Transient buildup and decay of thermoacoustic streaming

Augustsson, Per

2024

Transient buildup and decay of thermo-acoustic streaming

Franziska Martens[1,*], Wei Qiu[1], Ola Jakobsson[1] and Per Augustsson[1,*]

[1]Biomedical Engineering, Lund University (LTH), Sweden
[*]E-mail: franziska.martens@bme.lth.se, per.augustsson@bme.lth.se

Acoustofluidics 2024
14-16 August 2024
Uppsala University, SWEDEN

Introduction

We recently introduced the concept of thermoacoustic streaming in microchannels wherein a thermal field is generated inside an acoustic cavity. The result is a fast and controllable streaming for which the thermal energy is provided either by an LED light source [1], or a laser [2]. While in previous works we have measured this effect at steady state, we now present measurements of the build-up and decay. We believe that the presented approach can offer the basis for particle sorting or manipulation applications.

Methods

The setup was described directed into a microchannel, that was actuated with ultrasound, and which was filled with dye and 1-µm-sized fluorescent particles. The laser light was absorbed by the dye which heats the fluid locally. The build-up and decay of the thermo-acoustic streaming was recorded at 100 frames per second while turning the laser on and off. The particles were tracked in the imaging plane using a 2D tracking method of DefocusTracker [3] to map the build-up and decay of the thermoacoustic streaming velocity field. The setup, **Fig.1a**, is centered around the acoustofluidic chip with a long channel (375 µm in width, 150 µm in height), which is actuated with a piezoelectric transducer (piezo) near 2 MHz. A half-wavelength standing wave forms across the width. Laser light (785 nm) is guided into the channel and focused near the floor to a spot size of ~50 µm to realize the thermal gradient, **Fig.1b**. To ensure absorption in the liquid, indocyanine-green dye (ICG) was added to MilliQ-filtered water. The concentration of 0.000395 mg/ml led to an absorption of ~30% of the incoming light. The streaming was registered by tracking green, fluorescent particles (1 µm), which were illuminated with an LED. The timing of the camera, laser, and ultrasound was managed using an Analog Discovery (Diligent) with its software WaveForms.

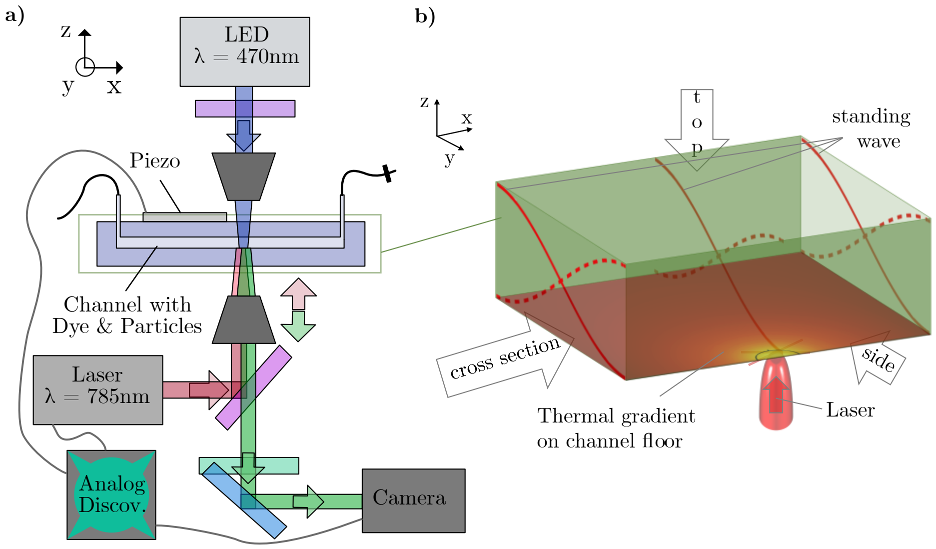

Figure 1: a) Fluorescence microscope imaging of thermoacoustic streaming. Acoustic streaming is induced with the piezo. The thermal gradient is generated by laser light absorption in solute dye molecules in the liquid. Timing of ultrasound onset, camera acquisition, and laser on/off was achieved with an analog discovery 2 (Diligent). b) The laser-induced thermal gradient is indicated on the channel floor. The ultrasound resonates between the channel's silicon and glass walls, generating a standing wave (red curves). Note the view-arrows and coordinate system for orientation.

Results and Discussion

We observed the thermoacoustic build-up and decay upon turning the laser on and off during constant actuation of ultrasound. The laser light, inducing the thermal gradient, was switched on at $\tau = 0$ ms and off at $\tau = 1500$ ms and images were acquired every 10 ms. **Figure 2** shows the resulting streaming patterns at different time points. At time zero, the streaming field is dominated by Rayleigh streaming (manual observation) but the streaming is too slow to be resolved clearly in the registered velocity field, **Fig. 2 (A)**. A thermoacoustic streaming pattern forms within 10 ms, **Fig. 2 (B)**, and the velocity increases rapidly while maintaining the same pattern, **Fig. 2 (C and D)**. After turning the laser off, the velocity decreases rapidly while maintaining essentially the same pattern, **Fig. 2 (E and F)** until reaching the steady-state velocity again, **Fig. 2 (G)**.

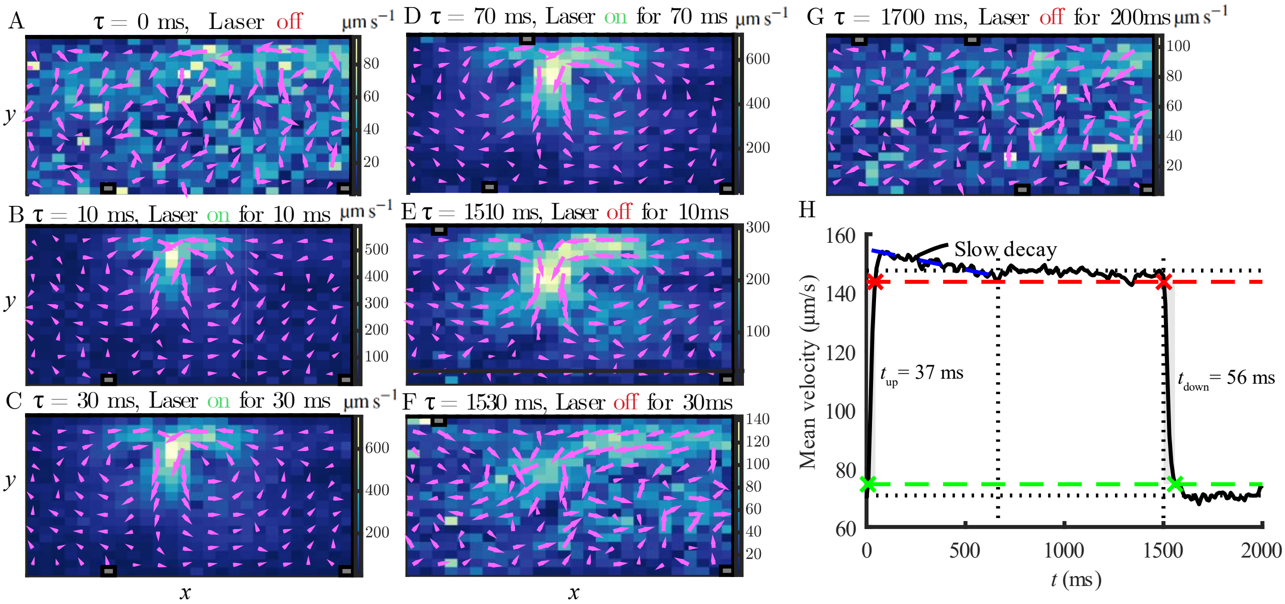

Figure 2: Build-up and decay of laser-induced thermoacoustic streaming showing the (A-D) build-up and (E-G) decay. (H) The velocity magnitude averaged over the field of view with rise time (5% to 95%) and fall time indicated with gray boxes. The blue dashed line emphasizes a slow decay after the laser onset. The red dashed line indicates where 95% of the maximum velocity is reached while the green dashed line indicates the decrease to 5% of the maximum velocity.

To analyze the build-up and decay times, we calculated the averaged velocity magnitude within the field of view and plotted as a function of time, **Fig. 2 (H)**. To estimate the build-up and decay from the averaged velocity magnitude we used the built-in MATLAB functions 'risetime.m' and 'falltime.m', respectively. The build-up time, from 5% to 95% of maximum (green and red dashed line), was 37 ms while the decay time was 56 ms. Notably, the maximum velocity is reached within the first 80 ms and thereafter the velocity decays until reaching a steady state after ~700 ms. The build-up of the streaming for a steady thermal field can be assumed to happen much faster than the build-up of the thermal field. The build-up and decay characteristics are thus primarily related to the establishment of the thermal field. The characteristic thermal diffusion time can be estimated by $t_{diff} = x^2/2\alpha$ with t_{diff}= diffusion time, x^2= diffusion length (here the distance from laser spot to farthest channel wall) and α= thermal diffusivity of water. That leaves: $t_{diff} = (375 \cdot 10^{-6}\mathrm{m})^2/(2 \cdot 0.145 \cdot 10^{-7}\mathrm{m}^2/\mathrm{s}) = 0.48$ s which is close to the above-mentioned point of steady state at 700 ms. Another factor that can influence the build-up and decay is the convective flow which transports heat in the system. At 700 µm/s, this effect cannot be neglected.

Conclusion

The thermoacoustic streaming builds up and decays within ~100 ms, but it takes 700 ms to reach a complete steady state. Comparing the velocity of the two streaming effects, we showed that the velocity amplitude of thermoacoustic streaming is ~10 times higher than that of the Rayleigh streaming. Based on these results we envision a detection-response-based particle guidance mechanism: an approaching particle can quickly be moved away from the channel center to the channel wall, while a particle that is further away from the heat source will remain in its position. In the coming, we will investigate timing the pulsing of the laser light or sound field to actuate the channel for a defined amount of time, to enable this targeted particle motion.

References

1. Qiu, W., et al., *Fast Microscale Acoustic Streaming Driven by a Temperature-Gradient-Induced Nondissipative Acoustic Body Force.* Physical Review Letters, 2021. **127**(6): p. 064501.
2. Martens, F., W. Qiu, and P. Augustsson. *Thermoacoustic streaming induced by asymmetric laser heating*. in *Acoustofluidics 2022*. 2022. Glasgow, United Kingdom.
3. Barnkob, R. and M. Rossi, *DefocusTracker: A Modular Toolbox for Defocusing-based, Single-Camera, 3D Particle Tracking.* Journal of Open Research Software, 2021. **9**(1): p. 22.