Generation of a square flow by acoustic streaming

T. CAMBONIE, D. HENRY, V. BOTTON, B. MOUDJED, H. BEN HADID

Laboratoire de Mécanique des Fluides et d'Acoustique, CNRS/Université de Lyon, Ecole Centrale de Lyon / Université Lyon 1 / INSA de Lyon, ECL, 36 Avenue Guy de Collongue, 69134 Ecully Cedex, France.

Abstract

Experimental and numerical investigations of acoustic streaming in water are described, with the objectives of using it as an efficient tool for mixing. The acoustic beam is produced by an ultrasonic transducer. This beam enters a square cavity at mid-height through a window, reflects successively on the other walls and leaves the cavity through the same window. The acoustic force existing inside these beams generates four jets, which drive a square flow inside the cavity. The properties of this square flow are described and the evolution of its dynamics, when the acoustic intensity is increased, is studied.

Key words: *Acoustic streaming, square flow, mixing*

1. Introduction

"Not only motion can create sound but also sound can create motion" [1]. This sentence by Sir J. Lighthill explains in a few words what acoustic streaming is: the possibility of driving stationary and quasi-stationary flows using acoustic waves. This phenomenon can be present in many applications ranging from biomedical applications (low intensity ultrasounds based diagnostics or high intensity ultrasounds based treatment) [2] to engineering applications (sono-chemistry, velocimetry, and potentially crystal growth). It can be undesired, such as in the case of prenatal echography, or used as a stirring solution in applications sensitive to heat and mass transfer. It is this possibility we want to consider, particularly for the crystallization of molten silicon, where acoustic streaming could provide an interesting non-invasive mixing tool. Indeed, during the solid front propagation, impurities rejected at this front migrate in the liquid phase leading to an impurity gradient if no adequate stirring is done. Because the impurity homogeneity is directly linked to the energetic efficiency of the photovoltaic cells we get from this crystallized silicon, it is essential to find an efficient and non-invasive way of mixing the liquid phase during the crystallization process.

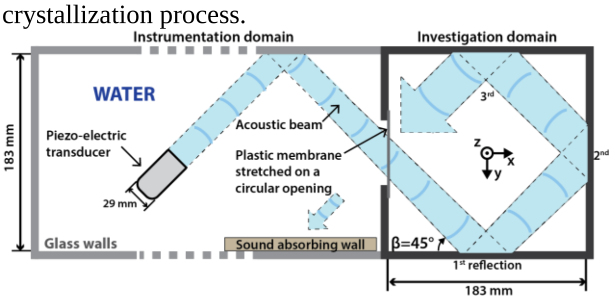

Figure 1: *Experimental setup*.

The acoustic streaming jet properties have been studied recently in our team in different rather academic situations: straight jets generated in the acoustic far field [3] or near field [4], oscillations of the far field jet [5], Y-shaped jets created by an acoustic beam reflecting on a glass wall [6]. In this paper, we present a more complex situation with four jets, which could be useful to generate efficient mixing in practical applications.

2. Experimental setup

In our experimental setup (Fig. 1), in a water tank, the acoustic beam is generated using a plane circular ultra-sonic transducer. This transducer is located in an instru-mentation area outside the measurement area. The acous-tic beam enters the measurement area through an open-ing in the separation wall between both areas, on which an elastic membrane has been stretched. The acoustic beam is able to pass through the membrane, which iso-lates the fluid of both areas. A 45° angle is given to the acoustic beam, which therefore totally reflects on the glass walls. As a result, it follows a square trajectory in the tank by successively reflecting at the middle of each wall before leaving the measurement area through the membrane, as sketched in Fig. 1.

A parametric study has been conducted with 6 different electrical powers P applied to the transducer, leading to different acoustic intensities. The velocity field has been measured by PIV in the horizontal symmetry plane of the experiment, at mid height in the cavity. Some numerical simulations of the experiment have also been performed, using the acoustic forcing presented in our previous papers [3-4, 6].

3. Mean velocity results

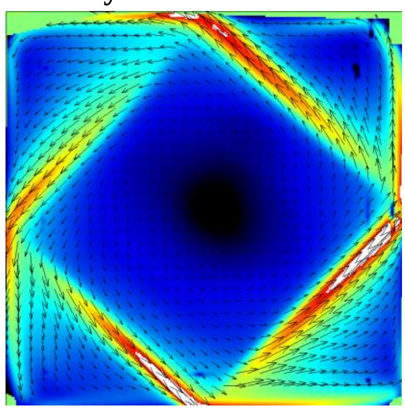

Figure 2: *Time-averaged velocity field obtained by PIV. The colors indicate the isovalues of the velocity intensity*.

Figure 2 shows the time-averaged velocity field, colored in velocity magnitude, obtained by PIV. In such figures, the acoustic beam enters the measurement area from the left. As expected, the acoustic beam follows a square trajectory inside the cavity. It leads to the formation of 2 different kind of structures: along the acoustic beam, 4 acoustic jets are created, accelerated from each wall by the acoustic forcing. For each jet, outside the acoustic forcing, the fluid continues by inertia along the wall on which it impinges, forming 4 inertial jets.

Figure 3 has been obtained by three-dimensional numerical simulations. It shows the three-dimensional topology of this flow using velocity magnitude isosurface. The colored plane is the plane where the PIV experiments took place. As we can see, the acoustic jets keep the cylindrical shape of the acoustic field, while the inertial jets have the typical shape of a skewed jet impacting a wall.

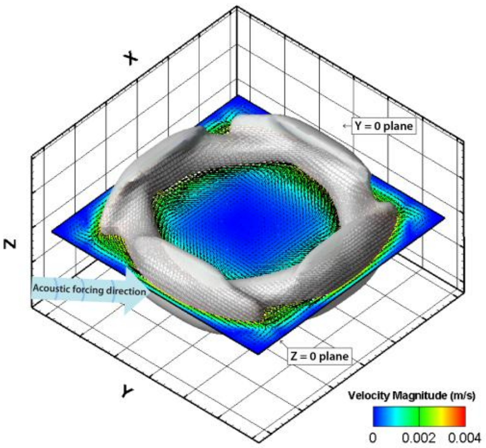

Figure 3: *Isosurface of the velocity magnitude obtained by numerical simulation, indicating the three-dimensional shape of the acoustic jets*.

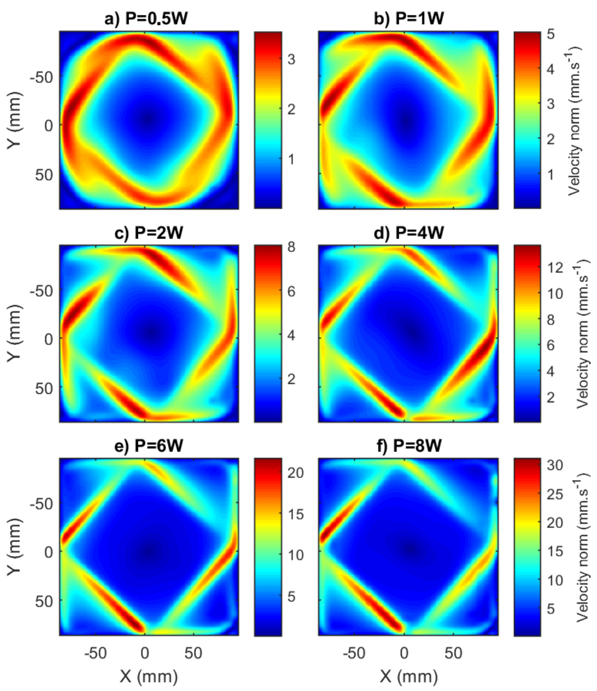

Figure 4: *Isovalues of the time-averaged velocity intensity obtained by PIV for different electrical powers P applied to the transducer*.

Figure 4 shows the evolution of the time-averaged flow topology when the intensity of the acoustic forcing is increased through an increase of the electrical power P applied to the transducer. We first see that the maximal velocities increase, ranging from 3 mm/s for P=0.5 W to 30 mm/s for P=8 W. We also observe that the topology of the flow changes. At low forcing, we have trajectories closer to circles, the inertial jets being quite close to the acoustic jets and far from the walls. In contrast, at high forcing, the velocity field is strongly influenced by the acoustic field. The acoustic jets follow closely the typical square shape of the acoustic beam, and the inertial jets stay very close to the walls.

4. Instantaneous dynamics

The PIV measurements of the flow generated by acoustic streaming indicate the presence of unsteadiness at any value of the electrical power.

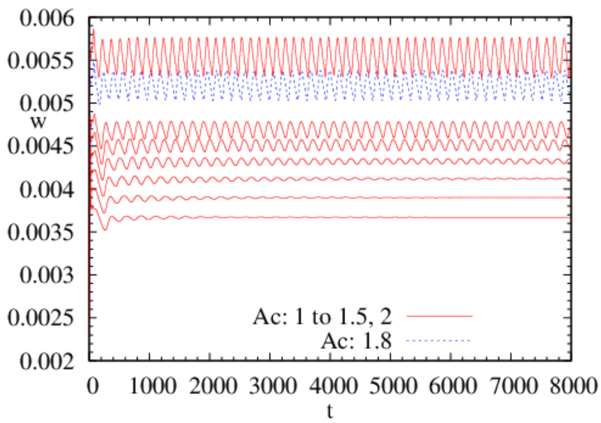

Figure 5: *Time variation of the velocity at a given point in the plane at mid-height in the cavity, obtained by numerical simulation for different acoustic intensity Ac given in watts. In each case, a perturbation is initially applied. The time t is expressed in seconds, while the velocity is given in m/s.*

In contrast, the numerical simulations give steady flows for small values of the acoustic power and a transition to unsteady flows when this acoustic power is increased. Figure 5 shows results obtained by numerical simulations at different acoustic powers Ac between 1 and 2 watts: in each case, the time variation of the velocity at a given point in the cavity is given, following the same initial perturbation. We can see that for Ac below 1.4 watts, the perturbation is attenuated and the signal tends to a steady state. In contrast, for Ac=1.5 watts, a periodic oscillation is maintained, and for larger Ac values, this oscillation becomes more complex and eventually leads to unsteadiness. These simulations then indicate a transition from steadiness to unsteadiness occurring for an acoustic power between 1.4 and 1.5 watts.

A characterization of the flow unsteadiness in the experiments has been performed from the detection of the maximal velocity crest lines. As shown in Fig. 6, the crest lines are detected along the acoustic jets and along the inertial jets. From these instantaneous pictures, spatio-temporal maps of the acoustic jet oscillation around its mean position can be obtained. An example of such spatio-temporal maps for different powers is given in Fig. 6. The shift of the jet ranges from minus to plus 4 mm. We see that the 1 W case exhibits very strong and regular oscillations, whereas the 0.5 and 2 W cases have weak amplitudes. When the power is further increased, the oscillations are less regular and have stronger frequencies.

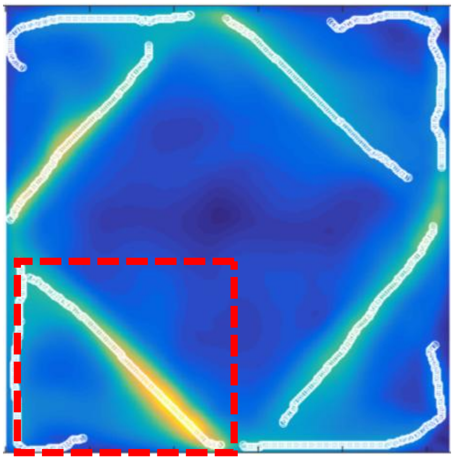

Figure 6: *White dots showing the crest lines for an instantaneous velocity field obtained by PIV.*

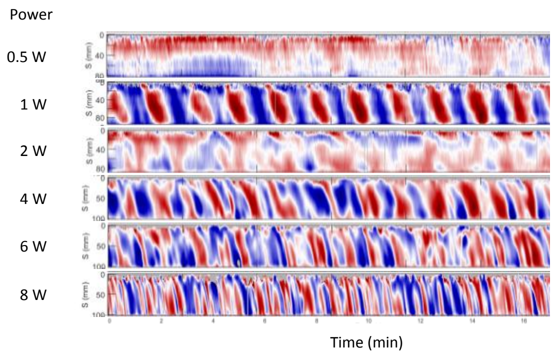

Figure 7: *Spatiotemporal maps showing the time evolution of the instantaneous crest line with respect to its mean position (crest line for the acoustic jet in the red square in Fig. 6). In blue (red), deviation towards the center (the corner).*

The unsteadiness has also been studied in the simulations. Some results are presented in Fig. 8 for a 4 W acoustic power. The black line (isovalue of the mean velocity) indicates the mean position of the jets, whereas the colored isolines give the mean velocity intensity perturbation (note that every five steps in the scale is mentioned with a red line). We see that the strongest perturbations occur on the corner side of the jets, rather close to the impingement points. These perturbations do not affect in the same way the different acoustic jets, being stronger for the jets closer to the entrance of the beam, where they could reach values almost up to 2 mm/s. The perturbations in the central area and in the inertial jets are clearly weaker.

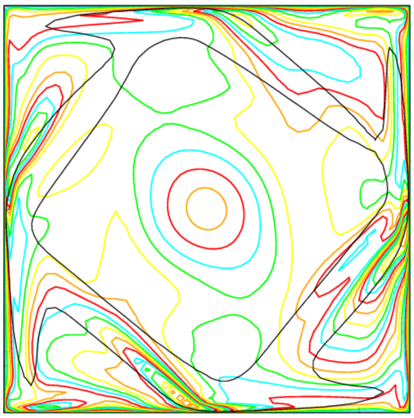

Figure 8: *Unsteady results obtained by numerical simulation for a 4 W acoustic power: isolines of the mean velocity intensity perturbation in the plane at mid-height (colored lines, with a step of 0.1 mm/s), isovalue of the mean velocity intensity at 5.4 mm/s (black line).*

5. Conclusion

In this work, it is shown by experimental and numerical approaches that acoustic streaming is an interesting and promising way to create a mixing in a tank, with a potential application to crystal growth situations. The idea to inject momentum all along the acoustic beam reflecting on the walls proves to be efficient: strong flows were created in the acoustic jets, but also along the walls and in the corners, and a swirling flow was generated in the central part of the cavity. These flows become also strongly unsteady when the acoustic power is increased, which would still improve the mixing. The unsteadiness affects principally the acoustic jets, and rather on their corner side.

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