



Study of the aerodynamic characteristics and dispersed composition of halite salt dust

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Abstract. The paper presents the results of a comprehensive study of the physical and particle-size characteristics of halite salt dust, which is widely used in industry and traditionally not regarded as a hazardous environmental pollutant. Nevertheless, under large-scale production conditions, crushing, handling, storage, and transportation processes are accompanied by additional crystal fragmentation, which may lead to the formation of fine fractions and dust aerosols. Under certain aerodynamic conditions, such particles are capable of dispersing beyond industrial sites, thereby contributing to the problem of industrial air pollution. The aim of the study was to provide a quantitative assessment of the dust-forming tendency of halite salt and to determine the characteristics of the resulting dust fraction. The research included an analysis of the particle size (granulometric) distribution of both the initial material and the generated dust, experimental investigations of particle entrainment by airflow, determination of dust particle settling velocities, and measurement of their true density using the pycnometric method. The obtained data make it possible to assess the potential migration capacity of the fine fraction and its contribution to aerosol pollution under large-scale production conditions. It is shown that even with a relatively small mass fraction of fine particles, the total emission volumes may be significant due to high production capacities. The results of the study can be used in the development of dust suppression measures, optimization of technological regimes, improvement of dust collection systems, and in the environmental assessment of enterprises involved in the processing and storage of halite salt.

Keywords: particle size distribution, particle entrainment, dust settling speed velocity, halite salt

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1. INTRODUCTION

The present study is aimed at a detailed investigation of the aerodynamic and particle-size characteristics of halite salt dust generated during its processing and handling operations. Considering the scale of production and the potential ability of fine particles to undergo aerosol transport, obtaining

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reliable data on particle size distribution and particle motion parameters in an air environment is of particular relevance.

The particle size distribution of halite salt dust was determined using microscopy in accordance with the requirements of GOST R 56929–2016. The application of a standardized methodology ensured the reproducibility of results and the accuracy of the quantitative assessment of particle size distribution. Microscopic analysis made it possible to establish the particle size range, identify predominant fractions, and obtain initial data for subsequent calculation of aerodynamic characteristics.

Further experimental studies were aimed at determining particle settling velocity and specific entrainment rate using specially designed laboratory setups. The study established the dependence of settling velocity on particle diameter and determined the mass distribution of the material with respect to settling velocities, which represents a derived characteristic of the initial particle size distribution of the dust. In addition, the threshold friction velocity (critical velocity for the onset of particle motion along a surface) and the initial entrainment velocity of halite salt dust by an airflow were determined experimentally. The obtained quantitative parameters are of practical importance for the engineering design of dust control systems, the selection and calculation of dust collection equipment, as well as for substantiating environmental protection measures aimed at reducing fine salt dust emissions into the atmosphere.

The settling velocity of particles is an integral aerodynamic characteristic of a dust material that determines its inertial properties in a gas flow. In vortex and centrifugal dust collectors, including counter-rotating swirling flows, collection efficiency is governed by the ratio of inertial forces acting on a particle to the aerodynamic drag of the medium. This ratio, derived from the well-known equation of particle motion in a gravitational field under steady-state conditions, is conveniently characterized by the Stokes number [1-4]:

$$Stk = \frac{\tau_p U}{L}, \quad (1)$$

Here, U is the characteristic flow velocity, L is the characteristic size of the apparatus (flow length), and τ_p – particle relaxation time (time constant in exponential decay of particle velocity due to resistance), which can be calculated using the formula:

$$\tau_p = \frac{w_s}{g}, \quad (2)$$

Where w_s is the dust settling velocity and g is the acceleration constant of free fall.

Settling velocity is an integral aerodynamic characteristic of dust particles that determines their ability to precipitate from a gas flow. In inertial and vortex dust collectors, this parameter defines the cut-off particle size, the probability of secondary entrainment, and the overall efficiency of the device.

An increase in flow velocity is not a universal means of improving collection efficiency, since it simultaneously enhances turbulent fluctuations and secondary particle re-entrainment. The rational selection of the operating regime should be carried out with due regard to the settling velocity of dispersed fractions, which determines their aerodynamic stability within a vortex field.

Thus, the present study is of interest both in terms of the obtained data themselves and from the standpoint of developing a methodology for determining these parameters and describing the experimental setups.

2. METHODS AND MATERIALS

Sieve analysis or dust microscopy makes it possible to obtain a stepwise passing function D , defined as the percentage ratio of the mass of all particles in a given sample with diameters smaller than δ to the total mass of the dust material. The value δ is always discrete, since the equivalent diameters of dust particles are specific and finite. However, if the intervals between adjacent particle sizes are sufficiently small compared with the observed variations in δ , the function $D(\delta)$ may, with

good approximation, be treated as continuous. Obtaining a continuous analytical function with a continuous derivative is an important task, since its determination facilitates the identification of patterns associated with dust suspension and transport. The function of the lognormal distribution of material mass over particle diameters is given by:

$$D(\delta) = \frac{100}{\sqrt{2\pi} \lg \sigma} \int_{-\infty}^{\lg \delta} e^{-\frac{(\lg \delta - \lg \delta_{50})^2}{2 \lg^2 \sigma}} d \lg \delta, \quad (3)$$

The integral in equation (3) cannot be expressed in terms of elementary functions, so it is transformed into a new argument t , which is called a normally distributed variable:

$$t = \frac{\lg \delta - \lg \delta_{50}}{\lg \sigma}, \quad (4)$$

The lognormal distribution is conveniently represented graphically on log-probability paper, since when plotted on such a grid the lognormal distribution appears as a straight line. On this grid, the logarithms of particle diameters are plotted along the abscissa (with the actual diameter values indicated), while along the ordinate the values of t (mass distribution from 0 to 100%) are plotted, with the corresponding values of the function $F(t)$ taken from the appropriate table. Dust microscopy was performed in accordance with [5] and similarly to the procedure described in [6]; a vortex chamber was used to distribute particles over the surface of a microscope slide, and the SPOTEXPLORER software package was applied for image analysis.

The settling velocity of dust particles is an important parameter in gravitational separation processes and is defined as the steady-state velocity of a particle moving in a quiescent medium under the balance of gravitational force, buoyancy (Archimedes' force), and aerodynamic drag. In experimental studies, particular attention is paid to the dependence of settling velocity on the equivalent particle diameter, which makes it possible to account for the actual particle shape through an equivalent sphere. It has been established that at low Reynolds numbers the settling velocity is proportional to the square of the equivalent diameter ($v \sim d_{\text{equivalent}}^2$), whereas with increasing diameter and transition to other flow regimes, the dependence becomes nonlinear and is determined by empirical drag coefficients [7-9].

To determine the settling velocity, a manually operated mechanical sedimentation chamber assembled similarly to the Kouzov sedimentation chamber was used. It consists of a starting section for dust entrainment, a vertical tube, and a sedimentation chamber that collects dust on plates positioned at the bottom of the structure. The appearance of the device is shown in Fig. 1.



a) Starter device assembled



b) Starter device, dust blowing plate



c) Plates for dust settling

Fig. 1. Appearance of the sedimentation chamber.

Fig. 4 shows photographs of dust collected from the six plates of the device. The plates are closed sequentially from bottom to top, thereby blocking the passage of dust to the plates located below. Subsequently, the dust layer from each plate is collected using a synthetic brush into a container, which is then labeled and weighed on laboratory scales. Micrographs of the dust obtained from each plate are presented in Fig. 2.

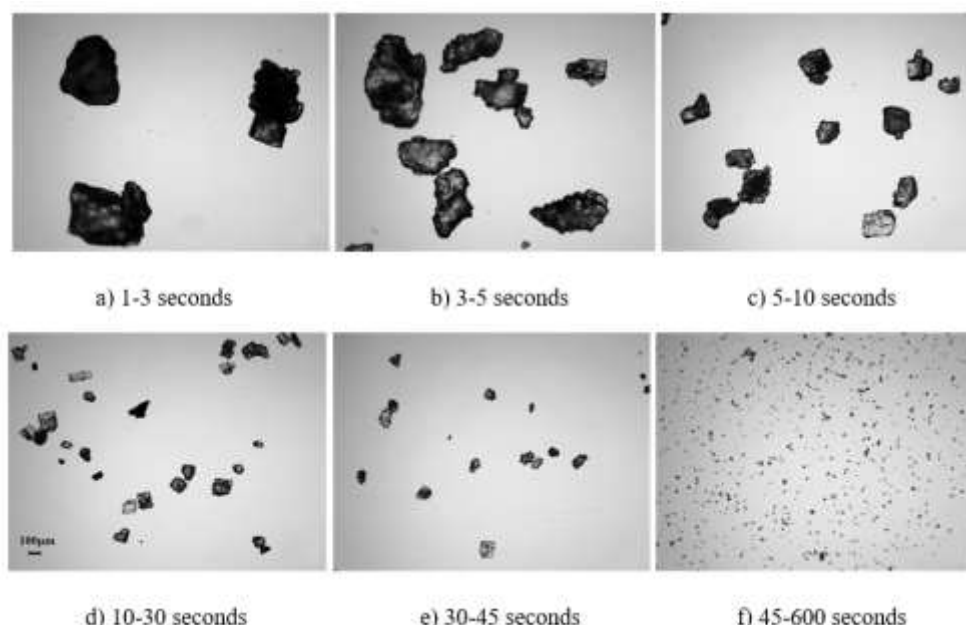


Fig. 2. Dust settling velocity depending on the equivalent diameter of halite dust.

It follows from Fig. 2 that each subsequent plate collects particles of smaller diameter compared to the previous one. This is explained by the fact that fine particles are characterized by lower settling velocities and, consequently, require a longer time to reach the corresponding plate located in the lower part of the apparatus after the beginning of the experiment. Thus, for each plate, the corresponding particle size ranges and the associated settling velocity intervals were determined.

Aerodynamic tests of halite dust were carried out in order to determine the maximum specific entrainment rate, a parameter introduced in the Novorossiysk methodology for calculating emissions from fugitive sources. This parameter characterizes the specific dust removal from a given surface area over a fixed time interval. The experimental objective was to determine the entrainment coefficients at different air flow velocities in a wind tunnel and subsequently to obtain an empirical power-law relationship between the specific entrainment rate and the flow velocity.

Measurement of the specific dust entrainment rate from various surface types is necessary for assessing the contribution of natural sources to PM_{10} concentration levels. Experimental studies, including those conducted in wind tunnels, demonstrate that the emission flux exhibits pronounced temporal variability and is largely governed by aerodynamic particle entrainment. It has been established that the specific entrainment rate depends both on the friction velocity (or free-stream velocity), typically following a power-law relationship, and on the particle size distribution and surface condition. The presence of a loose reservoir of fine particles promotes high emission values, whereas crust formation, gravel coverage, or increased cohesion of the fine fraction reduces the intensity of entrainment. Thus, the granulometric composition and structural state of the surface play a key role in controlling particle availability for aerodynamic removal [10-13].

The experimental setup used in this study is similar to that described in [14]. The dust sample was placed on a platform providing unobstructed airflow and allowing additional weighting of the structure. A dust sample (not less than 10 g) was applied onto a plate using a 6×6 cm stencil and evenly distributed with a synthetic brush. The sample mass was recorded using laboratory scales before and after the experiment. The layer thickness was selected to ensure its stability throughout the test; if necessary, the airflow velocity or the sample mass was adjusted.

The air velocity generated by a radial fan (SovPlym) and regulated by a transformer was monitored using a DMC-01 differential manometer at the central cross-section of the tube. The sample was positioned in the middle of the working section and exposed to the airflow for 3 minutes. After exposure, the sample was removed and reweighed to determine the mass of dust removed. The specific entrainment rate was calculated using the following equation:

$$q = \frac{m_1 - m_2}{t \cdot S}, \quad (5)$$

Here, q is the specific entrainment coefficient corresponding to the established airflow velocity. ($\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$); m_1 – initial mass of dust sample, g; m_2 – dust weight after the blowing-off process, g; t – time of exposure of the sample to the air flow, s; S – dust coating area on the plate, m^2 . The experiment is repeated for a range of speeds from the minimum starting speed of the particles to 8-12 m/s, depending on the properties of the substance. Once we have obtained a table showing the dependence of the blow-off coefficient on the air flow velocity, we can use this data to construct a power function, which has the following form:

$$Q = aV^b, \quad (6)$$

Here, Q is the power-law function describing the dependence of the specific entrainment rate on the airflow velocity. ($\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$); a and b are empirically determined coefficients, and V is the air flow velocity, m/s. This equation, obtained by regression analysis, allows the experimental data to be generalized for use in calculating the specific characteristics of the entrainment rate.

3. RESULTS AND DISCUSSION

Fig. 3 presents the integral particle size distribution by mass. The linear segment observed approximately in the range from 10 to 50 μm confirms the validity of the lognormal distribution law for dust within this interval. However, the curve as a whole deviates significantly from the straight line expected in this logarithmic probability coordinate system, suggesting that the collected sample represents a combination of several fragmentation processes that likely differed, for example, in abrasion and grinding duration. Based on our experience, such a function typically does not exhibit pronounced curvature, which indicates specific features either of the fragmentation processes themselves or of the subsequent transport of this dust.

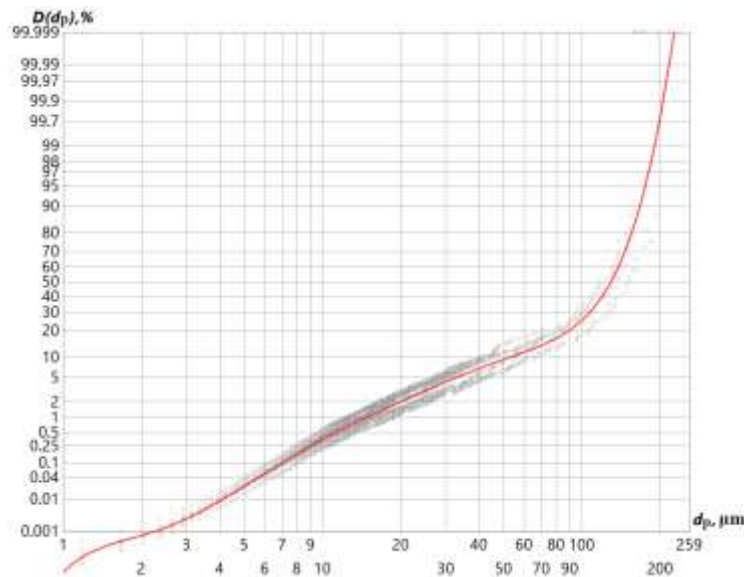


Fig. 3. Integral particle mass distribution function by diameter for halite salt dust. $R^2 = 0,94$.

In processing this series of dust images obtained using an optical microscope, a currently under-development version of the Spotexplorer FA software was used. It performs calculations according to the same algorithms as the original SPOTEXPLORER, but is supplemented with several additional features. The first feature is approximation using the open mathematical library ALGLIB, specifically

the smoothing cubic spline method (spline1dfit) and the least-squares rational approximation method based on Floater–Hormann barycentric rational functions.

The second feature is called “dataset merging”, which makes it possible to generate a single function from several photographs. This increases the dust particle sample size and refines the data. The result is equivalent to proportionally expanding the microscope’s field of view. The third feature is referred to as a virtual sieve. The essence of this useful processing method is that particles with diameters exceeding a specified value are excluded to allow cleaner comparison between the obtained images.

For example, it is useful if a large particle accidentally appears in the photographs, or if the particle size distribution is of interest only within a certain range, such as from 0 to 100 μm , rather than including all particles present on the microscope slide. Fig. 4 shows the same halite salt dust sample, but within the 0–100 μm range. Particles larger than 100 μm are generally not considered dust due to their excessively high settling velocity.

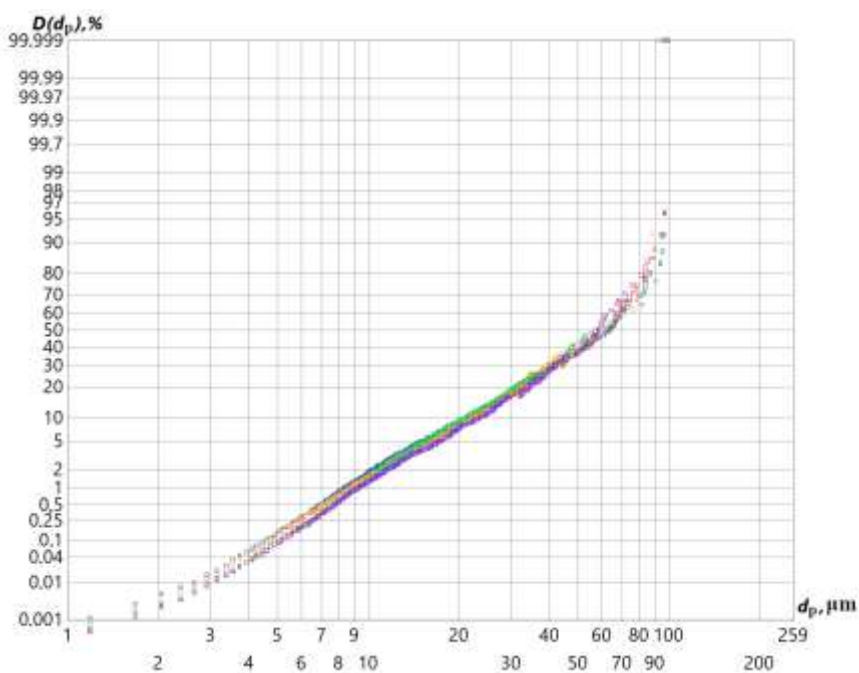


Fig. 4. Integral particle mass distribution function by diameter for halite salt dust using the SPOTEXPLORER FA program tool “Virtual Sieve” at a value of 100 μm .

For clarity, the main data on the particle size distribution of halite salt dust from Fig. 1-2 are summarized in Table 1. It presents the values D_5 , D_{50} , and D_{95} , each corresponding to a certain equivalent particle diameter. For D_n , this is interpreted as follows: “particles with diameters smaller than this value account for $n\%$ of the total mass”. Accordingly, the table provides data on the minimum, maximum, and median diameters for the entire studied sample, as well as for the particles most susceptible to airborne suspension.

Table 1. Table of D-pass values.

Part of the sample	D_5	D_{50}	D_{95}
The entire sample	32	140	200
$D_p < 100\mu\text{m}$	16	60	97

Table 2 presents the particle size ranges of dust collected on each plate of the sedimentator, as well as the corresponding average settling velocities. Fig. 5 shows the experimentally obtained dependence of settling velocity on the equivalent particle diameter, while Figure 6 presents the mass distribution of the material with respect to settling velocity. This distribution is essentially a derivative of the particle size distribution and was determined by weighing the dust sample collected from each individual plate.

Table 2. Passage D values for dust settling velocity.

Plate, №	D ₉₅ , µm	D ₅₀ , µm	D ₅ , µm	Average speed, cm/s
1	310	240	180	123
2	220	168	120	81
3	180	140	96	32
4	140	100	70	12
5	80	60	30	6
6	40	20	10	1

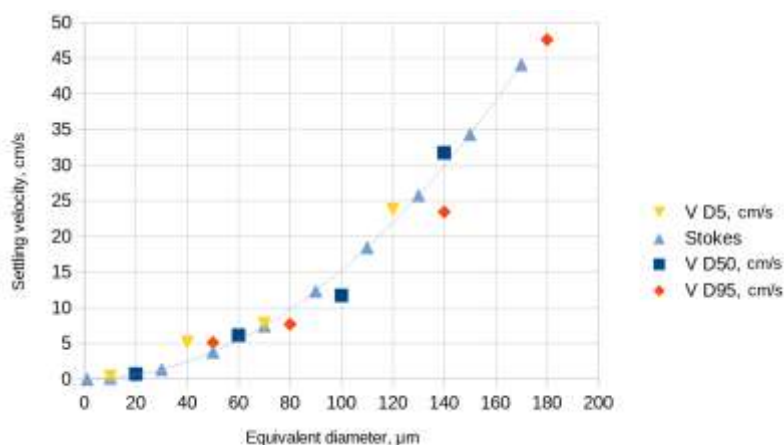


Fig. 5. Dependence of sedimentation velocity on equivalent diameter for halite dust particles.

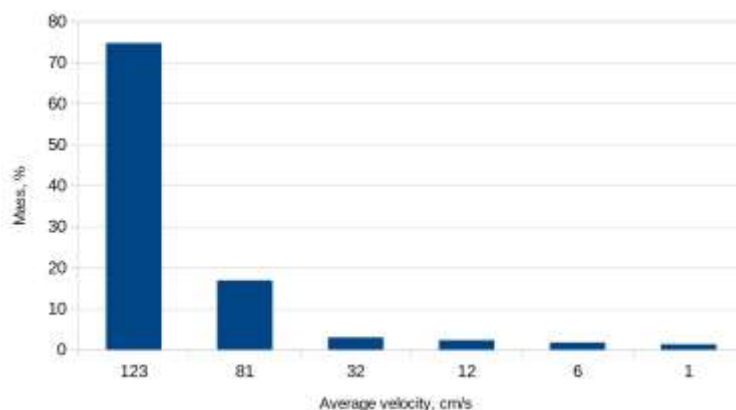


Fig. 6. Distribution of sample mass of halite dust by average settling velocity.

Formula (7) is Stokes' formula for dust settling, taking into account the dynamic shape coefficient [15]. Dust particles are not spherical, as required by the well-known Stokes formula, so the shape coefficient in this case acts as a correction factor established as a result of a series of experiments.

$$V = \frac{1}{18} \frac{\rho}{\chi \cdot \mu} \cdot g d^2, \quad (7)$$

Here, V is the settling velocity of a dust particle (m/s), ρ — true density of dust particles, determined by the pycnometric method, (2100 kg/m^3), μ — dynamic viscosity of air at temperature 20°C , ($1.82 \cdot 10^{-5} \text{ Pa}\cdot\text{s}$), g — acceleration of free fall, (9.8 m/s^2), d — particle diameter, (m), χ — dynamic shape factor, (4.2). Substituting these values into formula 7 will yield an analytical dependence of the settling velocity of particles on their equivalent diameters based on the results of a series of experiments.

Next, a table of the blowing-off coefficients q for the investigated air flow velocities was compiled. Using the standard Excel functions, a power-law function of the specific dust removal rate of halite salt was obtained by regression analysis:

$$Q = 0.00021 V^{5.93}, \quad (8)$$

The obtained power-law model, in combination with the storage coefficients, makes it possible to calculate dust emissions from fugitive (unorganized) sources, such as open storage piles, transportation, and handling operations. At low air velocities, this dust is hardly subject to blowing off; however, when the velocity exceeds 5 m/s , the specific dust removal rate increases very rapidly. Therefore, the dust can be considered highly susceptible to blowing off, due to the low content of fine particles that would otherwise slow down the entrainment process.

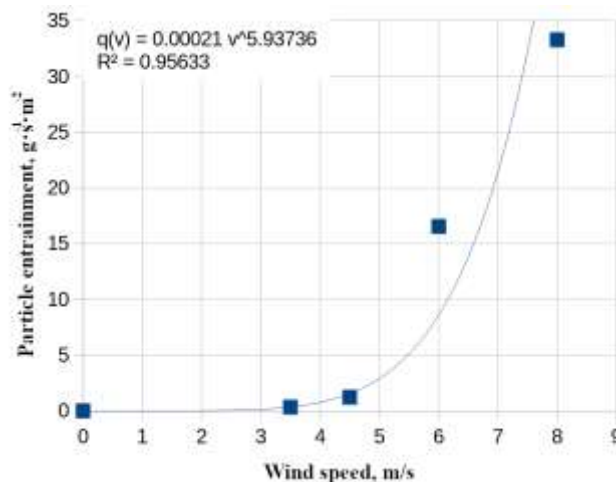


Fig. 7. Dependence of the specific dust entrainment coefficient on air flow velocity in an experimental wind tunnel.

4. CONCLUSIONS

The study investigated the particle size distribution, as well as the physical and aerodynamic characteristics of halite salt dust. The particle settling velocity and median diameter were determined — parameters of fundamental importance for the design of counter-swirl flow (CSF) dust collectors and for the development of dust suppression measures.

The presence of a fine fraction in the studied sample was confirmed: according to microscopic analysis, the PM_{10} fraction accounted for approximately 1.5%, which is consistent with sedimentation measurements (the proportion of particles with a settling velocity below 1 m/s was about 1.5%).

Despite the relatively low content of fine particles, their contribution to atmospheric air pollution under industrial conditions is significant. An experimental relationship between particle settling velocity and equivalent diameter was established for halite salt dust.

Aerodynamic tests showed that with an initial entrainment velocity of 3–3.5 m/s, a sharp increase in the specific dust entrainment rate is observed at an air flow velocity of about 5 m/s. This indicates a high susceptibility of halite salt dust to wind entrainment and potentially significant particulate emissions during open storage of the material.

The comprehensive study made it possible to obtain quantitative characteristics governing dust behavior during dispersion in the atmosphere, as well as to validate the methodological approach and experimental setup applicable for assessing dust generation and substantiating environmental protection measures.

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