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Minimization of Energy Consumption of Vortex Devices for Granulation of Materials

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Abstract: The article considers the possibility of efficient energy and environmental use of vortex devices for the granulation of solids. The factors influencing the energy consumption for generating a vortex flow with dispersed solid inclusions are analysed. A mathematical model for calculating the aerodynamic drag of a vortex apparatus in a clean gas flow, which was used in computer modelling, is presented. The main dependencies for determining the influence of the geometric dimensions of the vortex on its aerodynamic drag are also given. An analytical solution to the problem of minimising the aerodynamic drag of a vortex apparatus during the movement of a dispersed medium is considered. The forces acting on the particles in the cyclone chamber during interaction with the gas are analysed. In this paper, a general method for calculating the parameters of cyclone-vortex devices for dispersed media using the basic equations of hydrodynamics and gas dynamics is developed. The solution approach used in this paper can be extended to other vortex devices not considered in this work.

Keywords: aerodynamic drag, cyclone, vortex device, pelletising, medium dispersion factor, optimal geometric dimensions

1. Introduction

The creation of new cyclone-vortex devices, such as bladeless nozzle devices, more efficient dust cyclones for cleaning all types of gases from dust, creation of high-temperature cyclone combustion chambers, rational vortex burners with different types of swirlers, vortex devices for creating granular thermal insulation materials requires the use of a method for calculating cyclone-vortex devices (Pavlenko & Koshlak 2021, Browand 1983, Koshlak & Pavlenko 2020).

At present, cyclone-vortex devices are widely used in industry, in which bladed and bladeless swirlers swirl gas. These are vortex burners, cyclone furnaces, centrifugal nozzles, dust-cleaning cyclones, vortex tubes for cold production, and bladeless nozzles of axial and radial turbines.

Depending on the purpose, all vortex devices are differentiated by their design forms. Therefore, there is a wide variety of calculation methods, each of which is specific to only one device, and most of the available calculation methods are based on the use of experimental generalisations, the application of which is limited by the conditions of the experiments, and often the calculation results differ significantly from the experimental data. This situation hinders the creation of new, more efficient designs of cyclone-vortex devices, hinders the development of automated methods for their calculation, requires additional material costs for refinement, and requires highly qualified personnel for calculation and design. Therefore, it is of considerable practical and scientific interest to develop a unified method for calculating cyclone-vortex devices, which would allow generalising the available extensive experimental material on the parameters of cyclone-vortex devices, making improvements and being able to create optimal designs of cyclone-vortex devices.

The work aims to develop a unified theory for the calculation of cyclone-vortex devices in which a dispersed medium moves, with the help of which to generalise the available experimental material, based on which to develop new, more advanced engineering methods for calculating existing and newly developed cyclone-vortex devices with optimal dimensions.

2. Literature Review

The determination of analytical dependencies that relate the parameters of vortex devices in which a dispersed medium flow to their geometric dimensions is of considerable interest since it eliminates additional costs for conducting experiments and also makes it possible to understand better the physical essence of the processes occurring in vortex devices and to select their optimal dimensions that provide the specified parameters.

An important issue in the study of the processes of creating granular materials in vortex devices is the formation of symmetry of the vortex flow, which is usually achieved by increasing the number of outlets (Koshlak & Pavlenko 2019). Work (Pavlenko & Koshlak 2015) investigated the formation of an axisymmetric vortex ring by pulsed liquid pushing through a cyclone chamber. An idealised model of circulation, momentum, and energy was developed that ensures the symmetry of the forces of a multicomponent mixture. It is proved that the boundary vortex is "optimal" because it has maximum momentum, circulation, and volume for a given input energy. In (Golubtsov 1975), a mathematical model for calculating gas flow in a vortex apparatus, a granulator, is proposed. Based on the analysis of flows in granulators, it is concluded that any particle that enters the working space of a vortex granulator interacts equally with the swirling gas flow along the height of the chamber, which eliminates the slippage of individual particles and prevents the formation of stagnant zones in the vortex chamber. In (Kubin & Ladislas 1992), the velocity fields of the dispersed medium in the vortex apparatus were analysed. It is proved that the formation of turbulence in apparatus and devices with rotating flows is allowed by an effectively viscous medium model.

It is proved that the main reason for the intensification of swelling processes is that the process takes place in a dispersed medium, so hypothetically, the process of heat treatment of particles in a vortex flow significantly accelerates production compared to firing in a drum furnace (Zhu et al. 2022, Pavlenko et al. 2005). It is concluded that turbulent vortices in the furnace space significantly impact heat transfer processes and the possibility of controlling the pressure field by changing the geometric characteristics of the object under the conditions of unambiguousness of the mathematical model.

One of the main criteria that affects the economic feasibility of using vortex devices for foaming thermal insulation pellets is the aerodynamic drag of the vortex device. It should be borne in mind that, unlike the traditional method of blowing porous granules of heat-insulating material, when using vortex devices, it is necessary to consider the need for additional energy costs to overcome the aerodynamic resistance of the vortex granulator.

3. Problem Statement

Energy consumption for forming a material pellet in the vortex apparatus will include two components: the energy consumption for heating the dispersed medium and the energy consumption for creating and ensuring the statics of this system

$$Q = Q_{gr} + Q_{gas}$$

where:
Q_{gr} – energy consumption for heating the dispersed medium,
Q_{gas} – energy expenditure for creating and ensuring the statics of this system.

For the simplest case of binary feed mixture with components labelled 1 and 2, the energy taken by the material particles is determined from the differential equation of energy transfer and depends on the thermophysical characteristics of the mixture itself

$$C_p \rho \frac{dT}{d\tau} = div(\lambda \nabla T) + div(DcQ \cdot \nabla c_{10}) + (h_1 - h_2)I_1 + (C_{p1} - C_{p2})J_1 \nabla T$$

where:
C_p – isobaric heat capacity,
c – volume concentration,
$C_p c = C_{p1} c_1 + C_{p2} c_2$,
$div(\lambda \nabla T)$ – energy transfer by heat conduction,
$div(DcQ^* \nabla c_{10})$ – thermodiffusion,
$(h_1 - h_2)I_1$ – chemical potential,
$\left(C_{p1} - C_{p2}\right)J_1 \nabla T$ – enthalpy transfer due to diffusion,
Q^* – specific heat of isothermal transport.

In this case, energy spent for the creation and providing of static aerodynamic flow in the vortex chamber will be directly proportional to the aerodynamic drag

$$Q_{gas} = \zeta \cdot \overline{v_0} \cdot \frac{\overline{\rho}}{2}$$

where:
ζ – is the cyclone hydraulic resistance coefficient related to the velocity in the entire cyclone cross-section,
v_0 – the conditional velocity of the mixture in the cyclone,
$\overline{\rho}$ – is the average density of the mixture in the cyclone.

Minimisation of energy costs of universal vortex apparatuses for granulation of various materials will consist in minimisation of hydraulic resistance coefficient of cyclone

$$Q = f(\zeta) \rightarrow min.$$

Thus, the problem supply is reduced to the investigation of intensive drying of wet dispersed materials in a vortex flow, with a significant change of dispersed material volume from temperature. It is known that due to the presence of the solid phase in the flow, the drag of the swirling chamber is reduced because the fine fraction of particles suppresses isotropic turbulence (Lobanov 2013). Different models can account for the effects of fine-scale turbulence, but the most suitable turbulence model for vortex apparatuses is k-ε turbulence model (Stremlera et al. 2011, Domfeh et al. 2020).

In order to calculate the total losses of the vortex apparatus on pure flow, we relate their values to the dynamic pressure in the inlet nozzles and then, taking the losses as independent, sum up on all zones for the flow core and consider losses on friction against the wall, bottom and cover (Seraya & Demin 2012, Shanmugharaj & Rhee 2006, Tager 1971).

The total aerodynamic drag coefficient of the cyclone will be

$$\zeta = \zeta_{in} + \zeta_k + \zeta_W \quad (1)$$

where:
ζ_{in} – is the aerodynamic resistance of the inlet spigot,
ζ_k – the aerodynamic resistance of the chamber,
ζ_W – loss of aerodynamic drag against the wall.

Aerodynamic resistance of the chamber

$$\zeta_k = \zeta_A + \zeta_B^{'} + \zeta_B^{''} \quad (2)$$

where:
ζ_A – of aerodynamic drag of the main vortex zone,
$\zeta_B^{'}$ – of aerodynamic resistance of the initial vortex zone,
$\zeta_B^{''}$ – of aerodynamic resistance of the outlet nozzle.

The energy equation for the inlet cross-section corresponding to the outlet and the radius of the initial twist will be as follows

$$P_{in} + \frac{\rho_{in} W_{in}^2}{2} - \zeta_{in} \frac{\rho_{in} W_{in}^2}{2} = P_k + \frac{\rho_k W_k^2}{2} \quad (3)$$

where:
ρ – density,
W – radial flow velocity.

By the loss factor ζ_{in} we consider losses on vortex formation, friction against walls and static pressure recovery due to gas cooling

$$\zeta_{in} = \zeta_0 + \xi \frac{l}{d_{in}} - \zeta_T \quad (4)$$

where:
ζ_0 – is the coefficient of local losses,
ζ_T – friction loss coefficient.

The value of the coefficient of local losses depends on the gas-dynamic perfection of the flowing part of the inlet branch pipe and is determined by blowing on cold models (for different shapes of branch pipes). The coefficient of friction losses, depending on the roughness of walls and flow regime in inlet branch pipes, is a reference.

After transformation of the energy equation considering mass velocity recovery factor η and pressure for isothermal input $T_{in} = T_K$ we obtain

$$\zeta_K = \frac{P_{in}-P_K}{\frac{1}{2}\rho_{in}W_{in}^2} = \zeta_{in} - 1 + \frac{\eta^2}{\sigma_K} \tag{5}$$

where:
η – mass recovery factor,
σ_K – coefficient considering the unevenness of velocities in the chamber.

For the main vortex zone, integrating the law of change of velocity from pressure, we obtain

$$\zeta_A = \frac{P_k - P_1}{\frac{1}{2}\rho_{dx}W_{dx}^2} = \frac{\eta^2}{\sigma_K}\left[\frac{\left(\frac{R_k}{r_1}\right)^2 - 1}{\eta\left(\frac{2\cdot\pi\cdot H\cdot R_k}{m\cdot f_k}\right)^2} + \frac{2\cdot\left(\frac{R_K}{r_1}\right)^{2\cdot(k-1)} - 1}{2(k-1)}\right] \tag{6}$$

where:
R_k – the vortex chamber radius,
k – number of inlets for gas supply.

For the initial section of the vortex zone at $r_c < r \le r_1$ we obtain

$$\zeta_B' = \frac{P_1 - P_C}{\frac{1}{2}\rho_{in}W_{in}^2} = \frac{P_k\cdot\eta^2}{P_{in}}\left\{\frac{1-\left(\overline{\psi}\frac{r_C}{r_1}\right)}{\left(2A\frac{l_C}{R_k}\eta\right)^2} + \left(\frac{R_k}{r_1}\right)^{2(k-1)}\cdot\ln\left(\frac{r_1}{r_C}\right)^2\right\} \tag{6a}$$

where:
$A_0 = \frac{\pi\cdot K_C^2}{m f_K}$.

In the general case, when the nozzle is implemented as a nozzle with various auxiliary elements, e.g. to straighten the flow, it is necessary to consider the losses in the nozzle, which can be determined experimentally. If the nozzle is implemented as a hole in the cyclone bottom, then $\zeta_C = 0$, since the losses with the outlet are accounted for by the formula for ζ_B''.

The task will be to improve this analytical calculation of the aerodynamic drag of vortex apparatus for two-phase dispersed flow.

4. Analytical Solution of the Problem of Minimization of Aerodynamic Resistance of Vortex Apparatus When Disperse Medium Moves

For analytical investigation of aerodynamic processes in vortex apparatus at motion of disperse flow, it is necessary to consider forces that act on particles of disperse phase. Let us represent these particles as spherical granules in a disperse flow medium. Let's introduce physical quantity that allows taking into consideration resultant forces acting on spherical granule – dispersion factor of dispersion medium $rad\alpha_1$.

Coefficient of dispersion of medium $rad\alpha_1$ describes the deviation of the absolute velocity vector W_1 from the plane perpendicular to the rotation axis. Dispersivity coefficient of the medium $rad\alpha_1$ is determined by using the principle of minimum drag coefficient

$$\frac{\partial\xi_{ent}'}{\partial\, rad\,\alpha_1} = 0 \tag{7}$$

where:
α_1 – the angle equal to the deviation of the absolute velocity vector from a plane perpendicular to a rotation axis.

The dispersion coefficient of the medium will be equal to

$$rad\ a = \frac{180 \cdot \sum f'}{\pi R_0' R_n} \frac{1}{4\varepsilon} \frac{\left(1+\frac{m_0}{m_0'}\right)^2}{\left(\varepsilon' \pm \frac{M_0}{M_0'}\right)} \cdot \frac{T_1}{T_0^{/}} \tag{8}$$

where:
M_0 – momentum of the quantity of motion at the inlet to the cyclone chamber from the flow of spigots into the chamber,
m_0 – mass flow rate through the inlet spigots to the cyclone chamber,
ε – coefficient of initial momentum loss in the cyclone chamber,
R_0' – radius of the vortex apparatus in the cross-section of the chamber inlet,
R_n – vortex radius,
T_1 – temperature of the medium at the vortex chamber outlet,
$T_0^{/}$ – temperature of the medium at the inlet to the vortex chamber,
$\sum f'$ – total area of inlets to the vortex chamber.

Equation (7) will take the form

$$\xi_{ent}' = \left[\frac{1}{\phi \frac{R_n}{R_0'} \frac{\left(1+\frac{m_0}{m_0'}\right)}{\varepsilon\left(\varepsilon' \pm \frac{M_0}{M_0'}\right) \cdot \frac{T_0^{/}}{T_1} \cdot \sqrt{2 \cdot \frac{T_1}{T_0^{/}} - 1}} \left(1 - \frac{a}{tg\ rad\ \alpha_1}\right) cos\ rad\ \alpha_1} \right]^2 = \left[\frac{R_0' \varepsilon \left(\varepsilon' \pm \frac{M_0}{M_0'}\right) \cdot \frac{T_0^{/}}{T_1} \cdot \sqrt{2 \cdot \frac{T_1}{T_0^{/}} - 1}}{\phi R_n \left(1+\frac{m_0}{m_0'}\right)} \right]^2 \cdot [(1 - actgrad\ \alpha_1)\ cos\ rad\ \alpha_1]^2 \tag{9}$$

where:
ϕ – is the coefficient of velocity loss in the inlet spigots.

Assuming that ϕ и ε constants, the first derivative of this equation will be

$$\frac{\partial \xi_{ent}'}{\partial\ rad\ \alpha_1} = -2 \left(\frac{\varepsilon}{\phi} \frac{R_0'}{R_n} \frac{\varepsilon\left(\varepsilon' \pm \frac{M_0}{M_0'}\right) \cdot \frac{T_0^{/}}{T_1} \cdot \sqrt{2 \cdot \frac{T_1}{T_0^{/}} - 1}}{\left(1+\frac{m_0}{m_0'}\right)} \right) \cdot [(1 - actg\ rad\ \alpha_1)\ cos\ rad\ \alpha_1]^{-3} \cdot \left[-sin\ rad\ \alpha_1 (1 - actg\ rad\ \alpha_1) + \frac{a}{sin^2\ rad\ \alpha_1} cos\ rad\ \alpha_1 \right] \tag{10}$$

After transformations, equation (10) is transformed to the form

$$\frac{\partial \xi_{ent}^{'}}{\partial rad\ \alpha_1} = \frac{2\left(\frac{\varepsilon R_0^{'}}{\phi R_n} \frac{\varepsilon\left(\varepsilon^{'} \pm \frac{M_0}{M_0^{'}}\right)\cdot\frac{T_0^{/}}{T_1}\cdot\sqrt{2\cdot\frac{T_1}{T_0^{/}}-1}}{\left(1+\frac{m_0}{m_0^{'}}\right)}\right)\cdot\left[-\sin rad\ \alpha_1(1-actg\ rad\ \alpha_1)+\frac{a}{\sin^2 rad\ \alpha_1}\cos rad\ \alpha_1\right]}{[(1-actgrad\alpha_1)\cos rad\ \alpha_1]^3}. \qquad (11)$$

Considering that the main kinetic energy of turbulence belongs to large vortices (Pavlenko & Koshlak 2015) and that disperse impurity significantly reduces the turbulence energy, the turbulence energy of large vortices can be accounted for through the vortex drag.

When considering the interaction of gas with a particle located in a cyclone chamber, the same approach as in the case of free-fall of a particle is applied. Considering that the particle located in the cyclone chamber is affected by centrifugal force (since the particle rotates together with the flow around the vertical axis of the cyclone chamber), the role of weight forces here is played by centrifugal forces, which lead to the appearance of the radial velocity of the particle W_r. The flow resistance balances the centrifugal force, and the particle moves from the centre to the periphery of the cyclone with speed W_r by inertia.

When a laminar flow surrounds a particle with diameter d, the drag force will be determined:

$$Rs = \frac{24}{Re\frac{\pi\cdot d^2}{4}\frac{\rho\cdot {W_r}^2}{2}} \qquad (12)$$

where:
Re – Reynolds number,
d – particle diameter,
ρ – particle density.

Since the product of $\rho \cdot \nu = \mu$ – to the coefficient of dynamic viscosity, the drag force at the flowing of a ball body by laminar flow will be determined by the equation expressing Stokes's law, i.e.

$$Rs = 3 \cdot \pi \cdot d \cdot \mu \cdot W_r. \qquad (13)$$

The condition of balancing of centrifugal force by drag forces is written in the following form:

$$F_c = \frac{m\cdot W_{ui}^2}{2} = Rs = 3 \cdot \pi \cdot d \cdot \mu \cdot W_r, \qquad (14)$$

where:
m – the mass of the particle rotating around the axis at a distance R_i with speed W_{ui}, where the speed of a ball of mass $m = \frac{\pi\cdot d^3}{6} \cdot \rho_m$ will be determined by the following expression.

$$W_{ri} = \frac{d^2\cdot W_{ui}\cdot\rho_m}{18\cdot R_i\cdot\mu}. \qquad (15)$$

Determination of average particle velocity in radial direction

$$W_r = \frac{1}{R_c - R_f}\int_{R_f}^{R_c} W(r)dr \qquad (16)$$

where:
c – chamber,
f – friction,
a – middle,
m – center.

Assuming the linear law of change W_r in the direction from R_f to R_m, average velocity in radial direction can be determined

$$W_r = \frac{W_{rf}+W_{rm}}{2} \qquad (17)$$

where according to (15)

$$\begin{cases} W_{rf} = \frac{d^2 \cdot W_{uf}^2 \cdot \rho_m}{18 \cdot \mu \cdot R_f} \\ W_{rm} = \frac{d^2 \cdot W_{uf}^2 \cdot \rho_m}{18 \cdot \mu \cdot R_m} \end{cases}. \tag{18}$$

Where from

$$W_r = \frac{d^2 \cdot \rho_m}{36 \cdot \mu} \cdot \left(\frac{W_{uf}^2}{R_f} - \frac{W_{um}^2}{R_m} \right) \tag{19}$$

Assuming the law of twisting along the radius in the cyclone chamber $W_u \cdot r$ = const, we obtain

$$W_{uf} = W_{ua} \cdot \frac{R_a}{R_f}, \tag{20}$$

$$W_{um} = W_{ua} \cdot \frac{R_a}{R_m}. \tag{21}$$

Replacing in (18) W_{uf} and W_u with their values from (20) and (21), we will obtain the mean value of the velocity at particle motion from the tube radius to the chamber wall:

$$W_r = \frac{d^2 \cdot \rho_m}{36 \cdot \mu} \cdot W_{ua}^2 \cdot R_a^2 \cdot \frac{R_m^3 + R_f^3}{R_f^3 \cdot R_m^3}. \tag{22}$$

According to Fig. 6 we have (considering that W_{1r} is radial velocity component, m/s, W_{1a} – axial velocity component, m/s, W_1 – absolute velocity of particles in dispersed mixture, m/s)

$$L = \left(R_m - R_f \right) \cdot tg\beta \tag{23}$$

where:
$tg\beta = \frac{W_{1a}}{W_r}$,
$L = \frac{R_m - R_f}{W_r} \cdot W_{1a} = \tau \cdot W_{1a}$.

The length of the vortex chamber required for pelletising of particles with diameter d_{min} is determined by the following dependence

$$L_c = \frac{9D_c^2}{\varepsilon^2} \cdot \frac{\mu}{\rho_m} \cdot \frac{\frac{\Sigma f}{\pi \cdot R_0 \cdot R_f \cdot \cos\beta} \cdot \left(\frac{R_f}{R_c} \right)^4}{W_0 \cdot \frac{R_0}{R_c} \cdot \left[1 + \frac{R_f}{R_c} + \left(\frac{R_f}{R_c} \right)^3 + \left(\frac{R_f}{R_c} \right)^4 \right] \cdot d_{min}^{2\cos\beta}} \tag{24}$$

The following expression will determine the relative length of the vortex chamber

$$\frac{L_c}{D_c^2} = \frac{9}{\varepsilon^2 \sqrt{\frac{2\Delta P}{\rho}}} \cdot \frac{\mu}{\rho} \cdot \frac{\frac{\sum f}{\pi \cdot R_0 \cdot R_n \cdot \cos\beta}}{\phi_0 \left(1 - \frac{\sum f}{\pi \cdot R_0 \cdot R_n \cdot \cos\beta} \cdot \frac{1}{4 tg\alpha_1} \cdot \frac{1}{\varepsilon} \right) \cdot \cos\alpha_1} \cdot \frac{\left(\frac{R_{тр}}{R_{ц}} \right)^4}{\left[1 + \frac{R_{тр}}{R_{ц}} + \left(\frac{R_{тр}}{R_{ц}} \right)^3 + \left(\frac{R_{тр}}{R_{ц}} \right)^4 \right] \cdot d_{min}^2} \tag{25}$$

The coefficient of losses against the wall, considering (6), can be determined from the relation

$$\zeta_W = \frac{L_c \cdot R_k \int_0^{2\pi} \tau_{\phi 0} d\phi}{m \cdot f_k \cdot \frac{1}{2} \bar{\rho}_{in} W_{in}^2}, \tag{26}$$

where:
$\bar{\rho}_{in}$ – average density of the mixture at the chamber inlet,
f_k – chamber sectional area,
m – mass of the particle rotating around the axis,
$\tau_{\phi 0}$ – the angle of deviation of the vector of absolute flow velocity from the plane perpendicular to the rotation axis at the chamber inlet.

Using the known total pressure loss coefficient and considering the found length of the vortex chamber, determine the gas flow rate through the cyclone. Since $\Delta P = P_{Out} - P_{in} = \zeta \frac{\rho_{in} W_{in}^2}{2}$, $W_{in} = \frac{G}{\rho_{in} m \cdot f_K}$, then if we introduce a flow coefficient $\mu = \frac{1}{\sqrt{\zeta}}$, we obtain $G = \mu \cdot m \cdot f_K \sqrt{2 \cdot \Delta \rho_{in}}$.

According to (27), calculations for cyclones operating at a pressure drop of 800 Pa on mixtures of different dispersion compositions and different densities were made (Fig. 1). The figure shows that the dust with a size of 20 microns and more reaches the cyclone chamber wall already at its beginning and finer fractions – at longer length. The material loading parameters were taken as follows: gas at a speed of 20 m/s and a temperature of 272°C is fed to the side branch pipes, and air of 2 m/s with particles of the studied material is fed to the upper branch pipes. The material flow rate through both nozzles is 0.1 kg/s. The initial particle temperature was assumed to be 22°C.

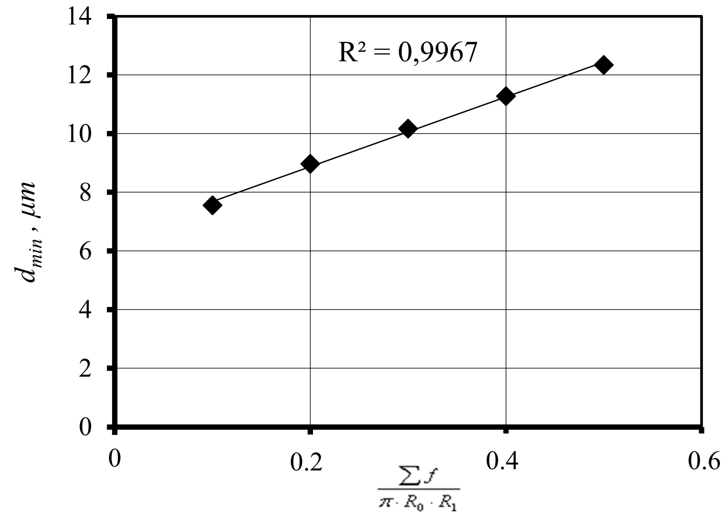

Fig. 1. Variation of particle diameter d_{min} across the complex $\frac{\sum f}{\pi \cdot R_0 \cdot R_1}$

Using computer modelling by finite element method, we calculate the aerodynamic drag of the vortex apparatus for each geometrical parameter separately since the independence of different zones was shown earlier. The optimisation criterion is the minimum aerodynamic drag of the apparatus. The optimisation methodology is adopted according to (Mulligan et al. 2016, Wu et al. 2012).

In (Wu et al. 2022, Yamasaki 2022, Yohana 2022, Yuge et al. 2021), the authors prove that three-dimensional modelling is based on time and space discretisation. It includes the main features related to crystallographic slip, dislocation dynamics, and long- and short-range interactions of dislocation segments.

Figure 2 shows the computer simulation results of the flow pressure distribution in the vortex apparatus. As the velocity of this flow increases, an increase in its twisting radius is observed up to a certain value. When the velocity is close to the flow velocity through the side spigots, the flows mix in the wall area of the chamber and move as one whole flow, but this increases the radius of the backflow zone. For this reason, the flow velocity of the particle inlet flow was chosen to be small to reduce the back current. During modelling, it was also found that increasing the flow rate in the side branch pipes decreases the residence time of particles in the vortex apparatus. The residence time of particles in the flow increases with increasing flow rate due to reduction of flow energy and, consequently, reduction of velocity.

Having built vortex apparatuses of different geometric sizes, let us determine the dependence of change in the total aerodynamic resistance when increasing the diameter of the vortex apparatus inlet nozzles.

As a model on which the calculation was checked, a vortex apparatus with a cylindrical part height of 1100 mm, diameter of 504 mm, nozzle height of 300 mm, nozzle diameter of 200 mm, and diameter of inlet nozzles 34 mm was taken. The total internal volume of the vortex apparatus is 0.1 m^3. The diameter of the inlet spigots should be selected at a minimum but acceptable for optimum air flow rate. As shown in Fig. 3, the variation of total aerodynamic drag obtained by computer simulation is sufficiently close to the analytical values (divergence less than 10%). That confirms the correctness of the analytical dependencies.

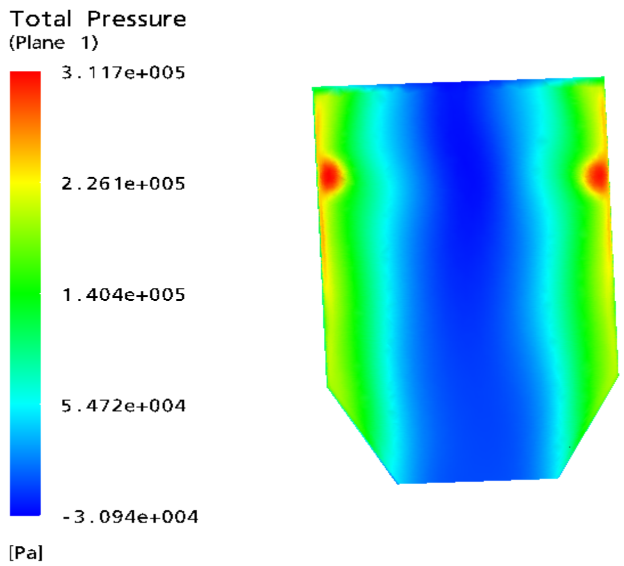

Fig. 2. Distribution of flow pressure over the cross-section of the vortex apparatus

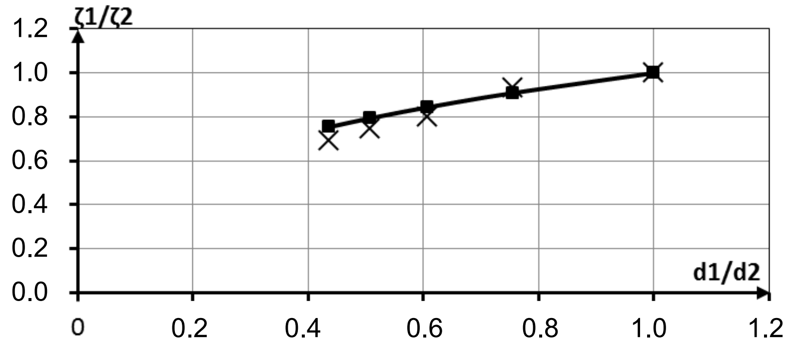

Fig. 3. Dependence of resistance ζ on changes in the diameter of inlet spigots according to the analytical dependences (solid line) and the results of computer simulation (cross): ζ1, ζ2 – the ratio of the total resistance of the inlet pipes for gas supply and the vortex chamber, d1, d2 – the diameter of the inlet pipe for gas supply and the diameter of the vortex chamber

From the point of view of minimising the aerodynamic drag, the nozzle height should be approximately equal to its diameter, and the nozzle diameter should be equal to 0.55 of the diameter of the swirl chamber. The optimum ratio of the height of the swirl chamber to its diameter is 0.9-1.2.

5. Conclusions

The article provides a comprehensive analysis of the issue of minimising the energy costs of vortex apparatuses for pelletising materials, the geometric and aerodynamic parameters of the dispersed medium in the vortex chamber and shows the influence of the flow on the aerodynamic parameters of the chamber itself.

The organisation of motion of dispersed flows in vortex apparatuses has been considered. Two options have been considered: computer simulation of the flow in the vortex apparatus and analytical solution of the equation of motion of the dispersed multicomponent medium, which allowed us to find the length of the vortex chamber required for particle diameter d_{min} pelletising.

The computer simulation results analysis showed that the maximum circumferential and radial particle velocities along the radius of the swirl chamber exceed the maximum flow velocities.

The developed dependences on calculating aerodynamic drag can be recommended for practical application in designing and operating vortex apparatuses for pelletising materials, as well as determining their energy consumption for the drive of blower machines.

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