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[1] V. Petrov, PhD of Technical Science, Associate Professor, *E-mail: 0673972002@ukr.net*
ORCID: 0000-0003-3262-9463
[1] A. Aleksashyn, PhD of Technical Science, Associate Professor, *E-mail: aleksashin48@gmail.com*
ORCID: 0000-0001-6423-4605
[2] S. Poznar, *E-mail: poznarss@gmail.com*
[1]Odesa National University of Technology, 112, Kanatna Str., Odesa, 65039, Ukraine
[2]SIC "Agro-Simo-Mashbud", Bugaevskaya, 46, Odessa, 65005, Ukraine

RESEARCH INTO THE AERODYNAMICS OF AIR FLOWS IN CYCLONES

Abstract

Human health is of high value, therefore, with the development of industry, the requirements for the impact on ecology and occupational safety and health ohs, including air quality, are increasing. There are many ways to purify air, one of which is cyclone separators (hereinafter: cyclones): horizontal and vertical. The geometric dimensions of cyclones depend on the volume of purified air, and the efficiency of purification depends on the design, therefore, cyclone designs must have optimal geometric parameters for effective dust removal. Models of vertical cyclones, worked out over the years, are widely used in the grain processing industry. Horizontal cyclones are less studied and have lower efficiency, but they are used in aggregate equipment, where they have certain advantages. In order to get further improvement, the models of horizontal cyclones, comparative studies of two types of cyclones were performed. The methodology for studying the aerodynamics of swirling air flow in difficult cyclone conditions in the ANSYS CFX package was applied. Three-dimensional models of horizontal and vertical cyclones designed for the same volume of purified air were made. In accordance with the recommendations the models of theoretical calculations and air flow parameters were taken into account. A 3d-mesh was built on the models of the study objects using the finite element method. Initial data and boundary conditions were assigned. The design of a horizontal cyclone used with the A1-BLC separator was taken as the object of study. The pressure isobars in various auxiliary vertical and horizontal planes are calculated. The lines of equal air flow velocities and their vector analogues were built, zones of maximum and minimum pressure on the cyclone elements were determined. The correspondence of the general pattern of pressure distribution along the wall in the circumferential direction was determined. The loads on the cyclone structural elements were calculated when the aerodynamic coefficient changes. The calculations were performed using a functional calculator with ANSYS CFX package. The air flow pressure on the inner cone was calculated by the finite element method using the ANSYS CFX package at an air velocity of 12 m/s. To verify the numerical correlation of the results obtained when studying the horizontal cyclone, a standard model of a vertical cyclone was used. Due to the movement (animation) of the auxiliary vertical planes, it is possible to consider the dynamics of changes in pressure and velocities of the dusty air flow in the calculated volume.

Keywords: horizontal cyclone, vertical cyclone, air pressure, computational aerodynamics, finite element method, ANSYS CFX package.

Introduction

Dust collection systems are used to remove particles from the air to combat air pollution. Dust collection is a critical aspect of maintaining a clean and safe work environment, especially in industries such as grain processing. Effective dust collection systems help to prevent respiratory problems, minimize fire hazards, and ensure the longevity of equipment. However, like any other system, dust collection systems can experience problems that hinder their effectiveness. This process is also useful for capturing valuable products that may have other uses.

In the grain processing industry, cyclones are widely used as process equipment to remove particles from the air stream. A high-speed rotating (air) flow is created in cyclones, which typically have cylindrical and conical shaped zones (Fig. 1a). Dusty air tangentially enters a vertical cyclone at high speed and moves in a spiral pattern, starting at the top and ending at the bottom, be- fore exiting the cyclone at the top in a swirling flow, having passed the return path through the center of the cyclone. Centrifugal and gravitational forces act on the heavier dust particles in the rotating flow, which give the particles a radial motion and the dust particles reach the conical walls of the cyclone and sink to the bottom of the cyclone, where they are removed through the sluice gate. The geometry of the conical part of the cyclone is designed to separate particles from the dust flow with an efficiency of 50%. In vertically oriented cyclones, one of the constituent forces significantly contributes to the separation - this is the force of gravity, which attracts heavier particles downward, allowing aerodynamically light dust particles and air to be carried upward through the central zone of the cyclone. The more revolutions the dust flow makes around the axis of the cyclone, the more dust particles are separated from the air. As a result, the height of the cyclone increases, which worsens other indicators (compactness, metal capacity, etc.), so these designs often take up a significant amount of space in the room. In horizontally oriented cyclones, instead of using centrifugal forces, dust must be separated using structural elements such as ribs, baffles and cavities, which in- crease the resistance to the air flow, which affects the overall performance of the cyclone. Horizontal cyclones are more prone to clogging with dust and product particles.

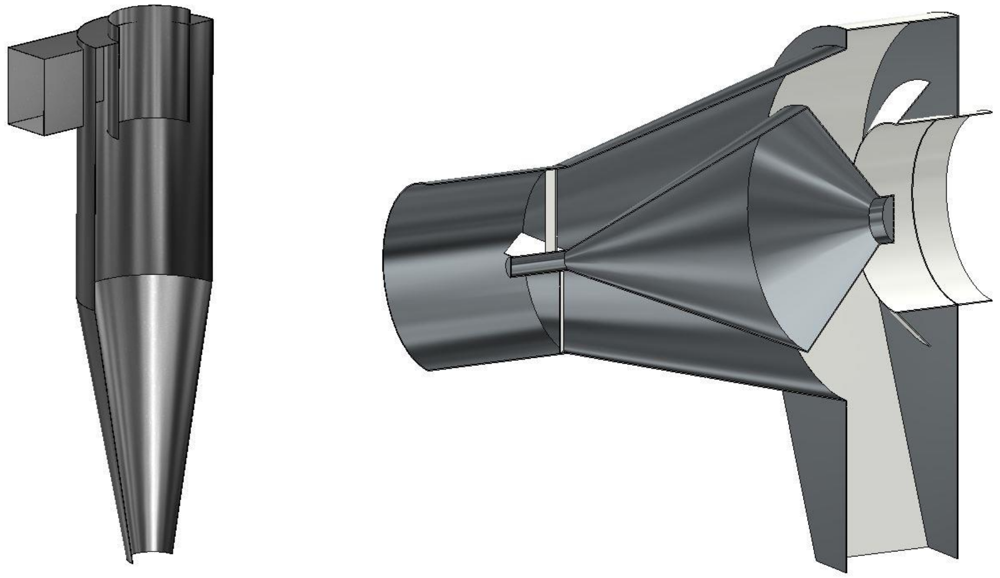


Fig. 1. Models in sections of vertical a) and horizontal b) cyclones

Cyclones operate as pre-separators, reducing the load on bag filters or cartridge collectors and minimizing the risk of contamination. Cyclones offer numerous advantages, including simple design, cost-effectiveness, high separation efficiency and versatility in particle separation applications. However, they also have limitations on the rang of particle size range, pressure drop, sensitivity to flow rate changes, potential particle re-entrainment and space requirements.

Literature review

Fig. 1 shows three-dimensional cross-sectional views of the horizontal and vertical cyclones being studied in this article. The geometric dimensions of the horizontal cyclone (Fig. 1a) are taken from the cyclone supplied with the A1-BLC separator, and a standard vertical cyclone was chosen as the baseline [1]. In addition, the basic geometric parameters of the inlets of both cyclones remain constant, as well as the air parameters at the inlet to the cyclones, while other design parameters change.

The operating conditions in the numerical simulations were assumed to correspond to the data given below. The gas phase is considered as air with a constant density of 1.225 kg/m^3 and a viscosity of 1.7894×10^{-5} kg/ms. The particle density is 2000 kg/m^3, and the particle size is 10 μm. The boundary condition at the gas inlet cross section is set as the inlet velocity (12 m/s), and it is assumed that the particle and gas inlet velocities are equal. The turbulence intensity is chosen to be equal to the standard 5%. There is no sticking on the cyclone walls.

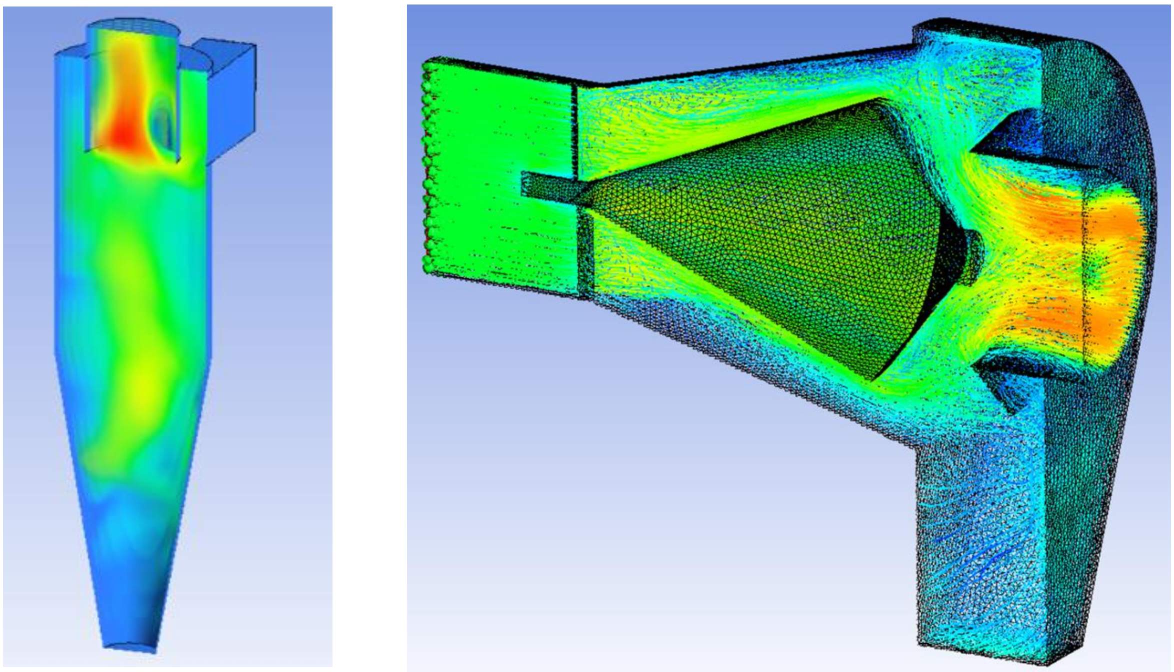
This study is unhended to reveal some features of the air flow in a horizontal cyclone. The task of this study was to estimate the air pressure distribution along the cylindrical wall and the volume of the horizontal cyclone.

Computational fluid dynamics (CFD) methods are used to study the improvement of the separation efficiency of solids and gases by adding tangential chambers to the conical part of a conventional cyclone separator. Of the existing methods for calculating the distribution of air pressure on structural elements, the most informative and widely used nowadays is the method of computational aerodynamics based on the ANSYS CFX complex [2, 3, 4, 5], which uses the Reynolds-mediated Navier-Stokes equation, and it must be closed by a turbulence model. In engineering calculations, a model consisting of two κ-ε turbulence equations is used. The k-ε turbulence model is a system of two equations in which the kinetic energy of turbulence k and the kinetic energy dissipation rate ε are calculated. This model uses wall functions. Due to its rather fast convergence and relative- ly small requirements for the amount of computer memory, the k-ε model is very popular in solving various practical problems.

Materials and methods

To carry out the study, models of horizontal and vertical cyclones were first built. The models included three-dimensional elements of the bodies, shells, reflectors, settling chambers and other elements, made in full size (Fig. 1).

The inlet air flow velocity was assumed to be 12 m/s. To model the trajectories of dusty air, first of all, a Boolean operation was performed, the volume of the internal elements of the cyclones (pipes, reflectors, etc.) was subtracted from the total calculated volume. This determined the volume in which the dusty air moves, and allows us to model its nature of movement, for example, vortices. In addition, this makes it possible to find the air pressure fields on the structural elements of the cyclones. To describe the mathematical model of the air flow in the cyclone, a 3d-mesh was built using the CFD generator. This is related to the fact that the flow has a number of particular features associated with the cyclone designs. The solution of the Reynolds-mediated Navier-Stokes equation, was carried out on the 3d-mesh built using the CFX computational package. The solution inconsistencies have a fairly good convergence, which indicates a good quality of the built 3d-mesh.



a b

Fig. 2. Distribution of air velocity in cyclone models: a) – vertical, b) – horizontal

Results and discussion

The patterns of flow velocity distribution on the surface of the cyclone cross-section in the plane of symmetry are presented in Fig. 2. In the model of a vertical cyclone (Fig. 2a), the zone of the air flow entering the cyclone, the zone of the air flow rising to the upper out- let, and the zone of the flow exiting the cyclone are characteristically distinguished. The velocity distribution has a real appearance, especially the swirling air flow rising upwards and reflecting the separation process that occurs in a vertical cyclone. It should be noted that the construction of the inlet pipe perpendicular to the vertical axis of the cyclone (which is caused by the technological requirements of production) contributes to an increase in the inlet resistance for the air flow and a decrease in the efficiency of dust flow separation. To reduce the direct flow from the inlet to the outlet, it is necessary to extend the length of the outlet pipe of the vertical cyclone downwards.

Let us consider the pattern of the velocity distribution of the dusty air flow in a horizontal cyclone (Fig. 2b). In the inlet cylindrical part of the horizontal cyclone, it is possible to observe a leveled velocity pattern. The air flow, running into the guide device, which consists of four blades made of strip metal, located at an angle of 45° to the flow, twists. This changes the pattern of the velocity field located between the conical surface of the inner cone and the conical surface of the horizontal cyclone body. It should be noted that, taking into account the large kinetic energy of the air flow, it hits the conical surface of the inner cone and, increasing its velocity, slides along it. At the same time, the velocity of the air flow in the cyclone body close to the inner conical surface de- creases, which does not lead to an increase in the centrifugal forces acting on the dust particles. A reverse air flow appears, which prevents the dust particles from approaching the cyclone body. Such a design error in choice of geometric dimensions of the cones of the horizontal cyclone and their layout does not contribute to obtaining an optimal process of dust and air separation.

The difference in velocity fields in the upper and lower zones between the conical surfaces can be explained by the fact that the blades of the guide device divide the air flow into four branches and they twist in space. Thus, different zones of different dusty air flows fall into the vertical section. When leaving the inter-conical space, the air flow enters the sedimentation chamber, where part of the flow continues to twist and descends downwards, these are mainly peripheral zones of air flows, which contain a high concentration of dust particles. Part of the dust slides along the inclined walls of the sedimentation chamber. In the lower part of the sedimentation chamber, the dust settles down and is removed by the rotary airlock. The main air flow, after leaving the inter-conical space, enters the outlet pipe of the horizontal cyclone and carries away some of the dust, which reduces its efficiency compared to a vertical cyclone. The efficiency can be partially improved by optimizing the design of the baffle. Its operation can be assessed by considering the horizontal cross-section of the cyclone (Fig. 3), when the air flow is divided by the outlet pipe, and the conical surface of the deflector helps to deflect the peripheral zones of the flow to the side walls of the sedimentation chamber. It should be noted that the inner conical surface of the deflector delays the return flow of dusty air and does not allow it to leave the sedimentation chamber.

Increase of the airflow velocity in the outlet leads to a narrowing of the flow in the straight section. Thus, in some areas the velocity of the purified air reaches 25 m/s. Taking into account the swirl of the air flows at the entrance to the sedimentation chamber, it is possible to explain the difference in the trajectories of the flows on the side walls of the sedimentation chamber.

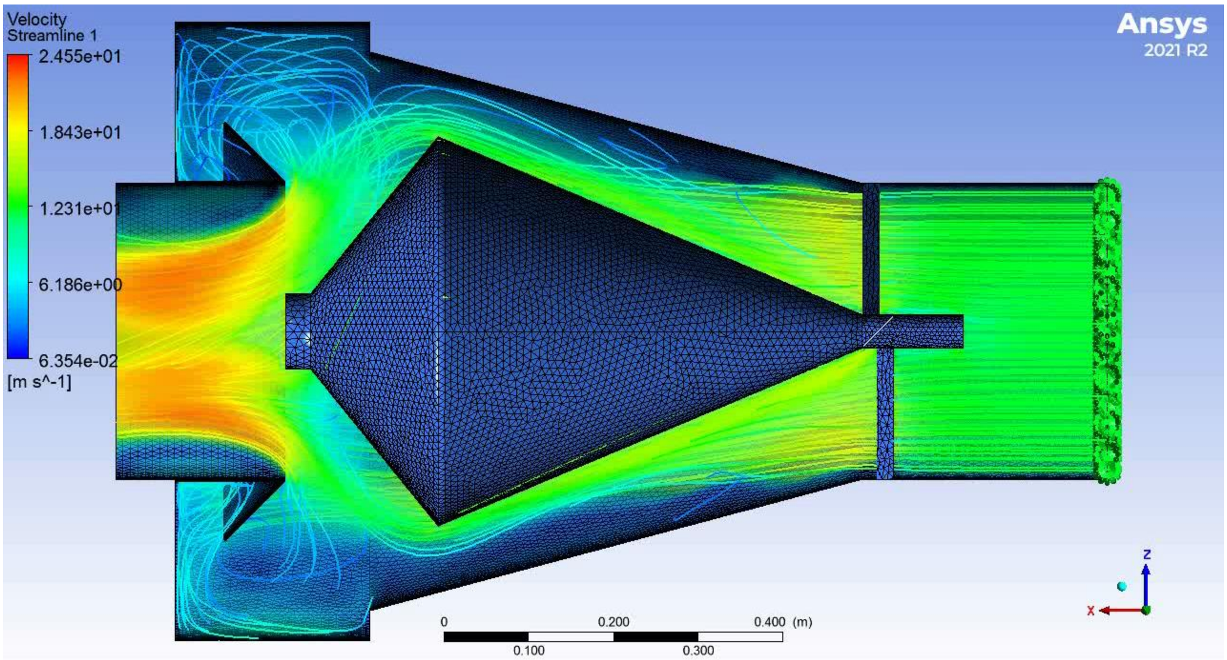
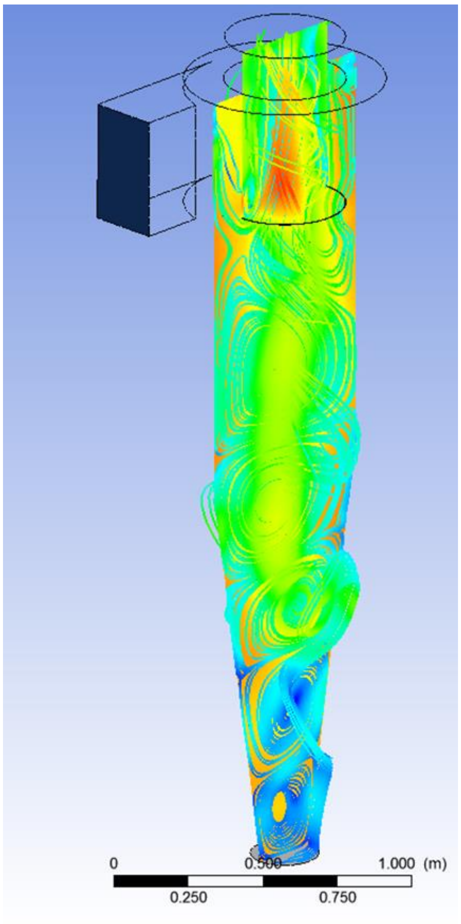
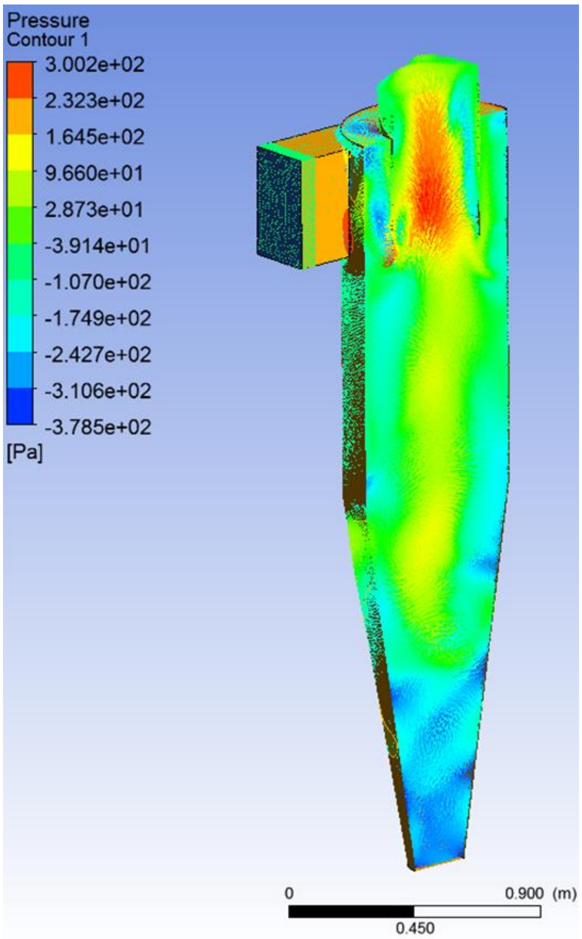


Fig. 3. Distribution of air flow velocities at the entrance to a horizontal cyclone (cross-section along the horizontal plane).



a

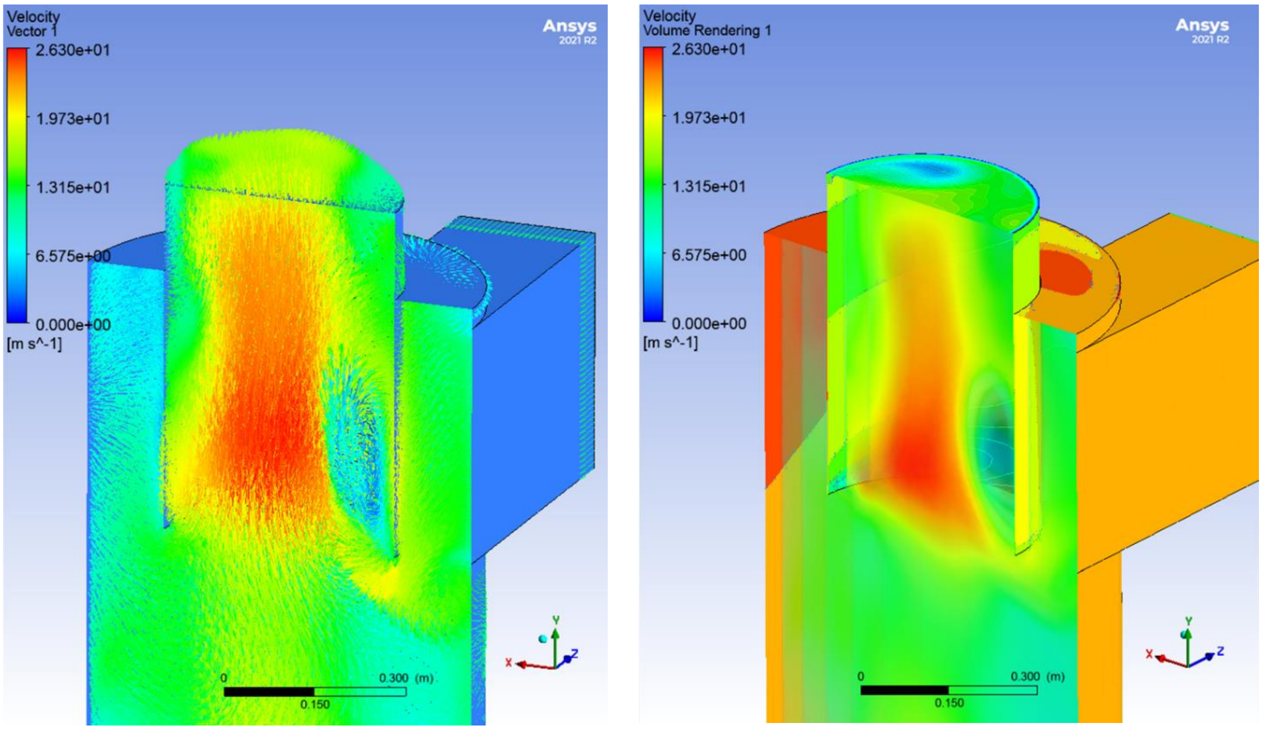


b

Fig. 4. Distribution of velocities a) and pressures b) in the meridional plane of a vertical cyclone

The insertion into the model of vertical cyclone the vertical plane of symmetry made it possible to assess the velocity distribution by plane and by volume (Fig. 4a). The lowest air flow velocity values were obtained in the dust particle removal zone by the sluice gate, which affects the separation efficiency indicators.

The pressure distribution patterns on the same plane (Fig. 4b) indicate that the k-ε turbulence model yielded an underestimated pressure value in the lower part of the sediment cone. We also have a decrease in the pressure value in the zone symmetrical to the cyclone inlet, and in the cylindrical zone above the inlet.



a b

Fig. 5. Distribution of air flow velocities at the outlet of a vertical cyclone

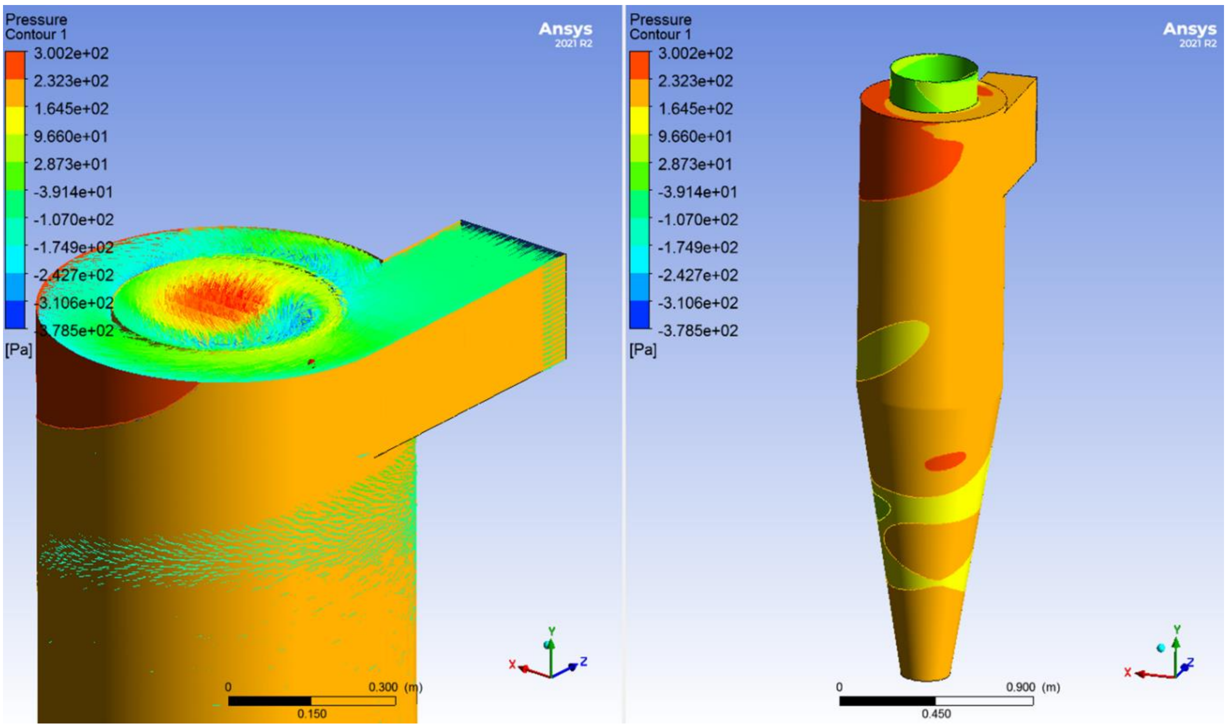


Fig. 6. Isobars of air pressure on the walls of a vertical cyclone

A similar picture is observed if we consider the location of the velocity fields in vector form at the exit from the vertical cyclone (Fig. 5a). This is a decrease in the velocity in the cyclone head in the zone opposite the inlet, on the left side in the figure. It should be noted that there is a significant air flow directly from the inlet to the outlet, which forms a significant rarefaction zone in the outlet. The rendering of this zone (Fig. 5b) in addition to confirming the information already obtained allows us to detect zones of reduced velocity in the outlet, which indicates the swirl of the air flow in the outlet zone.

The air pressure that occurs during the operation of a vertical cyclone is considered in the horizontal section of the snail of this cyclone (Fig. 6a). It should be noted that the inlet pipe is cut in half. At the inlet, a uniform pressure is observed over the entire plane. The highest pressure is observed on the opposite side of the housing from the air flow inlet and it reaches 300 Pa.

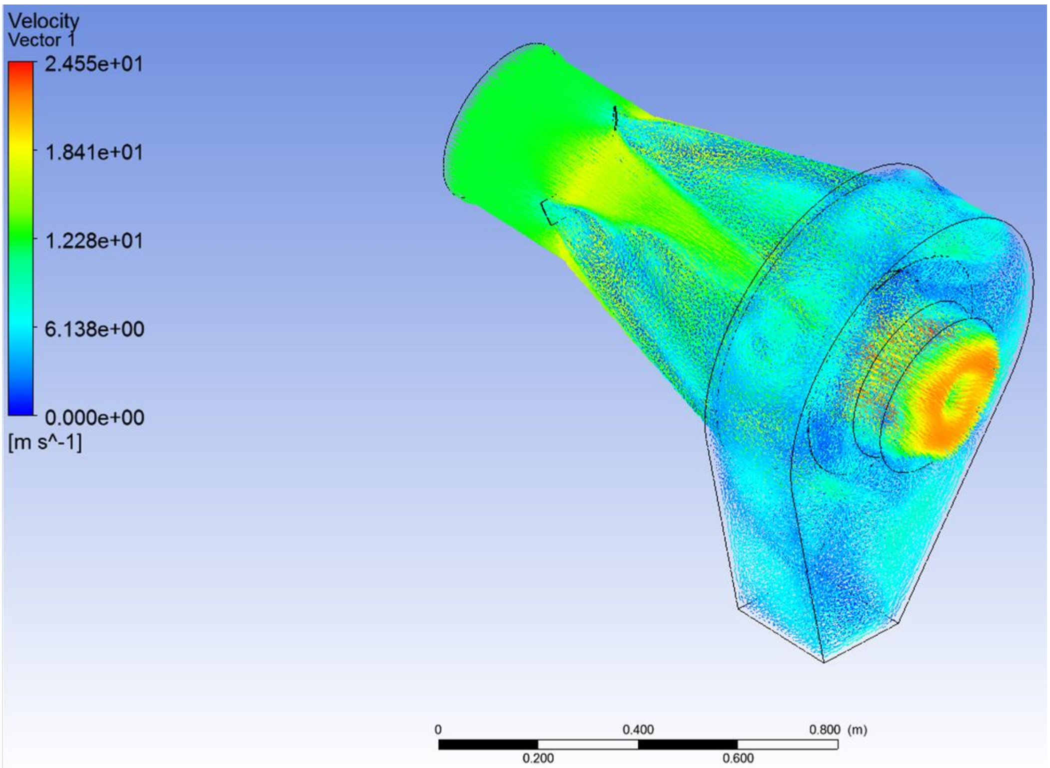


Fig. 7. Vector representation of air flow velocity fields in a horizontal cyclone

The main air flow goes down, so in the considered horizontal plane the pressure drops, which is confirmed by the experiment. It should be noted that in the outlet pipe, twisting of the outgoing air flow is also observed, which is indicated by the zones marked in red and blue. Fig. 6b shows the pressure zones (highlighted by isobars) on the walls of the housing of the vertical cyclone. Fig. 7 shows a picture of the distribution of velocity vectors in the volume of the horizontal cyclone. As follows from the obtained data, the blades of the guide device do not twist the dusty air flow enough, which reduces the efficiency of the horizontal cyclone. Therefore, in further experiments, it is necessary to pay more attention to the blades and revise their design to increase the centrifugal forces acting on dust particles.

By connecting the Function Calculator, we found the forces with which the air presses on the structural elements of the cyclones. The use of computational aerodynamics based on the ANSYS CFX complex made it possible to simulate horizontal and vertical cyclones, set calculation models, interactions of cyclone models and dusty air. This calculation model allows us to obtain various parameters of the air flow, as well as parameters of the interaction of the air flow and (pressure, force, nature of the load on various cyclone elements).

Conclusions

1. To study the horizontal cyclone, three-dimensional modeling was carried out in the ANSYS CFX software. To study the efficiency of the horizontal cyclone design, three-dimensional CFD modeling was carried out. Due to the low separation efficiency the horizontal cyclone, was compared with a conventional vertical cyclone. Velocity and pressure fields were compared.

2. The functional calculator built in ANSYS CFX provides a way to calculate the air load on the elements of a horizontal cyclone. Similar results were obtained for a vertical cyclone.

3. The use of numerical modeling in the grain processing industry is a new method for minimizing equipment design and achieving efficient optimal design. Computational fluid dynamics can provide accurate and detailed flow analysis in cyclone separators used in flour milling plants. In addition, maintenance costs will be significantly reduced by identifying critical elements and areas at the design stage and improving them.

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[1] **В.М. Петров, канд. техн. наук, доцент,** *E-mail: 0673972002@ukr.net*
[1] **А.В. Алексашин, канд. техн. наук, доцент,** *E-mail: aleksashin48@gmail.com*
[2] **С.С. Познар,** *E-mail: poznarss@gmail.com*
[1]Одеський національний технологічний університет, вул. Канатна, 112, м. Одеса, 65039, Україна
[2]НПО "Агро-Сімо-Машбуд", вул. Бугаївська, 46, м. Одеса, 65005, Україна

ДОСЛІДЖЕННЯ АЕРОДИНАМІКИ ПОВІТРЯНИХ ПОТОКІВ У ЦИКЛОНАХ

Анотація

Здоров'я людини має найвищу цінність, тому з розвитком промисловості зростають вимоги до впливу на екологію і безпеки праці, в тому числі до якості повітря. Існує багато способів очистки повітря, одним із них є циклонні сепаратори (далі: циклони): горизонтальні і вертикальні. Геометричні розміри циклонів залежать від об'єму очищуваного повітря, а ефективність очистки залежить від конструктивного виконання, тому конструкції циклонів повинні мати оптимальні геометричні параметри для ефективного видалення пилу. Моделі вертикальних циклонів, відпрацьовані роками, широко використовуються в зернопереробній промисловості. Горизонтальні циклони менш досліджені та мають меншу ефективність, але їх застосовують в агрегатному обладнанні, де вони мають певні переваги. Для подальшого удосконалення моделей горизонтальних циклонів виконані порівняльні дослідження двох типів циклонів. Застосовано методику дослідження аеродинаміки закрученого повітряного потоку в складних умовах циклонів в пакеті ANSYS CFX. Виконані трьохвимірні моделі горизонтального та вертикального циклонів, розрахованих на однаковий об'єм очищуваного повітря. З урахуванням рекомендацій прийняті моделі теоретичних розрахунків та параметри повітряного потоку. Враховуючи метод кінцевих елементів, побудована сітка на макетах об'єктів дослідження. Призначені початкові дані та граничні умови. В якості об'єкта дослідження взята конструкція горизонтального циклона, яка застосовується з сепаратором А1-БЛЦ. Знайдені ізобари тиску в різних допоміжних вертикальних та горизонтальних площинах. Побудовані лінії однакових швидкостей повітряних потоків та їх векторні аналоги, встановлені зони максимального та мінімального тиску на елементи циклонів. Встановлена відповідність загальної картини розподілу тиску по стінці в окружному напрямку при зміні аеродинамічного коефіцієнта. Визначені навантаження на елементи конструкцій циклонів. Розрахунки проводили використовуючи функціональний калькулятор, котрий вбудований в даний пакет ANSYS CFX. Тиск повітряного потоку на внутрішній конус оцінено методом кінцевих елементів, застосувавши пакет ANSYS CFX при швидкості повітря 12 м/с. Для перевірки числової відповідності отриманих результатів при досліджені горизонтального циклона використовувалася стандартна модель вертикального циклона. За рахунок руху (анімації) допоміжних вертикальних площин можливо розглянути динаміку зміни тиску та швидкостей запиленого потоку повітря в розрахунковому об'ємі.

Ключові слова: горизонтальний циклон, вертикальний циклон, повітряний тиск, обчислювальна аеродинаміка, метод кінцевих елементів, пакет ANSYS CFX.

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