The movement of a particle at nonlinear oscillations of high amplitude in the closed tube

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Abstract. The movement of a flat particle at longitudinal oscillations of gas of high amplitude in the closed tube is experimentally investigated. It is shown that the oscillating particle on an axis moves from the closed end to the piston with increase in oscillation swing, and in near to a wall in the opposite direction. In the radial direction drift of the oscillating particle comes from an axis to a tube wall. Such behavior of a particle is caused by acoustic streaming of gas in a tube. It is revealed that the increase in frequency of excitement of gas or length of a tube lead to growth of oscillation swing of a particle and increase of its average speed.

1. Introduction

Research of wave processes in limited working environments represents one of actual problems. The main models of wave dynamics of multiphase environments and a number of results in this area are presented in [1]. Important applied value has studying of oscillations of environments with strongly nonlinear fronts of waves of pressure and their impact on disperse systems which examples are gas mixes with drops or solid particles. The processes occurring thus are of interest at an intensification of liquid spraying for the purpose of purification of flue gases on harmful productions, sedimentation of particles in various technical devices, an intensification of hashing and burning. Coagulation of drops and particles (drops of machine oil and a tobacco smoke [2], drops of oleic acid [3], particles of the smoke received from combustion of a stick of an incense [4] with diameters of 1-10 microns at nonlinear oscillations in the closed tube with the e first eigenfrequency is investigated. Results of experimental studies of the accelerated coagulation and sedimentation of drops of a aerosol di-ethyl-hexyl-sebacate (DEHS) with a diameter of drops of 0.863 microns in the closed and opened tubes near resonant frequency, twice smaller the first eigenfrequency (a subharmonic resonance) are considered in [5, 6], and the shock-free mode of oscillations of an aerosol at the first eigenfrequency is studied in [7-10]. The theoretical description of the accelerated coagulation and sedimentation of aerosols on walls of a tube presents considerable difficulties. Therefore when modeling such phenomena there is a problem of both theoretical, and experimental studying of the movement of separate particles at nonlinear oscillations of homogeneous gas. In [11] drift of the easy sphere from expanded polystyrene

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with a diameter of 3.5 mm suspended in the axial direction on a thin wire in vertically located tube near the first eigenfrequency is analyzed. In work [12] the movement of a flat particle at nonlinear oscillations of gas in a tube and in an external field about the open end in the shock-free mode near the first eigenfrequency is in detail experimentally investigated.

The purpose of this work is research of drift of a flat particle in the closed tube at longitudinal oscillations of gas of high amplitude with small frequency excitation.

2. Experiment

Briefly we will describe setup and a technique of carrying out experiment. An experimental setup including a resonance tube, a system of excitation of oscillation, and a system for recording the process parameters. The tube was mounted horizontally. The tube consisted of identical sections with a length of 0.5 m and inside diameter $2R_0 = 0.048$ m. One section made of quartz glass was 1.2 m long. It is fixed to the closed end of the tube. The closed end of quartz section of a tube was accepted to the beginning of coordinates $x = 0$. The model of a particle represented a washer from expanded polystyrene with a diameter of 16.5 mm and 0.6 mm thick. The cylindrical polyethylene tubule was inserted into an opening of a washer. The full weight of a particle made 4.8 mg. Such particle was used for research of drift in the longitudinal direction along a tube axis. Other particle with a total weight of 2.5 mg had the following parameters: diameter is 8 mm, thickness is 0.4 mm. It was applied in experiments with the movement along a wall, at distance of 0.01 m from an internal surface, and radial the directions of a tube. Through a polyethylene tubule the scaffold with a diameter of 0.3 mm which stretched special arms in the longitudinal direction was passed. Existence of the tubule which is directing allowed avoiding undesirable cross oscillations of a particle in the course of its movement. For research of drift of a particle in the radial direction (with r = 0 on a tube axis) the special knot was made. It represented the cylinder 0.01 m high. Two medical needles 0.1 m long with distance between them 0.044 m were soldered to it. The cylinder was placed in a tube, adjoining to its wall. Through needles the scaffold with a diameter of 0.25 mm which passed through a polyethylene tubule of the tested particle was stretched with a tension. A standard compressor with the piston stroke $2l_0 = 0.086$ m and inside diameter of the cylinder $2R = 0.077$ m was used for the excitation of aerosol oscillation. The compressor cylinder was connected to the resonance tube via tapering adapter of height $h = 0.22$ m. For measurement of frequency of oscillations of the piston $\nu = \omega/2\pi$ where ω – cyclic frequency, the digital phototachometer AKTAKOM ATT-6000 was used. Frequency was measured with an accuracy of 0.05 Hz. Drift of a particle was fixed by a digital video camera "Panasonic" VSK 0631 (Japan) with a frequency of shooting of 25 frames per second. It was established on a support perpendicular to quartz section of a tube at distance of 0.5 m from it for increase in quality of the image and avoiding of oscillation when shooting and at turn. In case of drift of a particle in the radial direction shooting was conducted with distance of 0.05 m.

Measurements were taken in a tube by length L_0 = 2.7, 3.7, 4.7 m. In experiments with the movement of a particle along an axis it was established in section with $x = 0.3$ m. At research of dynamics of a particle near a wall she accommodated at $x = 0.9$ m. For measurements in the radial direction initial coordinates equaled: $x = 0.45$ m and $r = 4$ mm. Then the tube was densely closed by a cover. Tension on the electric motor via the autotransformer moved. It allowed to change smoothly turns of rotation of a rotor and, respectively, a frequency of oscillations of the piston. The video camera joined synchronously with the engine. Video filming fixed the movement of a particle at distance of 0.6 m along quartz section of a tube. In case of the movement of a particle in the radial direction video filming was conducted until a particle stop at some distance from a tube wall. Then the camera and the electric motor were cut out. Such experiment repeated several times for all values of frequencies and lengths of a tube. After each experiment the particle was returned in a starting position. For processing of results of video filming the video camera was connected to the computer. The received video images opened by means of Virtual Dub 1.5.3 where all video broke into shots, and time from the beginning of shooting corresponded to each shot. Transition from a shot to a shot allowed to record the provision of a particle in different time points.

3. Results

We will consider some experimental results received in the analysis of data of video filming. In Figure 1, *a* dependence of coordinate of a particle on time along a tube axis is presented. Points are represented by experimental data, the continuous line – approximation, the shaped line – average value of coordinate concerning which there are oscillations. Follows from Figure that the movement of a particle has oscillatory character. Thus time of the movement of a particle to the piston is more, than movement time by the closed end during one oscillation. It causes drift of a particle from the closed end of a tube towards the piston. In the experiments made for a case of a drift of a particle in a lengthwise direction near a wall back motion by the closed end of a tube is observed (Figure 1, *b*). And researches begin with the frequency of 8 Hz as with smaller frequencies driving of a particle is absent owing to a great influence of a sliding friction about a scaffold. Let's note similar nature of behavior of a particle for frequency period of the piston with a drift on a tube axis. Such behavior of a particle for all studied lengths of a tube and frequency excitation is caused by existence of an acoustic streaming [13, 14]. The toroidal-shaped vortex with the direction of flow of gas on an axis to the piston, and near a wall to the closed end is formed. The oscillation frequency of a particle equals to a frequency excitation of oscillations of gas. Similar dependences are observed at other oscillation frequencies of gas for all considered tube lengths.

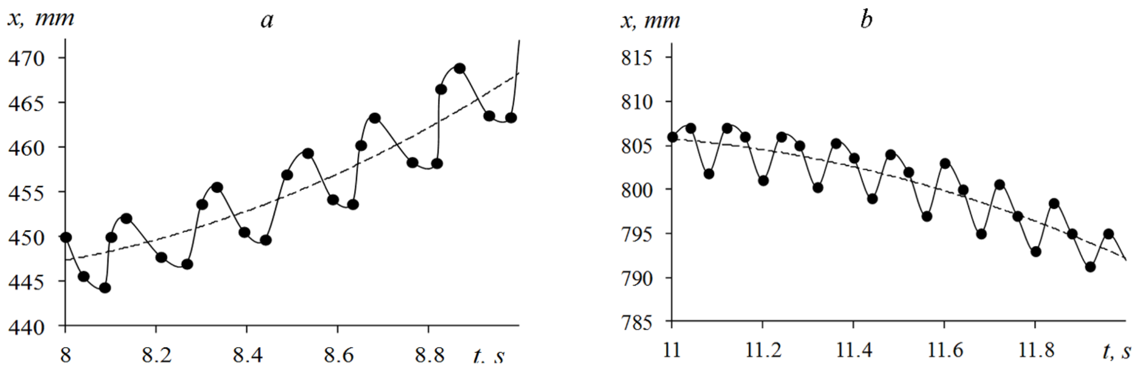

Figure 1. Dependence of coordinate of a particle along a tube length L_0 = 4.7 m from time: a) along an axis with a frequency of ν = 6 Hz, b) near a wall with a frequency of ν = 8 Hz. Points – the experimental dates, continuous and shaped lines – approximations.

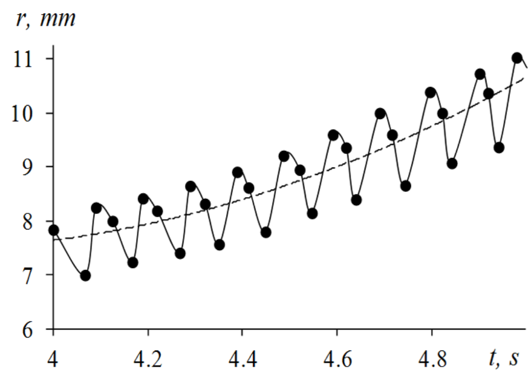

Figure 2. Dependence of coordinate of a particle in the radial direction from time for a tube length L_0 = 3.7 m with frequency ν = 10 Hz. Points – the experimental dates, continuous and shaped lines – approximations.

In Figure 2 dependence of coordinate of a particle is given in the radial direction from time. Thus the oscillating particle moves in the range from a point with coordinate r = 4 mm to some boundary point concerning which it oscillates with a constant amplitude without driving to a tube wall. In experiments this minimum interval equaled 7 mm, and maximal – 13 mm. The interval of driving of a particle from initial increased to a boundary point with growth of frequency.

From dependences of coordinate of a particle on time it is possible to obtain data on particle oscillation swing Δx (where $\Delta x = x_{max} - x_{min}$, x_{max} and x_{min} is the maximal and minimum values of coordinate for period oscillation of a particle concerning the centerline in Figure 1 and Figure 2). With driving of a particle along an axis from the closed end of a tube a range of its oscillations increases, reaching in the set mode of the value which is not exceeding the doubled piston oscillation amplitude. When driving a particle near a wall towards the closed end of a tube from which it is visible that the oscillation swing decreases. The increase in frequency accompanied with increase of intensity of oscillations of gas leads to height of a oscillation swing of a particle when driving in both directions. Thus the oscillation swing in near a wall is much less, than on a tube axis. It is caused by losses on a wall on viscosity, heat conductivity and change of conditions of a flow of a particle near an internal tube wall. Let's note that when driving a particle in the radial direction from an axis to a tube wall there is an increase in a oscillation swing from 0.01 mm to the maximal value in a boundary point which at ν = 10 Hz equal 2 mm.

Also data on the average speed of a particle were obtained. For the quantitative analysis of average speed of the movement along an axis and near a wall data for the set distance (from coordinate from 0.75 m to 0.9 m) where the maximum a oscillation swing in both directions was observed got out. In Figure 3, a dependences of average speed of $V_a = 0.15/t$ (m/s) of a particle of an axis and near a wall from the frequency of oscillations of gas are presented. With increase of frequency excitation of gas the average speed of drift of a particle grows. It is visible that the specified dependence in case of the movement near a wall has nonlinear the character caused by losses on walls. Thus average speed near a tube wall, for example, at a frequency of ν= 10 Hz is 3 times lower, than on an axis. It is possible to note that the increase in length of a tube with the set frequency leads to growth of average speed of a particle. In Figure 3, *b* dependence of average speed of a particle on frequency for a case of the movement of a particle would be given in the radial direction. It is visible that with increase in frequency of excitation of gas the average speed of the movement of a particle at distance of equal 7 mm increases, as well as at the movement of a particle in the longitudinal direction of a tube.

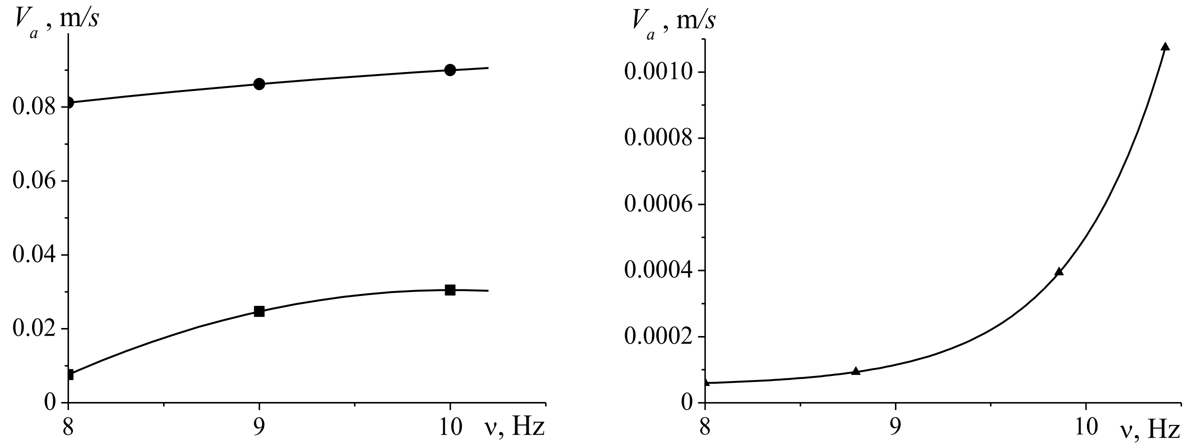

Figure 3. Dependence of average speed of a particle on the frequency of oscillations of gas for a tube length L_0 = 3.7m: a) ● – along a tube axis, ■ – near a wall, continuous lines – polynomial approximations; b) in the radial direction, the continuous line – exponential approximation.

4. Conclusions

As a result of experimental studies of dynamics of a particle at longitudinal oscillations of gas in a tube it is revealed that the particle moves, making longitudinal oscillations. On an axis – from the closed end to the piston, and near a wall – in the opposite direction. This movement is caused by the acoustic streaming of gas in a tube which are followed by formation of a toroidal vortex. In the radial direction the oscillating particle moves from an axis to a tube wall to a boundary point. It is revealed that with the fixed frequency with the movement of a particle on an axis from the closed end of a tube its oscillations swing increases, reaching the value which isn't exceeding the doubled amplitude of oscillations of the piston. In case of drift of a particle near a wall towards the closed end of a tube the specified swing on the contrary decreases. At the movement of a particle in the radial direction of a tube there is an increase in oscillations swing to the maximum value in a boundary point. It is established that the increase in frequency of excitement of gas leads to growth of oscillations swing of a particle for all directions and to growth of its average speed of the movement.

Acknowledgments

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