Acoustic streaming in microchannels: The trinity of analytics, numerics and experiments

This thesis presents studies of boundary-driven acoustic streaming in microfluidic channels, which is a steady flow of the fluid initiated by the interactions of an oscillating acoustic standing wave and the rigid walls of the microchannel. The studies present analysis of the acoustic resonance, the acoustic streaming flow, and the forces on suspended microparticles. The work is motivated by the application of particle focusing by acoustic radiation forces in medical, environmental and food sciences. Here acoustic streaming is most often unwanted, because it limits the focussability of particles smaller than a given critical size. One of the main goals of this thesis work has been to overcome this limitation. The main text of this thesis serves to give an introduction to the theory and numerical models applied in the five journal papers supplied in the Appendixes, which constitute this thesis work.

Based on first- and second-order perturbation theory, assuming small acoustic amplitudes, we derived the time-dependent governing equations under adiabatic conditions. The adiabatic first- and second-order equations are solved analytically for the acoustic field between two orthogonally oscillating plates. Furthermore, under general thermodynamic conditions, we derive the time-dependent first- and second-order equations for the conservation of mass, momentum, and energy. The coupling from fluid equations to particle motion is achieved through the expressions for the streaming-induced drag force and the acoustic radiation force acting on particles suspended in the fluid. Lastly, the numerical method is discussed, with emphasis on how proper numerical convergence is ensured.

Three numerical studies are presented, in which the acoustic resonance and the acoustic streaming flow are investigated, both in the transient regime and in the purely periodic state. The solutions for the periodic acoustic resonance and the steady streaming flow are used to simulate the motion of suspended particle in a Lagrangian description, which mimics experimental particle tracking velocimetry.

In the forth study, the numerical model is used to engineer a single roll streaming flow, which does not counteract the focusing by the acoustic radiation force, contrary to the usual quadrupolar streaming flow. The single roll streaming flow is observed experimentally in a nearly-square channel, and acoustophoretic focusing of E. coli bacteria and 0.6 µm particles is achieved. These particles are considerably smaller than the critical particle size of approximately 2 µm for the usual half-wavelength resonance in a rectangular channel.

The fifth study presents a quantitative comparison of analytical, numerical, and experimental results for the streaming-induced drag force dominated motion of particles suspended in a water-filled microchannel supporting a transverse half-wavelength resonance. The experimental and theoretical results agree within a mean relative difference of approximately 20%, a low deviation given state-of-the-art in the field. Furthermore, the analytical solution for the acoustic streaming in rectangular channels with arbitrary large height-to-width ratios is derived. This accommodates the analytical theory of acoustic streaming to applications within acoustofluidics.

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