Mathematical and computer models of the gas flow movement near the shaped cover of the rough grinding machine

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Abstract. The aim of the study is to improve working conditions for operators of grinding machines by ensuring sanitary standards for dustiness in the workplace. To achieve the goal, it is necessary: to develop a mathematical model for the dispersion of abrasive-cast iron dust when grinding fragile parts; mathematical and computer models of the aspiration of the rough grinding machine; to propose an engineering method for calculating the efficiency of a cover in the form of a built-in casing and the choice of elements of a dust removal and dust collection system for grinding machines of the class under discussion. The article presents the mathematical and computer models of aspiration of a roughing-grinding machine, implemented in modern software Ansys. The dependencies, describing the flows of velocity fields in the closed area of the grinding wheel are obtained, which influence the formation of flow lines near the shaped cover of the roughing-grinding machine, which will make it possible to determine the efficiency of the cover of the roughing-grinding machine, including the design stage in future.

1. Introduction
In the process of grinding, two dust streams (flames) are formed at the touch point between the parts and the grinding wheel. The first stream moves tangentially to the circumference of the grinding wheel (direct flame), the other flow is directed along the grinding wheel itself (reverse flame) (figure 1). The shape and direction of these dust streams can be seen from the firing lines generated by the grinding machine.

Figure 1. Dust streams formed during grinding process. 1 - cover, 2 - grinding wheel; 3 - direct flame; 4 - invisible part of the flame, 5 - reverse flame; 6 - workpiece in progress; 7 - dust intake.
When grinding without cooling, the main stream of dust particles has the shape of a wedge and is directed towards the rotation of the grinding wheel (figure 1). Wedge angle \( \phi \) - deviation of the main flow from the workpiece surface to be processed, depends on cutting conditions and on the physical and mechanical properties of the processed material [1].

The maximum efficiency of dust collection of abrasive metal dust during grinding can be achieved if the design features of the dust collector are observed, taking into account the direction of movement of dust particles, as well as the possibility of adjusting the design of the dust collector when the grinding wheel is worn out. It is important that the dust collector is organically connected with the protective casing of the grinding machine. Fencing-dust collectors with accumulators are considered perfect if they require slightly less air for effective dust extraction, due to the use of the kinetic energy of chips and dust flying away (figure 2) [2,3].

Figure 2. Dust collector fencing scheme for a grinding machine with a coarse dust accumulator. 1 - coarse dust accumulator; 2 - suction branch pipe; 3 - channel; 4 - partition; 5 - casing; 6 - damper to prevent dust from entering the workplace.

The efficiency of dust collection and the safety of the grinding process largely depend on the design parameters of the protective dust collector casing. The protective casing must meet certain requirements: the material of the casing must have maximum strength, preventing damage of the casing when the grinding wheel breaks; the cover area of the grinding wheel should be maximum, but not interfering with the processing of the workpiece; the ability to adjust the position of the casing along the spindle axis, taking into account the service wear of the wheel; the use of the casing as a dust collector taking into account the movement of the direction of dust flows; the possibility of attaching a dust collection device to the casing as the first stage of cleaning [2,3].

2. Mathematical model of aerodynamic calculation of the grinding machine shaped cover aspiration

As initial equations the Navier-Stokes and heat transfer equations are taken, as well as the boundary conditions [4-13]. The main equations of the process of interaction of ventilation flows are [4-13].

Continuity equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0, \tag{1}
\]

where \( x_i \) - i-spatial coordinate, m.

Equation of moments (motion):

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left( \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right) + G_i \tag{2}
\]

Heat transfer is determined by the equation:
\[
\frac{\partial (\rho h)}{\partial t} + \frac{\partial (\rho u_i h)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \mu \frac{\partial h}{\partial x_i} \right) + Q,
\]

where \( Q \) - heat source function, W/m\(^3\).

Energy equation for calculating temperature characteristics:
\[
\frac{\partial (\rho T)}{\partial t} + \frac{\partial (\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \frac{k}{c_p} \frac{\partial T}{\partial x_i} \right),
\]

here \( \rho \) – density, \( P \) – pressure, \( u_i \)– velocity vector components, \( T \) – temperature, \( x_i \)– coordinates, \( \mu \)– viscosity, \( c_p \)– specific heat, \( k \)– thermal conductivity; \( G_1 = -\rho \cdot g \) - gravity component; \( h \) – enthalpy.

When using the \( k-\omega \) equation turbulence models (1)-(2) are transformed to the form (4), in which the influence of fluctuation in the average velocity (in the form of turbulent kinetic energy) and the process of reducing this fluctuation due to viscosity (dissipation) are added.

Two additional equations for the transport of the kinetic energy of turbulence and an equation for the rate of dissipation of turbulent energy are also added (5)-(6).

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \left( \frac{\mu + \frac{\mu_t}{\sigma_{k1}}}{} \right) \frac{\partial k}{\partial x_j} \right) + P_k - \beta \cdot \rho \cdot k \cdot \omega,
\]

\[
\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial (\rho u_j \omega)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \left( \frac{\mu + \frac{\mu_t}{\sigma_{k1}}}{} \right) \frac{\partial \omega}{\partial x_j} \right) + \alpha_k \cdot \frac{\omega}{k} \cdot P_k - \beta_1 \cdot \rho \cdot \omega^2,
\]

\( k \)-equation:
\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_j k)}{\partial x_j} = P_k - \rho \cdot C_{\mu} \cdot k \cdot \omega + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial k}{\partial x_j} \right),
\]

\( \omega \)-equation:
\[
\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial (\rho u_j \omega)}{\partial x_j} = \frac{\omega}{k} \cdot P_k - C_{\omega 1} \cdot \rho \cdot \omega^2 + (1 - F) \cdot \frac{2 \cdot \rho}{\sigma_{\omega \omega}} \cdot \frac{\partial k}{\partial x_j} \cdot \frac{\partial \omega}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \frac{\mu + \frac{\mu_t}{\sigma_{\omega \omega}}}{} \right) \frac{\partial \omega}{\partial x_j},
\]

where \( \varphi = \varphi_1 \cdot F_1 + \varphi_2 \cdot (1 - F_1) \), where \( \eta = C_{\omega 1} \cdot \varphi_1 \cdot \frac{1}{\sigma_{\omega \omega}} \cdot \frac{1}{\sigma_{\omega \omega}} \),

\[
C_{\omega 1} = 0,55; C_{\omega 21} = 0,075; \sigma_{k1} = 2; \sigma_{\omega 1} = 2; C_\mu = 0,09
\]

\[
C_{\omega 2} = 0,44; C_{\omega 22} = 0,083; \sigma_{k2} = 1; \sigma_{\omega 2} = 1,17
\]

\( \mu_t \) - coefficient of turbulent dynamic viscosity, \( k \) - turbulent kinetic energy (in the case of laminar flows \( k=0 \)). The boundary conditions for the system of equations (1)–(9) are mass air flow \( G \) kg/s at the exit from the casing, which is removed from the rough grinding machine by a fan. In this case, the amount of removed air is determined depending on the diameter of the grinding wheel \( d_{\text{cim}} \) according to the formula, m\(^3\)/h:
The air speed is given by the formula:

\[ u_i = \frac{G}{\rho \cdot S}, \]  

(11)

where \( \rho \) – density, \( S \)-area of passage.

The estimated speed of air intake in the casing inlet is, m/s: \( \nu_0 = 0,25 \cdot \nu_{\text{circum}} \) - from the peripheral speed when the flame is directed into the inlet of the suction air duct; \( \nu_0 = (0,3...0,4) \cdot \nu_{\text{circum}} \) with the direction of the dust flame parallel to the suction opening of the connected air duct.

The peripheral speed of the grinding wheel is determined by the formula:

\[ \nu_{\text{circum}} = \frac{\pi \cdot d_{\text{circum}} \cdot n}{60 \cdot 1000}, \]  

(12)

where - grinding wheel speed, selected from the technical characteristics of the machine.

Figure 3. Basic design diagram.

Static outlet pressure 0 relative to external pressure (free boundary). \( P=0 \).

All pressures here and below are set and obtained in the results relative to the external pressure. To obtain the total pressure, it is necessary to add atmospheric pressure to these values.

On the inner walls of the adhesion conditions, the velocities are 0.

For the energy equation (3.3-3.4) the boundary conditions are set in two versions:

The heat flux \( q \) to the walls is determined from the formula:

\[ q = h \cdot (T_1 - T_2), \]  

(13)

where \( h \) – heat transfer coefficient, -outer wall temperature, -inner wall temperature. Further, the boundary value problem (3) - (13) can be solved numerically [4]-[13].

The equation of state for an ideal gas corresponds to the Mendeleev-Clapeyronlaw, the variable density can be calculated based on the formula:

\[ \rho = \frac{P \cdot M}{R \cdot T}, \]  

(14)

where \( \rho \) – air density, \( P \) – pressure, \( R \) - gas constant, J/(mole·K), \( T \) – temperature M-molecular weight (28.966 g/mole).

In calculations to determine the coefficient of dynamic viscosity, the Sutherland formula is used:

\[ \mu = \left( \frac{T}{273,15} \right)^2 \cdot \frac{273,15 + C_\mu}{T + C_\mu} \cdot \mu_0, \]  

(15)
where $C_s$ - Sutherland's constant; $\mu_0$ - dynamic viscosity coefficient under normal conditions, kg/m·s.

3. Computer model of the aspiration of a rough grinding machine and calculation results

A 3D model of the site was created starting from the air inlet (the place of contact between the wheel and the part - the formation of grinding) to the middle of the wheel. The 3D model simulates the internal air domain bounded by a wheel, a casing and free surfaces (air inlets and outlets) (fig.4).

Border conditions:

1. Wall, adhesion conditions (zero velocities). On this surface, air moves at the speed of the wheel.
2. Air flow inlet with the speed of 30.77 m/s.
3. Suction, flow rate 1080 m³/h.
4. Free surfaces with zero pressure relative to external atmospheric pressure. Air can enter and exit through these surfaces, depending on the parameters of the task. The gap between the grinding wheel and the casing is also a free surface that can be changed.

Table 1. Design parameters.

| Unit            | The quantity | Dimension |
|-----------------|--------------|-----------|
| Air density     | 1.225        | kg/m³     |
| Air viscosity   | 1.7894·10⁻⁵ | kg/m·s    |
| Wheel speed     | 980          | rev/min   |

Figure 4 shows the results of modeling the flow in the space between the grinding wheel and the casing, as well as in the cylindrical pipe of the suction hood.

Figure 5 shows the streamlines of velocities - the trajectories of the particles. Color is responsible for the numbering of trajectories.

Swirls at the beginning of the casing are shown in yellow, where the flow is split in different directions from the casing wall.

According to the CFD calculation results, the average particle velocity at the suction site is also 60 m/s, but a more complex pattern is observed with the velocity gradient distribution with local values up to 80 m/s.
4. Discussion

The developed model made it possible to determine the fields of flow velocities in the closed area of the grinding wheel and in the exhaust cylindrical branch pipe going to the fan. However, in order to clarify the picture of dustiness at the grinder's workplace, we will need to find out what is the field of the streamlines of the flow movement in the immediate vicinity of the shaped cover of the rough grinding machine, that is, in the space where the circle is not covered with a casing.

The resulting air velocity fields at the shaped cover of the grinding machine (in the open part of the grinding wheel), i.e. in the place where dust enters the air of the working area will be compared with the soaring speeds of various dust particles, which will ultimately determine the efficiency of their capture.

To calculate the efficiency of the rough grinding machine cover we are planning to use the results of dispersion analysis [15] of abrasive-cast iron dust during grinding, obtained earlier using Analysette22 NanoTec laser granulometer - a device of the High class.

5. Conclusion

1. The mathematical and computer models of the aspiration of the rough grinding machine have been developed, implemented in the modern software Ansys.

2. Dependences, that describe the flow velocity fields in the closed area of the grinding wheel, which affect the formation of flow lines near the shaped cover of the roughing-grinding machine have been obtained, which will make it possible in the future to determine the efficiency of the rough grinding machine cover, including the design stage.

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