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IMPROVING EFFICIENCY OF AIR PURIFIERS FROM WOOD DUST TO REDUCE INDUSTRIAL LOAD ON ENVIRONMENT

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Shevchenko S.A., Diakonov V.I., Pohorilyi V.K. ***Improving efficiency of air purifiers from wood dust to reduce industrial load on environment.***

Abstract. *The object of the study is cyclone cleaners with active working bodies. These cleaners are designed to separate wood particles from the air stream. The transition zone between the cleaner body and the active working body is considered, in which the axisymmetric flow changes both direction and speed. The purpose of this study is to develop a method for determining the radial and vertical components of the air flow velocity vector field in this zone.*

The research was carried out by the method of mathematical modeling. The following simplifications were used: streamlines were approximated by ellipse arcs; the flow of an ideal fluid was considered. The dust-air flow in the investigated zone of the cleaner is considered as a flow of an ideal fluid divided into elementary infinitely thin curved tubes. Since the flow in each of them is constant, it is possible to determine the modulus of the flow rate at a given point of the region, taking into account the variable cross-sectional area of such a tube.

Analytical dependences of the vertical and radial components of the vector field of the air flow velocity in the transition zone between the housing and the active working body of the air cleaner were obtained.

Key words: *wood particle, air purifier, rotor, flow line, vector field, air-flow velocity.*

Шевченко С.А., Д'яконов В.І., Погорілий В.К. ***Підвищення ефективності очисників повітря від деревного пилу для зменшення промислового навантаження на навколишнє середовище.***

Анотація. *Об'єктом дослідження є циклонні очисники з активними робочими органами. Ці очисники призначено для відділення частинок деревини від повітряного потоку. Розглянуто перехідну зону між корпусом очисника та активним робочим органом, в якій осесиметричний потік змінює як напрямок, так і швидкість. Метою даного дослідження є розробка методу визначення радіальної та вертикальної складових векторного поля швидкості повітряного потоку в цій зоні.*

Дослідження виконано методом математичного моделювання. Використовувалися такі спрощення: лінії течії апроксимувалися дугами еліпса; розглядалося течія ідеальної рідини. Пилоповітряний потік у досліджуваній зоні очисника розглянуто як потік ідеальної рідини, розділений на елементарні нескінченно тонкі криволінійні трубки. Оскільки в кожній з них потік є постійним, можна визначити модуль швидкості потоку в заданій точці області, враховуючи змінну площу поперечного перерізу такої трубки.

Отримано аналітичні залежності вертикальної та радіальної складових векторного поля швидкості повітряного потоку в перехідній зоні між корпусом та активним робочим органом очисника повітря.

Ключові слова: *деревна частинка, очисник повітря, ротор, лінія потоку, векторне поле, швидкість повітряного потоку.*

Introduction

Studies show that wood dust is harmful to the human pulmonary system and respiratory tract. For example, the article [1] proves that the concentration of wood dust about 4 mg/m^3 affects the body of woodworkers with less than 10-year experience, as follows, 53.7% of workers had a stuffy nose during work, 43.0% – redness of the eyes, 41.2% – itchy eyes, and 23.8% – runny nose.

Analysis of recent researches

The research [2] has shown that the potential health hazards from inhaling wood dust depend on the species of wood being treated. The most dangerous are the effects of wood particles of such hardwoods as oak, beech, teak, mahogany, walnut, and birch. In this case, the smaller the particles, the more harmful they can be.

Regarding the amount of wood dust generated at woodworking enterprises, the trends are contradictory. On the one hand, the use of wood as a restorative construction material is promising, and on the other – a growing number of forests perform mainly environmental functions. In the study [3], a method of optimizing the scheme of sawing logs on boards of rectangular and trapezoidal cross-section was proposed to make fuller use of wood in the manufacture of panel products. This allows increasing the total volume of boards made of logs. However, the analysis of the wood balance allows concluding that the specific volume of wood, which is converted into wood particles in the manufacture of 1 m^3 of boards, also increases due to the increase in the specific edge area of the manufactured boards.

The effect of wood particles on the human body indicates the need to increase the efficiency of air purifiers. Therefore, cleaning the air of wood particles and preventing environmental pollution is an important social issue. This determines the relevance of further research and development to increase the degree of air purification from wood dust.

At woodworking enterprises, dust collectors of various principles of operation are used to clean the air from wood dust. The efficiency of separation depends on the moisture content, particle size, and performance of the device [4]).

Inertial type purifiers (cyclones) have a simple design and are undemanding to operating conditions. Their disadvantage is a significant reduction in the degree of purification while reducing particle size. Typical dependences of cyclone properties on particle size, productivity, size of cylindrical and conical parts of a cyclone are given in [5].

The paper [6] describes some characteristics of the main types of cyclone collectors used in the woodworking industry and contains their comparative analysis. A new mathematical model of the polluted air flow is created, based on the joint consideration of the Navier-Stokes equations for a viscous compressible liquid (gas), the equation of continuity, state equations and equations of heat balance.

The research [7] analyzed the processes in the cyclone with the horizontal rotational multi-disk after-cleaner. Mathematical models of the dynamics of a two-phase medium of dusty air flow in the working areas of the developed rotational cyclone were developed.

In our opinion, a promising direction in the development of inertial air purifiers from wood dust is the use of active working bodies [8].

Currently, the use of computational hydrodynamics combined with the finite-element method is becoming more widespread. A typical method for solving computational hydrodynamics problems is the numerical solution of the Navier-Stokes equation or the Reynolds equation. For example, the authors of [9] simulated a turbulent gas flow in a Lapp cyclone using the Reynolds equation. Based on the obtained data and using the stochastic Lagrange model, this made it possible to model the motion of the dust-air-flow. The dependence of the particle trajectory (and, consequently, the purification efficiency) on the cyclone entry point was revealed.

In the study [10], a three-dimensional simulation of the flow in the cyclone was conducted using Fluent software. In this case, in particular, the effect of wall roughness on the flow field was studied. The increased wall roughness reduces the vortex length, which significantly reduces the separation efficiency.

To increase the separation efficiency of cyclone purifiers with active working bodies, it is necessary to model the movement of wood particles in the air-flow, which will allow optimizing the values of the design parameters of the purifier. A prerequisite for the implementation of such modeling is to determine the vector field of the air-flow velocity in the purifier.

The aim and objectives of research

The transition area between the housing of the purifier and the active working bodies, in which the axisymmetric flow changes both direction and speed are considered the most difficult to study. At the same time, the processes in the transition area significantly affect the efficiency of separation. This is explained as follows. When wood particles move in the transition area under gravity and resistance, they either slightly change the direction of movement and immediately fall into the storage area of the purifier, or the air-flow is transferred to the active working body. In this body, particles that have a sufficiently large descending velocity component will touch its surface and be carried by the boundary air layer beyond its boundaries, and fall into the exit of the cyclone. As the descending component of the speed is not enough to fall on the surface of the working body, particles will not be caught by it and will pass through the purifier. Therefore, the purpose of this research is to develop a method for determining the radial and vertical components of the vector field of the air-flow velocity in the area between the housing of the purifier and the active working body.

Research methodology

A review of the literature allows concluding that solving the problems of computational hydrodynamics by the method of finite differences or finite volumes in modeling the working process in a cyclone, requires significant computational power. It is worth noting that solving the problem of parametric optimization of the design of the purifier will require multiple repeats of calculations.

To simplify the use of the results of this study for numerical modeling of the movement of wood particles in the purifier, we will try to obtain analytical dependences of the components of the vector field of the flow velocity on the size of the purifier elements and air-flow through it. In this case, we consider the flow of an ideal liquid in the studied area of the purifier and divide it into elementary infinitely thin curvilinear flow tubes. Since within each of them, the flow is constant it will be possible to determine the modulus of the flow velocity at a given point in the area, taking into account the variable cross-sectional area of the flow tube. Determining the tangent to the flow line will allow calculating the required parameters of the vector field of the flow velocity.

Research results

A prerequisite for obtaining the desired dependencies in an analytical form is the use of analytical approximation of flow lines in the transition area of the purifier with active working body (see Fig. 1).

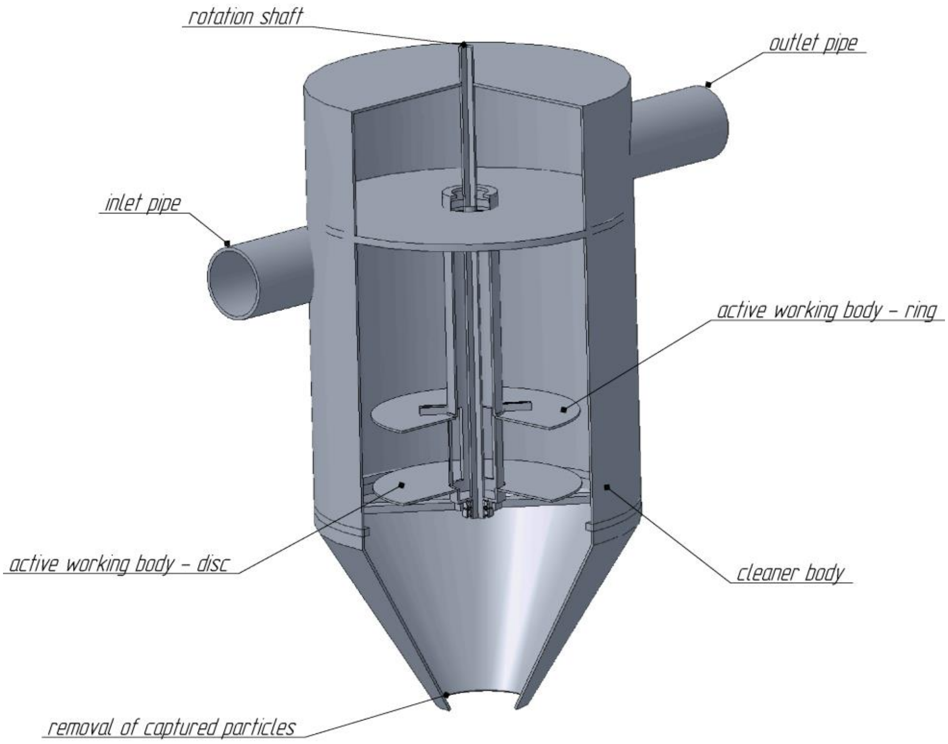

Fig. 1. Air purifier with active working body

Since the review of literature sources did not reveal such approximations, when choosing an approximation, we will pay special attention to the fact that the air-flow changes direction by 90 degrees when moving in the studied area of the purifier. Among the elements of the second-order curves on the plane, the arc of an ellipse has such a property so we will use it to approximate the flow line (see Fig. 2). Dividing the flow in the study area into elementary infinitely thin tubes, where the flow is constant, we will determine the air velocity in the tube taking into account the change in its cross-sectional area.

First of all, we define the equations of the corresponding ellipses. Note that the maximum value of the horizontal half-axis $a_{E\,max}$ is equal to the distance from the edge of the disk to the inner surface of the body of the purifier, and the vertical one $b_{E\,max}$ to the height of the air gap h (see Fig. 2):

$$\frac{(x-x_C)^2}{a_{E\,max}^2}+\frac{(z-z_C)^2}{b_{E\,max}^2}=1\ , \tag{1}$$

$$a_{E\,max}=R_B-R_D\ , \tag{2}$$

$$b_{E\,max}=h\ , \tag{3}$$

where $a_{E\,max}$ is the maximum value of the horizontal half-axis of the ellipse; $b_{E\,max}$ is the maximum value of the vertical half-axis of the ellipse, R_B is the radius of the air purifier housing, R_D is the radius of the active working body.

The eccentricity e of this ellipse is:

$$e = \frac{\sqrt{a_{E\,max}^2 - b_{E\,max}^2}}{a_{E\,max}} \; .. \qquad (4)$$

Determine the flow velocity at the point B (see Fig. 2). To do this, we obtain the equation of the ellipse that passes through this point:

$$\frac{(x - x_C)^2}{a_B^2} + \frac{(z - z_C)^2}{b_B^2} = 1, \qquad (5)$$

where a_B is the horizontal half-axis of the ellipse; b_B is the vertical half-axis of the ellipse.

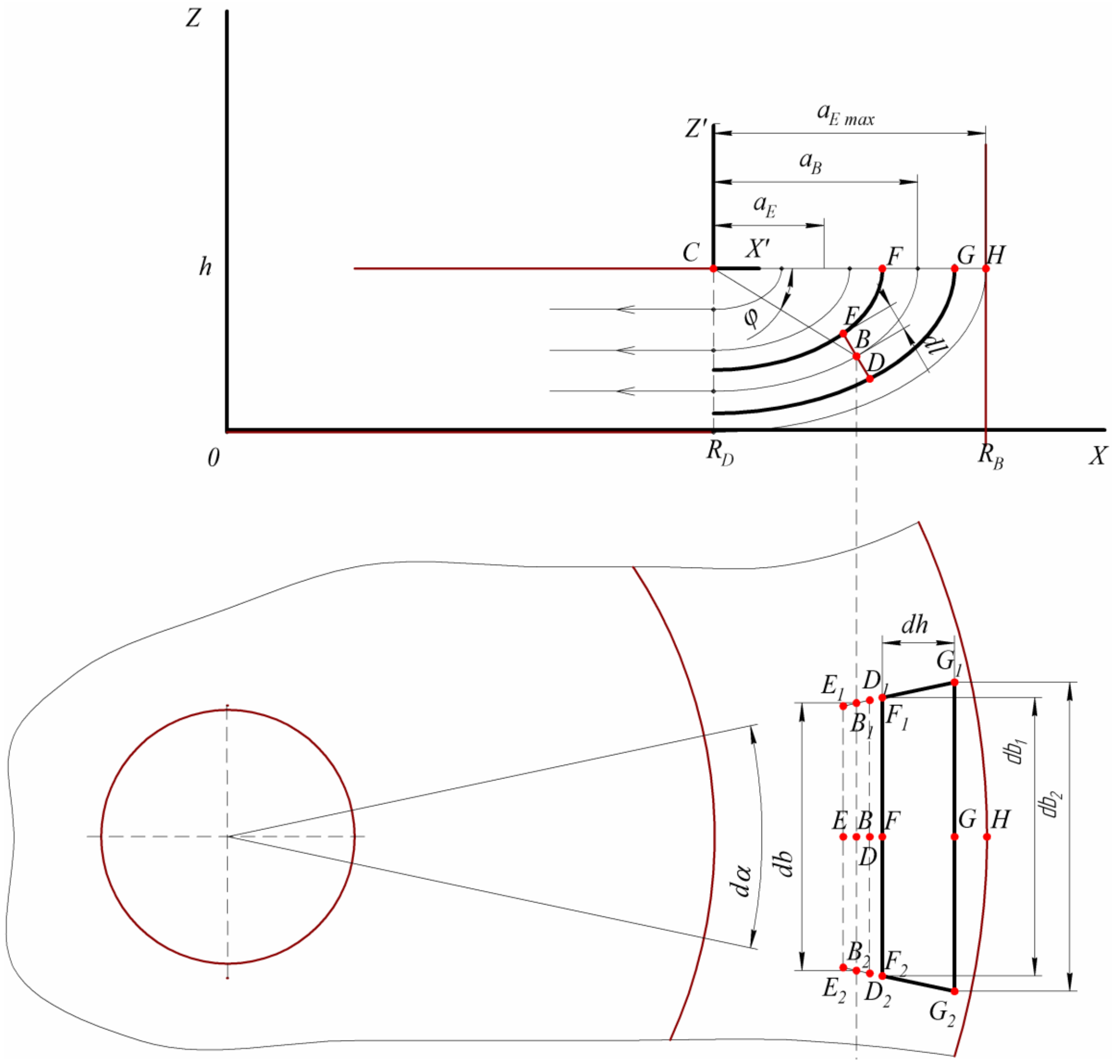

Fig. 2. Flow lines in the transition area of the air purifier with the active working body.

Based on the similarity of the ellipses, they will have the same eccentricity. Therefore,

$$\frac{(x - x_C)^2}{a_B^2} + \frac{(z - z_C)^2}{a_B^2(1 - e^2)} = 1. \qquad (6)$$

Since the ellipse passes through a given point $B(x_B, z_B)$, then:

$$\frac{(x_B - x_C)^2}{a_B^2} + \frac{(z_B - z_C)^2}{a_B^2(1 - e^2)} = 1. \qquad (7)$$

By this equation we find the length of the horizontal half-axis of the ellipse:

$$a_B = \sqrt{(x_B - R_D)^2 + (z_B - h)^2 \frac{(R_B - R_D)^2}{h^2}} . \tag{8}$$

We also determine the vertical axis of the ellipse:

$$b_B = a_B \frac{h}{R_B - R_D} . \tag{9}$$

Since the flow velocity vector is tangent to the flow line, we define the equation of the tangent to the ellipse passing through the point B:

$$z = -\frac{(1-e^2)(x_B - R_D)}{z_B - h} x + \frac{a_E^2(1-e^2)}{z_B - h} + h + \frac{R_D(x_B - R_D)\cdot(1-e^2)}{z_B - h} . \tag{10}$$

To simplify further calculations, we present the equation (10) as follows:

$$z = k_{TS}\, x + c_{TS} , \tag{11}$$

$$k_{TS} = -\frac{(1-e^2)(x_B - R_D)}{z_B - h} , \tag{12}$$

$$c_{TS} = \frac{a_E^2(1-e^2)}{z_B - h} + h + \frac{R_D(x_B - R_D)\cdot(1-e^2)}{z_B - h} , \tag{13}$$

where k_{TS} is the angular coefficient of the tangent to the flow line; c_{TS} is the constant in the equation of the tangent to the flow line.

The equation of the normal to the ellipse at a point B is obtained as the equation of the normal to the tangent, which passes through the specified point:

$$z = -\frac{x}{k_{TS}} + \frac{x_B}{k_{TS}} + z_B . \tag{14}$$

To simplify further calculations, we present the equation (14) as follows:

$$z = k_{NS}\, x + c_{NS} , \tag{15}$$

$$k_{NS} = -\frac{1}{k_{TS}} , \tag{16}$$

$$c_{NS} = \frac{x_B}{k_{TS}} + z_B , \tag{17}$$

where k_{TS} is the angular coefficient of the tangent to the flow line; c_{TS} is the constant in the equation of the tangent to the flow line.

Define a unit vector $\hat{e}_N$ parallel to the normal:

$$\hat{e}_N = \frac{\vec{i} + k_{NS}\vec{k}}{\sqrt{1+k_{NS}^2}} = \frac{1}{\sqrt{1+k_{NS}^2}}\vec{i} + \frac{k_{NS}}{\sqrt{1+k_{NS}^2}}\vec{k} . \tag{18}$$

Define a vector $\vec{\delta}_N$ of infinitesimal displacement dl parallels to the normal to the flow line:

$$\vec{\delta}_N = \hat{e}_N\, dl = \frac{dl}{\sqrt{1+k_{NS}^2}}\vec{i} + \frac{k_{NS}\, dl}{\sqrt{1+k_{NS}^2}}\vec{k} . \tag{19}$$

Using (19), we find the coordinates of the points D and E:

$$x_D = x_B + \frac{dl}{\sqrt{1+k_{NS}^2}} , \tag{20}$$

$$z_D = z_B + \frac{k_{NS}\, dl}{\sqrt{1+k_{NS}^2}} , \tag{21}$$

$$x_E = x_B - \frac{dl}{\sqrt{1+k_{NS}^2}} \ , \quad (22)$$

$$z_E = z_B - \frac{k_{NS}\, dl}{\sqrt{1+k_{NS}^2}} \ . \quad (23)$$

Construct a plane perpendicular to the flow line at a point B (and, consequently, the tangent to this line at a point B). Construct a segment of length db at the intersection of this plane:

$$db = x_B\, d\alpha \ . \quad (24)$$

Determine the area dS_1 of an equilateral trapezoid $E_1E_2D_2D_1$:

$$dS_1 = 2db\, dl \ . \quad (25)$$

Determine the area dS_2 of the trapezoid $E_3E_4D_4D_3$:

$$dS_2 = \frac{db_1 + db_2}{2} dh \ . \quad (26)$$

Determine the flow velocity V_2 in the gap between the active working body and the housing of the purifier:

$$V_2 = \frac{Q_1}{S_2} = \frac{Q_1}{\pi (R_B^2 - R_D^2)} \ . \quad (27)$$

This makes it possible to calculate the flow velocity at a point B, based on the velocity in the gap between the ring and the purifier housing and the ratio of the area of the trapezoid $E_3E_4D_4D_3$ and $E_1E_2D_2D_1$:

$$V_B = V_2 \frac{dS_2}{dS_1} = V_2 \left(\frac{2R_D(a_D - a_E)}{4x_B\, dl} + \frac{a_D^2 - a_E^2}{4x_B\, dl} \right), \quad (28)$$

$$a_D^2 = \left((x_B - x_C) + \frac{dl}{\sqrt{1+k_{NS}^2}} \right)^2 + \frac{\left((z_B - z_C) + \frac{k_{NS}\, dl}{\sqrt{1+k_{NS}^2}} \right)^2}{(1-e^2)}, \quad (29)$$

$$a_E^2 = \left((x_B - x_C) - \frac{dl}{\sqrt{1+k_{NS}^2}} \right)^2 + \frac{\left((z_B - z_C) - \frac{k_{NS}\, dl}{\sqrt{1+k_{NS}^2}} \right)^2}{(1-e^2)}, \quad (30)$$

where V_2 is the flow velocity in the gap between the active working body and the purifier housing.

Using (30), perform the auxiliary transformation required to simplify (28):

$$a_D = \sqrt{(x_B - R_D)^2 + \frac{(z_B - h)^2}{1-e^2}} \times$$

$$\times \sqrt{1 + \frac{2(x_B - R_D) + \frac{2(z_B - h)k_{NS}}{1-e^2}}{\sqrt{1+k_{NS}^2}\left((x_B - R_D)^2 + \frac{(z_B - h)^2}{1-e^2} \right)} dl + \frac{1 + \frac{k_{NS}^2}{1-e^2}}{(1+k_{NS}^2)\left((x_B - R_D)^2 + \frac{(z_B - h)^2}{1-e^2} \right)} dl^2} \ . \quad (31)$$

For further simplification (31), we decompose it into the Maclaurin series and limit ourselves to the first two elements of the series:

$$a_D \approx \sqrt{(x_B - R_D)^2 + \frac{(z_B - h)^2}{1-e^2}} \times$$

$$\times \left(1 + \frac{(x_B - R_D) + \dfrac{(z_B - h)k_{NS}}{1-e^2}}{\sqrt{1+k_{NS}^2}\left((x_B - R_D)^2 + \dfrac{(z_B - h)^2}{1-e^2} \right)} dl + \frac{1 + \dfrac{k_{NS}^2}{1-e^2}}{2(1+k_{NS}^2)\left((x_B - R_D)^2 + \dfrac{(z_B - h)^2}{1-e^2} \right)} dl^2 \right). \qquad (32)$$

Convert (30) in a similar way:

$$a_E \approx \sqrt{(x_B - R_D)^2 + \frac{(z_B - h)^2}{1-e^2}} \times$$

$$\times \left(1 - \frac{(x_B - R_D) + \dfrac{(z_B - h)k_{NS}}{1-e^2}}{\sqrt{1+k_{NS}^2}\left((x_B - R_D)^2 + \dfrac{(z_B - h)^2}{1-e^2} \right)} dl - \frac{1 + \dfrac{k_{NS}^2}{1-e^2}}{2(1+k_{NS}^2)\left((x_B - R_D)^2 + \dfrac{(z_B - h)^2}{1-e^2} \right)} dl^2 \right). \qquad (33)$$

Determine the flow velocity from (28) taking into account (29. 30. 32, 33):

$$V_B = V_2 \sqrt{1 + \frac{(R_B - R_D)^4 (z_B - h)^2}{h^4 (x_B - R_D)^2}} \left(1 + \frac{R_D}{x_B} \cdot \left[\frac{1}{\sqrt{1 + \dfrac{(R_B - R_D)^2 (z_B - h)^2}{h^2 (x_B - R_D)^2}}} - 1 \right] \right). \qquad (34)$$

To simplify the (34), we introduce an auxiliary function f_B:

$$f_B(x_B, z_B) = \frac{(R_B - R_D)^2 (z_B - h)^2}{h^2 (x_B - R_D)^2} \ . \qquad (35)$$

Using the (34) we simplify (35):

$$V_B(x_B, z_B) = \frac{Q_1}{\pi (R_B^2 - R_D^2)} \sqrt{1 + \frac{(R_B - R_D)^2}{h^2} f_B(x_B, z_B)} \left(1 + \frac{R_D}{x_B} \cdot \left[\frac{1}{\sqrt{1 + f_B(x_B, z_B)}} - 1 \right] \right). \qquad (36)$$

Using (36), determine the radial and vertical components of the flow velocity. To do this, define a unit vector $\hat{e}_T$ parallel to the tangent to the flow line at the point:

$$\hat{e}_T = \frac{\vec{i} + k_{TS}\vec{k}}{\sqrt{1+k_{TS}^2}} = \frac{1}{\sqrt{1+k_{TS}^2}} \vec{i} + \frac{k_{TS}}{\sqrt{1+k_{TS}^2}} \vec{k} \ , \qquad (37)$$

$$k_{TS} = \frac{h^2 (x_B - R_D)}{(R_B - R_D)^2 (h - z_B)} \ . \qquad (38)$$

Therefore, taking into account the direction of the flow, we obtain the dependences for determining the radial V_r and vertical V_v components of the flow velocity:

$$V_r(x_B, z_B) = -\frac{V_{Bcor}(x_B, z_B)}{\sqrt{1+k_{TS}^2}} \ , \qquad (39)$$

$$V_v(x_B, z_B) = -V_{Bcor}(x_B, z_B) \frac{k_{TS}}{\sqrt{1+k_{TS}^2}} \ . \qquad (40)$$

Conclusions

1. In this research, the analytical dependences of the vertical and radial components of the vector field of the air-flow velocity in the transition area between the housing and the active working body of the air purifier are obtained. The following simplifications were used: flow lines were approximated by ellipse arcs; the flow of an ideal liquid was considered.

2. A promising direction of further research is to determine the tangential component of the vector field of the air-flow velocity in the transition area. This will allow to model the movement and determine the trajectories of wood particles, which is necessary for determining the efficiency of separation and optimization of the design parameters of the purifier with an active working body.

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