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Thermoacoustic Streaming
熱音響流

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1. Introduction

Acoustic streaming is the time-averaged fluid motion that occurs when sound waves propagate in viscous fluids, which is typically associated with the dissipation of acoustic energy. The theories of acoustic streaming have been well established in isothermal condition since the seminal work done by Rayleigh[1)], Schlichting[2)], and Eckart[3)], but the underlying physics of the acoustic streaming in media with temperature gradients has not been understood. In this work, through comprehensive experiments and numerical simulation, we discover that temperature gradients induce a nondissipative acoustic body force which drives a new form of streaming and call it thermoacoustic streaming.

2. Materials and Methods

The measurements were conducted using a glass-silicon-glass sandwiched chip with a long straight microchannel of width W = 760 µm and height H = 370 µm. To generate a temperature gradient inside the channel, the light from a 470-nm light emitting diode (LED) was focused and shone through the water containing a dilute dye solution (0.1 wt% Orange G) that absorbs 99% of the LED light, see **Fig. 1**. The piezoelectric transducer glued on top of the chip was driven at 953 kHz with an input power of 88 mW, creating a half-wave standing wave field across the channel width with an acoustic energy density E_{ac} = 9.24 J/m^3. The induced 3D streaming field was measured using the general defocusing particle tracking technique[4)] by tracing 1.1 µm-diameter polystyrene particles (red fluorescence). The temperature field around the channel mid-height plane was probed using temperature-sensitive fluorescent dye (Rhodamine B) in a separated experiment.

The numerical model based on perturbation theory is an effective pressure acoustic model containing thermoviscous boundary layers[5)] and symmetry planes are applied to only simulate a quarter of the device, which enables 3D simulation including both solid (glass and silicon) and fluid domains. First, the temperature field T_0 induced by the LED is computed by matching the amplitude to the measured one. Then, the solid displacement $\boldsymbol{u}_1$ and the pressure p_1 in the fluid generated by the actuation of the transducer are computed, and finally the resulting streaming field $\boldsymbol{v}_2$ is obtained.

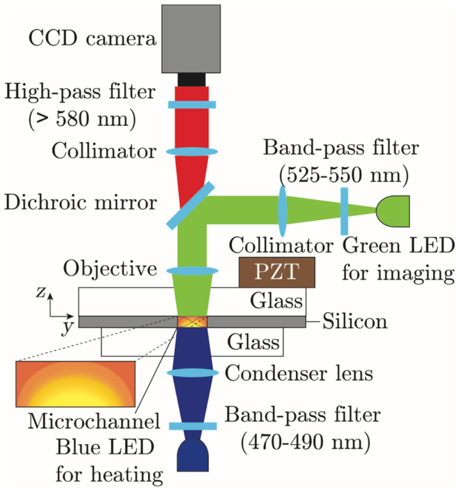

Fig. 1 Sketch of the acoustofluidic silicon chip (gray) sealed with two glass layers (white), which allows optical heating (blue LED) and particle tracking (green LED) in a volume of L = 1300 µm, W = 760 µm, and H = 370 µm. The blue light is absorbed by the aqueous dye solution, which forms a temperature gradient in the channel from low (orange) to high (yellow). Reproduced with permission from Ref. [6].

3. Results and Discussion

An example of the thermoacoustic streaming is shown in **Figs. 2(a)-2(e)**, under a temperature difference ΔT_0 = 3.71 K across the channel width, equivalent to a gradient G = 9.76 K/mm. Two counterrotating deformed cylindrical streaming rolls with a velocity amplitude $|\boldsymbol{v}_2| = 1074\ \mu\mathrm{m/s}$ are observed. The velocity amplitude is about 77 and 87 times higher than that of the Rayleigh streaming and the Rayleigh-Bénard convection under the same driving conditions.

The mechanism to generate this fast streaming is due to the acoustic body force $\boldsymbol{f}_{ac}$ arisen from the inhomogeneities of medium compressibility and density[7)]. In this experiment, the light heats the fluid from beneath, while the silicon sidewalls transport the heat away efficiently. Temperature gradients are therefore created in all three directions (in x and y directions by the Gaussian profile of the light intensity and the cooling from the silicon layer, and

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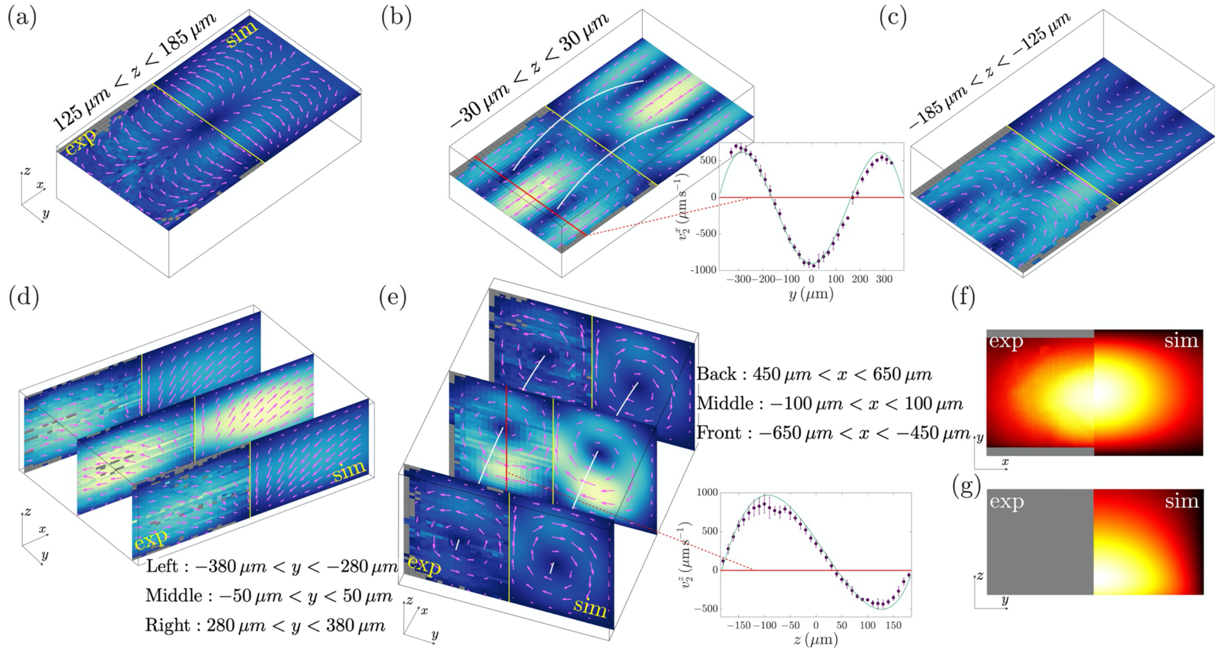

Fig. 2 (a)-(e) The measured (exp, left half) and simulated (sim, right half) thermoacoustic streaming for G = 9.76 K/mm averaged in the indicated intervals normal to x-y, x-z, and y-z planes. The vector plot (magenta) is the in-plane velocity and its magnitude is indicated by the color plot from 0 (dark blue) to 1042 μm/s (yellow). Spatial bins with no data points are excluded (gray). The centerlines of the two counterrotating deformed cylindrical streaming rolls are represented by the pair of curved lines (white) in (b) and (e). (f)-(g) Color plot of the measured and simulated temperature T_0 from 25.0 °C (black) to 30.1 (white) in x-y plane around z = 0 and in y-z plane at x = 0. No experimental data is available in y-z plane. Reproduced with permission from Ref. [6].

in the z direction by the absorption following Beer-Lambert law). The hottest region appears at the center of the channel bottom, as shown in **Figs. 2(f)-2(g).** The $\boldsymbol{f}_{ac}$ is expressed as[7]

$$\boldsymbol{f}_{\mathrm{ac}} = -\frac{1}{4}|p_1|^2\nabla\kappa_0 - \frac{1}{4}|\boldsymbol{v}_1|^2\nabla\rho_0, \qquad (1)$$

where κ_0 and ρ_0 are the medium compressibility and density. Both κ_0 and ρ_0 decrease with temperature within the temperature range in this experiment, thus $\boldsymbol{f}_{ac}$ points towards the high temperature region. The highest $\boldsymbol{f}_{ac}$ is obtained at the bottom due to the larger temperature gradient at the bottom than at the top of the channel (**Fig. 2(g)**). Consequently, in the channel bottom, $\boldsymbol{f}_{ac}$ pushes the fluid horizontally towards the channel vertical center y = 0 and due to mass conservation the fluid escapes outward along the x direction and upward along the z direction, leading to two deformed cylindrical flow rolls, which appear as four horizontal rolls (**Figs. 2(a)-2(c)**) when projected onto the x-y plane and as two vertical rolls (**Fig. 2(e)**) when projected onto the y-z plane. Though not shown here, we also found thermoacoustic streaming starts to alter Rayleigh streaming at G = 0.5 K/mm, and the full transition from Rayleigh streaming to thermoacoustic streaming is completed at G = 3.6 K/mm.

4. Conclusion

In this work, we discovered the thermoacoustic streaming in liquids driven by temperature-gradient-induced acoustic body force generated by light absorption. This streaming driven by a nondissipative force shows a significantly different origin compared to the conventional acoustic streaming associated with energy dissipation. Its velocity amplitude at a temperature gradient of 9.76 K/mm is nearly two orders of magnitude higher than that of the Rayleigh streaming and the Rayleigh-Bénard convection under the same driving conditions, and it starts to alter Rayleigh streaming at a temperature gradient of only 0.5 K/mm. The thermoacoustic streaming demonstrates clear potentials for spatiotemporal flow control and enhancement of heat transfer at the microscale, and our work provides the groundwork for studying the fundamental questions when sound fields are coupled with temperature fields.

References

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