UDC 621.9

# Part 3

# ASH AND SLAG HANDLING

## 3.3. Ash and slag properties

### 3.3.10. Investigation of influence of the particle shape and polydispersity on the critical velocities of dust and air flows while transporting the fine polydisperse materials in pneumatic conveying pipelines

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## ABSTRACT

The article provides brief results of analyzing the studies of various modes of pneumatic conveying of fine polydisperse bulk solids, presented in Russian and foreign sources of scientific and technical information. The following modes have been considered: plug flow, dilute- and dense-phase conveying with significantly different velocities of the flow, conveying of fine materials with particles of various sizes and geometric shape - from spherical to plate, sharp-cornered and even shell-acute. The results of analysis of pneumatic conveying technologies used in the energy sector of Russia and world-wide are described. The paper contains brief results of analyzing the research presented in scientific and technical information sources relating to definition of the shape and polydispersity of particles of fine polydisperse materials[1].

## 1. BRIEF DESCRIPTION OF PNEUMATIC CONVEYING TECHNOLOGIES APPLIED IN THE POWER SECTOR

Through the use of pneumatic conveying technologies, it’s possible to transport a wide variety of dry fine polydisperse materials used in various industries, both within the shops, and beyond. The materials transported may have different mechanical properties, chemical and mineralogical composition and particle size distribution, as well as various particle shape. Density of the transported particles can vary from 16 to 3200 kg/m$^3$ [1]. When transporting fine polydisperse materials in pneumatic conveying pipelines, one of the main important factors is a critical velocity of dust and air flow. The critical air velocity in the dust and air flow is used to determine the operating air velocity necessary for reliable operation of pneumatic conveying systems, which significantly affects the value of specific energy consumption for transporting bulk solids and erosion of pneumatic conveying equipment. There are various modes of pneumatic conveying of fine polydisperse materials such as ash, coal dust, sand etc. - plug flow, dilute- and dense-phase conveying. Under different conveying modes there are observed critical flow velocities, differ tenfold. Particles being transported have significantly different geometric shape - from spherical to plate, and even sharp-cornered and shell-acute, which also affects the nature of their transportation. It should be also taken into account the fact that particles in the flow react with each other.

Pipeline pneumatic conveying of bulk solids appeared in 1866 [2]. It is widely and successfully used in different branches of the world economy for several reasons: firstly, pneumatic conveying is a fairly reliable way to transport fine polydisperse materials in comparison with other types of transportation; secondly, it is more cost effective as compared with mechanical and hydraulic transport; thirdly, pneumatic conveying is more environmentally acceptable way of transporting materials from the point of view of impact on environment, because pneumatic pipeline is a closed element and, therefore, there’s no dusting. Also, pneumatic conveying systems are technologically flexible, they can have different configurations and transportation distances depending on the requirements of customers.

In the power industry pneumatic conveying is used to transport coal dust, ash and slag. Worldwide at thermal power plants millions of tons of coal are burnt. By that, quality of the burnt coal is significantly different depending on locations of coal mines and coal beds. Solid fuel combustion results in production of coal combustion by-products in the form of ash and slag with significantly different composition, depending on the quality of coal burnt and combustion conditions. Both coal dust and coal combustion by-products can be effectively pneumatically conveyed using dry method with no water use, thereby causing minimal damage to the surrounding environment and, at the same time, keeping the consumer properties of ash and slag.

At TPPs and boiler-houses different systems of coal ash transportation are applied [3]:

- mechanical ash removal systems;
- hydraulic ash removal systems;
- pneumatic ash handling systems;
- combined ash removal systems.

Coal ash transportation plants are divided into internal and external. Plants of internal pneumatic ash transportation are designed to convey ash from hoppers of electrostatic precipitators to intermediate hoppers or dry ash storage silos. Plants of external pneumatic ash transportation are designed to convey materials from intermediate hoppers or dry ash storage silos to ash disposal sites. According to [3] at TPPs the following plants of internal pneumatic ash conveying are used:

- gravity;
- airslides;
- vacuum plants;
- pressure plants with jet, pneumatic chamber and pneumatic scew pumps.

The article presents the results of reviewing scientific and technical information sources relating to critical velocities at pneumatic conveying of fine polydisperse materials in pressure units with diverse modes of transportation of bulk solids with different pneumatic conveying velocities. First of all, they are dilute- and dense-phase conveying modes for transportation of fine polydisperse materials. At the same time the particle size distribution and a shape of the transported particles significantly influence critical pneumatic conveying velocities. Gravity plants were not considered, since the main determinant parameter of pneumatic conveying in such systems is a natural angle of slope, but not particle size distribution of solids and particles shape. In such facilities modes of dilute- and dense-phase conveying of bulk solids are not available. Pneumatic conveying in airslides hasn’t been studied as well, since in such systems transporta-

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[1] Статья подготовлена по результатам выполнения исследований по гранту РФФИ №12-08-31145 «Исследование критических скоростей пылегазовых потоков при перемещении мелкофракционных полидисперсных материалов в пневмотранспортных трубопроводах»

tion in the fluidised bed occurs, but not in the mode of dilute- and dense-phase conveying. Furthermore, airslides are not widely used at thermal power plants due to their extreme technological inflexibility and short-range transportation. Vacuum units are used at TPPs quite rare in connection with a number of technical and technological limitations, and, therefore, their study is also inappropriate.

In Russia, India, England, Australia and other countries there have been conducted the studies of operating conditions and equipment of pneumatic conveying plants for transporting ash, coal dust and sand. In the Russian energy sector for many years experiments on pneumatic conveying of fine polydisperse materials were carried out on the pneumatic and hydraulic conveying testing area of the Siberian branch of VNIIG named after B.E. Vedeneyev (SibVNIIG, Krasnoyarsk city), dismantled in the 90s of the twentieth century. A characteristic feature of this testing area was a possibility of conducting there the experimental research using industrial equipment to simulate processes in a wide range of pneumatic conveying parameters, including the outrageous modes that can't be implemented at real operating pneumatic conveying installations of TPPs due to emergency restrictions. In Russia about 85 % of coal ash is transported by hydraulic ash removal systems, and only about 15 % - by pneumatic ones [4]. However, currently a transition from "wet" to "dry" coal ash removal systems is scheduled for the purpose of using these products in a dry form [5].

## 2. MODES OF PNEUMATIC CONVEYING OF FINE POLYDISPERSE MATERIALS

Fine polydisperse materials can be conveyed in pipelines by portions or continuously 24 hours a day, if necessary. It should be noted that in scientific and technical information sources there's no uniform terminology describing various pneumatic conveying modes. According to the processes occurring in pneumatic conveying pipelines there are two main groups of pneumatic conveying modes: dilute- and dense-phase conveying and fluidised bed conveying. Selecting the conveying mode is a very important factor that must be considered when designing pneumatic conveying systems. In case of fluidised bed conveying for transportation of bulk solids airslides are used, therefore this mode has not been investigated. A main group of the investigated modes is dilute- and dense-phase conveying of bulk solids.

### 2.1. Dilute- and dense-phase conveying of bulk solids

Such conveying modes are often used to transport fine bulk solids in various industries. Suspended particles are transported in the turbulized flow with velocities 2 ... 5 times exceeding the suspension velocity of particles. Pneumatic conveying in this case is characterized by large transportation distances (up to 1500 ... 2000 m) with capacity up to 300 t/h and specific air flow rates of 30...50 to 150...200 $m^3$ per 1 $m^3$ of material, increase in pneumatic mixture velocity along the pipeline (from 15...20 to 70 and even 100 m/s) due to the pressure drop and the flow expansion, significant range of pneumatic mixture concentration. There are low (0.1...5.0 kg/kg), medium (5...10 kg/kg) and high (10...400 kg/kg) mass concentrations [6].

### 2.1.1. Dilute-phase conveying of dust and air flow

In this conveying mode the mixture of air and fine polydisperse materials moves along the pipeline in the suspended state (Fig. 1).

By that air flow rate significantly exceeds the one of the transported material. Compared to dense-phase conveying, in this mode pressure is less, and the solids are conveyed at high velocities in a suspended state. To maintain the conveyed material in suspension it's necessary to ensure minimum transport air velocities ranging for the majority of materials from 12.7 to 30.5 m/s [7].

Dilute-phase conveying mode is characterized by the following parameters [7]:

- high conveying velocity - from 16.3 to 40.6 m/s;
- surplus working pressures - from 34.5 to 82.7 kPa and vacuum from 13.55 to 40.64 kPa.
- low mass concentrations (<0.5).

Restrictions on the use of dilute-phase conveying modes [7]. In this mode it is necessary to provide sufficiently high air flow rate and transport velocity, which leads to a sharp increase in energy consumption. For pneumatic conveying plants in case of dilute-phase conveying the following major disadvantages are also characteristic:

- increased erosion in pipelines;
- degradation of the brittle materials transported;
- relatively short conveying distance.

Critical velocities in dilute-phase conveying modes [7]. It's necessary to ensure certain critical pneumatic conveying velocities to maintain the material suspended and moved. Extra low velocity obstracts a transport ability of the material in the system, and unreasonably high velocity contributes to the growth of pressure loss, resulting in additional energy to overcome the resistance in the pipe. The transport velocity and hence the air flow rate are heavily influenced by material characteristics: particle shape, size distribution, mean particle size and density. All these factors affect the critical velocity of pneumatic conveying, pressure loss, air flow, etc.

### 2.1.2. Dense-phase conveying of dust and air flows

As opposed to the dilute-phase conveying mode at which the air flow rate significantly exceeds the flow rate of the transported material, and conveying occurs at high flow velocities, dense-phase conveying of dust and air flows has a significant advantage by effectively "pushing" high-concentrated bulk solids at relatively low conveying velocity in the pipeline [7]. This mode is suitable for transporting fragile materials. Thus, there is no increased erosion of the pipe material. Pneumatic conveying velocity at the starting section may be as low as 1 m/s for the majority of the transported materials, and the end section - about 10 m/s. In the dense-phase conveying mode the air flow rate is reduced to an absolute minimum, whereby it's possible to convey the material with a maximum density in the system.

In case of dense-phase conveying of dust and air flows the following basic modes are possible:

- pneumatic conveying of dust and air mixture with an axisymmetric distribution of the conveyed material across the pipeline section;
- plug mode of pneumatic conveying of bulk solids;
- pneumatic conveying with internal and external bypasses;
- fluidised bed conveying.

### Pneumatic conveying of dust and air mixture with an axisymmetric distribution of the conveyed material across the pipeline section

Main advantages of the dense-phase conveying mode are as follows: increase in conveying effectiveness due to lack of air slip through the transported material; erosion reduction due to less contact of particles with the pipe wall; material conveying velocity reduction under the same defined conditions.

Fig. 2 shows an example of the dense-phase conveying mode.

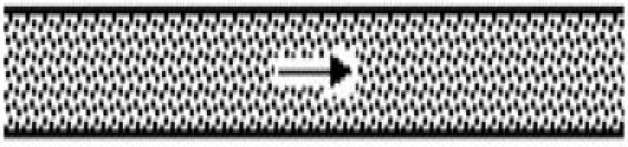

Fig 2. Dense-phase pneumatic conveying

This mode can be used for conveying dry pulverised, powdered and fine-grained solids at their aeration by the upflow up to mass concentration limits of 1000 ... 1500 kg/kg, with decrease in the bulk density by 5 ... 20 %. Aerated materials acquire pseudofluidisation properties and can be moved along the pipeline under pressure drop of the aerating air or by gravity – along chutes downhill for limited distances (up to 60...80 m) at velocities of 1.5 to 7 m/s, comparable with suspension velocities of particles and at comparable material and the carrier medium flow rates (1...5 kg/kg). Aeration at pneumatic lift and discharge of hoppers is carried out by air supply under the transported material, and at the horizontal conveying – by a co-jet along the conveying length through flexible hoses with exhaust valves along the pipeline or through the porous walls in pneumatic chutes. Dense-phase pneumatic conveying mode is characterized by moving a significant amount of material in the pipes of a small section (up to 30 t/h with diameter of 60 mm), small erosion in pipes and chutes, minor grinding and abrasion of the conveyed material, constant pressure drop along the conveying length and low specific energy consumption (to 1.5…1 kW·h/t) [6]. In this case, pneumatic conveying velocity is low and makes less than 5 m/s. Thus, such a method is the most cost effective pneumatic conveying mode in terms of minimizing energy consumption.

### Plug pneumatic conveying mode

In the plug mode various pasty materials and concrete mixtures (individual plugs), piece goods (pneumatic tube), capsules, containers (on rollers or air layer) and their compositions are conveyed.

In pipeline the materials are moved with velocities up to 5...15 m/s due to low air pressure difference (up to $10^4$ H/m$^2$) before and behind the plug [6].

Fig. 3. Pneumatic conveying in the plug mode

One example of the plug mode of conveying fine polydisperse materials with low velocity is presented in Fig. 3.

Under these transportation modes an average velocity of pneumatic mixture conveying is from 0.25 to 4 m/s. The mode is suitable for fragile and easily damaged materials [7]. By that, a part of material before and after the plug is transported in the lower generatric zone, forming a fixed bed. In this conveying mode wear is very low, even if erosive materials are transported.

Ideal plug mode of pneumatic conveying of bulk solids is shown in Fig. 4.

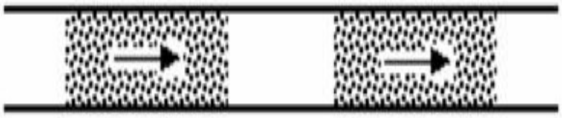

Fig. 4. Ideal plug mode of pneumatic conveying

In these modes pneumatic transport is carried out in a form of discrete plugs with a low pneumatic conveying velocity. The only difference from the previous mode is absence of the fixed bed of material in the lower layer [7]. However, in practice, implementation of this pneumatic conveying mode is not possible.

### Pneumatic conveying with internal and external bypasses

Another type of pneumatic conveying of bulk solids is a mode with internal and external bypasses. In this mode powdered bulk solids as aluminum and polycrystalline powders, finely-dispersed sand, coarse fly ash can be transported. According to [7] pneumatic conveying velocities in the pipeline are from 3 to 10.2 m/s, resulting in formation of plugs. With higher brace force, acting on the plug, the material becomes less breathable. For such materials it is necessary to supply air through the bypass tube into the place where air can transport the material, separating the plug.

In pneumatic conveying installations different types of bypasses can be used. For example, Fig. 5 and Fig. 6 show pneumatic conveying modes with internal bypass for the conveying air and a mode with additional external supply of compressed air along the pipeline length, respectively.

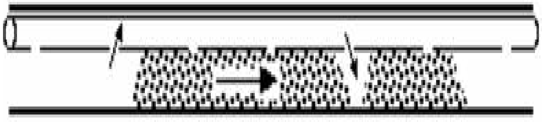

Fig. 5. Pneumatic conveying mode with internal bypass for conveying air

Basic ideas of these modes consist in controlling the plug length of material along the pipeline and prevention of supplying pressurized air through the conveyed material [7].

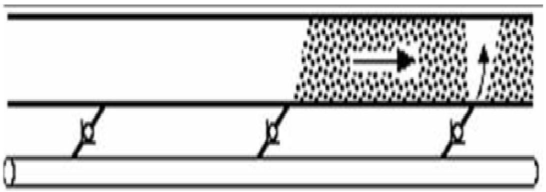

Fig. 6.Pneumatic conveying mode with additional supply of the compressed air along the pipeline

## 2.2. Pneumatic conveying in the fluidised bed

With the gradual decrease in pneumatic conveying velocity larger particles begin to drop out from the dust and air flow to the bottom of the pipe at a rate of saltation, resulting in fluidised bed formation. Fig. 7 shows an example of transporting fine polydisperse bulk solids conveyed in the fluidised bed. The mode is characterized by relatively low velocities. These transport velocities are lower than in case of dilute-phase conveying.

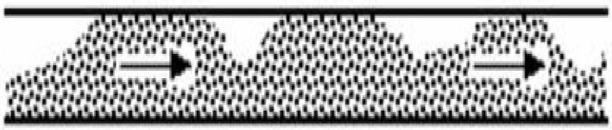

Fig. 7. Pneumatic conveying of bulk solids in the fluidised bed

The mode is characterized by reduced erosion in pipeline and non-degradation of the transported material. Therefore, in such modes the following materials are efficiently conveyed: cement, fly ash, coal dust, sand and other fine polydisperse erosive bulk solids [7].

In addition to the above-mentioned conveying modes it is possible to use pneumatic conveying of multifractional fine materials in unstable modes. However, non-stationary regimes are not considered here.

In contrast to the dilute-phase conveying mode the dense-phase one is far more sensitive to changes in the properties of materials: particle diameter, particle size distribution, shape, density, cohesion, and other factors.

## 3. ANALYSIS OF SCIENTIFIC AND TECHNICAL SOURCES RELATING TO DEFINITION OF A SHAPE AND POLYDISPERSITY OF PARTICLES OF FINE POLYDISPERSE MATERIALS

### 3.1. Review of existing sources of scientific and technical information on the definition of a shape of particles of fine polydisperse materials

Modes of pneumatic conveying of fine polydisperse bulk solids are significantly influenced by the shape of particles transported. Particle shape is a characteristic of particles, which is easy enough to describe qualitatively, but difficult to quantify. This is due to the fact that particles have three sizes, which are not the same. Dust and air flow is polydisperse, containing a large amount of particles with a variety of forms - from plate and shell-shaped to complex ones. For example, cenospheres may have a shape close to spherical particles. Particles of irregular shape with a large number of protrusions on the surface have various static and dynamic characteristics as compared to particles of regular shape. Under certain circumstances irregular particles may form more or less stable agglomerates much faster than particles of regular cubic or spherical shape, thus acquiring other properties of one newly-formed larger particle of another shape. With particle size reduction a value of their shape is decreasing. Thus, there is a relationship between particle size and its shape [8].

In available scientific and technical sources of information there wasn't found any universally accepted definition of the particle shape. In addition, there are no expressions (formulas) to calculate or estimate the shape factor of the conveyed particles. There are different approaches to the concept and to definition of the particle shape. The term "sphericity" is often used to determine the shape of particles. In accordance with [8] sphericity of particles $\psi$ is defined as follows:

$$\Psi = \frac{\textit{specific surface of the sphere of the same volume as the particle}}{\textit{specific surface of the particle}}$$

With more deviation of $\psi$ from 1.0, the less spherical is the particle.

According to [9], depending on the shape and surface nature, the irregularly shaped grains may be classified into one of the following groups:

- rounded particles with a smooth surface (pebbles, rolled river sand, cenospheres);
- round and cylindrical particles with a rough surface (activated carbon, sorbents, catalysts);
- particles with corners and cracks of quite irregular shape (crushed stone, rock sand, coke, ore, coal, shale, catalysts for the ammonia synthesis, crushed expanded clay).

Table 1 shows the shape factor for characteristic materials in accordance with data presented in [9].

Table 1. **Shape factor for the typical materials**

| № | Material | Shape factor |
|---|---|---|
| 1. | Coal, metallurgical coke | 0,45 |
| 2. | Aluminosilicates, silica gels, alumina gels | 0,50 |
| 3. | Anthracite | 0,67 |
| 4. | Crushed stone, gravel, rock sand | 0,70 |
| 5. | Rounded pebbles and sand | 0,75 |
| 6. | Activated carbon molded | 0,80 |

According to [10] the shape factor is a ratio of surface of the particle with irregular shape S to the surface of the ball $S_e$ whose volume is the volume of the non-spherical particle:

$$S_e = \pi d_e^2 = \pi\left(\frac{6\mathrm{W}}{\pi}\right)^{2/3} \tag{1}$$

$$k_f = \frac{S}{S_e} = 0{,}202\frac{\mathrm{S}}{\mathrm{W}^{2/3}} \tag{2}$$

where W is a volume of the sphere, mm$^3$.

In accordance with [10] for the ball $k_f = 1$, for other bodies $k_f > 1$. According to opinion of the authors [11], a quantity inverse to the shape factor, is called a sphericity factor $\psi$, and for the particle of any other shape $\psi < 1$.

In addition to $k_f$ factor, a solid particle of irregular shape can be characterized by dynamic shape factor $k_f^d$. It is a ratio of a factor of the particle arbitrary shape resistance to the factor of spherical particle resistance [12].

In sources [13] and [14], the shape factor is also expressed through the ratio of squares of the equivalent diameters $d_e$ и $d_e^{'}$, where $d_e$ is a diameter of the equivalent spherical particle, whose volume $W$ is equal to the volume of the considered particle [10]:

$$\mathrm{d_e} = \sqrt[3]{\frac{6\mathrm{W}}{\pi}} \tag{3}$$

where $d_e^{'}$ is diameter of the ball, which surface is equal to the surface of a grain of the non-spherical shape [10]:

$$\mathrm{d_e}' = \frac{S}{\pi} \tag{4}$$

Thus, the shape factor is expressed by the formula (5):

$$k_f = \left(\frac{d_{\text{э}}}{d_{\text{э}}^{'}}\right)^2 \tag{5}$$

According to opinion of the authors [10], the shape factor $k_f$ is a factor of the particle sphericity.

For non-spherical particles it may be insufficient to express the equivalent diameter as a diameter of spheres, equivalent to them in volume or surface. Therefore, the authors [15] propose to use a sedimentation diameter, which is found by the ratio of the particle surface to its volume. The opinion of these authors is based on the fair assumption that surface to volume ratios in case of spherical and non-spherical particles should be the same.

According to [17] in case of describing the properties of particles having an irregular shape, the concept of geometric shape factor $k_f$ is applied. It's alternative is the inverse value, called the sphericity factor $\psi$, i.e. $\psi = 1/k_f$. The factor $k_f$ is a ratio of the particle surface to the surface of an equivalent ball $S_e$:

$$k_f = \frac{S}{S_\text{э}} = \left(\frac{d_e}{d_e'}\right)^2 \qquad (6)$$

where $d_e$ and $d_e$' are diameters of balls, equivalent to the surface and volume of the particle.

Generally $k_f \geq 1$, $0 < \psi \leq 1$; for spherical particles $k_f = \psi = 1$. The factors $k_f$ and $\psi$ for regular solids can be found from Table 3. If particles having irregular shape are considered, $k_f$ and $\psi$ factors are to be determined experimentally; a rough estimation of these factors can be performed using Table 4. For estimations Table 5 can be used.

Table 2. **Geometric shape factor for some materials [16]**

| № | Material | Aggregate density of particles, kg/m$^3$ | The predominant form of particles | Geometric shape factor |
|---|---|---|---|---|
| 1. | Circulite | 2280 | Round and oblong with nostril surface | 1,3…1,5 |
| 2. | Expanded perlite powder | 2350…1850 | Lamina | 2,0…2,1 |
| 3. | Vermiculite | 2750 | Lamina | 1,9…2,0 |
| 4. | Expanded vermiculite | 1200…1000 | Plates | 1,4…1,5 |
| 5. | Powdered mica | 2700 | The same | 2,0…2,1 |
| 6. | Talk | 2750 | Tablets | 1,15…1,2 |
| 7. | Graphite | 2000…2400 | Flat and angular | 1,18…1,2 |
| 8. | Quartz sand | 2650 | Angular | 1,15…1,2 |

Table 3. **Factors of shape and sphericity of some regular solids**

| Solid | Tetrahedron | Cube | Octahedron | Dodecahedron | Icosahedron |
|---|---|---|---|---|---|
| $k_f$ | 1,49 | 1,24 | 1,18 | 1,10 | 1,07 |
| $\psi$ | 0,670 | 0,806 | 0,846 | 0,912 | 0,937 |

Continuation of table 3. **Factors of shape and sphericity of some regular solids**

| Prism | | | Cylinder | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $a \cdot a \cdot 2a$ | $a \cdot 2a \cdot 2a$ | $a \cdot 2a \cdot 3a$ | $h = d/2$ | $h = d/6$ | $h = d/20$ | $h = d/30$ | $h = d$ | $h = 1{,}5d$ | $h = 5d$ | $h = 10d$ |
| 1,30 | 1,31 | 1,38 | 1,21 | 1,68 | 3,10 | 4,55 | 2,28 | 1,16 | 1,45 | 1,72 |
| 0,767 | 0,761 | 0,725 | 0,827 | 0,594 | 0,323 | 0,220 | 0,438 | 0,860 | 0,691 | 0,580 |

Table 4. **Shape and sphericity factors of some materials**

| Form of particles | $k_f$ | $\psi$ |
|---|---|---|
| Round, rolled, without sharp corners: clay, chamotte, river sand, short cylinders etc. | 1,16…1,20 | 0,83…0,86 |
| Sharp-grained, scabrous, oblong: anthracite, non-rolled sand, etc. | 1,54 | 0,65 |
| Sand | | |
| - round | 1,20 | 0,83 |
| -angular | 1,37 | 0,73 |
| - sharp-cornered | 1,67 | 0,60 |
| Average for all the types of sand | 1,33 | 0,75 |
| Tungsten powder | 1,12 | 0,89 |
| Iron catalysts | 1,73 | 0,58 |
| Activated coal | | |
| $d$= 1…2 mm | 1,56 | 0,64 |
| $d$= 1,5 mm | 1,09 | 0,92 |
| $d$= 1,5…4,5 mm | 1,27 | 0,79 |
| Сланец | | |
| $d$= 2,5…11,2 mm | 2,35 | 0,426 |
| $d$= 34…62,5 mm | 1,32 | 0,758 |
| Hard coal | | |
| $d$= 6…11,25 mm | 1,87 | 0,536 |
| Blast-furnace coke | | |
| $d$= 6…11,25 mm | 2,48 | 0,403 |
| Gravel | | |
| $d$= 12…20 mm | 1,47 | 0,68 |
| $d$= 3,7 mm | 1,38 | 0,725 |
| Dust | | |
| - natural coal | 1,54 | 0,65 |
| - pulverized coal | 1,37 | 0,73 |
| - grate melted, spherical | 1,12 | 0,89 |
| - grate aggregated | 1,82 | 0,55 |
| Mica (flakes) | 3,57 | 0,28 |
| Crushed glass, nonablated | 1,54 | 0,65 |
| PVC suspension | 1,47 | 0,68 |
| Silica gel | 3,03…5,56 | 0,18…0,33 |
| Alumina silica gel | 1,82…4,0 | 0,25…0,55 |
| Raschig rings, Berl saddles | 3,3 | 0,3 |
| Crushed stone | | |
| $d$= 5…7 mm | 1,85 | 0,54 |
| $d$= 25…30 mm | 1,61 | 0,62 |
| Calcined alumina oxides | 2,32 | 0,43 |

Table 5. **Estimation of the shape and sphericity factors of particles of some materials**

| Characteristics of the particle shape | $k_f$ | $\psi$ |
|---|---|---|
| Round | 1,30 | 0,77 |
| Angular | 1,52 | 0,66 |
| Oblast | 1,72 | 0,58 |
| Plate | 2,33 | 0,43 |

### 3.2. Brief results of analyzing the sources of scientific and technical information relating to the influence of the material polydispersity on critical velocities of dust and air flow

If a layer of particulate material consists of particles of the same size, it is called a monodisperse one, a layer of substantially different size particles is called polydisperse. Thus, the material polydispersity is a characteristic of its non-uniform particle size. Polydispersity of the material is characterized by particle size distribution, which shows what proportion or percentage by weight, volume or a number of particles constitute certain particles or groups of particles in the analyzed sample.

There are many definitions of the material dispersion [18], for example:

1. Dispersity is a characteristic of particle size in disperse systems.
2. Dispersity is a physical quantity that characterizes the size of suspended particles in disperse systems.
3. Dispersity (fragmentation) is a degree of the body crushing (phase dispersity) in a homogeneous medium (dispersion medium). Dispersity measure is a ratio of the total surface of all particles to their total volume.
4. Dispersity is a characteristic of the pulverized material (cement, mineral powder, etc.) by the specific surface area (cm$^2$/g) or by weight of the powder, passed through the sieve of a certain size.
5. Dispersity is a degree of fragmentation, determined by the value inverse to the particle dimension; the smaller the particles, the greater dispersity. Or it's the value inverse to the particle size of the dispersed phase.

Particle size distribution of fine polydisperse bulk solids is characterized by the integral indicator of particle size of the material; in scientific and technical sources it's sometimes referred to as an average (mean) or an equivalent particle diameter. There are various ways of defining the integral parameter of the particle size of the material, given by different authors. Currently, to determine the particle size distribution of fine-grained materials with particle sizes from 0.5 microns to a few millimeters, sieving, microscopy, laser granulometry sedimentation are most widely used.

Table 6 shows the formulas for calculating the integral particle size parameter.

Table 6. **Methods for determining the integral particle size parameter**

| № п/п | Name | Formula | Notes | Source of information |
|---|---|---|---|---|
| 1. | Mean diameter | $d_{mean} = \frac{\sum_{i=1}^{n} d_i n_i}{n}$ (10) | $n$ — total number of particles,<br>$n_i$ — a number of particles of $i$- fraction<br>$d_i$ — mean diameter of particles of $i$-fraction | [17] |
| 2. | Geometric diameter | $d_{geo} = \frac{\sum_{i=1}^{n} (\lg d_i \cdot n_i)}{n}$ (11) | | [10] |
| 3. | Quadratic mean diameter (surface mean diameter) | $d_{S\,mean} = \sqrt{\frac{\sum_{i=1}^{n} d_i^2 n_i}{n}}$ (12) | Total particle surface is equal to a surface of the particle with a mean diameter multiplied by a number of particles | [17] |
| 4. | Volumetric mean diameter | $d_{V\,mean} = \sqrt[3]{\frac{\sum_{i=1}^{n} d_i^3 n_i}{n}}$ (13) | | [10] |
| 5. | Surface-volumetric mean diameter (Sauter mean diameter) | $d_{VS\,mean} = \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2}$ (14) | | [10] |
| 6. | Harmonic mean diameter | $d_{avharm} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{d_i}}$ (15) | $y_i$ — counting part of particles of $i$-fraction; specific particle surface with diameter $d_{mean}$ is equal to the mean specific surface of the considered particles | [17] |
| 7. | Mean diameter by mass | $d_{avm} = \sum_{i=1}^{n} g_i d_i$ (16) | $g_i$ – part of particles by mass | [17] |
| 8. | Median diameter | $d_{med}$ | Particle diameter, determined by 50% content of particles by mass | – |
| 9. | Modal diameter | $d_{mod}$ | Arithmetic mean diameter of particles of one fraction group having the maximum weight percentage in the sample | – |

| | | | | |
|---|---|---|---|---|
| 10. | Weighted mean diameter | $d_{w.mean} = \dfrac{\sum_{i=1}^{n} d_i \cdot m_i}{100}$ (17) | $d_i$ — mean particle size of $i$-fraction of the sieve analysis, defined as half the sum of sizes of two adjacent sieve meshes, $m_i$ — content of $i$-fraction by mass, % (sieve residue) | [19] |

Determination of the modal particle diameter. Histogram, constructed in rectangular coordinates (Fig. 8), where abscissa is the particle diameter by fractions, and the ordinate is the content of fractions in %, the point, fixing the maximum content is called mode, and the corresponding diameter is a modal diameter [18].

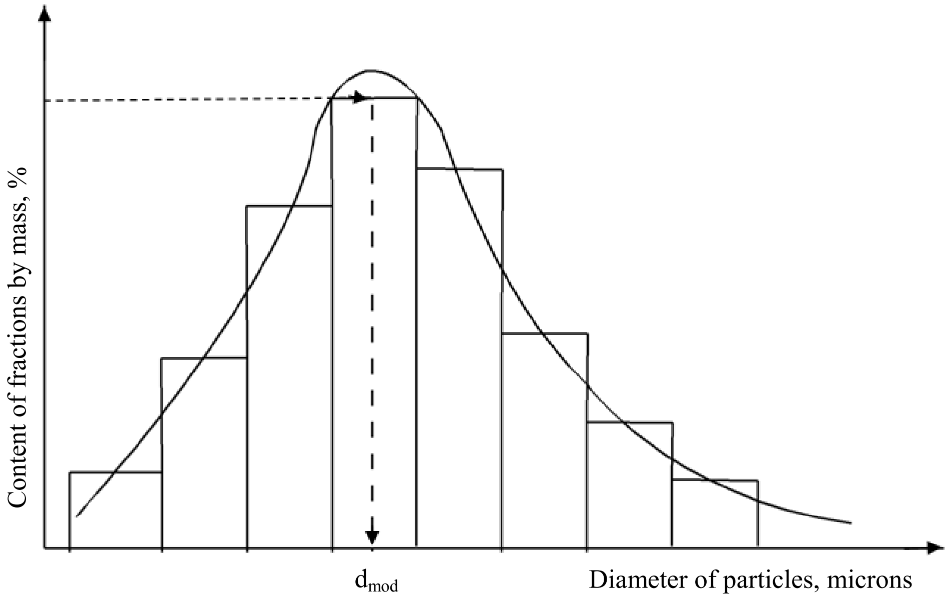

Fig. 8. Differential distribution of particle by fractions with the modal diameter definition

Determination of the median particle diameter. Median diameter is obtained on a cumulative curve plotted on a graph, where abscissa is a diameter of fractions, and the vertical axis is increasing in the total content (Fig. 9). A point on the curve, where the content is 50 %, is called the median, and the corresponding diameter is a median diameter [18].

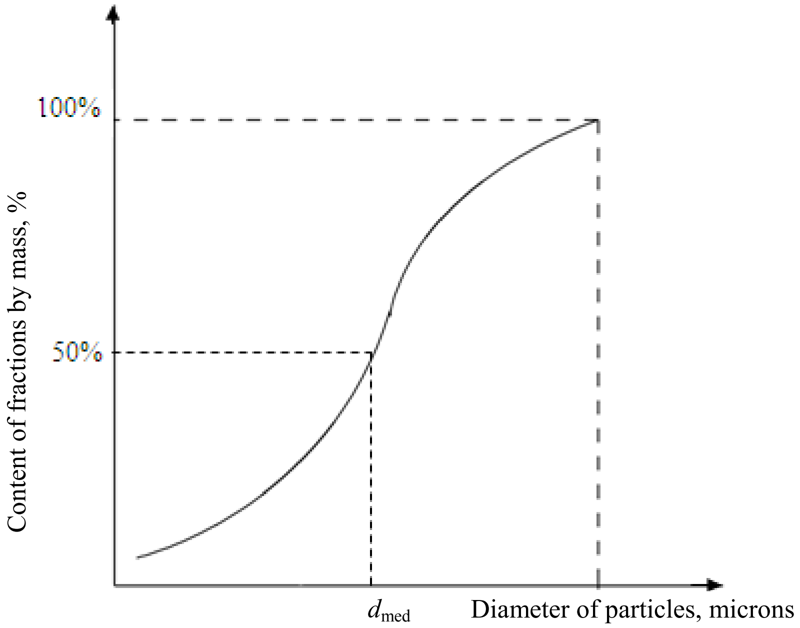

Fig. 9. Integral distribution of particles by fractions with the median diameter definition

To determine the weighted mean diameter of particles the formula (17) from [19] was used because it allows to consider particle size distribution of the material more completely and is, according to the authors' opinion, integral to estimate the mean diameter.

Polydispersity was indirectly considered when determining the mean particle diameter, but it's not enough to account for the influence of polydispersity of bulk solids with different particle sizes on critical velocities of dust and air flow at their transportation in pneumatic conveying pipelines. It's needed to develop a polydispersity factor, which is calculated when estimating critical velocities of dust and air flows transporting fine polydisperse materials in pneumatic conveying pipelines.

According to [20], the greater polydispersity index $k_d$ is, the more identical become the particles. The authors of [21] believe that the polydispersity index of Ekibastuz coal dust, milled using roller mills is 0.85. In [22] it's written that $k_d$ in case of milling brown coal in ball-tube mills is 0.85, while at grinding in hammer mills it's 1,2 ... 1,3. According to [23] $k_d$

ranged from 0.6 to 1.3. The authors of [24] suggest that $k_d$ is within 0.8 ... 1.4. In accordance with [24] $k_d$ is taken to be 1.0 for sand, for small-sized ore - 1.4 and for lime - 21. The specified values were obtained for the materials with the average particle size below 1 mm. $k_d$ = 21 was obtained for lime containing 20 % of particles with sizes of 1 to 2 mm (by mass). In addition to the above information on $k_d$ values given in [24], the authors of [25] report that $k_d$ varies from 0,8 to 1,3 for experiments with ash when changing the average particle diameter of 50 to 90 microns.

## CONCLUSION

Analyzing the studied Russian and foreign scientific and technical information sources on critical velocities of dust and air flows in pneumatic conveying pipelines with different modes of pneumatic transportation of fine polydisperse bulk solids it was found the following:

- studies conducted in different countries, contain the results applicable for specific conditions of conveying the materials;
- in the conducted experimental studies, the effect of particle shape and polydispersity on the critical velocities of dust and air flows wasn't considered;
- in scientific and technical sources of information the formulas for determining the factors of shape and polydispersity of particles of fine polydisperse materials weren't found.

It's necessary to conduct additional research in the field of the shape and polydispersity of various fine polydisperse materials to clarify the relationship for calculating critical velocity of dust and air flows at pneumatic conveying of fine polydisperse materials in pipelines considering the factors of shape and polydispersity of particles.

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