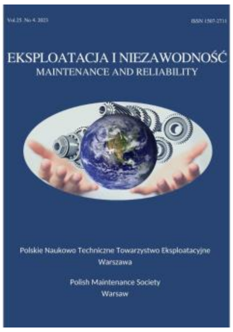

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Investigation into the Flow of Gas-Solids during Dry Dust Collectors Exploitation, as Applied in Domestic Energy Facilities – Numerical Analyses

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Highlights

- The dust particle dynamics can be modified by the design of a dust collector.
- The geometric structure in dust collectors is crucial for efficiency in the separators' operation.
- Increasing the number of rotor blades in collectors causes the dust compound to swirl stronger.
- The 8 items of blades result in 50% dust concentration along the internal walls.
- SolidWorks allows the analysis of dust removal processes in dust collectors, with good accuracy.

Abstract

The paper presents the results related to the simulation of dust-separating tangential cyclones: single cyclones of various geometries, and an axial multi-cyclone with fixed geometries and components. Its goal was to apply low-cost analyses for cyclones in industrial realization. Therefore, the presented research was applied with simulation methodology as a problem of Computational Fluid Dynamics. The models were analyzed using SolidWorks Flow Simulation software. The presented dust collectors are real-life objects, applied in industrial facilities. For a multi-cyclone, the increase in the number of blades, from 5 to 8, together with the change in the angle of a blade's pitch i.e., 30° and 45°, resulted in dust concentration along the internal walls from just 10% for 5 blades up to c.a. 37.5% for 6 blades, and c.a. 50% for 8 blades, whereas the dust concentration in the device's central part equals c.a. 20% for the last option. The model validation draws attention to the potential applicability of the software in flow issues alongside common and more complex numerical environments.

Keywords

the efficiency of dust extraction; energy consumption; multi-phase flow transport; technological transport; computational fluid dynamics; dust collector.

1. Introduction

The domestic situation in Poland, in the context of dust collection in energetic facilities, forms the introduction to this paper, to state the importance of using dust-separation technologies, in environments close to domestic residents.

Technical and technological development has led to a constant increase in mankind's demand for electricity and heat [31,39]; this can be produced in many ways, including from renewable energy sources, using wind farms, solar collectors

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[24,25], photovoltaic and photothermal installations and turbines, powered by flowing water. Unconventional energy also includes heat generation, resulting from the application of such devices as geothermal water or heat pump installations.

Despite the development and implementation of new technologies in the field of green energy in Poland, fossil fuels, such as hard coal and lignite, are still characterized by the largest share in the production of electricity and heat [16,46]. Additionally, according to the data of The National Centre for Balancing and Emissions Management emissions of TSP dust (Total Suspended Particles), PM10 and PM2.5 will increase, due, mainly, to the non-industrial combustion sector in households. One of the solutions to decrease their emission is the industrial application of cyclones.

1.1. Basics of the cyclones

A cyclone is a dust collector used to purify gases from solid particles both in the energy sector and in woodworking plants in the recycling industry or locksmithing. In the cyclone, the dusted gas is directed tangentially, or axially, into a cylindrical chamber and swirls around, as a result of which, heavier components, floating in the gas, are thrown onto the plane of the inner walls under the influence of centrifugal force. As a result of the friction forces of the particles against the surface of the walls, they lose kinetic energy and fall into the hopper under the influence of gravity. Clean air flows out of the separator through a centrally located channel. A detailed description of the action of the cyclone is presented by Niechciał [37]; the efficiency of the separation depends on the value of the centrifugal force acting on the dust.

The efficiency of the separator is determined by the velocity of the air stream, the profile of the cyclone's curvature, the mass of the solid particles and the length of time that the centrifugal forces operate.

Cyclones can be used as pre-separators, or as protection devices for more sensitive final filters, such as, in co-operation with a cyclone and a fabric filter (especially in axial cyclones or multicyclones —moistened filter bed filtration system in tracked vehicles used for the research by Dziubak and Boruta [15]).

The size of the solid particles, introduced into a cyclone, is of great importance for the construction of a cyclone. Small diameter cyclones are characterized by the high efficiency of dust removal with a low dust level and a high pressure drop. Large diameter cyclones are effective at high dust levels in the gas. In practical application, the tangential single cyclones are characterized by inlet of a larger diameter i.e., from 1 to 5 m in diameter according to Pivato [41]. By the way, the minimum particle size that can be collected by a cyclone generally decreases with decreasing cyclone size [21,28,33,35].

There are variants of dry and wet gas cyclones. Figure 1 shows a dry tangential cyclone, its technical designs, and physical objects attributes.

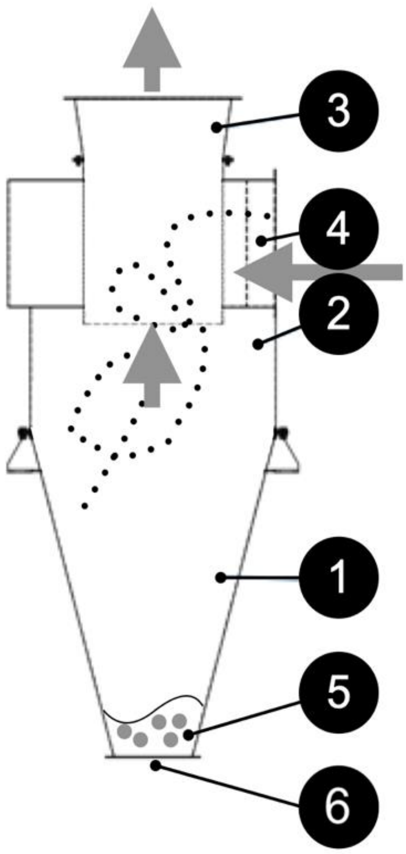

Figure 1. View of the internal structures of a dry centrifugal dust collector (own work inspired by [36]); 1 – chute, 2 – cylindrical cover, 3 – gas outlet pipe, 4 – inlet port, 5 – dust captured, 6 – dust removal nozzle, dotted spline: dusted air spin.

1.2. The structure of research contribution

The paper started by introducing a process of dedusting exhaust gases using selected types of separators, including the general description of cyclones. Section 2 presents the literature review related to such a topic. Section 2 is summarized with a research gap which guides the authors in their ongoing research. Section 3 presents the materials and methods applied and developed in this paper, such as the research objects, simulation assumptions and the general simulation-based research methodology. These developments are given in Section 3, whereas Section 4 is filled with the simulation modelling of tangential cyclones, including the research methodology description, significant results of the experiment with the models, and discussion thereof. Adapting an approach to sub-optimize the geometry of a dedusting tangential cyclone and air-dust separation device, with a view to applying it to the actual conditions of domestic entrepreneurs of electric power. The research presented in this paper is not an abstract or theoretical study, yet one that allows for the improvement of applied devices in the enterprise practice of electric power facilities. Consequently, experimental type of model's validation is given in Section 4. The paper is concluded in Section 5 which also includes the future research and development of the facilities presented.

2. Literature review

2.1. The body of current knowledge

The dust collector systems were supervised by Beaulac et al. [4]. Such a system consists of a cyclone with its centrifugal pump or fan [47] and filtering units [14] and a dust evacuation sub-system, together with dust transport circuits [4]. The cyclones can be divided into square and conventional ones. A detailed numerical analysis of the operation of a square cyclone is presented by Esmaeel and Hossein [20]. Other authors compared the efficiency of the square cyclone with and without a dipleg, as in [8,19,27]. Developing the extent of the cyclones solution, the multi-cyclones (MOS) are systems composed of many interconnected dedusting cells, horizontally mounted in the housing of the MOS dust collector. The efficiency of an MOS varies from 70% to over 90% [5,9,12].

Muschelknautz et al. [34] presented the research on the synthetic requirements for the design and integration of parallel cyclones into one system, in a situation of limited installation space. The author proposed a solution to improve cyclone performance by additionally wetting the dust particles. Collection and separation efficiency has also been investigated by others. Dziubak et al. [14] researched three different filtration partitions in cyclones (cellulose, cellulose and polyester, cellulose, polyester and nanofibers layer) in order to analyze separation efficiency, filtration performance, and pressure drop.

Mazyana et al. [30] presented issues related to the possibility of modernizing operating cyclone devices, to increase efficiency in dust extraction. The effect was achieved by adding tangential chambers to the conical section of a conventional cyclone separator.

Su et al. [44] presented a numerical study of the gas–solid flow, in square cyclone separators with three types of inlet configuration. The effects of the length of the gas outlet duct and shape, on the performance of cyclone separators were investigated by Souza et al. [43]. The influence of the inlet's cross-sectional shape on drops in pressure, using Computational Fluid Dynamics (CFD) modelling, including inlet cross-sectional shapes in the form of circle, ellipse, rectangle, square, and trapezoid, is described by Babaoğlu et al. [3].

The effect of cyclone dimensions on separation performance is significant. Yang et al. [48] studied the effect of inlet dimensions on the height of a maximum-efficiency cyclone (optimum cyclone height) through experiments and CFD simulations. The results showed that the height of a maximum-efficiency cyclone reduces with the reduction of the inlet dimensions. A complex review of the existing CFD studies of cyclone separators, operating over a wide range of solids loadings and at ambient and elevated temperatures, is presented by Nakhaei et al. [36].

Other geometric parameters that affect the performance of cyclone separators, are mainly the cone's height, the cylinder's height and the dip tube's height, next to the inlet's dimensions. In [17], four geometrical factors, namely the vortex finder diameter, the inlet width and height, and the cyclone's total height were considered to optimize a cyclone separator's geometry, vis-à-vis minimum pressure drops. Elsayed and Lacor [17] presented an original set of geometrical ratios that can be applied when modelling separators. Ithape et al. [23] focused on variations of this geometric parameters, by analyzing collection efficiency and pressure loss. Meanwhile, Singh et al. [42] solved the multi-objective, shape optimization problem of a cyclone separator. Elsayed and Lacor [17] computationally investigated four cyclone separators with different dust outlet geometries, namely, without a dustbin, with a dustbin, with dipleg and with a dustbin plus dipleg.

The presented conglomeration of publications allows us to group the research issues considered in them. The effects of such grouping, together with an indication of the research gap undertaken in this research paper, are presented in Section 2.2.

2.2. Summary of literature review

The above-described publications can be grouped in cohorts of certain problems, such as general consideration related to MOS and parallel cyclones, configuration and geometry of their fundamental equipment, substances and facilities applied altogether including flow parameters, cyclones' efficiency development, etc. The literature investigation can be summarized within cohorts of interrelated issues such as:

- General investigation on MOS, parallel cyclones [7,12,33],
- Geometry and configuration of the following elements:
  - Configuration of elements for inlets [3,7,10,17,43,44,48],
  - Cyclone separator's geometry [10,17,18,30,36,42,45],
  - Cyclone roof shape [29],
  - Cone geometry, parameters, and modifications [10,18,30,48],
  - Spiral guide vane [6],
  - Application of dipleg [8,20,27],
  - Divergent cyclone separator and small size cyclones [6,28,31,47],
- Substances and flow parameters:
  - Parameters of vortex length [2,17,26,48],
  - Investigation into filtration layers [12],
  - Parameters of gas–solid flow [43,44],
  - Dust extraction efficiency [30,45] and, consequently
- Cyclone efficiency [7,12,23,30,36,44,45,48].
- Efficiency can be changed by geometry, by increasing number of cells as in MOS [12], development of a cyclone inside [30] or other ways, e.g.: double stage cyclone [7], wetting the dust particles [34], development of filtration materials [12], etc.

Despite the high values of the efficiency of cyclones, considered in the best cases up to 90% as e.g. in [5,9,12,23,30,36], it is worth increasing this factor, since even greater improvements in the quality of cyclones can benefit the environment and the health of living organisms. Moreover, such a development should be undertaken with the tools ensuring low expenditures—consequently it is highly important to carefully choose materials and methos of research (e.g., a software for numerical or simulation-based analyses).

3. Material and methods

3.1. The research methodology

Computational Fluid Dynamics (CFD) allows engineers to validate cyclone separator designs before expensive physical prototypes are constructed. Many simulation packages are available to create, visualize, test and analyze conceptual models for problems concerning fluid flow, heat transfer and turbulence. These packages are for example Autodesk CFD, Simscale, Ansys, OpenFOAM and Altair. The type of research presented in this paper is less often carried out using SolidWorks software. Much more often, the modelling of the described phenomena is realized using Ansys software. However, SolidWorks is a more common, accessible, and less computationally demanding software, which also stands to the novelty of the work presented. In this paper, the analysis of the operation of centrifugal dust collectors was developed using the SolidWorks EDU Edition (version 2022) enriched by the Flow Simulation package licensed by Premium. One can consider that the accuracy of the simulation with SolidWorks cannot be guaranteed. The encoding of certain functions and procedures in any commercially successful information system can be given under such a discussion. There are certain opinions among experienced researchers' audience that the accuracy of the simulation can be guaranteed solely with application of the self-developed software as all the procedures, functions, libraries, etc. can be given under deep analyses and all their programming code is known to the author(s)-researcher(s). Yet application of a self-developed software introduces the risk that a certain study cannot be replicated by other researchers without similar tools as there is no assurance of universal availability of such a software. Moreover, SolidWorks seems to be the relatively cheap alternative among other software of that kind (based on the overview of computer-aided design engineering software [1]).

3.2. The main data for the developed investigation

The input data for simulation purposes (flow rate, gas temperature, density of the gaseous phase), specifying the future working conditions of real dust collectors, built and based on the simulation models developed, were provided by the Instal-Filter Company (Figure 2 and Figure 3). Some data and information (inlet velocity, pressure in the outlet section, particles size, density of the solid phase) were also provided by the power facility located in the Greater Poland Voivodeship, where constructed cyclones are to be installed for testing purposes.

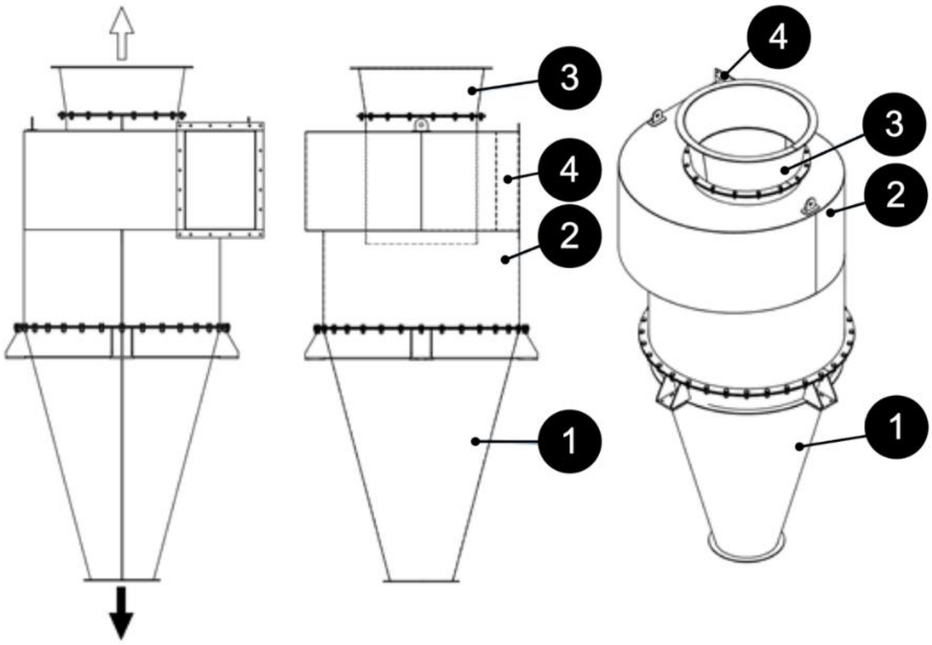

Figure 2. Views of the design of a dry centrifugal dust collector: 1 – dust chute, 2 – cylindrical part of the cyclone (cylindrical cover), 3 – diffuser and gas outlet (gas outlet pipe), 4 – inlet port (illustration borrowed and reproduced with the permission of the Instal-Filter S.A. entrepreneurship).

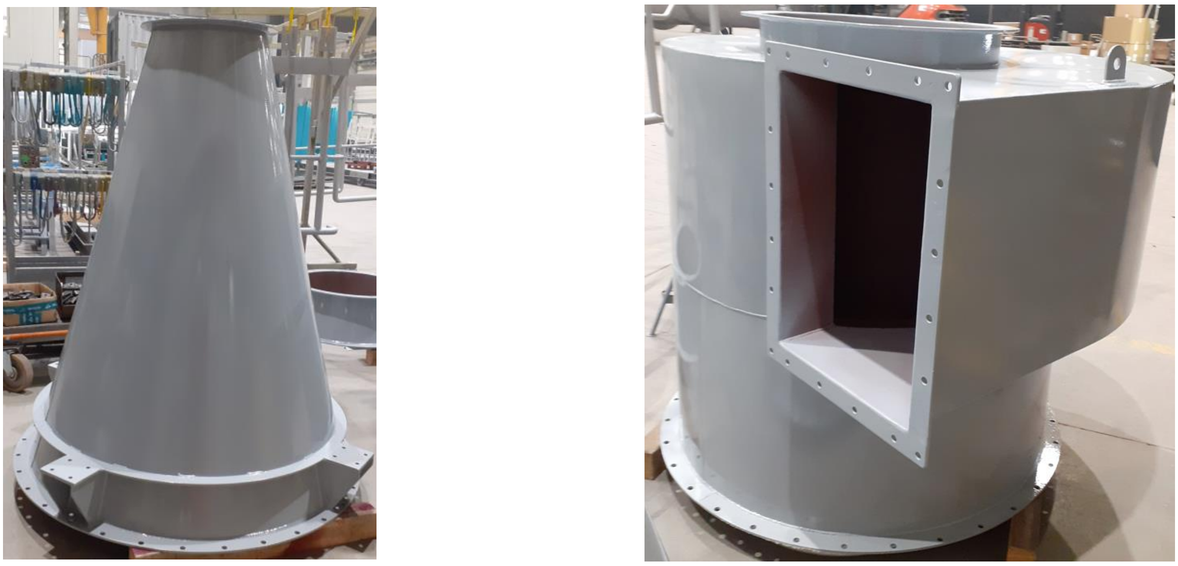

Figure 3. A dry centrifugal dust collector – details of its physical attributes: dust chute in the left photography; cyclone flue and gas inlet in the right photography; photos permitted by the Instal-Filter S.A. entrepreneurship.

The solid phase (coal dust) was defined, by the designers at SolidWorks software, to input dust characteristics manually. The flow of particles is introduced from the inlet, in the direction normal to the inlet face. The material of the dust collector is low carbon steel (hot rolled and etched) with the following designation 1.0037 S235JR, and known by its numerical classification and symbol; technical norm: PN-EN 10025-2:2019-11; air was used for the continuous phase. The condition of the velocity inlet boundary with a turbulent intensity set at 5% is applied to the inlet. Parameters of conducted simulation are set as given in Table 1 (this simulation set of parameters was advised by the company which has commissioned the study, especially in the case of section boundary conditions, turbulent intensity, gas temperature, density of the gaseous phase, and density of the solid phase). Forced volumetric flow rate is varied with other parameters being constant as the authors planned to analyze the dust purification phenomenon under varied forced volumetric flow. It is worth mentioning that the value of inlet velocity is the same in all the tangential cyclone alternatives, yet the geometrical parameters of cyclones are different – the constant parameter of inlet velocity ensures dust volume comparison for inlet vs. outlet of each cyclone.

Table 1. Parameters assumed in SolidWorks simulation modelling.

Description of the Parameters’	Attribute/Result
Numerical algorithm applied in the research	SIMPLE
Determination of representative samples of the component values on the surface of the control volumes	First-Order Upwind
Convergence condition for the continuity equation	10^{-5}
Shape of the cells in the computational mesh	Hexahedral
Total number of mesh cells	From 410 000 to 420 000
Mesh parameters	Curvature based mesh
Mesh quality	High
Section boundary conditions	Gas: – pressure inlet: atmospheric pressure – inlet velocity: 15 m/s – pressure in the outlet section: 100 500 Pa Particles: – size: from 10 μm to 30 μm (3 fractions, where the share of PM10 fraction exceeds 90%) – forced volumetric flow rate 0.3, 0.5, 0.7 m^3/s
Turbulent intensity	5%
Gas temperature	80°C
Density of the gaseous phase	0.810 kg/m^3
Density of the solid phase	500 kg/m^3

4. Computer simulation analysis of the operation of the selected gas dust dedusters

4.1. Data and parameters on the models of cyclones under investigation in Computational Fluid Dynamics simulation tool

Using the SolidWorks software intended for the three-dimensional design of objects, 3 models of tangential cyclones, with the same external dimensions and geometry of inlet and outlet openings, were created. They differ in the shape and dimensions of their bodies. The 3 models of dust collectors with such mandated parameters and body shapes adopted in the simulation analysis are the result of installation requirements and available space in the dedicated facility where they will operate in the future (recommendation of the organization commissioning the research). The analyzed models of dust collectors with such mandated different shapes and dimensions will be included as well in the creation of battery cyclones where the stream of dusty gas after entering the dust collector is distributed to individual, single cyclones which are parts of the battery’s construction. However, it is required to study individual cells at first.

The internal velocity distribution and stagnation density of air, polluted with PM10 lignite dust, were investigated, depending on the changing values of the set volume flow and the shape of the main chamber. Analysis of the operation of cyclones at a low aerodynamic diameter of 10 μm (PM10 dust) means that their efficiency may be lower than in the case of typical diameters for which they are designed, namely from 50 μm to 80 μm. In this situation, the least favorable operating conditions for cyclones were analyzed. Cyclones are independent units that act individually. Figure 4 shows the computer models developed for the objects.

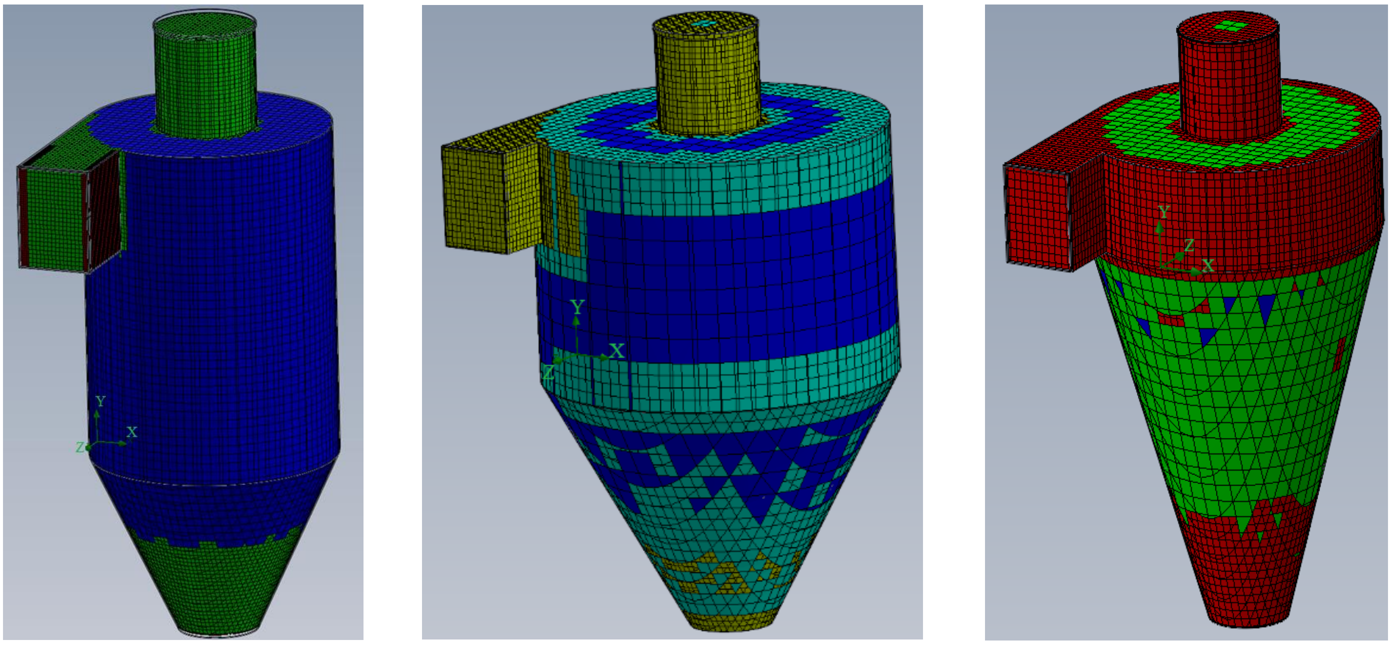

Figure 4. Computer models of designed cyclones: Cyclone No. 1 with a body height of 750 mm, a 250 mm hopper and a corpse diameter of 250 mm in the left photography; Cyclone No. 2 with a body height of 500 mm, a discharge hopper of 500 mm and a corpse diameter of 350 mm in the centered photography; Cyclone No. 3 with a body height of 150 mm, a discharge hopper of 850 mm and a hull diameter of 300 mm in the right photography (*x*, *y*, *z* – parameters of the Cartesian system).

The geometric models were imported into the SolidWorks' CFD component for the mesh construction. Computation was carried out using the solver of the SolidWorks Flow Simulation calculation package. CFD is a quantitative and qualitative prediction of the flow field and the trajectory of molecules inside a separator. In contrast to laboratory tests, the financial outlay and the time necessary to produce the models tested are being limited.

By generating a computational mesh, it is possible to control its quality using quality parameters in the form of grid perpendicularity, skewness, aspect ratio, etc. The geometrical models of the cyclone, as developed, together with the computational mesh were evaluated based on the value of the following features obtained: "Percentage of Elements with an Aspect Ratio < 3", where the value exceeds 82% and "Percentage of Elements with an Aspect Ratio > 10", where the value exceeds 8%.

The methodology applied in the research was as follows. The turbulent gas flow in the dust collector was described using the Navier-Stokes equations, modified by the Reynolds method. Reynolds-averaged Navier-Stokes equations are also known under the RANS acronym). The K-epsilon (k-ε) turbulence model was used in the simulation. A commonly used closing model for cyclone separators is the Reynolds Stress Model (RSM), which captures the anisotropic nature of the flow, in centrifugal separators.

The SIMPLE calculation algorithm was applied to solve the differential equations. First-Order Upwind interpolation was used to determine representative samples on the surface of the control volumes. Modelling the behavior of the flow of fine dust was achieved with the Discrete Phase Model (DPM). The impact of dust particles on the air flow was not considered.

The following sections present the main results obtained with above mentioned models of cyclone. In the Section 4.2., the influence of geometrical parameters of cyclones on the internal distribution of dust velocity and density is given. Whereas, in Section 4.3. the influence of the input volume flow on the internal distribution of dust density is presented. The presented research material has been enriched with MOS analyses in Section 4.4. And finally, the discussion of all the presented results is given in Section 4.5.

4.2. Observations on the influence of changes, in the geometrical dimensions of a cyclone, on the internal distribution of dust velocity and density, at a constant, initial volumetric flow

Figure 5 shows the results of the dynamic CFD analysis of the distribution of air velocity, polluted with lignite dust, for the cyclones modelled. According to Figure 4, in each case, the simulation results for Cyclone No. 1 are shown on the left; for Cyclone No. 2, they are shown in the middle; while for Cyclone No. 3, they are shown on the right. A gas flow analysis was carried out using SolidWorks Flow Simulation.

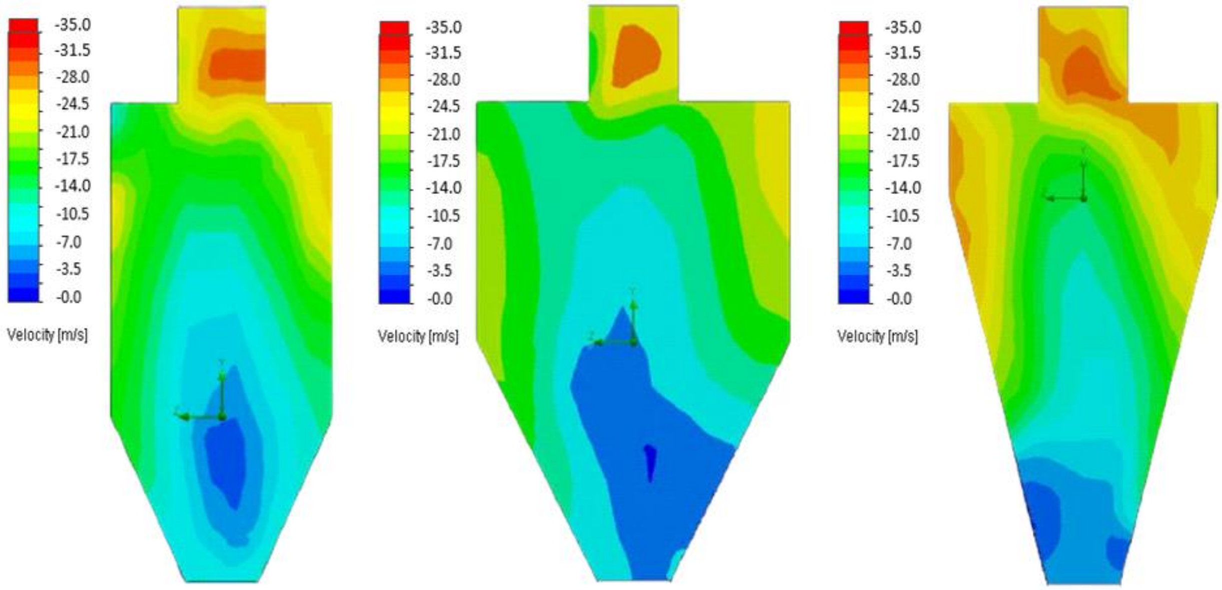

Figure 5. Longitudinal section of cyclones No. 1 in the left figure, No. 2 in the centered figure, No. 3 in the right figure, showing the internal velocity distribution of air, polluted with lignite dust, with a forced volumetric flow of 0.7 m^3/s.

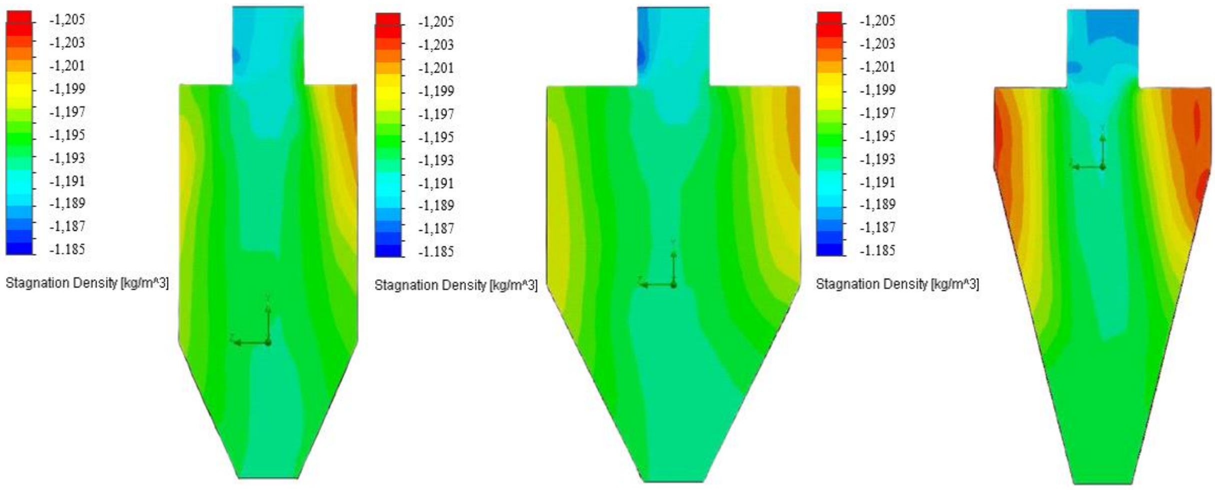

Figure 6. Longitudinal section of cyclones No. 1-3 showing the internal distribution of the density of air, polluted with lignite dust, with a forced volumetric flow of 0.7 m^3/s.

Figure 6 shows the results of the dynamic CFD analysis of the distribution of air density, polluted with lignite dust, for the cyclones modelled. A gas flow analysis was carried out using SolidWorks Flow Simulation.

The results of the distribution density of the polluted gas velocity and dust, presented in Figures 5 and 6 for Cyclone No. 1, showed the highest value of gas velocity accumulating just behind the dust collector inlet and at the outlet, with a value in the range of 28-30 m/s with a forced volumetric flow of 0.7 m^3/s. The velocity decreases significantly in the central part of the cyclone and at its funnel with values in the range of 3 to 7 m/s. It is important to note that in the lower parts of the cyclone, the falling dust is not pulled up again into the main gas stream. In the case of Cyclone No. 1, high velocity levels in the hopper can negatively affect the efficiency of the dedusting process. The highest concentration of dust occurs in the upper part of the body, just after the inlet to the device. The shape of the body and especially its diameter, in the smallest of all the dust collectors analyzed, allows the solid particles to reach the inner walls of the device housing in a short time which improves the efficiency of the dedusting process of this solution. At the outlet of Cyclone No. 1, the gas has approximately 76% less dust than at the inlet.

In the case of Cyclone No. 2, the velocity of the dusted gas, in the central part of the device, varies from 2 to 3.5 m/s. The speed of the solid particles is reduced faster, and the particles reach the inner wall of the housing more slowly than in other cyclones. This translates into the limited efficiency of the dedusting process. At the outlet of Cyclone No. 2, the gas has approximately 70% less dust than at the inlet. There is no movement of dust in the range of the main air stream.

In the case of Cyclone No. 3, due to its low body and high hopper, the rate of dust precipitation is limited. The highest amount of dust accumulates in the upper half of the body. Contaminants can be moved back to the main gas stream and then dusted off again. High speed is maintained almost throughout the whole body. The geometrical dimensions of Cyclone No. 3 do not allow any rapid precipitation of solid fractions into the funnel.

4.3. Observations of the influence of change in the input volume flow, on the internal distribution of dust density in the cyclone

An analysis of the impact of changes in the value of the air volume flow, as set at the inlet of the dedusting device, on the internal distribution of dust density, was carried out. Figures 7 and 8 show the density distribution of air, polluted with lignite dust, at a volume flow of 0.3 m^3/s and 0.5 m^3/s, for the three, simulated cyclones, as shown in Figure 4.

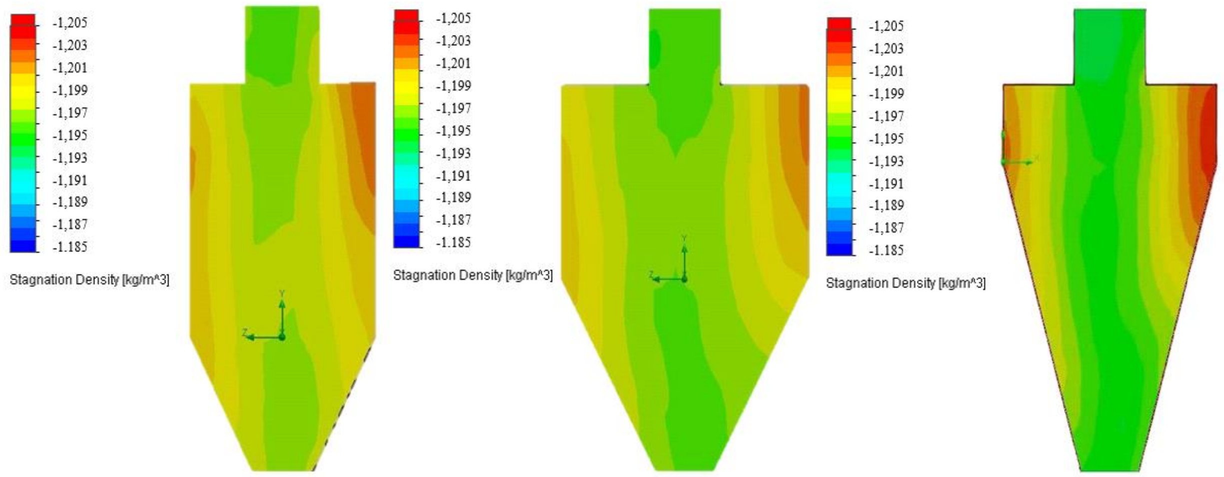

Figure 7. Longitudinal section of cyclones No. 1 in the left figure, No. 2 in the centered figure, No. 3 in the right figure, showing the internal distribution of the density of air, polluted with lignite dust, at a volume flow of 0.3 m^3/s.

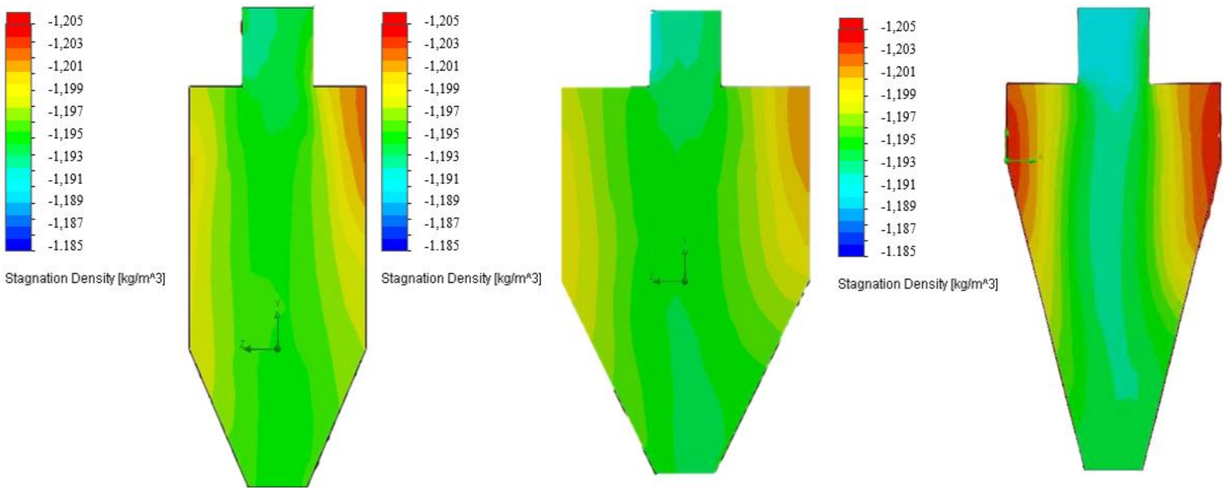

Figure 8. Longitudinal section of cyclones No. 1 in the left figure, No. 2 in the centered figure, No. 3 in the right figure, showing the internal distribution of the density of air, polluted with lignite dust, at a volume flow of 0.5 m^3/s.

An analysis of the impact on the internal distribution of dust density (Figures 7 and Figure 8) when changing the initial volume flow of dust-laden gas, shows a strong relation between these parameters. In the case of Cyclone No. 1, the highest amount of dust accumulates in the upper part of the body. At a low volumetric flow rate, the mainstream of fluid reaches a lower velocity, which translates into the limited value of the acting centrifugal force. Consequently, a significant amount of dust remains in gas flowing axially, with the efficient removal of dust being about 52%. Increasing the volume flow of dusted gas leads to an increase in the efficiency of the dedusting process by reducing the content of solid particles in the gas, in the central part of the dust collector.

Due to the wide body of dust collector No. 2, its efficiency is strongly related to the current value of the set volume flow of the flowing fluid. A decrease of the parameter value by 0.1 m^3/s causes a decrease in the efficiency of dust precipitation from the main gas stream by approximately 5%. Gas at the outlet of Cyclone No. 2, with a volume flow of 0.3 and 0.5 m^3/s has about 49% and 60% less dust than at the inlet. Cyclones with larger body diameters can operate at higher volumetric gas flow rates and thus achieve satisfactory dedusting efficiency levels. For Cyclone no. 3, its simultaneously low and wide body increases the gas and dust velocity in the upper part of the dust collector, thus preventing impurities from quickly cascading due to them being blown around at the boundary with the hopper. The gas at the outlet of Cyclone no. 3 has approximately 53% less dust than at the inlet. Increasing the gas flow with this solution may adversely affect operation of the cyclone and the rest of the equipment in the dedusting installation.

To validate the dust collector models, an experimental type of validation was carried out in a power plant located in the Greater Poland Voivodeship in Poland. All 3 physical models of the simulated cyclones were installed sequentially in the side channel section supporting the flue gas draft in the power plant (Figure 9). On the side duct there are special connector made of an M64 welding sleeve and a plug with a T9 thread (symbol P9). After its removal, the pressure of the flue gas inside the main duct of the so-called flue gas by-pass was examined using a probe type MPR500M and the dust level of the jet using a PCME STACK 990 analyzer. Then the velocities of the individual jets were calculated based on the pressure. After the parameters were determined, a system made of galvanized pipes with actual cyclones developed based on SolidWorks models was connected to the welding sleeve. Each cyclone was tested in turn of two parameters: (average) outlet velocity and the average dust level. Each experiment conducted in a power plant and a computer simulation was repeated three times to obtain the average outlet velocities. The results are summarized in Table 2.

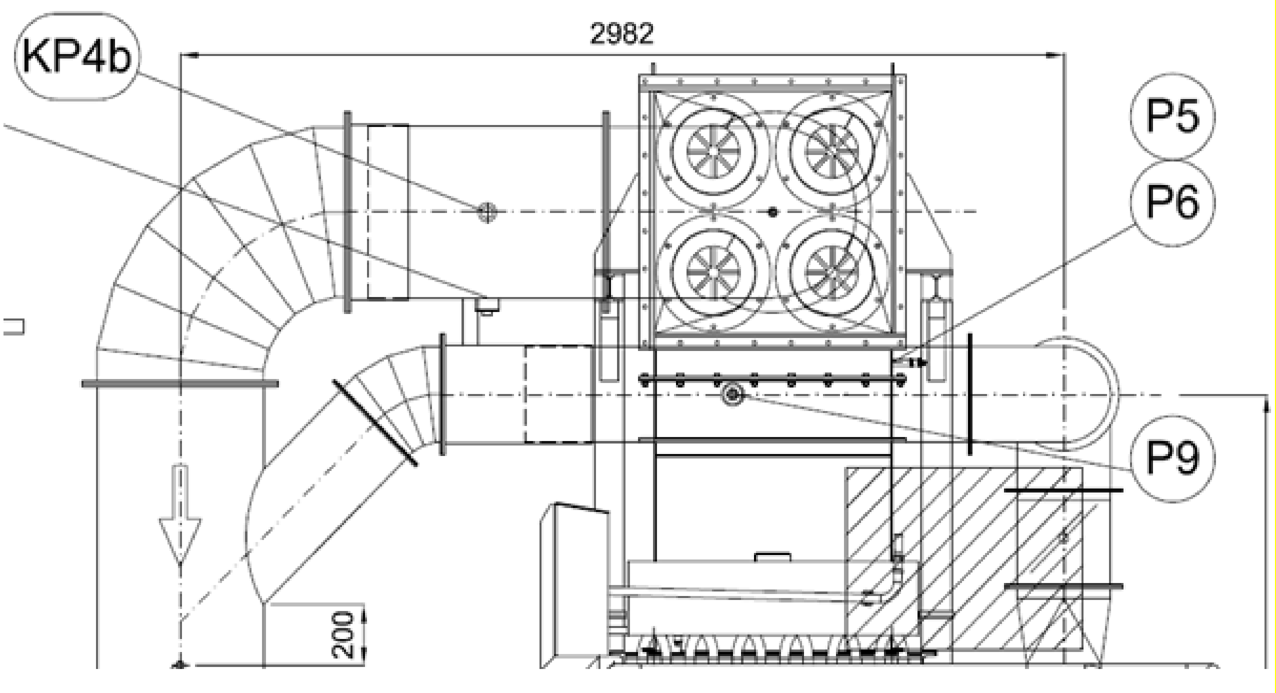

Figure 9. View of process plant with side channel and sampling area.

Table 2. Comparison of simulation and measurement parameters for the analyzed dust collectors.

Parameter \ Dust collector (cyclone) number	No. 1	No. 2	No. 3
Average outlet velocity – simulation model	29 m/s	25 m/s	28 m/s
Average outlet velocity – measurement	28 m/s	21 m/s	26 m/s
Efficiency of cyclone in case of PM10 dust purification – simulation model	76%	71%	65%
Efficiency of cyclone in case of PM10 dust purification – measurement	75%	67%	51%

In the case of Cyclone No. 1, the obtained results of the validation are in line with the ones obtained by measurements. The average outlet velocity of the actual dust collector and the efficiency of this device, determined by evaluating the degree of gas dusting, were slightly (negligibly) lower compared to the simulation results. In the case of Cyclone No. 2, the value of average outlet velocity under actual conditions was about 8% lower than the simulation result, as was the efficiency of the device under test. In the case of Cyclone no. 3 (with a high chute hopper), the simulation results yielded a device efficiency 14% higher than actual measurements. The last of the cyclones, despite a similar average outlet velocity to Cyclone No. 1, is characterized by a rather low efficiency. In each case, the overestimation of the obtained results of both parameters by simulation in relation to verification real measurements was demonstrated, where the discrepancies were highest for the cyclone with a low body and high chute hopper (Cyclone No. 3.). Figure 9 shows a view of the side channel as the installation location of the analyzed cyclones with the sampling location (symbol P9).

4.4. Analysis of the operation of a cyclone system, in the form of an axial MOS

Thanks to the use of several smaller cells in the construction of dust collectors, the efficiency of the dust purification process is increased (it increases as the diameter of the dust collector decreases). Such dust collectors ensure stable operation of the equipment with high efficiency of dust pre-removal. MOS dust collectors also have small dimensions (compared to the cyclones) and slightly increase the dimensions of the plant.

The cyclones presented in Sections 4.1.–4.3. enabled to achieve the efficiency values mentioned at the end of Section 4.3. Higher efficiency can be achieved by using a battery of cyclones. This is the contribution of this part of the paper.

To analyze the distribution of the velocity and the density of the stagnation of air, polluted with lignite dust, a complete, axial MOS, consisting of 6 cells working in parallel was applied. The units may differ in the number and inclination angle of the blades. MOS are applied for separating fine particles in the fluid catalytic cracking process operating at high temperatures and pressures [11,40], high solids concentration, temperature and pressure [13,28,33,34].

Figure 10 shows the single cell of the swirler, with its 5, designed blades inclined at an angle of 45° and a MOS, built based on single objects.

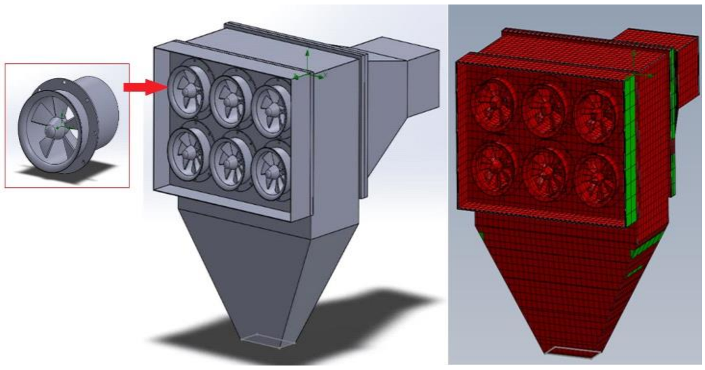

Figure 10. MOS type multi-cyclone, consisting of 6 cells with a blade pitch angle of 45° and a simulation mesh of the object.

The simulation analysis carried out, consisted in examining the density of the dust distribution dust inside the swirlers cells, depending on the number of blades used. In the simulation, the volumetric flow was 0.4 m^3/s while the inclination angle of the blades was 45°. Figure 11 shows the results of the simulation analysis in the plane behind the blades and at the outlet to the device chamber.

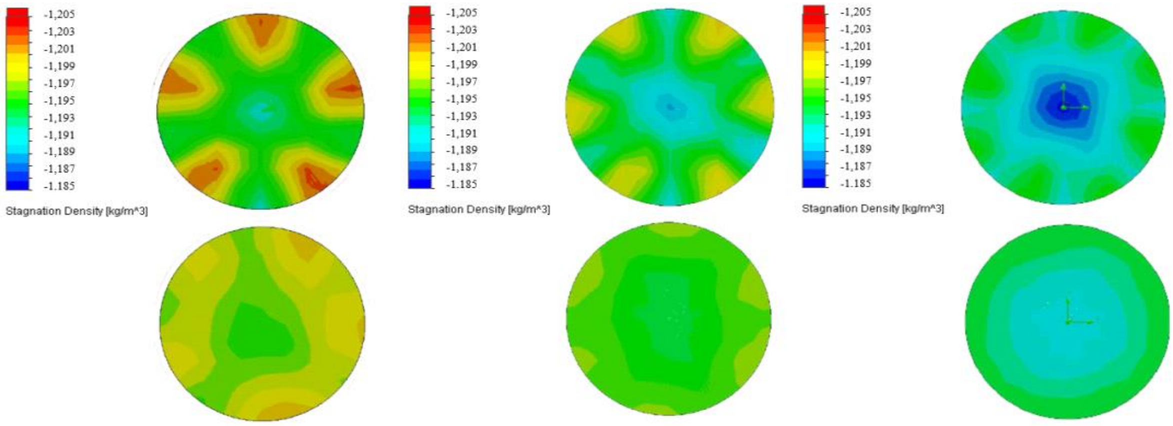

Figure 11. Longitudinal section of a MOS cell (cyclones No. 1 in the left figure, No. 2 in the centered figure, No. 3 in the right figure), equipped with 5 blades (left figure), 6 blades (centered figure) and 8 blades (right figure) inclined at an angle of 45°, showing the distribution of the density of the air, behind the blades and polluted with lignite dust (top row picture), and at the outlet (bottom row picture) with a volumetric flow of 0.4 m^3/s.

A comparative analysis of the distribution of the dust density in the internal volume of the dust collectors, with a change in the number of swirler blades in the dust collector, indicates that while 5 blades were used (Figure 11), the highest dust concentration was observed in the spaces between the blades. The uneven distribution of contaminants, in Cyclone No. 1, can lead to accelerated wear of structural component surfaces where more brown coal particles are pressed against the body. Increasing the number of blades to 6 makes the mainstream liquid swirl about more intensively, so that dirt just behind the blades of the dust collector is distributed more evenly. Due to centrifugal force, dust accumulates at the inner walls of the separator (approximately 37.5%). The use of 8 blades leads to a significant reduction in the dust content of the gas in the central volume of the deduster, behind the rotor. This type of swirler provides a useful distribution of solid fractions in the dedusted gas, with dust concentration at the internal walls being approximately 50%.

The analysis is complemented by establishing the influence of the inclination angle of the swirler blades on the distribution of dust inside the structure of the dust collector. For this purpose, 3 selected inclination angles of 30°, 45° and 60° were analyzed for 5 and 8 blades used (Figure 12 and Figure 13, respectively). The same volumetric flow was applied in both cases, i.e., 0.4 m^3/s.

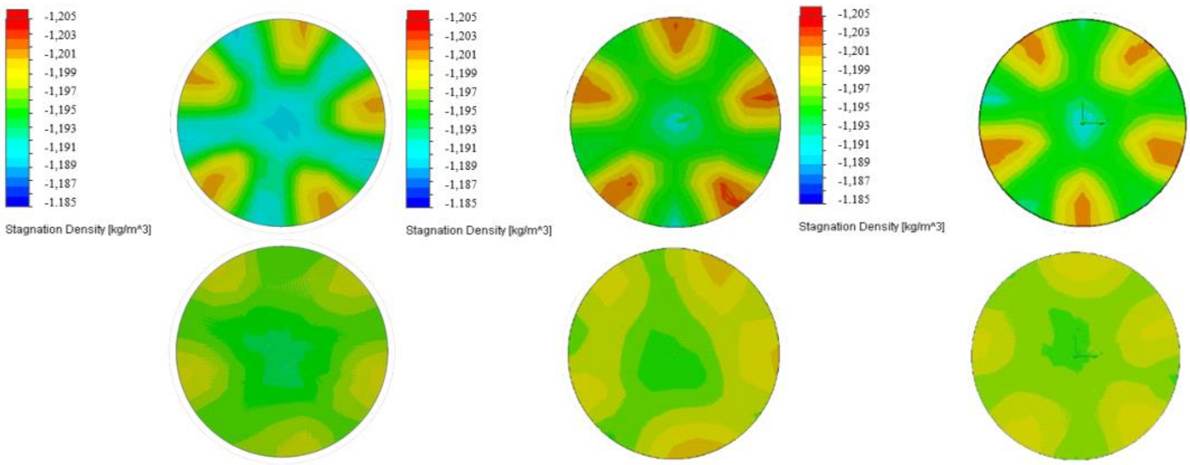

Figure 12. Longitudinal section of a MOS cell (cyclones No. 1 in the left figure, No. 2 in the centered figure, No. 3 in the right figure), equipped with 5 blades inclined at an angle of 30° (left figure), 45° (centered figure) and 60° (right figure) showing the distribution of the density of the air, behind the blades and polluted with lignite dust (top row pictures), and at the outlet (bottom row pictures) with a volumetric flow of 0.4 m^3/s.

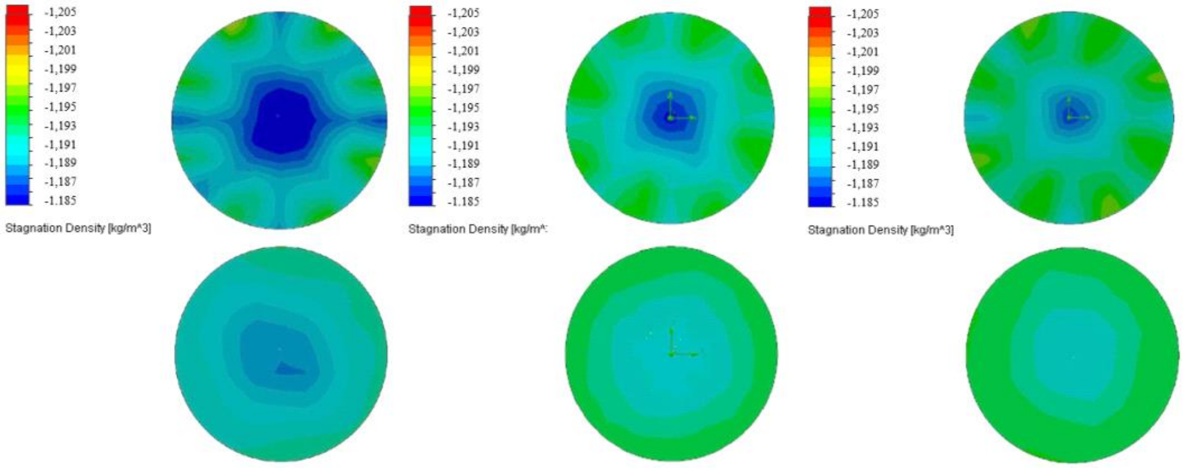

Figure 13. Longitudinal section of a MOS cell (cyclones No. 1 in the left figure, No. 2 in the centered figure, No. 3 in the right figure), equipped with 8 blades, inclined at an angle of 30° (left figure), 45° (centered figure) and 60° (right figure) showing the distribution of the density of the air, behind the blades, polluted with lignite dust (top row picture), and at the outlet (bottom row picture) with a volumetric flow of 0.4 m^3/s.

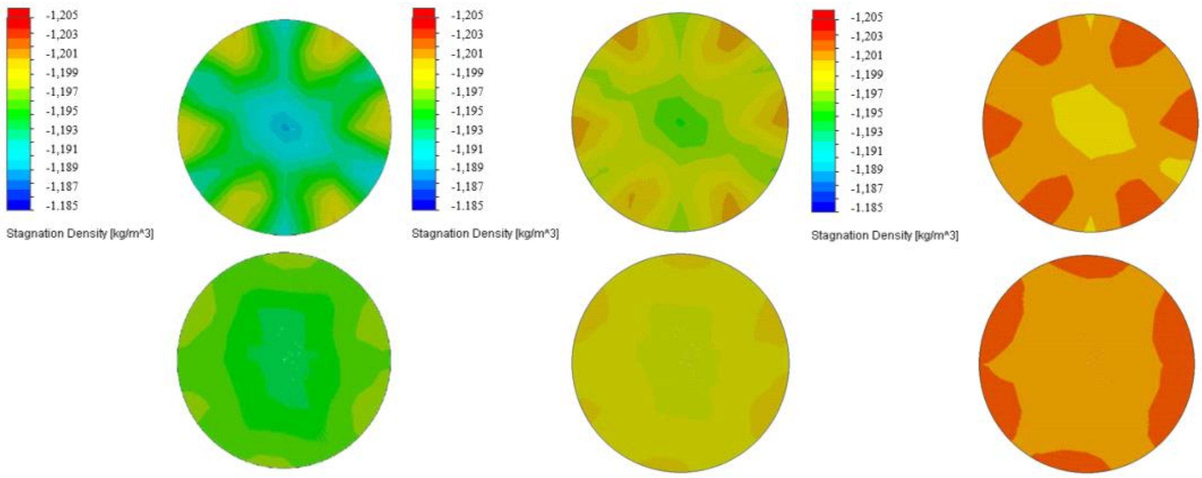

Figure 14. Longitudinal section of a MOS cell (cyclones No. 1 in the left figure, No. 2 in the centered figure, No. 3 in the right figure), equipped with 6 blades, inclined at an angle of 45° showing the distribution of the density of the air, behind the blades, polluted with lignite dust (top row picture) and at the outlet (bottom row picture) at a volumetric flow of 0.4 m^3/s (left figure), 0.3 m^3/s (centered figure) and 0.2 m^3/s (right figure).

The value of the pitch angle of the swirler blades determines the internal distribution of solid particles in the volume of gas to be dedusted. The high value of the pitch angle, with a limited number of blades (Figure 12), leads to the creation of large spaces between the blades, which limit the dust concentration along the inner walls of the dust collector body. Consequently, a chaotic movement of the fluid is also achieved in the central part of the separator. However, the effect is an increase in the degree of gas, swirling around in relation to variants with a low value of the blade pitch angle (30° and 45°). Increasing the number of blades from 5 to 8 leads to a situation where the fluid is swirled about more uniformly, in the separator chamber, such as at the inclination angle which equals 30°. In the central volume of the dust collector, allocated just behind the blades, there is a limited amount of dust, about 10%, which confirms the quality of the dust removal. However, the distribution of contaminants is not uniform in every location of the dust collector outlet. Increasing the inclination angle of the blades to 45° leads to a situation in which the largest amount of dust, approximately 50%, is located right next to the internal walls of the dust collector chamber, while in the central part, this is approximately 20%. However, the distribution of pollutants is even higher everywhere, which makes this solution the best of all those analyzed. The efficiency of the dedusting process can be increased when the volumetric flow reaches a higher value. Further increasing the inclination angle of the blades leads to a situation where approximately 50% of the dust is found in the space between the walls of the dust collector and the main, structural axis of the dust collector cell, which means that these pollutants can only be partially dedusted and will remain in the mainstream of flowing fluid, depending on the inlet cone diameter, mounted in the MOS housing.

In the last step, the effect of changing the initial volume flow of dust-laden gas, on the internal dust distribution, was examined. A simulation analysis was carried out for units with 6 blades inclined at an angle of 45° (Figure 14), for the stream in front of the dust collector, respectively 0.4 m^3/s, 0.3 m^3/s and 0.2 m^3/s.

An analysis of the changes to the distribution of the density of air polluted with dust, when the set value of the volumetric flow is changed, indicates an unfavorable distribution of solid fractions, especially where low values of forcing are applied. Setting the level of volumetric flow to 0.3 m^3/s, for a swirler with 6 blades, inclined at an angle of 45°, leads to low linear speeds inside the device, which does not achieve sufficiently high centrifugal force. The device may not work efficiently when installed in a MOS. To increase the efficiency of dedusting, it would be necessary to reduce the diameter of the device or increase the volumetric flow set. An increase in flow to 0.4 m^3/s would make it possible to obtain a more uniform distribution of dust, with the difference in its amount, immediately at the walls and the center, being approximately 15%. To increase the amount of dust surrounding the walls, a further increase in the volumetric flow or initial speed is required. The highest amounts of dust, both in the central volume and at the extreme points, are recorded for low volumetric flow values.

Table 3 presents a synthetic comparison of the obtained efficiencies of the MOS dust collector depending on the number of rotor blades applied in a single cell and their inclination angle.

Table 3. Comparison of the MOS efficiency depending on the number of blades of a single cell and their inclination angle.

Blade inclination angle / Blade number	30°	45°	60°
5	48%	64%	35%
6	67%	76%	60%
8	78%	89%	70%

4.5. Discussion of the simulation results

Based on the analysis given in Section 4.1. – 4.4., the following aspects of the results discussion results were defined:

- Cyclone No. 1 ensured the most favorable results among the analyzed alternative models. The shape of its body causes the fluid to be blown into the interior of the device in a way that allows the effective reduction of the dust content in the final sections, as well as at low values of the volumetric flow and velocity. Even with a volumetric flow rate of 0.3 m^3/s – and consequently a low velocity at the top of the filter – (12-13 m/s), the dust is continually thrown onto the inner walls of the body.
- The shape of Cyclone No. 1's body makes the dusted air spin faster while its height and the low location of the chute funnel prevent the contaminants from being blown backward into the main flow at this point.
- Cyclone No. 1 is suitable for installations aimed primarily at achieving highly efficient dust removal.
- Cyclone No. 2 is suitable for installations requiring a high volumetric flow and a medium level of dedusting efficiency.
- Cyclone No. 3 is the least effective of the alternatives analyzed. Its shape negatively affects the distribution of dust and air in the separator. This type of separator will work best in small installations with low flow rates. It would be advisable to consider combining it with another dust collector, to achieve a higher overall gas dedusting efficiency, especially with highly diverse types of dust.
- The velocity of the internal flow, along the center line, increases from the bottom to the top of the cyclones. Inlet velocity significantly affects the number of revolutions in the internal vortex. The vortex length and reverse flow increase with the velocity of the inlet.

- Results, of the MOS type analysis, indicate that increasing the number of rotor blades causes the dust-air compound to swirl more strongly; consequently, the contamination, collected behind the dust collector blades is more evenly distributed. An increase in the number of blades also increases the concentration of dust near the inner walls of the MOS cover, which, by increasing the inlet velocity of the flue gases, enables them to be more easily removed from the MOS.
- The inclination angle of the rotor blades (in each cell of the MOS dust collector) equal 30º resulting in a moderately effective initial swirl of dust. At this inclination angle, the number of blades has the greatest impact on the device's efficiency. It should be noted that, from a practical point of view, the blades may wear out more quickly, as the dust velocity is strongly reduced due to mutual collisions with blades.
- Of all analyzed blade inclination angles, the value of 45º allows for achieving the highest dust collection efficiency with expected good durability and reliability of the dust collection cells. A system of 8 blades inclined at this angle is the most common alternative applied in design practice. This is confirmed by the number of solutions of this type used on the Polish market.
- The use of blades with an inclination angle of 60º leads to a decrease in dust removal efficiency in every analyzed case. Part of the gas with the solid fraction enters directly behind the rotor of the device without significant turbulence, creating a chaotic movement of the fluid inside the cell, disrupting its normal operation. It can be assumed that the use of a larger number of blades than 8, in this case, will contribute to an increase in dust removal efficiency while increasing the total cost of the dust collector construction.

5. Conclusions

Precipitation of dust particles is the result of many complex phenomena, the dynamics of which can be modified, inter alia, by appropriately designing the structure of a given type of dust collector.

As demonstrated in the simulation analysis of the operation of the gas dust collectors modelled, the geometric structure of individual sections of the device is of great importance for efficiency in the operation of the separators. There are guidelines, in designing, which specify the dependencies between characteristic dimensions for such cyclones, which facilitates initial prototyping. Further changes in design may already become carried out, to adapt the dust collector to the specific operating conditions of the target facility.

5.1. Main research findings and their implication

Based on the co-related computer simulations and experimental tests it was shown that the design of centrifugal dust collectors for independent operation, with a high ratio of body length to its diameter, for quasi-homogeneous dust particles in the dedusted gas (with a significant share of PM10 dust in the total volume), is characterized by high overall efficiency. Increasing the diameter of the dust collector body while decreasing its length limits the effectiveness of the dust removal process. Moreover, it allows the device to operate at high volumetric gas flow. The modernization of the gas dedusting installation and the introduction of MOS-type dust collectors enable further increase the effectiveness of the dedusting process when using MOS cells equipped with 8 blades inclined at an angle of 45º. The high correlation of measurement and simulation results obtained using the extensive, but rarely applied in practice SolidWorks software, may indicate the usefulness of such an environment in the field of computer fluid mechanics for energy applications and contribute to the spread of its implementation, alongside software such as Ansys Fluent or xFlow Simulia.

5.2. Future research directions

It is worth mentioning future directions and potential applications related to the subject matter:

- Experimental analyses on the dry centrifugal dust collector with two inlets are to be considered. The dust collector models will be modified by including an additional (second) gas inlet port for the same and different heights and with a different shape of the internal channel. A solution with an arrangement that will meet adopted assumptions is going to be manufactured and tested at the facility. The aim of simulation and experimental research will permit the assessment of further efficiency improvement of the dedusting process in the event of greater diversity of the aerodynamic diameters of solid particles in the dedusted gas.

- As part of their research into modern solutions for flue-gas cleaning, the authors are working on sensitive cyclo-filters, which are to be integrated with the centrifugal dust collector, with the conical part removed and a filter / bag dust collector. The work involves CFD simulation studies (including other CFD software than SolidWorks Flow Simulation) as well as real-time measurements (obtained within actual facilities). The fabric filter in the cyclo-filter will consist of varied lengths of sleeves arranged horizontally inside the contaminated chamber. Parameters such as gas velocity in the pipes (measured by the PN-Z-04030-7:1994 standard), gaseous pollutants (using an automatic exhaust gas analyzer) and dust level will be measured. Cyclo-filters of various fabric materials will be analyzed. The test will be performed in the by-pass section of the existing boiler installation. The tests will be carried out at 3 levels of production load.
- The following investigations are also planned (all based on validated simulation studies), namely, the effect of the various selected construction materials, covering the internal walls of a cyclone, on the efficiency of the dedusting process and the drop in pressure inside the device and a friction forces distribution inside the device. Abrasion-resistant materials such as Densit Wear Flex 2000 with a thickness of 15-25 mm will be applied as linings, as the dust collector body and the chute can be covered.

Future scientific and research work should be focused on issues related to highly effective gas purification with the integration of various types of dust collectors (including centrifugal dust collectors) and the use of modern materials, both in construction and covering the internal structures of the exhaust gas path, reducing gas flow resistance, which will allow to reduce the electric energy consumption by components of the gas circulation system, such as exhaust gas fans. A further increase in the effectiveness of the dust removal process can be expected by using liquids that cover the inside walls of centrifugal dust collectors (development of wet gas dust collectors). Particular attention should be paid to solutions implementing a closed recirculation of the medium while minimizing losses of the recirculated liquid. This issue requires determining the appropriate gas inlet velocity for the designed dust collector structure, which should be suitable to make the liquid smoothly descend. Optimization issues related to determining the size of distributed liquid drops and their operation time should be aimed at maximizing separation efficiency and minimizing pressure drop and consumption of the working medium.

The current intensive development of renewable sources of energy and the implementation of technologies in this area, also in the case of high-power energy facilities, creates the need to develop research in the design of gas dust collectors for use in mixed installations intended for burning biomass and coal. The boilers with circulating fluidized beds are often applied. Thus, the gas–solid cyclones with a high solid loading, flow behaviors of gas and solids, and separation efficiency of solids in cyclones under non-steady state or transient operation conditions should be investigated and developed. The test results obtained in this research can be treated as reference data for further conclusions in the case of using dust removal units with the same or extended operating mechanism as cyclofilters or mosofilters in the installation. Thus, can be treated as the impact industry or scientific understanding.

5.3. Real-world applications of the research findings – the impact on industry

The obtained results targeted at the operation of the single centrifugal dust collectors with different geometric dimensions together with the dust collectors with the same physics of operation but using rotating masses in the form of multi-blade rotors. These results may enable a future investor to make a preliminary assessment of the validity of modernizing the current exhaust gas system based on one of these solutions (taking into account the expected gas purification efficiency, the required complexity of the device structure and the space occupied in the facility). The applied nature of the conducted research enables the identification of the design of the MOS solution with the highest separation efficiency of solid particles, with dominant PM10 diameters, which limited the costs and time of prototyping and testing a solution that meets the adopted assumptions. The obtained results may prove helpful in the case of facilities working with exhaust gas characterized by a similar dust granulometric composition.

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