Analysis of dust particle dynamics induced at open local exhausts by rotating cylinders

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Abstract. The paper investigates the behavior of dust particles in the spectrum of action of local ventilation extraction from processed cylindrical detail. For describing the behavior of dust particles in the swirling air currents there has been developed method of mathematical modeling and a computer program. The obtained results can be used for designing of local ventilation exhausts from the various types of lathes. There were proposed measures to reduce energy consumption for production of local exhaust ventilation.

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Introduction

The most reliable way of localization of dust discharges is the use of aspiration systems [1-3], the main element of which is the local extraction ventilation (LEV).

The influence of air flow induced by the rotating cylindrical detail is frequently neglected in calculating the local open ventilation exhausts from various types of lathes [4].

In work [5] it is shown that the air flow, the movement of which initiates this rotating cylinder, is potential. By imposing this flow on the flow of air, absorbing by LEV, we have received the desired velocity field and examined it in the movement of dust particles in the work [6]. However, it does not take into account the influence of the cylinder, and other elements of the process equipment. Condition of impermeability was violated on these solid boundary currents. By using the method of boundary integral equations [7-10], this difficulty was succeeded to overcome in work [11], where was investigated dust dynamics near to aspirating slot, embedded in an infinite flat wall in the spectrum of action of which there is a rotating cylinder. Other elements of the process equipment were not taken into account. There was studied flight of dust particles only for the Stokes flow of air.

This article objective is to analyze dust and air dynamics at local exhausts as induced by a rotating cylinder given then process equipment elements and to determine the effect of air flow induced by the cylinder rotation on dust aerosol caught by a suction fitting.

Deriving basic design relations

Let a multiply connected flow region be limited by boundary S on which the normal velocity is given as function of coordinates and time $v_n(x_0,t)$ where $x_0 \in S$. There may be impermeable cylinders (denoted by circles) within the region rotating at linear velocities v_i. We'll assume that there are sources (outflows) of $q(\xi,t)$ intensity unknown in advance distributed continuously along the boundary. Let linear vortexes be located in the cylinder centers $a_i(a_{i1},a_{i2})$ with circulations $L_i = 2\pi r_i \cdot v_i$,

where r_i is i cylinder radius. The impact of all these sources (outflows) and vortexes on inner point x of the flow area will be given by the integral equation:

$$v_n(x,t) = \int_S F(x,\xi)q(\xi,t)dS(\xi) + \sum_{i=1}^{m} L(a_i)G(x,a_i),$$

where $v_n(x,t)$ is the velocity at point $x(x_1,x_2)$ along $\vec{n} = \{n_1,n_2\}$ at the instant of time t; m is the number of rotating cylinders;

$$F(x,\xi) = \frac{n_1(x_1-\xi_1)+n_2(x_2-\xi_2)}{2\pi\left[(x_1-\xi_1)^2+(x_2-\xi_2)^2\right]};$$

$$G(x,a_i) = \frac{n_2(x_1-a_{i1})-n_1(x_2-a_{i2})}{2\pi\left[(x_1-a_{i1})^2+(x_2-a_{i2})^2\right]};$$

$dS(\xi)$ means that the integration variable is ξ.

Letting inner point to boundary point x_0 along the outward normal we have the boundary integral equation:

$$v_n(x_0,t) = -\frac{1}{2}q(x_0,t) + \int_S F(x_0,\xi)q(\xi,t)dS(\xi) + \sum_{i=1}^{m} L(a_i)G(x_0,a_i),$$

where the first term results from calculation of the integral singularity at $x_0 = \xi$, therefore the integral itself does not contain this point.

By discretizing the region boundary into N boundary intervals at each of which intensity $q(\xi,t)$ will be assumed to be constant we'll obtain a discrete countertype of (1):

$$v_n^p = -\frac{1}{2} q^p + \sum_{\substack{k=1,\\ k \neq p}}^{N} q^k F^{pk} + \sum_{i=1}^{m} L_i G_i^p$$

where $v_n^p = v_n(x_0^p, t)$; x_0^p is the middle of p interval; $q^p = q(x_0^p; t)$; $q^k = q(\xi^k, t)$; ξ^k is a random pint of k interval; $F^{pk} = \int_{\Delta S^k} F(x_0^p, \xi^k) dS(\xi^k)$ is an integral over k interval; $L_i = L(a_i)$, $G_i^p = G(x_0^p, a_i)$.

Searching through p values from 1 to N we have a set of N linear algebraic equations with N unknown variables solving which we'll find intensities of sources (outflows) $q^1, q^2, \ldots, q^N$ at the given instant of time t. Accordingly, the required velocity at inner point x will be determined from the formula:

$$v_n(x) = \sum_{k=1}^{N} q^k F^k + \sum_{i=1}^{m} L_i G_i \quad , \quad \text{where} \quad F^k = \int_{\Delta S^k} F(x, \xi^k) dS(\xi^k) \; ;$$

$$G_i = G(x, a_i). \qquad (3)$$

In order to plot the flow line it is required to set an initial point, calculate horizontal (v_x) and vertical (v_y) air velocity components at this point thus having defined flow direction $\vec{v}$; take a step in this direction and repeat the calculation procedure set forth above. The reverse calculation procedure is also possible when the flow line is plotted from the suction port, i.e. a step is taken in the direction opposite to vector $\vec{v}$. The calculation stops as soon as the air exhaust line is reached or as the flow line length exceeds the given value.

A dust particle path is plotted based on the following motion equation integration using the Runge-Kutta method:

$$\rho_1 \frac{\pi d_e^3}{6} \cdot \frac{d\vec{v}_1}{dt} = -\psi \cdot \frac{|\vec{v}_1 - \vec{v}|(\vec{v}_1 - \vec{v})}{2} \rho \chi S_m + \rho_1 \frac{\pi d_e^3}{6} \vec{g} \; ,$$

where ρ_1, ρ are dust particle and medium densities respectively; $\vec{v}_1$ is the particle velocity vector; $\vec{v}$ is the air velocity calculated from formula (3); d_e is an equivalent diameter; $S_m = \pi d_e^2 / 4$ is the transparent frontal area; χ is the particle dynamic form-factor; $\vec{g}$ is the gravity factor; ψ is the drag factor.

$$\psi = \begin{cases} 24/\mathrm{Re} \quad \text{at} \quad \mathrm{Re} < 1 \quad \text{(Stokes formula)}, \\ 24\left(1 + 1/6 \cdot \mathrm{Re}^{2/3}\right)/\mathrm{Re} \quad \text{at} \quad 1 \le \mathrm{Re} < 10^3 \text{ (Klyachko formula)}, \\ 24/\mathrm{Re} \cdot \left(1 + 0{,}065\,\mathrm{Re}^{2/3}\right)^{1{,}5} \quad \text{at} \quad \mathrm{Re} \ge 10^3 \text{ (Adamov formula)}. \end{cases} \qquad (2)$$

When a particle is hitting a solid wall tangential ($v_{2\tau}$) and normal (v_{2n}) velocities are calculated from the formula: $v_{2n} = -k \cdot v_{0n}$, $v_{2\tau} = v_{0\tau} + \eta \cdot f \cdot (1+k) \cdot v_{0n}$, where $\eta = \min\left\{-\frac{2v_{0\tau}}{7f(1+k)v_{0n}}, 1\right\}$; k is the coefficient of restitution ; f is the coefficient of sliding friction.

When dust particle paths are calculated in a region with time-variant boundary conditions in order to determine the air velocity the intensity of sources (outflows) distributed along the flow boundary must be recalculated at each instant of time by solving set (2).

There was Spectrum software program developed based on the algorithms described above to enable determining the field of velocities, plotting flow lines and paths of dust particles in multiply connected regions with complex boundaries where the normal velocity component may vary in time and where the given number of rotating cylinders can be present.

Results

The first design flow pattern is shown on Fig. 1. The flow area boundaries are given in accordance with a roll-turning machine induction scheme.

The flow lines were plotted from the suction port in increment of 0.001 m and at the interval of 0.005 m between the lines. The number of boundary intervals was about 760.

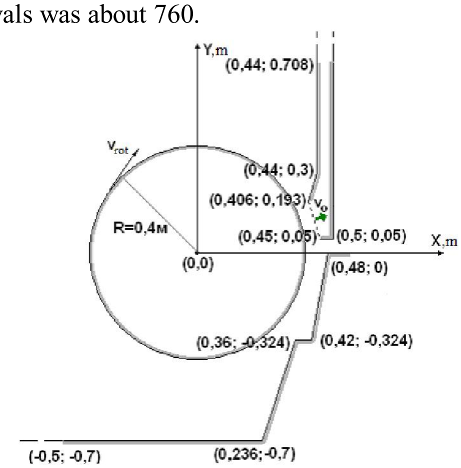

Fig. 1. The flow pattern induced at a local exhaust by a roll-turning machine

In case of a resting cylinder the intake flow comprises three segments (Fig. 2): I is above the cylinder; II is between the cylinder and the frame; III is between the local exhaust and the support. The air rate relation in these flows is 14:5:11 respectively.

When the cylinder is rotating clockwise at the linear velocity of 0.5 m/s (these parameters conform to the machine roll processing workflow) and the suction velocity of 0.5 m/s the flow pattern is changing significantly. Practically the whole suction volume includes flow III which is passing between the local exhaust and the support, circulating clockwise about the cylinder and getting into the suction port.

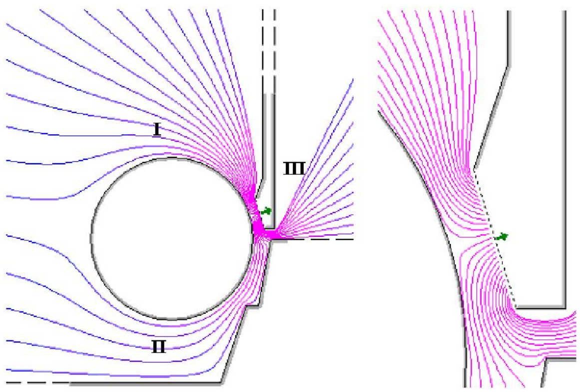

Fig. 2. Flow lines for a resting cylinder and velocity $v_0 = 2$ m/s

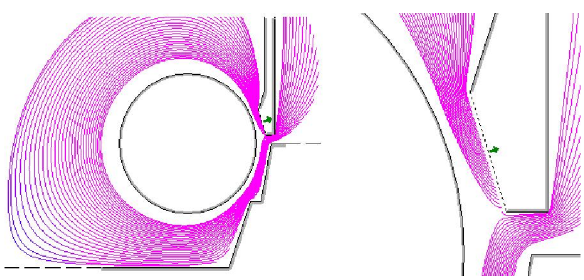

Fig. 3. Flow lines for a cylinder rotating at linear velocity $v_{rot} = 0.5$ m/s and $v_0 = 0.5$ m/s

With increase in the suction port velocity (Fig. 3-6) the intake flow is divided into three parts again. The area of the circulatory flow around the cylinder is decreased with increase in the suction velocity. It is obvious that with a considerable increase in the suction velocity the flow pattern will be similar Fig. 2.

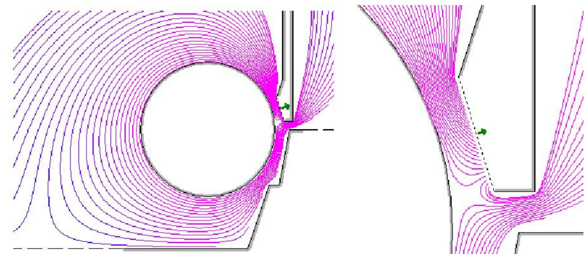

Fig. 4. Flow lines for a cylinder rotatingat linear velocity $v_{rot} = 0.5$ m/s and $v_0 = 1$ m/s

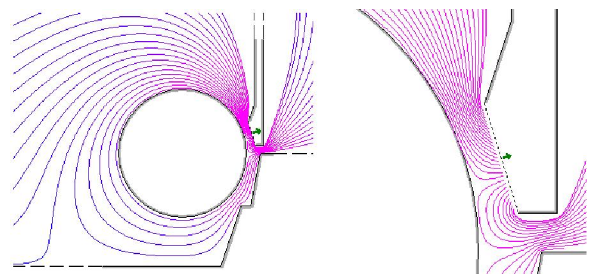

Fig. 5. Flow lines for a cylinder rotating at linear velocity $v_{rot} = 0.5$ m/s and $v_0 = 2$ m/s

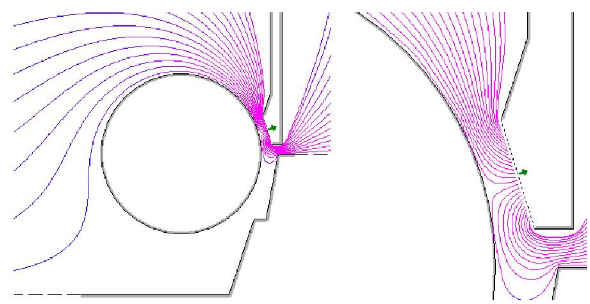

Fig. 6. Flow lines for a cylinder rotating at linear velocity $v_{rot} = 0.5$ m/s and $v_0 = 4$ m/s

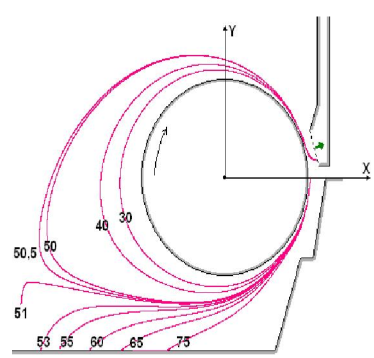

Fig. 7. Paths of dust particles having the density of 1000 kg/m^3 when a cylinder is rotating at linear velocity $v_{rot} = 0.5$ m/s and $v_0 = 1$ m/s

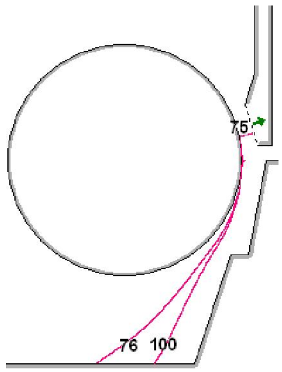

Fig. 8. Paths of dust particles having the density of 1000 kg/m^3 when a cylinder is rotating at linear velocity $v_{rot} = 0.5$ m/s and $v_0 = 2$ m/s

The paths of dust particles were plotted with the following parameters: integration step *h* = 0.001 m; dynamic form-factor $\chi = 1.8$; air density *p* = 1.205 kg/m^3; dynamical air viscosity μ – 0.0000178 Pa·s; coefficient of restitution *k* = 0.5; coefficient of sliding friction *f* = 0.5. Dust particle escape point $x_0 = 0.41$m; $y_0 = 0$ (approximate location of dust emissions when machining the cylinder/roll). The initial velocity of dust particles was assumed to be zero. When $v_0 / v_{rot} = 2$ (Fig. 7), due to a great influence from the circulatory flow around the cylinder, dust particles of min 50 µm are flying over the cylinder and being subsequently caught. Larger particles are settling on the machine frame.

When $v_0 / v_{rot} = 4$ (Fig. 8) n particles are flying over the cylinder because of a great influence from the flow induced by the local exhaust.

Table 1. Maximum diameters of dust particles caught by the local exhaust as shown on Fig. 1

ρ_p, kg/m^3	1000	2000	3000	4000	5000	6000	7000
$v_0 = 1$ m/s, $v_{rot} = 0$ m/s							
d_{max}, µm	271	180	143	121	107	97	89
$v_0 = 1$ m/s, $v_{rot} = 0.5$ m/s							
d_{max}, µm	50	36	29	25	23	20	19
$v_0 = 2$ m/s, $v_{rot} = 0.5$ m/s							
d_{max}, µm	75	51	41	36	31	28	26

It should be noted that the cylinder rotation has a significant impact on maximum diameter d_{max} of dust particles caught by the local exhaust (Table 1).

Let us analyze the roll-turning machine suction pattern without air inflow between the local exhaust and the support (Fig. 9) which corresponds to the case when a mechanical "screen" is installed to shut off air inflow from region III. In such case the exhaust air flow will be combined of two flows: above and below the cylinder (Fig. 10). When $v_0 / v_{rot} = 2$ a closed circulation region occurs around the cylinder (Fig. 11).

With increase in v_0 / v_{rot} the circulation region area is reduced and the local exhaust starts having a greater effect.

The paths of dust particles also have ellipsoid form at certain parameters (Fig. 12). A dust particle may fly around the cylinder several times, and then settle on the machine frame. The circulation region prevents dust particles from getting into the suction port. With increase in suction velocity there are no particles flying around the cylinder and starting from a certain size they start to be caught by the local exhaust (Table 2).

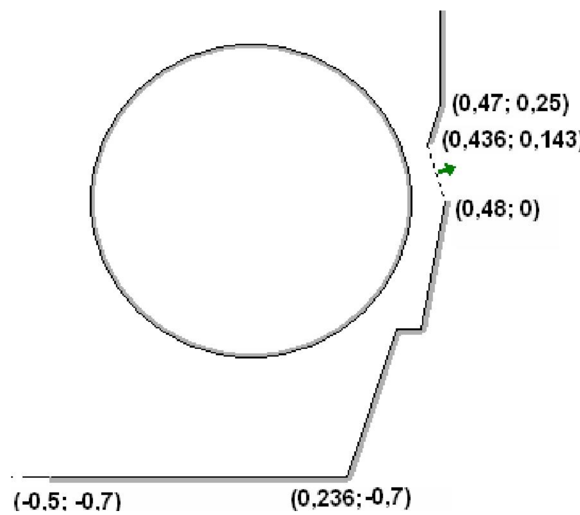

Fig. 9. The flow pattern induced at a local exhaust by a roll-turning machine without air inflow between the local exhaust and the support

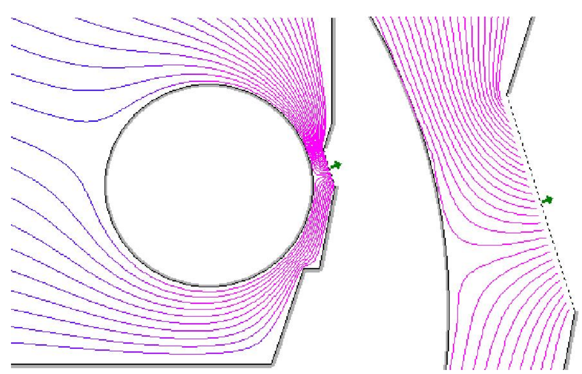

Fig. 10. Flow lines for a resting cylinder and suction velocity $v_0 = 1$ m/s

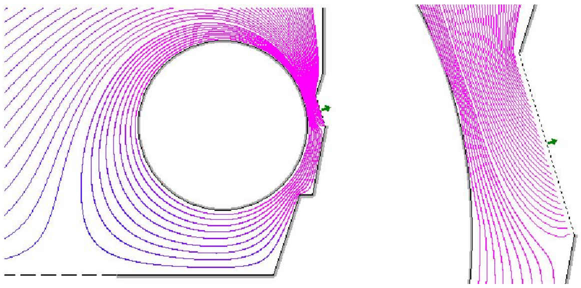

Fig. 11. Flow lines for a cylinder rotating at linear velocity $v_{rot} = 0.5$ m/s and $v_0 = 1$ m/s

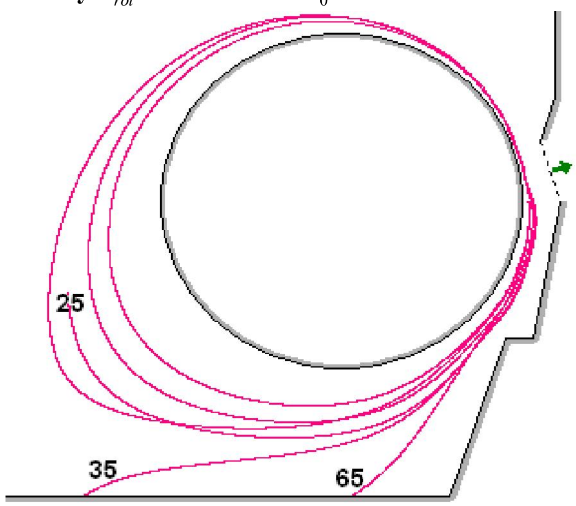

Fig. 12. Paths of dust particles having the density of 1000 kg/m³ when the cylinder is rotating at linear velocity $v_{rot} = 0.5$ m/s and $v_0 = 1$ m/s

Table 2. Maximum diameters of dust particles caught by the local exhaust as shown on Fig. 9

ρ_p, kg/m³	1000	2000	3000	4000	5000	6000	7000
$v_0 = 1$m/s, $v_{rot} = 0$m/s							
d_{max}, µm	283	188	148	126	111	101	92
$v_0 = 1$m/s, $v_{rot} = 0.5$m/s							
d_{max}, µm	0	0	0	0	0	0	0
$v_0 = 2$m/s, $v_{rot} = 0.5$m/s							
d_{max}, µm	144	99	79	68	60	55	51

Conclusions

In calculating of the local ventilation exhausts from rotating cylindrical details neglecting airflow initiated by it, leads to significant errors.

To determine the amount required for localization of dust emissions of aspiration performance system is fundamental need to find the ratio of the rate of absorption to linear velocity of rotation of cylinder.

Shielding of open local exhaust ventilation and respectively reduction of air inflows increases its efficiency. The computer program and results which were developed and obtained by using it, may be useful in designing of energy-efficient aspiration systems from various types of lathes, drilling, grinding, milling, and other wood processing machines with rotating cylindrical parts.

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