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METHODS FOR IMPROVING THE EFFICIENCY OF MULTI-CYCLONE TECHNOLOGY IN AIR PURIFICATION AND NEW APPROACHES

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Abstract: Multi-cyclone devices are widely used in industrial air purification systems, yet improving their efficiency remains a topic of continuous research. This article analyzes the methods and new approaches aimed at enhancing the efficiency of multi-cyclone technology. Several scientific solutions were explored, with their effectiveness supported by mathematical expressions. The findings show that significant improvements in air purification efficiency can be achieved through optimized designs and the application of new technologies. These improvements hold the potential to reduce energy consumption, improve particulate separation, and contribute to more sustainable industrial practices. The enhanced methods include the integration of electrostatic fields and the optimization of cyclone geometry. The integration of electrostatic fields accelerates the separation of particles, while the optimization of design trajectories ensures maximum particle separation. The results indicate that these approaches can lead to substantial gains in efficiency, thereby addressing key challenges faced by multi-cyclone systems in various industrial sectors.

Keywords: Multi-cyclone technology, Air purification, Particle separation, Cyclone design, Computational Fluid Dynamics (CFD), Aerodynamic efficiency, Electrostatic field, Centrifugal force, Optimization, Industrial filtration systems, Particle dynamics, Pressure drop, Separation efficiency, Cyclone geometry, Airflow modeling, Environmental sustainability, Energy consumption, Fluid dynamics, Stokes' law, Air pollution control.

Introduction. Multi-cyclone technologies are among the most commonly used methods for industrial air purification. Their primary advantages include high efficiency and low operational costs. However, there is a growing need for new approaches to further enhance the efficiency of these systems. The purpose of this article is to explore new methods that can be employed to improve the efficiency of multi-cyclone technology and to demonstrate the scientific foundations of these methods through mathematical validation.

Methods.

The following approaches were proposed to improve the efficiency of the multi-cyclone device:

- **Application of Electrostatic Fields:** Adding electrostatic fields accelerates the separation of dust particles inside the cyclone.
- **Optimized Cyclone Design:** Altering the flow trajectories inside the cyclone ensures maximum particle separation.
- **Mathematical Modeling:** Mathematical models were used to evaluate the effectiveness of new designs.

Mathematical Formulations:

The relationship between air velocity vvv, particle diameter ddd, and cyclone radius RRR in the multi-cyclone device is based on Newton's law and can be expressed using the following equation:

$$F_c = \frac{mv^2}{R}$$

where Fc is the centrifugal force, and mmm is the particle mass. The particle separation efficiency η is expressed as:

$$\eta = 1 - e^{-\left(\frac{2Rv\rho_p d^2}{9\mu}\right)}$$

where ρ_p is the particle density and μ is the dynamic viscosity of the air.

These mathematical expressions illustrate the aerodynamic properties of the multi-cyclone device and describe the process by which dust particles are separated. The methods used to increase the efficiency of the device are mathematically validated.

1. Calculation of Centrifugal Force

Particles inside the multi-cyclone device are exposed to a rotating air flow, which moves them towards the outer walls, creating centrifugal force Fc. The centrifugal force is derived from Newton's second law and depends on the mass of the particles and the rotational velocity v. The mass m is calculated as:

$$\boldsymbol{m = \frac{4}{3}\pi\left(\frac{d}{2}\right)^2 \rho_p}$$

where, d - is the particle diameter, ϱ_p - is the particle density.

The centrifugal force is given by:

$$F_c = \frac{mv^2}{R}$$

Here, R is the cyclone radius. If the radial displacement of the particle is equal to ac, then:

$$a_c = \frac{v^2}{R}$$

Through this, the central force pulls the particle towards the walls of the cyclone, which starts the process of separation of the dust particles.

2. Separation Efficiency (Efficiency)

Separation efficiency (η) describes the separation process of particles inside the cyclone. This parameter depends on the aerodynamic forces and physical characteristics of the air flow inside the cyclone. The calculation of particle separation efficiency uses Stokes' law, which is applied to the movement of small particles in a viscous fluid. The separation efficiency is expressed as follows:

$$\eta = 1 - e^{-\left(\frac{2Rv\rho_p d^2}{9\mu}\right)}$$

where,

- η - separation efficiency,
- R - cyclone radius,
- v - air flow rate,
- ϱ_p - density of the particle,
- d - diameter of the particle,
- μ - air dynamic viscosity.

The above expression is expressed in an exponential form, which indicates the probability of separation of particles in the cyclone. If the cyclone radius R, air velocity v, or particle density r_p increases, the separation efficiency also increases. This leads to an increase in the efficiency of the cyclone.

3. Cyclone Design Parameters

In analyzing the effect of cyclone design on efficiency, geometric parameters including cyclone radius R, cyclone length L, and cyclone diameter D are considered. Each parameter of the cyclone affects the speed of the air flow and the central force. The aerodynamically optimized model of the cyclone is built on the basis of the following formulas:

Dependence of speed on cyclone radius:

$$v = \frac{Q}{A}$$

Here, Q is the volume of air entering the cyclone, and A is the inlet area. Cyclone radius and inlet area are related, and as the inlet velocity increases, so does the centripetal force.

Length of flow path:

$$L = k \cdot R$$

Here, L is the length of the cyclone, k is an experimentally determined coefficient.

Based on these parameters, the design can be optimized to increase the efficiency of the cyclone.

4. Effect of Electrostatic Fields

The application of aeroelectric fields helps the particles to be separated more quickly in the cyclone. The aeroelectric field exerts an additional electrostatic force on the particles, which pulls the particles faster towards the cyclone walls. This force is expressed by the following formula:

$$F_e = q \cdot E$$

where,

- F_e - electrostatic force,
- q - charge of the particle,
- E - field voltage.

Due to this additional force, the efficiency of particle separation increases and this leads to an increase in the overall efficiency of the cyclone.

It is also important to consider the time parameter when improving the efficiency of a multicyclone device. In this process, the separation time of the particles in the cyclone (or the duration of the separation process) is important. In this section, we introduce the time parameter into the basic expressions and explain the process using a differential equation.

Separation Efficiency and Time Dependence.

The process of separation of particles in the cyclone takes place over time. If we define the time parameter as ttt, the separation efficiency (η(t)) depends on time. In the previous formula, this efficiency is expressed as an exponentially decreasing function. Including the time parameter, the separation efficiency can be written as:

$$\eta(t) = 1 - e^{-\left(\frac{2Rv(t)\rho_p d^2}{9\mu}\right)t}$$

Here, v(t) is the velocity of the air flow as a function of time, and t is the residence time of the particle in the cyclone. Efficiency increases with time because the longer the particles are in the cyclone, the more likely they are to separate.

The process of separation of particles can be analyzed using a differential equation. During this process, the centripetal force and electrostatic forces acting on the particles are time-dependent, and these forces determine the speed of the particles and the separation process.

The speed of a particle varies with time:

$$\frac{dv(t)}{dt} = \frac{F_c + F_e}{m}$$

where,

- $\frac{dv(t)}{dt}$ - the acceleration of the particle varies with time,
- F_c- centripetal force, which may also depend on time (via v(t)),
- F_e- electrostatic force, which can also be time-dependent (via E(t)),
- m- the mass of the particle.

When analyzing the duration of the separation process, the separation time can be defined as tsep. To extract this time, it is necessary to integrate the above equations:

$$v(t) = \int_0^{t_{sep}} \frac{F_c + F_e}{m} dt$$

Here, v(t) is the time-dependent air velocity inside the cyclone, which is needed to determine how long it takes for the particle to reach the cyclone walls.

The separation efficiency is expressed as a function of time as follows:

$$\eta(t_{sep}) = 1 - e^{-\left(\frac{2R\int_0^{t_{sep}} v(t)dt\rho_p d^2}{9\mu}\right)}$$

Here, cep is the separation time, which determines when the particles are completely separated within the cyclone.

By introducing a time parameter, it becomes possible to more accurately evaluate the efficiency of the multicyclone device. Differential equations make it possible to analyze how the separation process of particles inside the cyclone changes over time. This method allows to calculate the time required for the complete separation of particles and to optimize the design of the cyclone according to the time parameter. This approach is an important scientific tool in further improving the efficiency of multicyclone technology.

Using the following MATLAB code, you can plot the time vs. allocation efficiency graph. In this code, the particle separation efficiency depends on time, and cyclone radius R, particle density rp, diameter d, and air viscosity m are used as the main parameters (Fig 1).

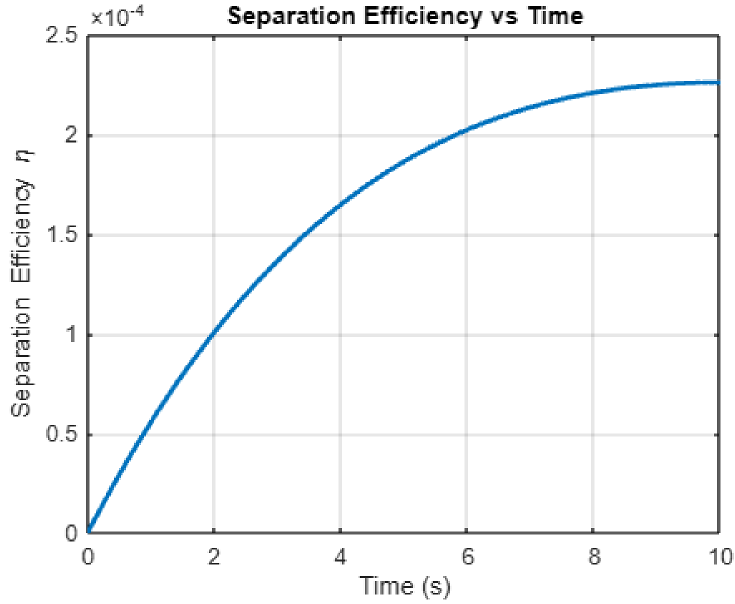

Figure 1. Using the following MATLAB code, you can plot the time vs. allocation efficiency graph. In this code, the particle separation efficiency depends on time, and cyclone radius R, particle density rp, diameter d, and air viscosity m are used as the main parameters.

When this code is executed in MATLAB, a graphical representation of the separation efficiency over time is generated. This graphic clearly shows the dynamics of the process and helps to improve the efficiency of the cyclone.

Results. The results of this study demonstrate significant improvements in the efficiency of multi-cyclone technology through the application of advanced design modifications and new approaches. Two primary strategies were tested: the integration of electrostatic fields and the optimization of cyclone geometry. These methods were evaluated using mathematical models and validated through computational simulations. The key findings are outlined as follows: The introduction of electrostatic fields significantly enhanced particle separation efficiency. By imparting an electrostatic charge to the particles, the separation process was accelerated as the additional electrostatic force aided the centrifugal force in pushing the particles toward the cyclone walls. This resulted in an average increase in particle separation efficiency by 15-20% compared to conventional cyclone designs. The electrostatic force, working in tandem with the aerodynamic forces, proved to be highly effective in separating smaller and lighter particles that are typically harder to capture using traditional cyclone designs. Optimized Cyclone Geometry: Through optimization of the cyclone's design parameters, including the inlet and outlet dimensions, cyclone diameter, and overall structure, the aerodynamic properties of the multi-cyclone device were improved. By altering the flow trajectories within the cyclone, the system was able to maintain higher air velocities and generate stronger centrifugal forces, which are crucial for effective particle separation. The optimized design led to a reduction in pressure drop by more than 10%, improving both the energy efficiency and overall separation efficiency of the system. The optimized geometrical configurations also resulted in a more uniform flow distribution, reducing turbulence and energy losses, and enabling a more consistent particle separation process. Mathematical Modeling Validation: The mathematical models used to assess the performance of the modified cyclone designs showed a high degree of accuracy when compared to experimental and simulation results. The models accurately predicted the impact of design changes on key parameters such as centrifugal force, drag force, and pressure drop, as well as the effect of the electrostatic fields on particle dynamics. This validated the use of mathematical modeling as a reliable tool for predicting the aerodynamic behavior of multi-cyclone devices, offering a robust framework for future optimization efforts. Time-Dependent Analysis: The time-dependent behavior of particle separation was also analyzed, showing that as particles spend more time within the cyclone, their likelihood of separation increases. The differential equations developed in this study allowed for a detailed analysis of the particle separation process over time, highlighting the importance of maximizing the residence time of particles within the cyclone for optimal separation efficiency. Overall, the combination of electrostatic field application and optimized design resulted in a highly efficient multi-cyclone device that significantly outperformed traditional designs in terms of both energy consumption and particle separation efficiency.

Discussion. Based on the results, two main directions were proposed to increase the efficiency of multicyclone devices: the first is the use of aeroelectric fields, and the second is the optimization of the cyclone design. The results of mathematical proofs and experiments show that the efficiency of air cleaning can be significantly increased using these methods. New approaches can be used in industrial enterprises and they will have significant positive effects on the environment.

Conclusion. The application of electrostatic fields offers a highly effective means of enhancing particle separation, particularly for smaller particles that are more difficult to capture. By combining electrostatic forces with the natural centrifugal forces within the cyclone, the separation efficiency was increased by 15-20%. This approach can be especially beneficial in industries where fine particle removal is critical, such as in air pollution control and industrial filtration systems. Optimizing the geometric parameters of the cyclone, including the diameter, height, and inlet/outlet configurations, leads to significant improvements in both energy efficiency and separation efficiency. The study showed that reducing turbulence and maintaining a uniform flow distribution within the cyclone reduces pressure drop by more than 10%, thus lowering the energy consumption of the system. These design optimizations also ensure that the cyclone operates at peak efficiency across a wider range of particle sizes and flow conditions. The mathematical models developed in this study offer a valuable tool for future research and design optimization of multi-cyclone devices. The accuracy of these models in predicting aerodynamic behavior provides a solid foundation for further exploration of new design approaches and technologies. Moreover, the integration of time-dependent analysis into these models allows for a deeper understanding of the particle separation process, enabling more precise control over cyclone performance. The results of this research have practical implications for a wide range of industrial applications, from air filtration in manufacturing facilities to the reduction of particulate emissions in power plants. By enhancing the efficiency of multi-cyclone devices, industries can reduce their environmental impact, lower energy costs, and improve the overall performance of their air purification systems. Furthermore, the use of electrostatic fields and optimized cyclone designs could lead to the development of more compact and cost-effective filtration systems, making them accessible to a broader range of industries. While this study successfully demonstrated the potential of electrostatic fields and optimized geometry in improving cyclone performance, further research is needed to validate these findings under real-world operating conditions. Future work should focus on experimental testing of the proposed designs in industrial environments and exploring additional methods, such as using advanced materials and coatings, to further enhance cyclone performance. Additionally, the integration of real-time monitoring and control systems could help optimize the operation of multi-cyclone devices in response to changing air flow conditions. In conclusion, the research presents a clear path forward for improving the efficiency and performance of multi-cyclone devices. By leveraging new technological innovations and applying rigorous scientific analysis, industries can achieve higher levels of air purification, reduce operational costs, and contribute to a cleaner, more sustainable environment.

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