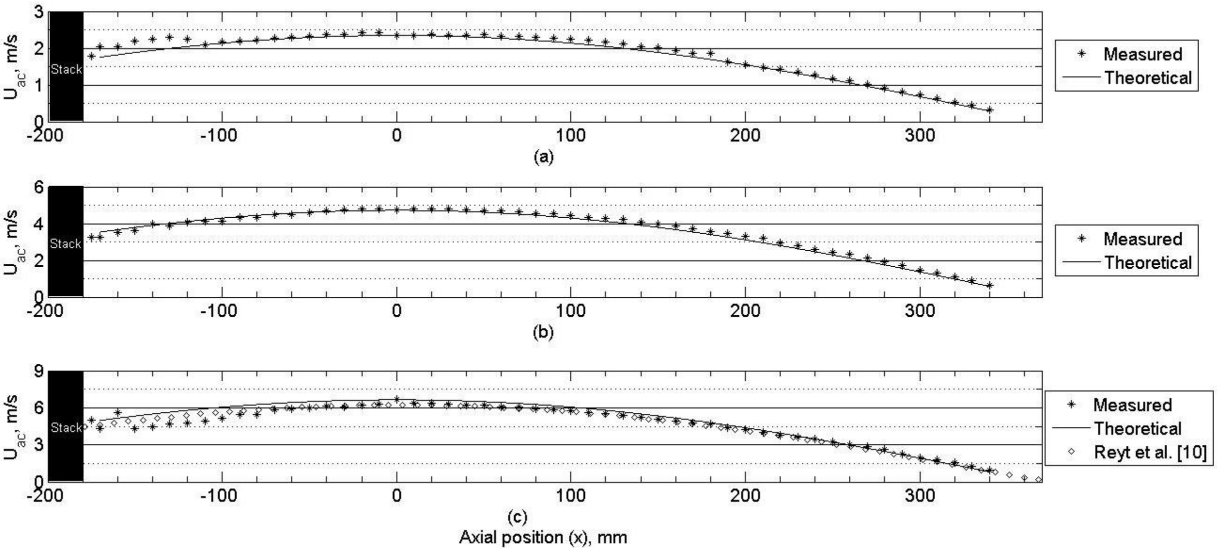


Figure 3: The axial distribution of the acoustic velocity amplitude at the center of the resonator at different acoustic levels (a) Exp# 1, (b) Exp# 2 and (c) Exp# 3.

The axial mean velocity is also obtained and compared with the theoretical expectations developed by Lord Rayleigh [2] for the description of streaming pattern generated by Reynolds stresses in the case of a wide channel; the derivation of Rayleigh streaming for the case of cylindrical guides is given for instance by [16].

Figure 4 shows results of the mean velocity measurements for experiments 1 to 3 together with theoretical expectations (and with results obtained by [10] Fig. 4c). From these results, three different regions are dissociated: the first region goes from the right end of the resonator up to the solid-vertical line, the second region is between the solid-vertical and dashed-vertical lines and the last region goes from the dashed-vertical line to the right edge of the stack. In the first region, there is a good agreement between the measured mean velocity and the theoretical values for the Rayleigh streaming velocity at low acoustic level (Fig. 4a). As the acoustic level is increased the discrepancy between the measurements and the theoretical expectations increases (Figs. 4b and c). Also, at the highest acoustic levels (Fig. 4c), our measurements are in good agreement with Reyt *et al*. measurements [10]. In this region, we can therefore conclude that the measured mean velocity is due to acoustic Rayleigh streaming only and hence the obtained distributions at high acoustic amplitude is similar to the observations in the literature [7]. This region corresponds to constant mean temperature along the guide and is further called the "cold streaming region". In the second region, it is observed that the measured mean velocity deviates from the theoretical expectations for Rayleigh streaming. Preliminary wall temperature measurements showed that the effect of the heat supplied to the stack extends to a distance from the hot end of the stack that increases with the electrical input power. We can suspect that in this region the measured mean velocity is affected by heat effects and further call this region the "hot streaming region". The objective of the next subsection is to investigate the role of convection in the mean velocity measurements conducted in this region. Finally, in the last region results for mean velocity measurements denote a velocity distribution with spikes and with rapid changes of sign. It was shown by previous research [11] that the Rayleigh streaming pattern is deformed near the stack ends due to the formation of vortices. Results obtained by [11] allow to estimate the size of this region which depends on the acoustic amplitude, its evaluation is shown in Fig. 4 (vertical dotted line) and this region is further called "end effect region".

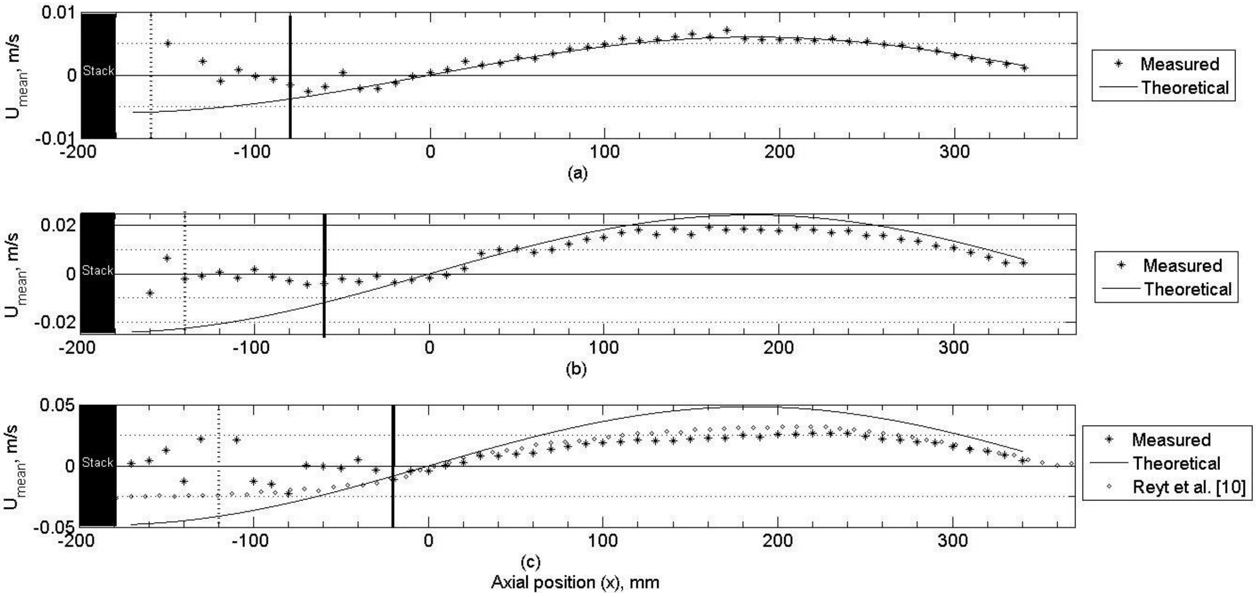


Figure 4: The axial distribution of the mean velocity at the centre of the resonator at different acoustic levels (a) Exp# 1, (b) Exp# 2 and (c) Exp# 3.

3.3 Convection and streaming velocities at different acoustic levels

In order to further investigate the phenomena that contribute to the measured mean axial velocity in the hot streaming region, it is necessary to de-couple these different phenomena. In this region, two different phenomena are suspected to contribute to the mean velocity: the Rayleigh streaming and the steady flow velocity created by natural convection which is due to the non-uniform temperature. Hereinafter, the flow velocity originated due to former phenomenon is referred to as convection velocity.

In order to measure the convection velocity contribution, the acoustic oscillations should be ceased. Hence, the plugs at the both ends of the resonator are removed; results correspond to those of experiments number 4, 5 and 6.

Figure 5 shows the results of the measured mean velocity for experiments 4 to 7. The results of both experiments 4 and 7 are quite similar which validates the proposed approach in which the plugs are removed at both ends of the guide to kill the acoustic oscillation and thus to measure the effect of convection on the mean velocity distribution. Also, it is observed that the convective velocity is zero in the cold streaming region which validates the assumption that the measured mean velocity in the cold streaming region is not influenced by convection effects. In addition, in the hot streaming region the convective velocity increases as the stack end is approached. It was found that the temperature distribution over the cross-section is not uniform in the hot streaming region and this non-uniformity is the source of convection. The increase in the measured mean velocity shown in Fig. 5 is roughly equal and opposite to the decrease expected for Rayleigh streaming as given by Fig. 4 along this region. Therefore, the addition of the convective velocity given by Fig. 5 and Rayleigh streaming expectations given by Fig. 4 in the hot streaming region gives zero mean velocity as actually obtained from measurements shown in Fig. 4. Quantitative comparison cannot be further proposed as the experimental conditions between set 1 to 3 and set 4 to 6 are not similar, especially for what concerns temperature distributions (see Table 1). Still, we can conclude that both convection and Rayleigh streaming have to be considered in simple devices as the one under study.

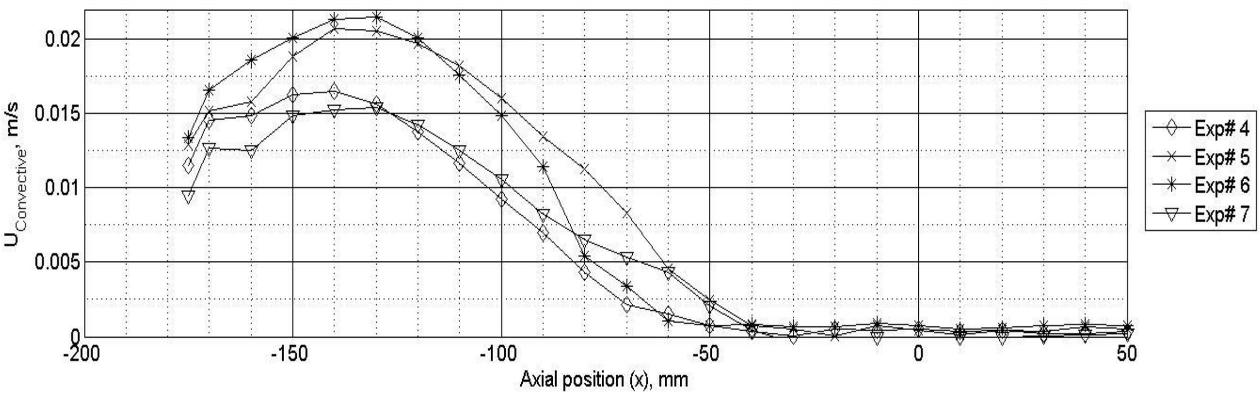


Figure 5: The axial convective velocity distribution at the center of the resonator at different experimental conditions.

4. Conclusions

In this study, the axial mean velocity in a simple thermoacoustic device has been measured along the axis of the resonator for different acoustic levels. Three different regions have been distinguished, namely the hot streaming region, the cold streaming region and the end-effects region. In the cold streaming region, there is a good agreement with the theoretical expectations for Rayleigh streaming at low acoustic level and the discrepancy increases as the acoustic level is increased which is in agreement with the literature. In the hot streaming region, there is no agreement with theoretical expectations of the streaming. The reason behind this disagreement is the effect of another phenomenon on the measured mean velocity. This phenomenon has been identified as convection and its effect on the mean velocity has been quantified. The last region is the end-effects region in which the mean axial velocity distribution mostly results from periodic vortex shedding at the exit of the stack channels.

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