ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2013, Vol. 2, No. 2, 09–16

Mathematical model of dust cleaning process in centrifugal-inertial dust collector

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Received February 5.2013: accepted March 26.2013

Abstract. The article is devoted to the problem of providing air cleaning from dust in various industries, using highly efficient apparatus, with the aim of bringing the volume of harmful emissions to the sanitary standards. The article presents new directions in creating of dust cleaning apparatus, based on the usage of centrifugal, inertial forces, by which the efficiency of dust collection could be significantly increased.

Key words: dust collecting , air cleaning, pollution, centrifugal, cyclone

Statement of the problem. An extremely important factor that affects the territorial organization of all socio-economic life and production efficiency are ecological environmental conditions, which have significantly deteriorated in the past decades in Ukraine. One of the main factors that affect the ecological environment, is the development of industry in outdated technologies and related excessive urbanization of many areas. The fundamental tenets of sustainable human development are based on an understanding of the close relationship between environmental, economical and social problems, which in turn leads to the unification of scientific achievements of the leading specialists from academic institutions involving market problems and economic-environmental studies. Thus, it is not only and not so much about a new direction in environmental science, but also about a new direction in the overall system of worldview and understanding of the latest issues of man and nature interaction, the recognition of man's and society's places in the nature, their sustainable development. It appears, that the only way to improve technological and environmental safety is the ecological education of the whole society and improvement of algorithms of actions with emergency response, using management international standards, especially the ISO 14001 and ISO 9000 [1,2].

Techno-genic stress in Ukraine is characterized not only by high level of impact on the environment, but also by its variety. Fatal cases and injuries during accidents and emergency situations of techno-genic character in Ukraine occur 5-8 times more often than in other industrialized European countries, indicating serious shortcomings and state system's developmental impairments in environmental and technological safety progress. And in this number of issues a significant contribution is made by enterprises, which emit a tremendous amount of environmental harmful substances and dust. That is why the problem of cleaning air from dust is one of the main goals of environmentalists around the world. The main role in solving this problem is given to the development of highly efficient dust collectors.

The analysis of recent research shows a significant risk for the environment and human health from dust substances' emissions that worsen ecological environment, cause premature wear of industrial equipment as well as of housing and utility objects, harm human health. In 2012, the average concentration of dust (undifferentiated composition) exceeded environmental safety standards in 23 cities of Ukraine [3, 4].

At present, a particularly acute problem is that of capturing fine dust, which due to its low density is dissipated and moves over long distances with flows of air. Complication of dust cleaning systems along with raising demands on their performance requires the adoption of specific measures to develop a highly efficient dust collecting apparatus.

Raising requirements for clean air lead to the necessity of improving the means and apparatus of dust collecting [6-8]. The conducted analysis has proved that currently there is no apparatus capable of highly effective capture of fine fraction dust, while the need for its allocation out of dusty flow is imperative.

The purpose of this work is localization of environmental threat of air pollution from dust, generated by manufacturing industry, which causes negative consequences for the environment.

Exposition of basic material. Dust cleaning belongs to the aerodynamic classification category of problems. In the flow distribution a material's particle is affected by two forces: mass force and power of flow, in different directions. Mass force depends on the density, acceleration and volume, namely on the third degree of characteristic particle diameter. Power of flow, however, depends on the resistance coefficient, on the dynamic pressure, caused by the relative velocity between the particle and carrying medium and the particle's square cut. For the resistance coefficient the most important is Reynolds number [5]. Thus, in case of simplified division, if we neglect the transition area, two zones are formed: - at low Reynolds numbers for the power of flow Stokes' law is valid and at high ones - quadratic resistance law.

In the practice of mathematical modeling of processes of aerodynamic classification, the most widespread are the so-called deterministic and stochastic models. The basis of deterministic models makes an idea of the process as a motion of non-interacting particles in a stationary flow of gas. Deterministic models allow for evaluation of the basic factors' influence on several division characteristics (the equilibrium particle's size, in some cases - limit size), but do not allow to obtain the calculated expressions for distribution curves, whose creation is possible only on the basis of stochastic models of classification processes, taking into account the cumulative effect of environmental random impacts on each particle.

From foregoing material it is implied that both deterministic and stochastic models of processes' classification do not take into account the structure of turbulent dusty flow and material particles of different granulometry motion specificity. Currently, the theoretical basis for creation of dust collection apparatus is designed from the standpoint of airflow and single particle interaction without consideration of air velocity pulsating components and scale of vortex structures in flow's transporting medium, that must be considered to ensure the adequacy of mathematical models, which describe the work of equipment, including classification of materials.

The small-weight particles motion process under the action of centrifugal force in turbulent flow consists of two processes: the continuous motion of particles, in direction to cyclone wall inside pulsating moles, carrying them, and the chaotic as to direction, frequency and amplitude motion of particles along with pulsating fields, carrying them [9-12].

In the viscous sub-layer, directly adjacent to the wall, the role of viscous stresses is dominant in comparison with turbulent stresses. Therefore, decisive parameters in the viscous sub-layer are fluid's kinematic viscosity coefficient v and dynamic velocity (friction velocity) u *. Outside the area of viscous sub-layer the role of viscous stresses in the continuous medium is rather insignificant. As the simplest approximation of carrying flow's pulsating structure in the near-wall area let us take the simplest dual-zone model (Gusev and Zajchyk, 1991), consisting of the viscous sub-layer with zero intensity pulsations and turbulent zone with constant intensity pulsations:

$$\left\langle u'_i u'_j \right\rangle = A_{ij} u_*^2 H(y-\delta).,\tag{1}$$

where: y - distance from the wall, A_{ij} - constants. Viscous sub-layer thickness δ is:

$$\delta = \delta + \frac{v}{u_*}, \ldots \delta_+ = const.\tag{2}$$

It is also assumed, that the scale of turbulence near the wall has a constant value:

$$T_L = T_+ \frac{v}{u_*^2}, \ldots T_+ = const.\tag{3}$$

Next we accept, that particles' averaged slide as to carrying flow is relatively small, so the influence of the effect of crossing trajectories for the period of particles' and turbulent whirlwinds' interaction can be neglected. Since we do not consider the reverse impact on carrying flow and particle collision, the equations system, which includes mass conservation equations, quantity of motion balance, for other moments of particles' velocity pulsations (dispersed phase turbulent stresses), the tensor of turbulent diffusion of particles splits: the concentration of Φ and intensity of transverse pulsations (v'^2_y) can be found independently from other hydrodynamic characteristics of the dispersed phase. For hydro-dynamically - developed flow, whose properties vary only in its normal direction, upon the absence of particles deposition, the following equations to determine Φ and Φ i (v'^2_y):

$$\Phi \frac{d\left\langle \upsilon'^2_y \right\rangle}{dy} + \left(\left\langle \upsilon'^2_y \right\rangle + g_u A_{yy} u_*^2 H(y-\delta) \right) \frac{d\Phi}{dy} = 0.\tag{4}$$

In accordance with the experimental data it will take $A_{yy} = 1$ and proceed to dimensionless variables:

$$\tau_p^2 \frac{d}{dy}\left[\Phi \left(\left\langle \upsilon'^2_y \right\rangle + g_u A_{yy} u_*^2 H(y-\delta) \right) \frac{d\left\langle \upsilon'^2_y \right\rangle}{dy} \right] +$$

$$+ 2\Phi \left(f_u A_{yy} u_*^2 H(y-\delta) - \left\langle \upsilon'^2_y \right\rangle \right) = 0,\tag{5}$$

$$\left\langle \upsilon'^2_{y_+} \right\rangle = \frac{\left\langle \upsilon'^2_y \right\rangle}{u_*^2},\ \ \lambda = \frac{y}{\delta} = \frac{y_+}{\delta_+},\ \ y_+ = \frac{y u_*}{v},$$

$$\tau_* = \frac{\tau_p u_*}{\delta} = \frac{\tau_+}{\delta_+},\ \ \tau_+ = \frac{\tau_p u_*^2}{v}.$$

Equations (3.13) and (3.14) in new variables take the form:

$$\Phi \frac{d\left\langle \upsilon'^2_{y_+} \right\rangle}{d\lambda} + \left(\left\langle \upsilon'^2_{y_+} \right\rangle + g_u H(\lambda - 1) \right) \frac{d\Phi}{d\lambda} = 0,\tag{6}$$

$$\tau_*^2 \frac{d}{d\lambda}\left[\Phi\left(\left\langle \upsilon'^2_{y_+}\right\rangle + g_u H(\lambda-1)\right)\frac{d\left\langle \upsilon'^2_{y_+}\right\rangle}{d\lambda}\right] + 2\Phi\left(f_u H(\lambda-1) - \left\langle \upsilon'^2_{y_+}\right\rangle\right) = 0. \quad (7)$$

Boundary conditions for (6) and (7) upon the absence of particles' deposition on the wall, are set in the form:

$$\tau_* \frac{d\left\langle \upsilon'^2_{y_+}\right\rangle}{d\lambda} = 2\frac{1-e_y^2}{1+e_y^2}\left(\frac{2\left\langle \upsilon'^2_{y_+}\right\rangle}{\pi}\right)^{1/2} \text{ with } \lambda = 0;$$

$$\frac{d\left\langle \upsilon'^2_{y_+}\right\rangle}{d\lambda} = 0, \ \Phi=1 \text{ with } \lambda = \infty. \quad (8)$$

Neglecting the influence of particles inertia during their interaction with turbulent whirlwinds, we put T_{Lp} equal to the Lagrangian scale, where we take $T_+ = \delta_+$. Then the involvement coefficients are:

$$f_u = \frac{1}{1+\tau_*}, \ g_u = \frac{1}{\tau_*(1+\tau_*)}.$$

Taking into account the (6), equation (7) can be transformed to the form:

$$\tau_*^2\left(\left\langle \upsilon'^2_{y_+}\right\rangle + g_u H(\lambda-1)\right)\frac{d^2\left\langle \upsilon'^2_{y_+}\right\rangle}{d\lambda^2} + 2\left(f_u H(\lambda-1) - \left\langle \upsilon'^2_{y_+}\right\rangle\right) = 0, \quad (9)$$

that allows to find (v'^2_{y+}) irrespective from Φ. Let us construct solution of the equation (3.18) in areas 0 < λ < 1 и 1 < λ < ∞, and then "staple" them.

In the area of viscous sub-layer (0 <λ <1) equation (9) reduces to:

$$\left\langle \upsilon'^2_{y_+}\right\rangle\left(\frac{d^2\left\langle \upsilon'^2_{y_+}\right\rangle}{d\lambda^2} - \frac{2}{\tau_*^2}\right) = 0. \quad (10)$$

The solution of (10), considering (8) will be:

$$\left\langle \upsilon'^2_{y_+}\right\rangle = 0 \text{ with: } 0 < \lambda < \lambda_0, \ \left\langle \upsilon'^2_{y_+}\right\rangle = \frac{(\lambda-\lambda_0)^2}{\tau_*^2}$$

$$\text{with: } \lambda_0 < \lambda < 1. \quad (11)$$

$$\left\langle \upsilon'^2_{y_+}\right\rangle = \left\langle \upsilon'^2_{y_+}(0)\right\rangle + \frac{2(1-e_y^2)}{\tau_*(1+e_y^2)}\left(\frac{2\left\langle \upsilon'^2_{y_+}(0)\right\rangle}{\pi}\right)^{1/2}\lambda + \frac{\lambda^2}{\tau_*^2}$$

$$\text{with: } 0 < \lambda < 1. \quad (12)$$

The solution of (11) takes place in case $\tau_* < \tau_{cr}$, and (12) is realized in case $\tau_* > \tau_{cr}$. Critical value τ_{cr} of inertia parameter τ_* is a bifurcation point and corresponds to the condition $\lambda_0 = 0$. In turbulent area (1 <λ <∞,) the equation (3.18) is written as:

$$\tau_*^2 \frac{d^2\left\langle \upsilon'^2_{y_+}\right\rangle}{d\lambda^2} + \frac{2\left(f_u - \left\langle \upsilon'^2_{y_+}\right\rangle\right)}{\left(\left\langle \upsilon'^2_{y_+}\right\rangle + g_u\right)} = 0\,. \quad (13)$$

To construct the analytical solution, let us linearize (13) taking in the denominator of the second term: $(v'y^2) = (v'y^2 (1))$. As a result, we obtain the approximate solution:

$$\left\langle \upsilon'^2_{y_+}\right\rangle = \left(\left\langle \upsilon'^2_{y_+}(1)\right\rangle - f_u\right)\exp\left[-\frac{2^{1/2}(\lambda-1)}{\tau_*\left(\left\langle \upsilon'^2_{y_+}(1)\right\rangle + g_u\right)^{1/2}}\right] + f_u$$

$$\text{with: } 1 < \lambda < \infty. \quad (14)$$

Solutions' stapling terms in viscous and turbulent zones appear as:

$$\left\langle \upsilon'^2_{y_+}(1)\right\rangle\left(\frac{d\left\langle \upsilon'^2_{y_+}\right\rangle}{d\lambda}\right)_{1-0} = \left(\left\langle \upsilon'^2_{y_+}(1)\right\rangle + g_u\right)\left(\frac{d\left\langle \upsilon'^2_{y_+}\right\rangle}{d\lambda}\right)_{1+0}. \quad (15)$$

From (11), (14) i (15) and (15) we derive the ratio for finding out: $(v'^2_{y+}(1))$ and λ_0 at $\tau_* < \tau_{cr}$:

$$\lambda_0 = 1 - \tau_*\left\langle \upsilon'^2_{y_+}(1)\right\rangle^{1/2}. \quad (16)$$

From (12), (14) i (15) we derive the ratio for finding out $(v'^2_{y+}(1))$:

$$\left(f_u - \left\langle \upsilon'^2_{y_+}(1)\right\rangle\right)\left(\left\langle \upsilon'^2_{y_+}(1)\right\rangle + g_u\right)^{1/2} =$$

$$= \left\langle \upsilon'^2_{y_+}(1)\right\rangle\left[\frac{2^{1/2}}{\tau_*} + \frac{2(1-e_y^2)}{\pi^{1/2}(1+e_y^2)}\left\langle \upsilon'^2_{y_+}(0)\right\rangle^{1/2}\right],$$

$$\left\langle \upsilon'^2_{y_+}(0)\right\rangle^{1/2} = -\frac{1-e_y^2}{\tau_*(1+e_y^2)}\left(\frac{2}{\pi}\right)^{1/2} +$$

$$+\left[\frac{2(1-e_y^2)^2}{\pi(1+e_y^2)^2\tau_*^2} + \left\langle \upsilon'^2_{y_+}(1)\right\rangle - \frac{1}{\tau_*^2}\right]^{1/2}. \quad (17)$$

A critical parameter of inertia is determined from the ratio $\tau_{cr}^{\ 2}(v'^2_{y+}(0\ 1$, which does not depend on recovery momentum coefficient $\boldsymbol{e}_y$ and is equal to 2,81.

Distribution of particles concentration, that satisfies the condition Φ (∞) = 1, is determined by the integral of equation (6) and described by the expression:

$$\Phi = \begin{cases} \left\langle \upsilon'^2_{y_+}(1)\right\rangle\left[\tau_*\left(\left\langle \upsilon'^2_{y_+}(1)\right\rangle + g_u\right)\left\langle \upsilon'^2_{y_+}\right\rangle\right]^{-1} & .\lambda < 1, \\ \left[\tau_*\left(\left\langle \upsilon'^2_{y_+}\right\rangle + g_u\right)\right]^{-1} & \lambda > 1. \end{cases} \quad (18)$$

Figure 1 shows the distribution of transverse velocity pulsations (v'_{y+}) and the concentration of particles that correspond to [10, 11, 13, 15], [16] and [17] by elastic collisions with the wall: $(e_y = 1)$, [10-13].

It is seen, that with increase of particles' inertia intensity of their speed pulsations increasingly deviates from the intensity pulsations in solid medium (1) and tends to a homogeneous distribution. The concentration of particles near the wall rises sharply, their accumulation in the viscous sub-layer area is observed. The phenomenon of accumulation of particles in inhomogeneous turbulent flows is explained by their turbulent migration (turboforez) from the area with high intensity of turbulent velocity pulsations to the area of low turbulence (particularly, to the viscous sub-layer on the surface that flows around). The theoretical interpretation of this phenomenon was given by Caporaloni et al (1975) and Reeks (1983).

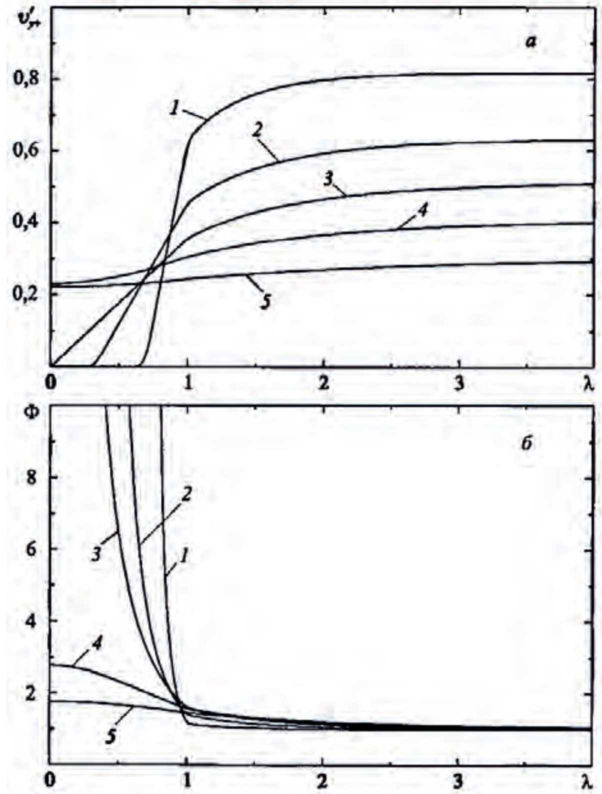


Fig. 1. The distribution of transverse velocity pulsations (a) and concentration (b) of particles in the near-wall area

Figure 2 illustrates the effect of particles' inertia on the values of velocity pulsations intensity and on concentration of particles on the wall.

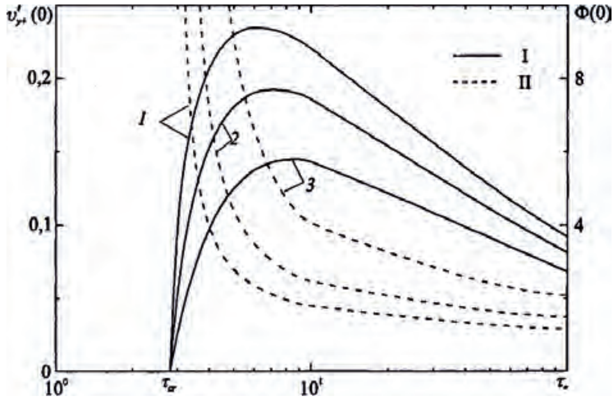


Fig. 2. The dependence of velocity fluctuations intensity (I) and particles' concentration (II) on the wall on the inertia parameter: 1 — e_y = 0,5; 2 — e_y = 0,8; 3 — e_y =- 1,0

As can be seen, pulsating energy of low inertial particles on the wall is zero, and the pulsations' intensity of inertial particles is different from zero. The effect of non-zero velocity pulsations on the viscous sub-layer and on the wall itself is due to diffusion mechanism of pulsations' transfer by mean of inertial particles from turbulent flow area. Attention is drawn to the availability of maximum in dependence of $v'_{y+}(0)$ from τ. Increasing of $v'_{y+}(0)$ along with rising of τ is explained by an increase of role of pulsations' diffusion transfer from turbulent area into the zone of viscous sub-layer. Reduction of $v'_{y+}(0)$ along with rising of τ after reaching the maximum is connected with decrease of intensity of velocity's pulsations in the dispersed phase, as more inertial parts are less engaged into turbulent motion of homogenous medium.

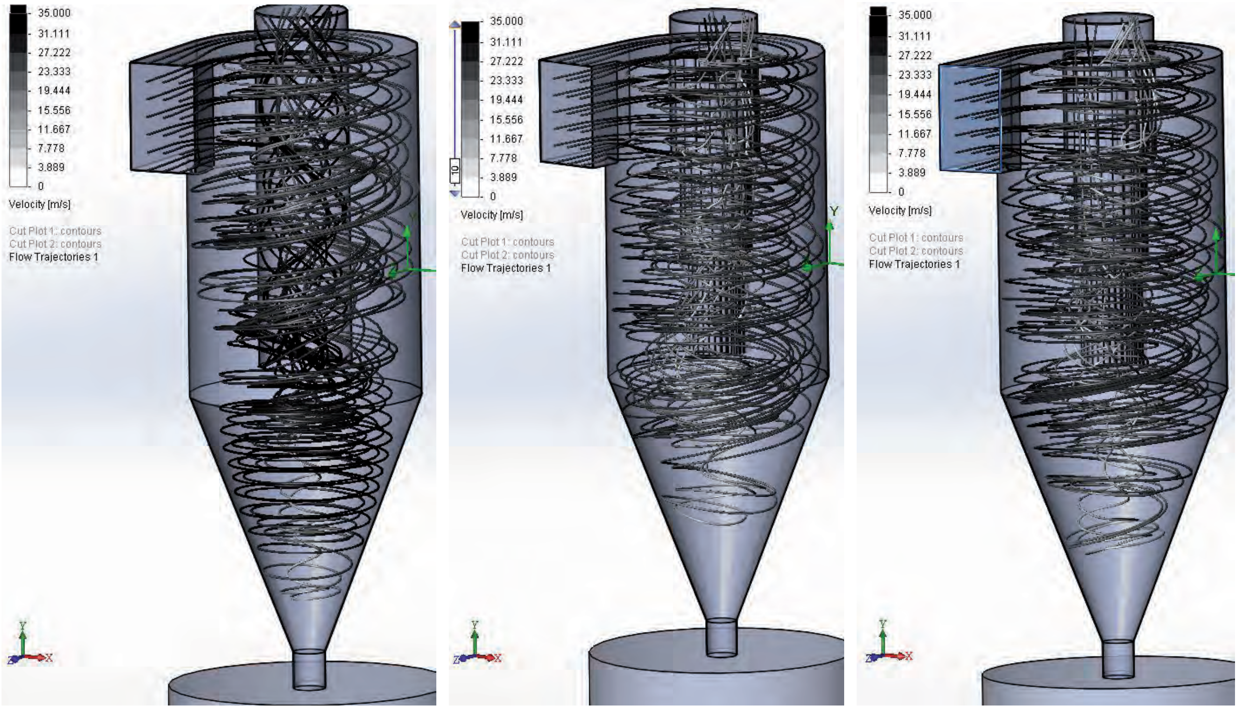
The concentration of particles on the wall tends to infinity $\tau < \tau_{cr}$ and tends to the unity at $\tau \to \infty$. With a decrease of impulse restitution coefficient e_y the intensity of pulsations falls, and the particles' accumulating effect in the viscous sub-layer slightly increases.

The analysis of pulsations' velocity intensity and of particles' concentration on the wall at different values of inertia parameter (particles' size) allow for a new design of inertial-centrifugal dust collector with changing angle of blinds attack as well as enables a more detailed study of air flow motion in an apparatus and the rejection of obviously failed designs at the stage of their development

Modeling will be conducted using the software package FlowVision from "TESYS" company [15]. For the research a solid model design with the following dimensions has been developed: diameter of cylindrical part – 0,5m; height of the cylindrical part – 0,75m; height of the conical part – 0,56m; dust outlet diameter – 0,07m; inlet height– 0,23m; inlet width – 0,15m; exhaust pipe diameter – 0,2m. Three variants of dust collector performance were considered. The first one - with three-cascade jalousie separator, with varying angle of blinds attack. Such jalousie separator is closed from the bottom side. The second one has the same blind's separator, but opens from the bottom side. If compared with traditional apparatus, the third model is performed with a traditional exhaust pipe.

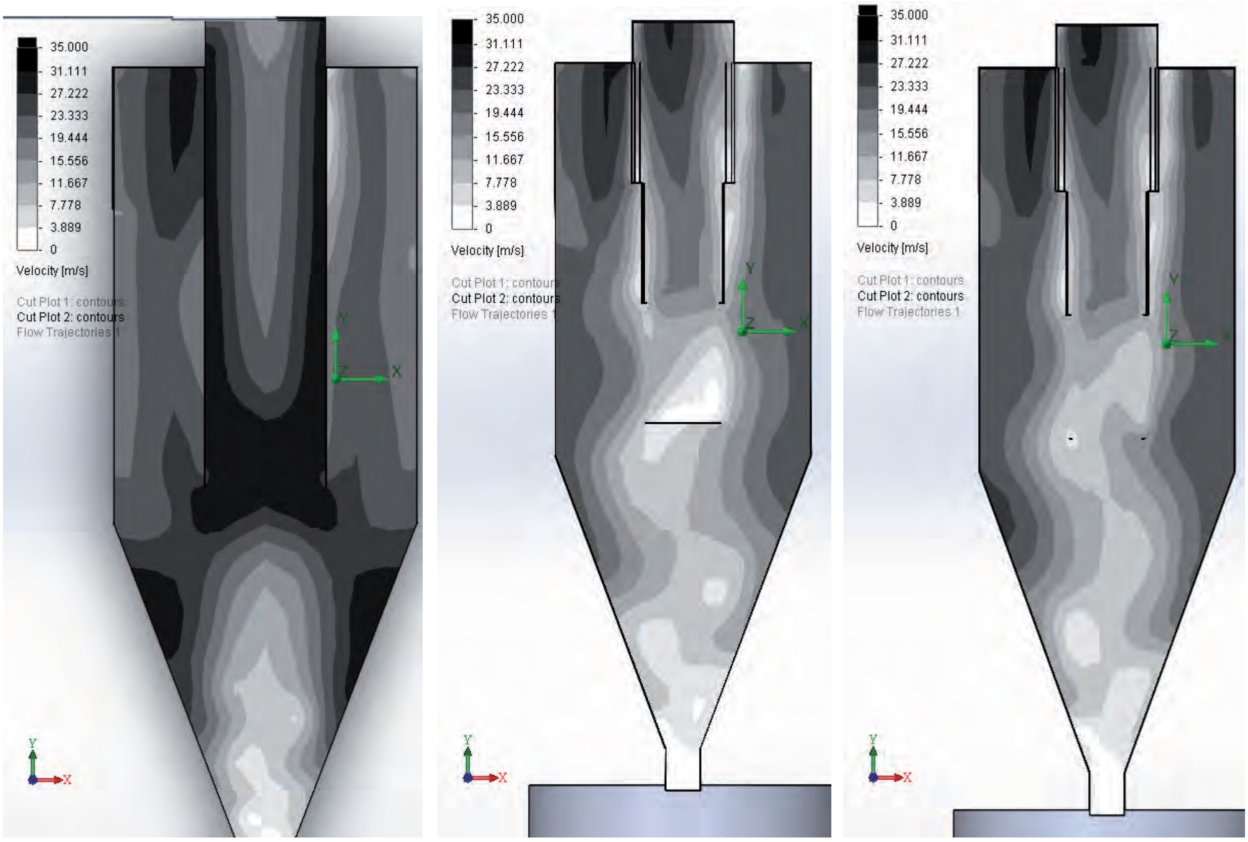
Figure 3 shows the trajectory of the air flows in apparatus of three designs.

The conducted analysis makes it possible to describe the aerodynamics of cyclone process in the new apparatus more precisely. Air flow gets into a dust collector through the tangential inlet pipe. Air flow velocity is 18m / s, which is the recommended value for this class of devices. Then the flow starts to rotate in the space between the exhaust pipe (Fig. **3**.a) or jalousie separator (Fig. 3 b, c) and the outer wall of the device, moving down. In the conical part of the device the flow makes a turn of 180 °, than rises and, continuing to rotate, goes out into the atmosphere. The negative feature of traditional cyclone with exhaust pipe is that near its lower edge air flows with high velocities are observed (Fig.3.a). Fine fast-response dust particles will be captured by these flows and, through the exhaust pipe, will get into the atmosphere. When jalousie separator is used, the air flow fills the cylindrical part of the device more evenly (Fig.3.b, c). In numerous publications a decisive influence of the cyclone's cylindrical part on the air purification



a b c

Fig. 3. Trajectories of air flow in a cyclone



a b c

Fig. 4. Distribution of airflow velocity' values

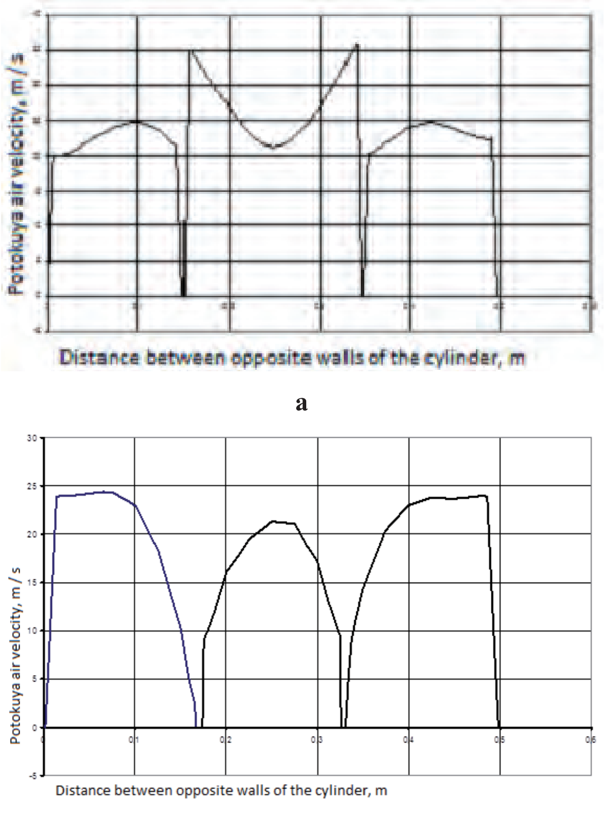
efficiency is indicated. Therefore, we will consider, what would be the distribution of airflow velocities and static pressure value in dust collector.

Figure 4 shows the distribution of the air flow absolute velocity's value at each section point, which passes through the cyclone axis. In the near-wall zone of the cyclone with jalousie separator the air flow velocity value is more uniform. Availability of traditional exhaust pipe causes numerous changes in velocity's value (Fig.2.a).

It is especially necessary to note the flow velocities in conical part. The use of jalousie separator of the developed design allows for a significant reduction of the value of air velocity in the cone. This will eliminate the ability of capturing dust particles by rising air flows and will help to improve the air purification efficiency [16,19].

Figure 5 shows the diagram of the airflow velocity changes in cross section, located in the middle of the cylindrical part of the apparatus. On the abscissa axis - the distance between opposite walls of the cylindrical part. For 0 the position on the left wall is accepted. The opposite wall corresponds to position 0.5 m. In the apparatus with traditional exhaust pipe air flow velocity value in separation zone varies in the range from 20 to 25m / s (Fig. 5 a). Close to cylindrical part walls and to exhaust pipe the velocity, due to adhesion, decreases to 0 m / s. In separation zone of apparatus with jalousie separator of suggested design f air low velocity is distributed more evenly (Fig. 4. b, c) and is about 24 m/s (Fig.5.b).

It is a positive fact that at its maximum level the obtained air velocity brings it close to the outer wall. Herewith the dust particle is affected by constact centrifugal force, which does not decrease with particle's moving away from the cyclone axis, as it is observed in the devices with traditional pipe.



a

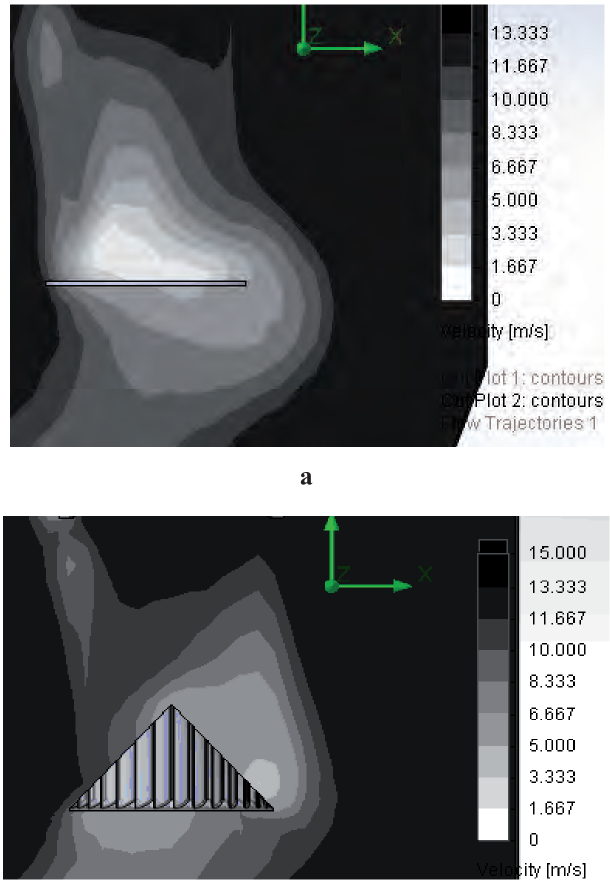
b

Fig. 5. Distribution of airflow velocity in horizontal section of cyclone

Application of jalousie separator of the developed design positively influences the air cleaning process. Air flow enters the separator throughout its height, and therefore plots of high velocity air do not form [17]. Due to the jalousie attack angle's change, throughout the whole height of jalousie separator the air flow velocity values are uniform and equal to about 3 m/s.

In the cyclone with bottom closed jalousie separator airflow velocities close to 0 m / s are observed. This will contribute to accumulation of fine dust in these areas. To eliminate this phenomenon it is recommended to perform the conical bottom of jalousie separator. Distribution of air flow velocities near such bottom is shown in Figure 4.b. 4.6

In separational zone of the cyclone with conventional exhaust pipe, the static pressure drop is about 2000 Pa (Fig.7.a). Using jalousie separator of the suggested design reduces pressure drop to 350 Pa (Fig.7.b, c). Reducing static pressure drop helps to reduce the amount of air involved in secondary flows. This creates the preconditions to increase dust collector's efficiency.

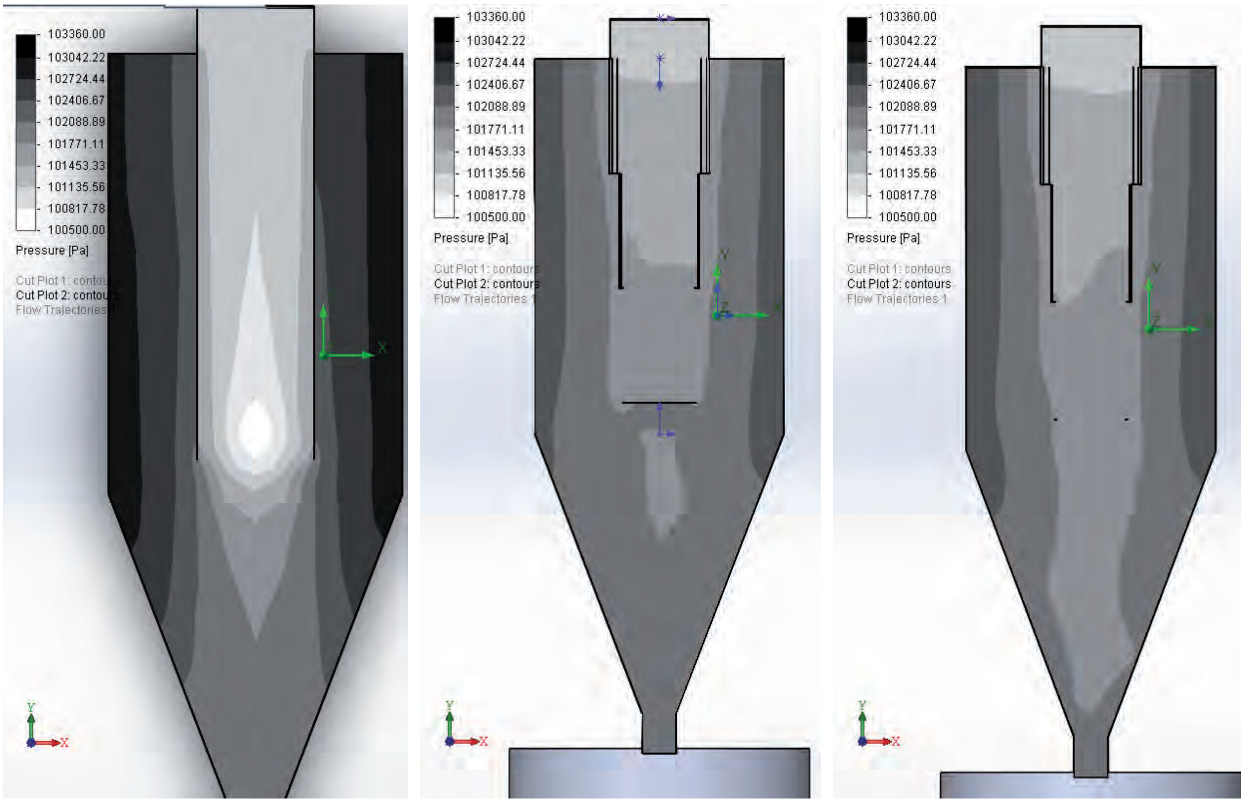


a

b

Fig. 6. Air flow's speed values near the bottom of jalousie separator

Conclusions. By creating a range of dust collectors we managed to obtain a significant increase (6 - 8%) of fine dust catching efficiency (8 and 16) 10^{-6}m, if compared with the standard - Cyclone CN-11along with reducing



a b c

Fig. 7. Distribution of static pressure values

the hydraulic resistance and metal consumption (smaller dimensions). The first type apparatus, where the small increase of performance have been achieved, anyway at 1-2% is of higher efficiency than standard unit [18-20].

Having created a range of dust collecting apparatus, we were able to meet the needs of a number of industries (in compliance with the requirements of MCL), hence depending on the dust type and technological conditions of production, the most appropriate for these requirements type of dust collector, for which we have created an automated system (using a computer), can be chosen.

Currently, the implementation of a number of suggested dust collectors to be used in wood processing, rubber waste's processing, cement production, manufacturing industry, is taking place.

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