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STUDY OF THE INFLUENCE OF THE DIMENSIONS OF THE CYCLONE INLET ON THE CYCLONE PERFORMANCE

Xodjiyev Muxsin Todjiyevich[1], Murodov Orif Jumayevich[2], Adilova Aziza Shuxratovna[3], Saidova Nozima A'lovidinovna[4]
[1, 2]Gulistan State University, Syrdarya region, Gulistan city, district 4, house 10.
[3]Tashkent Institute of Textile and Light Industry
Shohjahan str. 5, 100000, Tashkent, Republic of Uzbekistan.
[4]Bukhara Engineering and Technological Institute,
Q.Murtazaev str. 15, Uzbekistan.

E-mail: orifakadem81@gmail.com,

azizaadilova80@gmail.com, saidova_2022@mail.ru.

Annotation. The article presents the results of studies of the influence of the dimensions of the cyclone inlet on the performance of the cyclone and the structure of the flow field. The studies were carried out using calculations using the Reynolds Stress Turbulence Model (RTST). The results show that the maximum tangential velocity in the cyclone decreases with increasing size of the cyclone inlet. Increasing the size of the cyclone inlet led to a decrease in pressure drop. However, the cut-off diameter of the cyclone increased with the size of the cyclone inlet, where the efficiency of the cyclone decreased due to the weak vortex force. According to the results obtained, changing the dimensions of the width of the cyclone inlet had a greater effect on the cut-off diameter than the height of the cyclone inlet.
Keywords: Cyclone, Stairmand, dust, Solidworks Flow Simulation, Navier-Stokes equations, Mach number, turbulence, fluid dynamics (CFD).

Introduction. In cyclone separators, a highly swirling turbulent flow is used to separate phases of different densities. The typical geometrical layout of a dust cyclone used to separate particles from a dust stream is shown in Fig. 1, which corresponds to the "Stairmand" model of a high-efficiency cyclone. The tangential inlet creates a vortex motion of the dust flow, which pushes the particles to the outer wall, where they spiral downwards. The particles are eventually collected in a dust collector (or flow out through a dip tube) located at the bottom of the conical part of the cyclone body. The cleaned dust exits through the outlet pipe at the top. Swirl and turbulence are two competing phenomena in the separation process: swirl induces centrifugal force in the solid phase, which is the driving force for separation; turbulence disperses the solid particles and increases the probability that the particles will enter the outlet stream. Both phenomena are related to the particle size and the flow conditions in the cyclone [1].

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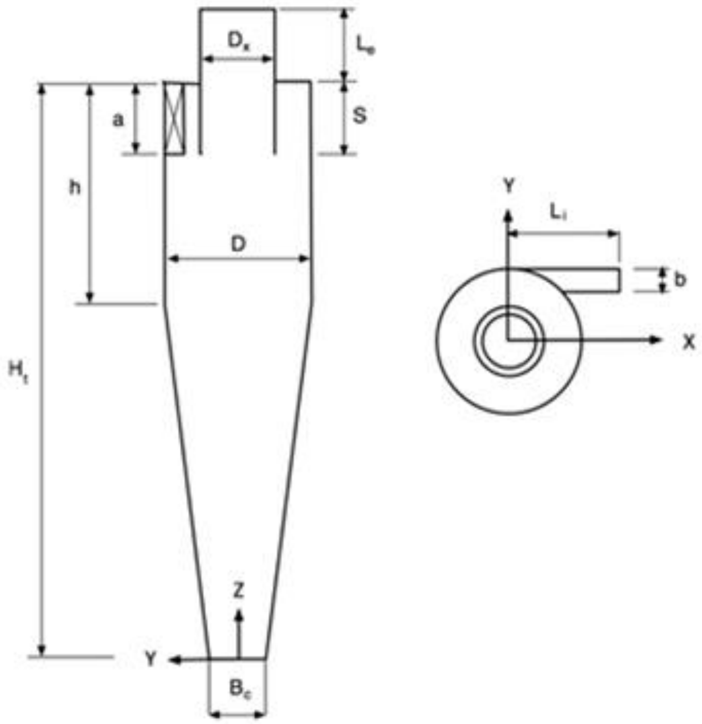

Fig. 1: The principle scheme of the cyclonic separator Stairmand.

While the cyclone geometry is simple, the flow is an extremely complex three-dimensional swirling flow. The complexity of the solid-phase dust flow pattern in cyclones has long been the subject of many experimental and theoretical works. Nowadays, laser Doppler anemometry (LDA) [2, 3] and particle image velocimetry (PIV) [4–6] are often used to experimentally study the flow pattern in cyclones. As for the theoretical work, computational fluid dynamics (CFD) codes have proven to be a useful tool for simulating cyclonic flows [1, 7–10]. The cyclone geometry affects the flow pattern and performance. The cyclone geometry is described by seven geometric parameters, namely, inlet height a and width b, vortex finder diameter Dx and length S, cylinder height h, total cyclone height Ht, and cone tip diameter Bc (Fig. 1(a)).

Many papers have reported the influence of the cyclone inlet section dimensions on the cyclone performance (pressure drop and cutoff diameter). Casal and Martinez-Benet [11] proposed the following empirical formula 1, for the dimensionless pressure drop (Euler number): $E_u = 20\left(\frac{ab}{D^2_x}\right)\left(\frac{S}{H_t h B_c}\right)^{1/3}$ (1)

i.e. linear dependence on the inlet area. Iozia and Leith [12-14] presented a correlation to estimate the cutoff diameter d50 and found a proportionality of (ab)0.61 [15-17]. Numerous studies have been conducted on the influence of geometric parameters on flow pattern and performance [8, 18-20], while the influence of cyclone inlet dimensions has remained largely unexplored. The studies devoted to the study of the influence of cyclone geometry only briefly report on the influence of inlet section dimensions on cyclone performance without sufficiently

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detailed information on their influence on flow patterns and velocity profiles. A new trend is the study of multi-entry cyclone [21-23].

The effect of cyclone inlet on the flow field and performance of cyclone separator was numerically investigated by Zhao et al. [24]. They compared the performance of two types of cyclones with a conventional single inlet and a spiral double inlet using the Reynolds stress turbulence model. The results show that the new type of cyclone separator with the addition of a spiral double inlet can improve the symmetry of the dust flow and enhance the particle separation efficiency. Although their results are for a double inlet cyclone, they confirm the importance of the effect of inlet dimensions on the performance of the cyclone separator. The significant effect of cyclone inlet dimensions on cyclone performance has been recognized in many papers [25]. For double inlet cyclone separators, Yunusov and Sultonov [26] reported the possibility of improving the cyclone efficiency without a significant increase in pressure drop by improving the cyclone inlet geometry. The effect of inlet angle has been verified by many researchers. Khodzhiev M.T [27] calculated the effect of inlet angle. The pressure drop of the cyclone decreases to a value 30% lower than that of a conventional cyclone when it becomes equal to 45°. However, Agzamov M.M. [28] reported a pressure drop decrease of only 15% for the same inlet angle. Thus, all the above-mentioned works did not study the effect of the inlet dimensions in height or width on the performance and flow pattern, but studied the effect of the inlet configurations or the effect of the number of inlets (single or double) or the shape of the inlet section (rectangular duct or nozzle). In this work, the effects of changing the width and height of the cyclone inlet on the pressure drop and the cutoff diameter were studied, and detailed information on the flow field structure and velocity profiles was obtained.

Methods and materials. Solidworks Flow Simulation provides a number of turbulence models for modeling swirling turbulent flow in a cyclonic separator. These range from the standard k-ε model to the more sophisticated Reynolds stress turbulence model. A large eddy simulation methodology is also available as an alternative to the Reynolds-averaged Navier-Stokes approach.

Navier-Stokes Equations

For incompressible fluid flow, the continuity and momentum balance equations are [29]:

$$\frac{d\overline{u_i}}{dx_i} = 0 \tag{2}$$

$$\frac{d\overline{u_i}}{dt} + \bar{u}\frac{d\overline{u_i}}{dx_j} = \frac{1}{\rho}\frac{\partial\bar{P}}{dx_i} + \gamma\frac{d^2\bar{u}_i}{dx_j dx_j} - \frac{\partial}{dx_i}R_{ij} \tag{3}$$

Where $\overline{u_i}$ — average speed, x_i — position, $\bar{P}$ - average pressure, ρ - density of heat, ν – kinematic viscosity of dust, $R_{ij} = \overline{u_j' u_j'}$ – Reynolds stress tensor. Here, $u_i' = u_i - \bar{u}_i$ – pulsating component of speed.

The Reynolds turbulence model provides differential transport equations for estimating the turbulence stress components.

$$\frac{\partial}{\partial t}R_{ij} + \bar{u}_k\frac{\partial}{\partial x_k}R_{ij} = \frac{\partial}{\partial x_k}\left(\frac{\gamma_t}{\sigma^k}\frac{\partial}{\partial x_k}R_{ij}\right) - \left[R_{ik}\frac{\partial\overline{u_j}}{\partial x_k} + R_{ik}\frac{\partial\overline{u_i}}{\partial x_k}\right] - C_1\frac{\varepsilon}{K}\left[R_{ij} - \frac{2}{3}\delta_{ij}K\right] - C_2\left[P_{ij} - \frac{2}{3}\delta_{ij}P\right] - \frac{2}{3}\delta_{ij}\varepsilon, \tag{4}$$

where the conditions of turbulence production P_{ij} are defined as [30]:

$$P_{ij} = -\left[R_{ik}\frac{d\overline{u_j}}{dx_k}\right] + R_{ik}\frac{d\overline{u_j}}{dx_k}, \quad P = \frac{1}{2}P_{ij} \tag{5}$$

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Where P is the fluctuating production of kinetic energy. is the turbulent viscosity; 6k = 1, C1 = 1.8, C2 = 0.6 are empirical constants. The transfer equation for the turbulence dissipation rate, ε, is defined as [31]:

$$\frac{\partial \varepsilon}{\partial t} + \bar{u}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(v + \frac{\gamma_t}{\sigma^{\varepsilon}}\right)\frac{\partial \varepsilon}{\partial x_j}\right] - C^{\varepsilon 1}\frac{\varepsilon}{K} R_{ij}\frac{\partial \bar{u}_i}{\partial x_j} - C^{\varepsilon 2}\frac{\varepsilon^2}{K}. \quad (6)$$

In the equation (7), $K = \frac{1}{2}u_i' u_i'$ – fluctuating kinetic energy, a ε – turbulence dissipation rate. Values of constants $\sigma^{\varepsilon} = 1.3, C^{\varepsilon 1} = 1.44$ and also $C^{\varepsilon 2} = 1.92$.

The Lagrangian discrete phase model in Solidworks Flow Simulation follows the Euler-Lagrange approach. The liquid phase is treated as a continuum by solving the time-averaged Navier-Stokes equations, and the dispersed phase is solved by tracking a large number of particles through the computational flow field. The dispersed phase can exchange momentum, mass, and energy with the liquid phase.

The fundamental assumption made in this model is that the dispersed second phase occupies a small volume fraction (typically less than 10–12%, where the volume fraction is the ratio of the total particle volume to the liquid volume), although high mass loading is acceptable. Particle trajectories are calculated individually at specified intervals during the liquid phase calculation. This makes the model suitable for simulating flows with particles. The particle loading in the cyclone separator is small (3–5%), so it can be safely assumed that the presence of particles does not affect the flow field [32]. In terms of the Eulerian-Lagrangian approach, the equation of particle motion is [33]

$$\frac{du_{pi}}{dt} = \frac{18\mu}{\rho_\rho d_\rho^2}\frac{C_D Re_\rho}{24}\left(u_i - u_{\rho i}\right) + \frac{g_{i(\rho_p - \rho)}}{\rho_\rho} \quad (7)$$

$$\frac{dx_{pi}}{dt} = u_{pi} \quad (8)$$

where is the term $\frac{18\mu}{\rho_p d_p^2}\frac{C_D Re_p}{24}\left(u_i - u_{pi}\right)$ - drag force per unit mass of a particle [34]. ρ and also μ dust density and dynamic viscosity respectively, ρ_p and dp — density and particle diameter respectively, C_D — drag coefficient, u_i and u_p dust velocity and particle velocity in direction i respectively, g_i is the acceleration of gravity in direction i, Re_p is the relative Reynolds number.

$$Re_p = \frac{\rho_p d_p |u - u_p|}{\mu} \quad (9)$$

In Solidworks Flow Simulation, the drag coefficient for spherical particles is calculated using the correlations developed by Morsi and Alexander [35] as a function of the relative Reynolds numbers Re_p. The particle motion equation was integrated along the trajectory of a single particle. Statistics on the collection efficiency were obtained by releasing a certain number of monodisperse particles at the cyclone inlet and by monitoring the number escaping through the outlet. Particle impacts with the cyclone walls were assumed to be perfectly elastic.

Boundary conditions

The inlet velocity boundary condition is used at the cyclone inlet, which means that the velocity normal to the inlet is specified. At the outlet, the outflow boundary condition is used. At the other boundaries, the no-slip boundary condition is used. The cyclone inlet velocity was 10 m/s for all cyclones, the air density was 1.20 kg/m^3 and the dynamic viscosity was 2.11·10^{-5} Pa·s. The turbulence intensity was 5% and the characteristic length was 0.09 of the inlet width.

Five cyclone configuration

Fig. 1(a) and Table 1 show the dimensions of the cyclones. In a swirling flow, the swirl number usually characterizes the degree of swirl. In cyclone separators, the swirling flow is

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characterized by the geometric swirl number. The geometric swirl number is a measure of the ratio of the tangential to axial impulse, determined by formula [8].

Table 1: Geometrical dimensions of the tested cyclone.

Table 1

Measurement	Size */D
Dust outlet diameter, D_x	0,5
Vortex finder immersion length, S	0,5
Diameter of the cone apex, B_c	0,375
Cylinder height, h	1,5
Cyclone height, H_t	4.0
Case diameter, D = 31 mm. The outlet section is located above the cylindrical surface of the barrel at Le = 0.5D. The inlet section is located at a distance Li = D from the center of the cyclone.	

Table 2: Design of a factorial experiment for cyclone inlet dimensions.

Table 2

	Calculation point 1	**Calculation point 2**	**Calculation point 3**	**Calculation point 4**
a- height of the cyclone inlet, m	0,225	0,225	0,2	0,2
b- cyclone inlet width, m	0,09	0,08	0,09	0,08

As can be seen from Table 2, each calculation point corresponds to different values of the cyclone inlet size. Calculation point 1 corresponds to the first experiment to study the effect of the cyclone inlet size. Accordingly, four experiments were conducted during the study.

Results and discussions. To study the influence of the geometric dimensions of the cyclone inlet on the pressure drop and flow velocity distribution, we conducted a parametric study based on a full factorial experiment. Figure 2 shows the influence of changing the geometric configuration of the cyclone inlet on the formation of the flow velocity distribution profile throughout the cyclone volume. At the same iteration, changing the width of the inlet led to an expansion of the fluctuation zone of the lower flow velocity (Fig. 2.B).

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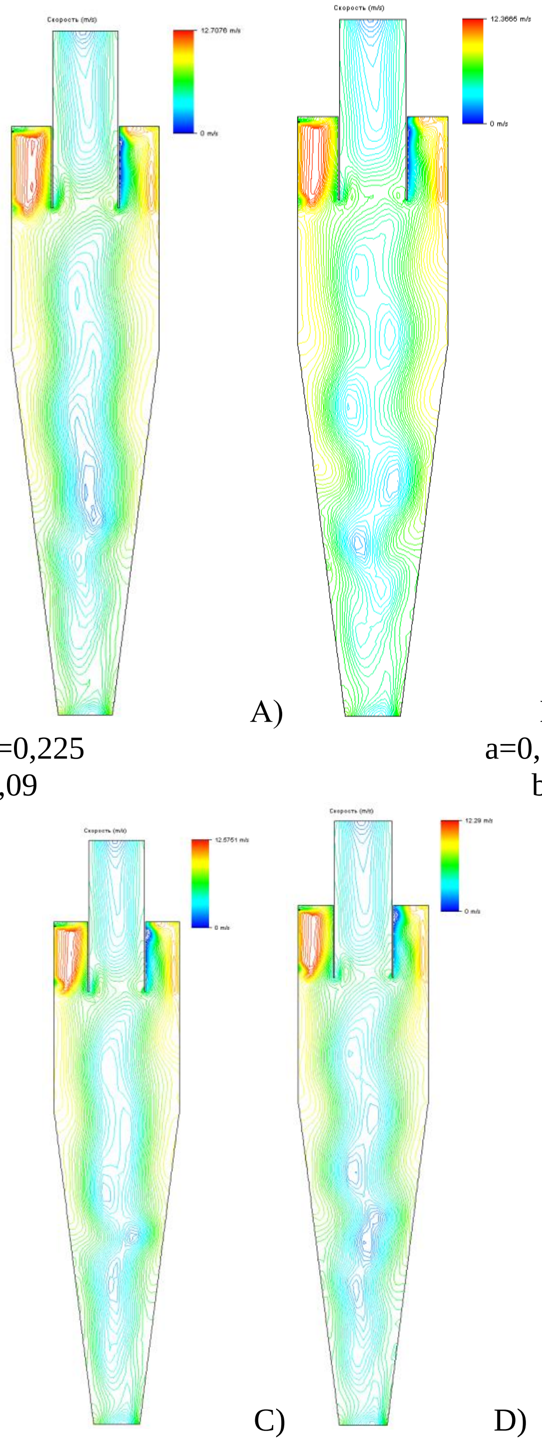

A) B)
a=0,225 a=0,225
b=0,09 b=0,08

C) D)
a=0,2 a=0,2
b=0,09 b=0,08

Fig. 2: Flow velocity profile in a cyclone for different values of geometric configuration (the iteration number is 100)

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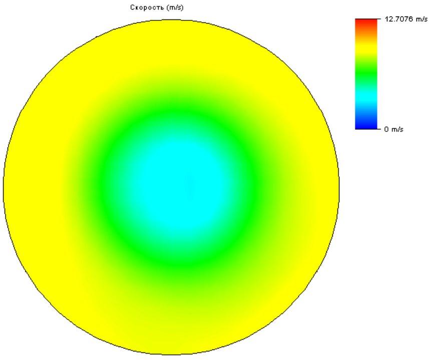
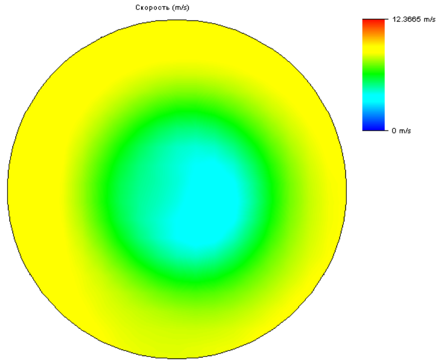
Figure 3 shows the flow velocity distributions across the cyclone cross section for the same iteration.



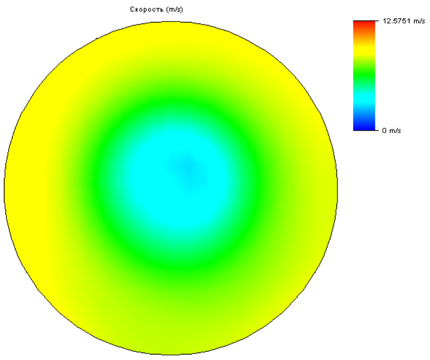
A

a=0,225
b=0,09



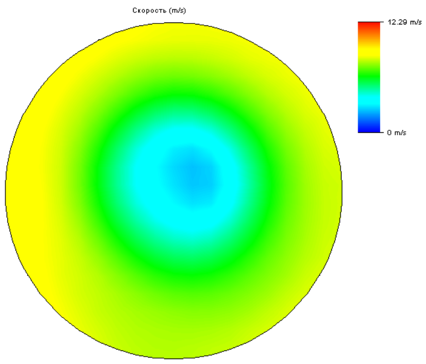
B

a=0,225
b=0,08



C

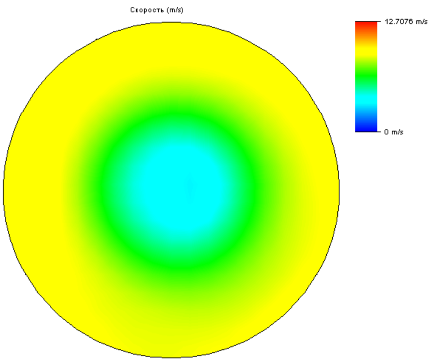
a=0,2
b=0,09



D

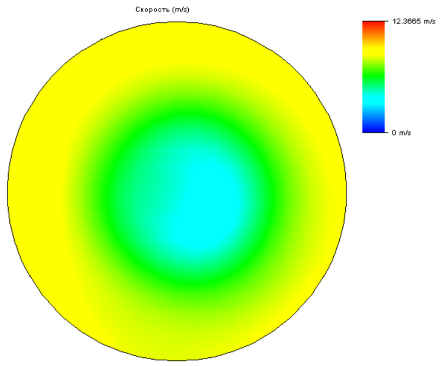
a=0,2
b=0,08

Fig. 3: Flow velocity profile in the cyclone cross section for different values of the geometric configuration (the iteration number is 100)



A

a=0,225
b=0,09



B

a=0,225
b=0,08

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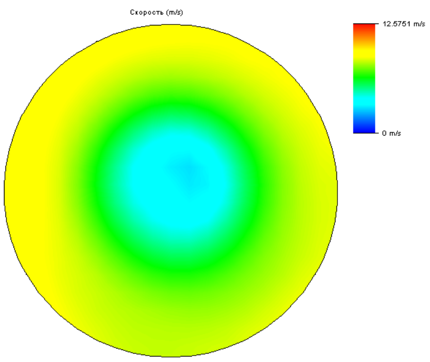
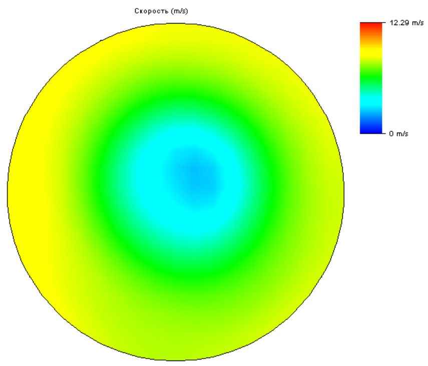


C

a=0,2
b=0,09

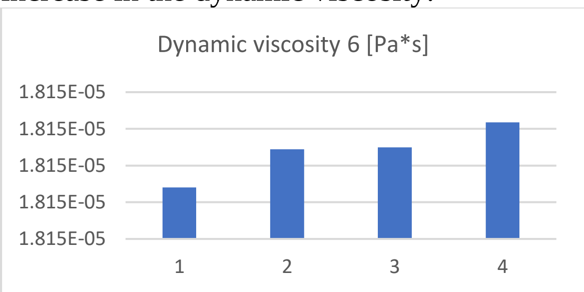


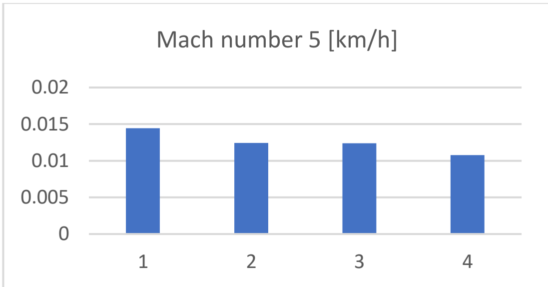
D

a=0,2
b=0,08

Fig. 4: Flow velocity profile in the cyclone cross section for different values of the geometric configuration (the iteration number is 100)

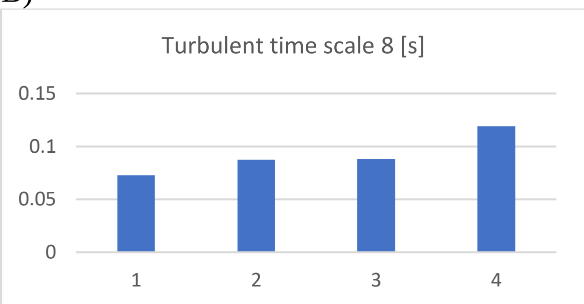
The results of the full factorial experiment are presented in Fig. 4, where the effects of changing the geometric configuration of the cyclone on the main flow characteristics are shown. Reducing the size of the cyclone inlet will clearly lead to a decrease in the mass and volume flow rate in the cyclone. However, this led to a decrease in the Mach number and an increase in the dynamic viscosity.

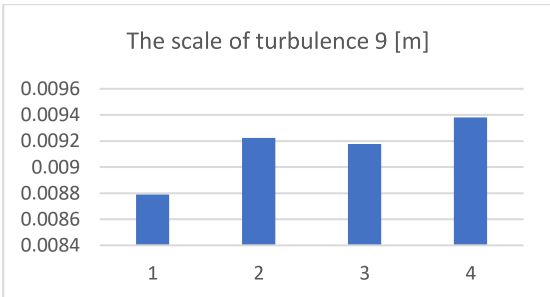




A)

B)





C)

D)

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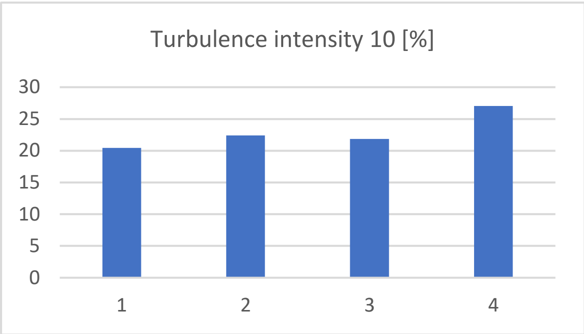
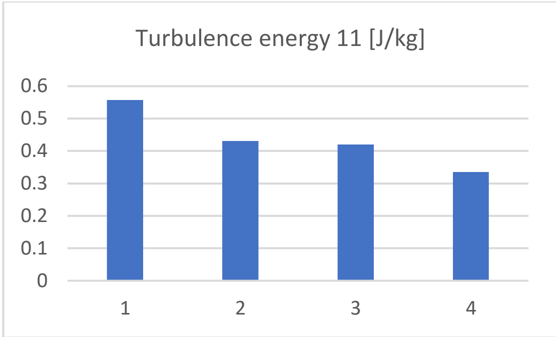
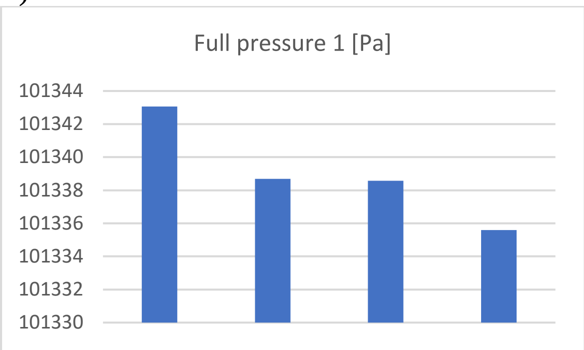


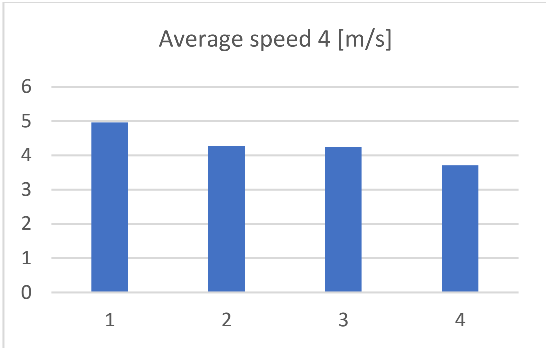
E)



F)



G)



H)

Fig. 5: Results of parametric studies of the influence of the cyclone inlet size on the flow hydrodynamics regime in the cyclone

It should be noted that the dynamic viscosity increased due to the decrease in the cyclone inlet size (Figure 5A). This increase led to a sharp increase in the turbulent time scale (Figure 5D) and the flow turbulence scale (Figure 4E). However, the turbulence intensity increased insignificantly as the cyclone inlet size decreased (Figure 4F). Accordingly, the pressure inside the cyclone decreased due to the decrease in the geometric dimensions of the cyclone inlet (Figure 4G). The Mach number is the ratio of the flow velocity at a given point in the dust flow to the local speed of sound propagation in the moving medium. Simply put, the Mach number is the velocity in the flow of matter divided by the speed of sound in this matter under the same conditions. In parametric calculations, due to a change in the cyclone inlet size, a slight decrease in the Mach number from 0.014 to 0.011 was observed.

CONCLUSION

1. To study the effect of the cyclone inlet geometric dimensions on the pressure drop and flow velocity distribution, we conducted a parametric study based on a full factorial experiment. We identified the effects of changing the cyclone inlet geometric configuration on the formation of the flow velocity distribution profile throughout the cyclone volume. In this regard, the Navier-Stokes equation was solved taking into account the Reynolds stress turbulence model, which made it possible to show an accurate prediction of the swirling flow pattern, axial velocity, tangential velocity, cutoff diameter and pressure drop in cyclone modeling.
2. The study shows the flow velocity distributions over the cyclone cross section at the same iteration. The results of the full factorial experiment show the effects of changing the cyclone

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geometric configuration on the main flow characteristics. Reducing the cyclone inlet size clearly led to a decrease in the mass and volume flow rate in the cyclone. However, this led to a decrease in the Mach number and an increase in the dynamic viscosity. It was found that the turbulence regime increased as the size of the inlet hole decreased.

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