Determination of the aspiration air consumption from equipment at the enterprises for the asbestos-cement products’ manufacturing

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Abstract. The authors refined the calculation model of dust distribution in the working air flow areas and zones from several sources for the enterprises producing chrysotile asbestos and cement products using a mathematical apparatus. Erasing these patterns, pilot studies of the aspiration volumes values from the enterprise molding workshop technological equipment were carried out. The amount dependences of the dust emission and the dust concentration in the air of the working zone on the aspiration air flow rates for the overflow unit were revealed. The optimal values of the specified parameters necessary to achieve the maximum permissible concentration of chrysotile asbestos dust in the working area air in the building materials’ production are determined.

1. Introduction
One of the main reasons for the aspiration systems’ ineffective operation in the molding workshops of enterprises for the building materials’ production is the incorrect selection of local aspiration and, as a result, the required volumes’ incorrectly calculated values of the air removed by aspiration plants. Too high volumes lead to a large entrainment of fine dust from the process equipment, which leads to its significant emission into the atmosphere [1]. Underestimation of the aspiration volume entails a significant amount of dust entering working areas. Thus, a decrease in aspiration consumption of 15-20% is accompanied by an increase in dust content to 1.5-2.5 TLV [2].

The extraction of dust particles from technological equipment can occur during loading and unloading, through leaks and free openings. A feature of the process is the availability of various ingredients served in the equipment. Therefore, it is necessary to consider the dust emission process for various, at least characteristic, particle sizes and their densities, i.e. factionally. In addition, due to the general exchange ventilation presence, the heat fluxes as well as the possible local aspiration, the distribution of air velocity near technological equipment has a complex spatial structure [3]. Particles, starting with a certain mass value, are practically not absorbed even in the immediate vicinity of the dust collector. Therefore, at first the particles’ mass is transferred from the technological equipment to the working area, and then the dust settles on the surface of the working platform.

2. A mass transfer mathematical model of building dust released from the technological equipment in the building materials’ production
In view of this, it is of considerable interest to consider the mass transfer process from technological equipment blown by a horizontal flow, in the presence of a vertical ascending heat flow or an aspiration area of local aspiration with a vertical flow [3]. Figure 1 shows the possible physical models of the mass transfer process from the process equipment. Case 1a corresponds to the coincidence case of the particle velocity and air flow’s direction in the X direction. Case 1 b is possible with the opposite direction of the particles and the air flow motion. Fig. 1c shows the most difficult case when there is a non-point or linear source of dust emissions, and the particles are released from some surface and at different angles to the outlet.

![Design diagram of the dust emission processes from technological equipment in the molding shop of an enterprise for the asbestos-cement products’ manufacturing: a - \( V_x \) and \( W_x \) coincide in direction; b - \( V_x \) and \( W_x \) are opposite in direction; c - the view in plan](image)

For the cases under consideration, we use the Pontryagin-Boguslavsky dust particles mass transfer probability equation [3]:

\[
\frac{\partial P}{\partial \tau} = W_x \frac{\partial P}{\partial X} + W_y \frac{\partial P}{\partial Y} + W_z \frac{\partial P}{\partial Z} + 0.5 \sum_{i=1}^{3} b_i \frac{\partial^2 P}{\partial X_i^2}. \tag{1}
\]

Further transformations of the equation (1) are possible after a detailed consideration of the dust particles motion equation. The differential equation of the solid dust particles’ mass center motion in the Lagrangian coordinate system has the form [3]:

\[
(1 - \zeta) m_v \frac{d\bar{W}}{d\tau} = \sum_{i=1}^{n} F_i. \tag{2}
\]
Where, \( \xi \) - is the added mass coefficient taking into account the resulting aerodynamic forces depending on the particle acceleration;
\( m_n \) - is the particle mass size \( d_n \);
\( \overline{W} \) - is a vector of the dust particles’ absolute velocity;
\( \tau \) - defines the process time;
\( \sum \overline{F} \) - denotes the sum of force vectors acting on a particle with \( d_n \).

It is known that for the case of air flow passing a spherical particle without taking into account the compressibility of the medium [3]

\[
\xi = 0.5 \frac{\rho_G}{\rho_D}.
\]

Where, \( \rho_G, \rho_D \) - define the gas and dust particles’ density, respectively.

In this case, the value \( \xi \) can be neglected.

The sum of the forces acting on the particle, based on the accepted statement of the problem (Figure 1), is equal to

\[
\sum_{i=1}^{n} \overline{F} = \overline{F_p} + \overline{F_G} + \overline{F_A},
\]  

(3)

Where, \( F_p \) - particle’s aerodynamic strength force;
\( F_G \) - gravity force;
\( F_A \) - Archimedes’ force.

The Archimedes’ forces in real conditions is small. Then, in the projection on the X, Y, Z axis, the system of differential equations describing the trajectories of the particles moving out of the technological equipment and moving under the initial impulse action in the upward and incoming flows has the form [3]:

\[
\begin{align*}
\frac{dW_x}{d\tau} &= F_{px} = -A(W_x + V_b); \\
\frac{dW_y}{d\tau} &= F_{py} = -AW_y; \\
\frac{dW_z}{d\tau} &= m_g = -A(W_b + V_z).
\end{align*}
\]

(4)

The solution of this second-order nonlinear differential equations’ system describing the particles’ motion was carried out by the numerical Runge-Kutta method. The authors in this case assumed that in the plane \( XY \) a number of characteristic sectors can be distinguished (Fig. 1.c) in quantity \( n \) with angles \( \varphi_i \). These sectors break down the dusty area of a dust source \( F_T \) also on \( n \) relevant plots with an area \( F_i \) so that:

\[
F_T = \sum_{i=1}^{n} F_{Ti}
\]

(5)

Through the middle of each sector \( \varphi_i \), i.e. crossing the angle \( \varphi_i/2 \) a vertical plane in the direction of which dust particles exit through the center of each \( n \) plots, is drawn. The particle output rate \( W_T \)
with size $d_D$ from a plot with an area $F_{Ti}$ depends on the conditions and processes taking place directly in the technological equipment itself and constitutes $W_{Ti},$ and the power and mass of dust emissions is equal to [3]

$$M_{Ti} = C_{Ti} F_{Ti} W_{Ti},$$

$$m_{Ti} = M_{Ti} \tau,$$  \hspace{1cm} (6)

Where, $C_{Ti}$ is the dust particles’ concentration at the exit from the technological equipment area $F_{Ti};$

$\tau$ defines the process time.

Therefore power $M_T$ and mass $m_T$ dust emissions from technological equipment across the area $F_T$ will make

$$M_T = \sum_{i=1}^{n} M_{Ti} = \sum_{i=1}^{n} C_{Ti} F_{Ti} W_{Ti};$$

$$m_T = M_T \tau = \sum_{i=1}^{n} m_{Ti}.$$  \hspace{1cm} (7)

In this problem formulation, the system of differential equations (4) takes the form [3]:

$$\left\{ \begin{array}{l}
  m_n \frac{dW_{X_i}}{d \tau} = -A(W_{X_i} - V_{B*}) \\
  m_n \frac{dW_{Z}}{d \tau} = m_n g = -A(W_B - V_Z)
\end{array} \right.$$

Here, the speed of the air flow running onto the dust source in the projection onto a plane passing through $\varphi_i/2,$ in the first approximation is equal

$$V_{B*} = \pm V_B \cos \alpha_i,$$

Where, $\alpha_i$ is the angle between the X axis and the plane passing vertically through the middle of the angle $\varphi_i,$ i.e. $\varphi_i/2.$

The first equation in the system (8) after the variables separation and integration takes the form:

$$W_{X_i} = V_{B*} + (W_{Hi} - V_{B*}) \exp(-A \tau/m_n).$$

At $t = 0,$ $W_{X_i} = W_{Hi}$ and $W_{X_i} - V_{B*} = C.$

Hence, $W_{X_i} = V_{B*} + (W_{Hi} - V_{B*}) \exp(-A \tau/m_n).$  \hspace{1cm} (9)

From the equation (9) it follows that for $t = 0$ and $W_{X_i} = W_{Hi},$ at $t \rightarrow \infty,$ i.e. for the very small particles of dust released during the asbestos-cement products’ manufacturing, $W_{X_i} \rightarrow V_{B*},$ and the particles get carried away by the air flow.

Further, the study determined the average velocity of the dust particle $d_D$ during $\tau_D$ by the expression
\[
\overline{W_{XYi}} = \frac{1}{\tau_H} \int_0^{\tau_H} W_{XYi} d\tau.
\] (10)

After integrating the equation (10) and the corresponding transformations we get:

\[
\overline{W_{XYi}} = +V_{B*} + \frac{(W_H - V_{B*})}{\tau_H B} [1 - \exp(-B\tau_H)].
\] (11)

Where, \( B = \frac{A}{m_p} \).

the authors performed the variables separation and integration for the second equation of the system (8)

\[
W_Z - V_Z - W_B = C \exp\left(-\frac{g\tau}{W_B}\right)
\]

At \( \tau = 0 \) and \( W_Z = 0 \)

\[
W_Z = (W_B + V_Z) \left[1 - \exp\left(-\frac{g\tau}{W_B}\right)\right]
\] (12)

Turning to speed averaging \( W_Z \) along the trajectory length, according to the formula (12), the following is obtained:

\[
\overline{W_Z} = (W_B + V_Z) \left[1 - \frac{W_B}{g\tau} \exp\left(-\frac{g\tau}{W_B}\right)\right]
\] (13)

The calculations show that averaging along the Z axis practically does not change the particles’ velocity. With such a statement of the problem, an analytical solution of the mass transfer probability equation (1) is already possible. When only the most significant stochastic phenomena are taken into account, it takes the following form [3]:

\[
\frac{\partial P}{\partial \tau} = \overline{W_{XYi}} \frac{\partial P}{\partial XY} + \overline{W_Z} \frac{\partial P}{\partial Z} + 0.5b_z \frac{\partial^2 P}{\partial Y^2}.
\] (14)

In the stochastic class mathematical models’ compilation, the theory of experimental design, evaluation of reproducibility, adequacy and significance was used [4-7]. The experimental studies’ reproducibility is estimated based on a comparison of Cochren’s calculated and tabular criteria at the confidence level \( p=0.05 \). The results showed that the interaction coefficients are significant, and the linear model is inadequate.

Further, the solution of this equation was carried out according to the method of dividing the equation into physical processes proposed by prof. E.I. Boguslavsky [8, 9] for the analytical solution of the mass transfer probability equations.

The boundary conditions for the equation (14) were adopted more general than in [8].

\[
P = K \text{ by } X = X \text{ and } Z = h
\] (15)

\[
P = a \text{ by } X = X \text{ and } Z = H
\] (16)

\[
P = 1 \text{ by } X = 0, Z = h \text{ and } \frac{a}{K} = a_0
\] (17)

Then after substitution and transformations it turns out [3]:
\[ P = 1 - \left[ 1 - \exp \left( -\left( \frac{X W_Z}{W_{XY}} - Z \right) \ln a_0 \left( \frac{\ln a_0}{H-h} \right) \right) \right] \text{erf} \left( Y \right) \] (18)

\[ (Y) = \left[ \frac{H_z^2}{2 \mu^2 b_Z (\tau - \tau_0)} \right] \] (19)

Where, \( H_z \) - is the distance traveled by a particle along the \( Z \) axis to a plane subsidence \( X = H \);

\( \bar{\mu}^2 \) - is the degree of the particle’s entrainment by a pulsating gas medium;

\( b_z \) - defines the gas flow diffusion coefficient;

\( \tau - \tau_0 = \tau_H \) - shows the time of the particles’ mass transferring process to the settling plane \( X = H \).

When considering time \( \tau \) two possibilities for large and small particles should be distinguished. For the settling particles:

\[ \tau_H = \frac{H_z}{W_Z} = \frac{H - h}{W_Z} \] (20)

For the particles carried away by the upward air flow, i.e. at \( W_z < 0 \):

\[ \tau_H = \frac{H_z}{W_Z} \cdot \frac{h}{W_Z} \]

Next, we checked the equation (18) under the following conditions:

1). \( X = 0, \ Z = 0 \)

\[ P = 1 - \left[ 1 - \exp \left( -\frac{h}{H-h} \ln a_0 \right) \right] \text{erf} \left( Y \right) \] (21)

2). \( X = X, \ Z = 0 \)

\[ P = 1 - \left[ 1 - \exp \left( -\left( \frac{X W_Z \ln a_0}{W_{XY} (H-h)} + \frac{\ln a_0}{H-h} \right) \right) \right] \text{erf} \left( Y \right); \] (22)

3). \( X = 0, \ Z = h, \ \frac{a}{K} = a_0 \)

\[ P = 1 \]

4). \( X = X, \ Z = h \)

\[ P = 1 - \left[ 1 - \exp \left( -\left( \frac{(W_Z X - W_{ZY}) \ln a_0}{W_{ZY} (H-h)} + \frac{\ln a_0}{H-h} \right) \right) \right] \text{erf} \left( Y \right); \] (23)

5). \( X = 0, \ Z = H, \ a = a_0 \)

\[ P = 1 - (1 - a_0) \text{erf} \left( Y \right); \] (24)

6). \( X = X, \ Z = H \)
\[ P = 1 - \left[ 1 - \exp\left( - \frac{W_Z X - W_{xy} H}{W_{xy} (H-h)} \ln a_0 + \frac{h \ln a_0}{(H-h)} \right) \right] \text{erf}(Y). \]  

(25)

The boundary condition \( a_0 \) by \( X = X \) and \( Z = H \) depends on the specific conditions of the task, for example, dusting. The value \( a_0 \) can be determined experimentally in the laboratory and production conditions or analytically with additional restrictions and justifications.

In view of the foregoing, the dust propagation probability in one direction is determined for two nearby sources (material transfer station).

If we consider \( \frac{P_{M_1 + M_2}}{P_{M_1} + P_{M_2}} = \frac{M_1 + M_2}{M_1 + M_2} \).

then, taking into account the formula (22)

\[ P_{M_1 + M_2} = \frac{1 - \left[ 1 - \exp\left( - \frac{(X - \Delta l) W_Z - Z}{W_{xy} (H-h)} + \frac{h \ln a_0}{(H-h)} \right) \right] \cdot M_1 +}{1 - \left[ 1 - \exp\left( - \frac{(X - \Delta l) W_Z - Z}{W_{xy} (H-h)} + \frac{h \ln a_0}{(H-h)} \right) \right] \cdot M_2} \]

(27)

As a result of the transformations the following is obtained:

\[ P_{M_1 + M_2} = 1 - \left[ \frac{1 - \exp\left( - \frac{(X - \Delta l) W_Z - Z}{W_{xy} (H-h)} + \frac{h \ln a_0}{(H-h)} \right) \cdot M_1 +}{M_1 + M_2} \right] \cdot M_2 \]

(28)

Solving (28).

\[ P_{M_1 + M_2} = 1 - \exp\left( - \frac{(X - \Delta l) W_Z - Z}{W_{xy} (H-h)} + \frac{h \ln a_0}{(H-h)} \right) \cdot M_2 \]

(29)

The following designations are introduced:
Thus, having

\[ P = \frac{G_{OD}}{G_{\max OD}} = \exp(-ax) \cdot \text{erf}(Y) \]  

(32)

From the equation (32) the dust accumulation intensity on the production area floor surface is obtained:

\[ G_{OD} = G_{\max OD} \cdot P \]

or the dust emission from process equipment:

\[ M_{\tau i} = G_{OD} F_{OD} = G_{\max OD} \overline{PF} \]

where

\[ \overline{PF} = \frac{\pi \phi}{360} \left[ 2 + \left( \frac{X_k^2}{a^3} + \frac{2X_k}{a^2} + \frac{2}{a^3} \right) \exp(-aX_k) \right] \cdot \text{erf}(Y) / X_k \]  

(33)

Thus, having the experimental data on \( G_{OD} \), it is possible to determine the parameters \( a \) and \( G_{\max OD} \) and calculate the dust emission power from the technological equipment [3, 8].
3. Determination of the aspiration air consumption of from the technological equipment in the building materials’ production based on chrysotile asbestos and cement

Further, taking into account these regularities, the authors determined the aspiration air consumption from the processing equipment in the molding workshop of the plant for the asbestos-cement products’ manufacturing. Taking into consideration the fact that in a number of studies [9-11], presented by the experimental methods, significantly different data were obtained on the choice of air flow removed from the standard production equipment - from 500 to 3500 m³/h, lack of calculation methods does not allow to achieve a unified approach to solving this problem.

In the study, the experimental approach recommended by V.N. Posokhin [12-14], in which the calculated aspiration intensity corresponds to a situation where the air parameters in the breathing zone correspond to the normalized zone.

At the asbestos-cement products’ manufacturing enterprise, the pilot tests were conducted. We studied the aspiration volumes, as well as the dust concentration in the production area of the molding workshop. The pilot industrial plant is shown in Figure 2.

![Figure 2. Installation diagram for determining the optimal aspiration volumes:](image)

1 - fan; 2 - dome damper; 3 - the sampling place; 4 - exhaustion aspiration from the transfer station; 5 – transfer station.

The dust measurements were carried out in accordance with GOST R 50820 - 95. The weight method was used, based on the dusty air passage through the filter with the subsequent determination of the captured dust weight. Having obtained the data on the amount of air passing through the filter, it is possible to calculate the weight content of dust in 1 m³ air [15]. In the molding workshop, dust concentration was determined using AFA filters. After sampling, the filters were dried and then weighed on an analytical balance. According to the experience and weighing results, the weight concentration of dust was calculated [16].

The aspiration air flow was determined by sampling and measurement in the aspiration ducts’ measured sections. The measurements of the velocity and flow rate of dust and gas flows were carried out according to GOST 17.2.4.06-90. The following equipment was used for the measurements in accordance with GOST 11161: the micromanometer of the MMN-2400 (5) -1.0 type with accuracy class 1.0, a glass thermometer in accordance with GOST 2823, ethyl alcohol in accordance with GOST 5962, and a solution density of 0.8095 g/cm³, rubber tubes type 1 according to GOST 3399 or polyethylene according to GOST 18599.

The studies were carried out taking into account the probabilistic stochastic approach [8].

When analyzing the data obtained, the dependences of the dust emission amount and the dust concentration in the working zone air on the aspiration air flow rates for the overflow unit are shown (Figure 3, Figure 4).

\[ M_t, \text{ kg/h} \]
4. Summary

Thus, the authors refined the calculation model of dust distribution in working areas and air flow zones from several sources for the enterprises manufacturing the products based on chrysotile asbestos and cement. The analytical dependence of finding the probability of dust propagation in one direction for two nearby sources is obtained.

It is determined that with the trap port open, starting with the flow rate of aspiration air 800 m³/h, dust reduction occurs. With the trap port closed, a decrease starting from 700 m³/h is observed. The asbestos-cement dust concentration in the working area air assumes the maximum permissible value (6 mg/m³) with the aspiration air volume 710 - 830 m³/h in case with a closed trap port. When the trap port is open, the dust concentration is significantly reduced, but cannot reach the maximum permissible concentration.

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