Archives of Environmental Protection
Vol. 50 no. 4 pp. 127–134

PL ISSN 2083-4772
DOI 10.24425/aep.2024.152902

Experimental and pilot model research of spiral cyclone with curvilinear channels

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Keywords: velocity, chanel, aerodynamic resistance, cyclone, curvilinear semi-ring, spiral case

Abstract: The advanced type of cyclone was applied to separate wood particulate matter from the air. The cyclone was designed in the laboratory of Vilnius TECH. A series of experimental studies was conducted both in the lab and under industrial conditions. These studies aimed to specify the air velocity and aerodynamic resistance in the experimental and pilot six-channel cyclone with spiral casings and curvilinear semi-rings. Air treatment efficiency was also determined. The highest air treatment efficiency achieved using experimental cyclone was 91.4%, while the pilot cyclone achieved an efficiency of 94. 5%. The industrial and experimental cyclones were found to have similar air treatment efficiency.

Introduction

Particulate matter (PM) consists of complex and varying mixtures of particles suspended in the air. These particles vary in size and composition and are produced by various natural and anthropogenic activities [Werner et al. 2016]. Particulate matter negatively impacts human health [Olszowski 2015; Zamani et al. 2021; Karjalainen et al. 2021], especially in workplace environments [Cheberyachko et al. 2022]. Air polluted with PM significantly contributes to the development of asthma [Keet et al. 2018; Zuo et al. 2019]. To address this issue, stricter environmental protection requirements are being implemented for industrial facilities, which are major point sources of atmospheric emissions. According to World Health Organization recommendations, limit values for criteria pollutants have been specified. Consequently, treating industrial air emissions containing PM has become increasingly important, often achieved using air treatment devices with various designs [Буров et al. 2012].

Cyclone air treatment systems operate on the principle of centrifugal force, which emerges as the air inside the device whirls in a tangential or axial direction [Baltrenas et al. 2022; Chlebnikovas et al. 2022; Chlebnikovas et al. 2021; Chlebnikovas 2021; Baltrėnas and Chlebnikovas 2019; Baltrėnas and Chlebnikovas 2018]. Cyclones are widely used for removing PM from air due to their simple structure and effective performance [Baltrėnas and Chlebnikovas 2019; Baltrėnas and Chlebnikovas 2018; Vaitiekūnas et al. 2014; Jasevičius et al. 2017; Baltrėnas and Baltrėnaitė 2018; El-Emam et al. 2019; El-Emam et al. 2021; Duran and Caldona 2020, Primus et al. 2021, Wasielewski et al. 2020, Janta-Lipińska et al. 2020]. A classic cyclone consists of a few components: a separation chamber, air inlet, and outlet paths. These devices are popular because they are easy to manufacture, compact, and low-maintenance, with relatively low aerodynamic resistance. Furthermore, they can treat air at high temperatures (300–500 ºC).

However, classic cyclones have notable drawbacks, including efficiency loss due to leakage, increased energy and pressure costs at high inlet velocities, and moderate removal efficiency for fine particles (<10 μm) PM [Bernardo et al. 2006]. To address these limitations, multi-channel cyclones were developed. These cyclones feature half-rings or other modification that extend the dusty air flow's residence time, enhancing PM removal efficiency. A conventional cyclone typically achieves about 80 % cleaning efficiency, whereas multi-channel designs can perform better [Bernardo et al. 2006]. The main drawback of multi-channel cyclones is the potential for clogging of internal components, such as half-rings, especially in the presence of moisture in the gas flow. To achieve higher efficiency, advanced cyclones with closed-circuit systems integrating curvilinear channels have been designed. These systems feature closed cylindrical circuits of various diameters arranged at an angle of $\varphi=\pi$, where pairs of the adjacent channels form a closed circuit [Bernardo et al. 2006].

Air velocity flow trajectory in the cyclone provide valuable insights into PM distribution and removal patterns [Bernardo

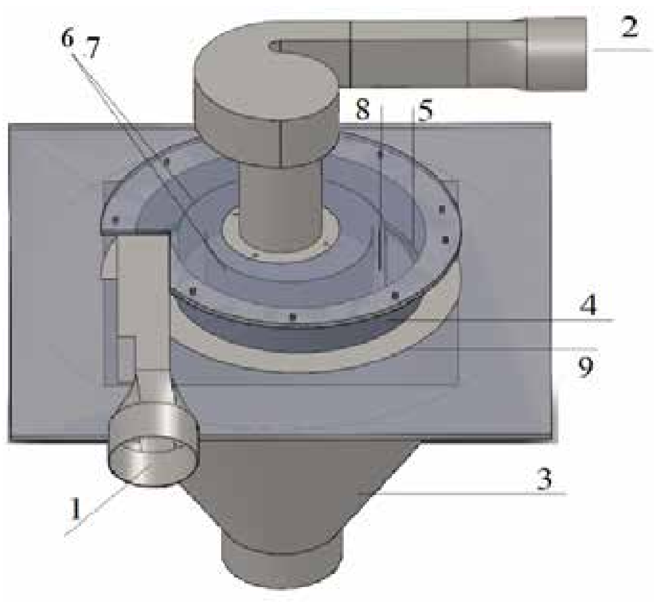

Fig. 1. Spiral multi-channel cyclone with unregulated gaps between the curvilinear semi-rings:
(1) inlet of air containing PM; (2) outlet of treated air;
(3) conic hopper; (4) spiral form separation chamber;
(5) articulated ring slots; (6) curvilinear channels;
(7) cylindrical semi-rings of different radius;
(8) gaps between the curvilinear channels;
(9) cyclone spiral case bottom

et al. 2006]. Aerodynamic resistance is a critical characteristic affecting energy consumption and system performance. Therefore, optimizing the internal design of a six-channel cyclone with a spiral casing is essential to balance efficiency and resistance. Simplifications and assumptions were made during the design and analysis phases to study airflow distribution and its impact on performance. Turbulence, influenced by air velocity, can reduce treatment efficiency, emphasizing the need for precise velocity control.

Multi-channel cyclones represent a promising alternative to classic designs, offering lower aerodynamic resistance and higher air cleaning efficiency. The novelty of the selected cyclone lies in its improved design, featuring six internal channels (i.e. a multichannel cyclone) inside the cyclone and a spiral body. Unlike traditional cyclones, the new design allows adjustable distances between semi-rings, enhancing flexibility and efficiency. Additionally, integrating advanced filtration stages and non-traditional materials contributes to sustainable and efficient gas stream purification [Chlebnikovas and Kilikevicius 2023; Vaišis et al. 2023]. Although the application of multi-channel cyclone technology to treat a larger gas volumes can reduce efficiency slightly (by up to 5%), this trade-off is outweighed by the benefits of enhanced performance and adaptability [Baltrėnas, and Chlebnikovas 2016].

The aim of this study was to investigate the aerodynamic resistance of advanced six-channel cyclone with a spiral casing, where the curvilinear semi-rings were positioned at a 50%/50% configuration. Additionally, the study evaluated the mean velocities in the cyclone channels and the efficiency of wood PM removal under both laboratory and industrial conditions.

Materials and Methods

It was found that 6-channel cyclone is more effective than 4- and 5-channel cyclones, which is why it was chosen for experimental research. Fig. 1 shows a spiral cyclone with unregulated gaps between the curvilinear semi rings. The design of cylindrical multi-channel cyclone includes air flow inlet and outlet vents, as well as a conic hopper (Fig.1).

A series of experimental studies on the cyclone pilot model with adjustable gaps between the curvilinear semi-rings was performed under industrial conditions at JSC *ABC Laiptai*. Fig. 3 shows the cyclone used in the study. The geometric dimensions of the experimental cyclone (Fig. 2) are as follows: diameter of the cylindrical body – 0.50 m; total cyclone height

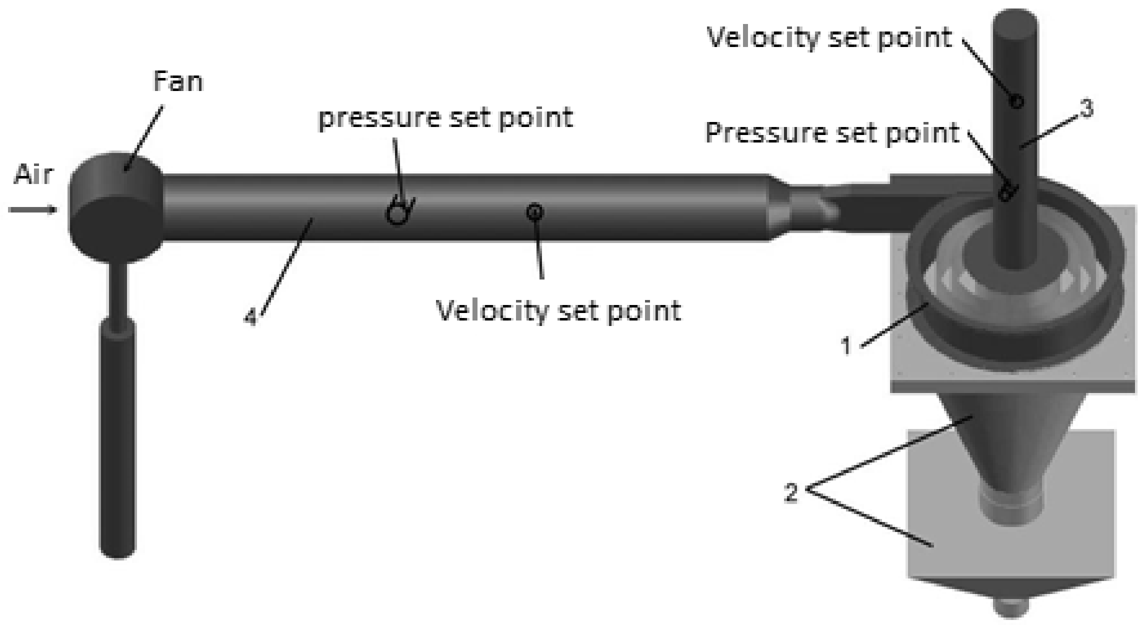

Fig. 2. The six-channel cyclone with adjustable gaps between the curvilinear semi-rings with the spiral case:
(1) multi-channel cyclone with a spiral case; (2) double hopper; (3) out air path; (4) duct of polluted air inlet

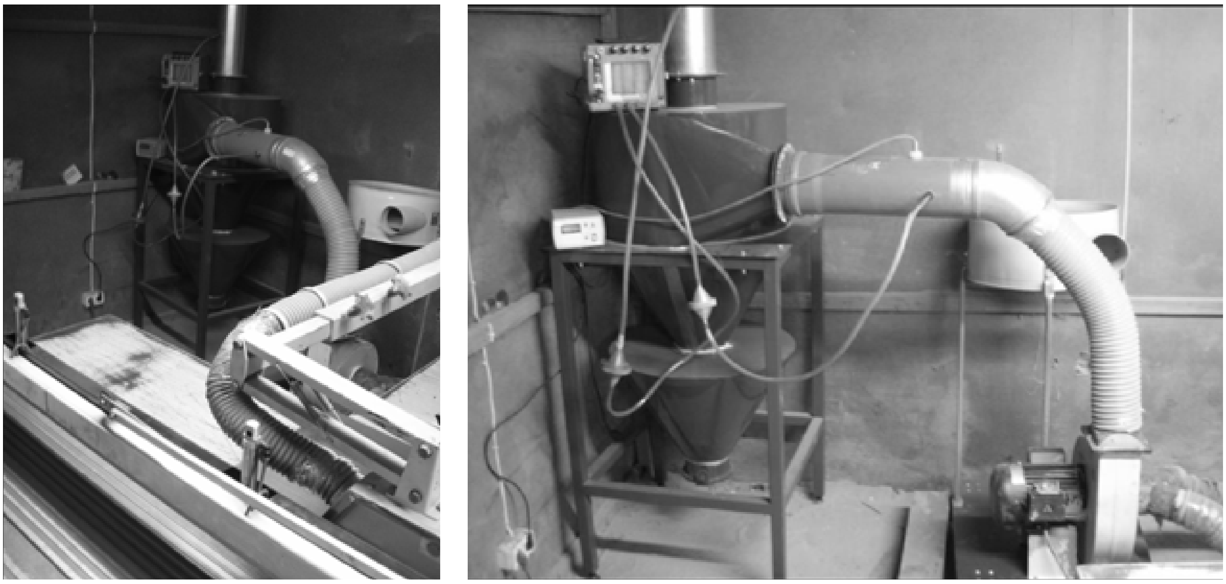

Fig. 3. Studies of the spiral six channel cyclone with adjustable gaps between the curvilinear semi-rings under industrial conditions

(including the conical bunker) – 0.72 m^2. These geometric dimensions are 50% larger in the industrial cyclone (Fig. 3). Experimental results are presented for the experimental cyclone tested in the laboratory (Fig. 2) and the pilot cyclone tested under industrial conditions (Fig. 3.).

Complex investigations of air velocities, aerodynamic resistance and wood particles removal from air were performed. Wood particulate matter (PM) was sifted through a sieve with a pore diameter of 50 µm using the analytical sieve shaker (AS 200 Digital). The size of the PM used in the experimental studies ranged from 0.5 to 50 µm. This particle size (<50 µm) was selected for experiments because it represents the dominant size range of PM generated by the selected wood industry company. The PM size distribution was analyzed using a FRITISCH laser granulometer, and the results are presented in Table 1.

The wood density was about 650 kg/m^3, and the average size of the wood PM was about 16.5 µm. The air treatment system consisted of a Flymo Twisret blower 2200 XV (capacity 2.2 kW), a spiral six-channel cyclone, and inlet and outlet air paths. In order to correctly determine PM concentration while collecting disposables air samples, isokinetic conditions were maintained. The gravimetric (weight-based) method was chosen for the determination of PM concentration. To ensure measurement of treatment efficiency, the mass of PM introduced into the duct before the cyclone and the mass collected in the hopper were monitored. The difference between the results obtained by these two methods was less than 9%.

Table 1. Dispersity of PM used in experiments

Dispersity, µm	Wood, %
0-1.0	0.6
1.0-2.5	3.9
2.5-10.0	26.1
10.0-15.0	25.9
15.0-20.0	20.6
20.0-50.0	22.9

The aerodynamic resistance of the cyclone was measured using a differential pressure meter (DSM-1) with a measuring range of 0–20 000 kPa and bias of ± 5%) Pa. Air velocity measurements were performed in each cyclone channel. The air velocity at each measurement point within the cyclone channels (1–6 channels and 1–5 points) was calculated using following formula:

$$V = \sqrt{\frac{2gP_D}{\rho_t}} \tag{1}$$

where g – free fall acceleration [m/s^2]; P_D – dynamic gas flow pressure at the measurement point [Pa]; ρ_t – gas density under measurement conditions [kg/m^3].

If the curvilinear semi-rings are arranged in a 50%/50% position (or another configuration), this means that the peripheral flow constitutes 50% of the total incoming flow, while the transit flow accounts for the remaining 50% of the total incoming flow.

The gas density (ρ_0) under the measurement conditions was calculated using the following formula:

$$\rho_t = 0.359 \cdot \rho_0 \frac{P}{273+t} \tag{2}$$

where ρ_0 – gas density, re-calculated under normal conditions (0 °C, 760 mmHg) [kg/m^3]; P – atmospheric pressure [mm Hg]; t – gas temperature in the air path [°C].

Statistical analysis.

Statistical analysis of the data was performed to evaluate the results. Mean values, standard deviation and confidence intervals were calculated. Excel 2021 software was used for these calculation, with a significance level of $p<0.05$. The obtained result of the analysis represent the arithmetic average of 3 measurements. If the distribution exceeded 6 %, additional tests were conducted to ensure accuracy.

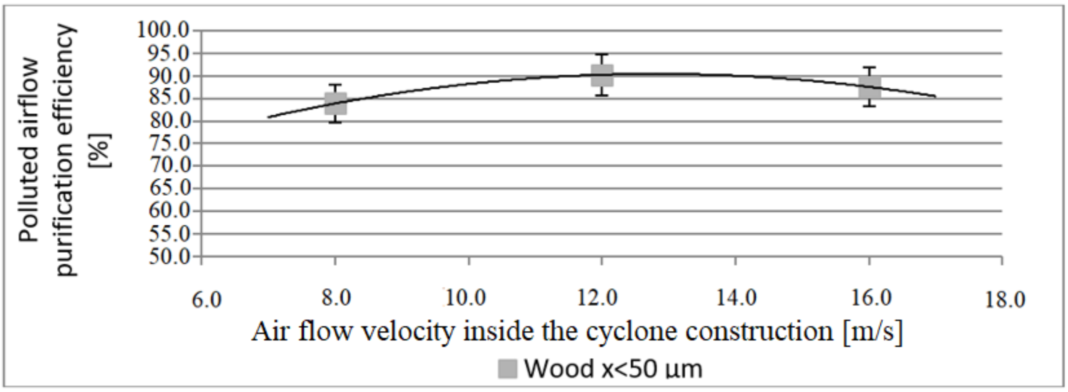

Fig. 4. Air treatment from wood particles, which dispersivity x<50 µm, efficiency, under the air velocity inside the cyclone design, when the air distribution ratio is 50%/50% under experimental conditions

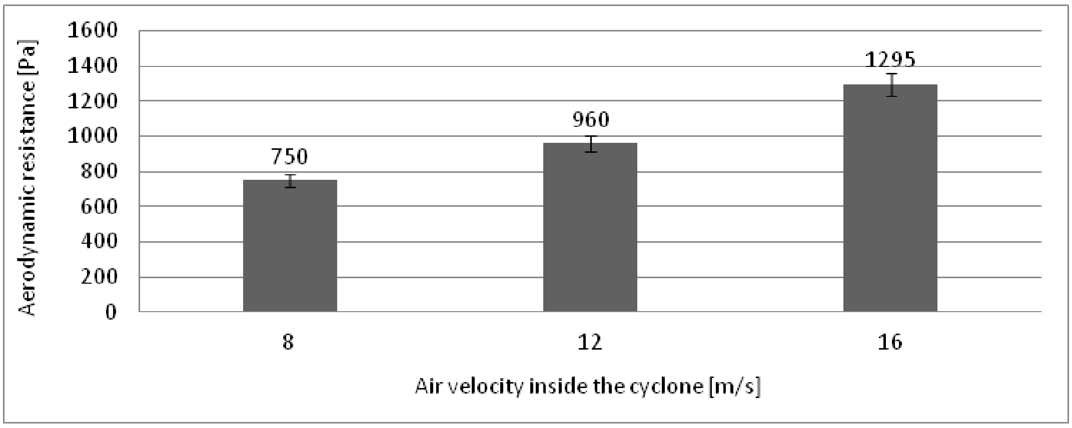

Fig. 5. Dependence of six-channel cyclone aerodynamic resistance on the air flow distribution ratio [50%/50%], under 8 m/s, 12 m/s and 16 m/s mean air flow velocities in the cyclone channels under experimental conditions

Results and Discussion

Laboratory conditions

The results of air treatment from wood particles x<50 µm in the six-channel cyclone under a 50%/50% air distribution ratio are presented in Fig. 4. The median size of the wood particles was 16.5 µm. The cyclone hopper should be cleaned of accumulated PM when it reaches approximately 80 % capacity. As the air velocity inside the cyclone increases from 8.0 to 12.0 m/s, the wood PM removal efficiency increases from 84.7 to 91.4 %. However, when the air velocity increases further from 12.0 to 16.0 m/s, the removal efficiency decreases from 91.4 to 88.3 %. The highest efficiency for wood PM removal was achieved at an air velocity of 12.0 m/s. The results of the aerodynamic resistance of the six-channel cyclone under experimental conditions are presented in Fig. 5.

The highest aerodynamic resistance among the investigated cases was determined at a mean air flow velocity of 16 m/s in the cyclone channels, with a fixed 50%/50% air distribution ratio. In this scenario, the aerodynamic resistance was determined to be 1295 (± 5%) Pa, which is 25.9% higher than the resistance at 12 m/s and 42.1 % higher than at 8 m/s.

The lowest aerodynamic resistance was recorded at the lowest air flow velocities (mean velocity of 8 m/s in the channels) with the 50%/50% air distribution ratio, i.e. when the peripheral air stream and the transit air stream were equal. In this case, the aerodynamic resistance was 750 (± 5 %) Pa.

The air velocity distribution in the six-channel cyclone channels under experimental conditions is presented in Table 2.

At a mean air velocity of 12.0 m/s, the inlet velocity into the cyclone velocity was measured at 12.3 m/s. For air entering the first curvilinear channel, the velocity slightly decreased to 12.0 m/s. Moving towards the middle of the

Table 2. Distribution of the air velocities [m/s] in the six-channel cyclone channels under experimental conditions

6 channels, 50%/50%						Mean value
Angle position of point in the channel	1	2	3	4	5	
Channel 1	12.1	12.2	12.2	12.4	12.4	12.3
Channel 2	12.1	11.9	11.9	11.8	11.8	11.9
Channel 3	12.0	12.0	12.4	12.5	12.2	12.2
Channel 4	12.1	12.1	12.3	12.5	12.4	12.3
Channel 5	11.9	11.9	12.0	12.0	11.9	11.9
Channel 6	11.9	12.0	12.0	12.5	12.5	12.2
Mean value						12.1

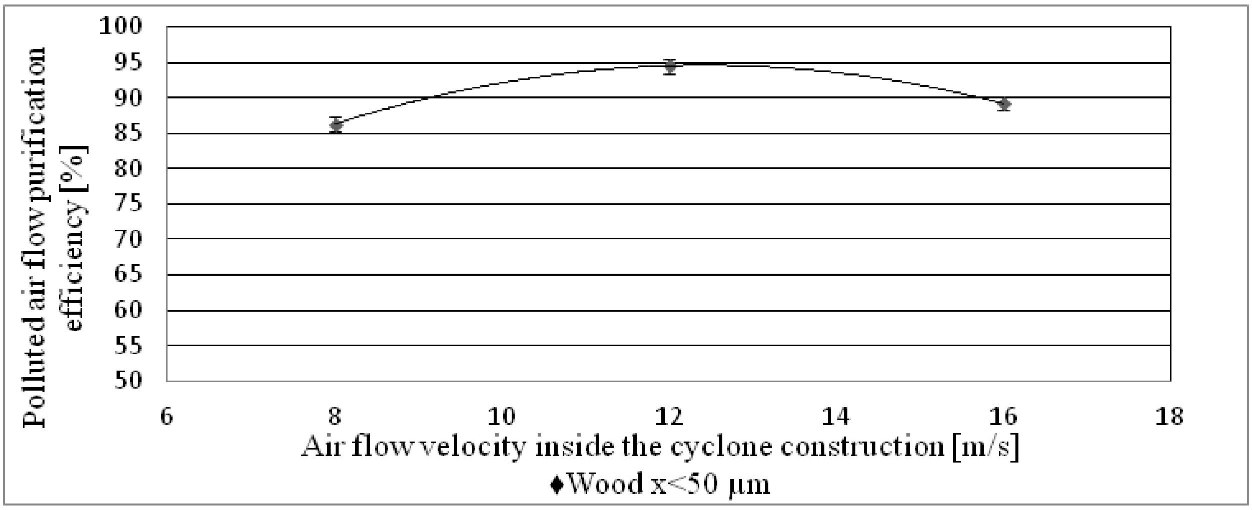

Fig. 6. Air treatment from wood particles, which dispersivity x<50 μm, efficiency, under the air flow velocity inside the pilot cyclone design, when the air flow distribution ratio is 50%/50% under industrial conditions

first channel, the velocity continued to decrease, reaching its minimum at measurement point No. 3, where the velocity was 0.7% lower compared to the inlet velocity. Towards the end of the first channel, the velocity increased again, with the highest velocity recorded at measurement point No. 5, reaching 12.1 m/s.

In the second channel, the lowest velocities in the entire cyclone were observed, except for the velocities at the first measuring point. At the second point, velocities slightly adjusted and differed reciprocally. The average speed in the second channel was 12.2 m/s.

In the third channel, the most significant velocity decreases were noted at the second and fourth measuring points, where velocity dropped to 11.2 m/s. Air velocity distribution was quite variable, with the highest velocities, approximately 12 m/s, occurring at the beginning and end of the channel. The maximum velocity of 12 m/s was recorded at point 1.

In the fourth channel, air velocities ranged from 11.2 to12.1 m/s, gradually decreasing from the beginning to the end of the channel, with a total difference of 2.9 %. The second point exhibited velocities nearly 1.5 times lower than those at the first point. The highest velocities were recorded at the first and sixth points, while the velocities at remaining points were approximately 11.4 m/s.

In the fifth channel, the most notable velocity drop occurred at the first measuring point, where a velocity of 11.5 m/s was recorded. Velocities were distributed variably, with the lowest values (11.5 m/s) detected at the beginning of the channel.

In the sixth channel, the sharpest velocity drop was observed at the first measuring point, where a velocity of 11.4 m/s was recorded. As in the fifth channel, the velocities were distributed unevenly, with the lowest values (11.4 m/s) occurring at the beginning of the channel.

When the mean air velocity is 12 m/s, the inlet velocity into the cyclone was estimated to be 10.8 m/s. For air entering the first curvilinear channel, the velocity slightly decreased to 10.7 m/s. Moving toward the middle of the first channel, the velocity increased. Toward the end of the first channel, the air velocity continued to rise, with the highest velocity (11.0 m/s) recorded at the fifth measurement point.

Industrial conditions

The air treatment efficiency of the six-channel cyclone with a spiral case for wood particles (x<50 μm) under industrial conditions, with a 50%/50% air distribution ratio, is presented in Fig. 6.

As the air flow velocity inside the cyclone increases from 8.0 to 12.0 m/s, the PM removal efficiency increases from 86.3 to 94.5 %. As the air flow velocity inside the cyclone increases from 12.0 to 16.0 m/s, the PM removal efficiency decreases from 94.5 to 89.2 %.

It was determined that the highest air treatment efficiency for wood PM was achieved when the air flow velocity was 12.0 m/s. The highest air treatment efficiency for wood PM using the experimental cyclone was 91.4%, while the highest air treatment efficiency achieved with the pilot cyclone was 94. 5%.

It was found that the industrial cyclone (Fig. 3) and the experimental cyclone (Fig. 2) have similar air treatment efficiency. Therefore, it can be concluded that the developed spiral cyclone with adjustable gaps between the curvilinear half-rings is effective and can be used in industry, e.g. in real-world conditions.

The removal efficiency of particulate matter in an air treatment device depends on such factors as the type and design of the air treatment device, air velocity, ambient meteorological conditions, and the nature, concentration, and size distribution of the PM. The multi-channel cyclone offers higher air cleaning efficiency compared to a traditional cyclone due to its more complex design, which is mainly characterized by the use of semi-rings or other modifications that allow for adjustments in the proportion of peripheral and transit air.

In a multi-channel cyclone, the ratio of peripheral to transit flow can be controlled in the inter-ring active filtration zone. As the gas moves through the cyclone channels, it is divided into peripheral (return) and transit (forward) flows, allowing the internal geometry of the cyclone to be adjusted based on the characteristics of the particulate matter in the polluted air, thus achieving the optimal configuration. The operating principle of multi-channel cyclones is that the PM is deposited through centrifugal forces and, additionally, by filtration in the

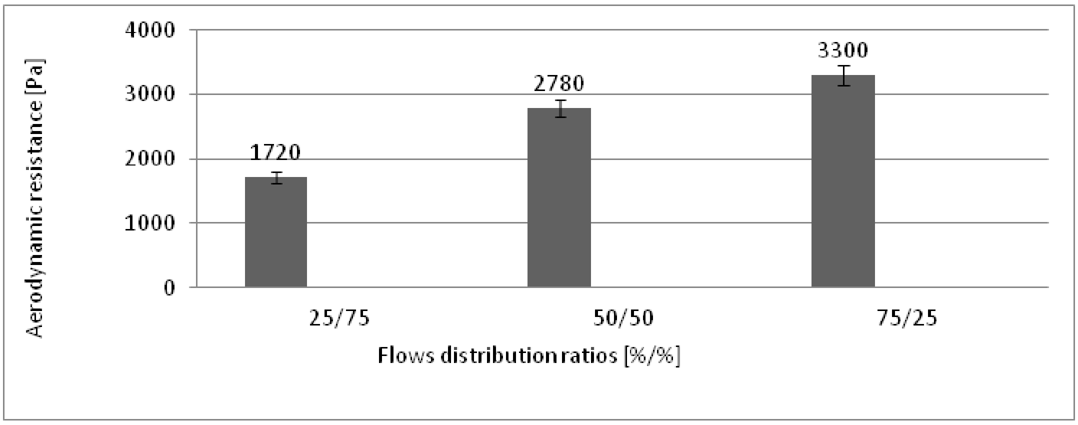

Fig. 7. Six-channel pilot cyclone with a spiral case aerodynamic resistance dependence on the distribution ratio at 12 m/s mean air velocity in the cyclone channels under industrial conditions

zone where the incoming (peripheral) and outgoing (transit) gas streams meet. These processes result in the interaction between the peripheral and transit flows (filtration) and the centrifugal, gravitational and adhesive forces, which are the most significant in magnitude, as well as drag, capillary and electrical forces acting on the PM. The interaction between the peripheral and transit flows creates additional turbulence, resulting in a more effective treatment process.

The average treatment efficiency achieved in a classic cyclone is around 80%. The adhesive properties (the bonding or adherence of particles to surfaces) mainly depend on the humidity of the environment, as well as the nature and size of the particles. Adhesive properties can have both positive and negative impacts on air cleaning performance. Their negative influence is evident when cracks in the internal structure of the air cleaning unit become filled with particulate matter, potentially reducing cleaning efficiency. On the other hand, the positive effect of adhesion occurs when particulate matter clumps together, resulting in an increase in particle size and increased capture efficiency. The phenomenon of adhesion has not been evaluated in these studies, and further experimental studies on a larger scale would be required to assess it. During the experimental tests, meteorological conditions remained virtually unchanged, so their influence on cleaning performance was minimal. However, meteorological conditions can influence PM removal efficiency, as they can affect both the adhesive properties of PM particles and the dynamic viscosity of the air flow – two parameters that impact air treatment efficiency.

The results of aerodynamic resistance of six-channel cyclone under industrial conditions are presented in Fig. 7.

When the air distribution ratio inside the cyclone design was 25%/75%, the aerodynamic resistance was 1720 (± 4%) Pa. For the six-channel cyclone with an air distribution ratio of 50%/50%, half of the peripheral flow is diverted into the previous channels, which prolongs the treatment of the polluted flow. As a result, the permeability of the treatment system is decreased, and the aerodynamic resistance increases. Under these conditions, with a mean air flow velocity of 12 m/s in the cyclone channels, the aerodynamic resistance is 2780 (± 5%) Pa.

When the air distribution ratio inside the cyclone design was 75%/25%, the aerodynamic resistance increased to 3300 (± 4.5%) Pa. It was determined that as the peripheral portion of the air flow increased from 25 to 75%, and the transit (moving to the next channel) air flow portion decreased from 75 to 25%, the aerodynamic resistance increased by 1.92 times.

The aerodynamic resistance of the six-channel cyclone was determined for an air distribution ratio of 50%/50%. In this case, half of the peripheral flow is diverted into the previous channels, prolonging the treatment of the polluted flow. As a result, the permeability of the treatment system is decreased, and the aerodynamic resistance is increased.

The air velocity distribution in the six-channel spiral cyclone channels under industrial conditions are presented in Table 3.

The average velocity of the second channel reached 11.1 m/s. In the third channel, the most significant velocity drop occurred at the first and second measurement points, where a value of 10.9 m/s was recorded. The air velocities in this channel were relatively uniform. In the fourth channel, velocities ranged from 11.4 to 11.6 m/s, with the velocity increasing from the beginning to the end of the channel. In the fifth channel, the most notable velocity decrease was observed in the first and second measurement points, where a value of 11.9 m/s was recorded. The air velocities in this channel varied,

Table 3. Distribution of air velocities [m/s] in the six channel pilot cyclone channels under industrial conditions

6 channels, 50%/50%						Mean value
	1	2	3	4	5	
Channel 1	10.8	10.7	10.8	11.0	11.0	10.9
Channel 2	10.9	10.9	11.1	11.1	11.4	11.1
Channel 3	11.2	11.4	11.3	11.5	11.5	11.4
Channel 4	11.4	11.5	11.6	11.6	11.6	11.5
Channel 5	11.9	11.9	12.0	12.1	12.3	12.0
Channel 6	12.4	12.4	12.6	12.6	12.7	12.5
Mean value						11.6

with the lowest velocities at the beginning and the highest at the end. Through the entire fifth channel, a gradual increase in the air velocity was noticed. In the sixth channel, a similar tendency for velocity growth was noted, with the maximum air velocity of 12.7 m/s recorded at the end.

Conclusions

1. It was determined that the results from the experimental and industrial research do not differ significantly. During laboratory tests, it was found that wood particles were removed from the air with an efficiency of 91.4%, while under industrial conditions, the efficiency increased to 94.5 %. It can be concluded that the six-channel cyclone is suitable for use in manufacturing, as it effectively removes extremely fine particles that are harmful to health. It is essential to ensure that the cyclone is designed with a six-channel system, maintaining a 50%/50% air distribution ratio and an air flow velocity of 12 m/s inside the cyclone.
2. The relationship between aerodynamic resistance and mean air flow velocity in the cyclone channels was determined. The investigated flow distribution ratio was 50%/50%, with an air flow velocity was 12.0 m/s. The aerodynamic resistance was 960 (± 5 %) Pa for the experimental cyclone and 2780 (± 5 %) Pa for the pilot cyclone.
3. The mean air velocities inside the cyclone design with six channels were determined for a 50%/50% curvilinear semi-rings layout. It was found that the air flow velocity inside the cyclone design, as in the case of the experimental model, is influenced by the amount of air directed into the peripheral channel. Diverting 50% of the air flow into the peripheral channel creates greater resistance at the point of diversion, causing the air velocity to become uneven. The formation of an 'air curtain' further disrupts the flow in the peripheral channel, leading to irregular increases and decreases in velocities.

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