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Volodymyr Maistruk

Department of Designing and Operation of Machines, Lviv Polytechnic National University,
12, S. Bandery Str., Lviv, Ukraine, e-mail: volodymyr.v.maistruk@lpnu.ua, ORCID 0000-0001-6982-8592

OPTIMIZATION OF CYCLONE OPERATING MODES WITH INTERMEDIATE DUST REMOVAL USING GAS FLOW STRUCTURE ANALYSIS

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Abstract. The analysis of works in which designs of the dust collecting devices which are often used in the industry are investigated is carried out. It is established that forecasting the work of dust collecting devices in certain conditions is most effective to perform methods of numerical modeling and simulation of the separation process, which are widely used for research of devices of this type. Using numerical simulation methods, it is defined the structure of the gas flow in the cyclone with intermediate dust removal for different modes of operation, which was obtained by suction of gas through the dust unloading holes at constant total costs. For this cyclone, the change in the radius of the tangential, radial, and axial velocity component for different operating modes is investigated. In the course of the research, it is established that in the separation space the tangential component of velocity with increasing radius changes according to the parabolic law. The maximum values are 16–17 m/s. The suction of part of the gas in the amount of up to 20 % through the dust unloading holes slightly reduces the tangential component of the speed (up to 5 %) in the separation zone. It is determined that in the conical part the maximum values of the tangential component of the velocity decrease to 6–7 m/s. The reduction occurs both due to the flow of gas flow from the descending to the ascending, and the suction of gas through the dust unloading holes. It is established that the radial component of the velocity varies from 1 m/s in the separation zone to 5.5 m/s in the conical part. It has been found that the suction of gas through dust unloading holes in the amount of more than 15 % of the total volume leads to a change in the direction of the radial velocity component in the conical part. It is determined that the axial component of the velocity of the separation zone receives maximum values of 9–11 m/s. In the conical part of the device, it decreases to 2–4 m/s. The suction of part of the air through the dust unloading holes leads to a shift of the axis of the internal vortex relative to the geometric axis of the apparatus below the lower end of the exhaust pipe.It is established that the creation of a directed flow of gas through the dust unloading holes in the additional dust collector in the amount of up to 15 % of the total gas volume contributes to a more efficient operation of the dust collector. A further increase in the amount of exhaust air leads to greater turbulence of the flow and less efficient operation of the apparatus.

Keywords: CFD modeling; degree of purification; hydraulic resistance; energy efficiency; tangential, radial, axial components of velocity

Introduction

Cyclone dust collectors are widely used in many industries to separate dispersed dust particles from the environment in which they are located. Their prevalence is due to geometric simplicity, compactness, satisfactory operation for high ambient temperatures. Cyclones also have good cleaning efficiency at low capital and operating costs. The main disadvantage of cyclones is the growing dependence of the degree of dust collection and energy consumption for pumping the dust stream through the dust collecting device. Significant energy costs for dust collection set the task of finding new original designs and technological solutions.

However, there are some difficulties in creating more advanced cyclone dust collectors, mainly due to the lack of accurate methods for predicting the performance of future devices, taking into account specific operating conditions.

Problem Statement

To solve practical problems in improving cyclone dust collecting devices, theoretical methods are of great importance, the use of which, using mathematical modeling, numerical methods, and modern computer technology, allows you to quickly and with high probability determine the parameters of the process, such as gas flow in the dust. Knowledge of the structure of the gas flow, in particular the distribution of tangential, radial, and axial velocity components along the radius of the device, will assess the effectiveness of the studied design of the dust collector from changes in its modes of operation.

Review of Modern Information Sources on the Subject of the Paper

Many Ukrainian and foreign researchers are working to improve the design of dust collectors. Thus, [1] conducted a study to assess the impact of the introduction of inefficient cyclone additional “bypass” pipe connecting the cyclone inlet and exhaust pipe, established mechanisms for improving the energy efficiency of the process of cleaning the air from dust, proved that the increase in cleaning is explained reducing the radial flow velocity under the cyclone exhaust pipe. The disadvantage of these devices, according to the authors, might be the accumulation of dust on the bypass pipe.

In [2], the effect of reducing the cross-section of the inlet pipe on the flow scheme and cyclone productivity was investigated. The research was conducted using CFD modeling. Based on the research results, an alternative design of the cyclone aimed at capturing small dust particles (<5 μm) was developed.

The absolute size of the cyclone, regardless of its design features, significantly affects its energy parameters. Thus, in [3] the dependence of the hydraulic resistance of cyclone CN-15 on the height of the cylindrical part, the depth of immersion of the exhaust pipe, the height of the conical part, the diameter of the exhaust pipe, the diameter of the dust pipe. In addition, this paper investigates the field of velocities of dust flow inside the dust collector, in particular, its tangential and axial components. The disadvantage of this work is that there is no study of the influence of the geometric dimensions of the elements of the device on the efficiency of its work.

In [4], the authors optimized ten geometric parameters of a standard Steyrmand cyclone using computational hydrodynamics methods.

In [5], an apparatus that can operate in both direct and countercurrent cyclone mode is considered. Calculations of the gas flow rate field and capture efficiency were performed using CFD programs for different geometric configurations. The results show that counter-cyclone cyclones are more efficient. However, upstream cyclones are more effective at trapping small particles.

Therefore, after analyzing the work on improving the operation of dust collectors, we can conclude that the efficiency of cyclones depends largely on the aerodynamics of the gas flow. As the tangential velocity of the gas flow in the cyclone increases, the forces that cause the particles to move in the radial direction increase. Accordingly, the time during which the particles reach the walls of the cylindrical part of the apparatus and are captured is reduced. The action of this factor largely determines the cleaning efficiency in the cyclone. The presence of radial and axial velocity components also affects the separation of dust particles.

Main Material Presentation

Knowledge of the structure of the gas flow, in particular the distribution of the tangential, radial, and axial components of the absolute velocity over the radius of the device, will assess the effectiveness of its work and determine the optimal amount of air suction. It is advisable to conduct research using methods of numerical modeling and simulation of the separation process (CFD - programs), which significantly speed up the research process and are much cheaper.

In this work, a cyclone with intermediate removal of precipitated dust (cyclone with PVP), which is created on the basis of cyclone CN-15, is investigated. The structure and principle of operation of this cyclone are presented in [6]. To increase the efficiency of dust cleaning in the studied apparatus, the annular space behind the dust unloading holes was connected to another dust collector using an additional fan, ie the obtained concentrated dust flow was fed to the second stage of cleaning (Fig. 1).

It is obvious that as the amount of exhaust air increases, the action of centrifugal radial flow will increase, and accordingly, more dust will be removed through the dust unloading holes outside the cyclone separation zone, increasing the cleaning efficiency. However, a significant increase in the amount of exhaust air leads to a decrease in the amount of gas passing through the cylindrical-conical separation space of the apparatus, reducing the twisting force of the flow and, accordingly, the centrifugal force acting on dust particles, which reduces the efficiency of dust collection in the apparatus. Therefore, for the effective operation of the cyclone with PVP, it was necessary to establish the optimal ratio between total air consumption and the consumption of exhaust air.

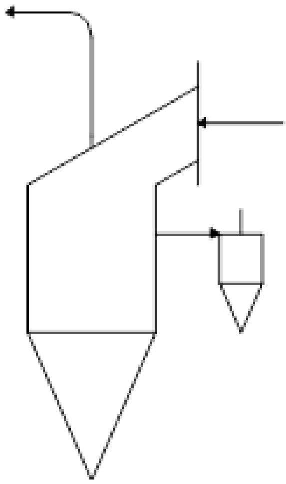

Fig. 1. Scheme of connection of the cyclone with the supply of dust flow to the additional dust collector

In this paper, research is conducted using CFD - programs used since the 1960s to calculate fluid dynamics in the aerospace industry, development, design, and manufacture of aircraft and jet engines, and later for aerodynamic research of road vehicles. As the computing power of modern computers continues to grow, CFD software packages are becoming increasingly available for use in the development of new devices in many industries [7]. Currently, hydrodynamic modeling of gas flows in devices of different designs based on CFD modeling is widely studied [8, 9].

A geometric 3D model was built for CFD modeling of a cyclone with intermediate dust removal. Then, using a grid generator, a computing grid was created for this model. All geometric transformations were performed in the CAD program, and the grid was created in the CFD program. Aerodynamic studies of this device were performed according to the method according to [10].

The standard k-ε model was used for the research, which is one of the most widely used turbulence models due to its simplicity in modeling the structure of turbulent flows. It does not require large computing power compared to other k-ε turbulent models.

The initial parameters for the study of these cyclones were the characteristics of the dust airflow: atmospheric pressure under normal conditions P_0 = 101325 Pa; ambient temperature under normal conditions T_0 = 293 K; air density ρ_{air} = 1.293 kg/m^3; dust - pulverized quartz, density ρ_{dust} = 2600 kg/m^3.

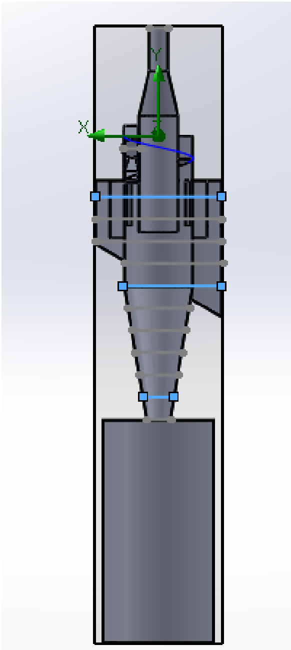

Fig. 2. Location of cross-sections of the apparatus in which the study was conducted

The following boundary conditions were set for the calculation: open flow – volumetric outflow costs – 0.2826 m^3/s (costs corresponded to a fictitious airspeed of 4 m/s); open pressure – ambient pressure; wall – a real wall.

It should be noted that studies using CFD programs were conducted for the case when cyclones operate on the suction line.

During the research of the device according to the scheme presented in Fig. 1, the volume of gas passing through the central exhaust pipe was changed from 0.2261 to 0.2826 m^3/s, and the amount of gas passing through the dust unloading holes was changed from 0 to 0.0565 m^3 / s. At the same time, the total volume of gas passing through the tangential inlet pipe of the device remained unchanged. A study was conducted for five values of gas flow through dust unloading holes: 0; 0.0141; 0.0283; 0.0424; 0.0565 m^3/s, which is 0 %, 5 %, 10 %, 15 %, 20 % of total air consumption, respectively.

The main parameters analyzed in this paper were the change in the radius and height of the device tangential, radial, and axial components of the velocity in the studied cyclone for different modes of operation of the device.

The components of the velocity of the studied cyclone were investigated in three horizontal planes relative to the axis of the apparatus in height (Fig. 2). In the cylindrical (separation) zone, the velocity field was investigated in a plane 400 mm above the plane of transition from the cylindrical to the conical part. In the conical part, the velocity field was investigated in a plane that is 500 mm lower than the plane of transition from the cylindrical to the conical part. Also, research was conducted in the plane of transition from the cylindrical to the conical. According to the research results, graphs of the dependence of the tangential, radial, and axial components of the flow velocity on the radius of the apparatus are constructed.

Results and Discussion

We analyze the tangential, radial, and axial velocity components for the studied cyclone in different operating modes. For the convenience of analyzing the results of the velocity graph, we divide it into three parts – separately for the plane in the cylindrical (separation) zone (Fig. 3–5), the plane of transition from the cylindrical to the conical (Fig. 6–8), and the plane in the conical part (Fig. 9–11). The positive and negative values of the velocity components are determined by the directions of the zero axes of the 3D model (Fig. 1). The positive value of the tangential component of the velocity corresponds to the positive direction of the Z-axis, the axial direction - Y, the radial - X.

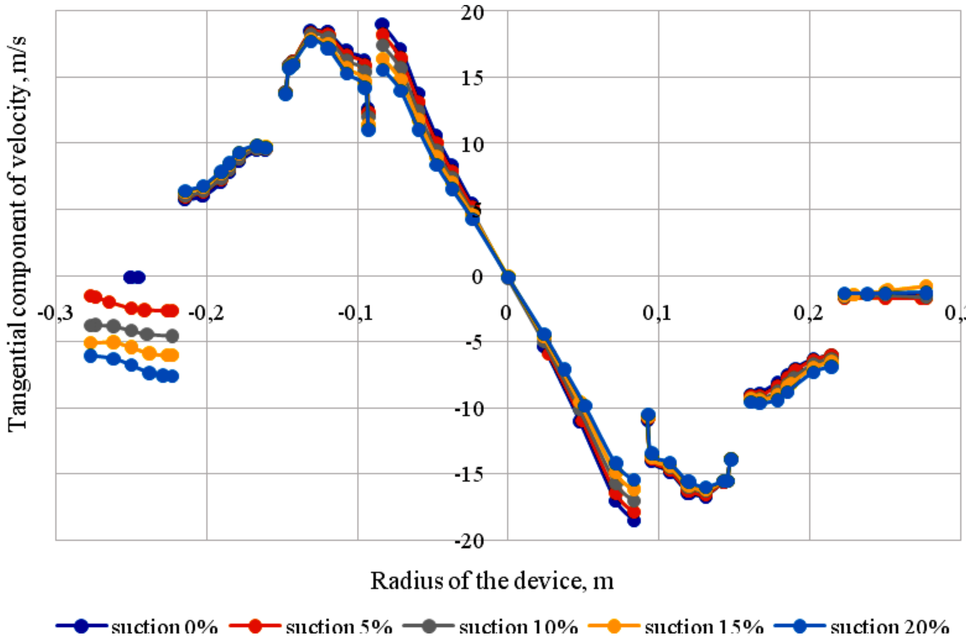

Fig. 3. Dependence of the change of the tangential component of the velocity along the radius of the apparatus in the cylindrical (separation) part of the apparatus

Tangential velocity is the dominant component of velocity in cyclones and a key factor responsible for the centrifugal force that transfers dust particles from the gas stream to the walls of the apparatus. This has a direct effect on the efficiency of particle capture (with increasing tangential velocity, the centrifugal force, and the capture efficiency increase). As shown in Figure 3, the distribution of the tangential component of the velocity is well axisymmetric in the investigated plane, which is a characteristic of the strongly twisted flow in the separation part of the cyclones. The tangential component of the velocity with increasing radius in the separation zone varies according to the parabolic law. It gets a value of about 10 m/s near the wall of the exhaust pipe, then with increasing radius increases to 16–17 m/s, and near the wall of the cylindrical body decreases to 13–14 m/s (Fig. 3). Behind the dust unloading holes, the tangential component of the absolute speed is in the range of 6–9 m/s.

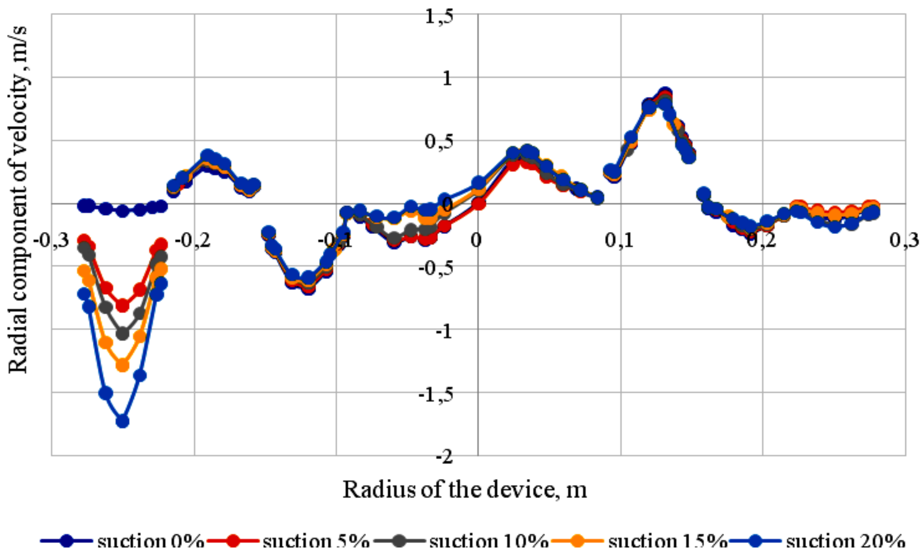

Fig. 4. Dependence of the change of the radial component of the velocity on the radius of the apparatus in the cylindrical (separation) part of the apparatus

The radial velocity component is insignificant in almost the entire separation space. In the upper part of the cylindrical body, it takes values in the range from 0 to 1 m/s (Fig. 4).

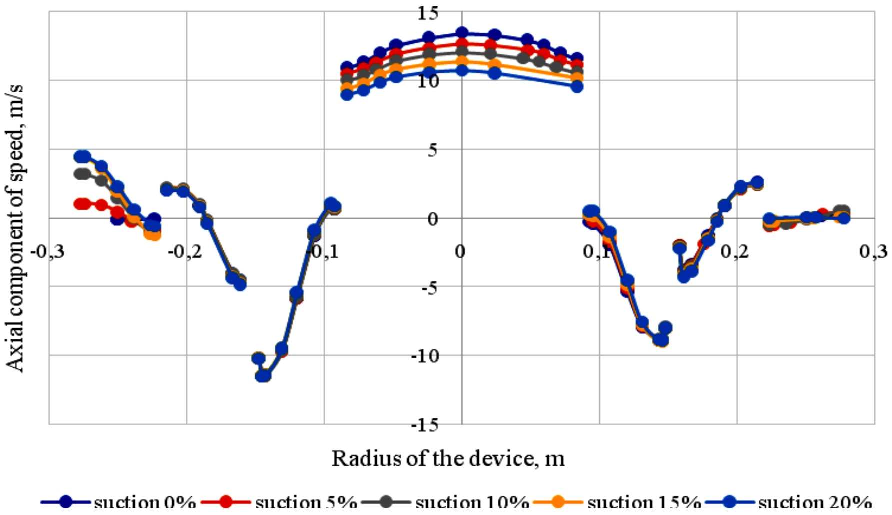

Fig. 5. Dependence of change of axial component of speed on the radius of the device in a cylindrical (separation) part of the device

In addition to the tangential, the axial component of the velocity also strongly affects the capture of dust particles in the cyclone. The graph of Fig. 5 shows that the axial component of the velocity has quite similar symmetry along the radial direction. The axial component of the velocity of the external vortex is directed downwards, and the internal component is directed upwards. The maximum value of the axial component of the speed is 9–11 m/s.

Comparison of five different values of the amount of exhaust air in the additional dust collector in Fig. 3–5 show that the suction of part of the air does not have much effect on the nature and values of the velocity components in the upper part of the separation space, because the gas in this area is just beginning to flow through the dust holes. The suction of air in the amount of 10–20 % leads to an increase in the axial component of the speed behind the dust unloading holes to 3.5–4.5 m/s. This value of the axial component of the speed contributes to the removal of trapped fine dust particles from the device through an additional pipe, and, accordingly, reduces the efficiency of the device [11].

The distribution of the tangential component of velocity in the plane of transition of the cylindrical part to the conical, as well as in the cylindrical part, is also axisymmetric. The maximum values of the tangential component of the velocity near the wall of the body of the device are 16–17 m/s (Fig. 6).

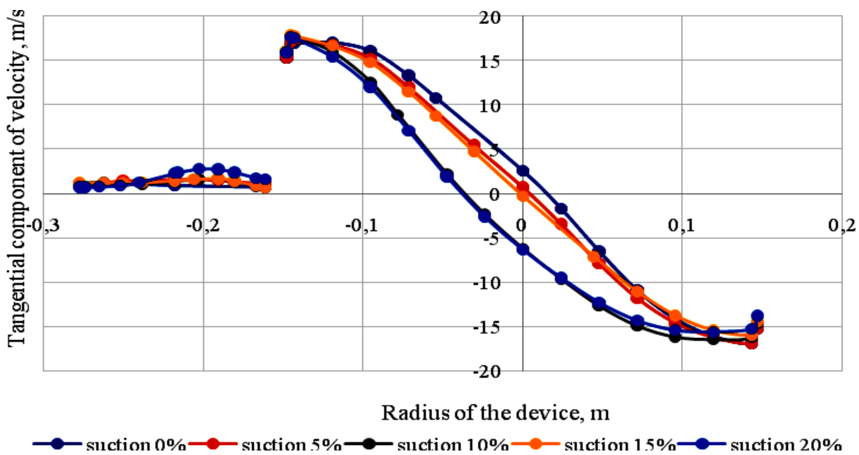

Fig. 6. Dependence of the change of the tangential component of the velocity along the radius of the apparatus in the plane of transition of the cylindrical to the conical part

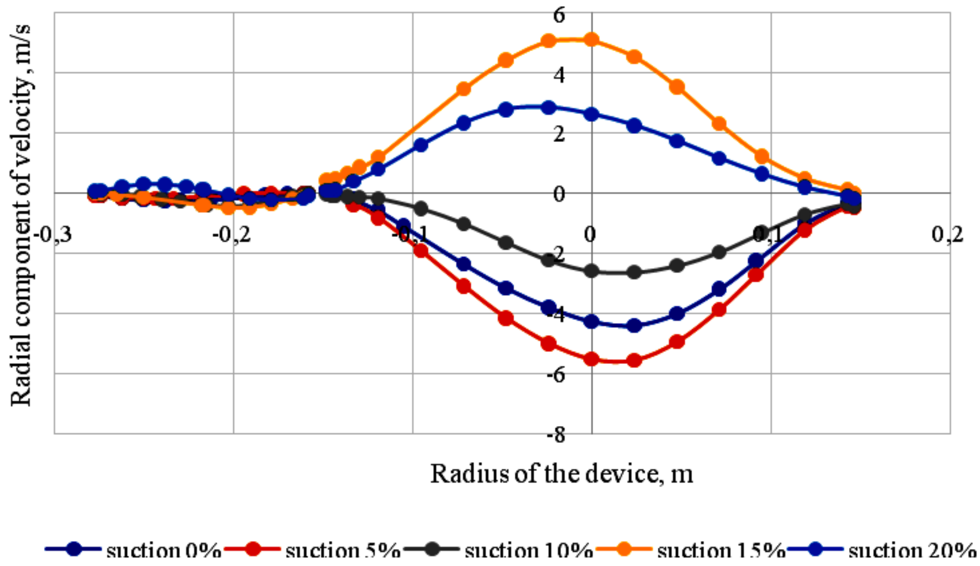

Fig. 7. Dependence of change of radial component of speed on the radius of the device in the plane of transition of a cylindrical part in conic

In the plane of transition of the cylindrical part to the conical radial component of the velocity gets values in the range from 0 to 5.5 m/s (Fig. 7). This is since in the cyclone, at the entrance to the exhaust pipe, the air layer is turbulent between the outer and inner vortex, and a secondary vortex is formed. This vortex is directed to the axis of the apparatus, which leads to the capture of fine dust from the external vortex and its removal into the exhaust pipe.

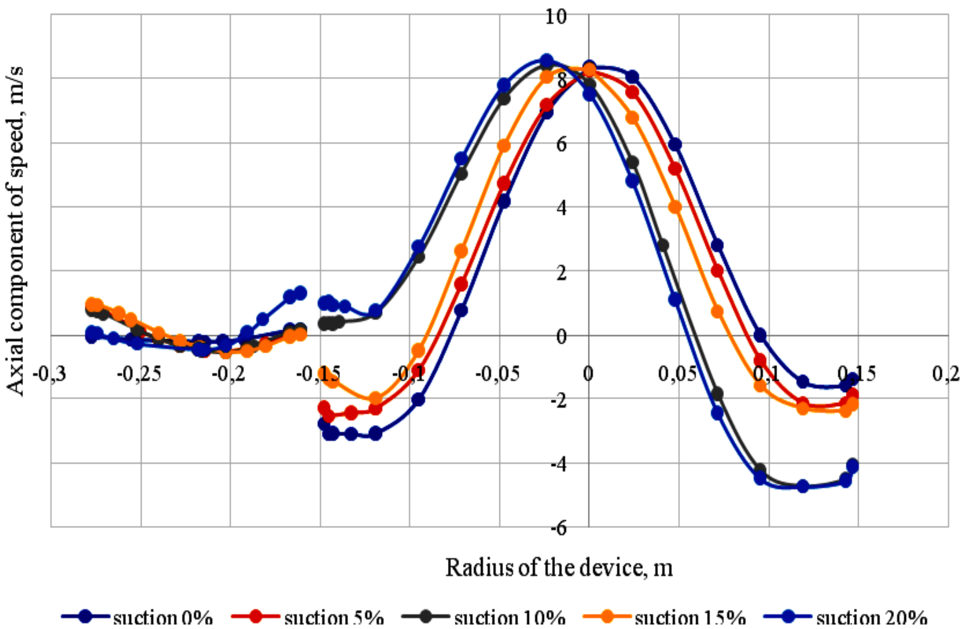

Fig. 8. Dependence of change of axial component of speed on the radius of the device in the plane of transition of a cylindrical part in conic

The largest values of the axial component of the velocity in the plane of transition of the cylindrical to the conical takes on the axis of the apparatus, which is equal to about 10 m/s (Fig. 8). Figure 8 shows that the axial velocity of the external vortex is directed downward, and the internal – upward.

The suction of part of the air through the dust unloading holes leads to a shift of the axis of the internal vortex relative to the geometric axis of the apparatus in the plane of transition of the cylindrical part to the conical. The consumption of exhaust air does not affect the maximum values of the axial speed.

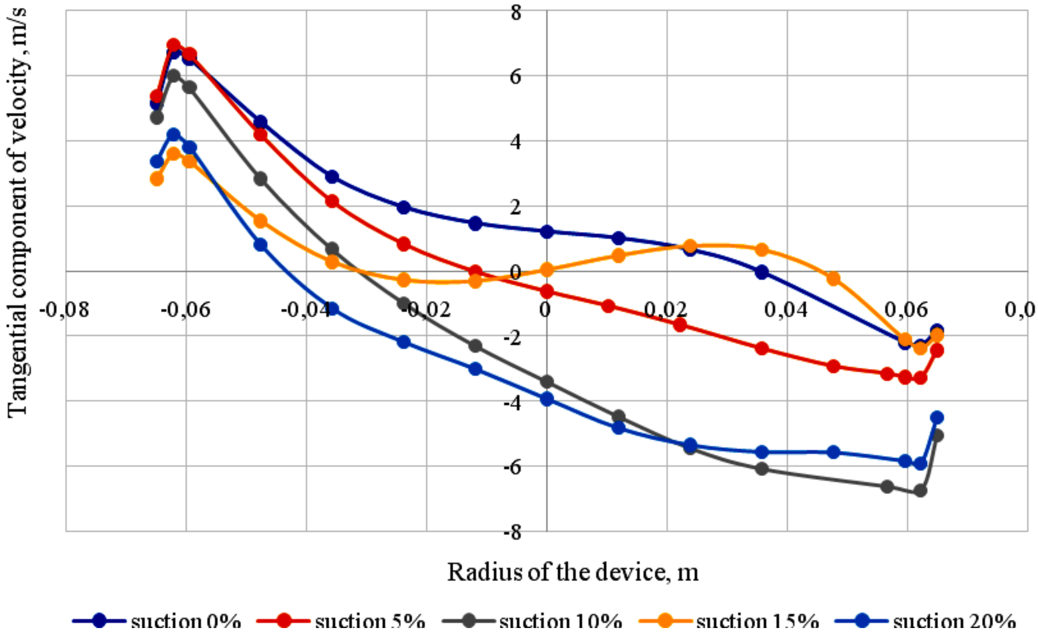

Fig. 9. Dependence of the change of the tangential component of the velocity along the radius of the apparatus in the conical part of the apparatus

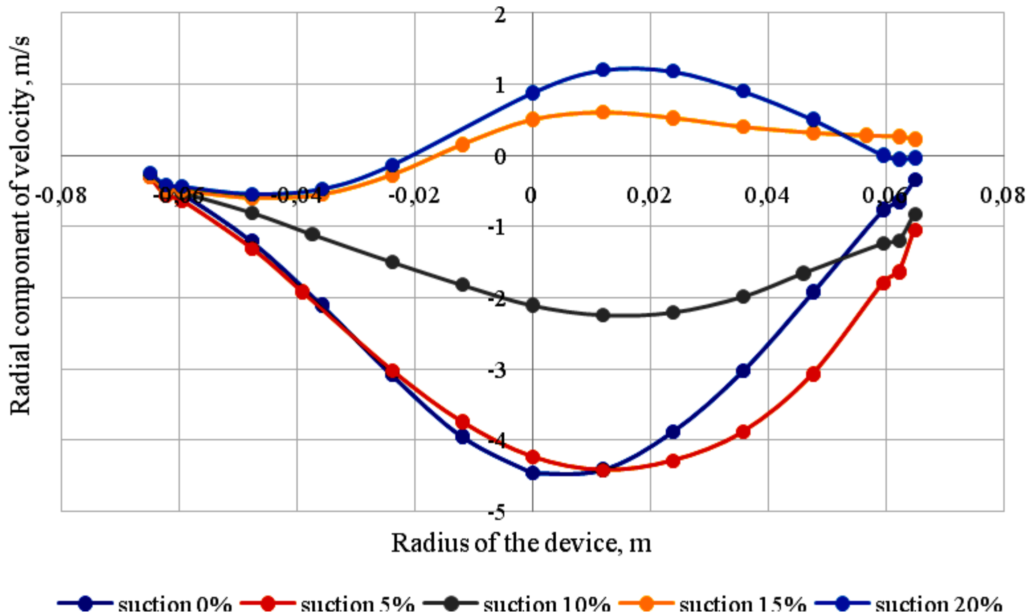

Fig. 10. Dependence of the change of the radial component of the velocity on the radius of the apparatus in the conical part of the apparatus

As the gas flow moves to the dust unloading pipe, the tangential component of the velocity decreases to 6–7 m/s (Fig. 9) near the wall of the conical part of the body of the device. The decrease in the tangential component of the velocity is primarily since the downward flow of gas passes into the upward one. In addition, the tangential component of the velocity is affected by the amount of air sucked through the additional dust collector.

In the conical part, the radial component of the velocity is up to 5.5 m/s (Fig. 10), which corresponds to the values of this component of the velocity in the plane of transition of the cylindrical part to the conical. This indicates that the flow of gas from the outer vortex to the inner is uniform throughout the height of the conical part.

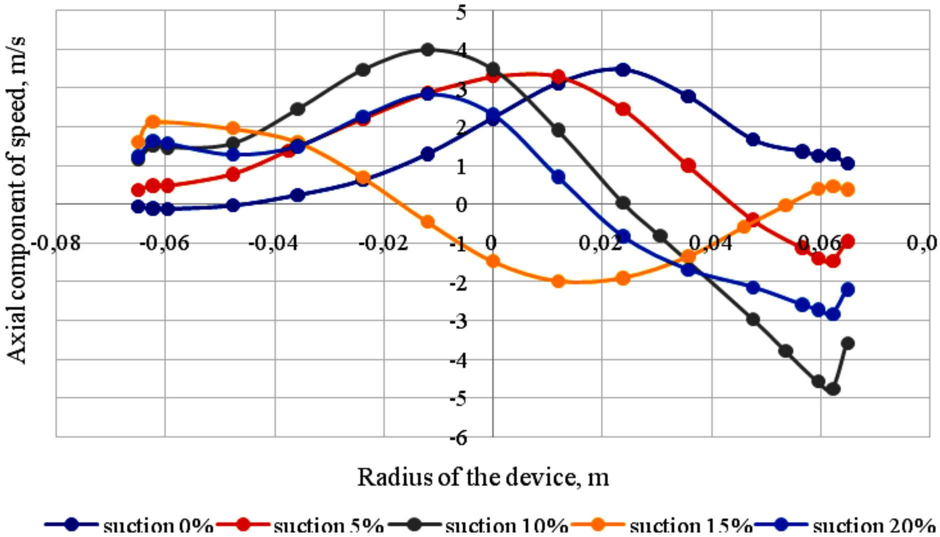

Fig. 11. Dependence of change of axial component of speed on the radius of the device in a conic part of the device.

Below the plane of the exhaust pipe on the radial component of the suction speed of the air in the additional dust collector has a great influence. The suction of more than 15 % of the total amount of gas entering the dust collector leads to a change in the direction of the radial velocity component. This in turn will create additional resistance to the deposition of dust particles.

In the conical part of the apparatus, the axial component of the velocity decreases as the gas flow to the dust discharge pipe decreases (Fig. 11). On the axis of the vortex moving upwards, the maximum value of the axial component of the velocity is 2–4 m / s. The suction of more than 10% of air through the dust unloading holes leads to a shift of the axis of the internal vortex relative to the geometric axis of the apparatus, both in the plane of transition of the cylindrical part in the conical and conical part. This also leads to a greater gradient of change in the axial component of the speed, and, accordingly, greater turbulence of the flow, which negatively affects the efficiency of the apparatus as a whole.

Conclusions

Therefore, after analyzing the movement of the gas flow in the cyclone with intermediate removal of dust with different values of the exhaust air in the additional dust collector, we can draw the following conclusions:

1. The method of simulating gas flow in dust collectors based on CFD modeling is a reliable and economical method for designing and optimizing the operation of cyclones.

2. Suction of part of the gas through the dust unloading holes changes the structure of the gas flow below the lower end of the exhaust pipe.

3. Creating a directed flow of gas through the dust unloading holes in the additional dust collector in the amount of up to 15 % of the total gas volume contributes to a more efficient operation of the dust collector. Further increase in the amount of exhaust air leads to greater turbulence of the flow and less efficient operation of the device.

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