The Influence of a Nonuniform Acoustic Field on Small-Scale Processes at a Heterogeneous Boundary

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Abstract—An experiment is conducted on estimating the velocity of a Schlichting boundary flow arising when a focused field falls on a rigid boundary in a liquid. The velocity of a small-scale Schlichting flow is determined by an indirect method from the characteristics of the cocurrent Rayleigh flow using the particle image velocimetry method. The velocity of the Schlichting flow attained in experiments gives us the possibility of significantly accelerating mass-transfer processes at a heterogeneous boundary, which is confirmed by experimental results on acoustic intensification of rapid growth of salt monocrystals conducted under strictly controlled laboratory conditions.

INTRODUCTION

Usually an acoustic field causes phenomena (such as diffraction, scattering on inhomogeneous media, nonlinear interaction, and self-interaction of waves) with spatial scalls on the order of, or many orders higher than, the wavelength. Effects generated by acoustic waves with characteristic scales substantially less than the wavelength are sufficiently rare. More often than not, these are secondary effects of the acoustic field arising at the liquid—solid interface and generating wall liquid flows. Some of these effects have important practical application. For instance, the generation of acoustic flows at a heterogeneous boundary—so-called Schlichting flows, which play a determining role in acoustic-field intensification of heat-mass exchange at this boundary [1]. In such flows, the acoustic field energy with a scale on the order of wavelength λ passes over to a transversal scale of the acoustic boundary layer with a characteristic size of $\delta \sim \sqrt{\nu/\omega}$, where ν is the kinematic viscosity of the liquid and ω is the cyclical radiation frequency. If we are talking about an ultrasonic field in the megahertz range falling on the boundary, then the energy passes from millimeter to micron scales. At an radiation frequency of 1 MHz, the boundary layer thickness in water at room temperature is 0.4×10^{-3} mm.

A critical parameter determining the intensifying action of a Schlichting flow on the heat-mass exchange processes is its velocity. In order to develop intense boundary flows, the falling acoustic field should be substantially nonuniform; i.e., a certain transverse gradient of the vibrational velocity should exist, directed along the heterogeneous boundary. As well, there should exist the possibility of controlling heat-mass exchange processes at this boundary, changing the spatial distribution of the velocity in near-boundary flows. This is achieved via a controlled change in intensity, frequency, and the spatial structure of the acoustic field falling on the boundary.

A theory related to describing near-boundary hydrodynamic flows was elaborated in detail and quite complex [2, 3]. As pertains to flows generated by the acoustic field, their description is insufficient [1, 4]. Usually, the steady velocity of the Schlichting flow is estimated by the expression $u/V = M_a k\delta$, justified under the condition $M_a k\delta \ll 1$, where $M_a = V/c$ is the acoustic Mach number, V is the vibration velocity in an acoustic wave, k is the wave vector modulus, and δ is the boundary layer thickness [4]. However, these estimates are too rough for practical application, since they do not take into account transverse nonuniformity of the acoustic field. Studies exist [5, 6] where the velocity of Schlichting flows at a rigid boundary has been experimentally estimated. The interface was located in the zone of Fresnel diffraction of the field created by a piston in their at frequencies on the order of 1 MHz. It was shown that the velocity of near-boundary flows for acoustic field intensities at the initial aperture of the radiator on the order several W/cm² were fractions of mm/s. Similar values of the tangential velocity close to the boundary are easily attained by hydrodynamic means, and at such Schlichting flow velocities, acoustic means of accelerating mass trans-

fer at a heterogeneous boundary cannot compete with hydrodynamic ones. Obviously, for practical application of acoustic methods in processes of intensifying heat-mass exchange, it is necessary to increase the transverse gradients of the vibrational velocity of the field falling normally on the solid phase interface. The use of an intense focused ultrasonic field yielding the maximum possible transverse gradients of the vibrational velocity seems quite promising.

The aim of this study is to demonstrate the possibilities of a focused acoustic field for creating at a heterogeneous boundary Schlichting flows with velocities that are sufficient for effective intensification of mass-exchange processes at this boundary, in particular, processes of controlled growth of salt monocrystals.

EXPERIMENTAL

The idea of how to estimate the velocity of so small-scale a flow as a Schlichting flow is quite simple. As an acoustic field propagates in a viscous liquid, when there is a solid boundary in this liquid, three types of flows can form: Schlichting, the Rayleigh flow cocurrent with it, and a large-scale Eckhardt flow. Such flows are differentiated by the mechanisms of their appearance and, importantly for the experimental situation considered in this study, the time of stabilization. For a Schlichting flow, the time of stabilization is hundreds of milliseconds, for a Rayleigh flow, it is tens of microseconds, and an Eckhardt flow enters a steady-state regime of tens of seconds. If it is possible to fix the Rayleigh flow which is the cocurrent for Schlichting flow, then it is possible with confidence to state that the velocity of the Schlichting flow is at least no less than the velocity of the Rayleigh flow.

To record the field of flow velocities arising in the liquid under ultrasound, the particle image velocimetry (PIV) method was applied [7]. The experimental setup at which measurements were conducted is depicted schematically in Fig. [1].

To visualize flows into distilled water filling an acoustic bath (*1*), white-colored particles of submicron size were introduced as markers; they were prepared from polyvinyl acetate latex. Using laser system (*2*) consisting of a 200 mW green Nd:Yag laser with a cylindrical lens, the plane containing the acoustic axis of concentrator (*3*) was illuminated. As a solid boundary, glass plate (*4*) was used, which was set up parallel to the focal plane and shifted from it toward the concentrator at relatively small distances (3–5 mm). A flow visualized by laser radiation scattered on the tracer particles was filmed from above by a computer-controlled Videoscan-415-USB camera (*5*). The size of the filming area was 30×20 mm^2.

For the purposes of the experiment, piezoceramic concentrator (*3*) was prepared with a working frequency of 1.5 MHz, a focal distance of 50 mm, and a full aperture angle of 53°. Distribution of the field created by the concentrator along the acoustic axis and in
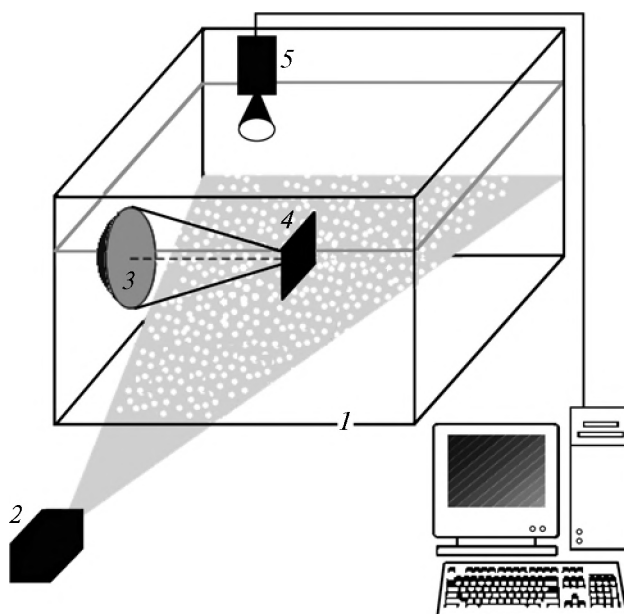

Fig. 1. Scheme of the setup for studying Schlichting flows.

the focal plane are presented in Figs. 2 and 3, respectively. The solid line in the figures depicts the corresponding theoretical dependences of the field created by the concentrator, constructed after the model shown in [8].

In studying the linear field of the concentrator, a miniature MHA9 calibrated hydrophone was used with a #315 preamplifier (Force Technology, Denmark) with the following characteristics: sensitivity 501.2 nV/Pa ± 2 dB in the band from 1 to 40 MHz; active element, a PVD film with a thickness of 9 μm and an effective size of 150 μm.

The process of measuring the flow velocity was as follows: after switch-on of optical illuminating system (*2*) and onset of camera recording (*5*), a continuous acoustic field was excited. The acoustic field amplitude in the focal area was kept at a level of 5×10^5 Pa, and the video-recording rate was 25 fps. The video image was processed on a computer using standard PIV algorithms. As well, we obtained two-dimensional fields of flow velocity, in lattice points, created by various moments in time. The relative measurement error of the velocity at a fixed point was 5%; the spatial resolution (grid spacing) was about 1 mm.

Analysis of the video recording has shown that after switch-on of sound immediately from the location of the irradiated plate where the focal area of the concentrator was positioned, a narrow jet arises moving along the acoustic axis toward the concentrator. The time of appearance and stabilization of the flow velocity in immediate proximity to the surface of the plate did not exceed the interframe interval: 4×10^{-2} s. Obviously, this is an average-scale Rayleigh flow, the presence of which unambiguously testifies to the appearance of
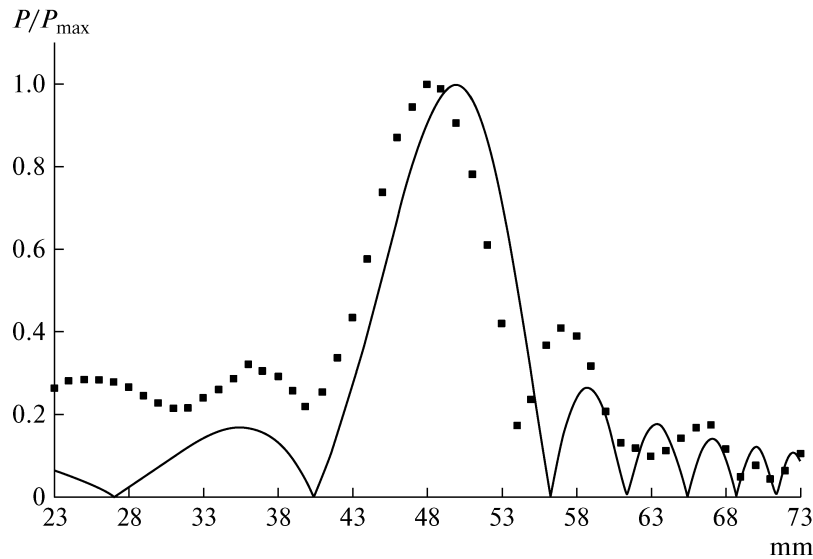
Fig. 2. Distribution of the field of the concentrator along the acoustic axis.
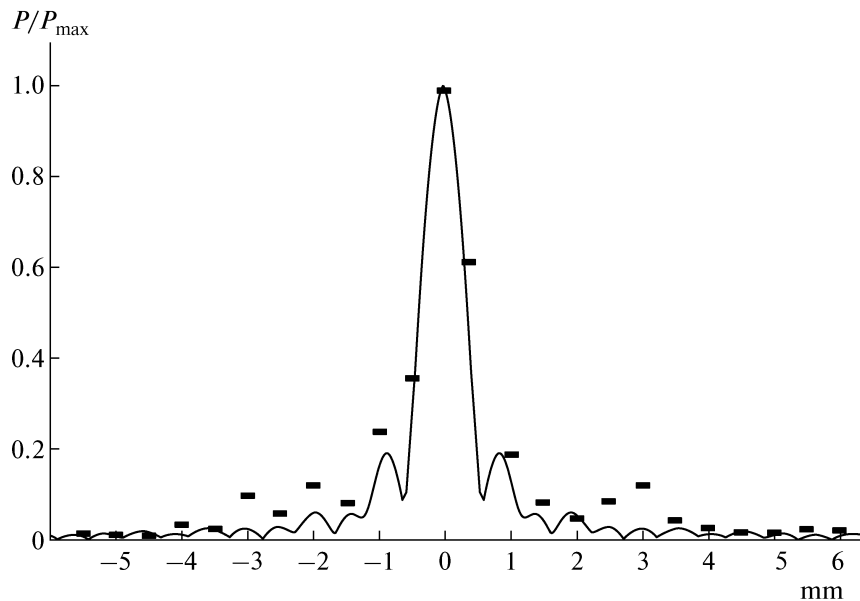

Fig. 3. Distribution of the field of the concentrator in the focal plane.

Schlichting boundary microflows. The velocity field corresponding to a fully established Rayleigh flow is shown in Fig. 4; the time of switching on the electric field is 10 s.

Under the conditions of this experiment, after approximately 10 s, a slower but larger-scale counter-directional flow begins to develop; i.e., the picture of the formation and competition of Rayleigh and Eck-hardt flows is observed.

The video image of the films in the time interval of 0—10 s was studied numerically with algorithms based on frame-by-frame cross-correlation processing of

video signals. The velocity of the Schlichting boundary flow can be estimated by direct measurement of the velocity of the cocurrent Rayleigh flow. This proved to be no less than 4 mm/s. This exceeds the estimate of the Schlichting flow velocity by approximately an order, which can be done based on examining the situation in [1].

Analysis of Figs. 3 and 4 shows that the characteristic transverse scale of the changing of the velocity of intense Schlichting flows in fact corresponds to the diameter of the focal spot (~3 mm) and the velocity of these flows is already sufficient for significant intensi-

fication of mass-exchange processes at a heterogeneous boundary [9]. The results of this experiment have shown that using a focused field under conditions ensuring a sufficient transverse gradient of the field and its sufficient intensity, it is possible to solve problems of local action on the mass-exchange process at the boundary and of spatial control of this mass exchange, for instance, by scanning with the focal area over the target surface.

The necessity of selective and rigidly controlled action by the acoustic field arises in attempting to create methods for acoustically intensifying the rapid growth of salt monocrystals [10].

APPLICATION OF ACOUSTIC INTENSIFICATION OF THE CRYSTAL GROWTH PROCESS TO REAL OBJECTS

Experiments on acoustic intensification of rapid growth of salt monocrystals have been conducted on a laboratory setup, represented schematically in Fig. 5 [10].

The main experimental setup was a hermetic acoustic bath (*1*) from a transparent plastic, which was simultaneously a liquid ultrathermostat with a temperature-regulation accuracy of up to 0.5°C. A focused ultrasonic source (*2*) was built into one of the side walls of the bath—a piezoceramic spherical concentrator analogous to the one described in Fig. 1.

At the center of the bath was a cylindrical quartz cavity (*3*) with the studied crystal and an attached block of technological equipment. The axis of symmetry of the cavity coincided with the acoustic axis of the spherical concentrator and the optical axis of the recording system of the growth rate of the crystal surface (described below). The ends of the cavity were transparent to sound and light and made of a nonbirefringement material. The studied crystal surface (*4*) was the (100) face of the monocrystal potassium dihydrogen phosphate (KDP). In the setup, a technique of exact (to 0.2 mm) positioning of the studied crystal over three coordinates was implemented. In the cavity there was a KDP solution; an NaCl solution of the same density as the KDP solution was the immersion medium filling the bath. Along with acoustic action, hydromechanical action on the crystal was provided for, for which the cavity was equipped with a propeller stirrer (*8*). The temperature of the solution in the cavity was fixed by a thermistor sensor (*9*). The optical transparency of the route necessary for the system recording the rate of crystal growth is ensured by optical inset (*5*) in radiator (*2*). This is necessary for measuring in real time the growth rate (dissolution) of the studied crystal surface by nonlinear-optical means. In the system for accurately (0.1 μm/min) determining the growth rate, the birefringence capability of the KDP crystal was used [11]. The beam of a He—Ne laser (*6*) passed through the system, illuminating the crystal,
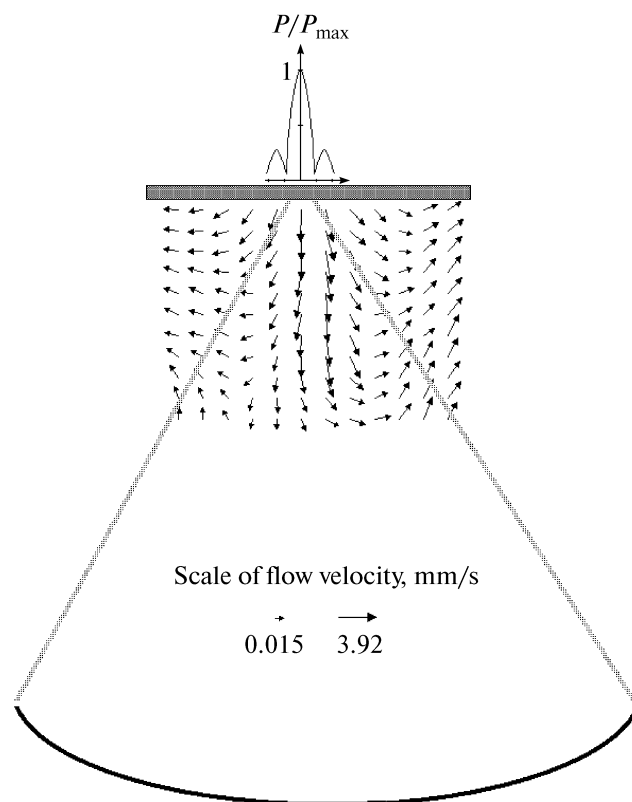

Fig. 4. Established Rayleigh flow after 10 s after the acoustic field was switched on.
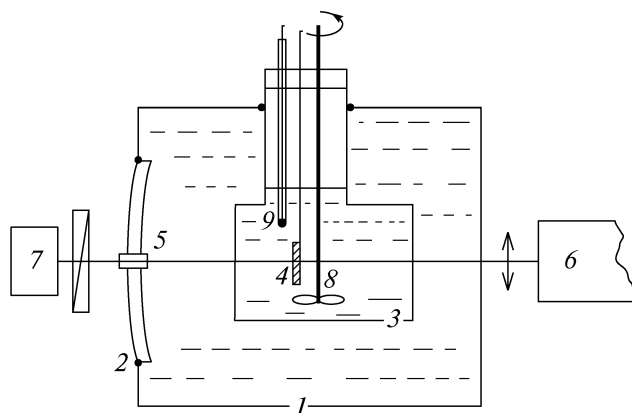

Fig. 5. Experimental setup.

and its output intensity, recorded by photoreceiver (*7*), is a periodic (16 μm) function of the crystal thickness. In experiments in real time, signals of the optical system and thermal sensor were digitized. The recording gives the time and temperature dependences of the growth rate. Analysis of records makes it possible to evaluate the efficiency of hydromechanical and acoustic action on the growing surface of the crystal under other equal conditions.
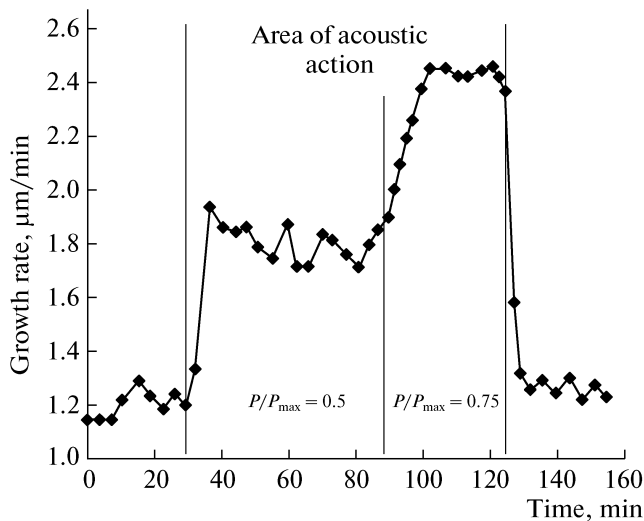
Fig. 6. Record of monocrystal growth.

In experiments, the size of the crystal seed corresponded to the scale of intense Schlichting flows. In principle, the action of Schlichting flows can be extended to larger scales, applying mechanical scanning over the focal area.

The (100) face of the KDP monocrystal with an initial size no larger than 1.5×1.5 mm was regenerated in solution with a saturation temperature of approximately 45°C; it grew under supercooling of approximately 5°C until its size attained $\sim 2 \times 2$ mm. Samples prepared in this way were normally insonified along the acoustic axis in the focal plane of the spherical concentrator.

Figure 6 shows a record of monocrystal growth. Time intervals of field action are highlighted, and the relative amplitude of action is shown (the field of flow velocities corresponding to the given acoustic-hydrodynamic situation is shown in Fig. 4). The maximum amplitude of acoustic action P_{max} was chosen from the conditions of noncritical heating of the growing surface of the crystal [12].

As is seen from Fig. 6, at a sound pressure amplitude of $\sim 0.5 P_{max}$, growth acceleration of the observed face begins and at $P \sim 0.75 P_{max}$, a growth rate is established that is approximately two times faster than the characteristic rate for conditions of free convection; i.e., a nearly kinetic growth regime is established. For the given crystal size in passing to the kinetic regime, an increase in crystal growth by a factor of 2–2.5 is characteristic in comparison to its value under conditions of free convection [13]. We were unable to measure the growth rate at the maximum amplitude of action, since operation of the optical measuring system was violated by intense ultrasound.

Under usual hydrodynamic action on the crystal phase to ensure the kinetic regime in which the rate of crystal growth is extreme, a flow velocity of ~ 10 cm/s

is necessary [9]. Thus, the result of those experiments show that the intensifying action of Schlichting boundary microflows induced by focused ultrasound are equivalent to the action of an external hydrodynamic flow with a velocity on the order of the vibration velcoity in an acoustic field. Under the conditions of our experiment, the vibration velocity at a focus of ~ 30 cm/s corresponded to pressure P_{max}.

CONCLUSIONS

Thus, under the conditions of our experiment, we were able to estimate the velocity of a Schlichting flow arising when a focused field fell on a solid boundary located in a liquid. The achieved velocity of ~ 4 mm/s made it possible to significantly accelerate the mass-exchange processes at a heterogeneous boundary, which is confirmed by the results of experiments on acoustic intensification of rapid growth of salt monocrystals conducted in strictly controlled laboratory conditions.

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