Multidiszciplináris tudományok, 12. kötet. (2022) 4 sz. pp. 178-188 **https://doi.org/10.35925/j.multi.2022.4.19**

OPTIMISING THE STRUCTURAL DESIGN OF THE AEROCYCLONE TO THE PREFERRED PARTICLE SIZE

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Abstract
In many areas of life, we can encounter dust pollution. To avoid their harmful effects, it is necessary to choose the right dust collection equipment. In engineering practice, in addition to the function of the machine, material and production costs are also important parameters to consider when choosing a machine. Therefore, in addition to the design of a cyclone with appropriate geometric dimensions, attention has been paid to the cost of the material. The flow simulation was performed with the SC/Tetra software using the k-omega model.

Keywords: *cyclone, optimization, CFD*

1. Introduction

In many areas of everyday life, we encounter solid particles that pollute the air, commonly known as particulate matter. Particulate matter is always a two-phase or even three-phase system with any shape, structure and density. Both solid and liquid particles can form this disperse system. Only those particles with a fall velocity of less than 300 cm/s at 20 °C and atmospheric pressure can be called dust particles. Because of their size variation, their physical chemical and flow properties differ considerably (Koncz, 1970).

Depending on their size and chemical composition, dusts can cause various health and environmental hazards, as well as industrial accidents and incidents. For health exposure, several types of dust can be distinguished in terms of legislation. These include E, A and U dust.

- E-dust: also known as respirable dust fraction, this refers to particles of a size that can easily enter the human body through the mouth and nose. The best known E-dust is pollen and in the industrial environment it is cement and sand. The particle size is less than 100 micrometer.
- A dust: means the fraction of dust that also enters the alveoli of the lungs. It includes many fumes and quartz dusts smaller than 5 micrometer.
- U-dust: the finest powder, built up by nanoparticles. The most dangerous is the inhalable fraction 2.5-10 micrometer, because it is deposited in the airways and consequently impairs the lungs'

ability to exchange air. Inadequate oxygen uptake leads to cardiovascular disease (Esta Absaugtechnik, Website).

The best-known industrial accident caused by dust is the well-known dust explosion. In a dust explosion, small particles with a high specific surface area mix with air to form a combustible mixture, which, in the presence of an ignition source, explodes and burns. Three things must be present simultaneously in space and time for this process to occur:

- a sufficient amount of dust,
- the right amount of oxygen,
- an ignition source.

In general, it is true that dusts of combustible materials will also be combustible, and these can be divided into three groups according to their flammability. They can be dusts of combustible materials that are easily combustible, dusts of combustible materials that are moderately combustible and dusts of combustible materials that are not easily combustible.

Powders in the food industry (flour, cocoa, sugar) are highly flammable combustible substances, and small amounts of these substances are enough to cause an explosion. There are powders that are dusts of combustible materials, but they do not float in the air for long periods of time and therefore pose a much lower risk of dust explosion. The probability of a dust explosion occurring can be reduced by limiting the presence of one of the three conditions. If the technology is dusty, it is necessary to use dust collectors, which must be designed to be very powerful because of the possibility of dust explosion. The concentration of dust in the device will not be constant, but if it is exceeded by even a small volume, a dust explosion may occur if the other two conditions are present.

Minimising the ignition source is also problematic, because a small spark can be enough to start an ignition. The amount of oxygen can be reduced more simply by using inert gases. Such inert gases are nitrogen and carbon dioxide. However, inert gas explosion protection is only a solution for closed systems (Zólyomi et al., 2016).

As industrial production increased, cyclones to separate different materials became more common. Depending on whether the solid particles are separated from gaseous or liquid matter, two basic types can be distinguished: aero-cyclones and hydrocyclones. Their popularity is due to their simple construction, ease of maintenance, low cost of production and the fact that they contain no moving parts.

2. Historical review

The efficiency of gas-solid separation in a cyclone can depend on a number of factors (Fatahian et al., 2018) such as inlet velocity, diameter size, viscosity and the saturation of the flow with solid particles. As the inlet velocity increases, the cyclone efficiency increases, but so does the pressure difference. If the diameter of the cyclone is reduced, the centrifugal force will increase and hence the efficiency will improve.

It can be seen that efficiency is difficult to improve and requires trade-offs. By connecting cyclones in parallel, multicyclones can be created, which also increases efficiency and reduces the size of the boundary layer. Several scientific papers investigate how changes in the geometry and size of different parts of the cyclone affect its operational characteristics.

Hossein Fatahian and his colleagues compared a traditional cylindrical cyclone and a rectangular cyclone. The efficiency of separation was higher for the conventional cyclone than for the square mantle, but the laminar flow structure could be used to increase the efficiency in both cases.

S. Bernardo et al (Bernardo et al., 2006) used the Reynolds turbulence model to describe the flow of the gas-solid system within the cyclone. The inlet stub is placed in three different positions. At 30°, 45° and then 60° compared to the traditional tangential flow position. The authors compared pressure drop and separation efficiency. The result of the study is that the efficiency can be increased to 77,2 % instead of 54,4 % in the 45° case with the same operating parameters.

Sakura Ganegama Bogodage and Andrew Y.T. Leung (Bogodage and Leung, 2015) simulations to show that the important parts for separation are the vortex finder tube, the conical part and the collection tank. By increasing the distance between the conical part and the lower collection tank, both the pressure drop and the separation efficiency increased. In this case the particle size was at least 2 μm in each simulation.

3. The aim of the study

In engineering practice, a common method of surface cleaning is grit blasting. Solid particles of different sizes and physical and chemical properties are sprayed onto the surface to be cleaned using compressed air. The particles can be classified according to their material and shape. The most commonly encountered grit materials are: steel, corundum, glass, garnet sand, zinc shot and aluminium wire grit. The choice of grit and particle size should be made according to the material of the surface to be cleaned and the surface quality to be achieved. In granular spraying, slower-particled media are separated by a filter, while faster-particled media are separated by a cyclone. In all cases, the grit can be reused, but efficiency and economy should be considered alongside environmental considerations.

Because of the above considerations, the aim of the simulations is to find the cyclone with the most appropriate size and proportions for the chosen boundary grain. In practical applications, the time required for the homogenization and surface cleaning process increases significantly for grains of size 0-50 micrometre, and therefore the boundary grain size of the cyclones is 60 micrometre. Particles larger than this are collected in a dust collection tank at the bottom of the cyclone and can be reused in subsequent cleaning processes with a still favourable surface cleaning efficiency. There are no references in the literature or in standards as to the explosive properties of glass bead dust. Thus, a GO-NOGO test was carried out in the laboratory of the Institute of Mechanical Engineering and Chemical Engineering of the Faculty of Mechanical Engineering and Informatics of the University of Miskolc to determine the explosive power of the smallest available glass bead dispersant, as illustrated in the following steps (Figure 1). The GO-NOGO test is suitable to establish that the material is explosive o or not. During the test try to prepare an explosion with electric arc. It can be seen that glass bead is not explosive under the required conditions.

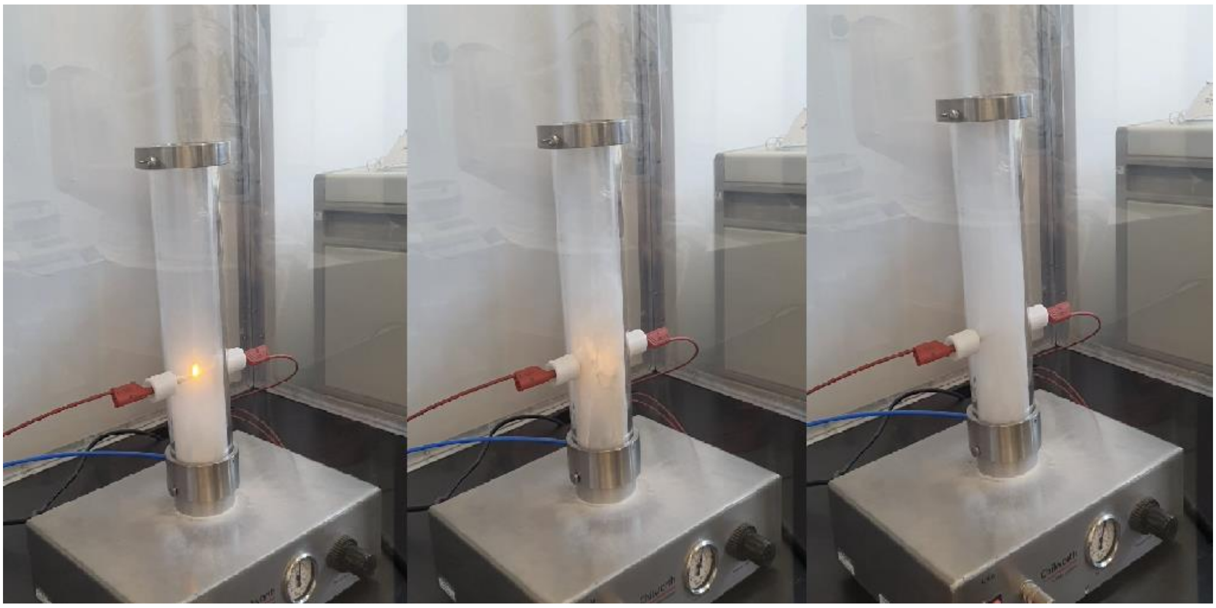

Figure 1. *Dust explosion experiment*

After preliminary calculations, four cyclones of different sizes were investigated. Their mean particle sizes were derived from the formulas for the boundary grit defined by different researchers. The formulas are:

Rosin, Rammler and Intelmann formula:

$$d_h = \sqrt[3]{\frac{\eta \cdot g}{\pi \cdot \gamma \cdot v_{st}}} \cdot \sqrt{A - \left(1 - \frac{A}{D}\right) \cdot \frac{1}{U}} \tag{1}$$

C. N. Devies formula (Koncz, 1970):

$$d_h = \frac{3}{2} \cdot \sqrt{\frac{D^2 \cdot g \cdot \eta}{8 \cdot \rho \cdot w_b \cdot h}\left[1 - \left(\frac{d_i}{D}\right)^4\right]} \tag{2}$$

E. Feifel's formula (Koncz, 1970):

$$d_h = \sqrt[3]{\frac{g \cdot d_i^2 \cdot \eta}{2 \cdot \rho \cdot w_b \cdot r_b} \cdot \tan \alpha} \tag{3}$$

Fejes G.-Tarján G. formula (Sakura, 2015):

$$d_h = \sqrt{\frac{A_b^2 \cdot 9 \cdot g \cdot \eta}{\pi \cdot \rho} \cdot \frac{1}{h_o \cdot Q} \cdot \left(\frac{R}{R_0}\right)^{2n}} \tag{4}$$

The dimensions of the structural elements are based on literature recommendations, which can be used to calculate the tablecloth. It can be clearly determined that the E. Feifel cyclone requires the least amount of feedstock. However, in this case, the amount of waste material is also the largest. The cyclone based on the formula of Rosin et al. has the best material utilisation.

4. Numerical flow simulations

During the simulation four different cyclone geometries investigated with these geometric parameters:

Table 1.

Type/ description	C. N. Devies	Feifel	Rosin	G. Fejes and G. Tarján
Cylinder diameter, mm	740	100	680	700
Cylinder height, mm	200	100	300	200
Cone height, mm	600	300	900	600
Cone bottom diameter, mm	120	20	120	150
Vortex pipe diameter, mm	100	17	30	66
Vortex height, mm	628	225	720	475
Inlet section, mm	120x80	40x20	40x70	120x80

4.1. Model by E. Feifel theory

The inlet velocity is significant compared to the size of the cyclone, hence one of the largest pressure drops in this geometry and the load on the whole structure. Unlike other cyclones, only maximum and minimum pressure values are recorded. This significant pressure drop, which can be considered as the cyclone's resistance, is expected to be accompanied by a significant degree of dust suppression.

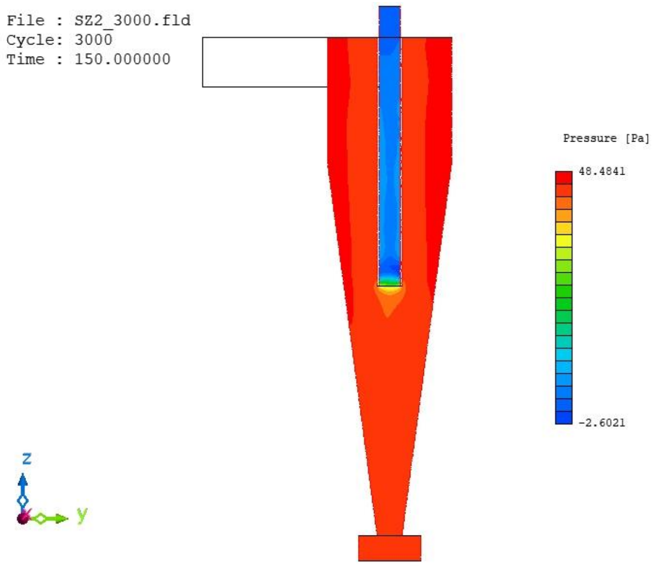

Figure 2. *Pressure distribution in EF type*

The maximum value is 48.5 Pa, while the minimum is -2.6 Pa, which occurs in the vortex detector tube. The latter can be interpreted as a suction effect to remove unseparated particles from the device. The maximum velocity is 9,5 m/s, which is just below the upper limit of 10-12 m/s that is still permissible in engineering practice. This velocity value occurs in the vortex detector tube. In the design of the cyclones, care should be taken to ensure that the conical part and the dust collector are at an appropriate distance from each other to avoid backflow from the dust collector.

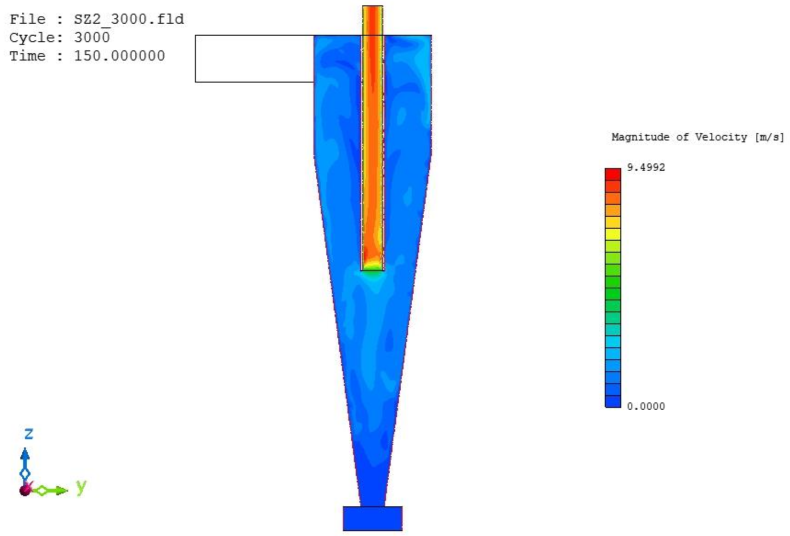

Figure 3. *Velocity distribution in EF type*

These backflows significantly reduce the degree of dust removal. It can be seen that the velocity at the bottom of the dust container and the conical shroud is 0 m/s, which leads to the conclusion that no backflows have occurred in this case. This is supported by the fact that, uniquely among the geometries studied, all the incoming particles were separated during the process η=100 %.

4.2. Model by C. N. Devies theory (Concept A)

Compared to cyclone EF type, you can see very nicely the fields associated with different pressure magnitudes decreasing towards the cyclone centerline. The minimum value in this case also occurs in the vortex finder tube, with a value of approximately -3 Pa. It can be seen that the pressure drop is much smaller due to the larger diameter, despite the nearly identical inlet velocity, and does not load the entire cylindrical and conical shale body.

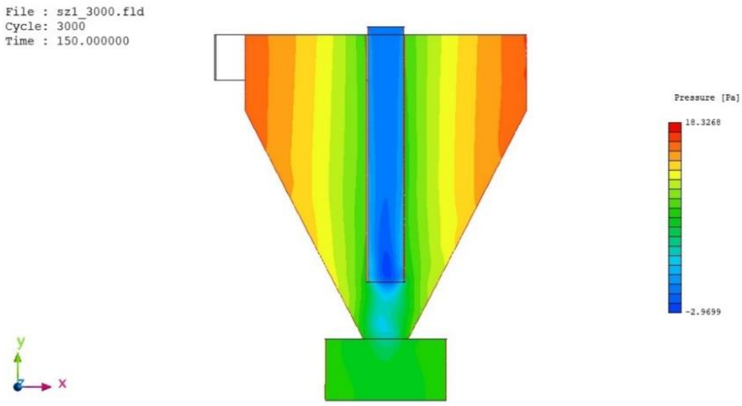

Figure 4. *Pressure distribution in CND type*

The maximum velocity at the bottom of the vortex detector tube is 4 m/s, which is in line with the limits for flow velocities in engineering practice. It is interesting to note that while the maximum velocity was present throughout the vortex finder tube in cyclone EF type, in this case it only appeared at the bottom cross-section.

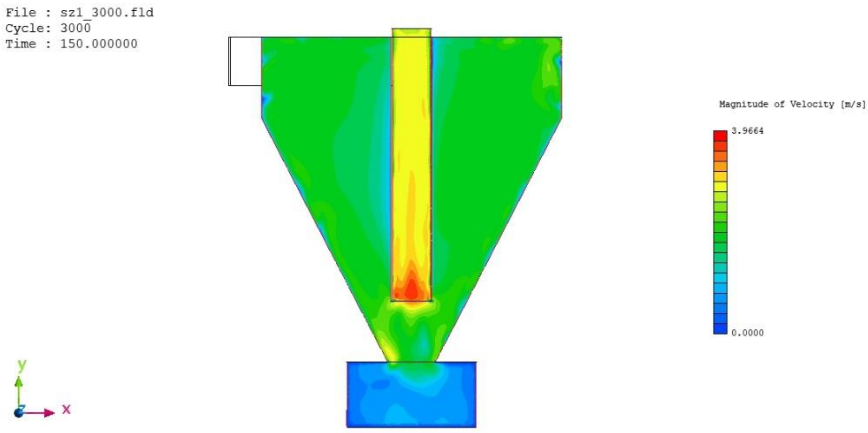

Figure 5. *Velocity distribution in CND type*

The lower dust collector tank shows that the velocity does not reach zero, only along the tank wall, so expect backflow in this design. If this cyclone is selected, it is worth considering a cylindrical transition under the conical section to the lower tank to avoid these backflows. The dust removal rate of the cyclone is η=99 %, a total of 135000 particles entered the unit, of which only 1297 left.

4.3. Cyclone derived from the formula of Rosin et al.

Of all the cyclones presented so far, this case exhibited the smallest pressure drop, because both the maximum and minimum pressure in the vortex finder tube are significantly lower than in the cyclones presented previously. However, the nature of the stratification of the fields differs from that of the cyclone generated by the C. N. Devies formula, because in this case the maximum pressures are present much longer within the structure.

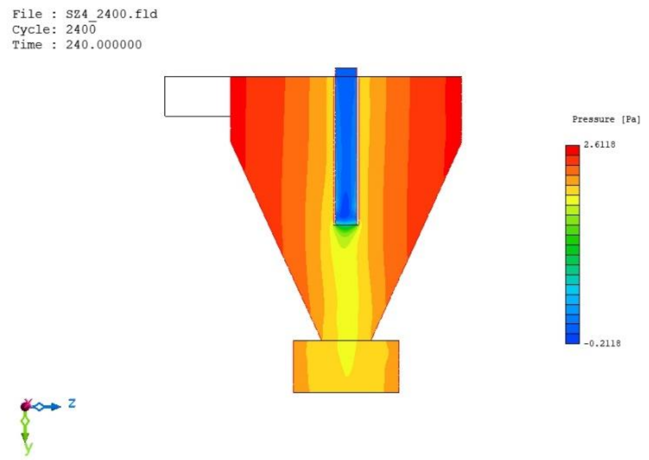

Figure 6. *Pressure distribution in R type*

In contrast to the previous cases, the particles in the cyclone moved at very low speeds as soon as they entered. The maximum velocity in the vortex finder tube was also only 0.6 m/s higher than the entry velocity. However, even in this design, this maximum value was only present in the lower 1/3 of the vortex tube. The generation of backflows that negatively affect the degree of dust removal is unlikely due to the small velocity values that are typical for the whole cyclone. A total of 247446 particles entered the cyclone, of which 236180 were separated, resulting in a dust removal efficiency of η=95.4 %.

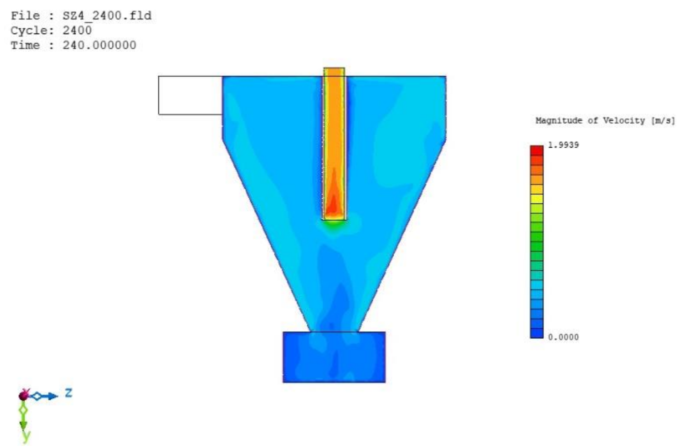

Figure 7. *Velocity distribution in R type*

4.4. Cyclone derived from the formulas of G. Fejes and G. Tarján

The maximum value of the glass particle velocity is 14.6 m/s, which does not correspond to the 10-12 m/s flow velocity for airborne materials in engineering practice. With the exception of the vortex finder tube, the velocity is close to zero throughout the cyclone, so that agitation of the separated dust by backflows is not expected in this case.

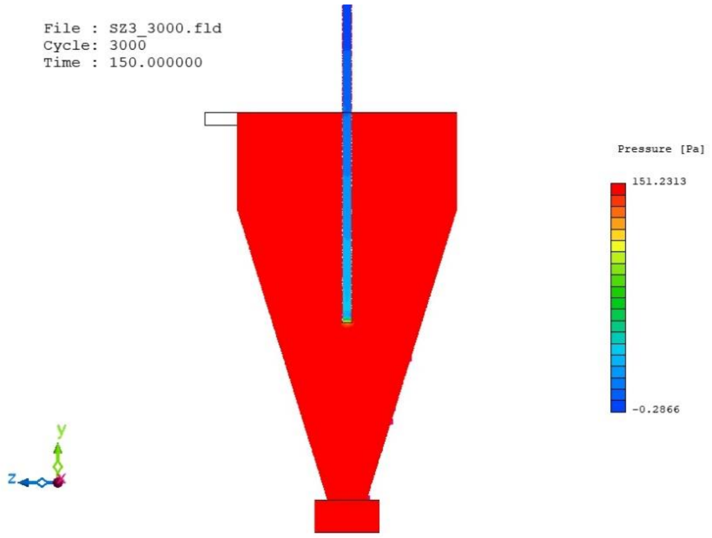

Figure 8. *Pressure distribution in FT type*

The dust removal rate is 99.9 % of the 27,000 incoming particles, only 8 of which were not separated. The two smallest particle sizes in the simulation are 50 and 55 micrometer so the cyclone boundary particle size is smaller than the calculated 60 micrometer but larger than 50 micrometer.

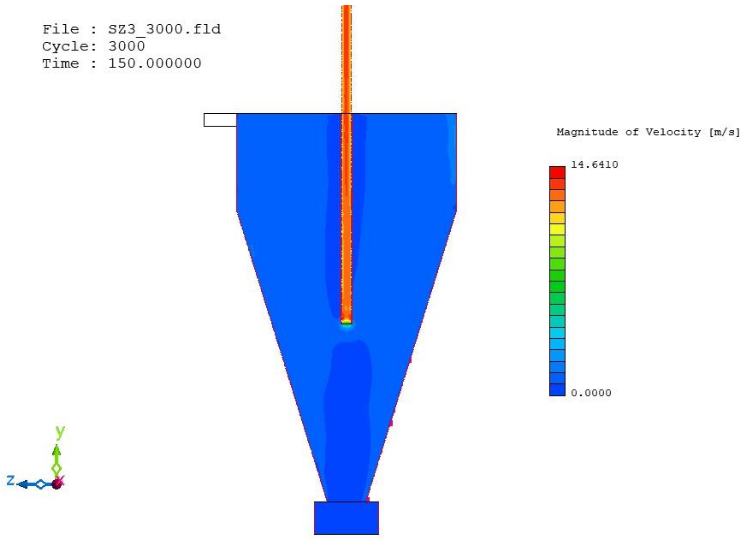

Figure 9. *Velocity distribution in FT type*

5. Summary of the flow simulation results

There are no significant differences in the efficiency of dust collection between cyclones.

The closest to the desired boundary particle size of 60 micrometer was the cyclone designed according to the formula of Rosin, Rammler and Intellmann.

The pressure loss values differed greatly from each other, regardless of the fact that the inlet velocities were nearly identical.

The simulations showed the expected results in all four cases as follows:

- A vacuum occurs in the vortex detector tube,
- The velocity of the particles in the dust container is zero,
- Pressure decreased towards the cyclone centerline.

In order to minimize the number of particles smaller than 60 micrometer the most suitable cyclone is designed according to the formula of Rosin et al. The 95.4 % degree of dust removal suggests that this cyclone also removes smaller particles than the desired 60 micrometer but the smallest amount is the smallest.

6. Conclusion

At the beginning of this article, the concept of dust and its harmful effects were introduced. The reasons for and purpose of the investigation are set out below. The formula for the four boundary particles was presented, from which the geometry of cyclones was determined. In order to minimize the number of particles smaller than 60 μm the most suitable cyclone is designed according to the formula of Rosin et al. The 95,4 % degree of dust removal suggests that this cyclone also removes particles smaller than the desired 60 μm, but in the smallest amount. This cyclone is also the most suitable for the desired task, taking into account the material utilisation.

Nomenclature

A	Inlet cross section	m^2
D,	Cylinder diameter	m
d1	diameter of the vortex finder	m
dh	limiting particle size	m
di	vortex pipe diameter	m
h	length of the vortex pipe	m
h0	height at the entry point of the dusty gas	m
Q	Volume flow rate	m^3/s
R	Cylinder radius	m
R0	radius at the entry point of the dusty gas	m
rb	inlet radius	m
t	residence time	s
U	number of circulation	
w_b	inlet velocity	m/s
w_{st}	tangential velocity	m/s
η	dynamic viscosity	Pas
ρ	density of the particle	kg/m3

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