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Simulation model of abrasive material motion

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Summary. The paper describes a simulation model of the motion of an abrasive material, the implementation of which is developed to the special modeling algorithm. The model allows to predict the effect of the parameters of jet-abrasive two-phase flow on the distribution of abrasive particles on the surface of the rail for certain time, when starting and on the move. The author's computer program for the implementation of the simulation model is developed.

Key words: the two-phase flow, abrasive material, simulation model.

INTRODUCTION

Currently the problem connected with the appearance of wheel pairs of locomotives slipping and skidding is not solved sufficiently. Slipping and skidding take place when traction or braking force applied to the wheel from the side of the locomotive exceed cohesion force between wheel and the rail and so they are directly related to traffic safety.

Therefore, the main task when conducting the locomotive is to avoid an opportunity of appearance and increase the process of slipping or skidding through the realization of a consistently high value of cohesion coefficient of wheel and rail.

ANALYSIS OF RECENT STUDIES AND PUBLICATIONS

In works [4, 11, 13, 17] analysis of researches of methods for increasing and stabilizing the friction interaction of locomotive wheels with the rails is considered. It is known that many of them give an opportunity to significantly increase implemented coefficient of cohesion. For example, the positive effect is provided by chemical methods of cleaning the surfaces of rails, electric arc, plasma, laser cleaning, applying in a zone of contact of wheels and rails particles of solids and others. However, the application of most of these methods entails significant difficulties in the operation and might cause unwanted side effects, are uneconomic, etc. Definition of the most effective methods for increasing the cohesion of the wheels with the rails in operation is performed by the method of expert estimations, where it is necessary to involve knowledge, intuition, and experience of many competent and highly qualified professionals-experts [7, 11, 22].

Analysis of the results of the expert survey had showed that the most effective is the method of increasing the friction between wheel and rail is impact of two-phase jet-abrasive flow [3, 8, 14, 19]. In this case, abrasive material (sand) under the action of compressed air is directed on the surface of rail, affecting wheel-rail friction contact status, which is specifically:

- removing surface dirt,
- formation of surface roughness, which, depending on the mode of influence can provide a significant increase in the coefficient of cohesion,
- proper filing of sand in contact of wheel and rail.

In the works [9, 23] it is shown that, in terms of traction, the best result is achieved when applying sand in one layer with some distance between the grains (0.06 kg/m^2).

OBJECTIVES

Study of the process of movement of abrasive particles from the nozzle with consideration of various factors because of the high complexity of the retrieval and analysis of results in the implementation of the bench and field experiments, so the purpose of this work is to create a simulation model describing the influence process of the motion of particles on the dynamics of the distribution of the width of the rail head for certain time.

THE RESEARCH RESULTS

Created simulation model is based on the use of algorithmic models implemented on a personal computer, to study the process of the movement of abrasive particles. For realization of the method a special modeling algorithm was developed and a block scheme of it is presented in Fig.1. In accordance with it programmatically generated information describing the elementary processes of the system taking into account interrelations and mutual influences. The modeling algorithm was built in accordance with the logical structure of the system and with maintain the consistency of the proceeding processes and displaying the main states of the system.

The main stages of the developed model are:

1. Modeling the input and external influences.

2. Reproduction of the work of the modeled process (modeling algorithm).

3. Processing the simulation results and their interpretation.

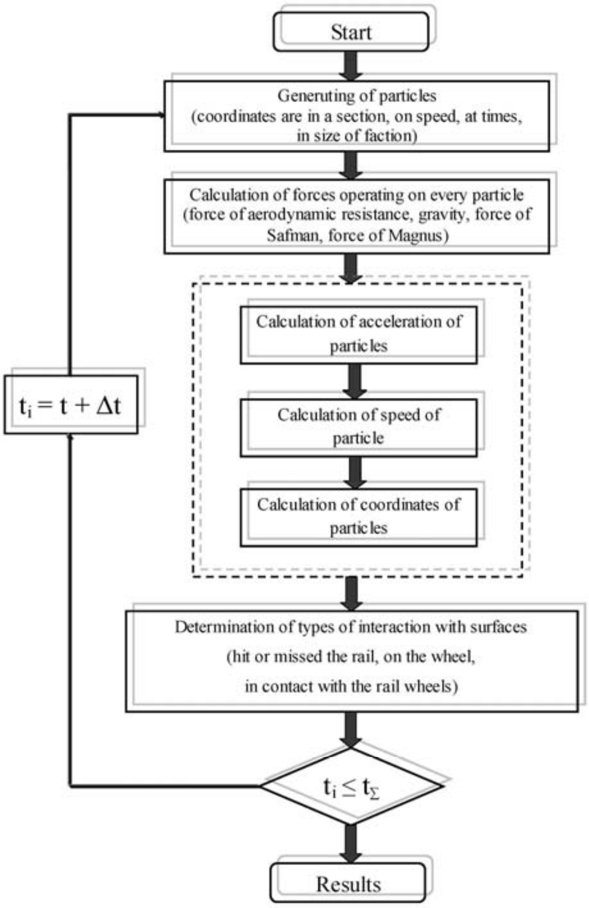

Fig. 1. Simulation model algorithm block scheme

The system may contain elements of continuous and discrete steps, be influenced by many random factors (a side wind, air eddies in the area of contact, etc), so the use of the developed simulation model allows to investigate dynamics of functioning of the process over time. The model allows you to easily change the values of parameters of the process and its initial conditions.

Simulation results are an important factor for decision-making when checking for new ideas, as it allows to investigate the large number of alternatives (options), considering different scenarios for any input. It allows to make predictions when discussing the future system or the studied processes in those cases when in reality it might lead to economic costs [17, 18, 21].

As this method of simulation is numerical, results obtained on completion of the simulation, correspond to the fixed values of parameters of the investigated process and its initial conditions. For the analysis of the developed method you need to repeatedly simulate the process of its functioning, varying the input data entering, so you can get the statistics of the results, which then can be approximated. Implementation of the developed model was made on a personal computer with high performance.

In the basis of the developed simulation model is the method of particles (discrete-cell), involving the calculation of provisions and the relevant parameters for each simulation particles at different points in time, and also an important feature of this method is the possibility of accounting for the effects of a large number of diverse factors. This allows you to get detailed space and time considering picture of the distribution of the particle flow on the surface. Model of the motion of two-phase flow describes the motion of particles, taking into account collisions of the particles in the flow and their reflection from the surface of rails and wheels. Performing numerical simulation of the motion of particle, size distribution, speed, time, and their spatial location in the cross section of the nozzle (coordinates of each particle), at the initial moment of time is determined by the terms of the problem as well as the technological parameters of the feeding device. Each particle simulation is set in accordance with one real particle number is a numerical experiment determined on the basis of the volume concentration of the flow specified in the initial conditions. Particles are modeled as hard balls with given density.

When describing two-phase flow (solid abrasive particles in the air stream) discrete-path based approach (Euler-Lagrange) is used. This is justified by the choice of the method of particles to create the model and the fact that this approach is used for simulation of two-phase flows with solid phase. Thus for the particles Lagrange method is used, and for the air phase it’s Euler method [1, 10, 30]. For visual illustrations of opportunities of use of the Lagrangian trajectory method for studying the behavior of solid particles in turbulent streams of air [26, 27, 28] works can be considered.

The calculation scheme of the model of the motion of particles and particles parameters scheme at the exit of the nozzle is presented on Fig. 2, 3.

Let’s consider the motion of particles through a pipeline under the influence of carrier air flow.

The distribution of particle size has been studied in metrological laboratory of PAO «Luganskteplovoz» on a universal measuring microscope UIM-21 (Fig. 4). For the research the abrasive material (sand moulding) is used according to GOST 2138-91 and images of it are presented on Fig. 5. The sand creates the best cohesion conditions of locomotive wheels with the rails as a result of homogeneity of particle sizes (0.2-0.5 mm), the largest quartz content (not less than 75%) and the minimum content of harmful, especially clay (not more than 3%), impurities and inclusions.

More clearly the geometrical form of the investigated abrasive particles can be seen and their sizes determined, using a microscope MPB-3 (Fig. 6).

The plot of the distribution density of values of the diameter of abrasive particles P_i is shown in Fig. 7.

Studied particles have clearly expressed a crystalline structure, and are rather close to spherical in shape. According to the classification proposed Murdasov A.V. in his works [15, 20], studied abrasive particles by type of form can be taken an isometric.

At the beginning of the modeling particles are generated according to the law of uniform distribution (from the theory of probability): coordinates in the cross section of the nozzle, speed, diameter and time.

Uniform distribution in the numerical line interval [a, b], a<b, is a probability distributions, having a density:

$$p(x) = \begin{cases} \dfrac{1}{b-a}, & x \in [a,b], \\ 0, & x \notin [a,b]. \end{cases} \tag{1}$$

Distribution function is determined by formula:

$$F(x) = \begin{cases} 0, & x \le a, \\ \dfrac{x-a}{b-a}, & a < x \le b, \\ 1, & x > b. \end{cases} \tag{2}$$

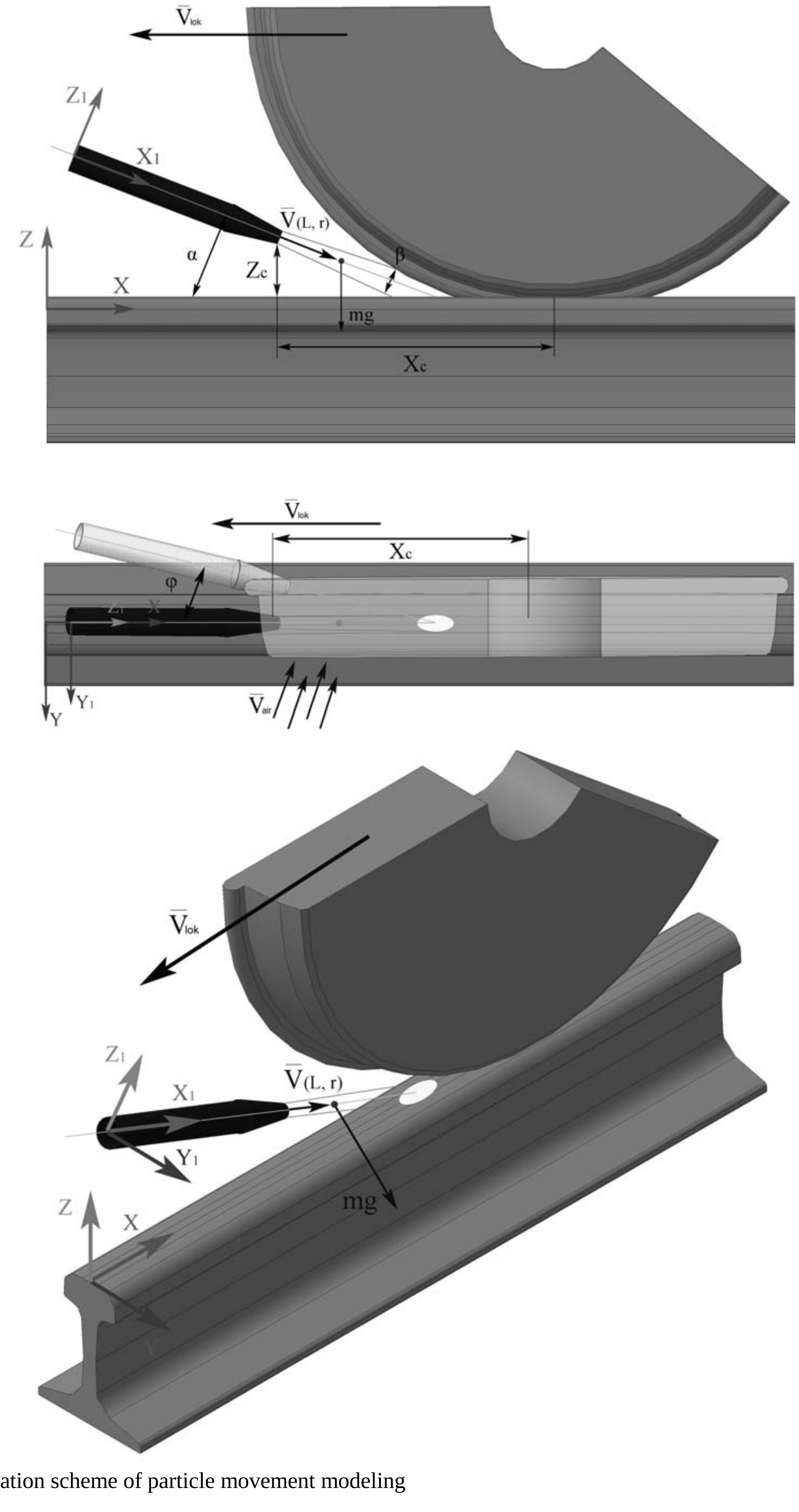

Fig. 2. Calculation scheme of particle movement modeling

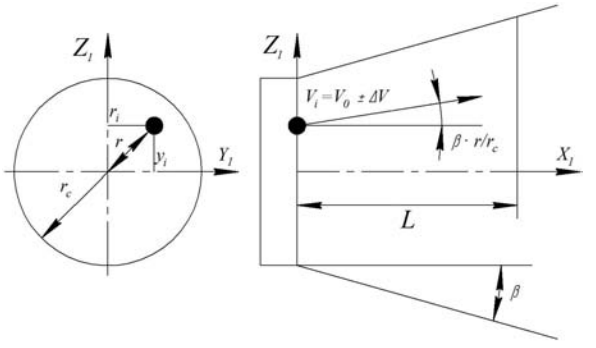

Fig. 3. Particles parameters scheme at the exit of the nozzle

Fig. 4. The universal measuring microscope UIM-21

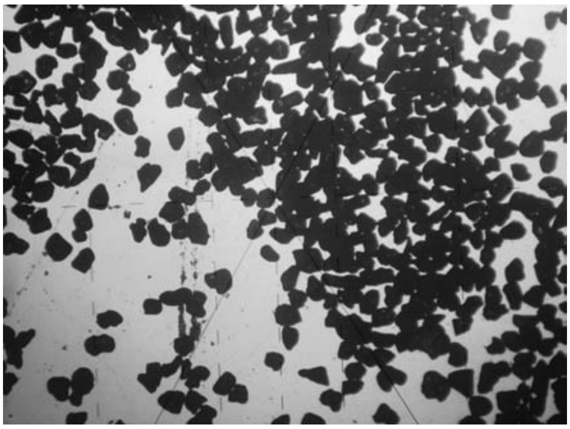

Fig. 5. Picture of abrasive material taken with UIM-21 microscope

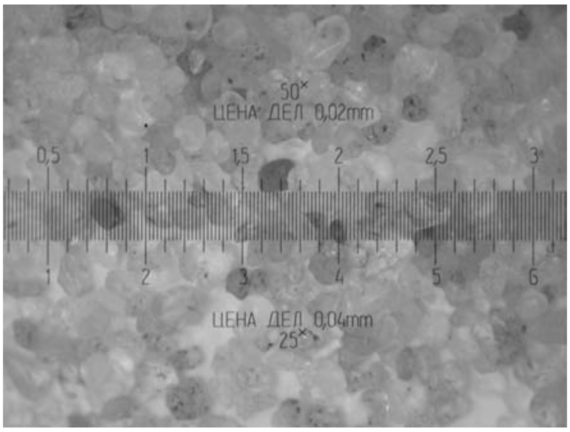

Fig. 6. Picture of abrasive material taken with MPB-3 microscope

And characteristics function respectively is:

$$\varphi(t) = \frac{1}{it(b-a)}(e^{itb} - e^{ita}). \tag{3}$$

After an output from the nozzle the particles are influented by speed field of the carrier-phase, consisting of several air flows (Fig. 2): air stream from the nozzle $\vec{V}(L,r)$, locomotive movement conditioned air flow $\vec{V}_{lok}$ and wind conditioned air flow of arbitrary speed and direction $\vec{V}_{air}$.

Thus, the motion of the particles of sand from the nozzle to the contact surfaces of wheel and rail are exposed to the air flow with the speed of:

$$\vec{V}_n = \vec{V}(L,r) + \vec{V}_{air} - \vec{V}_{lok}, \tag{4}$$

where: L is the distance from the nozzle exit,

r is distance from the central axis of the nozzle.

We shall consider $\vec{V}_{air}$ and $\vec{V}_{lok}$ have a uniform distribution of speeds and these speed and direction of flow are known. The orientation of vector $\vec{V}(L,r)$ depends on the orientation of the nozzle on the rail.

Immediately after the release of particles from the nozzle the process of expansion jets cross-section begins. It takes place because of influence of waves of depression, which penetrate the volume of jet and move particles, that are no more limited by walls of nozzle, its radius to the external border.

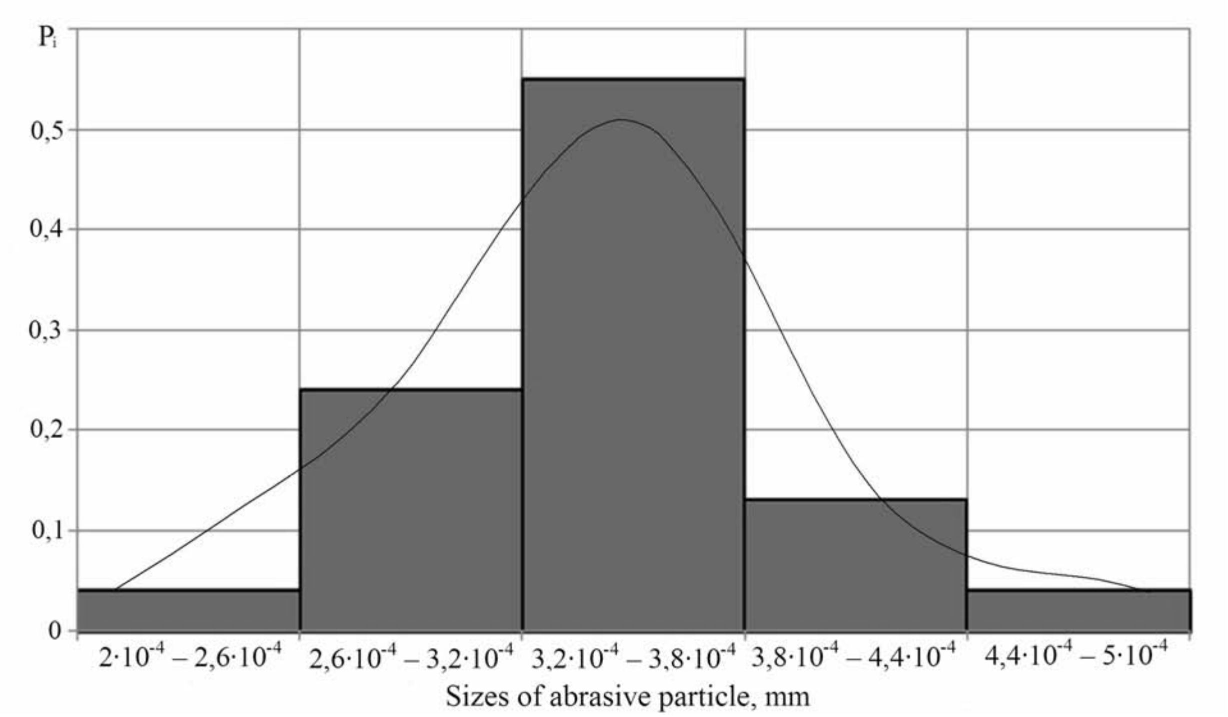

Fig. 7. The plot of the distribution density of values of the diameter of abrasive particles

For the description of the jet speed field as the distance from the nozzle use the dependence obtained in [31] when modeling of two-phase turbulent jet with solid particles:

$$V(L,r)=V_0\left(1-\frac{3c\rho_B L}{2d_a\rho_a}\right)^{1/2}\left[1-\left(\frac{r}{R_c+Ltg\beta}\right)^{3/2}\right]^2, \quad (5)$$

where: V_0 is initial axial flow speed at the nozzle exit, c is particle form depending coefficient, ρ_{air} is air density, L is the distance from the nozzle exit, d_a is the mathematical expectation of the diameters of spherical particles,

ρ_a is abrasive density, r_c is constructive nozzle radius, β is flow angle.

Equation of motion of a single solid particles in a turbulent gas flow is:

$$\rho_a\frac{\pi d_{ai}^3}{6}\frac{d\vec{V}_i}{dt}=\sum_k \vec{F}_i^k(r_a,t), \quad (6)$$

where: d_{ai} is diameter of i sand particle, $\vec{V}_i$ is speed of i-й particle, $\vec{F}_i^k(r_a,t)$ are external forces influenting the particle, r_a is particle coordinate, t is time.

Primary structural factors affecting the movement of particles in the flow of the carrier-phase are: gravity, the force of aerodynamic resistance, Safman force, Magnus force, turboforez force (due to the pressure gradient), the thermoforez force and interaction between the particles.

In the pipeline on a grain of sand force of aerodynamic resistance $\vec{F}_A$ (Fig. 8) takes action, cause of which is the difference in air velocity U and speed of a particle that moves in V (Fig. 9). The action of the aerodynamic resistance force leads to the acceleration of particles, if $U>V$ and, on the contrary, to the slowdown in the case when $U<V$. Formula of aerodynamic force has the following form:

$$\vec{F}_A=C_D\rho\frac{\pi d_p^2}{4}\frac{\left|\vec{U}-\vec{V}\right|\left(\vec{U}-\vec{V}\right)}{2}, \quad (7)$$

where: C_D is aerodynamic resistance coefficient of particles, ρ is the density of the gas, $\vec{U}$ is gas speed projection.

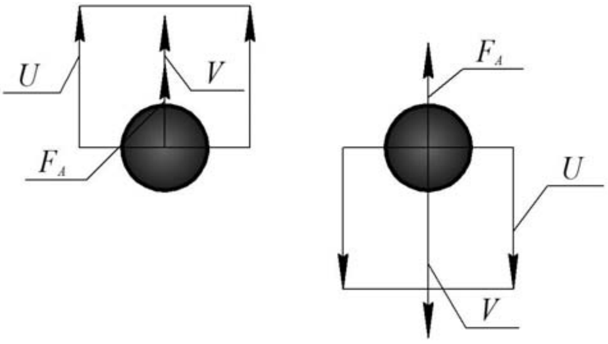

Fig. 8. Scheme of motion of a particle under the action of the aerodynamic resistance force

Along with the aerodynamic resistance force $\vec{F}_A$ gravity force $\vec{F}_g$ acts on the particle, which is one of the most important power of the factors determining the dynamics of the particles. Influence of gravity on the movement of particles will be significant and its accounting is needed.

An expression for the force of gravity has the following form:

$$\vec{F}_g = \rho_p \frac{\pi d_p^3}{6} \vec{g}. \qquad (8)$$

The heterogeneity of the profile of the averaged speed of carrying flow of air causes the action of the Safman force on a particle $\vec{F}_S$, the difference in relative velocities of the flow of the particles with different parties leads to the differential pressure. The motion of particles is performed in the direction of low pressure (Fig. 9) [28]. The Safman force acting on a particle moving in a stream with a linear profile speed is determined by the following formula:

$$F_S = k_S \nu^{1/2} \rho d_p^2 (U_x - V_x) \left(\frac{dU_x}{dr} \right)^{1/2}. \qquad (9)$$

In case when $U_x / (\nu dU_x / dr)^{1/2} << 1$, coefficient value is $k_S = 1{,}61$ [30],
ν is coefficient of kinematic viscosity.

Safman forces can have a significant impact on the movement of particles as they move in the near-wall region, where there are large gradients of the averaged speed of air carrier.

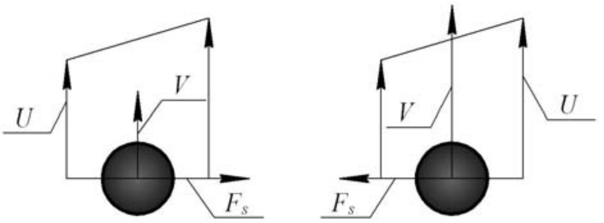

Fig. 9. Scheme of transverse particle motion in a nonuniform flow under the action of Safman forces

During movement in the gas flow particles of complex shape (non-spherical) always revolve. With regard to the spherical particles, they will also rotate in the flow of heterogeneous profile speed. Spinning particle entrains air. As a result, on the side where the direction of the flow and rotational elements of the gas are the same, the pressure becomes low in comparison with the area where these directions are opposite. Thus, the particle will move towards the low pressure (Fig. 10). The magnitude of the force acting on a particle at its rotation is described by the Magnus force $\vec{F}_M$ [2, 24]:

$$\vec{F}_M = k_M \rho \left(\frac{d_p}{2} \right)^3 \left(\vec{W} \times \vec{\omega}_p \right), \qquad (10)$$

where: $k_M(Re)$– factor, variable depending on the Reynolds number,
$\vec{W}$ – the constrain speed of the flow,
$\vec{\omega}_p$ – speed of rotation of the particles.

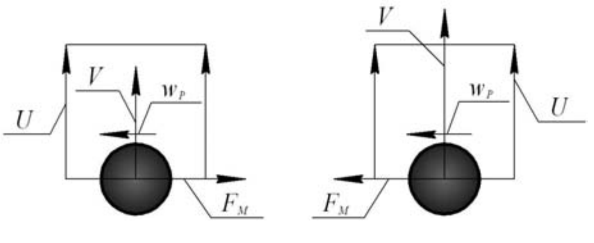

Fig. 10. Scheme of migration of a rotating particle under the action of Magnus force

Analysis of the influence of Magnus force on motion of particles held in [29]. It is shown that the Magnus force is almost always then Safman force. However, the neglect of transverse displacement of particles due to the actions of the Magnus force in high-speed flows, which are implementing large speed gradients of gas and, consequently, higher speed of rotation of particles, is illegal.

When departing from the nozzle on the particle there are the force of aerodynamic resistance from possible side winds $\vec{F}_{A1}$ and the force of air resistance from the movement of the locomotive $\vec{F}_{A2}$.

Reason of occurrence of thermoforez force is the heterogeneity of the temperature profile of the carrier gas. In view of the fact that in the present case, the temperature gradients are small, thermoforez force is not taken into account.

In [12] it's shown, when the supply of sand of locomotive sand system (1 g/l) already in the initial section of a jet in solid phase particles are moving segmentally not influencing each other. At a distance of 40 mm from the outlet section of the nozzle concentration of the flow decreases so that the free air space is more than 12 times the size of the particles and their probability of collision during the movement of the rail surface (or wheel) does not exceed 1%. Given this fact, the interaction between the particles can be neglected.

Turboforez force occurs because of the heterogeneous pulsing speed profile of carrier gas. In this work the turboforez force is ignored.

The algorithm of operation of the simulation model of the motion of abrasive material from the nozzle to the contact surfaces of wheel and rail (Fig. 1) is the following sequence of actions.

1. According to the given consumption of sand Q_n and the mathematical expectation of the size of abrasive particles (Fig. 7) is determined by the performance of the sand system (the number of particles in a unit of time). Then, using the model of a Poisson stream, each particle is assigned to the time of appearance t_i in the $0 \ldots t_\Sigma$ interval. In addition, each particle of the randomly settings:

– the starting point coordinates (y_i, z_i) in the nozzle section (Fig. 2, 3),

– speed of movement on exit from the nozzle in the range $V_i = V_0 \pm \Delta V$, где $\Delta V = 0.05 \cdot V_0$,

– speed orientation V_i,

– angle $\beta \cdot r / r_c$ to the flow axis,

– the size of particles in accordance with the distribution presented in Fig. 7.

2. At each step of integration, on the generated sequence of appearance of particles, the need to include in the calculation of particle condition $t \geq t_i$, where t is current time, is checked. If the condition $t \geq t_i$ is executed, the particle is included in the list of the particles in flight.

3. For each particle in flight, determined by the forces acting on a particle (right part of the equation 6). Using the Verle algorithm, according to which the calculation of the position of the particle is on its previous $\vec{r}(t-\Delta t)$ and current $\vec{r}(t+\Delta t)$ coordinate takes place. Given that the first derivative by time is speed $\vec{v}(t)$, and the second is acceleration $\vec{a}(t)$, numerical integration of the equations of motion (6) can be written as:

$$\vec{r}(t+\Delta t) = \vec{r}(t) + \vec{v}(t)\Delta t + \frac{1}{2}\vec{a}(t)\Delta t^2 + \\ + \frac{1}{6}\vec{b}(t)\Delta t^3 + O(\Delta t^4), \tag{11}$$

$$\vec{r}(t-\Delta t) = \vec{r}(t) - \vec{v}(t)\Delta t + \frac{1}{2}\vec{a}(t)\Delta t^2 + \\ - \frac{1}{6}\vec{b}(t)\Delta t^3 + O(\Delta t^4), \tag{12}$$

where: t is time, Δt is step of integration of time, $\vec{r}(t)$ is the position of a particle at time t, $\vec{v}(t)$ is particle speed, $\vec{a}(t)$ particle acceleration.

Adding these two equations and expressing $\vec{r}(t+\Delta t)$, we have the following:

$$\vec{r}(t+\Delta t) = 2\vec{r}(t) - \vec{r}(t-\Delta t) + \vec{a}(t)\Delta t^2 + O(\Delta t^4). \tag{13}$$

As we integrate the equations of Newton, acceleration of particles are easily expressed through the force, which in its turn is a function of position $\vec{r}(t)$:

$$\vec{a}(t)=\frac{\vec{F}(\vec{r}(t))}{m}=-\frac{1}{m}\nabla U_p(\vec{r}(t)), \qquad (14)$$

where: m is particle mass, U_p particle potential energy.

The expression for the speed can be obtained by subtracting equation (12) from equation (11):

$$\vec{v}(t)=\frac{1}{2}\Delta t\,[\vec{r}(t+\Delta t)-\vec{r}(t-\Delta t)]+O(\Delta t^2). \qquad (15)$$

As a result, the new values are determined by accelerations, velocities and coordinates of the particles.

4. Using the new coordinates of the particles, a check is performed for the interaction of particles with the surface of rail and wheels. There are several variants of interaction:

- particle moves in the direction of the rail surface. In this case, there is no additional action,
- particle has reached the surface. In this case, you define the parameters for the interaction of particles with the surface (the particle speed at the moment of impact, angle of attack, the coordinates of the point on the surface, the speed with which the particle is reflected from the surface). Information about the interaction entered the statistics of particle interaction with a surface,
- particle got into the contact area between the wheel and rail. Information about the paid statistics particles caught in contact, and the particle is excluded from further consideration,
- particle crossed the boundaries of the space, which may be a collision with the surface of rail or wheels. Particle is excluded from further consideration.

5. If calculation time did not exceeded t_Σ, the calculation continues from the second paragraph of this algorithm.

6. After completion of settlements processing of statistics information about the interactions of particles with the surface of particles, trapped in a wheel-rail contact.

For modeling of the system on a PC as a computer program, modeling algorithm was recorded on the input universal algorithmic language C++ in the Borland C++ Builder 6.0 environement [5].In the program interface window (Fig. 11) input of the initial data for modeling is held.

Developed program the first time, the Using for a series of calculations for the purpose of selection of the parameters of filing of an abrasive material, providing the necessary modes of interaction of particles with the surface of the sand. Results of modeling are presented on Fig. 12-15.

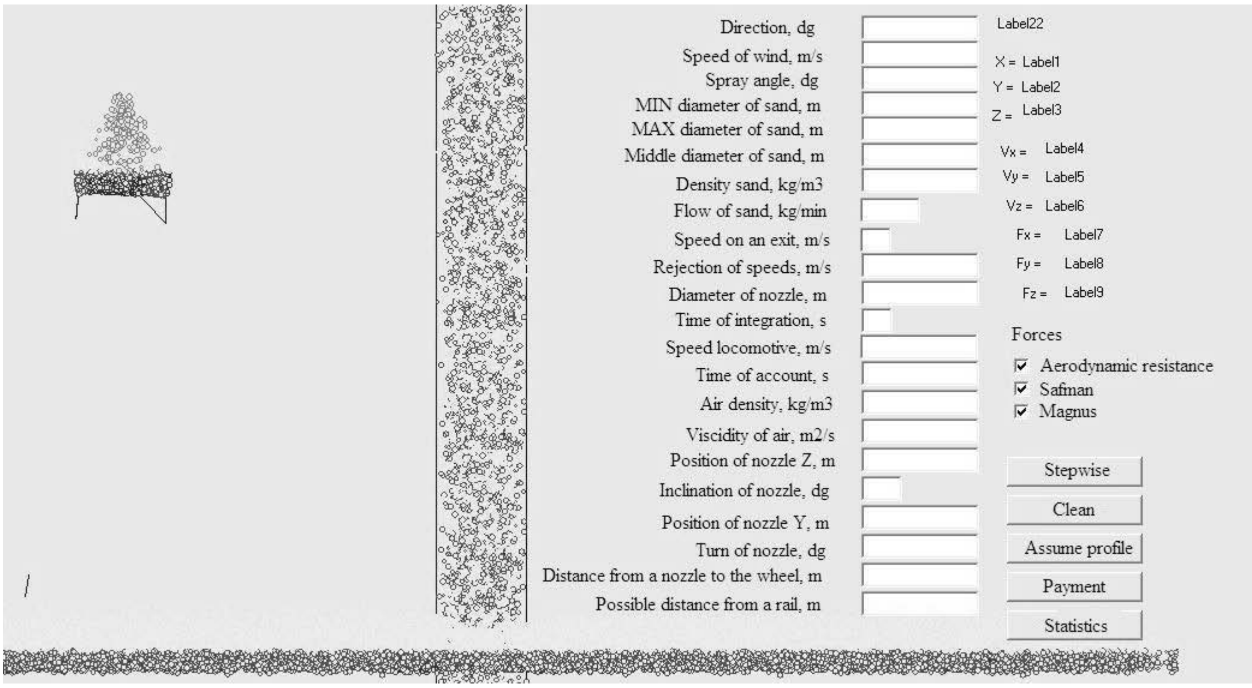

Fig. 11. The interface of the simulation model implemented in the form of a computer program

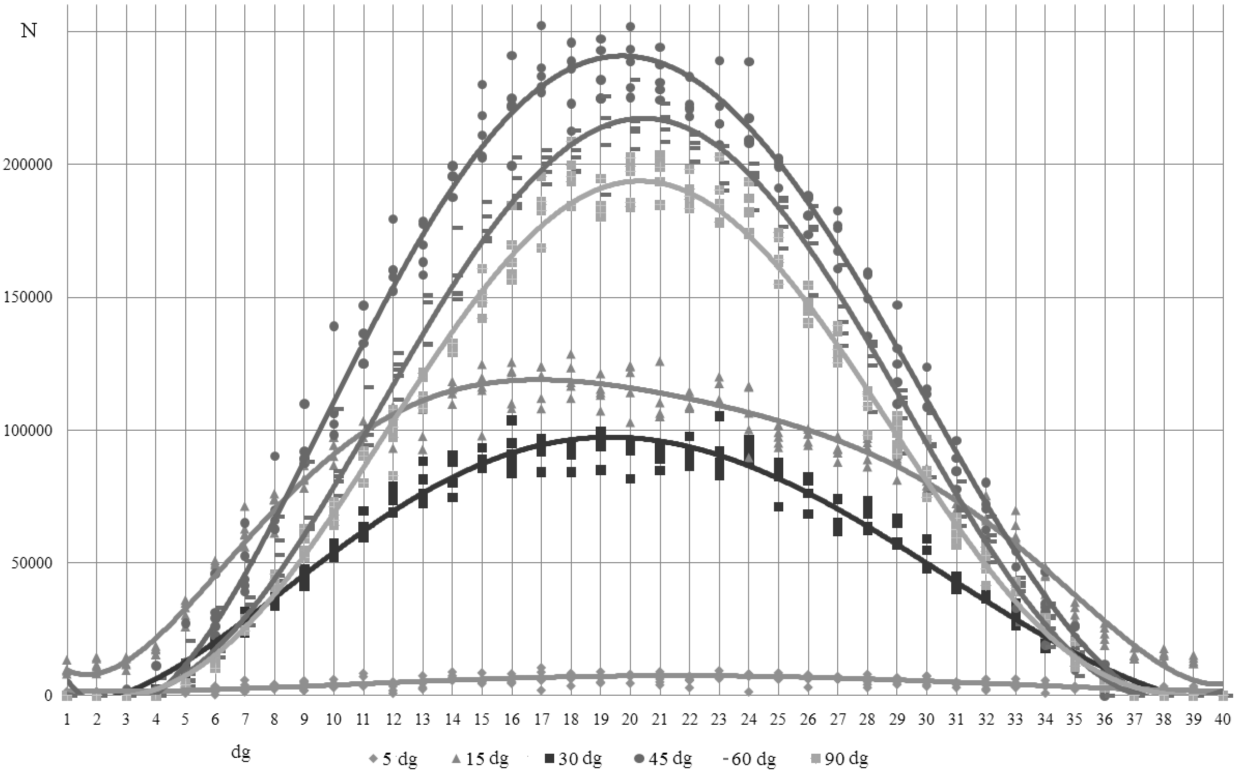

Fig. 12. Distribution of particles on the surface of rail from the different angles of filing

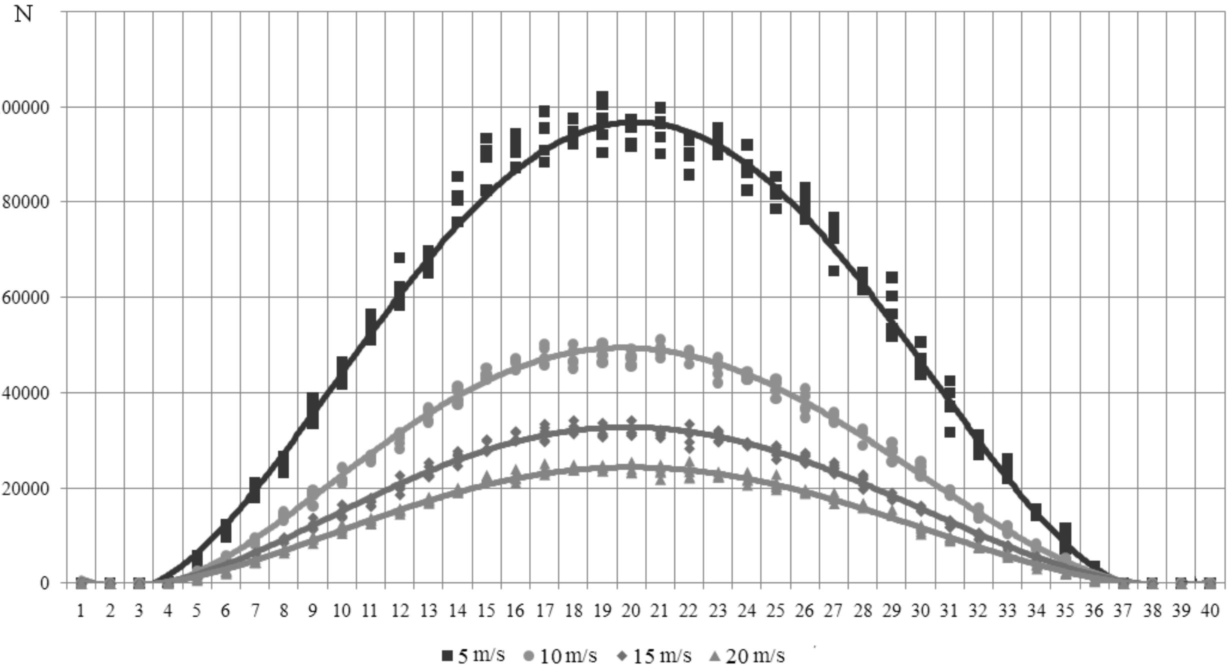

Fig. 13. Distribution of particles on the surface of the rail at various locomotive speeds (the flow speed is 10 m/s)

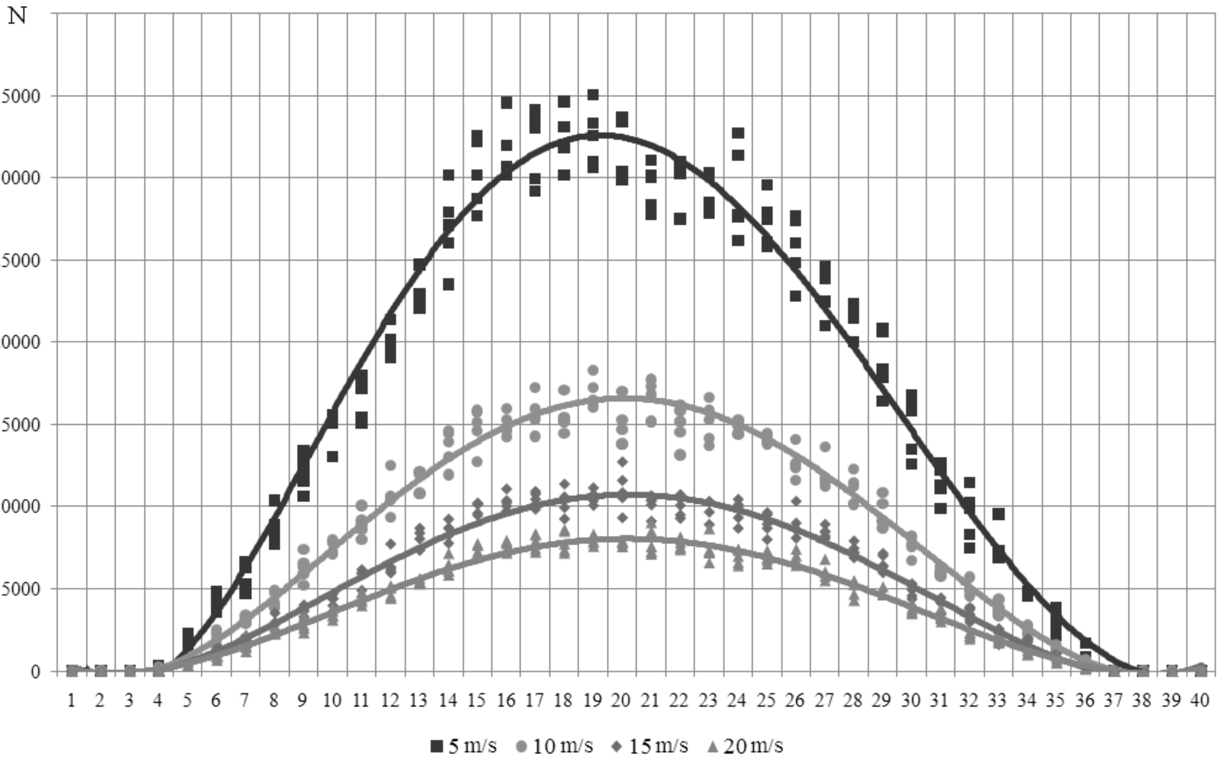

Fig. 14. Distribution of particles on the surface of the rail at various locomotive speeds (the flow speed is 30 m/s)

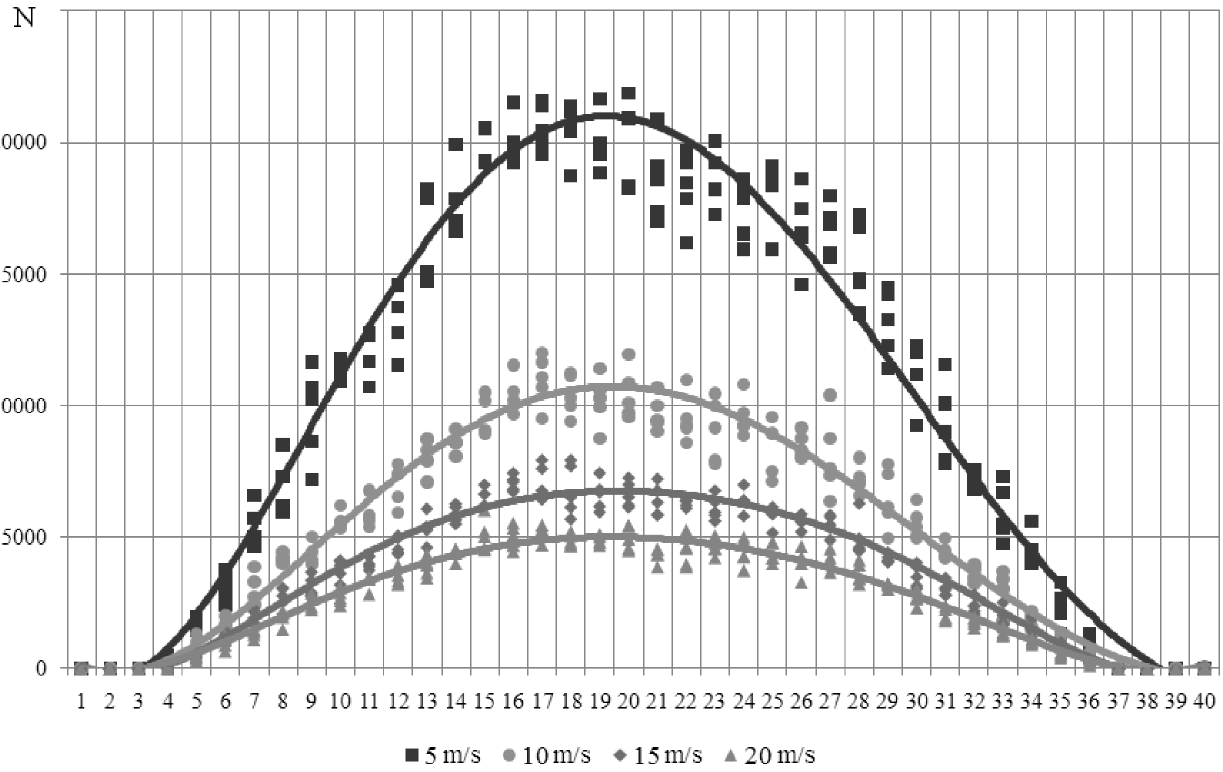

Fig. 15. Distribution of particles on the surface of the rail at various locomotive speeds (the flow speed is 50 m/s)

CONCLUSIONS

1. Modeling based on the first time developed simulation model of the motion of an abrasive material allows to predict the effect of the parameters of jet-abrasive two-phase flow on the distribution of abrasive particles on the surface of the rail for certain time, when starting and on the move.

2. The simulation results allow to adjust the parameters of the system of jet-abrasive influence on the formation of the surface layer of the rail and put up the dependence of the performance of this system on the speed of motion of a locomotive.

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ИМИТАЦИОННАЯ МОДЕЛЬ ДВИЖЕНИЯ АБРАЗИВНОГО МАТЕРИАЛА

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Аннотация. В работе рассматривается имитационная модель движения абразивного материала, реализация которой выполняется по разработанному специальному моделирующему алгоритму. Модель позволяет спрогнозировать влияние параметров струйно-абразивного двухфазного потока на распределение абразивных частиц по исследуемой поверхности рельса в течение определенного времени, при трогании и движении со скоростью. Разработано авторскую компьютерную программу для реализации данной имитационной модели.

Ключевые слова: двухфазный поток, абразивный материал, имитационная модель.