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Numerical simulation of collection efficiency in separator with inclined double-T elements

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Abstract. The article considers the problem of improving efficiency for capturing solid particles in the production of silicon dioxide. The authors propose a separator with inclined double-T elements. The operating principle of the device is described. It is shown that particles are captured from gas due to centrifugal forces when they pass through elements. The main parameters affecting the collection efficiency of the separator are the inlet gas velocity, which determines the centrifugal force of the swirls, the particle density, and the diameter of the particles determining the inertial knocking out of the structured flow. Numerical simulations have shown the device's efficiency with inclined double-T elements in collecting fumed silica solids of 1 to 15 μm in size, a density of 2000 to 3000 kg/m^3, and the inlet velocity of 3 to 10 m/s changes from 20.8 to 100%. Pressure loss of separator with inclined double-T elements is 168 to 1880 Pa at inlet gas velocity from 3 to 10 m/s.

1. Introduction

Improving energy efficiency and conservation of production lines in power, chemical, metallurgical, and other industries is crucial since it determines the cost value of the product and, as a result, its competitiveness in markets. This problem is of particular importance in plasma application for production purposes. In particular, plasmatrons are used to obtain fumed silica (silicon dioxide) – a translucent powder with high adsorption properties, which is widely used to produce various lubricants, paints, coatings, plastic, artificial leather, rubber, and other materials [1–4]. However, frequent maintenance is the main difficulty of using plasmatrons. Each production line operates under the vacuum created by the fan. Therefore, the fan works at maximum power with high hydraulic resistance, reducing its residual life and leading to periodic breakdowns. The key system for decreasing pressure loss of the fumed silica production line is the product's collection system after the plasmatron [5,6]. Therefore, an essential task in applying plasma technologies for industrial purposes is to reduce the hydraulic resistance of the separation systems. In addition, the development of new devices for capturing fine (fumed silica) particles having relatively a low-pressure loss is an urgent task [7,8].

The authors of the work proposed a separator with inclined double-T elements to solve this problem (Figure 1). The device can be implemented in the fumed silica production to decrease a production area. This work aims to study an energy-efficient device for capturing solid particles of silicon dioxide with a size of 1 to 15 μm.

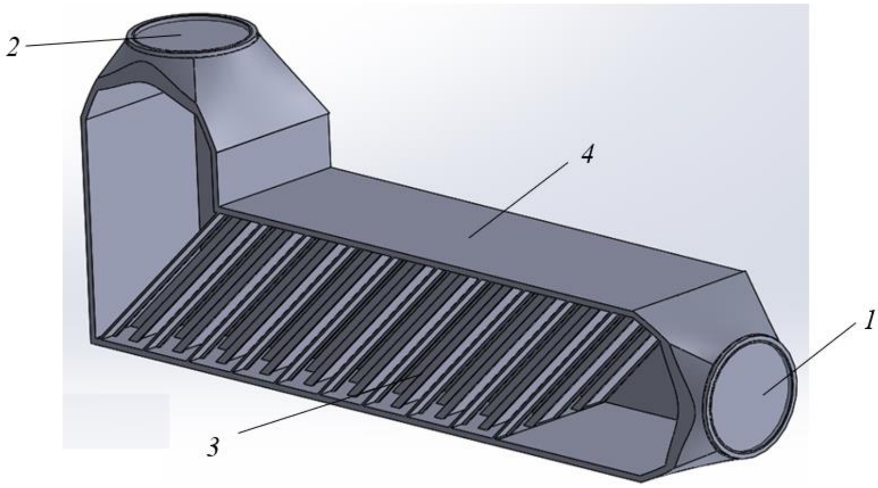

Figure 1. Simplified 3D separator model with inclined double-T elements: 1 – inlet; 2 – outlet; 3 – double-T elements; 4 – body.

2. Study objects and methods

The proposed separator consists of several rows of inclined double-T elements contained in a body. Rows of double-T elements have a chess order. The inclination angle of each element is equal to 30º, which provides the free gas flow along the length of the device. The attaching double-T elements to the internal walls of the body can be made in different ways: by welding, installing a grating with inserted elements, and others. Figure 1 presents a simplified model of the proposed device as there is no bunker. It is supposed that the bottom of the device under double-T elements has perforation, through which captured silicon dioxide particles can discharge to the bunker. The separation of silicon dioxide particles from the gas using the device with inclined double-T elements is described in the following way. First, the gas flow with the particles enters the device via the inlet pipe 1, then distributes over the entire height and width of the device. After passing rows of double-T elements, the gas flow structure becomes wave-shaped due to the subsequent shrinking and expanding channels. As the gas envelops the rows of double-T elements, centrifugal forces emerge, under which silicon dioxide particles are ejected from the structured flow and fall to the bottom of the device. Compared with cyclones, the separation efficiency of the developed device will be higher because of the enlarged centrifugal forces due to the formation of the plurality of vortices with a small radius equal to half the length of the element. The arrangement of elements in the device is made as: a circle drawn from the center of any projection of the element passes through the outer points of the elements of the adjacent rows. This arrangement of inclined elements allowed the formation of vortices with maximum possible values of centrifugal forces [9].

Numerical simulation to find the collecting efficiency of fine silicon dioxide particles from the gas and the pressure loss for the developed device was carried out using Ansys. The geometric dimensions of the 3D model (Figure 1) are as follows: 50 mm diameter of the inlet and outlet pipes, 365 mm length of the device, 80 mm height and width of the device. The number of rows of inclined double-T elements is 19 with the length of 15.5 mm, the width of the projection of the double-T elements is 5 mm, the thickness of the wall is 1 mm, the maximum height of the elements is 145 mm.

A k-ω SST turbulence model was used in the numerical simulation. Partial differential equations (Navier-Stokes equation) were also given [10]:

$$\frac{\partial \vec{v}}{\partial t} = -\left(\vec{v} \cdot \nabla\right)\vec{v} + \nu\Delta\vec{v} - \frac{1}{\rho}\nabla p + \vec{f}, \quad (1)$$

where ∇ is nabla; Δ is vector Laplacian; t is time, s; ν is kinematic viscosity coefficient, m^2/s; ρ is density, kg/m^3; p is pressure, Pa; $\vec{v}$ is velocity vector field; $\vec{f}$ is vector field of mass forces.

The Navier-Stokes equation is combined with the continuity equation as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{2}$$

The following parameters were specified during numerical simulations: gas temperature (t = 20 °C), air kinematic viscosity (ν = $15.06 \cdot 10^{-6}$ m^2/s), silicon dioxide particle density ρ_a (2000–3000 kg/m^3), particle diameter (1–15 µm), the initial velocity of the gas flow W (3–10 m/s), the number of particles at the inlet of the device (n = 1000). The particle adhesion condition was applied to the walls of the double-T elements to simplify the computational model, i. e. when the particle was in contact with the element wall, it was considered that the separator captured the particle.

The separation efficiency E of silicon dioxide particles from the gas flow was calculated as follows:

$$E = 1 - \frac{n_k}{n}, \tag{3}$$

where n_k is the number of particles that remained after cleaning in the separator.

The formula determined the pressure loss in the separator with inclined double-T elements:

$$\Delta p = p_1 - p_2, \tag{4}$$

In the study, we made the following assumptions. First, the gas flow in the separator is stationary. Second, the dust concentration excludes particle-to-particle interaction. Third, the influence of particles on the motion of the carrier medium was not taken into account.

3. Results and discussion

The results were presented graphically in Figures 2–6. The efficiency of the double-T element separator is on average 67.3%. Moreover, the separation efficiency increases when the inlet gas velocity grows from 3 to 10 m/s. This fact is due to the increased centrifugal force of vortices, which occurs near double-T elements. Thus, the average silicon dioxide efficiency is 57.2, 65.1, 70.8, and 76.1% at velocities of 3, 5, 7, and 10 m/s, respectively. By increasing the density of particles from 2000 to 3000 kg/m^3, the separation efficiency of the device enhanced as well, since particles with a higher density are more likely to be ejected from the vortex flow due to increased mass. The separator's efficiency averages 63.3, 67.1, and 71.6%, with particle densities of 2000, 2330, and 3000 kg/m^3, respectively.

The size of the particles affects the efficiency of the separator. Studies reveal three regions of particle size depending on the inlet gas velocity (more precise particle size ranges will be presented below): up to 3 µm, from 4–7 to 10 µm, and from 8–11 µm to 7–15 µm. The efficiency is not more than 45% for particles up to 3 µm in size since they pushed out of the structured flow with great difficulty. The efficiency goes up to 100% for particles with a size above 3 µm due to the more significant influence of centrifugal forces on particles. The pressure loss for the separator with inclined double-T elements ranges from 168 Pa to 1880 Pa at the inlet gas velocity of 3 to 10 m/s (Figure 6).

The collection efficiency of silicon dioxide particles by the separator with inclined double-T elements at the gas velocity of 3 m/s averages 53.1, 56.3, and 62.2% at a density of 2000, 2330, and 3000 kg/m^3, respectively. At a particle size less than 3 µm, the efficiency averages 30.6, 33.4, and 35.5% with densities of 2000, 2330, and 3000 kg/m^3, respectively. When the particle size is between 4 and 10 µm, the separator has an average efficiency of 48.5, 51.9, and 58.4% with particle densities of 2000, 2330, and 3000 kg/m^3, respectively. The separator's efficiency is more than 99.9% for particles of 15 µm and above (Figure 2).

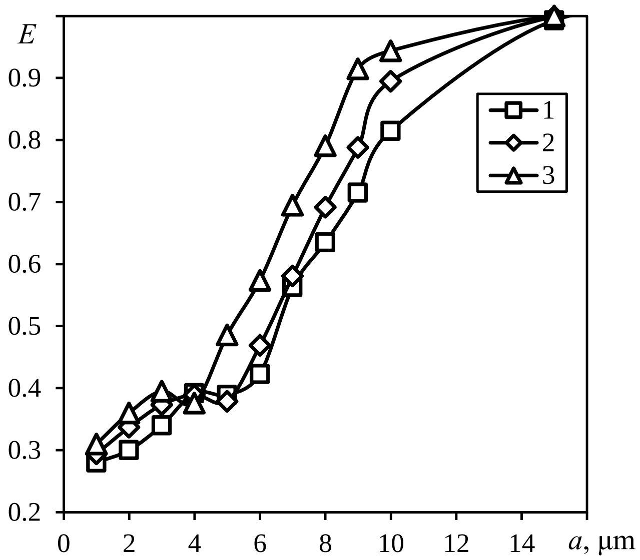

Figure 2. Separation efficiency versus particle size under different particle densities ρ_a, kg/m^3: 1 – 2000; 2 – 2330; 3 – 3000. Inlet gas velocity W = 3 m/s.

The efficiency of silicon dioxide particles by the developed separator at the gas velocity of 5 m/s is on average 60.6, 64.7, and 69.9% at the density of 2000, 2330, and 3000 kg/m^3, respectively. In the first region, characterized by the particle size range of 1 to 3 µm, the separation efficiency is on average 27.5, 33.1, and 34.3% with particle densities of 2000, 2330, and 3000 kg/m^3, respectively. The second region (particle size range of 4 to 9 µm) has the efficiency averages 52.1, 57.1, and 63.3% with particle densities of 2000, 2330, and 3000 kg/m^3, respectively. For particles larger than 10 µm, the collecting efficiency is more than 97.3% at a density of 2000 to 3000 kg/m^3 (Figure 3).

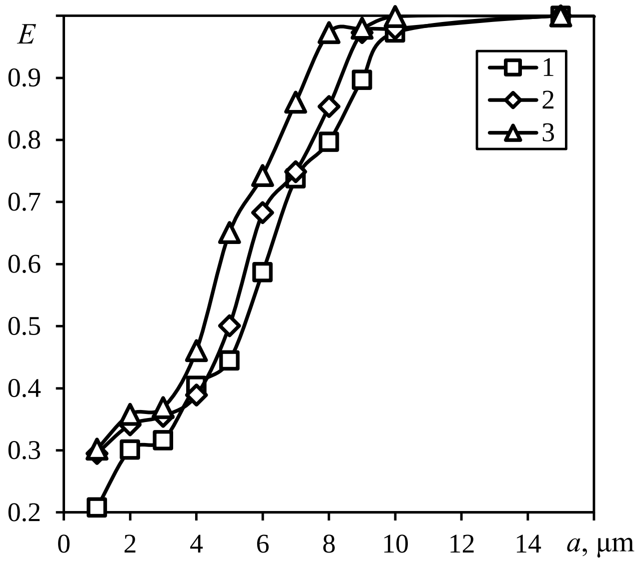

Figure 3. Separation efficiency versus particle size under different particle densities ρ_a, kg/m^3: 1 – 2000; 2 – 2330; 3 – 3000. Inlet gas velocity W = 5 m/s.

The separation efficiency of the device for silicon dioxide particles at the gas velocity of 7 m/s is on average 67.6, 70.7, and 74.3% at the density of 2000, 2330, and 3000 kg/m^3, respectively. For particles with a size less than 3 µm, the average efficiency of the separator is 32.7, 34.3, and 35.4% at particle densities of 2000, 2330, and 3000 kg/m^3, respectively. For particles of 4 to 8 µm in size, the efficiency averages 55.8, 59.8, and 64.7% with particle densities of 2000, 2330, and 3000 kg/m^3, respectively. For particles larger than 9 µm, the separator's efficiency is greater than 97.6% (Figure 4).

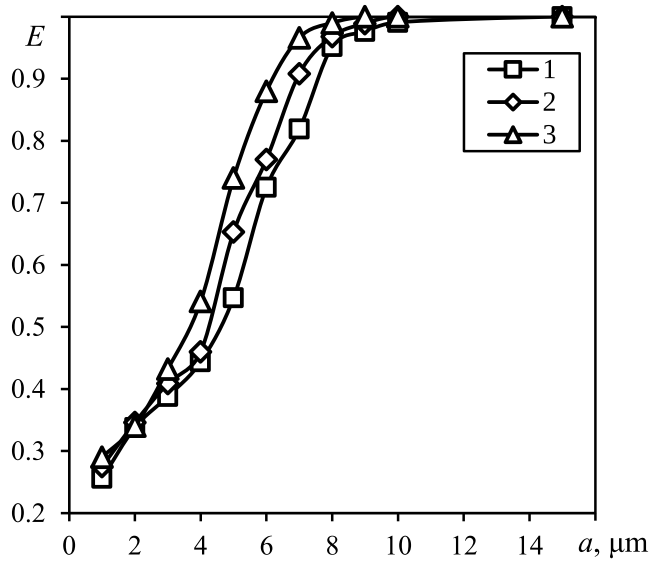

Figure 4. Separation efficiency versus particle size under different particle densities ρ_a, kg/m^3: 1 – 2000; 2 – 2330; 3 – 3000. Inlet gas velocity W = 7 m/s.

The separator's efficiency with inclined double-T elements at the inlet velocity of the dust-laden gas of 10 m/s is on average 72.1, 76.4, and 79.7% at the density of the particles 2000, 2330, and 3000 kg/m^3, respectively. We note that there are no clear regions marked before. For the first region, the average efficiency of the device is 31.6, 35.7, and 40.7% at particle densities of 2000, 2330, and 3000 kg/m^3, respectively. At particles with sizes between 4 and 7 μm, the separator efficiency averages 56.2, 63.1, and 68.2% at particle densities of 2000, 2330, and 3000 kg/m^3, respectively. For particles larger than 8 μm, the efficiency is more than 99.2% (Figure 5).

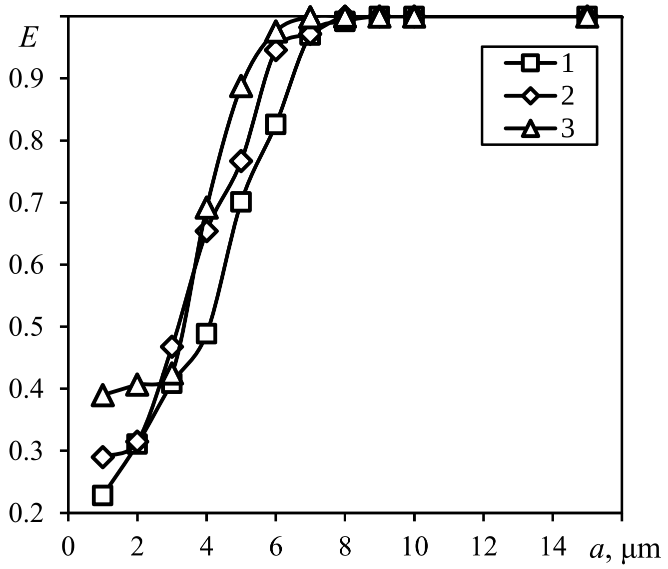

Figure 5. Separation efficiency versus particle size under different particle densities ρ_a, kg/m^3: 1 – 2000; 2 – 2330; 3 – 3000. Inlet gas velocity W = 10 m/s.

A relationship between the pressure loss in the separator with inclined double-T elements and the gas inlet velocity was received through the numerical simulations:

$$\Delta p = 18.4W^2. \quad (5)$$

The minimum pressure loss in the separator was 168 Pa at the inlet gas velocity of 3 m/s. The pressure loss in the device does not exceed 1000 Pa at W = 7 m/s. The maximum pressure loss of 1880 Pa was found at the inlet gas velocity of 10 m/s (Fig. 6).

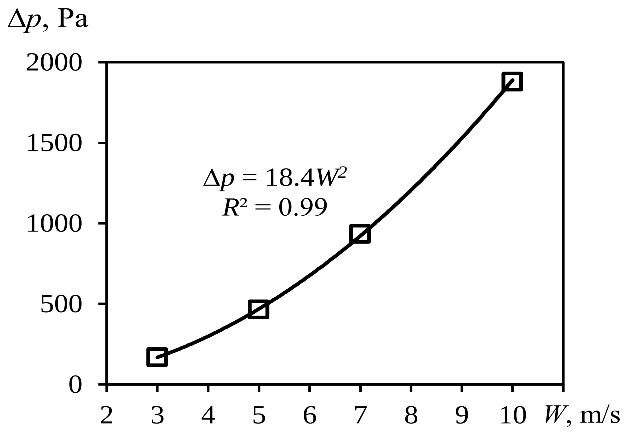

Figure 6. Pressure loss versus inlet gas velocity.

4. Conclusion

Results have shown that implementing the separator with inclined double-T elements to capture silicon dioxide particles in the industries is an effective solution. Three areas of efficiency for different particle size ranges were distinguished. It was found that with 19 rows of inclined double-T elements, the average efficiency is at least 50%. Typically, the gas velocity is less than 5 m/s after a plasmatron, where a low-pressure loss of 500 Pa can be achieved. In order to increase the efficiency of the proposed separator, it is possible to increase the number of elements. Therefore, the following work is planned to study the separator's efficiency and its pressure drop at different geometries of the elements.

Acknowledgments

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