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DETERMINATION OF THE LIFTING HEIGHT OF DUST PARTICLES AFTER A MASS EXPLOSION IN AN IRON ORE OPEN PIT

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Abstract. Open pit mining is accompanied by emissions of fine dust and hazardous gases into the atmosphere. This is related to the operation of open pit transport, drilling and blasting operations. The release of harmful components into the quarry space and the increase in their concentrations has a negative impact on the health of working personnel and leads to pollution of the environment. In doing so, the nature of fine dust and gases pollution depends on the mining technology and meteorological factors.

The problem of reduced effectiveness of dust suppression methods after mass explosions in open pits is relate to insufficient research into the formation of dust and gas cloud. Additional theoretical and experimental research into the dust dynamics of blasting operations is therefore need.

The article discusses the stages of formation of the dust and gas cloud after a mass explosion in an iron ore open pit. The results of experimental studies of the evolution of the dust and gas cloud at different points in time after the detonation of borehole charges are presented. Relations for determination of density and dynamic viscosity of gases, gas mixture and gas-dust aerosol are given. A formula for determining the time and height of ascent of spherical dust particles at the dynamic stage of dust and gas cloud formation is obtain. In this case, the assumption is madid that there is no mutual influence of the dynamic and thermal factors after detonation of the charges. The elevation of dust particles due to temperature differences during the heat stage of dust and gas cloud formation is determined. Based on the analysis of the calculation results, the duration of the dynamic stage of cloud formation is determined. It is established that, following the release of solid and gaseous detonation products into the atmosphere, a height distribution of dust particles is observed as a function of their diameter. That said during, the dynamic stage of dust and gas cloud formation, the height of dust particle lift is directly proportional to their diameter, while during the heat stage the inverse relationship is observe. That at the beginning of the thermal stage the deposition of coarse dust particles takes place are established. In this process, fine dust particles rise to a maximum height and are then carried outside the open pit by the airflow.

Keywords: dust and gas cloud, formation stage, dust particles, lifting height.

1. Introduction

Open pit mining releases harmful dust fractions and gases into the atmosphere. This is cause by the operation of open pit transport, and drilling and blasting operations. In the latter case, there is an intense release of solid and gaseous detonation products (dust particles and gases) into the atmosphere [1, 2]. In this case, the intensity of dust emissions and height of the dust and gas cloud (DGC) rise depend on the strength of the rock, its humidity, drilling methods, type of explosive, borehole plug design and other factors.

Emissions of harmful dust particles (up to 10 μm) and gases pollute the environment and reduce worker safety [2, 3, 4, 5].

Reducing dust and gases emissions from a mass explosion in a quarry is achieve by wetting the rock, using hydraulic irrigation [6], the use of hydraulic plug and emulsion explosives [7].

In some cases, dust suppression methods do not produce the desired results. This is due to a lack of information on the mechanism of DGC formation and development. Therefore, a study of the formation patterns of DGC after mass explosions in quarries is an urgent task.

A mass explosion in an open pit releases detonation products into the atmosphere. The quantity and composition of the gases depend on the chemical composition of the explosive.

During detonation, a chemical reaction produces carbon monoxides (CO_x), nitrogen oxides (NO_x), sulphur oxides (SO_x) and other gases [1, 8]. The use of emulsion explosives can minimize the emission of harmful gases.

The purpose of the work is to determination the lifting height of the dust particles after a mass explosion in an iron ore open pit.

2. Methods

The article uses the results of theoretical and experimental studies of the formation of DGC in quarries, the relations for determining the physical parameters of gases and gas mixtures, the method of separation of variables.

3. Theoretical and experimental part

In [4] the result of studies of the shape and composition of dust clouds after mass explosions in the "Taffs Well Quarry" are presented. Sizes of dust particles that settle outside the open pit are determined.

In [8] empirical formulas for determining the altitude of the DGC ascent under the action of the dynamic impulse and taking into account the thermal stratification of the atmosphere are presented. Time of dynamic ascent of dust particles is taken as 1 s. It was found that cloud dispersal occurs 55÷65 s after the mass explosion.

In [9], the results of numerical simulation of the development of DGC after detonation of charges in a quarry are presented. The stages of cloud formation are considered. Plots of changes in height of dust particles rise in the upper edge of DGC at the thermal stage are presented.

In [10], a formula for determining the height of ascent of a DGC under the action of a dynamic impulse, depending on the initial velocity of the detonation products, charge mass, borehole depth and rock strength, was derived.

In [11], three stages of DGC formation are considered:

1. In the first (initial) phase, there is a partial filtration of gases through the plug material and a release of material from the borehole (up to 0.18 s).

2. In the second (dynamic) stage, an intense release of detonation products into the atmosphere occurs (0.18 to 0.8 s).

3. In the third (heat) stage, upward ejection flows occur. This is due to the temperature difference between the outside and the inside of the cloud (0.8 to 30 s).

The cloud then disperses.

Once the cloud reaches its maximum height, it begins to disperse due to air currents. This results in the transfer of fine dust fractions by airflow outside the open pit.

Figure 1 represents the results of video footage opoljf DGC formation after a mass explosion in a non-metallic open pit.

a) *b*) *c*)

Figure 1 – Formation of a DGC in a non-metallic open pit through 0.054 s (*a*), 0.270 s (*b*) and 0.864 s (*c*)

Each of the stages of DGC formation (Fig. 1) by the following time intervals are characterized:

1. The initial stage (Fig. 1, *a*) lasting up to 0.054 s.
2. The dynamic stage (Fig. 1, *b*) lasting from 0.054 to 0.270 s.
3. Heat stage (Fig. 1, *c*) lasting from 0.270 to 0.864 s.

Detonation residue release velocity and dust particle relaxation time are determined by the formulas [8, 11]:

$$u_r = 0.053 u_d \sqrt{\frac{1}{0.33 + \left(l_z l_e^{-1}\right)\left(\rho_z \rho_e^{-1}\right)}}; \tag{1}$$

$$\tau = \rho D^2 \left(18 \mu_{mix}\right)^{-1}, \tag{2}$$

where u_d is velocity of detonation of the explosive, m/s; l_z is borehole plug length, m; l_{exp} is explosive charge length, m; ρ_z is bulk density of plug material, kg/m^3; ρ_e is explosive substance density, kg/m^3; μ_{mix} is dynamic viscosity of the gas mixture, Pa·s; ρ is the material density of particles, kg/m^3; D is dust particle diameter, m.

Accept the following assumption: there is no mutual influence of dynamic and temperature factors in the formation of the DGC.

Let us consider the dynamic stage of formation of DGC. In this case the dust particle motion is due to dynamic impulse and is described by differential equation

$$m \frac{dU}{dt} = -mg - \xi \frac{\rho_{mix} U^2}{2} \frac{\pi D^2}{4}, \tag{3}$$

where g = 9.81 m/s^2 is acceleration of gravity; $m = 6^{-1} \rho \pi D^3$ is dust particle mass, kg; ρ_{mix} is densities of the gas mixture, kg/m^3; $\xi = f(Re)$ is particle resistance coefficient; Re is Reynolds number; U is dust particle velocity, m/s; t is time, s.

The Reynolds number for dust particles is determined according by formula

$$Re = UD\rho\mu_{mix}^{-1}. \quad (4)$$

During the dynamic stage of DGC formation, a transitional and turbulent dust particle flow around regime is observed (*Re* > 1). The formula is therefore used to determine the resistance coefficient [11]

$$\xi = \frac{A}{Re^{-n}}, \quad (5)$$

where A and $n < 1$ is numerical coefficients whose values depends on the Reynolds number.

Substituting (5) into the differential equation (3) presents difficulties in solving the equation. Therefore, let us assume that there is a laminar flow around the dust particles at $Re < 1$. In this case, the drag coefficient of the dust particles is determined by the Stokes formula

$$\xi = 24Re^{-1}. \quad (6)$$

After dividing both parts of the differential equation (3) by m and substituting (6), get

$$\frac{dU}{dt} = -g - \frac{18\mu_{mix}}{D^2\rho}U. \quad (7)$$

To solve equation (7) we use the method of separation of variables

$$\int_{U_0}^{U} \frac{dU}{\left(-g - \frac{18\mu_{mix}}{D^2\rho}U\right)} = \int_0^t dt, \quad (8)$$

where U_0 is initial velocity of the dust particle, m/s.

After integration and transformations we get

$$U = \frac{\left(18U_0\mu_{mix} + g\rho D^2\right)e^{-\left(\frac{18\mu_{mix}}{D^2\rho}t\right)} - g\rho D^2}{18\mu_{mix}}. \quad (9)$$

Under the action of gravity, the velocity of a dust particle at some height will become zero. Accept $U = 0$ and $U_0 = u_r$. After transformations (9) we obtain the formulas for determining the time and lifting height of dust particle at the dynamic stage of DGC formation:

$$t = t_{din} = \frac{\rho D^2}{18\mu_{mix}} ln\left(\frac{g\rho D^2}{g\rho D^2 + 18u_r\mu_{mix}}\right); \tag{10}$$

$$H_{din} = t_{din}u_r = \frac{u_r\rho D^2}{18\mu_{mix}} ln\left(\frac{g\rho D^2}{g\rho D^2 + 18u_r\mu_{mix}}\right). \tag{11}$$

In [11] the maximum lifting height of dust particles above the surface of the blasted rock block at the end of the DGC formation are determined

$$H_{max} = \frac{0.5u_r\tau^{-1} + g}{\frac{3g}{2\rho D}\frac{T_1P_a}{P_0}\left[\frac{\rho_{air}}{T_{air}} - \frac{(\rho_{mix})_0}{T_{mix}}\right]}, \tag{12}$$

where T_{air} is air temperature in the open pit, K; T_{mix} is the temperature of the gas mixture in the DGC, K; ρ_{air} is air density in the open pit, kg/m^3; $(\rho_{mix})_0$ is density of the gas mixture at normal conditions, kg/m^3; P_{air} is atmospheric pressure at the bottom of the open pit, Pa; P_0 = 101325 Pa is atmospheric air pressure under normal conditions; T_1 = 293 K is the temperature at which 1 mole of gas occupies a volume of 24.04 L (at pressure P_0 = 101325 Pa).

From expressions (11) and (12) it follows that the lifting height of the dust particle ascent at the heat stage of DGC formation is determined by the formula

$$H_{cal} = H_{max} - H_{din}. \tag{13}$$

The initial weighted average mass concentration of dust particles in the DGC is determined by the experimental formula

$$c_0 = C_0\rho = 3{,}25 \cdot 10^{-6} q_y N^{1.68}, \tag{14}$$

where C_0 is initial volume concentration of dust particles in the DGC, %; q_y is specific dust quantity after charges detonation, kg/kg; N is total charge capacity, ton.

The density and dynamic viscosity of the gas in the detonation products are determined by formulas:

$$\rho_i = (\rho_i)_0 \left(P_h P_0^{-1}\right)\left(T_0 T_{mix}^{-1}\right); \tag{15}$$

$$\mu_i = (\mu_i)_0 \frac{T_0 + Z_i}{T_{mix} + Z_i} \left(\frac{T_{mix}}{T_0} \right)^{1.5}, \quad (16)$$

where $(\rho_i)_0$ is gas density at normal conditions, kg/m^3; $(\mu_i)_0$ is dynamic gas viscosity at normal conditions, Pa·s; Z_i is sutherland constant for gas, K.

In the absence of reference data on the value of the Z_i constant, an approximate formula can be used $Z \approx 1{,}5T_{boil}$, where T_{boil} is boiling point, K.

Density and dynamic viscosity [12] of the gas mixture in detonation products:

$$\rho_{mix} = \sum_{i=1}^{K} 0{,}01 \rho_i C_i ; \quad (17)$$

$$\mu_{mix} = \sum_{i=1}^{K} \left(y_i \eta_i \sqrt{M_i} \right) \left[\sum_{i=1}^{K} \left(y_i \sqrt{M_i} \right) \right]^{-1}, \quad (18)$$

where $i = 1,\ldots,K$ is gas mixture component number; K is the amount of gas in the gas mixture; y_i is molar fraction of gas, mole/mole; M_i is gas molecular weight, kg/mole; μ_i is dynamic gas viscosity, Pa·s; C_i is gas volume concentration, %.

Input data for the calculations: explosive substance is “Anemix”; velocity of detonation is $u_d = 4800$ m/s; explosive density is $\rho_e = 1230$ kg/m^3; borehole plug material is boring sludge; bulk density of plug material is $\rho_z = 1800$ kg/m^3; borehole diameter is $d = 0.250$ m; charge length is $l_{exp} = 11$ m; borehole plug length is $l_z = 7$ m; open pit depth is $H = 300$ m; air temperature in the open pit is $T_{air} = 273$ K; the temperature of the gas mixture in the DGC is $T_{mix} = 550$ K; dust particle diameters is $D = 10 \div 100$ µm; material density of particles is $\rho = 3440$ kg/m^3; mass concentrations of gases in the DGC is $c_{NO2} = c_{NO} = 3$ mg/m^3, $c_{CO} = 250$ mg/m^3; specific dust quantity after charges detonation is $q_y = 0{,}029$ kg/kg; rock type is shales (strength factor $f = 5 \div 6$).

4. Results and discussion

Figure 2 shows the results of calculating dust particle lifting heights during the dynamic and heat stages of DGC formation.

At the dynamic stage of DGC formation (Fig. 2, *a*) the height of dust particles rise is directly proportional to their diameter. The minimum lifting height ($H_{din} = 0.79$ m) is reached by dust particles with a diameter of 10 µm. The maximum lifting height ($H_{din} = 44.41$ m) is reached by dust particles with a diameter of 100 µm.

According to [10] the lifting height of the top edge of the DGC above the surface of the blasted block (during the dynamic stage) can be up to 60 m. The gas flow rate from the borehole was considered to be in the range of 820 to 1400 m/s. The duration of the dynamic stage varied in the range 0.050 to 0.110 s.

The results of calculation according to formula (10) show that at the dynamic stage of DGC formation the ascent time of dust particles with diameter from 10 to

100 μm changes respectively in the range from 0.007009 to 0.392 s. The exit velocity of the residual detonation products is 226.5 m/s. As previously mentioned, the duration of the dynamic stage can vary from 0.18 to 0.8 s [11].

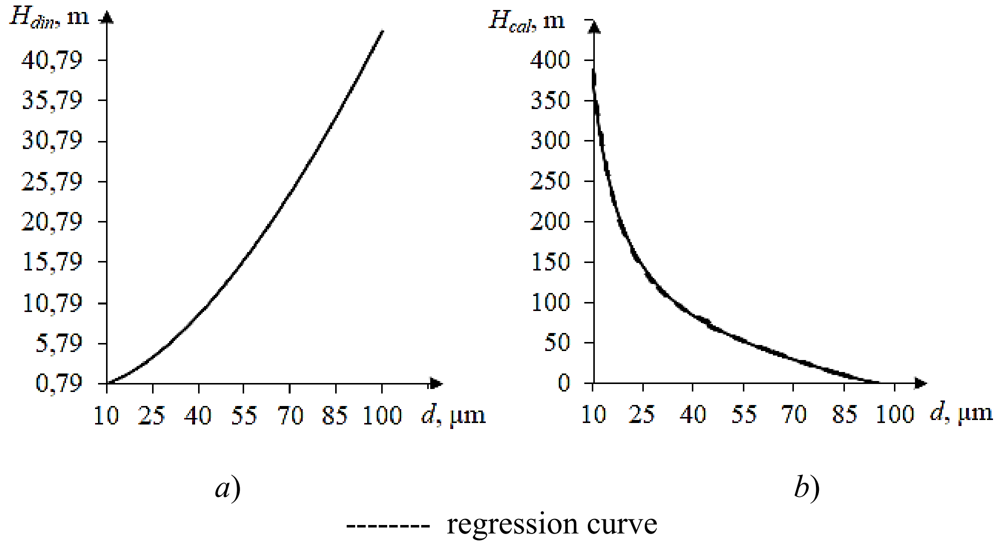

Figure 2 – Dependencies of dust particle lifting height on particle diameter during the dynamic (*a*) and thermal (*b*) stages of DGC formation

In Fig. 2, *a*, the directly proportional dependence of the height of dust particles on the particle diameter is explained by the increase of the dynamic impulse of the body with increasing mass (at constant velocity).

At the heat stage of formation of DGC (Fig. 2, *b*) the height of rise of dust particles is inversely proportional to their diameter. The minimum lifting height (H_{cal} = 0) is reached by dust particles with diameter from 94 to 100 μm. The maximum lifting height (H_{cal} = 373.4 m) is reached by dust particles with a diameter of 10 μm.

According to [11] maximum lifting height of dust particles with diameter from 1 to 100 μm above the surface of the blasted block (at the end of the heat stage of DGC formation) varies from 603.8 to 6.6 m, respectively.

In fig. 2, *b*, the inversely proportional relationship between the height of dust particle lift and the particle diameter is explained by the following factors. During the thermal stage of DGC formation, upward ejection currents arise. As a result, a lifting force acts on the dust particle. As the diameter of the particle increases, gravity increases accordingly. This limits the lifting height of the particle. If gravity exceeds the lifting force, dust particle deposition begins.

Thus, during the dynamic and heat stages of DGC formation (Fig. 2), there is a fractional separation of dust particles by height. In the dynamic stage, larger dust particles rise to greater heights, while in the heat stage the opposite process is observed.

For the curve in Figure 2, b, a composite regression relationship is obtained

$$H_{cal} = \begin{cases} 5010{,}8 \cdot D^{-1.083}, \; R^2 = 0.9985 \quad at \;\; 0 \le D \le 45 \; \mu m; \\ 0.0108 \cdot D^2 - 2.9835 \cdot D + 188.86, \; R^2 = 0.9994 \quad at \;\; 45 \prec D \le 100 \; \mu m. \end{cases} \tag{20}$$

where R^2 is determination coefficient.

An analysis of the works [9, 10, 11] shows that when determining the height of dust particle lift, there is a difference in the results obtained. Specifically, a determining parameter that affects the accuracy of the calculations is the particle resistance coefficient.

5. Conclusions

The following conclusions can be drawn from the study:

1. In the dynamic stage of DGC formation, the lifting height of dust particles is directly proportional to their diameter, while in the heat stage the inverse relationship is observed. Thus, at each stage of DGC development, there is an opposite separation of dust particles in terms of height of ascent.

2. At the beginning of the heat stage of DGC formation, dust particles with a diameter of 94 to 100 μm are deposited. This is due to the predominant influence of the force of gravity.

3. For the given conditions, the time for the dynamic stage of DGC formation is 0.392 s.

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ВИЗНАЧЕННЯ ВИСОТИ ПІДЙОМУ ЧАСТИНОК ПИЛУ ПІСЛЯ МАСОВОГО ВИБУХУ У ЗАЛІЗОРУДНОМУ КАР'ЄРІ

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Анотація. Відкрита розробка родовищ корисних копалин супроводжується викидами в атмосферу дрібнодисперсного пилу та шкідливих газів. Це пов’язано з роботою кар'єрного транспорту, буровими і вибуховими роботами. Викид шкідливих компонентів у кар'єрний простір та підвищення їх концентрацій негативно впливає на здоров'я працюючого персоналу та призводить до забруднення навколишнього середовища. При цьому характер забруднення дрібнодисперсним пилом та газами залежить від технології гірничих робіт та метеорологічних факторів.

Проблема зниження ефективності способів пригнічення пилу після масових вибухів у кар'єрах пов'язана з недостатньою вивченістю процесу формування пилогазової хмари. У зв'язку з цим необхідні додаткові теоретичні та експериментальні дослідження пилової динаміки при вибухових роботах.

У статті розглянуто стадії формування пилогазової хмари після масового вибуху у залізорудному кар'єрі. Наведено результати експериментальних досліджень еволюції пилегазової хмари в різні моменти часу після детонації свердловинних зарядів. Наведено співвідношення для визначення щільності та динамічної в'язкості газів, газової суміші та газопилового аерозолю. Отримано формулу для визначення часу та висоти підйому сферичних частинок пилу на динамічній стадії формування пилогазової хмари. При цьому робиться припущення про відсутність взаємного впливу динамічного та теплового факторів після детонації зарядів. Визначено висоту підйому частинок пилу під дією різниці температур на тепловій стадії формування пилогазової хмари. На базі аналізу результатів розрахунку визначено тривалість динамічної стадії формування хмари. Виявлено, що після викиду в атмосферу твердих та газоподібних продуктів детонації відбувається розподіл часток пилу по висоті залежно від їх діаметра. При цьому на динамічній стадії формування пилегазової хмари висота підйому частинки пилу прямо пропорційна їх діаметру, а на тепловій стадії спостерігається зворотна залежність. Встановлено, що на початку теплової стадії відбувається осадження великих частинок пилу. В цьому процесі дрібнодисперсні частинки пилу піднімаються на максимальну висоту, а потім переносяться повітряним потоком за межі кар'єру.

Ключові слова: пилогазова хмара, стадія формування, частки пилу, висота підйому.