Flows structure and intensity during liquid and body oscillations in variable cross-section channel

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Abstract. The present study investigates the intensity and structure of averaged flows at oscillating fluid flow in a vertical axisymmetric channel of variable cross-section. The results demonstrate that oscillating of the fluid induces the formation of strong flows throughout each of the channel segments. The magnitude of these flows is contingent upon the influence of a free oscillating solid body. The results indicate that the presence of a spherical body in the channel has the effect of either intensifying or weakening the fluid's flow rate in response to both the amplitude of the oscillation and the body's relative position within the channel.

1 Introduction

A variety of techniques are employed to enhance the efficacy of heat and mass transfer in a multitude of technological procedures. One of the more straightforward and efficacious approaches is the incorporation of flow-type reactors in certain designs that exhibit a periodic change in length. The vortex motion that arises near the curved boundaries significantly accelerates the rate of liquid mixing. A substantial number of studies [1-3] are dedicated to the investigation of flow structures generated within channels of varying cross-sectional areas under conditions of unchanging or fluctuating fluid flow within channels exhibiting different curvatures. The influence of channel shape (curvature) and fluid velocity (Reynolds number) is considered. Nevertheless, experimental studies investigating the phenomenon of fluid oscillations at zero flow rate in such geometries of axisymmetric channels, particularly in the context of free phase inclusions, have not received sufficient attention.

It is demonstrated that in the low-frequency limit (for viscous fluid fluctuations), they can be employed to describe averaged flows (and, consequently, mass transfer phenomena) excited by fluid fluctuations in porous media, which are a system of interconnected pores – channels of different cross-section. This approach to modelling is fully applicable to axisymmetric channels with periodically varying radius [3] and plane wavy channel [4]. A channel of variable cross-section is a system of interconnected pores representing the spaces between the substance forming the skeleton of a porous medium. In this context and geometry, Darcy's law is applicable. Previous studies [5] have demonstrated that the

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structures and intensity of averaged flows in an axisymmetric channel of variable cross-section under oscillating fluid flow in the channel excite the averaged flow in the form of a system of toroidal vortices. In [6], a new vibration effect was found when increasing the amplitude of oscillations at a fixed frequency leads to the effect of phase inclusion retention and its oscillations relative to the mean position at a given frequency of oscillations of the liquid column. The effect has a threshold character and was identified by the parameter defining the threshold of occurrence of the effect of holding the body in a quasi-equilibrium state.

The present work is dedicated to the investigation of the structure and intensity characteristics of the averaged flows produced by oscillatory motion of a liquid column within an inclined channel of varying cross-sectional dimensions. The case of a free phase inclusion with a solid boundary (plastic sphere) located in the channel is considered. The cases with and without the body are compared in relation to the frequency and amplitude of vibration of the liquid column. The velocity in the axial section of the channel is considered to be a characteristic of intensity.

2 Experimental setup and methods

The experimental setup consists of a hydraulic circuit, a pump and an experimental cuvette (axisymmetric channel with variable radial dimension). The experimental cuvette *1* in Figure 1 is constructed from Plexiglas in the shape of a parallelepiped, with a length of 225 mm and a width/height of 40 mm. The cuvette is designed from two symmetrical parts, each containing grooves of variable depth along the long side. The radial dimension of the channel varies along the axis, with a maximum value of $R_1 = 15.0$ mm and a minimum value of $R_2 = 6.2$ mm at the two extremes with a spatial period of $\lambda = 42.0$ mm between equal five radial sections. Fluid oscillations in the channel of variable cross-section are set by means of an electrodynamic bench with a hydraulic pump *2* mounted on it by means of stretchable rubber membranes. A pump operating on the push-pull principle ensures a harmonic change in the volume of the pumped liquid within a closed hydraulic circuit, in accordance with the law of proportionality $\sim \sin \Omega t$, where $\Omega = 2\pi f$ is the radian frequency of fluid oscillation. The electrodynamic bench is powered by the APS-1213 power supply *3*, and the amplitude and frequency of vibrations are set by a digital generator (Zet 210) via a personal computer *4*.

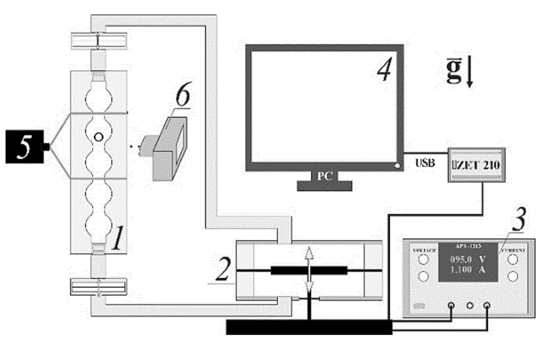

Fig. 1. Scheme of the experimental setup.

In the experiments investigations are conducted at vibration frequencies $f = 4$ and 6 Hz over a broad range of fluid oscillation amplitudes b (volume of the oscillating liquid). The amplitude of fluid oscillation in the channel is controlled by means of an oscillation pump. The parameter b is measured by the range of oscillation of suspended particles in the working fluid. The visualiser particles in the liquid are composed of plastic and have an average size of $d_P = 60$ µm, with an average density of $\rho_P = 1.040$ g/cm³. Since, according to earlier studies, it can be stated that the flow in the channel is viscous, measurements of the displacement of the visualiser particles are carried out in a wide cross-section of the channel cell. In this area, the fluid oscillations are close to piston oscillations, the suspended particles make uniform oscillations relative to their mean position, and hence b is constant. The amplitude of fluid oscillations in the experiments reaches values comparable to the inhomogeneity of the wall relief. To avoid the influence of liquid flows and channel walls, particles near the channel axis are considered. A polyoxymethylene (POM) solid ball of $d_B = 6.0$ mm diameter and $\rho_B = 1.380$ g/cm^3 density is used as a phase inclusion. Two water-glycerol solutions were used as the working fluid in the experiments: the first with a density of $\rho_{L1} = 1.290$ g/cm^3 and a viscosity of $\nu_{L1} = 45.0$ cSt and the second with a density of $\rho_{L2} = 1.297$ g/cm^3 and a viscosity of $\nu_{L2} = 23.9$ cSt. The density of the working fluid is augmented as a consequence of the dissolution of sodium iodide, NaI.

In a previous study [6], a novel and intriguing vibration phenomenon was identified. In the absence of vibration, the body sinks in the fluid and shifts along the channel axis in a downward direction within the gravitational field. Nevertheless, when the amplitude of fluid vibrations is increased at a fixed frequency, at a certain threshold value, the phenomenon of phase inclusion retention by the oscillating flow becomes apparent. In this instance, the body is observed to be suspended in the narrowing of the channel (Fig. 2). The figure presents photographic images of the body in its extreme position following a time period equivalent to the oscillation period of the fluid. The body oscillates relative to a zero-mean position with a frequency equal to the frequency of oscillation of the liquid column. Periodic flow rate of the fluid pumped through the channel results in the generation of average flows in each of the channel cells.

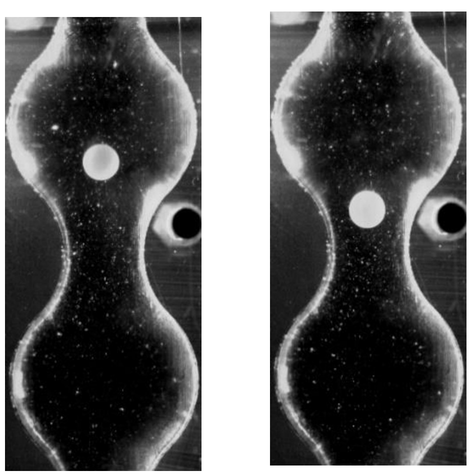

Fig. 2. Photographs of the body position in the channel of variable cross-section in the body holding mode at $b = 2.6$ mm, $f = 4$ Hz and $\nu_{L1} = 45.0$ cSt. The time step between the frames is $t = T/2$.

Consequently, the present study is concerned with the investigation of the impact of the oscillating body in the channel on the structure and intensity of the averaged flows. In the present experimental study, the structure of averaged flows excited by fluid and body oscillations is investigated by particle image velocimetry (PIV) method [7]. For these experiments, a continuous laser beam (see Fig. 1, *5*) with a wavelength of 532 nm and a pulse repetition rate of 1 kHz was used at a fluence of 1000 mJ/cm². The PIV method necessitates the creation of a laser knife within the flow plane, which serves to determine the spatial

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distribution of light-scattering particles. This enables a detailed investigation of the flow structure. Video registration of the position of tracer particles of the visualiser is conducted using a high-speed camera *6* (Optronis CamRecord CL600x2), which is stationary in the laboratory frame of reference, with a capture frequency that is a multiple of the fluid oscillation frequency. Subsequently, the velocity video storyboard is loaded and analyzed in a specialized programme, PIVLab, in which the displacement of the visualizer particles is determined on successive frames. The Fast Fourier Transform method is used to determine the displacement (direction and velocity) of a fluid by tracking the displacement of particles. Following the averaging of a series of frames from a single experiment, information pertaining to the velocity and structure of the averaged fluid flows in a channel of variable cross-section is extracted.

3 Results and discussion

At a fixed frequency of oscillations of the liquid column, in the regime of the 'hold-up' effect of a heavy solid body, the amplitude of its oscillations nonlinearly increases with increasing amplitude of fluid oscillations (Fig. 3). The observed dynamics is completely determined by the fluid amplitude as the flow intensity increases. At large amplitudes of fluid oscillations, the range $2b$ of body oscillations reaches values comparable to the characteristic dimensions of the channel.

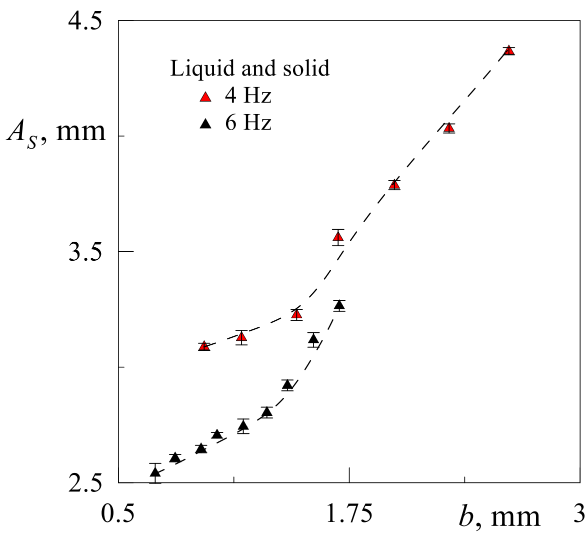

Fig. 3. The dependence of the amplitude of oscillation of the body in the mode of its 'holding up' on the given amplitude of oscillation of the liquid column for $\nu_{L1} = 45.0$ cSt.

It is important to note that as the frequency of oscillations of the liquid column increases, the amplitude of body oscillations with equal value of b decreases. This phenomenon may be attributed to the inertia of the body in conjunction with the instantaneous velocity of the fluid. At a lower frequency of fluid oscillations, the body is entrained by a less intensive flow, though this is proportional to the average fluid flow rate b . The body's position also changes at different frequencies [6]. At higher frequencies, the body moves closer to the narrowing of the channel. Consequently, the aforementioned dependence of $A_S(b)$ is observed. As a result of body oscillations in a quasi-stationary state of equilibrium (body suspension) near the channel constriction, the velocity of averaged flows V is considered. In all experiments

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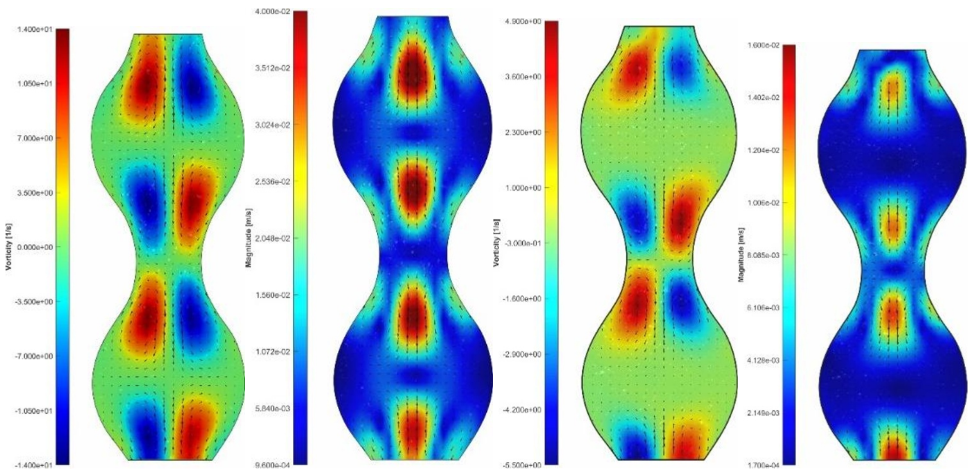
by the PIV method, the structure of the averaged flow is determined, namely, the parameter - vorticity, and the velocity of the averaged flows is determined from the velocity magnitude of the flows. The characteristic picture of the vorticity field and velocity magnitude are shown in Figure 4. The structure of the averaged flows (in the absence of a body) in each of the channel cells is a pair of toroidal axisymmetric vortices of opposite twist, localized near the channel constriction, stretched across the channel axis of variable cross-section. The structure of the averaged flows is similar in each of the channel cells.

It is important to note that in all cases, the maximum value of the velocity near the channel axis is investigated. The longitudinal velocity V near the axis in the cross-section passing through the center of the toroidal vortex can be employed as a metric for the intensity of the averaged flows. The averaged flows (vorticity) exhibit a similar structure at different frequencies. However, due to the difference in flow velocity, the size of vortices at lower frequencies is larger. The velocity maximum (maximum velocity magnitude) is observed in the area of toroidal vortices localization. It is also noteworthy that the velocity magnitude maps of the fluid flow clearly delineate the regions in proximity to the channel walls, where the fluid exhibits viscous boundary layer behavior. The intensity maxima are also localized near the channel constriction, where the instantaneous velocity is larger than in the wide part of the channel.

In the presence of a body in the variable cross-section channel, the picture of averaged flows does not change qualitatively (Fig. 4 and Fig. 5). The structure in the form of two toroidal vortices of opposite twist is preserved, but their intensity changes. The presence of a body leads to a change in the flow intensity along the channel axis only in the cell where it is located and practically does not affect the structure and intensity in other cells. In the vicinity of the body, the intensity of the vortices is diminished, with the vortices themselves being pushed closer to the cavity walls. An intriguing phenomenon is the variation of the flow velocity along the channel axis. At a frequency of $f = 4$ Hz, a notable amplitude of body oscillations is achieved, which affects the increase in the intensity of the averaged fluid flow (see Fig. 5, b compared with Fig. 4, b). The oscillatory motion of the body results in the intensification of the main fluid flow at a considerable distance from the channel constriction. The average position of the body in question, with respect to which the oscillations are made, is situated at a considerable distance from the channel constriction. At $f = 6$ Hz, when there is a displacement of the body closer to the narrowing of the channel and with a relatively small amplitude of oscillation, a phenomenon like 'locking/blocking' for the fluid by means of the body can be observed (see Fig. 5, d compared with Fig. 4, d).



a b c d

Fig. 4. The velocity fields with maps of vorticity (a, c) and velocity magnitude of the steady flow (b, d) at the $\nu_{L1} = 45.0$ cSt for the parameters: a, b – $f = 4$ Hz and $b = 2.62$ mm; c, d – $f = 6$ Hz and $b = 1.18$ mm.

Given the considerable size of the body in relation to the narrow section of the channel and the thickness of the boundary layers, this results in a blockage of the fluid flow. A viscous boundary layer is a region of viscous fluid flow of small transverse thickness formed directly at the curved channel wall and determined like $\delta = \sqrt{2\nu_L/\Omega}$. At $f = 6$ Hz and $\nu_{L1} = 45.0$ cSt the thickness of the Stokes boundary layer is nearly $\delta \approx 1.55$ mm. It can be seen that the size of the body plus two thicknesses of the viscous boundary layer are of the order of 9 mm, while the diametral size of the channel in the narrow part is of the order of 12 mm. These dimensions appear to be essential for the velocity of the averaged fluid flow. This results in a reduction in the fluid intensity along the channel axis in the map of the velocity magnitude of the averaged flow velocity.

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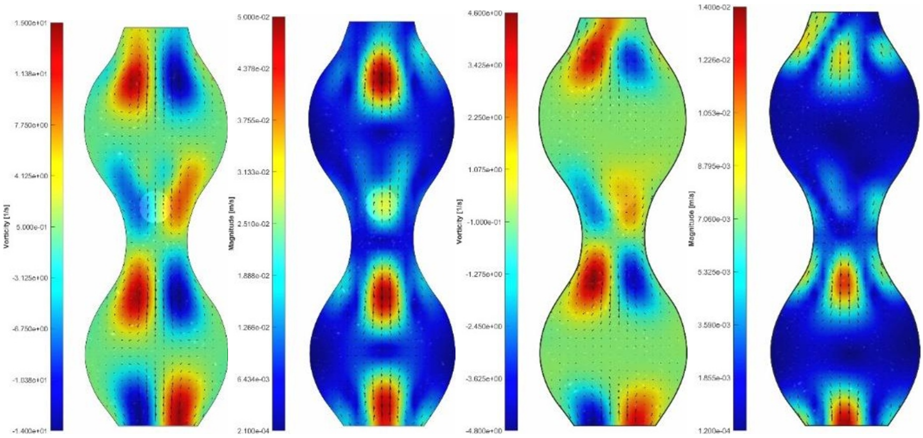
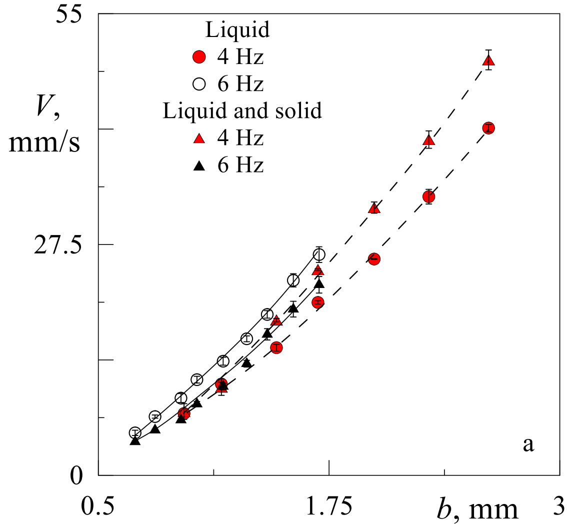


a b c d

Fig. 5. The velocity fields with maps of vorticity (a, c) and velocity magnitude of the steady flow (b, d) with the solid body in the channel at the $\nu_{L1} = 45.0$ cSt for the parameters: a, b – $f = 4$ Hz and $b = 2.62$ mm; c, d – $f = 6$ Hz and $b = 1.18$ mm.

Figure 6 shows an assembly of the values of the velocity magnitude of averaged flows taken near the cavity axis from the amplitude of fluid oscillations at different vibration frequencies. The cases without and with the presence of a body in the channel are compared. At a density of $\rho_{L1} = 1.290$ g/cm^3 and a viscosity $\nu_{L1} = 45.0$ cSt of liquid the character of change (growth) of the velocity value is identical for the two described cases at $\nu_{L2} = 23.9$ cSt. The influence of the presence of a body in the channel on the intensity of the velocity of the averaged flows according to the previously described specificity is clearly traced. Figure 6a illustrates that at a frequency of 4 Hz, there is an increase in the intensity of the flow velocity in the vicinity of the cavity's axis. The body, as it oscillates relative to the mean, pumps the averaged flow without obstructing it in the narrow part of the channel. At a frequency of 6 Hz (Figure 6a), the body is localised in closer proximity to the narrow part of the channel and low amplitude oscillations, which results in the suppression of the intensive average fluid flow in a particular cell of the chanel.



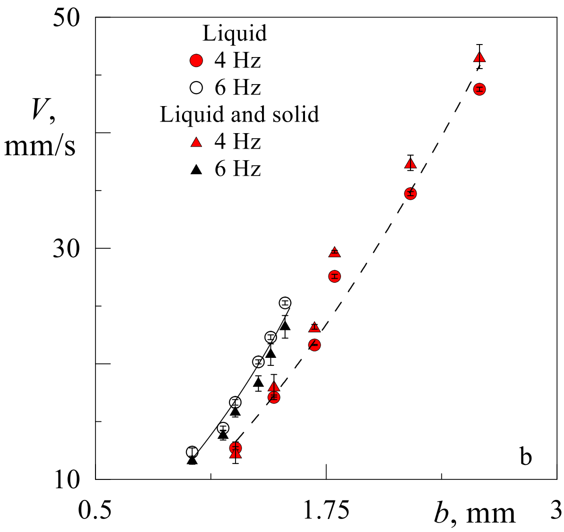


Fig. 6. The velocity of the averaged flows depending on the amplitude of fluid oscillations for the viscosity of the liquid $\nu_{L1} = 45.0$ cSt (a) and $\nu_{L2} = 23.9$ cSt (b).

It should be noted that when the viscosity is halved while the density remains the same ($\rho_{L2} = 1.297$ g/cm^3 and $\nu_{L2} = 23.9$ cSt), the effect observed with the presence of a body in the channel is reduced, but does not disappear completely (see Figure 6b). Probably, to a greater extent, the effect is due to the viscous interaction between the oscillating fluid flow and the body. Substantial analysis requires additional experiments over a wide range of fluid viscosities and relative body sizes.

The newly identified oscillatory phenomenon is of significant scientific interest, and further research is planned to gain a more comprehensive understanding of its properties.

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Nevertheless, the discovered effect is of significant practical importance in the context of developing effective methods of mass transfer control in heterogeneous hydrodynamic systems, as well as developing methods of vibration control of flow intensity in such systems (for example porous media).

4 Conclusion

The effect of oscillations of a free spherical body in an oscillating fluid in a vertical axisymmetric channel of variable cross-section is studied experimentally. In cases where a heavy phase inclusion is situated in a quasi-equilibrium position and oscillates relative to its average position within a fluid, the intensity of the average fluid flows during periodic pumping in a channel with a varying cross-section differs quantitatively from the case without a body. This study has demonstrated the potential of such a medium to both increase the velocity of averaged flows and reduce their overall intensity depending on the vibration parameters. This effect is determined by the frequency of oscillation of the fluid column, the amplitude of the body's oscillation, and its relative position. The newly discovered phenomenon is of great scientific interest and further research is planned.

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