Standing-wave thermoacoustic engines and refrigerators utilize gas oscillations and stacks to produce thermoacoustic effects. The flow morphology at the inlets/exits of the stack affects the heat transfer processes and the viscous flow losses in the heat exchangers. In this work, the flow morphology and the size of the disturbance zone are investigated experimentally for different plate-end shapes (rectangular, circular and triangular) at different drive ratios, using Particle Image Velocimetry. The plates are placed inside a resonator filled with air at atmospheric conditions and the oscillations are generated by a loudspeaker operates at the resonance frequency of the system. The size of the disturbance zone is identified as the distance between the furthest axial location the vortex reaches and the location at which it forms. The results reveal that the size of the disturbance zone generally increases with the increase of the drive ratio for all plate-end shapes. At the same drive ratio, the use of circular-end plates reduces the size of disturbance zones with respect to rectangular-end plates. The use of triangular-end plates with 30° cone angle causes further reduction in the disturbance zone size. The flow morphology in all cases is presented and analyzed qualitatively.

At a drive ratio of 3 %, the disturbance zone extends to a distance of 5.6 mm, 3.3 mm and 1.7 mm for the rectangular, circular and triangular ends, respectively. These values are 14.7 mm, 12 mm and 10.6 mm at a drive ratio of 7 %.

Keywords: Particle Image Velocimetry, oscillating flow, thermoacoustics, stacks, flow morphology.

1. Introduction

Thermoacoustic systems are promising technologies that convert any source of heat, including solar energy and waste heat, into acoustic wave and vice versa. These systems are reliable and require nearly no maintenance as the mechanical moving parts are almost eliminated. Also, they use environmentally friendly gases. Description and analyze of these systems can be found in [1]. Operation with solar energy and waste heat are demonstrated in [2-3], respectively. However, the available design tools of thermoacoustic systems depend on the linear theory developed by Rott [4], which do not consider non-
linear phenomena. These non-linearities, like streaming, harmonic generation, turbulence generation and viscous dissipation inside the stack and near the walls of the resonator, deteriorate the performance of the thermoacoustic systems [1]. These phenomena have been the focus of some previous research [5-7]. However, further research is needed to deeply understand these phenomena and hence to improve the performance of thermoacoustic systems, in order to increase their economic competitiveness with respect to conventional technologies, either in terms of the overall conversion efficiency or in terms of the power density.

The main viscous dissipation mechanisms include the vortex generation at the inlets/exits of the stack due to sudden contraction/expansion, respectively, and the dissipation at the resonator’s wall, which has an effect on the velocity distribution inside the resonator [8]. These mechanisms dissipate the flow kinetic energy into heat, and thus deteriorate the overall conversion efficiency.

Understanding the viscous dissipation mechanisms in the main thermoacoustic components such as stacks and heat exchangers requires some advanced measurement techniques for the oscillating flow around and inside these components. Particle image velocimetry (PIV) is a common technique used to visualize flow morphology. For simplicity, the stack is usually modelled as a set of parallel plates separated by a certain distance.

The oscillating flow around a set of parallel plates have been investigated. For instance, Benon et al. [9] experimentally studied the effects of the plate thickness on the formation of vortices at the end of the parallel plate stack. Berson et al.[10] measured the velocity field inside an oscillating boundary layer between the parallel plates of the stacks using PIV. The effect of different parameters (e.g. plate separation, dynamic pressure, stack blockage ratio, etc...) on the flow morphology around and inside the stack was studied experimentally in [11-16] for a limited range of operating conditions. Also, some numerical studies have been carried-out and comparisons with measurements have been made in [17-19]. Aben et al. [20] have investigated the characteristics of the flow (vortices and streaming velocity) around parallel stacks inside a standing wave thermoacoustic resonator utilizing PIV, for a limited range of drive ratios (up to 2%) which is defined as the ratio between the dynamic pressure and the mean pressure. Also, they have studied the effects of the drive ratio, the plate thickness, the plate spacing, and the end-plate shape on the vortex shedding at the entrance of the parallel plate stack.

In the studies mentioned above, the pressure amplitude level was low (i.e. drive ratio up to 2%). Since the nonlinear phenomena have significant impact on the flow characteristics at high pressure amplitudes, the current study has investigated the effects of the plate-end shape (i.e. circular, rectangular and triangular) on the size of the disturbance zone for high drive ratios (i.e. up to 7%).

2. Experimental apparatus and measurement systems

2.1 Experimental setup

A schematic for the experimental setup used in the current study is shown in Fig. 1. The resonator is made of an acrylic square duct with a side length of 48 mm and a length of 990 mm. The resonator is closed from one end while the other end is attached to a loudspeaker (Massive Toro-104, maximum power rating of 1200W) through an acrylic cone has length of 195 mm. The loudspeaker is placed inside a steel enclosure (cylindrical tube with inner diameter of 240 mm and length of 450 mm). The loudspeaker is driven by a power amplifier (B & K Amplifier Type 2734) which is connected to a function generator (Tektronix AFG 3251). In all experiments, the resonator is filled with air at atmospheric conditions and the speaker operates at the resonance frequency of the system (i.e. 81 Hz). Based on this configuration and at these conditions, when the speaker operates at the resonance frequency of the system, a standing-wave with a nearly quarter-wave length mode is generated.

In order to study the flow morphology at the inlet/exit of the stack, a set of parallel plates is used to mimic the stack. The set of the parallel plates is placed at the center of the resonator duct. In this work,
three different sets are used. As shown in Fig. 2, each set has a certain plate-end shape (rectangular, circular and triangular ($\theta =30^\circ$)). Also, each set consists of three identical plates. The thickness of each plate is 10 mm and the plate spacing is 4 mm. As the length of the plate (i.e. 150 mm) is finite, the effects of one end on the other should be eliminated. Hence, the Keulegan-Carpenter number ($K_C$), which is defined as the ratio between the gas particle displacement and the length of the plate, should be much less than 1 to avoid interactions between the vortices before and after the stack. In the present work, the value of $K_C$ ranges from 0.065 to 0.18 which corresponds to drive ratios of 2.1% and 7.1%, respectively.

Figure 1: (a) Schematic for the experimental setup, and (b) Photo for the apparatus and the measurement system.
2.2 Pressure measurements

A piezo-resistive pressure microphone (Endevco, Model 8530C) is attached to the closed end of the resonator to monitor the dynamic pressure \( P_{\text{dyn}} \). The microphone signal is amplified through a signal amplifier and then the amplified signal is monitored on a digital oscilloscope. The loudspeaker is able to achieve a drive ratio \( DR = \frac{P_{\text{dynamic}}}{\text{Mean pressure}} \times 100\% \) up to 12.7%.

In order to determine the resonance frequency of the system. A frequency response is performed in which the dynamic pressure is recorded over a large frequency range. As shown in Fig. 3, the dynamic pressure peaks at frequency of 81 Hz which represents the resonance frequency of the system. Also, the second dynamic pressure peak occurs at a frequency much higher that the resonance frequency which indicates that the current design reduces the harmonics significantly, thanks to the variation in cross sectional area employed in the system [21].

2.3 PIV measurements

PIV system is used to visualize the flow pattern at the inlet/exit of the plates. The PIV system consists of two main components which are the laser light source and the camera. The laser light source is a ND: YLF laser (Dantec Dynamics, model: LDY303-PIV) has a wave length of 527 nm and maximum repetition rate of 10 kHz. The laser sheet illuminates the plane at the center of the duct and parallel to the direction of the gas oscillations. A CMOS camera (Photron SA1.1) with a maximum frame rate of 5400 frames/s and a resolution of 1024x1024 Pixels\(^2\) is used to capture images. The sampling frequency of the camera is set to 1000 Hz and the time between the two successive frames is set to 5 µs. A
prime lens (60 mm, Nikon AF) is attached to the camera. The camera is mounted on a traverse mechanism to facilitate the measurements in the axial direction. The synchronization between the camera and the laser source is accomplished via a timer box (NI, Model: 80N77). These settings allow large dynamic range for the velocities expected.

A powder seeding generator (Dantec Dynamics, Model: 10F01) is used to supply the resonator with titanium dioxide particles of mean particle diameter of 0.4 µm. The resonator is cleaned before each experiment because the seeding particles were deposited on the walls of the resonator which reduces the laser light intensity.

In this work, the raw images captured by the camera are used directly to provide a qualitative estimate of the effects of the plate-end shape on the oscillating flow morphology.

3. Results and discussion

Some basic measurements in the empty (without plates) resonator were conducted in order to predict the performance of the system and validate the numerical model built by DeltaEc [22]. As shown in Fig. 4, the drive ratio is linearly proportional to the input voltage up to drive ratio of approximately 7%. At higher drive ratios, the measurements deviate from the DeltaEc predictions. This discrepancy is due the non-linear phenomena associated with high drive ratios that are not modelled since DeltaEc relies on the linear theory of Rott [4]. As shown in Fig. 5, the axial acoustic velocity amplitude distribution over the axial distance at the center of the duct shows a nearly quarter-wave mode of operation.

![Figure 4: The measured and the DeltaEc variation of the drive ratio with the input voltage to the loudspeaker.](image)

![Figure 5: The measured and DeltaEc axial acoustic velocity amplitude distribution for the empty resonator at the resonance frequency at drive ratio of 7.1%.](image)

The plates are then placed inside the resonator to study the effects of the plate-end shape on the Disturbance Zone Size (DZS). The DZS is defined as the distance between the furthest axial location the vortices reached and the point at which they separated from the plate. In Fig. 6, the DSZ is bounded by two vertical dashed yellow lines. Also, the vortices are defined by black dots in the flow field as indicated by the red arrows. The black dots formed due to the lack of seeding particles at the center of the vortex due to the centrifugal force that pushed the seeding particles away from the vortex center.

As shown in Fig. 6a, as the drive ratio is increased from 2.1% to 7.1%, the size of the disturbance zone increases from 4.3 mm to 14.7 mm. In Fig. 6b, there is no disturbance at the lowest drive ratio (2.1%). However, for a drive ratio of 7.1%, the DZS increases up to 10.6 mm. In Fig. 6c, as the drive ratio is increased from 3% to 7.1%, the size of the disturbance zone increases from 3.3 mm to 12 mm.
Figure 7 summarizes the effect of the drive ratio on the DZS for different plate-end shapes. It is apparent that the DZS is linearly proportional with the drive ratio for different plate-end shapes. Also, at all drive ratios, the triangular plate-end and rectangular plate-end have the smallest and the largest DZS, respectively, with the circular-end plates in between.

Figure 6: The size of the disturbance zone at different drive ratios and for three different plate-end shapes: (a) Rectangular, (b) Triangular, and (c) Circular.
4. Conclusions

The DZS around parallel plates with different plate-end shapes in oscillating flow has been investigated at different drive ratios using PIV. The minimum DZS is observed with the plates have triangular end shape (θ = 30°). The largest DZS is observed with the plates have rectangular end-shape.

A linear proportional relationship between the DZS and the drive ratio is observed up to drive ratio of approximately 7%.

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[22] L. A. N. Laboratory, DeltaEC, Los Alamos NM 87545.