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Analysis of the dedusting process in a rectangular chamber filter

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Purifying air from dust is a very important, current topic. There are many methods to minimize the amount of dust, one of them being chamber filters. This paper presents the research results of a newly designed rectangular chamber filter. The efficiency of the dedusting process is influenced by contamination properties, but also by the construction of the apparatus, inlet, and outlet location, the ratio of certain dimensions, and the gas flow rate. The airflow containing solid particles is a multi-phase, difficult-to-describe issue, therefore an attempt to determine the trajectory of particle movement in the apparatus was carried out using the PIV method. A decrease in the dedusting efficiency was observed with the increase of the gas flow rate, as well as for smaller diameters of the solid particles. The obtained values of the efficiency of the apparatus are comparable with the values obtained for the constructions discussed in other papers.

Keywords: purifying air, chamber filter, PIV.

INTRODUCTION

Technological processes, as well as numerous anthropogenic activities, are very often associated with the emission of the dust generated during their lifespan[1, 2]. It is an important and difficult topic, because the generated pollutants pose a direct threat to both the broadly understood environment and the people living in its surroundings[3, 4]. There are standards that define the limit values for dust concentrations in air, which are set by bodies such as the European Parliament and the Council of the European Union. In Europe, one of the applicable regulations is Directive 2008/50/EC of the European Parliament and the Council concerning ambient air quality and cleaner air for Europe[5].

An increased awareness of the harmfulness of human activities to the environment, proceeding in accordance with the sustainable development trend, and an improvement of work ergonomics are just some of the factors that influence the fact that appropriate solutions for eliminating or reducing the emission of pollutants are still being sought[6, 7]. Industrial areas for which it is particularly important to include underground space and traffic construction in mountainous areas, tunnel engineering, (especially in Germany and Japan)[8], the wood industry[9], the construction industry, and the plastics processing industry[10].

Dedusting of gases (including air) is performed with the use of devices, or sets of devices, called dust collectors[11]. The basic quantity required in the design or selection of appropriate equipment for the dedusting process of a gas stream is the concentration of particles suspended in it. Additionally, important parameters are dimensions (and their distribution), shape, mass, density, adhesiveness, and physical and chemical properties[12, 13]. Many conducted experimental studies, as well as numerical calculations, concerned the impact of the concentration, distribution and characteristics of the movement of dust particles on the course of the dedusting process, as well as on its efficiency[8]. The efficiency of the dedusting process, according to the general definition, is the ratio of the mass of particles retained in the dust collector to the mass of particles fed to the dust collector. In literature, one can also find the definition that efficiency is a speed of separation[14]. Despite the multitude of studies, there is still no clear information that allows for a full explanation of the dedusting mechanism, the illustration of the trajectory of pollution particles, and the linking of the flow distribution with the efficiency of the process. This is due to, among others, the complexity of the process – i.e. the characteristics of multiphase flow[15].

Dust collectors have been used in industry for a very long time. Their beginning can be associated with the Roots blower, which was developed in 1859[16]. Already existing constructions are still modified in order to improve their efficiency and to optimize their economic aspect[17]. The efficiency of a dedusting system is based on the correct transport of dust and the proper separation of dust from the transporting medium. In addition to the properties of solid particles, the efficiency of a dust collector is determined by air flow velocity[18], and thus the pressure (directly dependent on it) difference occurring at different locations in the system[19]. Temperature and flow humidity are also important[20].

One of the simplest dedusting methods is used in dry gravity dust collectors. Gravity is used to separate solid particles from the gas stream. It is a simple and effective method, but only in the presence of large solid particles. This means that it is mainly used when dealing with particles larger than 50 μm, which are in a sufficiently high concentration. It is also a very effective process of initial dedusting (first stage of dedusting), which allows the remaining equipment that is operating in the system to be protected against mechanical damage. Moreover, it also reduces the need for frequent cleaning[21]. For the process to take place effectively, certain conditions must be met. The dimensions of the settling chamber, its length L, and height H must be selected so that the dust has time to fall to the bottom, from where it will be irreversibly separated[6]. Similar guidelines should be followed when designing cyclones[22].

The aim of this research work is to present a rectangular chamber dust collector, which was designed and made on a test scale. The results of laboratory tests for the developed construction will be presented, which in turn allows the device's operation to be characterized. The main focus was on determining the efficiency of the device, characterizing the flow, and linking the most important input variables with the obtained dedust effect.

MATERIALS AND METHODS

The subject of this study concerns a chamber filter. It was assumed that a camera will work in the portrait orientation. The dust collector has a rectangular chamber (an alternative to cylindrical filters that are discussed in scientific publications), the bottom of which is bevelled on four sides (prism shape). The system has inlet and outlet nozzles with an internal diameter of 32 mm, which are located coaxial to the direction of the gas flow in its upper part. There is also a chute that allows for the periodic removal of solid particles that were separated in the apparatus. Figure 1 shows the proposed solution.

The designed chamber filter was made of colorless plexiglass plates (PMMA). The choice of construction material was related to the requirements for the test stand - strength, mechanical resistance, and transparency (enabling the observation of the process inside the apparatus). The plates were cut with a router in accordance with the assumed dimensions. The elements were then connected with glue.

Figure 2 shows the scheme of the test stand that was used to determine the movement of solid particles inside the chamber filter, as well as the dedusting efficiency.

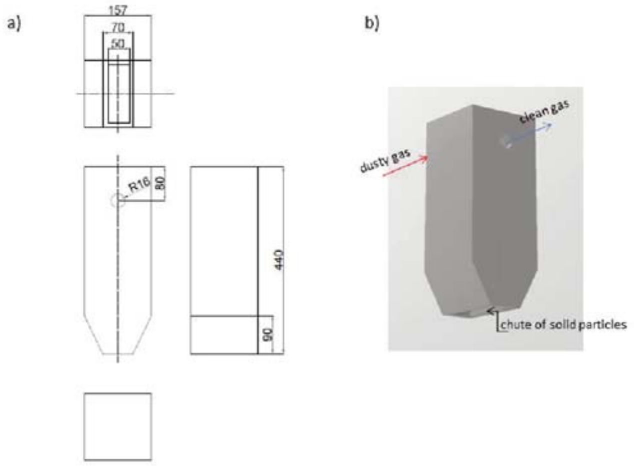

Figure 1. Designed chamber filter a) the construction drawing, b) a visualization

The experimental stand consisted of an autotransformer (the use of which made it possible to adjust the voltage, and thus the power of the blower's motor), a blower, the tested chamber filter, a rotameter, a Sony Action Cam FDR - X3000 camera, scales, and a computer with the appropriate software. The camera was positioned perpendicular to the direction of the tested flow. The camera had a matrix with a resolution of 8.2 megapixels, and an Exmar image sensor with a diagonal length of 2.5 inches. A Balanced Optical Steady Shot image stabilizer was also used.

The research methodology is presented schematically in Figure 3.

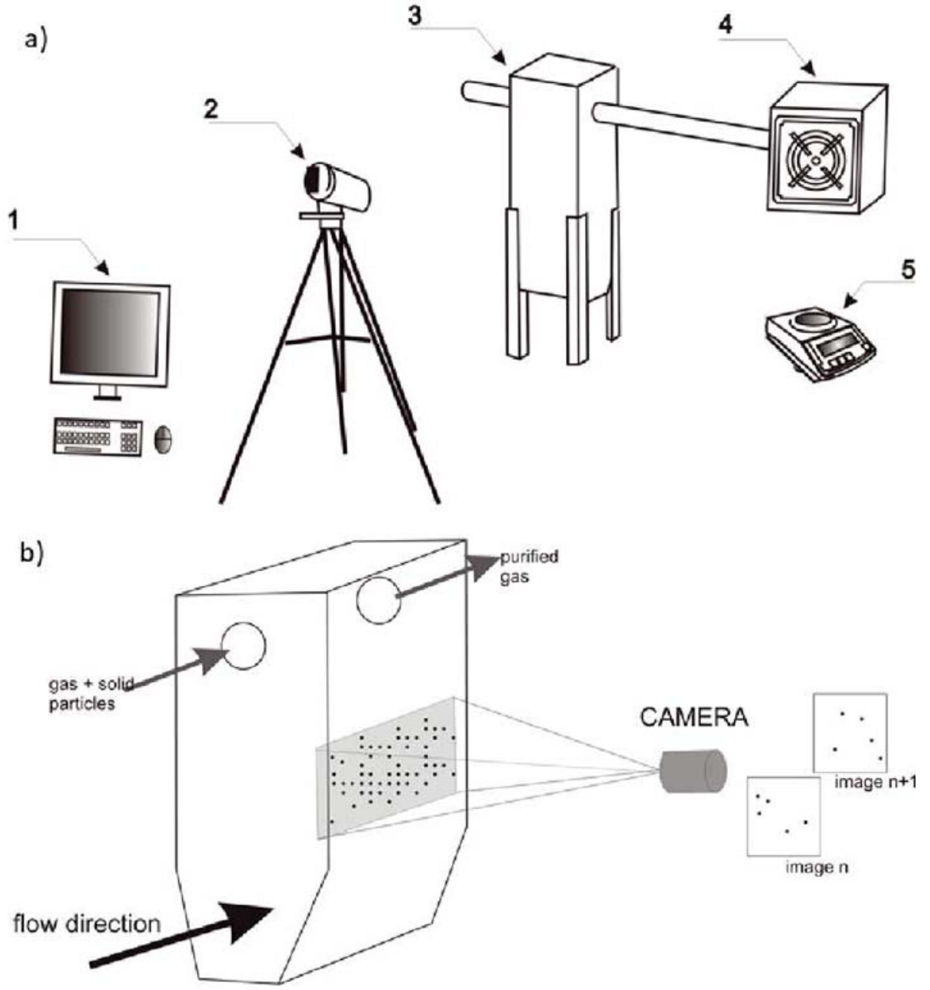

Figure 2. The experimental stand a) main elements of the stand: 1 – PC computer, 2 – camera, 3 – chamber filter, 4 – blower, 5 – laboratory scales, b) scheme of experimental setup

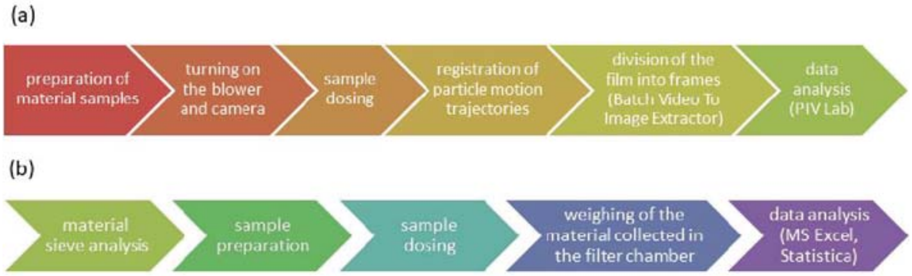

Figure 3. Measurement methodology: a) determining the trajectory of the movement of particles, b) determining the efficiency of the dedusting process

The tests were performed at various gas flow rates within the range of $0.83 \cdot 10^{-4} - 7.2 \cdot 10^{-4}$ m^3/s. When determining the trajectory of the movement of particles, expanded polystyrene particles were used as the research material. A constant number of particles was assumed and introduced into the dedusting chamber during each test. In turn, quartz sand was used to assess the efficiency of the apparatus. Material samples were fractionated using sieve analysis. A weighed amount of material was placed in a RETSCH vibrating screen that was equipped with a set of test sieves. The separation was carried out in a given period of time (900 sec) and at a specified frequency (50 Hz). The following fractions were obtained: below $100 \cdot 10^{-6}$ m, $100–150 \cdot 10^{-6}$ m, $150–200 \cdot 10^{-6}$ m, $200–300 \cdot 10^{-6}$ m, $300–400 \cdot 10^{-6}$ m, and $400–500 \cdot 10^{-6}$ m. From the sand prepared in this way, samples of 0.001 kg, 0.0025 kg, 0.005 kg and 0.010 kg were weighed. After the set test time (45 seconds) ended, the system was turned off and the sand remaining in the chamber was collected and weighed again. Based on these measurements, the efficiency of the chamber filter was calculated in accordance with the following formula:

$$\eta = \frac{m_n}{m_0} \cdot 100\%, \tag{1}$$

where:

η – efficiency,

m_0 – starting weight (kg),

m_n – mass of the collected solid from the dedusting chamber after the dedusting process (kg).

RESULTS

Determining the trajectory of the motion of particles

Based on the analysis carried out in PIVlab software, the directions, terminal points of movement and average velocities of the particles in the apparatus were visualized. Figure 4 shows an example of the velocity distributions of polystyrene particles inside the dedusting chamber at the air flow rate of $2.9 \cdot 10^{-4}$ m^3/s.

After the particles were introduced into the air stream in the dust separator, they fell to the bottom of the apparatus due to the force of gravity. The secondary flow picked some of them up, however, their lift was significantly below the air outlet nozzle, which caused the particles to remain in the apparatus after the process was completed. In this case, the maximum recorded speed was 1.4 m/s, which was achieved by the particles at about ¾ of the height of the dedusting chamber. Figure 5 presents a comparison of images obtained at various gas flow rates.

It can be seen that at the flow rate of $6.8 \cdot 10^{-4}$ m^3/s., the secondary flow caused the polystyrene particles to rise to higher levels of the dedusting chamber than in the case of the flow rates of $2.9 \cdot 10^{-4}$ m^3/s and $6.0 \cdot 10^{-4}$ m^3/s. In turn, at the flow rate of $2.9 \cdot 10^{-4}$ m^3/s, the particles of expanded polystyrene can be observed at the lowest level of the dedusting chamber. From these examples, it can be concluded that the higher flow rates caused the particles to be lifted closer to the gas stream flowing between the inlet and outlet nozzles. This poses a risk of particle entrainment and reduced efficiency. The figures also show that the highest average linear

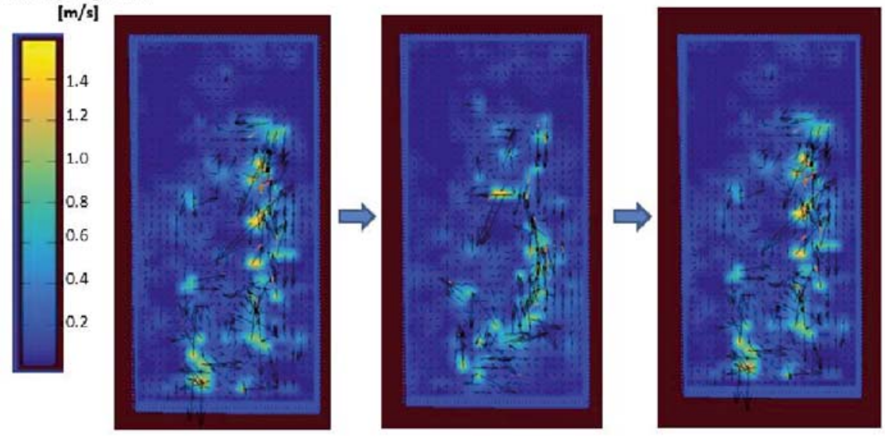

Figure 4. An example of the velocity distribution of the solid particles inside the dedusting chamber at a specific air flow rate $\dot{V}_g = 2.9 \cdot 10^{-4} \frac{m^3}{s}$ (images obtained on the basis of successive video frames)

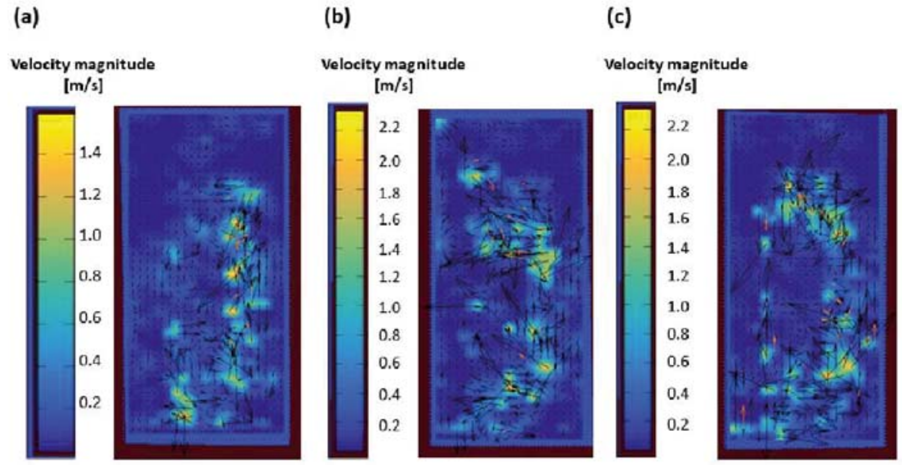

Figure 5. Distribution of the velocity of solid particles (polystyrene) inside the dedusting chamber at the air flow rate of: a) $2.9\cdot10^{-4}\,\frac{m^3}{s}$, b) $6.0\cdot10^{-4}\,\frac{m^3}{s}$, c) $6.8\cdot10^{-4}\,\frac{m^3}{s}$.

velocity is at the rate of $6.8 \cdot 10^{-4}$ m^3/s, and the lowest at the rate of $2.9 \cdot 10^{-4}$ m^3/s.

Determining of dust removal efficiency

Based on the obtained experimental data, the efficiency of the apparatus was calculated according to formula (1). Afterwards, graphs that show the dependence between the efficiency (η) and the particle diameter of the solid and the airflow rate were plotted using the Statistica program. Figure 6 shows the results obtained in the case of the starting weight of a sample of 0.0025 kg.

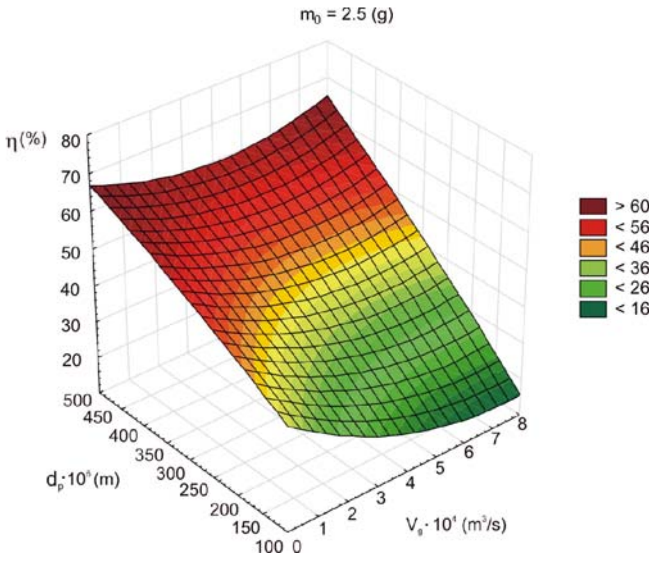

Figure 6. Efficiency of the dedusting process for samples with a starting mass of 2.5 g

The highest efficiency was observed for the 400–500 $\cdot$ 10^{-6} m fractions, and for the gas flow rate of $0.83 \cdot 10^{-4}$ m^3/s. In turn, the lowest efficiency was observed for the fractions of 100 $\cdot$ 10^{-6} m (15.2%) and for the fractions of 100 - 150 $\cdot$ 10^{-6} m (12.4%) when the flow rate was $7.2 \cdot 10^{-4}$ m^3/s. It can be seen that dedusting in the case of larger particle fractions is much more effective than for smaller ones. For example, for the flow rate of $6.1 \cdot 10^{-4}$ m^3/s, the efficiency for the 400–500 μm fractions was 63.2%, while for the 100–150 $\cdot$ 10^{-6} m fractions it was only 27.6%. Apart from particle size, the flow rate also has a large influence on the efficiency of the apparatus. The greater the flow rate, the lower its performance.

Figure 7 shows the results obtained for a sample when the initial mass of the solid was equal to 10 g.

When comparing Figures 6 and 7, it can be observed that the initial mass of the sample (dust concentration) also affects the obtained results. Higher efficiency values were obtained with higher concentrations. For example, with the same air flow rate for the fraction of 400–500 $\cdot$ 10^{-6} m, for a starting weight of 0.0025 kg, an efficiency of 56% was obtained, and for a starting weight of 0.010 kg – 70%.

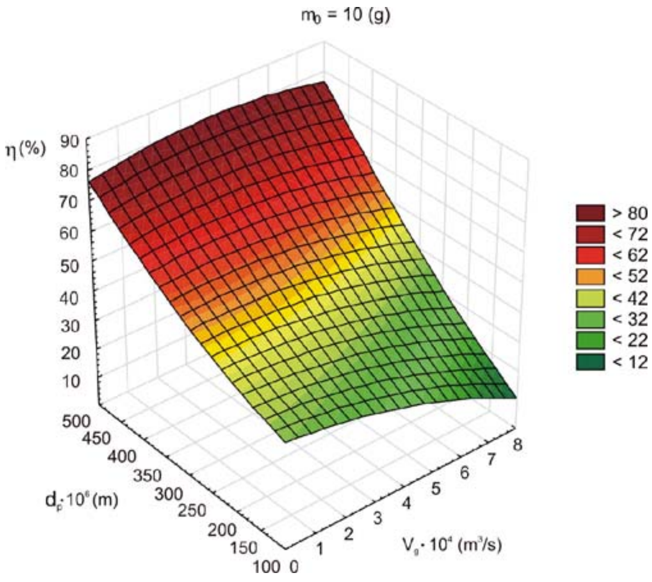

Figure 7. Efficiency of the dedusting process for the samples with an initial mass of 10 g

Using a nonlinear estimation, a relationship was developed that allows the efficiency of the apparatus to be calculated as a function of the analyzed parameters. The relationship is described by the following formula:

$$\eta = A \cdot \left(d_p\right)^B \cdot \left(V_g\right)^C \cdot 100\%$$

where:
η – efficiency,
A = 47.46940,
B = 0.62628,
C = –0.06554,

d_p – average particle diameter (m),
V_g – gas flow rate (m^3/s).

The value of the R coefficient for the proposed correlation was equal to 0.908.

The influence of solid body density on the dedusting process

Three materials of the same spherical shape and differing bulk density were used for the tests. The obtained results are presented in Table 1.

It can be seen that with an air flow rate of $0.83 \cdot 10^{-4}$ m^3/s for samples 1 and 2, a high efficiency of the dedusting process was obtained, and it amounted to 91%. At a higher gas flow rate ($7.2 \cdot 10^{-4}$ m^3/s), significant discrepancies can be observed – for the sample with a lower apparent density, the efficiency of the apparatus was lower (69%) when compared to the efficiency obtained for the sample with a higher apparent density (80%). Larger amplitudes between the efficiency values as a function of the air flow rate were obtained for the sample with a lower apparent density. The lowest efficiency was observed for the sample of foamed polystyrene – 52%. Based on the obtained results, it can be concluded that the apparent density of the sample has a significant impact on the dedusting process.

Table 1. The obtained research results

Sample	Apparent density (kg/m^3)	Flow rate (m^3/s)	Efficiency [%]
Sample 1 – sugar sprinkles	860	$0.83 \cdot 10^{-4}$	91
		$7.2 \cdot 10^{-4}$	80
Sample 2 – sugar sprinkles	490	$0.83 \cdot 10^{-4}$	91
		$7.2 \cdot 10^{-4}$	69
Sample 3 – expanded polystyrene	10	$0.83 \cdot 10^{-4}$	52

CONCLUSIONS

This study aimed to propose and develop a modified design of a chamber filter that allows for the obtaining of higher dust removal efficiency values when compared to the alternative devices described in the literature.

Based on the performed experiments, it can be seen that an increase in the gas flow rate causes an intensification of the secondary flow. As a consequence, particles that were originally separated in the settling chamber are lifted from the bottom of the apparatus to higher and higher heights, and this generates the risk of their entrainment and their return to the gas stream. Such a phenomenon leads to negative consequences, i.e. a reduction in the efficiency of the process. In addition, increasing the gas flow rate causes an increase in the average velocity of the particles in the dedusting chamber, which may in turn affect the operation of the device, and in the case of prolonged, more intensive use, may result in faster wear (erosion) and an increase in the failure rate of the apparatus. It was observed that the most visible effect of the changes in the gas flow rate occurred for the fractions with the smallest ($d < 100 \cdot 10^{-6}$ m) and the largest diameters ($d = 400–500 \cdot 10^{-6}$ m).

In the case of fractions with smaller diameters, the efficiency of the apparatus decreased significantly, while for fractions with larger particle diameters, the efficiency of the process increased. The tests were performed on different initial sample weights of 0.0025 kg, 0.005 kg, and 0.010 kg. The influence of dust concentration on the efficiency of the dedusting process was noticed. The last analyzed dependence concerned the influence of the particle bulk density on the efficiency of the process. Based on the obtained results, it was found that the air flow rate had a greater impact on the efficiency of the process in the case of lower densities of apparent solid particles. The lowest dust removal efficiency was observed for the sample with the lowest apparent density of 10 kg/m^3.

The research results were compared with the own previous investigations[23, 24]. The obtained values of the efficiency of the apparatus are comparable with the values obtained for the construction discussed in[24] – a cylindrical chamber filter. Moreover, they are significantly higher than in the case of the apparatus presented in the publication[23].

To sum up, it can be stated that the proposed construction is an interesting and promising alternative to already known solutions. The proposed equation can be successfully used in the design of this type of chamber filter, and also when selecting their operating conditions.

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