Jr. of Industrial Pollution Control 33(1)(2017) pp 767-774
www.icontrolpollution.com
Review

ON DUST AND GAS GENERATION UPON MULTIPLE BLASTS IN OPEN-PIT MINES

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(Received 06 April, 2017; accepted 08 April, 2017)

Key words: Dust, Concentration, Explosive charge, Explosive charge diameter, Detonation velocity, Open-pit mine, Blast, explosion

ABSTRACT

This article discusses the influence of explosive charge diameter and type of explosive substance on generation of fine dust. Dependences of dust generation intensity for various size fractions and dust concentration upon blasting for operation conditions of open-pit mines of building materials. Calculation procedures of dust and gas pollutions upon blasting operations are reviewed and analyzed. Sample calculation of dust and gas pollution according to the proposed procedure is given with consideration of gas dynamic processes in blasthole charging pocket, blasting and drilling parameters, properties of explosive substances and rock massif, including results of commercial approbation in open-pit mines of building materials. Results of commercial experiment are given, the known calculation procedures of dust and gas emissions upon blasting and drilling operations in open-pit mines are analyzed.

INTRODUCTION

In Huge amounts of dust and gas are emitted into environment upon multiple blasts. The amount of explosive charge for multiple blasts in open-pit mines reaches 300 t to 1000 t, and the weight of blasted rocks amounts to 5 million t. According to particle size distribution of blasted rocks of various strength it is established that in terms of 1 kg of explosive substance upon multiple blasts the dust and gas cloud contains from 80 g to 320 g of 20 μm size fraction (Adushkin, 1996). It has been shown in Beresnevich and Mikhailov, 1990; that specific amount of dust per unit of rocks depends on rock strength and increases with increase in mining depth and varies in the range of 30 g/m^3 to 160 g/m^3.

EXPERIMENTAL

Nowadays several procedures for calculations of dust and gas environmental pollutions upon multiple blasts in open-pit mines are known, such as the procedure for calculations of harmful emissions (effluents) for open-pit mining (on the basis of specific performances) developed in Skochinsky Mining institute (Procedures of calculation of harmful emissions (effluents) for equipment of open-pit mines (on the basis of specific performances, 1990), Unified Program of air pollution estimation, Ecolog, ver. 3 (Integral Company), Mining operations, ver. 1.1.0.4 (Integral Company), and others. The software packages Ecolog, ver. 3.00 and Mining operations, ver 1.1.0.4 (Integral Company) are based on the procedures in procedures of calculation of harmful emissions (effluents) for equipment of open-pit mines (on the basis of specific performances, 1990), however, they do not take into account energy properties of explosive substances (ES) and their detonation velocities, drilling and blasting parameters (borehole diameters and their amount, explosive charge weight in borehole). A procedure is discussed in (Menzhulin and Paramonov, 1997) which calculates dust size fractions generated in near

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zone of blast with accounting for the use of various explosive charge designs, ES types and properties of blasted massif. This procedure is based on the theory of destruction including kinetics of accumulation of induced fracturing resulted from blasting loads on rock massif with consideration for gas dynamic processes in explosive charge pockets, detonation properties of fractured rocks. This procedure is implemented in Dust software developed by Saint Petersburg Mining Institute. it should be mentioned that this procedure accounts for dust generation only in near zone of blast and does not account for dust generation due to additional crushing upon rock displacement.

This work proposes calculation procedure of dust generation with consideration for peculiar features of the above listed procedures, as well as reveals dependences estimating dust and gas emissions upon blasting of various ES on the basis of known blast parameters of ammonites: the most popular explosives for drilling and blasting.

The amount of pollutants emitted upon blasting in open-pit mines was determined in the course of experiments performed at OAO Kamennogorsk department of open-pit mines and ZAO Gavrilovskoe department of open-pit mines, Leningrad oblast. The experiments were performed with granite and granite gneiss, their Protodyakonov strength coefficient varies in the range of 12-14.

In order to approbate the calculation procedure with regard to conditions of Kamennogorsk deposit model experiments were performed with rock samples (Larichev, *et al.*, 2009). Convergence of results of laboratory tests, calculations, measurements of dust and gas emissions (Procedures of calculation of harmful emissions (effluents) for equipment of open-pit mines (on the basis of specific performances, 1990; Menzhulin and Paramonov, 1997; Larichev, *et al.*, 2009a; Larichev, *et al.*, 2010; Shmeleva, *et al.*, 2006), obtained upon pilot multiple blasts, makes it possible to apply them for estimation of new ES types, to forecast polluting emissions upon blasting using boreholes of various diameters in deposits and open-pit mines, as well as to apply the proposed procedure in counter-explosive criminalistics for identification of ES type and weight on the basis explosion products, weight and size fractions of dust.

Numerical calculations (Larichev, *et al.*, 2009) of dust generation according to the procedure in (Menzhulin and Paramonov, 1997), developed in Saint Petersburg Mining institute, confirmed their convergence with experimental data on the basis of weight estimation by size fractions generated upon blasting of borehole charges.

RESULTS

Analysis of experimental and calculated data Tables 1-4 using the procedures (Procedures of calculation of harmful emissions (effluents) for equipment of open-pit mines (on the basis of specific performances, 1990; Menzhulin and Paramonov, 1997) in (Larichev, *et al.*, 2009; Larichev, *et al.*, 2009a; Larichev, *et al.*, 2010) and measurements of harmful pollutions (Shmeleva, *et al.*, 2006) by OAO Kamennogorsk department of open-pit mines demonstrates that the dust amount generated upon blasting and calculations differ by not more than 15%, which confirms possibility of the developed procedure to estimate dust and gas generation.

1. Example of calculations of harmful emissions resulted from ammonite No. 6 ZhV using the procedure (Procedures of calculation of harmful emissions (effluents) for equipment of open-pit mines (on the basis of specific performances, 1990), of Skochinsky Mining institute for conditions of OAO Kamennogorsk department of open-pit mines in terms of single blast of 30 t ES, $d_{Bore} = 252\ mm$, $\rho_{ES} = 950\ kg/m^3$. The Protodyakonov strength coefficient of granite is in the range of 12-14.

Weight of harmful gases (carbon oxide, nitrogen oxides), emitted with dust and gas cloud (DGC):

$$m_{G1} = \sum_{i=1}^{2} q_{Speci} \cdot K \cdot A \cdot 10^{-6} = 9.4 \cdot 1.25 \cdot 30000 \cdot 10^{-6} + 2.6 \cdot 1.4 \cdot 30000 \cdot 10^{-6} = 461700 \cdot 10^{-6}, \quad t$$

Weight of harmful gases remaining in blasted rock mass (RM) and gradually released into environment:

$$m_{G2} = \sum_{i=1}^{2} C_{RMi} \cdot Q_{RM} \cdot (K_P - 1) \cdot 10^{-9}\ \text{t.}$$

$$C_{RMi} = K \cdot A \cdot 10^3 / Q_{RM}(K_P - 1) \quad \text{mg/m}^3$$

$$C_{RMCO} = 3.6 \cdot 1.25 \cdot 30000 \cdot 10^3 / 30000(1.4 - 1) = 11.25 \cdot 10^3\ \text{mg/m}^3$$

$$C_{RMNOx} = 0.93 \cdot 1.4 \cdot 30000 \cdot 10^3 / 30000(1.4 - 1) = 3.255 \cdot 10^3\ \text{mg/m}^3$$

$$m_{G2CO} = 11,25 \cdot 10^3 \cdot 30000 \cdot (1.4 - 1) \cdot 10^{-9} = 13.5 \cdot 10^{-2}\ \text{t.}$$

$$m_{G2NO_x} = 3.255 \cdot 10^3 \cdot 30000 \cdot (1.4 - 1) \cdot 10^{-9} = 3.9 \cdot 10^{-2}\ \text{t.}$$

Calculation of total weight of harmful gases emitted upon blast (in terms of conventional CO):

$$M_G = m_{G1CO} + m_{G2CO} + (m_{G1NO_X} + m_{G2NO_X})6.5\ \text{t.}$$

$$M_G = (352500 + 135000 + (109200 + 39000)6.5) \cdot 10^{-6} = 1450800 \cdot 10^{-6} = 1.45\ \text{t.}$$

Weight of solid particles (dust) emitted with DGC:

$$m_D = q_D K_2 Q_{RM} \cdot 10^{-3}\ \text{t}$$

Table 1. Universal coefficients of dust and gas emissions

ES type	Protodyakonov strength coefficient	ES density, kg/m³	D, m/s	d_{Bore}, $10^{-3} m$	Gas emission coefficient for ammonite $K_{G_{AMM}}$	Dust emission coefficient for ammonite $K_{D_{AMM}}$
Ammonite No. 6 ZhV	12-14	950	4500	252	1	1
				220	0.947	0.663
				165	0.614	0.606
				130	0.682	0.586
				112.5	0.666	0.423
				75	0.833	0.165
		1200	5300	252	1.384	1.403
				220	1.313	1.065
				165	0.852	0.912
				130	0.945	0.831
				112.5	0.923	0.598
				75	1.155	0.233
Grammonite 79/21		870	4300	252	0.698	0.907
				220	0.920	0.616
				165	0.596	0.549
				130	0.590	0.530
				112.5	0.647	0.388
				75	0.810	0.151
		1200	4800	252	1.342	1.156
				220	1.276	0.770
				165	0.826	0.685
				130	0.921	0.642
				112.5	0.898	0.493
				75	1.123	0.194
Sibirite		1000	5080	252	0.346	0.355
				220	0.324	0.197
				165	0.213	0.185
				130	0.234	0.177
				112.5	0.229	0.130
				75	0.287	0.050
		1200	6000	252	0.473	0.445
				220	0.450	0.290
				165	0.293	0.269
				130	0.324	0.256
				112.5	0.317	0.183
				75	0.396	0.058

$q_D = 0.11\, kg/m^3$, $m_D = 0.11 \cdot 1 \cdot 30000 \cdot 10^{-3} = 3.3$ t

Total weigh of harmful substances emitted upon single blast:

$$M_\Sigma = m_{G1} + m_{G2} + m_D \text{ t}$$

$$M_\Sigma = (461700 + 174000) \cdot 10^{-6} + 3.3 = 3.9 \text{ t}$$

Total weigh of harmful substances emitted upon single blast:

$$M_{\Sigma year} = M_\Sigma \cdot 3 \cdot 12 \text{ t}$$

$$M_{\Sigma year} = 36 \cdot 3.9 = 140.4 \text{ t/year.}$$

All coefficients Table 1 were calculated using the procedure in Menzhulin and Paramonov, 1997, which enable forecasting of dust and gas weights upon the use of various explosive boreholes, various

Table 2. Dust and gas emissions after blasting of 1 kg ES

ES type	ES density, kg/m³	D, m/s	d_{Bore}, $10^{-3}m$	Calculated dust weight $kg/1kg\ ES$	Calculated gas weight $kg/1kg\ ES$
Ammonite No. 6 ZhV	950	4500	252	0.110	0.063
			220	0.073	0.060
			165	0.067	0.039
			130	0.064	0.043
			112.5	0.047	0.042
			75	0.018	0.052
	1200	5300	252	0.154	0.087
			220	0.117	0.083
			165	0.100	0.054
			130	0.091	0.060
			112.5	0.066	0.058
			75	0.026	0.072
Grammonite 79/21	870	4300	252	0.099	0.044
			220	0.068	0.058
			165	0.060	0.038
			130	0.058	0.037
			112.5	0.043	0.041
			75	0.017	0.051
	1200	4800	252	0.127	0.085
			220	0.085	0.080
			165	0.075	0.052
			130	0.071	0.058
			112.5	0.054	0.056
			75	0.021	0.071
Sibirite	1000	5080	252	0.039	0.022
			220	0.022	0.020
			165	0.020	0.013
			130	0.019	0.015
			112.5	0.014	0.014
			75	0.005	0.018
	1200	6000	252	0.049	0.030
			220	0.032	0.028
			165	0.030	0.018
			130	0.028	0.020
			112.5	0.020	0.019
			75	0.006	0.025

Table 3. Properties of some explosive substances

Explosive substance	Brisancy, mm	Fugacity, cm³	Detonating velocity, m/s	Density, g/cm³	Heat of explosion, kJ/kg	Trinitrotoluene equivalent
Tetranitropentaerytrite	16	500	7520	1510	5800	1.37
Ammonite No. 6ZhV	14	360	4500	950	4355	1.03
Grammonite 79/21	25	360	4300	870	4300	1.02
Sibirite 1200	17	400	6000	1200	4100	0.96
Trinitrotoluene	16	285	6600	1660	4228	1
Plastic explosive (PE-4)	21	280	7000	1440	5440	1.28
Hexogen	24	470	8380	1800	5500	1.3

Table 4. Adjustment rock strength coefficients of dust emission as a function of rock strength for water free ES and emulsified ES

Protodyakonov strength coefficient	Specific dust emission (q_D, kg/m^3), according to Skochinsky Mining Institute	Adjustment rock strength coefficients	Specific dust emission (q_D, kg/m^3), according to Skochinsky Mining Institute	Adjustment rock strength coefficients
	For emulsified ES		For water-free ES	
2-4	0.015	0.3-0.33	0.03	0.27-0.33
4-6	0.02	0.4-0.44	0.04	0.36-0.44
6-8	0.025	0.5-0.55	0.05	0.45-0.55
8-10	0.03-0.04	0.66-0.8	0.06-0.08	0.66-0.72
10-12	0.04-0.045	0.89-0.9	0.08-0.09	0.81-0.88
12-14	0.045-0.05	1	0.09-0.11	1
14-16	0.05-0.06	1.11-1.2	0.11-0.13	1.18-1.22
16-18	0.06-0.08	1.33-1.6	0.13-0.16	1.44-1.46

types of ES with various detonation velocities and density.

Therefore, it would be reasonable to introduce the notions of ammonite dust equivalent and ammonite gas equivalent similar to trinitrotoluene equivalent, that is, amount (weight) of dust and gas after blasting of ammonite No. 6ZhV (density 950 kg/m^3, detonation rate 4500 m/s) as one of the most widely used ES in open-pit mines.

$K_{G_{AMM}}$ is the coefficient of gas emission in terms of ammonite No. 6ZhV (density 950 kg/m^3, detonation velocity 4500 m/s); $K_{D_{AMM}}$ is the coefficient of dust emission in terms of ammonite No. 6ZhV (density 950 kg/m^3, detonation velocity 4500 m/s).

Therefore, in order to determine the amounts of gas and dust emitted upon blast it is required to calculate the amounts of dust and gas using Eqs. 1.1-1.6 for ES: ammonite No. 6ZhV (density 950 kg/m^3, detonation velocity 4500 m/s), and then to multiply by $K_{D_{AMM}}$ or $K_{G_{AMM}}$, respectively.

Dust and gas emissions upon ES blasting in terms of 1 kg ES are summarized in Table 2.

The data are given for dust $d_N \leq 300\,\mu m$ according to the proposed procedure.

Using the data in Table 3 it is possible to interrelate the ES trinitrotoluene equivalent with dust or gas equivalents.

When ammonite No. 6ZhV with the density of 950 g/cm^3 is used as ES, the emissions of dust with size fraction of $d_i \leq 300\,\mu m$ are 0.11÷0.018 kg/1 kg ES. Taking into account that 1 kg of ammonite No. 6 ZhV in terms of energy=1.03 kg of trinitrotoluene, upon blasting of 1 kg of trinitrotoluene with the density of 1660 g/cm^3 the emissions of dust with size fraction of $d_i \leq 300\,\mu m$ are 0.1068÷0.017 kg/1 kg ES, hence, the proposed procedure can be applied in blasting technique upon determination of ES weight and composition.

In order to calculate dust and gas emissions in rocks with strength differing from that of granite (Protodyakonov strength coefficient of 12-14) it is required to apply conversion rock strength coefficients of dust emission summarized in Table 4.

DISCUSSION

Therefore, it is possible to estimate the difference in dust emissions under identical conditions varying only by strength of blasted rocks. For instance, 141.68 t of dust are generated at OAO Kamennogorsk department of open-pit mines in one year, provided that Protodyakonov strength coefficient of granite rocks varies in the range from 12 to 14, and in the case of rock blasting with the strength of 8-10 the dust emissions are 93.5 t/year to 113.344 t/year.

Table 5 illustrates application of ammonite dust and gas equivalents, as well as summarizes emitted amounts of dust and gas upon multiple blasts of various ES and borehole diameters.

Aiming at estimation of emitted dust with regard to size fractions for Kamennogorsk open-pit mines the weights of dust after blasting of various ES were calculated using the procedure (Menzhulin and Paramonov, 1997), it was established that the 0-300 size fraction is emitted in amount of 110.69 t. The ratios of dust size fractions in DGC (the data are comprised of dust contents after blasting of ammonite No. 6ZhV, grammonite 79/21, sibirite-1000 with the densities of 950, 870, and 1000 kg/m^3, respectively), are summarized in Table 6.

Data analysis demonstrates that when ammonite No. 6ZhV with the density of 950 kg/m^3 is used

Table 5. Experiments and calculations

ES type	ES density, kg/m³	D, m/s	d_{bore}, $10^{-3} m$	Calculated dust weight * $10^3 kg / year$	Calculated dust weight ** $10^3 kg / year$	Calculated dust weight *** $10^3 kg / year$	Experimental dust weight $10^3 kg / year$	Calculated gas weight $10^3 kg / year$
Ammonite No. 6 ZhV	950	4500	252	59.81		118.8		67.68
			220	39.46		78.8		64.08
			165	36.25		72.0		41.58
			130	35.09		69.6		46.14
			112.5	25.30		50.2		45.05
			75	9.89	118.8	19.6	141.68	56.38
	1200	5300	252	83.95		166.6		93.84
			220	63.74		126.5		88.85
			165	54.54		108.3		57.65
			130	49.73		98.7		63.98
			112.5	35.76		71.0		62.46
			75	13.96		27.7		78.18
Grammonite 79/21	870	4300	252	54.24		107.8		65.52
			220	36.86		73.2		62.28
			165	32.85		65.2		40.32
			130	31.72		63.0		45.00
			112.5	23.23		46.1		43.81
			75	9.02		17.9		54.82
	1200	4800	252	69.12	107.8	137.3	129.70	90.85
			220	46.08		91.5		86.36
			165	40.95		81.4		55.91
			130	38.42		76.3		62.40
			112.5	29.47		58.6		60.75
			75	11.61		23.0		76.01
Sibirite	1000	5080	252	76.56		42.2		23.40
			220	49.72		23.4		21.96
			165	45.68		21.9	50.76****	14.40
			130	40.04		21.0		15.84
			112.5	32.92		15.4		15.48
			75	12.67		5.94		19.44
	1200	6000	252	107.91	42.2	52.9		32.04
			220	71.74		34.5		30.45
			165	66.74		32.0	64.06****	19.80
			130	63.33		30.4		21.96
			112.5	46.08		21.7		21.44
			75	14.49		6.8		26.83

Note: * The data are given for dust $d_i \le 150\,\mu m$ according to the procedure (Menzhulin and Paramonov 1997); ** The data are given for dust $d_i \le 300\,\mu m$ according to the procedure (Procedures of calculation of harmful emissions (effluents) for equipment of open-pit mines (on the basis of specific performances, 1990); *** The data are given for dust $d_i \le 300\,\mu m$ according to the proposed procedure; ****Forecasted experimental dust weight $d_i \le 300\,\mu m$

Table 6. Comparison of dust fractions in dust and gas cloud upon blasting by various ES

	Quantitative composition of dust, %			
	Size fraction 0-40	**Size fraction 40-75**	**Size fraction 75-150**	**Size fraction 0-150**
Average	0.182	3.185	96.63	100
For ammonite No. 6ZhV	0.283	3.305	96.41	100
For grammonite 79/21	0.145	2.979	96.87	100
For sibirite -1000	0.118	3.268	96.61	100
	Quantitative composition of dust, %			
	Size fraction 0-150		Size fraction 150-300	Size fraction 0-300
Average	54.030		45.968	100
For ammonite No. 6ZhV	53.885		46.113	100
For grammonite 79/21	53.686		46.312	100
For sibirite -1000	54.519		45.479	100

Table 7. Quantitative composition of dust after blasting of ammonite No. 6ZhV with the density of 950 g/cm^3 at $D_{Bore} = 252\ mm$

R/R_0	**Quantitative composition of dust, %**			
	Size fraction 0-40	**Size fraction 40-75**	**Size fraction 75-150**	**Size fraction 0-150**
1	0.044	0.33	6.54	6.91
2	0.053	0.36	8.81	9.22
3	0.033	0.40	10.37	10.80
4	0.032	0.41	10.57	11.01
5	0.031	0.35	10.77	11.15
6	0.026	0.34	10.54	10.91
7	0.017	0.31	9.90	10.23
8	0.016	0.29	9.87	10.18
9	0.014	0.27	9.57	9.85
10	0.013	0.25	9.47	9.73

as ES the dust size fractions 0-40, 40-75, 75-150 are emitted in amount of 0.0109, 0.191, and 57.794 t/year, respectively, and the dust size fractions 0-150, 150-300 in amount of 59.81 and 50.886 t/year, respectively.

Table 7 summarizes quantitative composition of dust after blasting of ammonite No. 6ZhV with the density of 950 g/cm^3 at $D_{Bore} = 252\ mm$ on the basis of procedure (Menzhulin and Paramonov 1997).

CONCLUSIONS

Therefore, this work analyzed known calculation procedures of dust and gas emissions upon drilling and blasting. It is proposed to estimate the dust and gas emissions using ammonite dust and gas equivalents. The proposed method makes it possible to estimate environmental situation at drilling and blasting sites for various ES and blasting conditions.

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