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Improved dusty gas cleaning in open-cast automobile transport

To cite this article: V E Zinurov *et al* 2022 *J. Phys.: Conf. Ser.* **2388** 012141

Improved dusty gas cleaning in open-cast automobile transport

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Abstract. Service life extension of internal combustion engines is an urgent task for open-cast automobile transport. Dust contamination of oil and constructive elements of the internal combustion engine accelerates its wear and tear, resulting in breakage. The authors developed a separation device with sections of double-T elements as a replacement for the first stage cleaning device in open-cast automobile transport. Numerical results show that the proposed separation device provides gas cleaning with high efficiency from fine, medium, and coarse solid particles. The use of this device improved the overall efficiency of gas cleaning and extended the service life of the fine filter, which has a positive effect on the internal combustion engine. Studies have shown that the separation device has an average efficiency of 81.2% with the following parameters: dust particle size 5–20 μm, dust particle density 1000–7000 kg/m^3, inlet gas velocity 3–15 m/s.

1. Introduction

The important task of the machine building complex is to increase the service life of internal combustion engines (ICE) of open-cast automobile transport. The service life of the ICE is affected by factors such as the reduced thermal regime, unstable regime, increased load, and the motor speed operating regime. But the most negative impact is abrasive dust entering the engine through the air system [1,2].

The engines of transport operating in high-dust environments are subject to wear, because they treat about 200 m^3 of air per hour with a dust concentration greater than 6 g/m^3, and fine solid particles may get into the motor oil through leakage. This is the main cause of the engine crankshaft bearings wear. Therefore, the problem of improving the cleaning of air entering the engine of opencast automobile transport is relevant [3–5].

The most common gas cleaning separators used in open-cast automobile transport include inertial, centrifugal, and filtering devices. In the inertial dust separators, solid particles dispersed in the gas are separated by inertia when the direction of the gas flow changes dramatically. Particles are ejected from the main gas flow, providing cleaning air. In centrifugal dust separators, a centrifugal force acts on the dusty gas flow, which occurs because of the design features, for example, due to the tangential inlet pipe of the device [6]. The dust particles are thrown by centrifugal forces to the wall of the device body and gradually, under the action of gravitational forces, are moved down to the bottom of the dust collector. One of the most common types of apparatus are various modifications of gas cyclones. The main advantages of cyclones include the high efficiency of separating particles larger than 20 μm from the air, ease of operation, repairability, and workability at high pressures and temperatures. However, a significant disadvantage of cyclones is the low separation efficiency of fine particles with a size of less than 10–20 μm [7].

Note that inertial or centrifugal dust collectors are often combined with filtering devices to achieve high separation efficiency. However, these devices quickly become clogged with the high dust content of the gas, resulting in reduced efficiency and increased pressure loss. As a result, fine particles unintentionally enter the combustion chamber, oil, etc. ICE parts, which accelerates the breakdown of the internal combustion engine. Therefore, the task of developing new technical devices for cleaning gas from fine particles with improved characteristics relative to the traditional devices is relevant [8–10].

The authors of this work developed a new device with sections of double-T elements for gas cleaning from coarse, medium, and fine particles to replace inertial and centrifugal separators [11]. The aim of this work is to numerically simulate the separation process of cleaning gas from dust in the separation device with sections of double-T elements.

2. Methodology

The separation device with sections of double-T elements is shown in figure 1. The device has a cylindrical body, inside which there are six sections of double-T elements and a cylindrical pipe, which is a continuation of an inlet pipe. The upper part of the body has an output pipe. The output pipe of the lower part of the separator is used as a dust bunker.

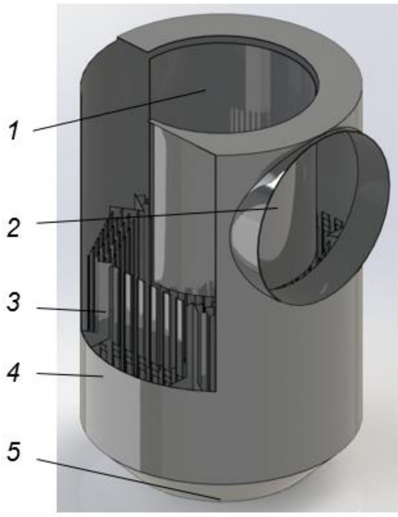

Figure 1. Separation device with sections of double-T elements (section view): 1 – inlet pipe; 2 – outlet pipe; 3 – section of double-T elements; 4 – cylindrical body; 5 – outlet pipe for dust bunker.

The gas cleaning from dust particles in the separation device occurs primarily by inertial, gravitational, and centrifugal forces. The device operates as follows. When the dusty gas flow enters the device through the inlet pipe, it moves along the inner cylindrical pipe to the lower part of the device, after which it sharply changes direction by 90–180° and passes through the sections of double-T elements. When the gas moves between sections, centrifugal forces appear, rejecting particles on the walls of double-T elements, and then the cleaned gas moves on the outlet of the device to the outlet pipe. Dust particles fall into the dust bunker via the outlet pipe. Thus, the separation of dust particles from the gas is observed both due to inertial forces when the flow direction from the inner cylindrical pipe towards the sections of the double-T elements is turned, and due to centrifugal forces when enveloped by a dusty gas flow the rows of double-T elements, as well as due to gravitational forces during the passage of dust flow throughout the device.

Note that most of the medium and coarse particles are separated from the gas flow by inertial and gravitational forces. Fine particles are separated from the gas by passing through rows of double-T elements as a result of centrifugal forces. These elements also act as agglomerators that contribute to the coagulation process of fine particles that are more easily captured in the device.

To achieve the maximum value of centrifugal force in the rows of the separation device, the double-T element relative to each other were arranged at a distance *L*, which is determined by the following formula:

$$L = \frac{h_1 + b}{2}, \tag{1}$$

where h_1 is the ramp length of double-T element, m; b is the length double-T element, m (figure 2).

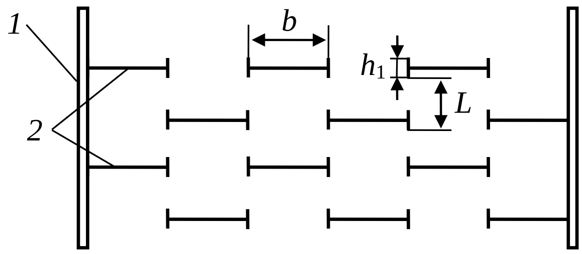

Figure 2. Scheme of a section of double-T elements (top view): 1 – section wall; 2 – double-T elements.

Each section of double-T elements consists of four rows with six elements. Previously [7], it was found that the minimum pressure drop of the design is achieved at the ratio h_1/b equals 0.24. However, in this study, this value was assumed to be 0.25, because it greatly simplifies manufacturing. In this case, the length of the double-T element is 4 times the length of the ramps of the double-T elements [8-9].

Numerical calculations were carried out using the ANSYS Fluent package. A three-dimensional model of the separation device with double-T element sections was constructed using the Autodesk Inventor. The three-dimensional model has the following geometric dimensions: the diameter of the cylindrical body is 450 mm, the height of the device is 680 mm, the diameters of the inlet and outlet pipes are 300 mm, the diameter of the inner pipe is 310 mm, the length of the double-T element b is 14 mm, the length of the ramp of the double-T element h_1 is 3.5 mm, and the wall thickness of the double-T elements is 0.4 mm.

During the study, the following boundary conditions are set: the gas velocity at the inlet pipe of the device varies from 3 to 15 m/s, the pressure at the outlet pipe is 101325 Pa. Note that a no-slip condition is set on the outlet pipe designed for the dust bunker to simulate collecting particles from the gas. On all other solid surfaces of the separation device, the particle bouncing condition is specified. The ambient temperature t_0 is taken equal to 20 °C, the density of the gas ρ is equal to 1.22 kg/m^3, and the dynamic viscosity of the air equals $18.1 \cdot 10^{-6}$ Pa·s. The size of the dust particles changes from 5 to 20 μm. The density of particles ρ_a varies from 1000 to 7000 kg/m^3. To obtain the efficiency dependence of gas cleaning versus the dust particle size and the dependence of the pressure drop coefficient versus the inlet gas velocity, the particle density ρ_a is set to 1000 kg/m^3. It is known that at higher dust content, the separation efficiency is much greater than at lower content. Therefore, to simplify some calculations, the particle content is assumed to be a single value of 1000 kg/m^3.

The efficiency of the separation device with sections of double-T elements *E* was evaluated using the following equation:

$$E = 1 - \frac{n_k}{n}, \tag{2}$$

where n_k is the number of solid particles separated by the device.

The coefficient of pressure drop ξ of the separation device with sections of double-T elements was calculated using the following formula:

$$\xi = \frac{2\Delta p}{\rho W^2}, \tag{3}$$

where Δ*p* is the pressure drop of the separation device, Pa; ρ is the density of the gas, kg/m^3; *W* is the gas flow velocity at the device inlet, m/s.

The Stokes number Stk was defined by the following equation:

$$\mathrm{Stk} = \frac{\rho_a a^2 W}{b\mu}, \tag{4}$$

3. Results and discussion

In the course of the research, an exponential dependence is obtained between the efficiency of cleaning the gas from dust particles by a separation device under the change of the Stokes number (figure 3). The minimum efficiency of the gas cleaning process for particles ranged from 5–20 μm is 64.5%, the maximum efficiency is 98.2%. The average efficiency of the gas cleaning from dust particles of 5–20 μm in size and density of 1000–7000 kg/m^3 by the separation device is 81.2% (figure 4).

The high separation efficiency for dust particles up to 20 μm in size in the separation device is achieved by the action of centrifugal forces generated by the gas flowing the row of double-T elements. The distance between adjacent rows of double-T elements is 8.75 mm, calculated by the equation (1). Thus, the radius of rotation of the particles is much smaller than that of other separators, for example, in cyclones, which causes centrifugal forces of significantly higher values in the developed separation device. The average pressure drop of the separation device is 11.7 Pa (figure 5).

At Stokes values of 0.3 to 17.8, 18.1 to 55.1 and above 56.2, the efficiency of cleaning the gas from dust particles averages 71.2, 83.9, and 94.8%, respectively. As the calculation equation (4) shows, the Stokes number includes parameters such as particle density $\rho_{a,\ the}$ particle diameter *a*, gas velocity *W, the* length of double-T elements *b*. Thus, the initial analysis of the dusty gas flow, including particle size distribution and particle density makes it possible to calculate the gas velocity and the length of double-T elements using the obtained dependency to achieve maximum efficiency (figure 3).

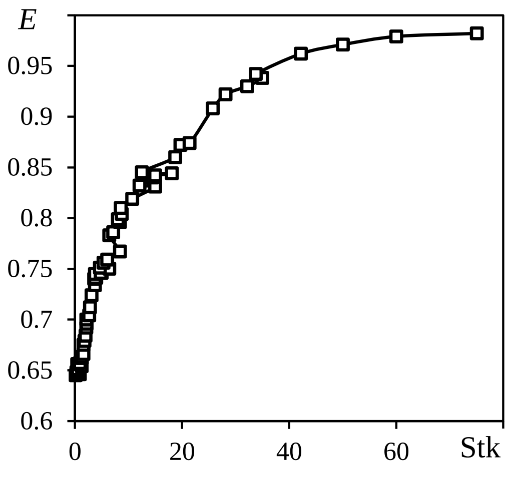

Figure 3. Separation efficiency versus Stokes number.

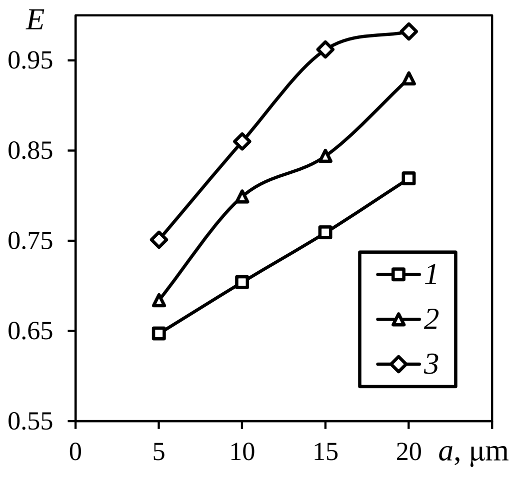

Figure 4. Separation efficiency versus particle size at different particle density, kg/m^3: 1 – 1000; 2 – 3000; 3 – 7000. Inlet gas velocity *W* = 15 m/s.

The efficiency of cleaning gas streams of dust particles between 5 and 20 μm is on average 73.2, 81.4 and 88.8% with particle densities of 1000, 3000, and 7000 kg/m3, respectively. With dust particle sizes up to 10 and 20 μm and dust densities ranging from 1000 to 7000 kg/m3, the efficiency of the separation device averages 74.1 and 88.3%, respectively. It should be noted that as the particle size and density increase, the efficiency of gas flow cleaning increases as noted above (figure 4).

The obtained quadratic dependence of the pressure drop coefficient of the separation device on the inlet gas velocity shows that at a certain W, the resistance of the separator decreases, which reduces the energy cost of air intake. It is noted that the minimum coefficient of pressure drop $\xi = 11.54$ is achieved at the inlet gas velocity $W = 12$ m/s. This is due to the fact that at certain velocities, a stable gas flow structure is formed inside the separation device, and the number of vortices with different sizes that disrupt this structure is reduced. Studies indicate that at gas flow velocities in the range of 10–15 m/s, the pressure drop of the separation device is minimal, the average value is 11.56 (figure 5).

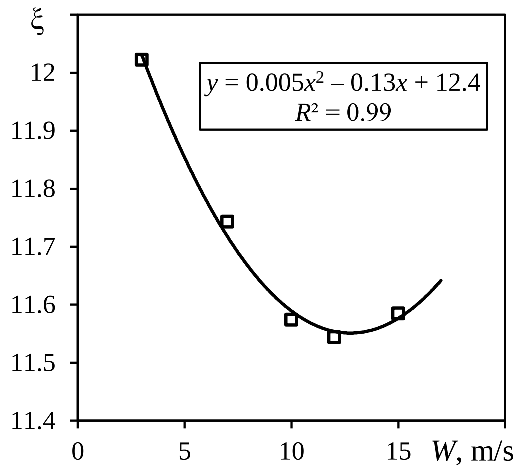

Figure 5. Pressure drop coefficient versus the inlet gas velocity.

The results demonstrate that the developed separation device with sections of double-T elements can be implemented in open-cast automobile transport as a replacement for inertial and centrifugal separators. Studies show that the separation efficiency of the device improves with increasing particle diameter and particle density. Thus, in addition to the high efficiency of cleaning the gas from particles larger than 20 μm, the separation device successfully separates gases from particles smaller than 20 μm, which reduces the load on the next cleaning unit – the filter air cleaner. This makes it possible to increase the overall efficiency of cleaning gas flow from solids and to increase the service life of filter air cleaners. The consequence of this is the increased integrity of open-cast automobile transport ICE.

4. Conclusions

The new separation device with sections of double-T elements is developed to clean a dusty gas. On the basis of numerical results, it is shown that the separation device can be used for coarse and fine particles with high efficiency. In particular, the maximum efficiency of the gas cleaning from solid particles 5–20 μm in size equals at least 94% at Stokes number more than 56.2. The minimum pressure drop of the separation device is 11.56 at the inlet gas velocities ranging from 10 to 15 m/s. The obtained dependencies for separation efficiency depending on different parameters provides to select process and design characteristics to achieve maximum efficiency with minimal pressure loss. The advantages of the developed separation device with sections of double-T elements are the high efficiency of cleaning gas from fine, medium, and coarse particles, ease of operation, and repairability.

Acknowledgments
The reported study was funded by the scholarship of the President of Russia (№ SP-3577.2022.1).

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