Article citation info:
GORBUNOV M, KRAVCHENKO K, BUREIKA G, GERLICI J, NOZHENKO O, VAIČIŪNAS G, BUČINSKAS V, STEIŠŪNAS S. Estimation of sand electrification influence on locomotive wheel / rail adhesion processes. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2019; 21 (3): 460–467, http://dx.doi.org/10.17531/ein.2019.3.12.

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# ESTIMATION OF SAND ELECTRIFICATION INFLUENCE ON LOCOMOTIVE WHEEL/ RAIL ADHESION PROCESSES

# OCENA WPŁYWU ELEKTRYZACJI PIASKU NA PRZYCZEPNOŚĆ W PUNKCIE STYKU KOŁA POCIĄGU Z SZYNĄ

*The article describes a method of increasing the adhesion of the wheel to the rail based on the preliminary electrification of the abrasive-air mixture before its feed into a contact. A simulation model of the movement of sand in the system "injecting nozzle of a sandbox - a rail" is presented. The effectiveness of the proposed method to improve adhesion is confirmed experimentally. The results of experiments carried out on a friction machine, which characterize the change in friction ratio depending on the temperature with different methods of sand supply, are presented. The reduction in the consumption of sand caused by its electrification and the supply of a rational amount of abrasive substance into the contact of the wheel with the rail is estimated.*

***Keywords***: *railway transport, wheel/rail contact, friction ratio, adhesion phenomena, adhesion coefficient, particle method, sand electrification.*

*W artykule opisano metodę zwiększania przyczepności koła pociągu do szyny polegającą na wstępnej elektryzacji mieszaniny powietrza i substancji ściernej przed jej podaniem pod koła w punkcie styku koła z szyną. Przedstawiono symulacyjny model ruchu piasku w układzie "dysza wtryskowa piasecznicy-szyna". Skuteczność proponowanej metody poprawy przyczepności badano doświadczalnie. Przedstawiono wyniki eksperymentów przeprowadzonych na maszynie ściernej, które pokazują zmiany współczynnika tarcia w zależności od temperatury przy różnych metodach podawania piasku. Oszacowano jaki wpływ na stopień zmniejszenia zużycia piasku wywiera jego wcześniejsza elektryzacja oraz racjonalne dozowanie.*

***Słowa kluczowe***: *punkt styku koła z szyną, współczynnik tarcia, zjawiska przyczepności, współczynnik przyczepności, metoda cząstek, elektryzacja piasku.*

## 1. Introduction

The desire for threshold of use of traction effort and power of locomotives is associated with an increased tendency of the driven wheelsets to slippage. This determines the need to use different means to increase the level of the adhesion of the locomotive wheels with rails and to ensure the stability of the traction [25, 26]. On the other hand, a high value of the adhesive coefficient is a major factor for realizing the maximum braking force of a train when using friction brakes and significantly increases the level of traffic safety [20]. This is especially true in case of emergency braking or an emergency stopping of trains before prohibitive traffic lights have turned on unexpectedly, i. e. it is essential to avoid the case of the railway station overruns or SPAD - signal passing at danger [16]. The most common way to increase adhesion is to use silica sand or other mineral materials similar in hardness properties. This method, along with indisputable advantages (high efficiency, ease of use, relative cheapness) has obvious disadvantages: clogging of ballast, increased wear of wheels and rails [7, 23], increased resistance to movement in traction mode. Given the above disadvantages, the optimization of the use of sand is relevant.

The spraying of sand into the wheel–rail contact is one of the most effective ways to enhance the friction between the driven wheels and rail under conditions of low adhesion, especially on intensive acceleration or emergency braking running modes. The scientific works carried out by worldwide researchers on reasons of low adhesion showed that wheel/ rail adhesion coefficient (the ratio of normal to friction force in the contact) varied between 0.04 and 0.55, averaging 0.3 in dry conditions. The impact of adding moisture to the rail reduced this average to 0.2, still the leaves can reduce the adhesion coefficient as low as 0.02 [23, 24]. Other causes of low adhesion have been identified as: general moisture/dampness combined with contaminants such as rust, ice, coal dust, leaf, spilled diesel fuel/ lubricating oils/flange lubricating grease/hydraulic fluid, airborne kerosene from nearby airports, or other chemicals from industrial sites [3].

Lewis S. R. et al. and Wang et al. [24, 35] carried out comprehensive research work using a full-scale laboratory rail–wheel test machine to find the position for the hose and sand flow rates that give optimum sand entrainment to the contact. It was found that ideally the hose should be aimed at the rail or nip and be as close to that contact as safely possible. Reduction in sand flow rate below the 2 kg/ min threshold significantly reduced the amount of sand entering the contact. Relatively small movements in the hose/ nozzle from its ideal position and cross winds significantly reduced sand entrainment.

The hypothesis of rail dew and leaf films formation on rails between 5–10 a. m. and 8–12 p. m. was investigated in scientific work [16]. They considered key parameters that affect the wheel/rai bonding mechanism and assumed as iron oxides, temperature, pressure and leaf components. Jin *et al.* [17] investigated the effects of wheel/ rail contact various surfaces on the adhesion coefficient in the experiment way. Researchers revealed that when rolling speeds increase, the adhesion coefficient decreases for the same wheelset creepage and water contamination, but increases for oil contamination.

It should be noted that there is a lack of fundamental understanding on the influence of sanding parameters, such as particle size distribution, feed rate, and number of sanding axles (among others), on the adhesion recovery, wear, and train detection [1, 10]. In order to understand the effect of sand rash on improving the adhesion, it is necessary a thorough examination of the wheel's adhesion / friction phenomenon, especially in the presence of the third body in the wheel/ rail contact [12, 21]. Original equations for wear rate as a function of asperity height and lubricant thickness were developed [29]. Gained equations closely represented the experimental data and properly modelled the sliding contact.

A lot of mathematical models are using worldwide for investigation wheel/ rail contact phenomena. The influences of the five contact models – Kik–Piotrowski, STRIPES, ANALYN, CONTACT and Kalker (FASTSIM) – on the wheel wear prediction were investigated from viewpoints of calculation efficiency and accuracy [34]. The results indicated that using Hertz theory and FASTSIM to solve the normal and tangential contact problem, respectively, in the wheel wear simulation is a mostly reasoned choice in order to consider a compromise between the calculation efficiency and accuracy.
Comprehensive field investigations into adhesion recovery in leaf-contaminated wheel/ rail contact were performed by Arias-Cuevas & Li [2]. Three differently sized and Dutch Railways standard silica sands were used in the testing. Besides the instant adhesion enhancement upon sanding, the remaining friction level left for subsequent traction passages was also examined. It was concluded that the adhesion tends to increase gradually with the driven wheel passages, the adhesion recovery without sanding maybe more than seven times slower than with sanding. The next one finding is that the adhesion improvement by sanding is strongly dependent on the particle size used. The performance of the largest sand particles used in this work is effective compared to the baseline (i. e. no sand application), but much less effective than smaller sized sands.

The article [2] describes a laboratory investigation of the influence of three sanding parameters (i.e., feed rate, particle size, and slip) on the adhesion and electrical insulation in dry wheel–rail contacts. Gained results showed that using smaller particle sizes and higher feed rates promotes the lubrication and causes more electrical insulation in the wheel–rail contact. A necessary condition for complex simulations of vehicle drive dynamics and traction control when running on adhesion limit, is an advanced creep force modelling taking into account large longitudinal creep and contact ellipse geometry [8, 13, 31]. Presented methods allow to simulate various real wheel–rail contact conditions using one parameter set considering the vehicle speed, longitudinal, lateral and spin creep and shape of contact ellipse.

It should be pay attention, that the friction and slipping between the wheel and rail can cause undesirable creep noise – squeal. Experimental measurements and theoretical investigations of wheel squeal occurrences showed an increasing possibility for a squeal event to occur as the relative humidity increases [15, 27]. Curve squeal is the result of the lateral force in rolling contact of rail and wheels along curves. The test rig results showed that the lateral adhesion ratio decreases lightly with the increase of relative humidity and that squeal is more likely in high relative humidity. The main conclusion drawn from the squeal prediction model comparison was that the squeal phenomenon was strongly related to the properties of the adhesion coefficient. It was noted that the critical creepage decreases with the increase of the relative humidity, which means negative damping occurs for lower angle of wheel attack. The investigation the effectiveness of sand firing to restore adequate levels of adhesion on a contaminated rail head by using full scale laboratory test facility are described by Lewis S. R. et al. [23]. It was determined that ideal density of sand needs to be embedded into contact in order to restore adhesion is greater than 7.78 g/m yet lower than 106.0 g/m.

Sand application reduces the high creepage due to liquid contaminants, simultaneously increasing the attainable adhesion levels. Contrary to earlier findings, it was observed that the degree of sanding does influence the adhesion creepage characteristics, low sanding rates resulting in higher adhesion levels and lower creepage as compared to medium/high sanding rates. The wear and adhesion studies indicate that the beneficial effects of sanding in improving adhesion are more than offset by the increased wear rates [19].

An original test method for examination of leaf and humidity influence on the coefficient of friction between the wheel and rail was used by Olofsson and Sundvall [30]. These researchers placed the pin-on-disc tribometer in a climate chamber and used it as a test equipment. By using an elm leaf as the lubricant, the coefficient of friction was reduced four time compared with the unlubricated case. However, the coefficient of friction decreased even more when the rail lubricant was used as a lubricant, but the leaves inclined to reduce the effect of the lubricant when both were present. The full scale roller rig for investigation of wheel/ rail adhesion was used by Zhang et al. [36] and the numerical simulation were carried-out by modifying Kalker's FASTSIM program. It was noticed that under the condition of dry and clean surfaces, the adhesion coefficient keep high values and do not drop much for all range of speed tested. Under oil contamination conditions, this coefficient drops to a very low level and does not change much with speeds. No matter what are the conditions the adhesion coefficient decrease with an increasing in axle load.

The article of Lewis R. et al [22] describes the findings of series twin disc machine adhesion tests that examined the impact of oil and water mixtures on adhesion at the wheel/ rail contact. The tests showed that drying a wet contact can initially give a reduction in adhesion, that increased roughness results in increased adhesion in the presence of oil, and that increased contact pressure improves adhesion in the presence of oil. Scientists Magheri et al. [28] approached the integration between the differential and multibody modelling. This kind of integration was almost absent, especially in the railway field. Only differential modelling allows accurate analysis of the wheel/ rail contact problem (in terms of contact forces, position and shape of the contact patch, stresses and strains), while multibody modelling is generally accepted as the current standard for studying railway dynamics [6].

In high-speed railways, adhesion between wheel and rail is a very important function to maintain safety and stable operation from the standpoint of braking and driving, in particular under wet conditions at the wheel/rail interface [5]. This research work is mainly focused on the effects of surface roughness and water temperature on the wheel/ rail adhesion under wet conditions. Based upon these experimental results, a considerable method to improve the wheel/ rail adhesion coefficient under wet conditions by raising the water temperature or increasing the standard deviation of roughness height or controlling the roughness orientation was suggested.

Global research works performed in recent years ensured the progress to better understand and predict low well/ rail adhesion, and major improvements to the extent and quality of sanding systems on locomotives or trains, are definitely to have contributed to a reduction in the overall risk in railway traffic. The slip and sliding processes of rail vehicle driven wheels cause overextending of fuel consumption as well. Our research group has been carried out the tests to investigate how the electrification of the sand in the locomotive system influence on the smoothness of sand coverage, i. e. to ensure the uniformity of the sand layer on the rails, in order to improve wheel/ rail adhesion process. In another hand, we aimed to find-out the dependence between train velocity and amount of firing sand. Finally, we proposed modernisation of the sanding system set-up which delivers the reasoned amount of sand to the wheel/ rail interface.

## 2. Modelling of sand electrification in locomotive sanding system

The scientific works [11, 41] have proved that, from the point of view of traction, the best result is achieved when sand is fed in one layer with a certain distance between the sand grains (Fig. 1). When sand is fed by operated sand systems, a hump is formed on the rail surface. At speeds of up to 40 km/h, there is an excessive feed of sand into the area of contact of the wheels with the rails, predetermining the main costs of its use, is observed.

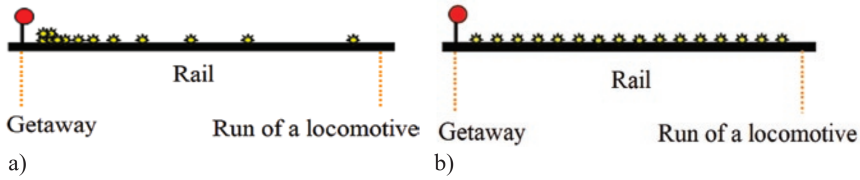


*Fig. 1. Sand distribution on the rail surface: a – under operating conditions; b - required distribution*

To achieve the required distribution of sand on the rail surface, it is proposed to pre-electrify the abrasive-air jets before directly feeding it into contact. According to the analysis in the scientific and technical literature [39], there are a number of methods for transferring charge to fine dispersed particles (Fig. 2). The most acceptable for the sand system of the locomotive is static electrification, which includes electrostatic and tribostatic charging of abrasive particles.

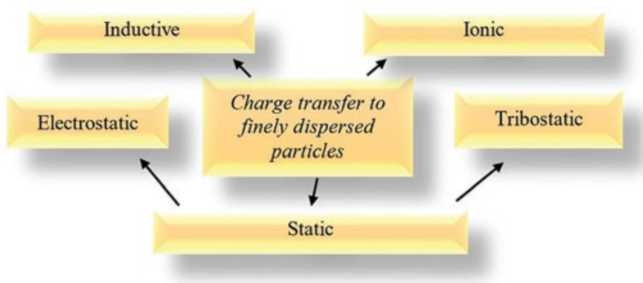


*Fig. 2. Methods of charge transfer to finely dispersed particles*

Tribostatic charging is based on the friction of abrasive particles against the walls of the pipeline. In this case, the charging material must be hydrophobic with a high dielectric penetrability. The transfer of charge to the particles does not require the creation of additional equipment for obtaining high voltage like in electrostatic charging. The complexity of the method lies in the optimal selection and arrangement of the dielectric material. However, both considered methods are acceptable for applying to a locomotive.

Based on the electrostatic charging of sand grains, a sand system in which the speed and amount of sand supplied to the contact depends on the running speed of the locomotive has been developed (Fig. 3). The control of the performance of the sandbox is implemented by a measuring-recording unit installed in front of the sandbox injecting nozzle. When an electric current is passed from the power source *6* through the central conductor *4*, a concentric magnetic field between the central conductor *4* and the electrode *5* located in the branch pipe *3* in front of the nozzle *1* is created. The sand is drawn in by the air flow from the branch pipe *2* into the union coupling *3*, when moving along which it gets a static charge, flies past a receiver *10* made of copper in the form of a ring. A measuring voltmeter *11* connected to the receiver *10* reacts to a static charge of a sand grain that moves inside the receiver *10*. The control system *9* connected to the measuring voltmeter *11* is regulated by an electro-pneumatic multi-position valve *7* with allowance for the speed meter *8* (the higher the speed of the locomotive, the greater the internal diameter of the pipe *3* for feeding the sand, and higher performance of the sandbox is).

After the branch pipe *1*, the required amount of sand moves through the pipeline *15*, where the electrodes *13* and *14* create a strong electric field, which is regulated by the power source *12*, depending on the running speed of the locomotive, and recharges the sand. Under the influence of electrical forces, abrasive bulk material (sand) falls apart to one layer. After this sand is fixed on the rail due to adhesive forces. When sand particles interact with the rail, electro-erosion destruction of the surface layer of pollution occurs on the rail *16* [42]. In this connection, the adhesion qualities of the rail *16* are increased, the coupling characteristics of the locomotive are improved.

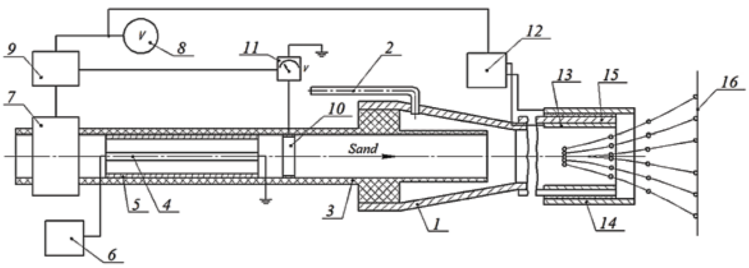


*Fig. 3. Scheme of the sand system of the locomotive based on the electrostatic charging of sand: 1 – injecting nozzle; 2, 3 – branch pipes; 4 - centre conductor; 5 - electrode; 6 - power supply source; 7 – electro-pneumatic multi-position valve; 8 - speedometer; 9 - control system; 10 - receiver; 11 - measuring voltmeter; 12 - adjustable power supply source; 13, 14 - electrodes; 15 - pipeline; 16 - rail*

The value of the required voltage supplied to the electrodes 13, 14, depending on the running speed of the locomotive for sand distribution with a distance between particles equal to three of their radii is determined on the basis of simulation modelling in the ‘injecting nozzle of sandbox - rail’ system.

The developed simulation model is based on the particle method [14, 37]. Along with the method of finite elements, boundary element, etc., the particle method is one of the discretization methods. In this case, the motion of each of the particles is considered. The state of a physical system is determined by the attributes of a finite ensemble of particles, and the evolution of the system is determined by the interaction of particles between themselves and the environment. An important feature of the method is the possibility of taking into account the influence of a large number of factors of various nature.

To describe the two-phase flow (solid particles in a gaseous medium), the Euler-Lagrange discrete-trajectory approach was used. This is dictated both by the choice of the particle method for creating a simulation model and by the fact that this approach is used to simulate two-phase flows with a solid phase. Thereby for the particles, the Lagrange method and for the gaseous phase, the Euler method is used.

The motion of particles through a pipeline under the influence of a carrying air stream is considered (Fig. 4). At the entrance of the pipeline, the particles appear randomly (both in terms of time and section). The equation of motion of each of the particles has the following form:

$$\rho_p \frac{\pi d_p^3}{6} \frac{dv_i}{d\tau} = \sum_i F_i\left(r_p, \tau\right), \tag{1}$$

where $\rho_\rho -$ is the density of the particle material; $d_p -$ is particle diameter; $\nu_i -$ is particle velocity projection; $F_i\left(r_p, \tau\right) -$ is external forces acting on the particle; $r_p -$ is a coordinate of particles; $\tau -$ is time.

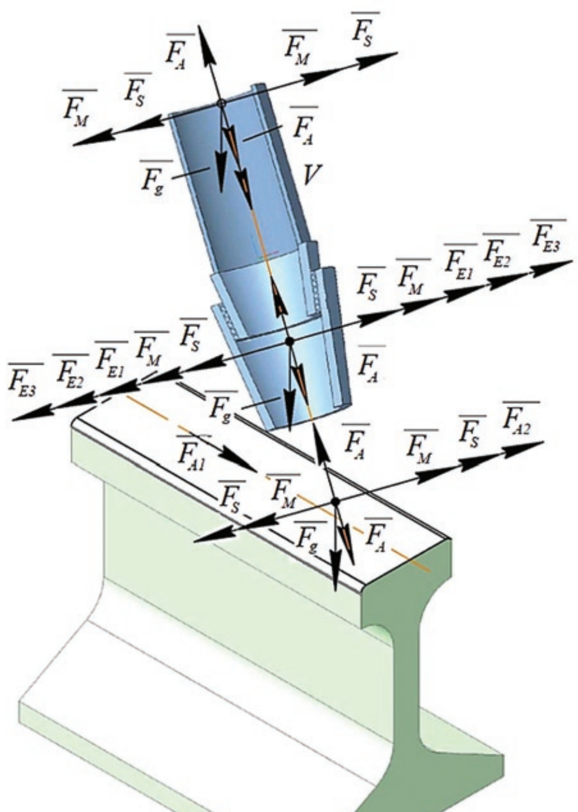


*Fig. 4. The scheme of action of forces in the system 'injecting nozzle of sandbox– rail': $F_M$ is the force of Magnus; $F_S$ is Seffman's force; $F_A$ is aerodynamic acceleration force; $F_g$ is gravity; $F_{E1}$ is the electric force due to the accelerating electric field; $F_{E2}$ is the electric force due to the polarization of the particles; $F_{E3}$ is electric force due to the interaction of charged particles*

In the pipeline, a force of aerodynamic drag acts on a grain of sand $\vec{F}_A$, the cause of occurrence of which is the difference between the gas velocity and the velocity of the particle moving in it. The action of this force leads to acceleration or deceleration of the particle:

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

where $C_D -$ is the drag coefficient of the particle; $\rho -$ is gas density; $\vec{U} -$ is gas velocity projection.

Along with the force of aerodynamic drag $\vec{F}_A$ the gravity $\vec{F}_g$ is one of the most important force factors determining the dynamics of particles:

$$\vec{F}_g = \rho_p \frac{\pi d_p^3}{6} \vec{g}. \tag{3}$$

The heterogeneity of the profile of the averaged carrier gas velocity is described by the Saffman force $\vec{F}_S$ [32], in this connection the difference in the relative flow velocities of the particle from different sides leads to the occurrence in the pressure drop. The movement of particles is carried out in the direction of the pressure drop (Fig. 2):

$$\vec{F}_S = k_S \nu^{1/2} \rho d_p^2 (U_x - V_x)\left(\frac{dU_x}{dr}\right)^{1/2}, \tag{4}$$

where $\nu$ – is the coefficient of kinematic viscosity; $k_S -$ is the Saffman lift coefficient, being equal to 1.615.

When moving in a gas flow particles rotate, entraining the gas. As a result, on the side where the directions of flow and rotation of the gas elements coincide, the pressure becomes lower compared to the area where these directions are opposite. Thus, the particle will move in the direction of reduced pressure. The magnitude of the force acting on the particle during its rotation is described by the Magnus force $\vec{F}_M$ :

$$\vec{F}_M = k_M \cdot \rho \cdot \left(\frac{d_p}{2}\right)^3 \cdot \left(\vec{W} \times \vec{\omega}_p\right); \tag{5}$$

where $k_M(\mathrm{Re})$ – is the coefficient convertible depending on the Reynolds number; $\vec{W} -$ is a transfer velocity relative to flow; $\vec{\omega}_p -$ is particle rotation speed.

When a particle hits a charging device, electrical forces additionally act on the particle as follows:

*a) the electric force conditioned by the accelerating electric field:*

$$F_{\acute{y}1} = qE(x); \tag{6}$$

where $q -$ is the electric charge; $E -$ field strength;

*b) electric force conditioned by the polarization of particles:*

$$F_{\acute{y}2} = \frac{\pi}{2} \varepsilon_0 d^3 \frac{\varepsilon - 1}{\varepsilon + 2} E \frac{dE}{dx}; \tag{7}$$

where $\varepsilon_0 -$ is electric constant; $\varepsilon -$ is the dielectric permeability;

*c) electric force conditioned by the interaction of charged particles:*

$$F_{ý3} = \frac{q^2}{4\pi\varepsilon_0 L_1^2}; \quad (8)$$

where $L -$ is the distance between the particles.

When leaving the nozzle, the sand is influenced by the force of aerodynamic resistance from the possible side wind $\vec{F}_{A1}$ и and the force of air resistance from the running of the locomotive $\vec{F}_{A2}$ (the running of the locomotive up to a speed of *10 km/h* was considered).

## 3. Results of sand electrification modelling

The simulation model for the movement of loose material is based on the particle method [14]. Along with the finite element method, boundary elements, etc., the particle method is one of the discretization methods. In this case, the motion of each of the particles is considered. The state of a physical system is determined by the attributes of a finite ensemble of particles, and the evolution of a system is determined by the interaction of particles between themselves and the environment. An important feature of the method is the possibility of taking into account the influence of a large number of factors of various nature.

On the basis of the developed simulation model composed considering formulas 1-8, a computer program was created in the C++ Builder 6 software environment of the movement of particles through a pipeline, their electric charging, and interaction with the rail surface [18]. As a result of simulation modelling, the effect of voltage on the charge of sand grains, the radius, and angle of sand dispersal was determined (Fig. 5, Fig. 6). The graphs in Fig. 5 and Fig. 6 show that for the required distribution of sand over the contact patch and reduction of its flow rate, the supplied voltage should be 450 V, and the electric charge should equal $1.502 \cdot 10^{-11}$ C.

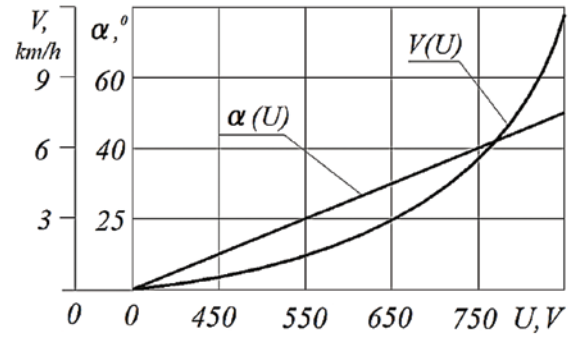


*Fig. 5. Dependences of the sand dispersal angle α and the speed of movement V on the supplied voltage U*

The experiments performed indicate that upon the electrification of particles, they uniformly distribute over the metal surface into one layer. The photos registered during the process of executing the experiments are shown in Fig. 7, where the difference of sand dispersal with the electrification of abrasive particles (Fig. 7, b) and without it (Fig. 7, a) is clearly demonstrated. The input voltage of the transformers supplied to the input of the coil was 14 kV. The time from the moment of opening of the mechanical valve in both experiments was 3 seconds. Fig.7 shows that, in the absence of electrification, there is a negative phenomenon of the adhesion of the wheel with the rail - the formation of a gravity hump and a gap between the surfaces of the adhesion (contact) is observed. While the charged abrasive particles evenly distribute over the surface in one layer and are retained on it.

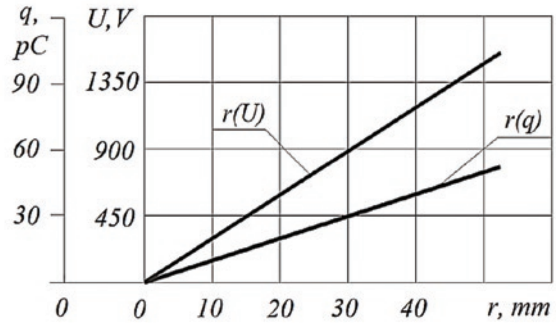


*Fig. 6. Dependences of the dispersal radius r on the supplied voltage U and electric charge q*

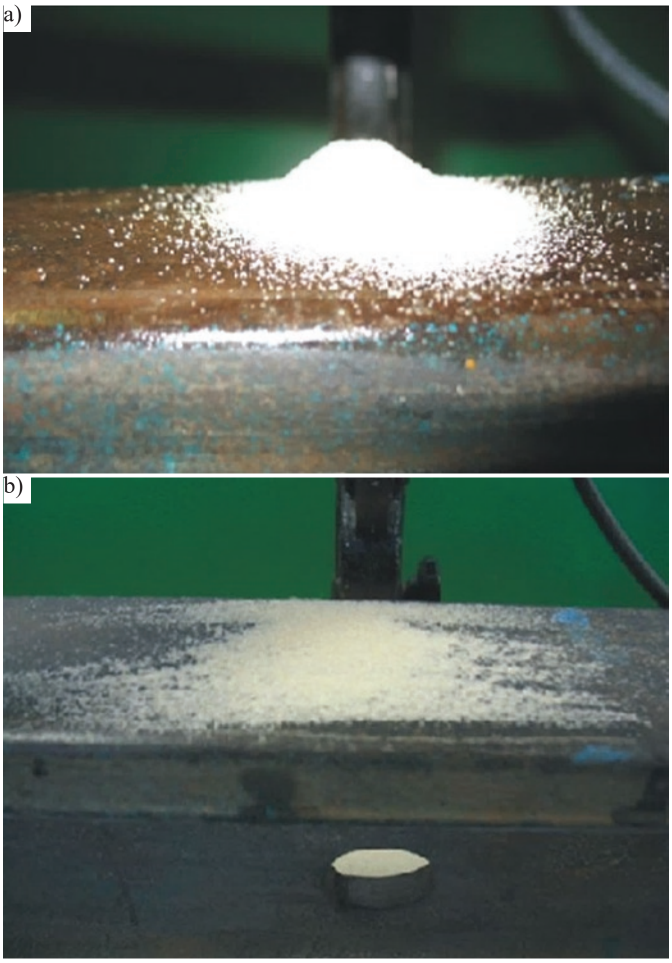


*Fig. 7. Photo registration of sand dispersal: a - without electrostatic charging, b - with electrostatic charging*

Evaluation of the efficiency of supplying electrified sand to wheel contact with a rail was carried out on an improved experimental stand installation 'Friction machine for studying frictional properties of contact' at the Department of Railway Transport of Volodymyr Dahl East Ukrainian National University [38, 40].

The processing of the data was performed by the computer program 'FrictionMachine'. The initial data for the program are the results of sensor calibration and the results of experiments. The program approximates the dependencies obtained and performs the regression analysis by the method of least-squares.

The processed results of experiments in the form of dependences of the friction coefficient on the temperature in contact under different frictional states are shown in Figure 8. Fig. 8 shows that the supply of electrified sand to oily rails allows the increase of the friction coefficient in oily contact from 0.25 to 0.4 (Fig. 8a), on water-covered rails from 0.35 to 0.5 (Fig. 8b).

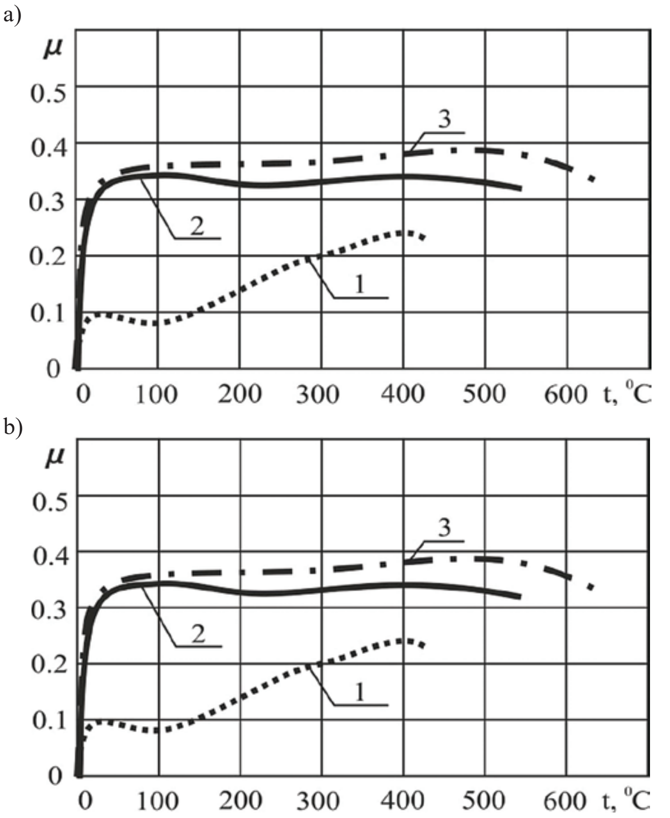


*Fig. 8. Experimental dependences of the friction coefficient on the temperature in contact: a - oily rails; b - water-covered rails (1 - without sand; 2 - with the addition of sand; 3 - with the addition of electrified sand)*

Compared to the supply of non-electrified sand, the friction coefficient of a wheel with a rail for oily rails is increased by 16%, for water-covered rails - by 20% [9, 18].

## 4. Efficiency of applying electrified sand in the contact of a wheel with a rail

Evaluation of the effectiveness of applying this method was performed by comparing the mass of abrasive material supplied to the contact without electrification *m* (Fig. 9, a) and with electrification $m_e$ (Fig. 9, b).

According to the formula [18], the efficiency of application of electrified sand estimated by reducing the consumption rate of abrasive bulky material will be equal to the ratio of *m* to $m_e$:

$$\Delta E = \frac{a^2 \cdot \rho \cdot tg\gamma}{0.24 \cdot m_e}; \qquad (9)$$

where a – is the width of the sand distribution on the rail surface, m; $\gamma$ – is an angle of the natural sloping of sand, grad; $\rho$ – is density of dry sand, $kg/m^3$.

The angle of repose of sand $\gamma$ depends on its moisture and clay content. In sand systems of a locomotive, the sand with the moisture content of not more than 0.5%, the clay component of no more than 3%, and the angle of repose $\gamma$ of 40 degrees is used. The density of dry sand is $\rho = 1400 - 1600$ $kg/m^3$. According to the formula *9*, we obtain that the consumption rate of sand will decrease by 12 times when electrification is used.

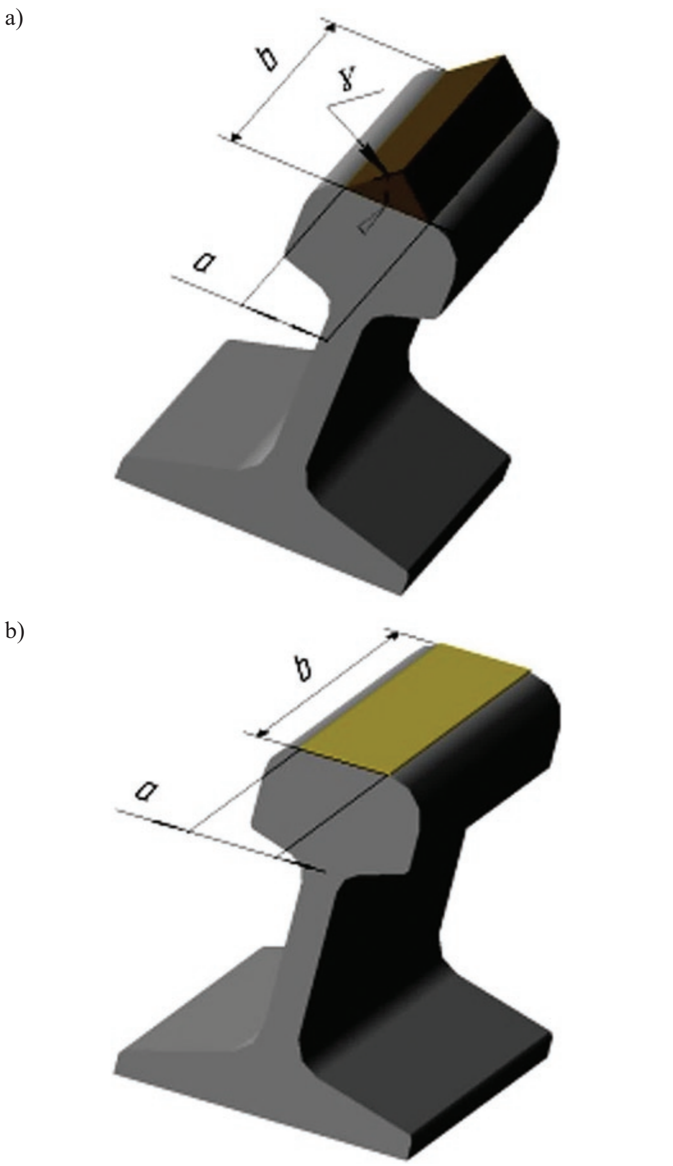


*Fig. 9. Schemes of the mound of abrasive bulk material on the rail: a - without electrification; b - with electrification*

Fuel consumption rate is reduced by using various ways [4]. Sustained realization of the locomotive force of thrust is inevitably accompanied by sliding of the driving axles. As traction increases, the sliding increases as well [43]. Then sliding begins to increase faster than the force of thrust, and then a violation of the stability of the realization of the force of thrust is detected. And when the relative slipping speed reaches about 1.5–2.0%, the further growth of the force of thrust stops and the wheel slipping begins. Thus, if the actual sliding speeds on the locomotive being used exceed the specified speed, this will mean that, during the operation of the locomotive, either periodic wheel slipping of individual axes or their slipping with a corresponding loss of energy were observed. The supply of electrified sand to the contact of the wheel with the rail reduces the sliding speed, respectively, reduces the consumption of fuel or electricity.

In the operation of trains, there are railway lines or even whole railway stretches, where the operating locomotive may show a significantly large excess of relative sliding of the driving axles (the phenomenon of ‘disturbing’ movement). In this case, the additional fuel consumption for the operation of forces of thrust in the contact of the wheels with the rails increases dramatically.

Thus, the additional costs of fuel or electric power of a locomotive due to slipping may comprise a significant proportion of the total cost of moving trains. These costs will depend on the design features of the locomotive, as well as on the actual operating conditions that determine the actual number and duration of the slipping of the driving axles.

It follows that the use of new sand systems with electrification of sand, which allow the reduction of sliding and prevent the occurrence of slipping, ensures stable operation of trains, reduction of wear of wheel tires and rails, and some reduction in fuel consumption or electricity for traction is observed as well.

## Conclusions

1. The developed simulation model describes the effect of the electric charge of particles of an abrasive material (sand) on the injecting process and on the uniform distribution of sand on the rail surface.
2. For the effective distribution of particles of abrasive bulky material (sand) on the rail surface, an electrical voltage of 450 V is necessary, the value of the electric charge is $1.502 \cdot 10^{-11}$ C.
3. Experimental dependences of the friction coefficient in the contact with electrified sand substantiate the expediency of sand electrification. These dependencies make it possible to refine the mathematical models for determining the adhesion force at the traction mode of the locomotive.
4. Pre-electrification of the abrasive-air mixture supplied to the tribological contact of the wheel with the rail ensures the uniform distribution of sand on the rolling surface of the rail. Electrified sand instantly cleans the contacting surfaces of the wheel and rail from contamination as a result of their electro-erosion destruction. Compared to non-electrified sand, the friction coefficient in the wheel-rail contact is increased by 16% for oily rails and 20% for water-covered rails.
5. The supply of electrified sand guarantees not only the optimal traction and adhesion as well as braking qualities of locomotives, but also decreases the energy loss of the locomotive by reducing the path travelled by train at the time of slipping. Using the developed sand system allows decreasing the consumption of sand by 12 times and reducing the wear of the rolling surfaces of the wheels and the rail.

***Acknowledgements***

*This research was funded by a grant (No. S-LU-18-12) from the Research Council of Lithuania. This research was performed in cooperation with the Volodymyr Dahl East Ukrainian National University, Ukraine.*

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