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Time-resolved Particle Image Velocimetry of the flow in an acoustic standing wave tube

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ABSTRACT

The flow field in an acoustic standing wave tube was measured using time-resolved particle image velocimetry (PIV). Verifications were made through comparisons between measured and predicted acoustic particle velocities in the spatial domain and the time domain. The accuracy of the time-resolved PIV system was satisfactory, at least for the periodic flow velocity component. The steady streaming flow field was then obtained through synchronous data acquisition. The streaming flow featured recirculation patterns which were different from classical Rayleigh or Schlichting streaming patterns. One possible reason is that the streaming Reynolds number was too low for classical streaming to occur.

INTRODUCTION

Thermoacoustic cooling is a technology that produces cooling power through the utilization of the energy in high amplitude acoustic waves. Periodic compression and expansion of gas particles, combined with heat transfer within regions near boundaries, results in heat pumping cycles that employ environmentally benign working fluids. The second law efficiency of thermoacoustic refrigerators is generally low when compared to that of domestic refrigerators based on vapor compression cycles. Heat transfer between the stack and heat exchangers is arguably one of the main factors limiting the thermodynamic efficiency of thermoacoustic systems. Experimental studies [2, 3] were performed in order to characterize the heat transfer coefficient of heat exchangers in acoustic standing waves. The interaction of large amplitude oscillating acoustic flows with the stack and heat exchangers created complex flow patterns designated as streaming. Streaming flow [2] contributes significantly to heat transfer. In the case of thermoacoustic engines, jet pumps and tapered thermal buffer tube have been employed to suppress Gedeon and Raleigh streaming, respectively [1].

Particle image velocimetry (PIV) has been successfully applied to measure acoustic and streaming velocities inside a resonator [4, 5]. Nabavi et al [4, 5] measured simultaneously the acoustic (A.C) and streaming (D.C) velocities inside the resonator. They also established criteria for the formation of regular (classical) and irregular streaming structures based on the streaming Reynolds number. The classical streaming structure is typically comprised of two outer streaming vortices per quarter-wavelength of the acoustic wave, which are symmetric about the channel centre line. In irregular streaming, the shape and the number of streaming vortices are different from the regular case. Details of the flow field around key internal components of thermoacoustic systems were reported in recent studies [6, 7]. Previous experimental PIV studies have used phase locked ensemble averaged data for acoustic particle velocity determination. The present study reports time-resolved PIV data for acoustic particle velocities. This approach should allow the identification of periodic phenomena that are not synchronous with the dominant excitation frequency, in addition to the mean flow component.

EXPERIMENTAL METHODS

The schematic of the experimental setup is presented in Figure 1. The acoustic resonator (j) used in this experimental study had a square cross section, 4cm×4cm and a length of 98 cm.

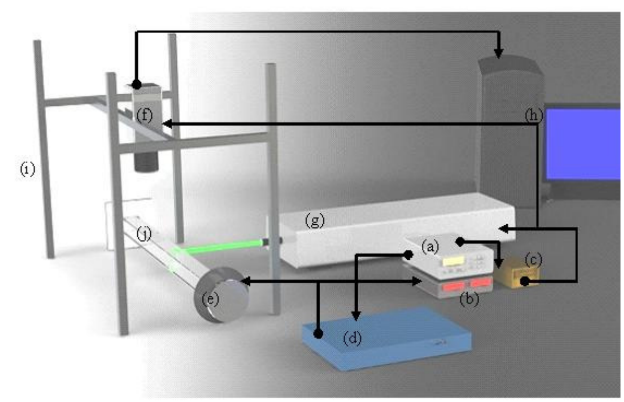

Figure 1: Schematic of the experimental setup. (a) Function generator; (b) Power analyzer; (c) Synchronization unit; (d) Power amplifier; (e) Acoustic driver; (f) CCD camera; (g) Laser; (h) Computer with frame grabber; (i) Traversing mechanism; (j) Resonator tube.

The walls of the resonator were 9 mm thick. A 200 W acoustic driver (e) with a DC coil resistance of 8 Ω excited the acoustic standing wave in the resonator. A function generator (a) produced a sinusoidal excitation signal which was fed to a

200 W RMS power amplifier (d). A power analyzer (b) was connected in parallel with the acoustic driver to monitor the instantaneous true RMS voltage, current and power fed to the acoustic driver. Two high resolution ICP pressure transducers were mounted flush near the two extremities of the resonator for measuring the dynamic pressure.

The particle image velocimetry (PIV) system was a dual-cavity, time-resolved (TR) Nd:YLF laser (g) with a maximum repetition rate of 10 kHz per cavity. A CCD-CMOS camera (f) with a frame rate of 2000 fps and a resolution of 1280×1024 pixels was used. The pixel pitch of the camera was 12μm. The camera was mounted on a traversing mechanism (i) which allowed mapping of the velocity field over the entire length of the resonator. A controller unit (c) supplied by the PIV system manufacturer was employed in order to synchronize the camera and the laser. A Laskin nozzle seeding generator, using olive oil, produced 1μm particles which were used to seed the flow.

DATA ACQUISITION AND PROCESSING

In order to validate the PIV methodology, acoustic particle velocities were measured at different phases (θ) within one acoustic cycle by phase locking the laser and camera with the excitation signal. Velocity data were obtained for 13 phase values, namely, θ = 0, 36, 72, 90, 108, 144, 180, 216, 252, 270, 288, 324 and 360 degrees. The synchronization unit used the TTL signal generated by the signal generator as input. A time lag, τ was introduced between the TTL signal and the trigger signal for the camera and laser was introduced in the PIV software to obtain acoustic particle velocities at different phase values.

For each phase value, a total of 200 images were captured in double frame mode. Velocity fields were processed from these images and then an ensemble averaged velocity map was obtained at each individual phase.

RESULTS AND DISCUSSION

Verification of the measured data

In order to verify the validity of the experimental data obtained from PIV, comparisons were made with acoustic particle velocities predicted from linear theory and measured acoustic pressures. The peak dynamic pressure amplitude measured at the driven and the rigid ends of resonator were 227.45 Pa and 731.45 Pa, respectively. The mean pressure inside the resonator was atmospheric and the mean temperature was 395 K. Measured acoustic particle velocities were obtained for excitation frequencies (f) of 198, 396 and 1137 Hz, for which the resonator length corresponds to one-half, full and three wavelengths. A rigid, perfectly reflecting termination was assumed at the closed end. The results are shown in the spatial domain and in the time domain in Figures 2 and 5, respectively. Figure 2 shows a comparison between the measured and predicted axial component of the acoustic particle velocities at 1137 Hz in the spatial domain, for two different phases. The horizontal axis depicts the distance from the driven end of the standing wave tube. The experimental results are in good agreement with the theoretical results. Figure 3 shows the measured velocity vector map for the two phases shown in Figure 2. The vertical axis (y) of Figure 3 represent the transverse distance within the resonator tube, with origin at the center of the tube, while the horizontal axis (x) represent the axial direction. Again only a portion of the transverse plane is presented. The velocity vectors in each sub-figure of Figure 3 are normalized with respect to the vector with greatest amplitude. Vector plots display the velocity map in a two dimensional plane. The velocity vectors in Figures 3a and 3b are equal in magnitude, but opposite in direction.

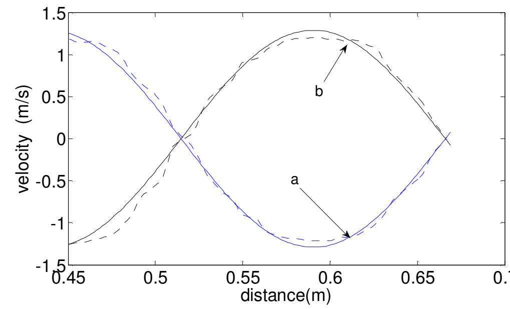

Figure 2: Axial component of the acoustic particle velocity vs. axial distance at f = 1137 Hz. Measured (dashed line) and predicted (solid line) axial acoustic particle velocities for (a): θ = 180° and (b): θ = 0°

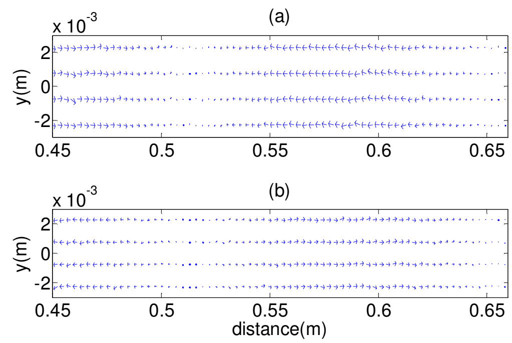

Figure 3: Velocity vector map at (a): θ = 180° and (b): θ = 0° (as shown in Figure 2).

Measured ensemble-averaged axial acoustic particle velocities at different phases for an excitation frequency of 1137 Hz are shown in Figure 4. This figure illustrates the standing wave nature of the acoustic flow inside the resonator. In order to obtain comparisons between experimental and theoretical results in the time domain, the particle velocities were obtained at different locations inside the resonator. These locations are indicated in Figure 4. For each location, ensemble-averaged acoustic velocities were experimentally obtained through PIV for 13 different phases. Figure 5 shows a comparison between predicted and measured acoustic velocities in the time domain for the four spatial locations identified in Figure 4. A good agreement between the experimental data and theoretical results was obtained. These results support the accuracy of the PIV method to measure the acoustic flow field inside the resonator.

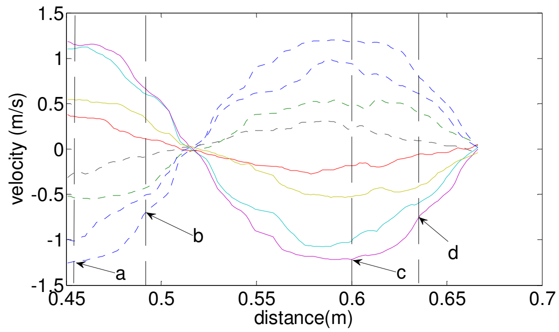

Figure 4: Velocity profiles at different phases of acoustic cycle at f = 1137 Hz. The axial velocity components are shown for θ = 0°, 72°, 108°, 0°, 144°, 180°, 252°, 288° and 324°

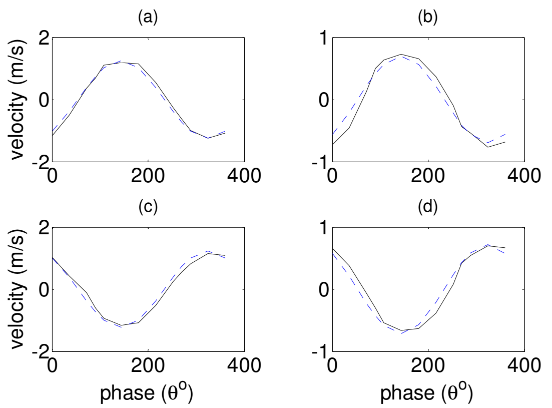

Figure 5: velocity profile at different locations. (a) 0.45 m, (b) 0.49 m, (c) 0.6 m, (d) 0.64m. Predicted (solid line), measured (dashed line). The locations are shown in Figure 4.

Streaming velocities

The streaming velocities were also determined experimentally at f = 1137 Hz, for the same conditions as for previous figures. The method described by Nabavi et al [4] was followed to estimate the streaming velocities. The time duration between two laser pulses (Δt) of the PIV system was made equal to the time period corresponding to f. The cross-correlation between the images thus obtained yields the streaming velocity. Results are shown in Figure 6. Streamlines are superimposed on the streaming velocity vectors to help in the visualization of the streaming flow. Non classical streaming patterns (as described in introduction) are observed in Figure 6. As stated in a previous study on streaming flows [5], classical streaming patterns are observed at streaming Reynolds numbers (Re_s) greater than 6.5, defined in equation 1.

$$Re_s = \frac{u_{max}^2}{\upsilon\omega} \tag{1}$$

u_{max} is the maximum streaming velocity, υ is the kinematic viscosity and ω is the frequency of the acoustic flow in rad/s. In the case of the present study, Re_s was found out to be 0.41, which is much smaller than the value required for realizing classical streaming structures.

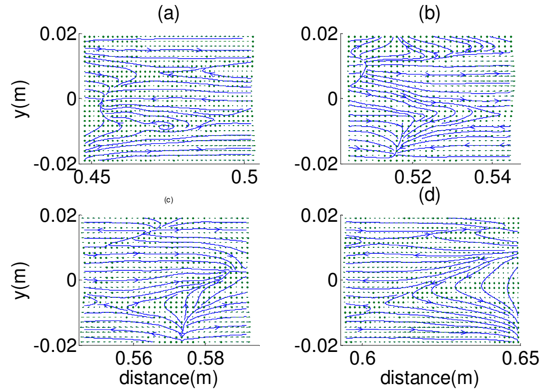

Figure 6: Streaming velocities at f = 1137 Hz. (a) x = 0.45-0.5 m, (b) x = 0.5-0.54 m, (c) x = 0.54-0.59 m, (d) x = 0.59-0.65 m,

TIME RESOLVED EXPERIMENTAL STUDY OF THE ACOUSTIC FLOW

Most previous PIV studies [4, 5, 6, 7] reported results with good spatial resolution, but with limited temporal resolution. There is a need for time-resolved studies in acoustics in general, and thermoacoustics in particular. This is useful to characterize unsteady flows that are not synchronous with the dominant periodic excitation. In order to obtain data in the time domain, phase locked data are usually obtained at different phases within an acoustic cycle. The reason for this is the limitation in the hardware capacity, namely, the laser repetition rate and the camera frame rate. Transient acoustic phenomena such as the formation of streaming structures or vortex formation behind stack plates, as well as turbulence, could be better understood from time-resolved data. Recent development in the hardware of PIV systems make it possible to capture time-resolved images. The study presented here is one such attempt at obtaining high temporal resolution data for an acoustic flow. In the study presented here the acoustic resonator was excited at 198 Hz which is near the typical operating frequency of thermoacoustic refrigerators. Images were captured at 4000 Hz, which means that for each acoustic cycle 20 data points were captured. The camera field of view was set in the middle region of the resonator along the transverse axis. Figure 7 shows a comparison between measured and the predicted axial component of the acoustic particle velocities. The linear acoustic model slightly overpredicted the acoustic velocity, but overall the experimental results agree well with theoretical results obtained linear acoustic models. Figure 8 presents velocity vector maps at four different locations in the time domain. The four different locations are shown in Figure 7. The frequency content of the time-resolved velocity vector map was obtained from the time history of the velocity vectors from the two-dimensional vector maps. The power spectral density (PSD) of the velocity vector time history was calculated and is shown in Figure 9. For calculating PSD the total time history comprising of 40000 data points was considered, with a record length NFFT=1024, a Hann window was used for each segment with an overlap of 50%. The major component occurs at the excitation frequency of 198 Hz, as expected, with smaller components corresponding to higher harmonics. The frequency spectrum analysis also reveals components at frequencies other than harmonics of the excitation frequency. As illustrated in Figure 9, secondary tonal components (identified by dotted line) are visible adjacent to higher harmonics (identified by dashed line) at 600, 1400 and 1800 Hz.

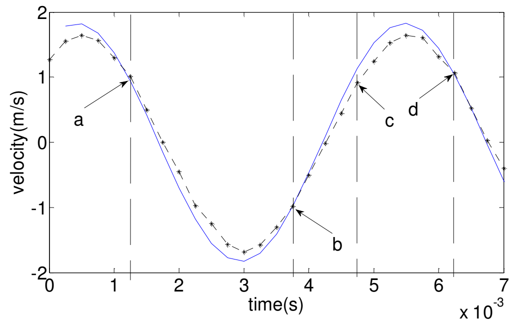

Figure 7: Axial component of acoustic velocity vs. time. Measured (dashed line) and predicted (solid line) acoustic velocities.

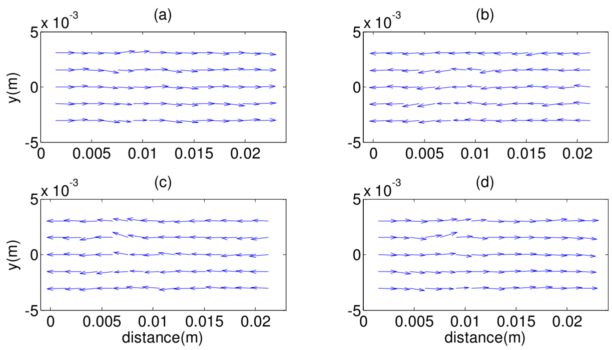

Figure 8: Instantaneous velocity vector maps at different time instants. (a) t = 3*T/20, (b) t = 7*T/20, (c) t = 13T/20, (d) t = 17T/20. T is the time period.

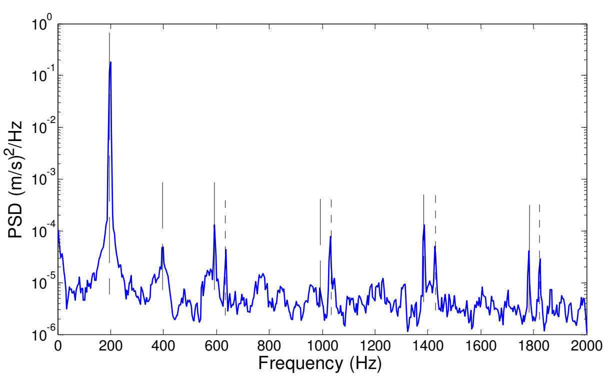

Figure 9: Power spectral density of the acoustic velocity vector.

CONCLUSION

The flow field in an acoustic standing wave tube was investigated using a time-resolved PIV system. The results were in satisfactory agreement with theoretical predictions obtained from linear acoustic models. The standing wave nature of the flow was reproduced by plotting acoustic velocities at different phases of one acoustic cycle. Streaming velocities were also obtained at 1137 Hz. Due to low streaming Reynolds numbers, non classical streaming patterns were observed. A Time-resolved PIV study of the acoustic flow at the typical operating frequency of thermoacoustic refrigerators i.e. 198 Hz was performed. A frequency domain analysis of the time histories of the velocity vector was performed and it can be inferred from the results that TR-PIV allowed the resolution of higher harmonics of the excitation frequency along with frequency components which were not synchronous with the excitation frequency. In phase-locked PIV data, flow components which are at frequencies other than multiples of the excitation frequency can not be detected. Thus TR-PIV offers a tool for resolving higher harmonics and asynchronous components of the acoustic flow.

It can be concluded that time resolved PIV systems accurately measure the steady and transient acoustic particle velocities occurring inside a thermoacoustic refrigerator. TR-PIV can in the future help gain a better understanding of vortex formation behind stacks, and other streaming flows within thermoacoustic heat pumping devices.

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