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Effects of surface profile on a boundary-driven acoustic streaming field

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Introduction

Control of boundary-driven streaming in acoustofluidic systems is vital for various microfluidic applications either to generate it as a positive mechanism (e.g. microfluidic mixing, heat/mass transfer and fluid pumping) or suppressing it as an undesired disturbance (e.g. particle/cell focusing). It has been shown that two-dimensional (2D) and three-dimensional (3D) boundary-driven streaming can be solved from the limiting velocity method as long as the curvature of the surface is small compared to the viscous penetration depth, δ_v.[1, 2] In this work, acoustic streaming fields in 2D rectangular enclosures that have structured textures, which do not satisfy this condition are numerically studied by full modelling of Reynolds stresses and the effects of surface profile amplitude on a boundary-driven acoustic streaming field are investigated. Specifically, a sine-wave shaped profile on a boundary parallel to the particle oscillations is considered, which is found to have large influences on both the magnitude of acoustic streaming velocities and streaming patterns.

Model description

Fig. 1(a) & (b) show respectively the model and a magnified view of A on the top wall of the fluid chamber, where a sine wave shaped boundary is considered. It is determined by two parameters, h_0 and λ_s, which are respectively the amplitude and wavelength of this sine-wave. The standing wave field in this chamber is generated by the vibration of its left wall, which is driven at f = 1 MHz and a half-wavelength resonance in the x direction of fluid chamber is established. Only half of the chamber is modelled for the numerical efficiency so in both steps the bottom wall of the fluid chamber is considered as a symmetric boundary. The results presented here are for λ_s = 3.3 μm.

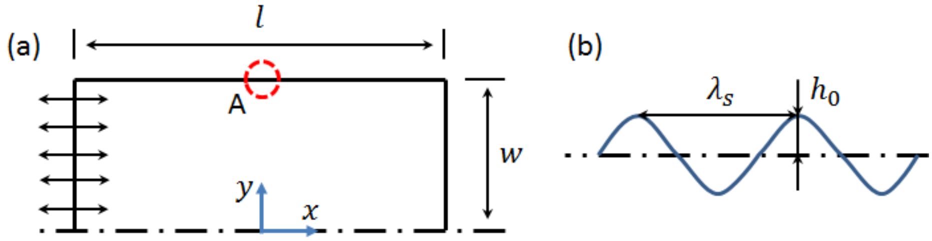

Fig. 1 Illustration of the model: (a) excitation, coordinates and dimensions of the model; (b) showing a magnified view of A in (a), where λ_s and h_0 represent respectively its wavelength and amplitude.

Results

In the first step the linear wave equation is solved in the frequency domain. Then, the Reynolds stress force can be calculated and with it the driving force for the second step, creeping flow, solved by the stationary solution. A series of surface profiles with diverse h_0 ranging from 0.1 nm to 20 μm were studied. The modelled results in two cases respectively with h_0 = 0.1 nm and h_0 = 0.53 μm are shown and compared in Fig. 2, where acoustic pressure field, acoustic streaming field and a magnification of acoustic streaming field near the viscous boundary are presented. It can be seen from Fig. 2 (a) & (c) that half wavelength resonances are formed in the x direction of the fluid chamber for both cases and the pressure magnitudes of them are similar, which means that the amplitude of the surface profile has little effect on the first-order acoustic pressure field. However, a significant difference is found for these cases in both magnitudes of acoustic streaming velocities and streaming patterns. It is found that in cases where h_0 are extremely small, e.g. Fig. 2 (b), the modelled streaming fields are the classical boundary-driven streaming patterns. When h_0 reaches to a certain value (around 10 nm), the number of inner vortices is found to be dependent on λ_s such that there are two inner streaming vortices within each wavelength, Fig. 2 (f). However, there is less impact on the pattern of outer streaming, Fig. 2 (d). With a further increase of h_0, some interesting phenomena are observed (graphs not shown): (1) a global growth trend is obtained for the maximum inner streaming velocity, which grows less quickly after h_0 exceeds δ_v; (2) the maximum outer streaming velocities firstly increase rapidly to its peak when h_0 is approximately half of δ_v and then decreases to the maximum streaming velocity in an enclosure with flat boundaries when h_0 reaches close to δ_v. With a further increase of h_0, the maximum outer streaming velocity further decrease and then reverses in direction.

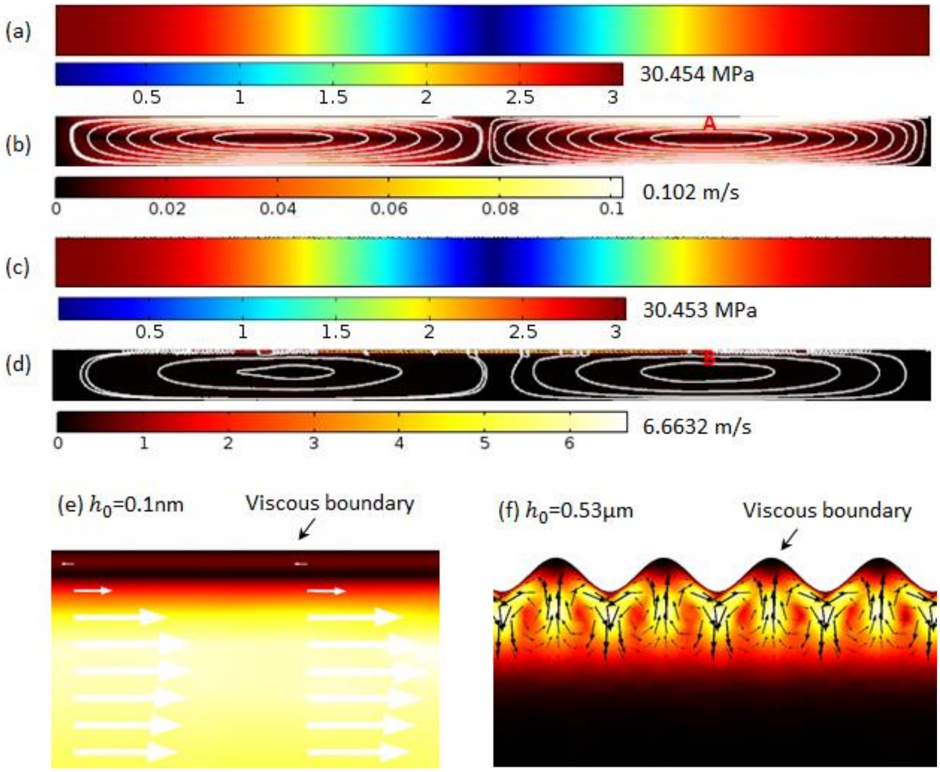

Fig. 2 Modelled acoustic pressure and acoustic streaming fields: (a) acoustic pressure field in an enclosure with h_0 = 0.1 nm; (b) acoustic streaming field in an enclosure with h_0 = 0.1nm; (c) acoustic pressure field in an enclosure with h_0 = 0.53 μm; (d) acoustic streaming field in an enclosure with h_0 = 0.53 μm; (e) magnification of A in (b) with arrow plot of streaming velocity field; (f) magnification of B in (d) with arrow plot of streaming velocity field, where A and B are local areas close to the boundary.

Conclusions

The effects of surface profile on a boundary-driven acoustic streaming field have been numerically investigated for the case of a sine wave shaped profile on the boundary that is parallel to the direction of acoustic oscillations in rectangular enclosures. It was found that this kind of surface has significant influence not only on the magnitude of streaming velocities, but also on the streaming patterns. The dramatic increase of the number of inner vortices and magnitude of streaming velocity could significantly enhance mass transfer in acoustofluidic devices, which is of potential use in applications where acoustic streaming has a positive effect, such as microfluidic mixing, fluid-pumping and battery systems that are diffusion limited.

References

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[2] Lei, J., M. Hill, and P. Glynne-Jones, Numerical simulation of 3D boundary-driven acoustic streaming in microfluidic devices. Lab Chip, 2013. 14(3): p. 532-41.