Effects of transverse temperature gradient on acoustic and streaming velocity fields in a resonant cavity

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Effects of transverse temperature gradient on acoustic and streaming velocity fields inside a gas-filled rectangular enclosure subject to acoustic standing wave are investigated experimentally. Synchronized particle image velocimetry technique has been used to measure the acoustic and streaming velocity fields. The results show that the temperature difference between the top and the bottom walls deforms the symmetric streaming vortices about the channel's centerline to the asymmetric ones. As the temperature difference increases, the amplitude of streaming velocity increases. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2960576]

Interaction of acoustic waves in a viscous fluid and solid boundaries creates some nonlinear phenomena. One of them is acoustic streaming, a stationary flow which has rotational character and its velocity increases with the sound intensity. The study of acoustic streaming is very important in different areas of physics and engineering.[1,2] The classical streaming structure in a resonator predicted by Rayleigh theory is typically comprised of two streaming vortices per quarter wavelength of the acoustic wave which are symmetric about the channel centerline.

The influence of the axial temperature gradient (i.e., the temperature gradient in the direction of the acoustic wave propagation) on acoustic streaming has been extensively studied analytically, numerically and experimentally. Rott[3] derived a simplified analytical formula for the acoustic streaming including the effect of variable tube wall temperature. Aktas and Farouk[4] numerically investigated thermal convection in a two dimensional (2D) resonator. They reported that the influence of mechanically induced periodic oscillations on the heat transfer characteristics of the system is significant only in the presence of steady streaming flows. Thompson *et al.*[5] experimentally investigated the influence of axial temperature gradient on the behavior of the streaming flow. They observed that as the magnitude of the axial temperature gradient increases, the shape of streaming vortices becomes distorted.

The influence of transverse temperature gradient (i.e., the temperature gradient normal to the direction of acoustic wave propagation) on acoustic streaming is scarcely studied. Very recently, only one study has numerically investigated this behavior.[6] They considered the temperature dependent conductivity and viscosity in their model and conducted simulations at top-bottom wall temperature difference of 0, 20, and 60 °C. At 20 and 60 °C, they found that the classical two symmetric streaming vortices are distorted to one vortex. However, they did not study the transitional behavior of streaming vortices due to the gradual increase in the temperature gradient. Furthermore, they did not support their numerical results with theoretical explanation or experimental measurement.

Particle image velocimetry (PIV) has been used for the measurements of acoustic streaming by many researchers.[7] In the present study, we have experimentally investigated the influence of transverse temperature gradient on the acoustic and streaming patterns using the synchronized PIV technique. The transitional behavior of streaming vortices due to the gradual increase in the transverse temperature gradient is presented and physically explained.

The experimental setup developed to measure the acoustic and streaming velocity fields inside the standing wave tube is shown in Fig. 1. The acoustic chamber is a Plexiglas channel with the length of $L=105$ cm and the inner width and height of $H=4$ cm. The walls of the channel are 10 mm thick. The 2D acoustic and streaming velocities inside the channel are measured using synchronized PIV.[8] A 120 mJ Nd:YAG (neodymium-doped yttrium aluminum garnet) laser is used as a light source for the PIV measurements. A charge coupled device camera with the resolution of 1600×1200 pixels is used to image the flow. The camera is connected to a PC equipped with a frame grabber that acquired 8 bit images at a rate of 30 Hz. A special loudspeaker driver is used to excite the acoustic standing wave inside the tube.

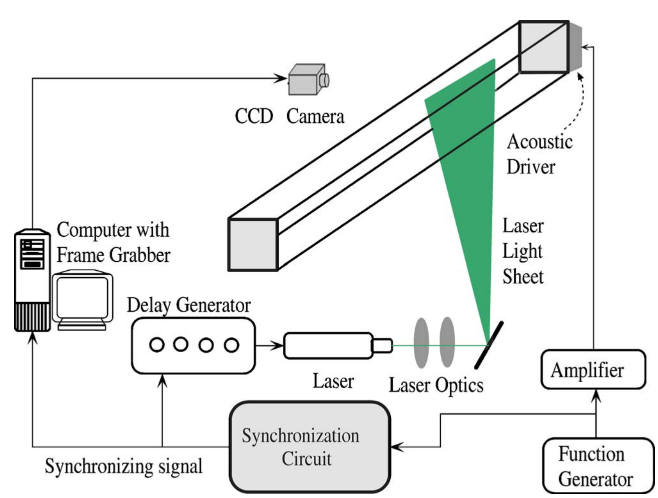

FIG. 1. (Color online) Schematic of the experimental setup.

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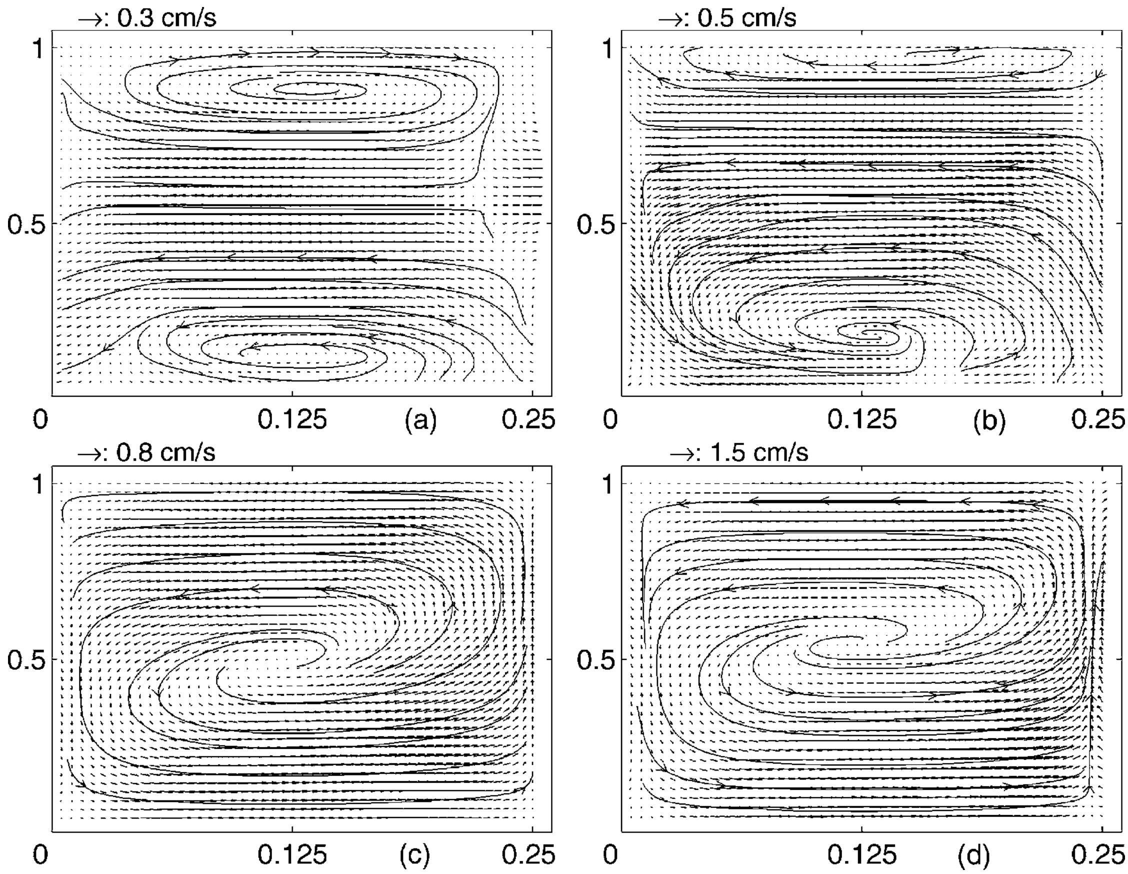

FIG. 2. The streaming structures in the quarter-wavelength region of the resonator for (a) $\Delta T=0$ °C, (b) $\Delta T=0.3$ °C, (c) $\Delta T=0.8$ °C, and (d) $\Delta T=3$ °C. Horizontal axis is x/λ and vertical axis is y/H.

A Function generator is used to generate the sinusoidal wave. The signal from the function generator is amplified by a 220 W amplifier.

The driver frequency is set equal to $f=976$ Hz resulting in the formation of three complete standing waves inside the channel. The camera field of view is set equal to 10 cm in horizontal and 8 cm in vertical that allows to capture the streaming velocity field in the quarter-wavelength ($\lambda/4$) region. The maximum acoustic pressure is measured to be 775 Pa. Four different thermal boundary conditions are considered which are $\Delta T=0$ (isothermal), $\Delta T=0.3$ °C, $\Delta T=0.8$ °C, and $\Delta T=3$ °C, where ΔT is the temperature difference between the bottom and the top walls (i.e., $\Delta T=T_{\text{bottom}}-T_{\text{top}}$). To achieve isothermal boundary condition, the resonator is placed inside a large water tank of dimensions $50\times 50\times 90$ cm^3. To achieve differentially heated horizontal walls, the resonator is placed on top of an aluminum plate ($150\times 10\times 2$ cm^3). Two electric strip heaters are attached to the bottom of the aluminum plate. Constant temperature of the aluminum plate is maintained by using a proportional integral derivative (PID) controller. Five thermocouples were placed along the aluminum plate to act as a feedback to the PID controller.

The streaming velocity vectors along with the streamlines for the four cases are shown in Fig. 2. For isothermal case [Fig. 2(a)], two streaming vortices per quarter wavelength of the acoustic wave which are symmetric about the channel center line are clearly observed. As the bottom wall is slightly heated [$\Delta T=0.3$ °C, Fig. 2(b)], the bottom vortex vertically expands and the top one vertically contracts. At higher temperature differences [$\Delta T=0.8$ °C, and 3 °C, Figs. 2(c) and 2(d)], the top vortex is totally disappeared.

For the cases studied, the x component of the streaming velocity (u_{st}) along the y axis at $x/\lambda=1/8$ (i.e., across the center of the vortex), and the y component of the streaming velocity (v_{st}) along the y axis at $x/\lambda=2/9$ (close to the end of the vortex) are shown in Figs. 3(a) and 3(b), respectively. The plots show that as ΔT increases from 0 to 3 °C, the maximum amplitude of u_{st} increases from 0.74 to 3.1 cm/s and the maximum amplitude of v_{st} increases from 0.13 to 2.25 cm/s. As observed, the percentage of increase of v_{st} is larger than that of u_{st}. The point at which the v_{st} crosses the zero velocity axis can be considered as the border of the two vortices. This border for the isothermal case is close to the channel centerline [point A in Fig. 3(b)]. Whereas, for $\Delta T=0.3$ °C is close to the top wall [point B in Fig. 3(b)].

As shown in Figs. 2 and 3, two physical phenomena concerning the acoustic streaming in a resonator with differentially heated horizontal walls are observed: (1) increase in acoustic streaming amplitude and (2) distortion of the symmetrical streaming structure. To explain the observed phenomena, we have investigated the effect of transverse temperature gradient on the acoustic velocity field. The axial acoustic velocities (u_a) at the velocity antinode for $\Delta T=0$, 1, 15, and 35 °C, are plotted in Fig. 4. The results at higher values of ΔT are also presented to signify this effect. Figure 4 shows that u_a is influenced by the transverse temperature gradient and its magnitude increases with an increase in ΔT.

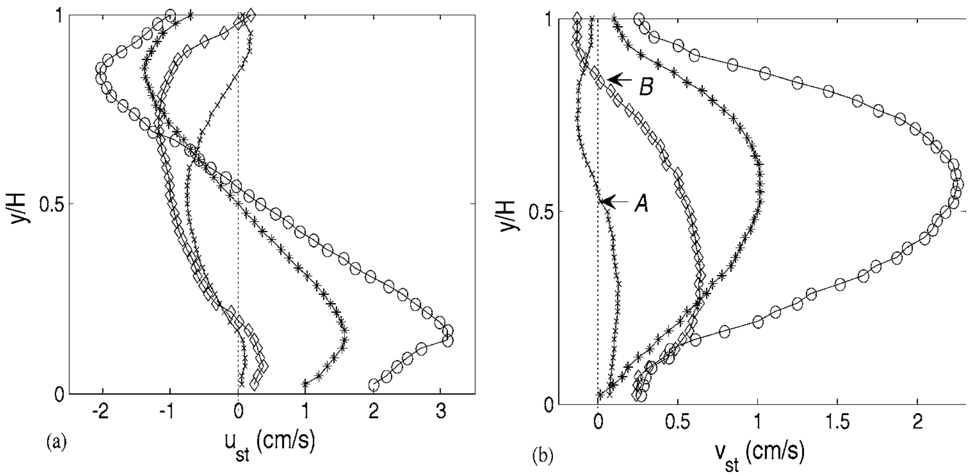

FIG. 3. (a) The x component of the streaming velocity along the y axis at $x/\lambda=1/8$, and (b) the y component of the streaming velocity along the y axis at $x/\lambda=1/4$ for $\Delta T=0$ °C (×), $\Delta T=0.3$ °C (◇), $\Delta T=0.8$ °C (*), and $\Delta T=3$ °C (○).

The physical explanation of the observed phenomena can now be provided as follows. The increase in the acoustic velocity due to the transverse temperature gradient results in an increase in the average mass transport velocity values which are, in fact, the streaming velocities. That might be the reason for the increase in both components of the streaming velocity in the presence of a transverse temperature gradient. Furthermore, as shown in Figs. 3(a) and 3(b), by increasing ΔT from 0 to 0.3 °C, the maximum amplitude of u_{st} increases from 0.74 to 1.17 cm/s and from 0.74 to 0.96 cm/s for the bottom and top vortices, respectively. Whereas, for the same increase in ΔT, the maximum amplitude of v_{st} increases from 0.13 to 0.64 cm/s for the bottom vortex, and remains almost constant (i.e., 0.13 cm/s) for the top vortex. This analysis shows that the amplitude of v_{st} increases significantly with an increase in ΔT for the bottom vortex, which makes the bottom vortex more energetic than the top one. This difference in the vortex energy causes the bottom vortex to expand vertically and eventually eliminate the top vortex.

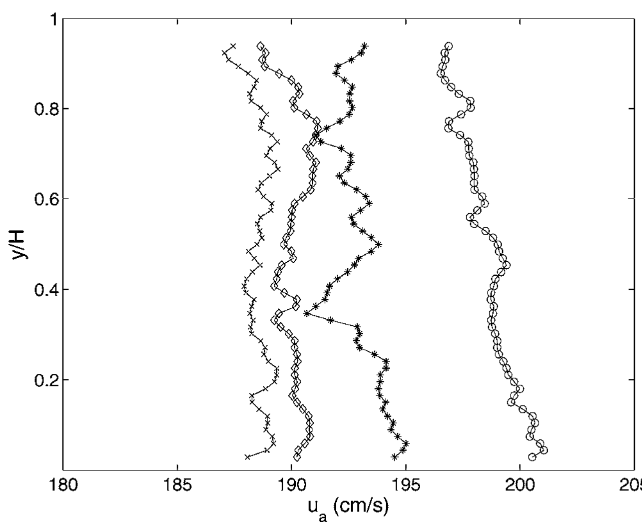

FIG. 4. The axial acoustic velocity (u_a) at the velocity antinode for $\Delta T=0$ °C (×), $\Delta T=1$ °C (◇), $\Delta T=15$ °C (*), and $\Delta T=35$ °C (○). The acoustic velocities are acquired at the phase corresponding to the maximum velocity fluctuation.

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