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PROPERTIES OF SOLID PARTICLE DISTRIBUTION IN TWO-PHASE LAMINAR BOUNDARY LAYERS OF VARIOUS SHAPES AND PARTICLE SEDIMENTATION

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Abstract. The behaviour of solid particles in two-phase laminar boundary layer for various streamlining shapes (flat plate, curved surface and cone) was experimentally investigated. The velocity distributions of gas and particles as well as particle mass concentration were measured in the vicinity of surfaces. Particle sedimentation on surfaces was measured simultaneously. Parameters of the experiments were the following: free stream velocity – 1.5 and 3 m/s; particle size – 12, 23 and 32 mkm; particle mass concentration – 0.01 kg/m^3.

Key words: dispersed phase, streamlining of various shapes, distributions of particle velocity and mass concentration, dust sedimentation on surfaces.

1. INTRODUCTION

A large number of technological and natural processes is bound with the motion of solid particles in gaseous flows, e.g., combustion of solid fuels, processes in scrubbers, pneumotransport, diffusion of solid suspension in the atmosphere. These processes are accompanied by the deposition of solid particles on the working surfaces of various devices.

The process of sedimentation on a body surface streamlined by two-phase flow, is substantially stipulated by the particle motion and their distribution near the wall. The object of our experimental investigation was to obtain data for building and improving a numerical model of particle sedimentation. This model may be applied for sedimentation prediction on real objects for the conditions differing from those in the laboratory.

2. AERODYNAMICAL BENCH

The experiments were carried out in a disconnected vertical two-phase wind-channel with an open working space (Fig.1).

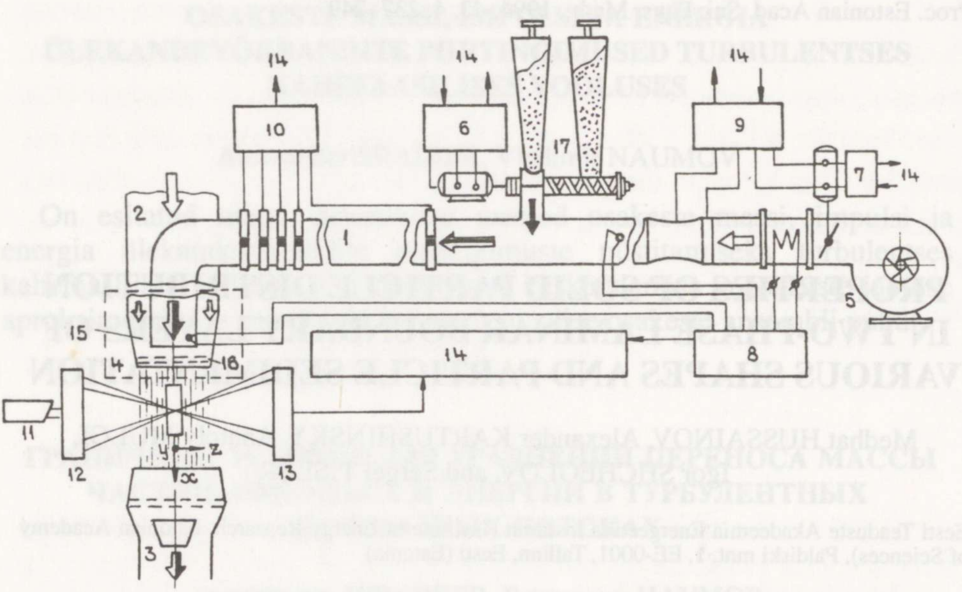


Fig. 1. Aerodynamical bench: *1* – main channel; *2* – channel of accompanying pure air flux; *3* – a dust suck-out channel; *4* – a device for the formation of the given flow field; *5* – blower; *6* – dispersed phase dosimeter; *7* – pure air dosimeter; *8* – thermocontroller; *9* – flowmeter; *10* – pressure converter; *11* – He-Ne laser; *12* – sending optics; *13* – receiving optics; *14* – registering, processing and controlling system; *15* – confuser; *16* – system of grates; *17* – particle screw feeder.

The aerodynamical bench consisted of the following parts: main channel (Pos. *1*) for two-phase flow formation and transportation; a channel of accompanying pure air flux (Pos. *2*); a device (Pos. *4*) for the formation of a flow field with the given parameters in the working space of the wind-channel; a dust suck-out channel (Pos. *3*). Besides, the aerodynamical bench contained various power (Pos. *5*, *17*), processing (Pos. *6*, *7*, *8*), controlling (Pos. *9*, *10*) and measuring (Pos. *11*, *12*, *13*, *14*) equipment, which provided the formation and transport of two-phase flow with the given parameters.

The wind-channel started functioning by injecting solid suspension into the open working space with its following ejection through the diffuser. Two-phase flow was formed by the forming device (Pos. *4*) consisting of a cylindrical tube with a diameter of 100 mm and a length of 3 m, which was installed along the axis of the forming device for the input of two-phase admixture. After the exit from the cylindrical tube and passing through the system of grates (Pos. *16*), the formed two-phase suspension expanded and entered the open working space supported by the flux of pure air on either side. Three grates with the mesh sizes of 0.63, 0.315 and 0.315 mm and with the distance of 12 mm between them, are used for smoothing the parameters of the inflow, i.e., a uniform free stream was formed. Uniformity of the two-phase flow with the given parameters was obtained by varying pure air flow in one of the channels, two-phase flow in another and in the diffuser.

3. EXPERIMENTAL CONDITIONS

A flat plate, curved and conical surfaces were used as models for investigation (see Figs. 2, 3). The models had the following dimensions:

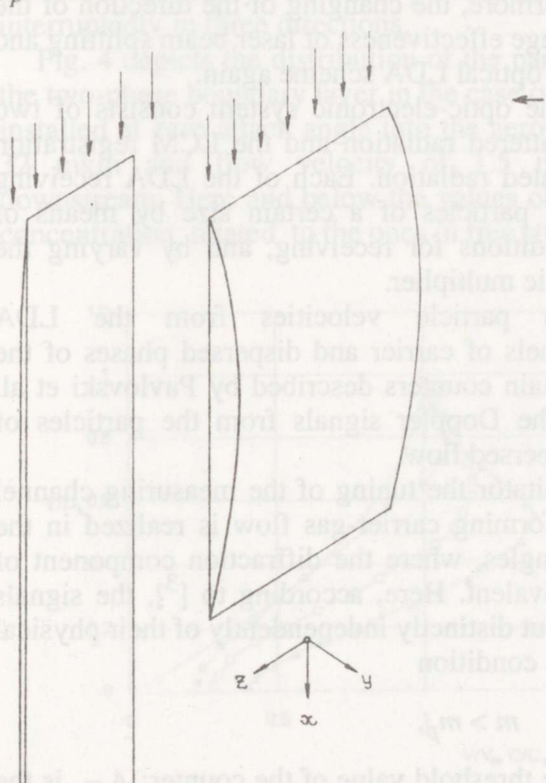
- stainless steel flat plate – length 500 mm, width 100 mm, thickness 2 mm;
- aluminium alloy model with a curved surface – length 320 mm, the curvature radius 300 mm, thickness in middle cross section 50 mm, width 170 mm;
- four aluminium alloy cones with the values of vertex angle of 30, 45, 60 and 90 degrees and with the base diameter of 100 mm.

The surface quality was characterized by the height of unevennesses of the surface profile in ten points, which equaled 6.3 mkm for all the models. This value corresponds to the N14 of surface quality according to the international classification.

Each model was installed vertically in the working space of the wind-channel with the help of a special holder. The design of the holders enabled to vary the value of the attack angle.

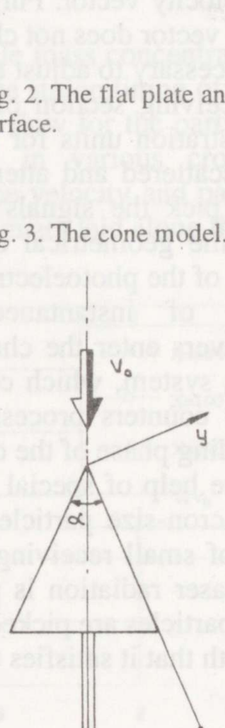
Electrocorundum powders with the density of 3950 kg/m^3 were used with the average particle sizes 12, 23 and 32 mkm. The deviation from the average size did not exceed 30%.

The main parameters of laboratory tests (flow velocity V_0, particle size δ_p, particle mass concentration C_0) were stipulated by the steady



← Fig. 2. The flat plate and the curved surface.

Fig. 3. The cone model.



formation of a two-phase laminar boundary layer on streamlining models and by uniform inflow of the dispersed phase into the working space of the wind-channel. The values of flow velocity V_0 were 1.5 and 3 m/s. The value of particle mass concentration C_0 was 0.01 kg/m^3 for the flat plate and curved surface streamlining and 0.0044 kg/m^3 for the conical surface streamlining.

4. MEASURING OF VELOCITY AND PARTICLE MASS CONCENTRATION

The distributions of local averaged parameters (velocity and particle mass concentration) of two-phase flow in the vicinity of various shapes were measured with the help of an optic-electronic system which included a specially devised laser Doppler anemometer (LDA) and a laser concentration measurer (LCM) for determining relative particle concentration with the aid of methods described in [1].

The LDA consists of two channels (each channel for the concrete phase of dispersed flow), the sending sections of the LDA-channels are combined. One of the LDA beams is used in the optic scheme of the LCM. The peculiarity of the LDA is the operative changing of the direction of the sensitivity vector, i.e., the direction of a measured projection of the particle velocity vector. Furthermore, the changing of the direction of the sensitivity vector does not change effectiveness of laser beam splitting and it is not necessary to adjust the optical LDA scheme again.

The receiving section of the optic-electronic system consists of two LDA registration units for scattered radiation and the LCM registration units for scattered and attenuated radiation. Each of the LDA receiving units can pick the signals of particles of a certain size by means of changing the geometrical conditions for receiving, and by varying the sensitivity of the photoelectronic multiplier.

Signals of instantaneous particle velocities from the LDA photoreceivers enter the channels of carrier and dispersed phases of the processing system, which contain counters described by Pavlovski et al. [2]. These counters process the Doppler signals from the particles of corresponding phase of the dispersed flow.

With the help of special imitator the tuning of the measuring channel for the micron-size particles forming carrier-gas flow is realized in the direction of small receiving angles, where the diffraction component of scattered laser radiation is prevalent. Here, according to [3], the signals from fine particles are picked out distinctly independently of their physical nature. With that it satisfies the condition

$$m > m_p,$$

where $m = A\sim / A=$; m_p is the threshold value of the counter; $A\sim$ is the Doppler component of the signal; $A=$ is the constant component of the signal.

In this channel the selection of signals proceeding from the particles of dispersed phase is carried out both by amplitude when signals are neglected as signals of overloading [4], and by modulating the depth ($m < m_p$) automatically with the help of the counter.

The conditions for registering signals only from the dispersed phase particles are created in the measuring channel of the dispersed phase by varying the receiving geometry and by reducing photoreceiver sensitivity. For processing the signals, the Doppler component is picked out, and amplified to the level of

$$A_{\sim S} > U_p,$$

where $A_{\sim S}$ is the Doppler component of a signal from the dispersed phase particles; U_p is the working threshold of the counter and comes to the input of the counter.

The LCM receiving system for the direct attenuated beam is oriented to the probing beam, while the LCM registration system of scattered radiation in the measuring volume is oriented, under some small angle, to the probing beam. The system "lens-apertures" which forms the field of vision of the device in the channel of scattered light, permits to choose the measuring fields proceeding from the requirements of the experiment.

The optic-electronic system was installed on a special coordinate device controlled by PC, which permitted to scan the flow continuously or interruptedly in three directions.

Fig. 4 depicts the distribution of the particle mass concentration inside the two-phase boundary layer in the case of the streamlining of a flat plate installed at zero attack angle into the aerosol flow for the particle size of 32 mkm and flow velocity of 1.5 m/s in various cross-sections downstream. Here and below the values of the velocity and particle mass concentration related to the ones in free stream are laid along the abscissa

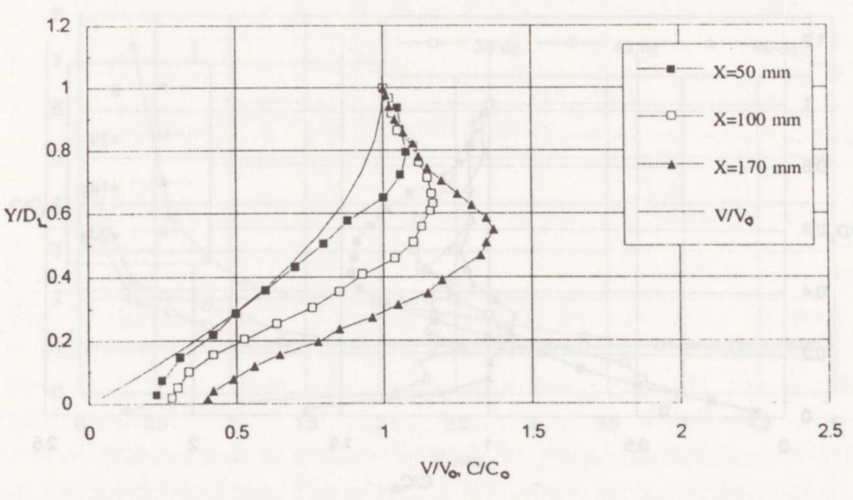


Fig. 4. Axial velocity of gas V/V_0 and concentration C/C_0 profiles on a flat plate. $\delta_p = 32$ mkm, $V_0 = 1.5$ m/s.

axis (V/V_0, C/C_0); transversal coordinate of the boundary layer Y related to the theoretical thickness of laminar boundary layer D_L is laid along the ordinate axis. It is evident that the distribution of the particle mass concentration has its maximum within the two-phase boundary layer. The value of this maximum grows downstream while it immerses into the boundary layer.

Fig. 5 depicts the distribution of the particle mass concentration in the cross-section of 100 mm downstream for various values of the particle size and flow velocity of 1.5 m/s. The attack angle is zero. One can see that the value of the concentration maximum for fine particles is greater than that for rougher particles.

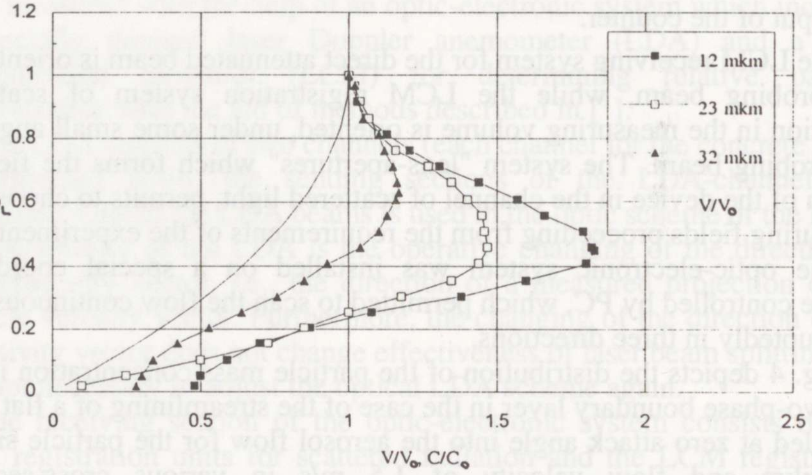


Fig. 5. Axial velocity of gas V/V_0 and concentration C/C_0 profiles on a flat plate. $V_0 = 1.5$ m/s, $X = 100$ mm.

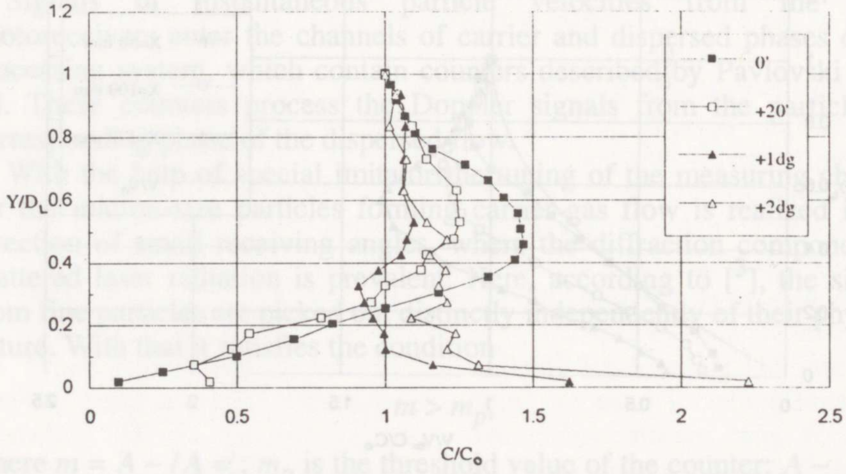


Fig. 6. Concentration C/C_0 profiles on a flat plate. $\delta_p = 23$ mkm, $V_0 = 1.5$ m/s, $X = 100$ mm.

The transformation of the concentration profile caused due to changing the attack angle is represented in Fig. 6 in the cross-section of 100 mm for the particle size of 23 mkm and flow velocity of 1.5 m/s. Substantial transformation takes place with changing the value of the attack angle from 0 to 1 degree. The subsequent increasing of the attack angle causes the concentration growth in the vicinity of a flat plate (Fig. 6).

The distributions of the particle mass concentration in various cross sections of the curved surface for the particle size of 23 mkm and flow velocity of 3 m/s is depicted in Fig. 7. The concentration profile is transformed along the surface. In upper cross sections the concentration maximum is located in the vicinity of the surface, but downstream it moves away from the surface and its value decreases (Fig. 7).

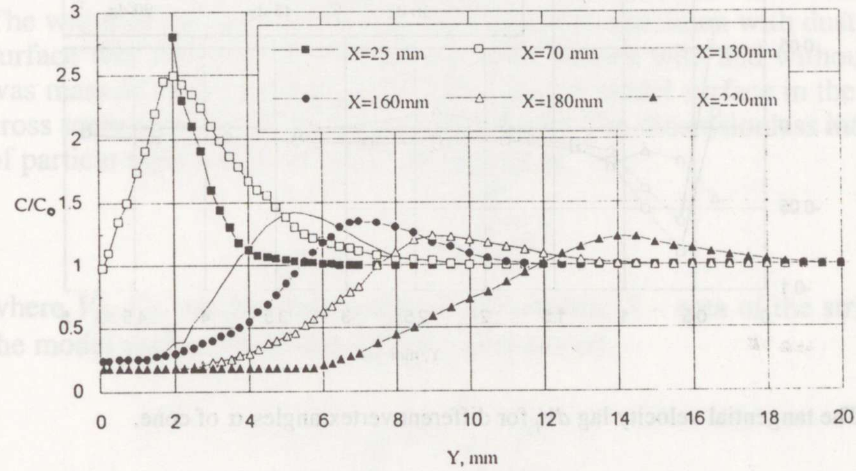


Fig. 7. Concentration C/C_0 profiles on the curved surface. δ_p = 23 mkm, V_0 = 3 m/s.

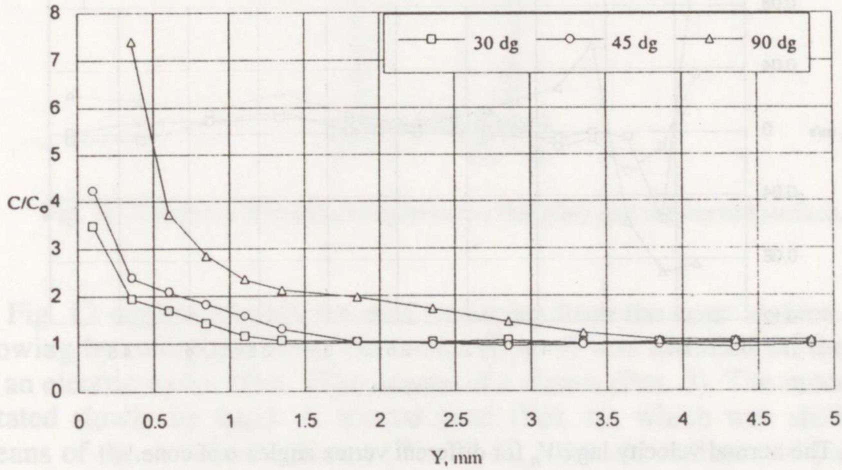


Fig. 8. Distribution of particle mass concentration C/C_0 near the wall for different vertex angles α of cone.

Fig. 8 represents the distributions of the particle mass concentration in the vicinity of conical surface for various values of the vertex angle, the particle size of 23 mkm and flow velocity of 1.5 m/s. Here concentration profiles have maxima near the conical surface. The increase of the value of the attack angle results in the growth of the concentration.

Figs. 9 and 10 show the distributions of tangential dV_t and normal dV_n velocity lag in the cross section of 50 mm for various values of the cone vertex angle. The velocity lag slightly depends on the attack angle outside the boundary layer. But inside it the increase of attack angle leads to a decrease in the tangential lag and the growth of the normal lag.

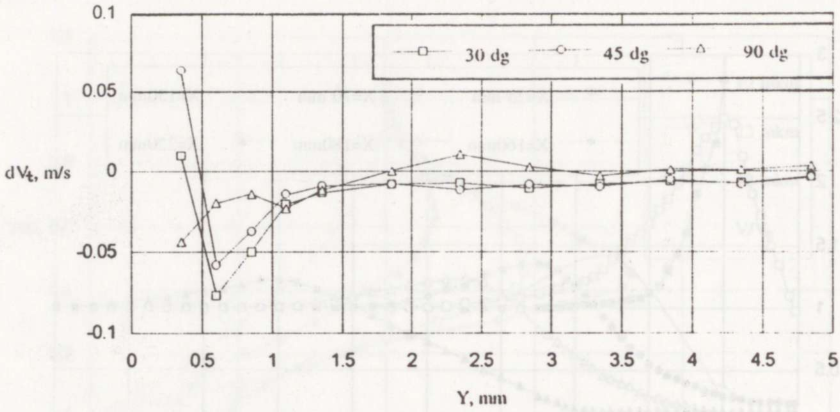


Fig. 9. The tangential velocity lag dV_t for different vertex angles α of cone.

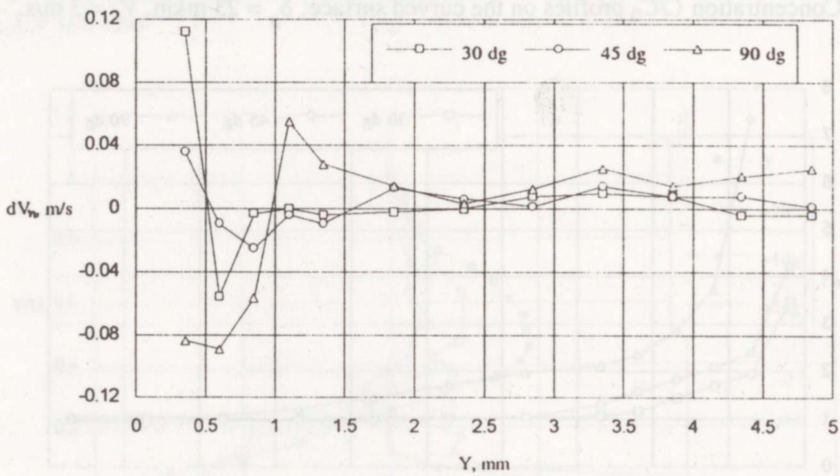


Fig. 10. The normal velocity lag dV_n for different vertex angles α of cone.

5. PARTICLE SEDIMENTATION MEASURING

The amount of sedimented particles and their distribution along the surfaces were measured by a special weighing method.

A special bench for removing dust from the surface of the flat-plate and curved surface is shown in Fig. 11. After blowing by two-phase flow during the given period of time *t* the model (Pos. *4*) with sedimented dust on its surface was installed on the fixed plate (Pos. *3*) by means of a holder (Pos. *2*). The sedimented particles were removed from the surface with the help of a head (Pos. *1*), which could move along a rod (Pos. *5*). The removed dust fell down on the surface of the film specimen (Pos. *6*), which was installed on the slab (Pos. *7*). The mass of the specimen had been measured beforehand. The width of the head determined the width of the stripe on the model surface from which the particles were removed. The width of the head was 3 mm. Then the film specimen with dust on its surface was weighed. The difference of its masses with and without dust was mass *M* of the particles sedimented on the model surface in the given cross section during the given period of time *t*. The dimensionless intensity of particle sedimentation *I* was determined as

$$I = \frac{M}{V_0 C_0 S t},$$

where V_0, C_0, are the parameters of free stream; *S* – area of the stripe on the model surface from which dust was removed.

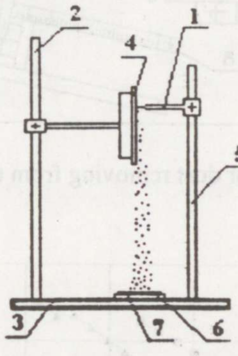


Fig. 11. Bench for dust removing from the flat plate and the curved surface.

Fig. 12 depicts a bench for dust removing from the cone surface. After blowing by two-phase flow, the model (Pos. *4*) was installed on the shaft of an electric motor (Pos. 2) by means of a sleeve (Pos. *3*). The model was rotated slowly by hand. A special head (Pos. *6*), which was shifted by means of the coordinate device (Pos. *7, 8*), removed sedimented particles from the model surface. The particles fell down on the surface of the film specimen (Pos. *10*), which was installed on the slab (Pos. *9*). The width of pure stripes on the model surface was determined by the width of the head and was equal to 3 mm. The subsequent determination of the sedimentation intensity I was similar to that in the case of the flat-plate and curved surface.

Fig. 13 shows that the sedimentation intensity for a flat plate installed at zero attack angle grows downstream, but it reduces with the growth in flow velocity and particle size. Here and below I is dimensionless sedimentation intensity; Re_x is the Reynolds number along the surface. Particle sedimentation substantially depends on the value of the attack angle (Fig. 14). It grows with the increase of the angle.

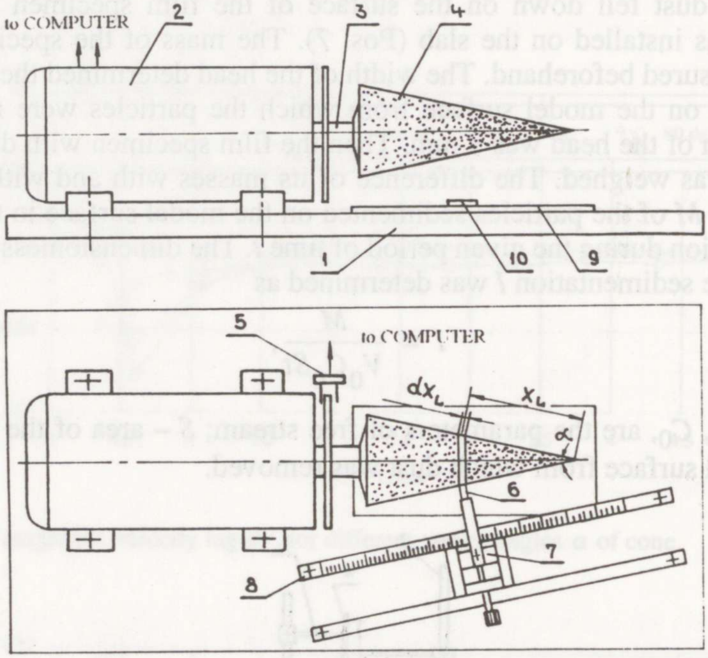


Fig. 12. Bench for dust removing from the cone surface.

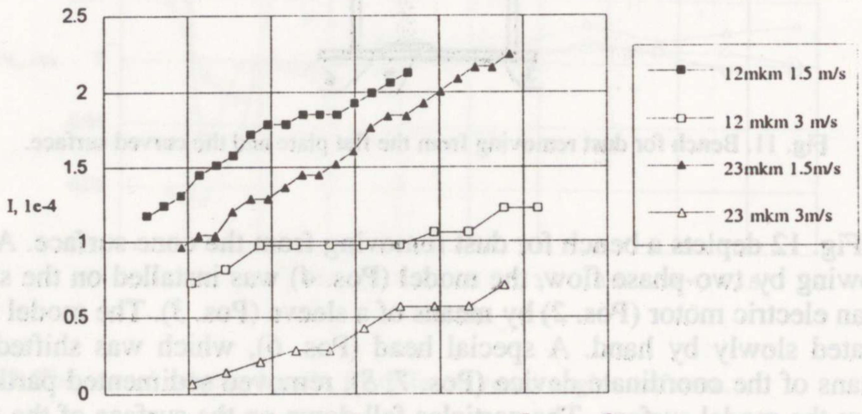


Fig. 13. Intensity of particle sedimentation I along the plate.

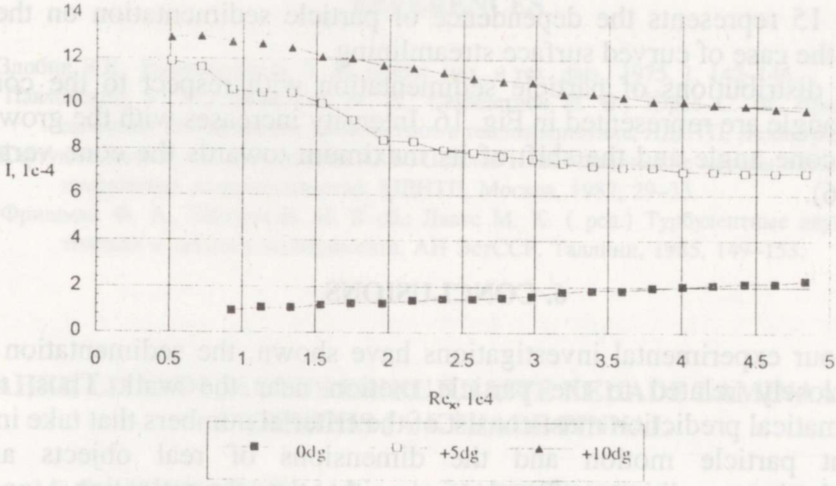


Fig. 14. Intensity of particle sedimentation I along the plate. $\delta_p = 23$ mkm, $V_0 = 1.5$ m/s.

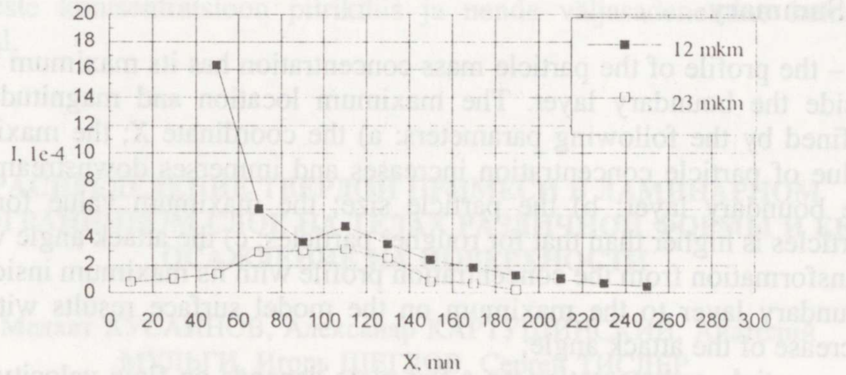


Fig. 15. Intensity of particle sedimentation I along the curved surface. $V_0 = 3$ m/s.

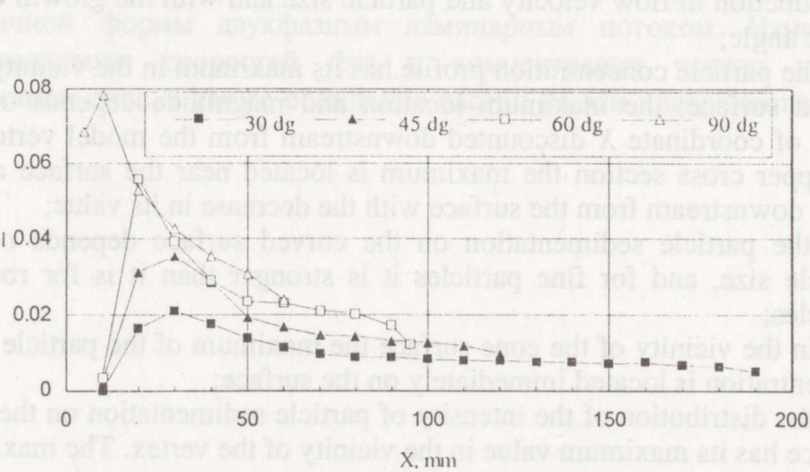


Fig. 16. Intensity of particle sedimentation I for different vertex angles α of cone.

Fig. 15 represents the dependence of particle sedimentation on their size in the case of curved surface streamlining.

The distributions of particle sedimentation with respect to the cone vertex angle are represented in Fig. 16. Intensity increases with the growth of the cone angle and the shift of its maximum towards the cone vertex (Fig. 16).

6. CONCLUSIONS

As our experimental investigations have shown, the sedimentation is very closely related to the particle motion near the wall. Thus, the mathematical prediction must consist of the criterial numbers that take into account particle motion and the dimensions of real objects and atmospheric conditions. To begin with the investigation, good approximation of numerical results and test data for laboratory conditions should be available. This data afford the sedimentation prediction under different conditions of further studies.

Summary

– the profile of the particle mass concentration has its maximum value inside the boundary layer. The maximum location and magnitude are defined by the following parameters: a) the coordinate X; the maximum value of particle concentration increases and immerses downstream into the boundary layer; b) the particle size; the maximum value for fine particles is higher than that for rougher particles; c) the attack angle value; transformation from the concentration profile with its maximum inside the boundary layer to the maximum on the model surface results with the increase of the attack angle;

– particle sedimentation on a flat plate depends on flow velocity, also on particle size and the attack angle. The sedimentation is intensified with the reduction in flow velocity and particle size and with the growth of the attack angle;

– the particle concentration profile has its maximum in the vicinity of a curved surface; the maximum location and magnitude depends on the value of coordinate X discounted downstream from the model vertex. In the upper cross section the maximum is located near the surface and it shifts downstream from the surface with the decrease in its value;

– the particle sedimentation on the curved surface depends on the particle size, and for fine particles it is stronger than it is for rougher particles;

– in the vicinity of the cone surface the maximum of the particle mass concentration is located immediately on the surface;

– the distribution of the intensity of particle sedimentation on the cone surface has its maximum value in the vicinity of the vertex. The maximum value increases with the vertex angle.

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TAHKE LISANDI JAOTUS ERIKUJULISTE KEHADE LAMINAARSES PIIRIKIHIS JA KEHADE PINNAL

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Eksperimentaalselt on uuritud erikujuliste kehade uhtmist kahefaasilise laminaarse voolusega. On määratud mõlema faasi kiirusjaotused ning osakeste kontsentratsioon piirikihis ja nende väljasadenemine kehade pinnal.

РАСПРЕДЕЛЕНИЕ ТВЕРДОЙ ПРИМЕСИ В ЛАМИНАРНОМ ПОГРАНИЧНОМ СЛОЕ НА ТЕЛАХ РАЗЛИЧНОЙ ФОРМЫ И ЕЕ ОСАЖДЕНИЕ НА ПОВЕРХНОСТИ

Медхат ХУСАИНОВ, Александр КАРТУШИНСКИЙ, Анатолий МУЛЬГИ, Игорь ЩЕГЛОВ, Сергей ТИСЛЕР

Проведено экспериментальное исследование обтекания тел различной формы двухфазным ламинарным потоком. Измерены распределения скоростей фаз и концентрации частиц в пограничном слое, а также осаждение частиц на эти поверхности.