Oscillating solid sphere and fluid flow in an axisymmetric sinusoidal channel: light and heavy body cases

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Abstract. The dynamics of a solid spherical body in a "hold-up" state caused by an oscillating fluid flow in an axisymmetric channel is investigated experimentally. The shape of the channel is sinusoidal, i.e., the radius varies periodically along its axis. The effect is studied for bodies of different size and relative density to the fluid. The effect of fluid viscosity, amplitude and frequency of oscillation of the fluid column is studied. The intensity of the averaged flows is analyzed. Particular attention is paid to the methodology of data processing of averaged flows. The experimental data are generalized to the plane of the control dimensionless parameters.

1 Introduction

For the energy efficient technology development and research, there is a need for new methods to optimise the mass exchange processes between different types of phase inclusions and the environment. Under the influence of complicating factors, in particular external vibrational effects, it is also important to study the dynamics of phase inclusions in different types of systems. Microparticles, bodies of various shapes, gas bubbles and droplets of other liquids [1–3] can be used as phase inclusions. A common model for theoretical and, to a lesser extent, experimental study is an axisymmetric or plane system in the form of a channel with curved (sinusoidal) walls [4, 5] filled with liquid, in which the dynamics of the phase inclusions or the structure of the liquid flows is considered.

Previously [6] was found that when increasing the amplitude of oscillations at a fixed frequency in the threshold manner appear effect of phase inclusion "hold-up" and observed its oscillation relative to the mean position at a given oscillation frequency. The fluid flow intensity and the structure of the averaged flows were determined in the presence of a body and with the body in a vertical channel during oscillations of a liquid column.

This paper follows on from and generalizes an experimental study of solid spherical phase inclusions in liquid which oscillate in an axially varying channel (variable cross-section or sinusoidal channel). The dynamics of both light and heavy plastic spheres at different amplitudes and frequencies of fluid column oscillations is investigated. Attention

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is paid to the threshold of the "hold-up" effect depending on the fluid viscosity, frequency and amplitude of oscillations. The data are analyzed and generalized on the plane of control parameters responsible for the dynamics of the system.

2 Experimental apparatus and methods

Experimental cuvette represents a Plexiglas parallelepiped with a length of 225 mm and a width/height of 40 mm in which made of two symmetrical parts, each containing grooves of variable depth along the long side. The channel is a variable cross-section with a minimum radial size of $R_1 = 6.2$ mm and maximum of $R_2 = 15.0$ mm. Fluid oscillations in the axisymmetric sinusoidal channel are set using an electrodynamic bench with a hydraulic push-pull principal pump. In accordance with the law of proportionality $\sim \sin \Omega t$, a pump operating on the ensures a harmonic change of the volume of the pumped fluid in a closed hydraulic circuit., where $\Omega = 2\pi f_{vib}$ is the radian frequency of fluid oscillation. In the experiments, the amplitude of oscillation of the liquid column b and the frequency f_{vib} of its oscillation are varied. The frequency range is $f_{vib} = 2-10$ Hz. The working fluids used in the experiments are a water-glycerine solutions with dissolved NaI salt and PMS silicone oils. The fluids are chosen to have similar densities but different viscosities. Plastic spheres of different materials with different diameters are used as test bodies. The detailed body parameters and physicochemical properties of the fluids are given in Table 1.

Table 1. Parameters of the solid body and characteristics of the working liquids.

№	Body	ρ_B, g/cm^3	D_B, mm	Working liquid	ν_L, cSt	ρ_L, g/cm^3	$\rho = \frac{\rho_B}{\rho_L}$
1	Polyoxymethylene (POM)	1.380	6.0, 8.0	Water-glycerine solution+NaI	13.7 ± 0.2	1.293	1.067
					23.9 ± 0.3	1.297	1.063
					27.3 ± 0.2	1.295	1.067
					45.0 ± 0.5	1.290	1.070
					100.0 ± 0.5	1.295	1.067
2	ABS-plastic	1.035	5.9	Silicone oil (PMS)	27.0 ± 0.3	0.952	1.087
					100.0 ± 0.5	0.966	1.071
3	Polypropylene (PP)	0.889	4.0, 8.0	Silicone oil (PMS)	27.0 ± 0.3	0.952	0.934
					50.0 ± 0.5	0.960	0.926
		0.920	6.0		27.0 ± 0.3	0.952	0.966
					50.0 ± 0.5	0.960	0.958

Previously published paper [6] provide a detailed description of the experimental setup, the principle of operation, the design of its components and the methodology of the

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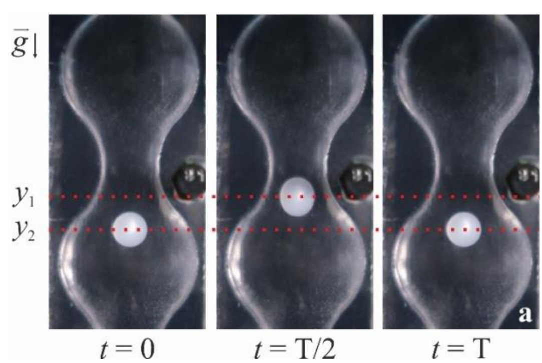
experiment. In all experiments, the video registration of the position of the tracer particles of the visualizer (in order to identify the amplitude b) is carried out by means of a high-speed camera, which is stationary in the laboratory reference frame, with a recording frequency that is a multiple of the fluid oscillation frequency. Video registration of the phase inclusion position in the axisymmetric sinusoidal channel is performed using a digital photo and video camera with a frame rate of 60 to 240 frames per second. The specialised software ImageJ was used for frame-by-frame processing of the experiments.

3 Experimental results and analyse

3.1 Oscillatory body dynamics

At oscillations of a liquid column in a vertical axisymmetric channel of variable cross section it is found [6] that when increasing the amplitude of oscillations at a fixed frequency the threshold effect of phase inclusion "hold-up" and its oscillation relative to the mean position at a given oscillation frequency. In the setting of the present study, experiments have been carried out in a wide range of viscosities of the working fluid at different body sizes. Attention is paid to a more detailed consideration of the new vibration effect for both heavy and light bodies. For all cases considered, a small difference in the density of the body and the surrounding fluid is characteristic. However, it is necessary to take into account the effect of the gravity field, because in the absence of vibrations the rate of immersion of heavy bodies/resurfacing of light bodies is active. Figure 1 shows photographs of the position of the light (a) and heavy (b) bodies after a time equal to half a period. The body in both cases is localized near the narrowing of the channel and oscillates relative to some average position, but due to the density difference it oscillates either in the upper or in the lower part of the cell. The coordinate y_1 corresponds to the extreme upper position of the body's center of mass, and the coordinate y_2 corresponds to the extreme lower position. The direction of the y axis coincides with the direction of the free fall acceleration vector g .



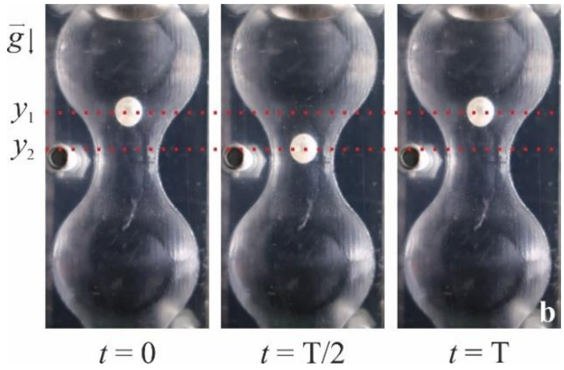
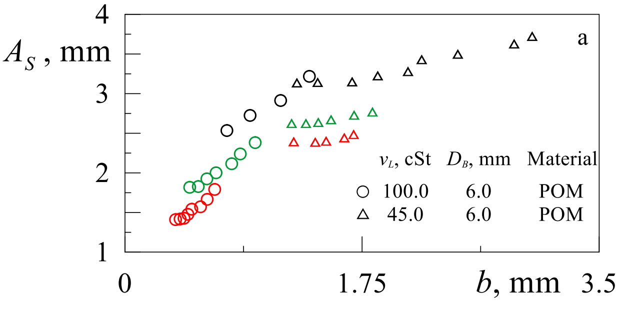


Fig. 1. Photographs of the relative position of the phase inclusion for the period of its oscillation at the parameters: a – $D_B = 8.0$ mm, material PP, $\nu_L = 50.0$ cSt, $A_S = 3.81$ mm, $b = 1.54$ mm; b – $D_B = 5.9$ mm, material ABS, $\nu_L = 27.0$ cSt, $A_S = 4.01$ mm, $b = 1.27$ mm.

For all the bodies considered in the experiments, the effect of suspension on fluid oscillations is found. The effect is caused by reaching a certain threshold of the amplitude of the fluid oscillation b and thus of the amplitude of the body oscillation A_S, defined as $A_S = (y_2 - y_1)/2$. The value of the oscillation amplitude of the body A_S when the quasi-equilibrium position of the body is reached remains constant with gradual increase and decrease, which indicates the absence of hysteresis. Figure 2 shows the dependence of the amplitude of the body oscillation A_S on the amplitude of the fluid oscillation b in the state of “hold-up” of the body oscillating relative to the its mean position (see Figure 1). Results are presented for bodies of different materials and fluid viscosities at varying frequencies and amplitudes of fluid oscillations. Hereinafter in the graphs, color is used to indicate the frequency of oscillation: black color indicates the results at frequency $f_{vib} = 4.0$ Hz, purple at $f_{vib} = 5.0$ Hz, green at $f_{vib} = 6.0$ Hz, red at $f_{vib} = 8.0$ Hz and blue at $f_{vib} = 10.0$ Hz. The graph shows the results for the heavy bodies in water-glycerin solution +NaI (Figure 2a, for POM) and for the heavy (ABS) and light (PP) bodies in PMS silicone oil (Figure 2b).



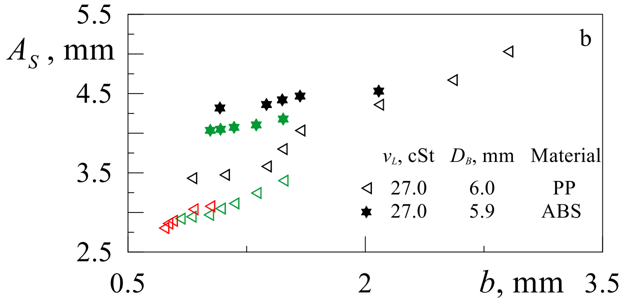
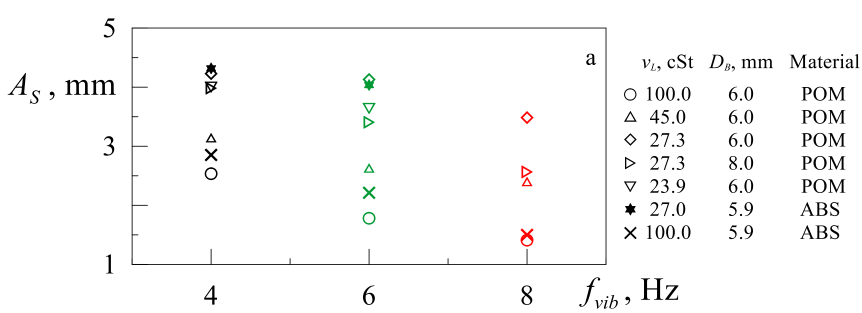


Fig. 2. Dependence of the amplitude of oscillations of the phase inclusion on the amplitude of oscillations of the liquid column.

Both for heavy bodies and for light bodies it is characteristic that with increasing frequency a smaller amplitude A_S is required to reach the quasi-equilibrium position. The character of change of A_S at variation of viscosity is different, that probably is determined by a profile of a liquid flow connected with viscous interaction of a liquid with walls of a channel and a body, however the general is increase of A_S with growth of b .

3.2 “Hold-up” effect threshold

Due to the absence of hysteresis in the amplitude of fluid oscillations and sufficiently small step of b , the threshold value of the amplitude of body oscillations is defined as the value of the A_S when the effect of “hold-up” occurs. The amplitude of body oscillations at the threshold of the “suspended” state effect, against the background of its oscillations, depends on the frequency f_{vib} and size D_B of the body. Figure 3 shows that as the frequency increases, the “hold-up” effect is observed at a smaller amplitude of the body oscillations. A similar dependence can be observed for bodies of different sizes. For different bodies (POM and ABS) in different fluids, but at close viscosities, the dependencies are similar. One of the determining parameters is therefore the viscous interaction between the fluid and the body. It should also be noted that for close viscosities of liquids, but with increasing frequency, the threshold of A_S becomes more stratified. For the same body-liquid pair, but at different viscosities, it can be seen that a smaller amplitude is required to achieve the effect studied in this paper.



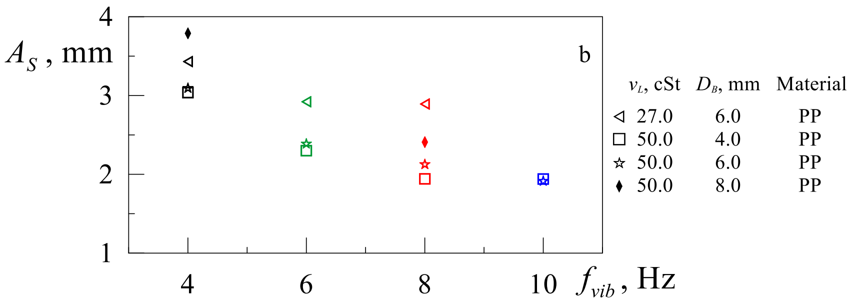


Fig. 3. Dependence of the threshold value of the amplitude of body oscillations on the f_{vib} for heavy bodies (a) relative to the working liquids and for the light bodies (b) at different viscosities.

Analysis of the experimental results has shown that the threshold of the effect of keeping the body in a quasi-equilibrium state is related to the amplitude of its oscillations, the frequency of the oscillations and the viscosity of the fluid. Since the amplitude and frequency determine the acceleration of the body, and the viscosity of the fluid determines the magnitude of the viscous interaction between the body and the viscous boundary layer in the narrow part of the channel, two dimensionless parameters are introduced to generalize the results obtained. The first A_S/R_B is the value of the threshold amplitude of the body oscillations at the moment of manifestation of the "hold-up" effect, measured in units of its characteristic size of the body, $R_B = D_B/2$. The second parameter is a combination of the two and is related to the ratio of the average vibrational acceleration of the body to the acceleration of gravity $A_S\Omega^2/g$, introduced in [6] which is equal to known parameter of dimensionless acceleration of gravity Γ in degree minus one, and the dimensionless frequency ω. The dimensionless frequency $\omega = \Omega R_1^2/\nu_L$ is determined by the ratio of the characteristic size of the channel in the narrow part, where the viscous boundary layer thickness is significant to the Stokes viscous boundary layer near the wall. Good agreement can be seen between the data on the dimensionless parameter plane (Figure 4) and the dependence of the threshold value A_S/R_B from $\Gamma \cdot \omega$.

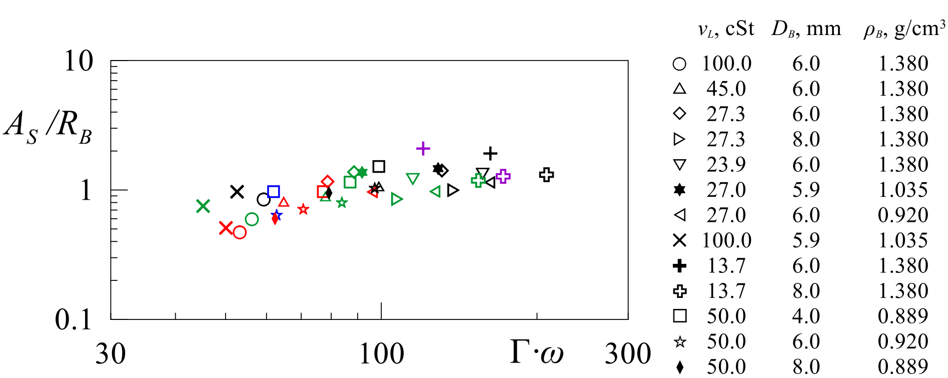


Fig. 4. The dependence of the dimensionless threshold value of A_S on the parameter $\Gamma \cdot \omega$.

3.3 Processing methods and analysis of the velocity of averaged flows

The processing of the results of the video registration of the flows (displacement of the tracer particles) in the channel during oscillations of the liquid column was carried out on the basis of the storyboard of the video files of the high-speed video recording. In order to obtain quantitative results, the PIV method was used, which implies the use of correlation algorithms for processing tracer images, in which the entire flow field is divided into elementary measurement areas, for each of which the correlation function of the displacement of visualizer particles is calculated. Image processing allows us to calculate particle displacements over a time equal to the interval between video frames and to construct a two-component velocity field. The initial results of the study of the structure and intensity of the averaged flow and the influence of the presence of a body in a variable cross section channel are presented in [7]. At the subsequent processing of results at other viscosity and large amplitudes of fluid oscillations it was found that the method of data selection for analysis affects the final result of calculation and determination of velocity magnitude and vorticity field. Thus, for comparison, data processing of averaged flow structures in channel without body at $f_{vib} = 4.0$ Hz, $b = 3.0$ mm and $\nu_L = 45.0$ cSt by two methods of selecting the frames of the experiment. The typical structure of averaged flow in the axial section of the channel for two processing methods is shown in Figure 5 and 6. The first method is to sample frames through the period of fluid oscillation when the displacement of the fluid column is in the same phase (Figure 5). The second method is frame-by-frame processing of consecutive frames of at least 5 periods and then averaging over all frames (Figure 6). According to the first method, the result is incorrect. The flow velocities are low, which does not correspond to large amplitudes of the liquid column (Figure 5a). The structure of the flows is also blurred and is only clearly expressed in the central part of each of the channel cells (Figure 5b). Due to the shape of the channel, the flow velocity differs significantly in the narrow and wide parts of the channel. As the cross-sectional area in the narrow part is smaller, the velocity in this part is higher than in the wide part of the channel for the same flow rate. When selecting frames through a period in the narrow part of the channel, the displacement of particles is intense and over long distances, resulting in a 'blurring' of the averaged flow image (Figure 5c) and making it impossible to measure the magnitude of the flow.

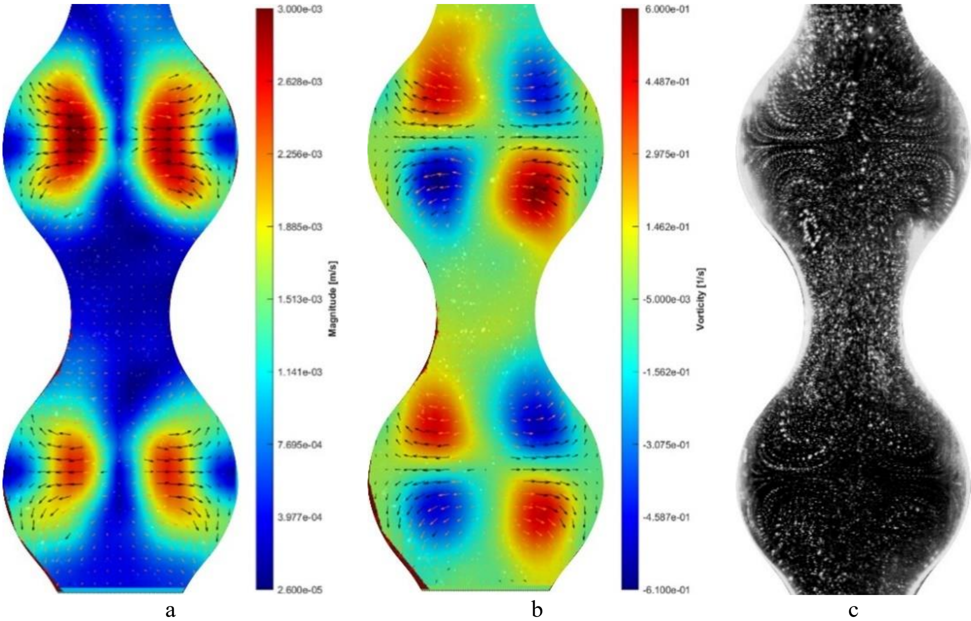


Fig. 5. The magnitude of the velocity of the fluid flow (a) and the vorticity field (b). Fragment (c) shows the tracking visualization of the flow in the axial plane.

In the case of successive frame processing, particle displacement is correctly accounted for in all parts of the channel and then averaged over the time period. This gives correct velocity values (Figure 6a) and a complete picture of the averaged flows (Figure 6b).

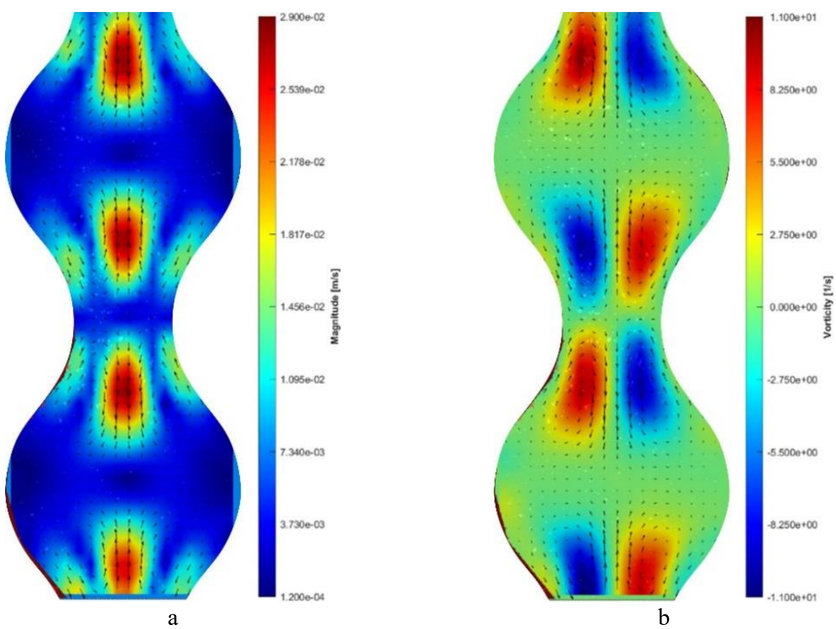


Fig. 6. The magnitude of the velocity of the fluid flow (a) and the vorticity field (b).

The experiments determine the intensity of the averaged flow (velocity v_{ax}) near the axial coordinate of the channel. The velocity maximum is in the region near the centers of the toroidal vortices in each of the channel cells. Only the cell in which the body is located is considered and compared to the case without the body [7]. Analyses of the magnitude of the velocity as a function of a given amplitude of the vibration of the fluid column and of the viscosity are shown in Figure 7a. The shaded points correspond to the velocity value of the averaged flows in the presence of the body in the channel (POM, 6 mm) and the empty points to its absence. Note that the velocity is proportional to the square of the oscillation amplitude of the fluid column ($v_{ax} \sim b^2$) in all cases considered. With increasing viscosity, for the same value of b , the velocity of the flows decreases both with and without a body. This effect may be due to the viscous motion of the fluid in the channel and the significant thickness of the viscous boundary layer as the viscosity of the working fluid increases. The points on the graph stratify in magnitude as a function of oscillation frequency and fluid viscosity. By introducing the dimensionless parameters V and Re, all the experimental points of the velocity of the averaged flows are in satisfactory agreement (Figure 7b). Here $V = \dfrac{v_{ax} R_1}{\nu_L}$ – is the dimensionless velocity of the averaged flows, and $Re = \dfrac{b^2 \Omega}{\nu_L}$ – is the Reynolds number, which characterizes the ratio of inertial forces to viscous friction forces.

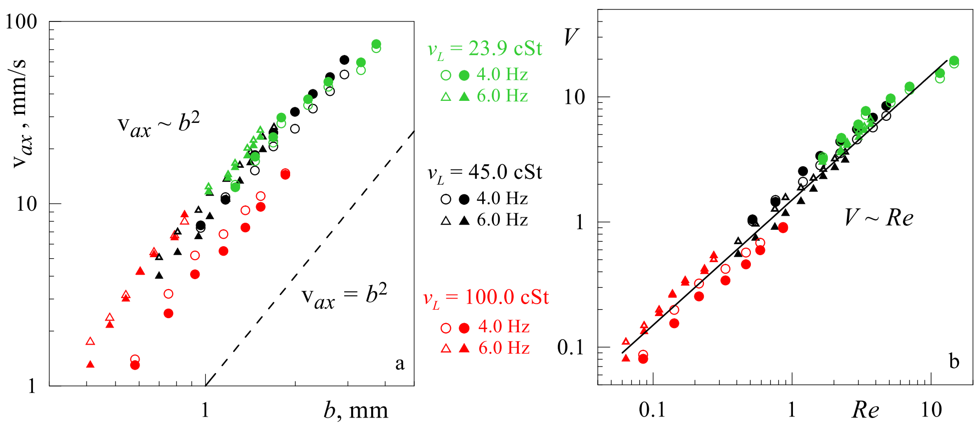


Fig. 7. The velocity of the averaged flows depending on the amplitude of fluid oscillations for the different viscosities of the liquid (a) and on the plane of the dimensionless parameters (b).

Thus, the dimensionless velocity is proportional to the Reynolds number, which is qualitatively consistent with the results obtained in other studies in an axisymmetric channel of variable cross-section [8] and in a flat channel with wavy channel walls [9].

4 Conclusion

The dynamics of a spherical solid body in an oscillating fluid flow in an axisymmetric sinusoidal channel with a variable cross-section have been the subject of experimental investigation. The phenomenon of oscillatory quasi-equilibrium in the phase inclusion (the “hold-up” effect) has been subjected to a comprehensive and systematic investigation. It is shown that such behavior is characteristic of both heavy and light bodies with respect to the oscillating liquid. The threshold manifestation of the effect of “hold-up” of the body is analyzed. It is shown that the control parameter responsible for the threshold value of the body oscillation amplitude is the vibrational acceleration of the body and viscous interaction with the Stokes boundary layer. A generalization of the experimental results of the intensity of the averaged flows is carried out. It is shown that the velocity of the averaged flows is proportional to the square of a given oscillation amplitude, both in the case without a body and with a freely oscillating body in the channel. The dimensionless parameter plane shows a direct dependence of the dimensionless velocity on the Reynolds number. As the Reynolds number increases, the velocity of the averaged flows increases in all cases considered. The described effects are crucial for the development of effective methods for the control of phase inclusions and problems related to the development of methods for the intensification of mass transfer processes.

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