Influence of cyclone construction parameters on the efficiency of dust removal

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Abstract. Gas dedusting involves the removal of aerosol particles from them. The gas dedusting process is carried out in devices called dust collectors. The use of a specific dust removal process depends on the characteristics of the pollutant emission source and the required degree of gas dedusting. The dust removal process is a complex system of forces acting in the dust collector to remove dust particles from the gas and to deposit them on the collector surface. The centrifugal dust collectors use the mechanism of centrifugal forces by introducing an aerosol stream into rotational motion. These types of dust collectors are often used in industry due to the simple construction, the lack of moving parts, the ability to work in conditions of high temperature and high pressure, low manufacturing costs and easy operation. A cyclone with a tangential inlet is one of the types of centrifugal separators in which the gas flows tangentially to the cylindrical part, then spirals downwards where it changes direction to the opposite and leaves the cyclone with the central exhaust pipe. Cyclones are commonly used in Poland in small heating plants equipped with WR grate boilers where coal is burned. The most important factors affecting the efficiency of dust removal are the physicochemical properties of aerosol particles and their sizes. For example, a reduction in the particle size leads to a reduction in the efficiency of the forces emitting particles from the gas, and thus the efficiency of dust removal decreases. The geometric shape of the cyclone is relatively simple, but its structural dimensions have an effect on the gas movement and, as a result, the efficiency of dust removal. Increasing the efficiency of the cyclone is the subject of many studies. This publication presents information on cyclones with tangential inlet and the effect of their design parameters on the efficiency of dust removal. A total of 5 types of cyclones with tangential inlet were analyzed, including two high efficiency cyclones, two general use cyclones and one high performance cyclone. The analysis showed that the size of cyclone construction parameters affects the size of the particle's limit diameter, the pressure drop and, as a result, the cyclone efficiency.

1. Introduction
Gas dedusting is a process that involves removing aerosol particles from them. The particles in the gas to be purified may be in solid or liquid state. The removal of solid particles takes place in the dust collectors, while the liquid particles in the drop separators. The characteristics of the emission source and the required dust removal efficiency are one of the basic criteria for the selection of an appropriate gas dedusting method and dust collector construction. In addition, it is necessary to know the size of the gas stream, the concentration of aerosol particles and their physicochemical properties. Directly the size of the particles affects the efficiency of the dust removal mechanism, so knowledge of the characteristic parameters of particles such as diameter, density, mass or size distribution is necessary.
to predict the dust removal effect. Unfortunately, the properties of the gas stream and the aerosol particles contained in it cannot always be determined based on the characteristics of the emission source. Therefore, in the newly designed technological installations, data on this subject is obtained from theoretical calculations or modelling.

The gas dedusting process is a complex system of forces in the dust collector space (including gravitational, inertia, diffusion or electrostatic forces), the aim of which is to remove particles from the gas and place them on the surface of the dedusting device. The operation of individual forces can occur individually or in groups, but the action of one of the forces is always dominant. Increasing the efficiency of the dust removal process can be achieved by increasing the share of one of the operating mechanisms. Due to the heterogeneity of aerosol systems, there are many dedusting devices that differ primarily in the principles of operation and construction solutions. The division of dust collectors results, first of all from the physical principles of the dust removal process, the method of removing aerosol particles from the gas, the similarities in construction solutions and the state of the dust itself. The main types of dust collectors used in the industry are dust chambers, inertia chambers, cyclones, multicyclones, filters, electrostatic precipitators and scrubbers. In the further part of the publication, the focus was on devices that use the mechanism of centrifugal forces, namely on cyclones [1-14].

2. Centrifugal dust collectors - cyclones
Cyclones due to their simple construction, the lack of moving parts and the ability to work in difficult conditions are widely used in the industry. In addition, they are characterized by relatively low execution costs and simple operation. The main disadvantage of cyclones is the significant pressure drop required for effective dust removal, relatively quick wear due to erosion and low dust removal efficiency in the particle range below 15μm [11-13].

In the cyclones, a spiral or vortex motion of the aerosol stream is used to induce centrifugal force on the particles. This is accomplished by introducing an aerosol stream tangentially into the cylindrical part of the device, axially or through. Figure 1 shows the diagrams of selected cyclones.

![Cyclones with inlet: a) tangential, b) axial, c) through](image)

**Figure 1.** Cyclones with inlet: a) tangential, b) axial, c) through

The construction of the cyclone is not complicated, however, the gas flow profile inside the device is complex and depends on many parameters, first of all, its geometry and dimensions. The stream of pollinated gas flows tangentially into the cyclone, then slightly deviates towards the wall and further falls down in a spiral motion. The gas stream reaches the bottom of the cone after about 2-7 turns. At the bottom of the cyclone, the gas changes direction and travels with the internal spiral along the
cyclone axis towards the outlet duct. In the zone between the outer and inner spirals, the spin speed is the highest and determines the efficiency of dust removal.

The efficiency of cyclone dedusting increases with: increasing the diameter and density of particles in the gas, reducing the diameter of the cyclone, increasing the gas speed to preserve the condition $u_i \leq u_p$ ($u_i$ - speed of gas inlet to the cyclone, $u_p$ - speed of entrainment of particles) increasing the adhesion of particles to the walls of the cyclone.

The pressure drop $\Delta p$ that occurs during the gas flow between the inlet duct and the outlet duct is a key factor to pay attention to when designing and operating the cyclones. The pressure drop occurs as a result of frictional resistance, energy loss during compression, expansion and turbulence of the gas, but depends primarily on the shape of the cyclone. The basic dimensions of the cyclone with tangential inlet are shown in Figure 2 [1, 11-13].

![Figure 2. Reverse flow cyclone with dimensions](image)

The shape of the cyclone determines the proportions of its basic dimensions with respect to the diameter. Dimensions of standard cyclones with reverse gas flow and tangential inlet are shown in Table 1.

| Table 1. Dimensions of standard cyclones with reverse gas flow and tangential inlet [11-14] |
|-----------------------------------------------|
| Dimension | Cyclone high efficiency I | Cyclone general use I | Cyclone high efficiency II | Cyclone general use II | Cyclone high performance |
|-----------|--------------------------|-----------------------|---------------------------|-----------------------|--------------------------|
| D         | 1.0                      | 1.0                   | 1.0                       | 1.0                   | 1.0                      |
| a         | 0.5                      | 0.44                  | 0.5                       | 0.5                   | 0.583                    |
| b         | 0.2                      | 0.21                  | 0.25                      | 0.25                  | 0.208                    |
| S         | 0.5                      | 0.5                   | 0.625                     | 0.6                  | 0.583                    |
| De        | 0.5                      | 0.4                   | 0.5                       | 0.5                   | 0.5                      |
| h         | 1.5                      | 1.4                   | 2.0                       | 1.75                  | 1.333                    |
| H         | 4.0                      | 3.9                   | 4.0                       | 3.75                  | 3.17                     |
| B         | 0.375                    | 0.4                   | 0.25                      | 0.4                  | 0.5                      |
| K'        | 55.1                     | 64.6                  | 50.4                      | 47.7                 | 41.5                     |
Any changes in the dimensions of the cyclones can usually cause unfavourable pressure drops or cyclone efficiency, so it is good to follow the general design guidelines for the construction. In order to prevent particles from entering the inlet stream from entering the cyclone outlet duct, the condition $a \leq S$ must be observed. Increasing the height of the cyclone $H$ increases the efficiency, however, it is recommended to maintain the condition $H \geq 3D$ to keep the vortex in the cone. High dust removal efficiency is obtained while maintaining $S/De \leq 1$ or $S/B \leq 1$ ratio when $B > De$. The $De/D$ ratio influences the pressure loss and thus the efficiency of dust removal and should be from about 0.4 to 0.5. The condition $a > b$ affects the increase in the efficiency of dust removal, but in order to reduce $\Delta p$, the inlet cross section $ab \geq \pi De^2/4$ should be maintained. The increase in dust removal efficiency can also be achieved, among others, by sucking gas at various points of the cyclone, using an electric field, agglomeration of aerosol particles and recirculation of a portion of the dust stream [11-13].

3. The scope and methodology of cyclone efficiency calculations

In this publication was calculated of general efficiency ($\eta$) and particle diameter corresponding to 50% dust removal efficiency ($d_{P50}$) of cyclones with standard dimensions as in table 1. The calculations were carried out for 6 work variants, which differ in the size of gas flow. Other assumptions for all work variants were the same. The input data for calculations were given in table 2. The particle size distribution in gas was shown in table 3.

| Initial data | Variant  |
|--------------|----------|
| $V_G$, m$^3$/h | I | II | III | IV | V | VI |
| 3500 | 6000 | 12200 | 18000 | 25000 | 100000 |
| $\rho_G$, kg/m$^3$ | 0.918 |
| $\rho_P$, kg/m$^3$ | 1750 |
| $\mu_G$, kg/m$^s$ | $2.15 \times 10^{-5}$ |
| $T$, K | 393 |
| $g$, m/s$^2$ | 9.81 |

Table 2. The distribution of particle sizes in gas

| $d_p$, μm | $x_i$, % |
|-----------|---------|
| 5-10      | 17      |
| 10-20     | 20      |
| 20-30     | 21      |
| 30-50     | 15      |
| 50-70     | 13      |
| 70-100    | 14      |

Table 3. Input data for calculations

The optimal real diameter of the cyclone was calculated from the formula [8]:

$$D_{real} = 0.074\left[\frac{V_G^2 \rho_G^2}{\mu_G g (\rho_P - \rho_G)} \left(1 - \frac{b}{D}\right)^{0.454} \right] \left(\frac{a}{b}\right)^3 (1)$$

The actual dimensions of the cyclone result from the actual diameter. For example, the actual height of the gas inlet to the cyclone was calculated from the formula [11]:

$$a_{real} = a \cdot D_{real} (2)$$

The remaining dimensions of the cyclone were calculated analogically. The gas velocity at the inlet to the cyclone was calculated from the formula [11]:

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The fractional efficiency of dedusting for individual fractions of particles in the gas was calculated from the formula [11]:

\[ \eta_i = 1 - \exp \left( -2 \cdot (\psi_i \cdot K_i)^{\frac{1}{n}} \right) \]  

(4)

where:

\( n \) - wind exponent, which was calculated from the formula [11]:

\[ n = 1 - (1 - 0.667 \cdot D_{\text{real}}^{0.14}) \left( \frac{T}{293} \right)^{0.3} \]  

(5)

\( \psi_i \) - inertial parameter, which was calculated from the formula [11]:

\[ \psi_i = \frac{(1 + n) \cdot (d_{pi} \cdot 10^{-6})^2 \cdot \rho_p \cdot u_i}{18 \cdot \mu \cdot D_{\text{real}}} \]  

(6)

The total efficiency of the cyclone is the sum of the efficiency for individual \( d_{pi} \) particle diameters. The natural length of the cyclone was calculated from the formula [11]:

\[ l = 2.3 \cdot D_e \left( \frac{D}{a \cdot b} \right)^{1/n} \]  

(7)

The effective volume of the cyclone, depending on the condition fulfilled was calculated from the formula [11]:

\[ V = \begin{cases} \frac{\pi \cdot D^2}{4} \cdot (h - S) + \frac{\pi \cdot D^2}{4} \left( \frac{l + S - h}{3} \right) \left( 1 + \frac{d}{D} + \frac{d^2}{D^2} \right) \cdot \frac{\pi \cdot D_e^2 \cdot l}{4} & \text{dla } l < (H - S) \\
\frac{\pi \cdot D^2}{4} \left( h - S \right) + \frac{H - h}{3} \left( 1 + \frac{B}{D} + \frac{B^2}{D^2} \right) \cdot (H - S) & \text{dla } l > (H - S) \end{cases} \]  

(8)

(9)

where:

\( d \) - diameter of the core at the point of change of the vortex flow direction to the opposite one, which was calculated from the formula [11]:

\[ d = D - (D - B) \left( \frac{l + S - h}{H - h} \right) \]  

(10)

The volume of the annular space above the edge of the outlet duct to the center of the inlet duct was calculated by the formula [11]:

\[ V_S = \frac{\pi \cdot (S - a)}{2} \left( D^2 - D_e^2 \right) \]  

(11)

The cyclone shape factor \( K \) was calculated from the formula [11]:
The particle diameter of the particle corresponding to 50% efficiency was calculated from the formula [11]:

\[ d_{p50} = \left( \frac{0.6931}{c} \right)^{n+1} \]  (13)

where:

\( c \) - coefficient \( c \), which was calculated from the formula [11]:

\[ c = 2 \left( \frac{K \cdot \frac{V}{g} \cdot p_{\rho} \cdot (n+1)}{18 \cdot \mu \cdot D^{3}} \right)^{n+1} \]  (14)

4. Results and discussion

The results of calculations for the assumptions made were presented in table 4. Based on the developed results, the Spearman rank correlation of independent variables, i.e. individual cyclone dimensions into dependent variables, i.e. dust extraction efficiency and particle diameter corresponding to 50% efficiency was analyzed. The analysis was performed using the Statistica software package. Rank correlation takes values from -1 to +1. Rank correlation shows any dependence, also non-linear. The higher the value of the correlation coefficient, the greater the dependence between variables. In the calculation results table 5, there were showed the obtained results of the Spearman rank correlation.

**Table 4. The calculation results**

|                           | Variant |   I   |   II  |   III |   IV  |   V   |   VI  |
|---------------------------|---------|-------|-------|-------|-------|-------|-------|
| **High efficiency cyclone I** |         |       |       |       |       |       |       |
| D_{real}, m               |         | 0.57  | 0.72  | 1.00  | 1.19  | 1.39  | 2.60  |
| \( \eta \), %             |         | 96.9  | 96.3  | 95.6  | 95.1  | 94.7  | 92.8  |
| \( d_{p50} \), \( \mu m \) |         | 1.280 | 1.369 | 1.503 | 1.584 | 1.657 | 2.014 |
| **High efficiency cyclone I** |         |       |       |       |       |       |       |
| D_{real}, m               |         | 0.57  | 0.73  | 1.01  | 1.20  | 1.40  | 2.62  |
| \( \eta \), %             |         | 97.4  | 96.9  | 96.3  | 95.8  | 95.4  | 93.7  |
| \( d_{p50} \), \( \mu m \) |         | 1.129 | 1.221 | 1.355 | 1.435 | 1.507 | 1.854 |
| **General use cyclone I**  |         |       |       |       |       |       |       |
| D_{real}, m               |         | 0.45  | 0.57  | 0.79  | 0.95  | 1.10  | 2.06  |
| \( \eta \), %             |         | 97.8  | 97.4  | 96.7  | 96.3  | 96.0  | 94.3  |
| \( d_{p50} \), \( \mu m \) |         | 1.102 | 1.164 | 1.260 | 1.321 | 1.376 | 1.659 |
| **General use cyclone II** |         |       |       |       |       |       |       |
| D_{real}, m               |         | 0.45  | 0.57  | 0.79  | 0.95  | 1.10  | 2.06  |
| \( \eta \), %             |         | 97.7  | 97.2  | 96.7  | 96.2  | 95.8  | 94.1  |
| \( d_{p50} \), \( \mu m \) |         | 1.106 | 1.176 | 1.282 | 1.347 | 1.406 | 1.699 |
| **High performance cyclone** |         |       |       |       |       |       |       |
| D_{real}, m               |         | 0.51  | 0.65  | 0.90  | 1.07  | 1.24  | 2.33  |
| \( \eta \), %             |         | 96.5  | 95.9  | 95.1  | 94.6  | 94.2  | 92.1  |
| \( d_{p50} \), \( \mu m \) |         | 1.373 | 1.460 | 1.591 | 1.671 | 1.740 | 2.096 |
Table 5. The results of Spearman's rank correlation analysis

| Independent variables | Dependent variables | efficiency | d_{50} |
|-----------------------|---------------------|------------|--------|
| D                     | -0.91               | 0.87       |
| a                     | -0.97               | 0.94       |
| b                     | -0.85               | 0.78       |
| S                     | -0.92               | 0.88       |
| De                    | -0.94               | 0.90       |
| h                     | -0.79               | 0.72       |
| H                     | -0.83               | 0.77       |
| B                     | -0.95               | 0.94       |

Based on the results obtained for the assumptions, it can be noticed that as the volume flow of gases flowing through the cyclone increases, all of its structural dimensions increase, the particle diameter of the d_{50} increases, and the overall efficiency of dust removal decreases. In any case, the overall efficiency of dedusting is high, above 90%. The highest efficiency of dedusting in each analyzed variant was obtained in the general use cyclone I. The lowest efficiency was obtained in the high performance cyclone. Analogously, the smallest particle diameters (d_{50}) were obtained in the general use cyclone I, and the highest in the high performance cyclone. Based on the analysis of Spearman's rank correlation, it can be seen that all independent variables have a very high impact on dependent variables, which means that each cyclone design dimension affects the efficiency of dust removal and particle diameter.

5. Conclusions

The calculation of cyclone removal efficiency depends on the properties of the aerosol stream and the design parameters of the dedusting device. This publication presents, among others, information on cyclones and the impact of their construction parameters on the efficiency of dust removal and the particle diameter of the particle corresponding to 50% efficiency. Based on literature data, it is known that the most important factors affecting the efficiency of dust removal are the physicochemical properties of aerosol particles and their sizes. The geometric shape of the cyclone is relatively simple, but its structural dimensions have an effect on gas movement and the efficiency of dust removal. The paper presents the results of calculations of the overall dust removal efficiency and the particle diameter (d_{50}) for different types of cyclones with standard dimensions. Analyzing the results obtained, it can be noticed that in every variant of the cyclone operation the same trend of changes in values is maintained. Spearman's rank correlation showed that each cyclone design dimension has a high impact on the dust removal efficiency and the particle diameter. For the assumed design assumptions, the overall dust removal efficiency is at a high level above 90%.

The information contained in the article is a valuable source of information on calculations for cyclones, and may provide an introduction to further analysis of the impact of cyclone construction on the efficiency of its operation.

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