БЕЗОПАСНОСТЬ ГОРНОГО ПРОИЗВОДСТВА

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Numerical modeling of open pit ventilation when varying the location of the dust and gas cloud

Pavel V. Amosov[1]
[1] Institute of North Industrial Ecology Problems KSC RAS, Apatity, Russia
e-mail: p.amosov@ksc.ru

Abstract

Research objective *is to estimate the effect of bulk explosion location and the initial height of the dust and gas cloud on open-pit natural ventilation time and the level of air contamination of the upper edge of the open pit down the wind.*
Methods of research. *Computer modeling of aerodynamics and gaseous component transfer in the 2D geometry is carried out with the COMSOL software. To calculate the aerodynamic characteristics, the approximation of the incompressible fluid with the standard k–ε turbulence model was carried out. Gaseous component distribution was modeled using the numerical solution to the convection-diffusion equation of contaminant transfer. Numerical experiments under the fixed initial concentration of the gaseous component and the speed of the incoming wind flow have been carried out for three locations of bulk explosions and six values of the initial height (from 70 to 420 m with a step of 70 m) of the dust and gas cloud.*
Research results and analysis. *Spatial distributions of the model's aerodynamic characteristics and contaminants gaseous component when reaching the maximum permissible concentration in the modeled area have been obtained. The estimated time of the open-pit natural ventilation and the dynamics of the open-pit upper edge air contamination dynamics down the wind have been analyzed. The complex and diversified nature of open pit ventilation for various locations of bulk explosions has been recorded. The undulating character of contaminant loss has been predicted (with different heights of peaks) conditioned by the presence of vortex formation in the open pit.*
Conclusion and scope of results. *For the recirculation scheme of ventilation, the situations with the bulk explosion locations shifted to the windward edge of the open pit are the longest. It has been shown that the reduction in the dust and gas cloud lift does not always ensure the reduction in the contamination level at the upper edge of the open pit down the wind.*

Keywords: *open pit; bulk explosion; ventilation; lift; dust and gas cloud; contamination; numerical modeling.*

Introduction. The studies of open-pit aerology greats (Beresnevich P. V., Bitkolov N. Z., Konorev M. M., Mikhailov V. A., Nesterenko G. F., Nikitin V. S., Pavlov A. I., Ushakov K. Z., Filatov S. S. and others [1–6]) contain rich experimental and theoretical material on the issues of open-pit aeration in the course of blasting operations. These studies contain analytical expressions that make it possible to estimate the dimensions of the dust and gas cloud (DGC), its height dynamics depending on the temperature drop in the atmospheric layer, the depth of the wells blasted, and other meteorological and process parameters. The methods and means of protection against dust and toxic gas and the issues of open-pit atmospheric composition control have been discussed in detail.

In paper [7], the author depicted the emerging tendency of using several codes (Flowvision, ANSYS Fluent, ANSYS CFX, COMSOL, etc) to solve the tasks of mining aerology and open-pit aerology [8–15]. It has been conditioned by some factors, including the invention of high-end computers, the development of the software systems of computational dynamics of fluid, and training of a new generation of specialists in the field of information technology. The indicated papers deal with the issue of occupational safety for miners that remains up to date.

Based on the method of numerical modeling, paper [7] analyses the estimated time of open-pit natural ventilation when varying three parameters of the computer model, namely the location of bulk explosions, the initial concentration of the gaseous component in the DGC, and the speed of the incoming wind flow. The issues of DGC initial height effect on open-pit ventilation time and the level of air contamination in the upper edge of the open pit remained undiscussed. This study presents new results concerning the indicated issues to correct these defects.

The research objective is to estimate the effect of bulk explosion location and the initial height of the DGC on open-pit natural ventilation time and the level of air contamination of the upper edge of the open pit down the wind.

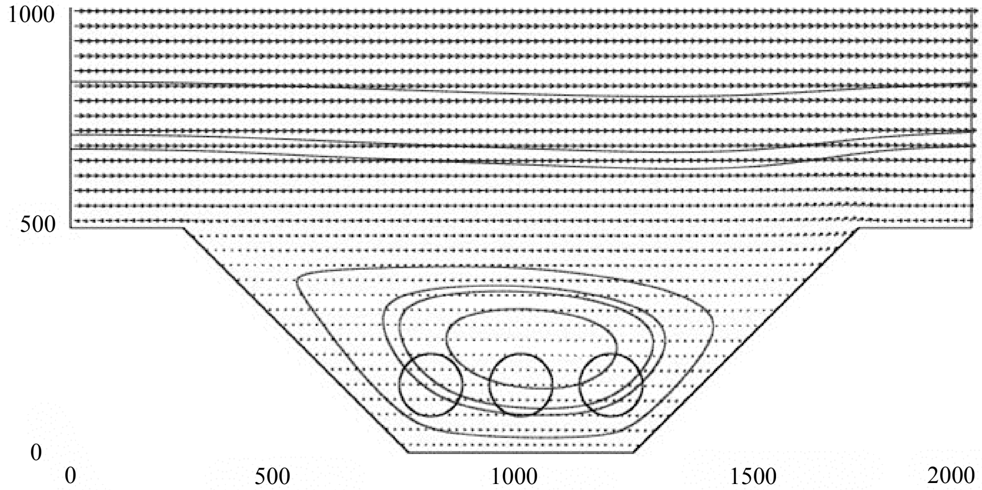

Figure 1. Stationary velocity field and streamlines in the geometric scheme of the open pit model (the contours of the circles show three locations of bulk explosions: left–central–right)

Рисунок 1. Стационарное поле скорости и линии тока в геометрической схеме модели карьера (контуры окружностей демонстрируют три местоположения массовых взрывов: левое–центральное–правое)

Computer model description and the methods of research. To reach the set research objective, the previously constructed COMSOL [16, 17] 2D model of open-pit atmospheric air and gas dynamics has been used [7]. The selected geometry of an open pit (Figure 1) ventilated as per the recirculation scheme [6, p. 34] has been chosen: 500 m deep, 1500 m long in the direction of the wind (relative length of the open pit in the direction of the wind is 3, angle of slope of the leeward pit edge is more than 15°).

In numerical experiments, the following model’s parameters vary. The location of bulk explosions (Figure 1): left – not far from the leeward pit edge and pit bottom border, central – along the center of the pit bottom, and right – not far from the windward pit edge and pit bottom border. The initial lift of the DGC ranges between 70 and 420 m with the step of 70 m.

The calculations hold two parameters fix, namely the initial concentration of the gaseous component in the cloud is accepted equal to 100 maximum permissible concentration (MPC), and the speed of the incoming wind flow at the pit edge 10 m high is equal to 5 m/s.

On the inflow boundary of the model, to set the velocity profile, the logarithmic function is used [18].

For each location of the bulk explosion, one calculation of aerodynamic parameters and six calculations for the initial height of the gaseous cloud are carried out.

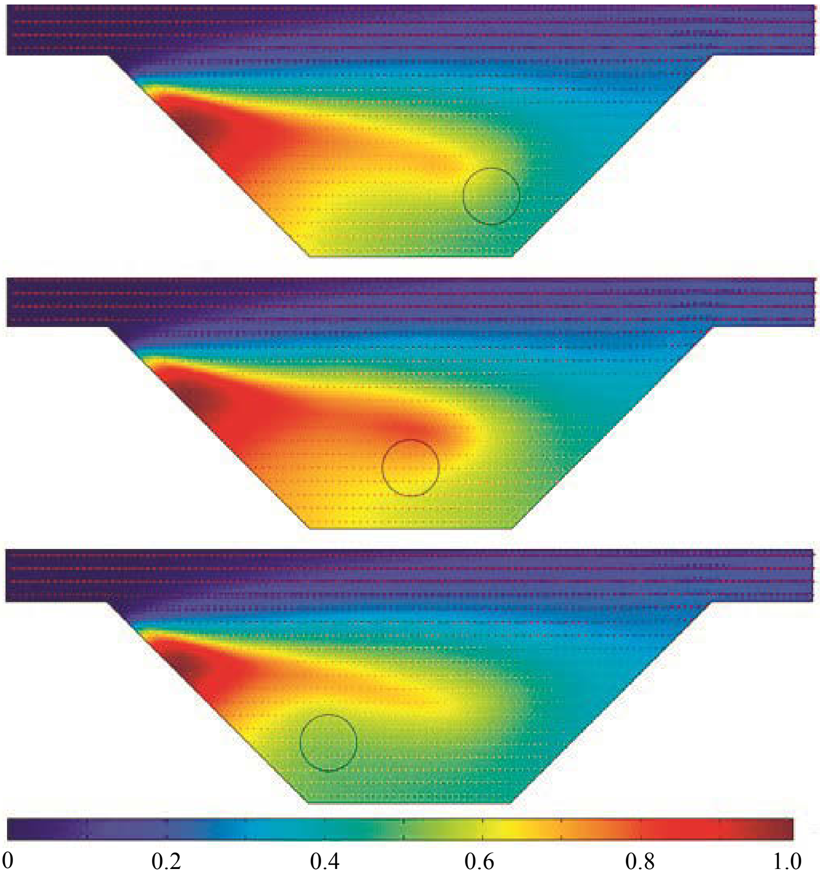

Figure 2. Spatial distribution of contamination in the open pit volume at the time of reaching the MPC level (in the legend – MPC units)
Рисунок 2. Пространственное распределение загрязнения в объеме карьера на моменты времени достижения уровня ПДК (в легенде – единицы ПДК)

Numerical experiments have been carried out at the Extra fine grid (the number of freedom degree is 58,964, and the number of triangular elements is 5,526). The results are analyzed by stages in the same sequence as in paper [7].

At the first stage, open-pit atmosphere aerodynamics is calculated in the approximation of the incompressible fluid (the equation of continuity and the Navier–Stokes equation averaged according to Reynolds) applying the standard k–ε turbulence model (equation of turbulence kinetic energy and its dissipation speed) [19–21]. To obtain the spatial distribution of aerodynamics parameters (field of velocities and the coefficients of eddy viscosity), the stationary problem is solved. Calculation stability is reached by selecting the solver (Direct UMFPACK) and the values of the damping ratios (Isotropic diffusion) for momentum conservation equations and (Turbulence isotropic diffusion) for the k–ε model equations at point 0.5. At the same step, the eddy diffusion coefficient is calculated through the averaging of eddy viscosity ratios spatial distribution by the volume of the modeled area applying the Prandtl–Schmidt number [2].

At the second stage, the distribution of the gaseous component of contamination is modeled by solving the classic nonstationary convection-diffusion equation of passive impurity transfer before contamination in the area modeled reaches the MPC. Calculation stability is ensured by the selection of the indicated solver and damp ratio value (Isotropic diffusion) at the level of 0.75. At this stage, to reach the MPC, multiple numerical experiments had to be carried out to neatly “catch” the estimated time of natural ventilation.

Table 1. The estimated time of ventilation of the open pit with a variation of the initial location of the dust and gas cloud, s

Таблица 1. Расчетное время проветривания карьера при вариации начального местоположения ПГО, с

Initial height of the DGC center, m	Bulk explosions location		
	left	central	right
70	1563	1666	1754
140	1552	1668	1817
210	1501	1723	1917
280	1476	1872	2012
350	1424	1479	1873
420	1352	1346	1272

Each stage undoubtedly employs the initial and boundary conditions required for calculation (e.g. see [22]).

The estimated time of open-pit natural ventilation is analyzed as well as the atmospheric contamination level at the upper edge of the open pit down the wind, depending on the initial lift of the gaseous cloud and the location of the bulk explosion site.

Analyzing the results of numerical experiments. A typical scene of the spatial distribution of contamination in an open pit when reaching the MPC for three locations of bulk explosions under the same initial height of DGC is presented in Figure 2. It can be seen that the area next to the leeward wall is clarified last of all (at the benchmarks near 350 m; zone of stagnation develops there), and the structure of the contamination area for various locations of bulk explosions has particular differences.

Table 1 and Figure 3 illustrate the results for open pit ventilation time under the indicated parameters variation. For the overwhelming majority of the studied situations, the longest processes of ventilation are the situations of the right location of bulk explosions. However, there are some exceptions which are shown in Figure 3 and Table 1.

It seems that for a recirculation scheme of ventilation, the longest are the situations of bulk explosion locations shifted towards the windward pit edge.

Graphs arrangement in Figure 3 testifies to the complex and diversified nature of open-pit ventilation for various locations of bulk explosions. Only in the left location of the bulk explosion, the “behavior” of the graph is rather simple with a gradual (close to the linear dependence) reduction in ventilation time with the increase in the initial height of DGC. In this case, with the growth of DGC initial height, contaminants enter the airflow that carries the contaminants out of the open pit, faster. For the central and the right location, the scene is more complex: up to the height of 280 m (this benchmark approximates to the center of a large vortex formation (Figure 1)) the growth of ventilation time is predicated. However, after that with the growth of DGC initial height, there is a sharp drop. The obtained result seems to be rather fair because under the DGC initial height values of 350 and 420 m for central and right locations, the main volume of contamination does not travel (together with the reverse flow along the pit bottom) towards the leeward pit edge into the zone of stagnation but heads directly out of the modeled area. The longest process of ventilation is predicted for the DGC initial height of 280 m which is conditioned by the fully formed structure of air flows and is fair within the limits of the applied model approximations.

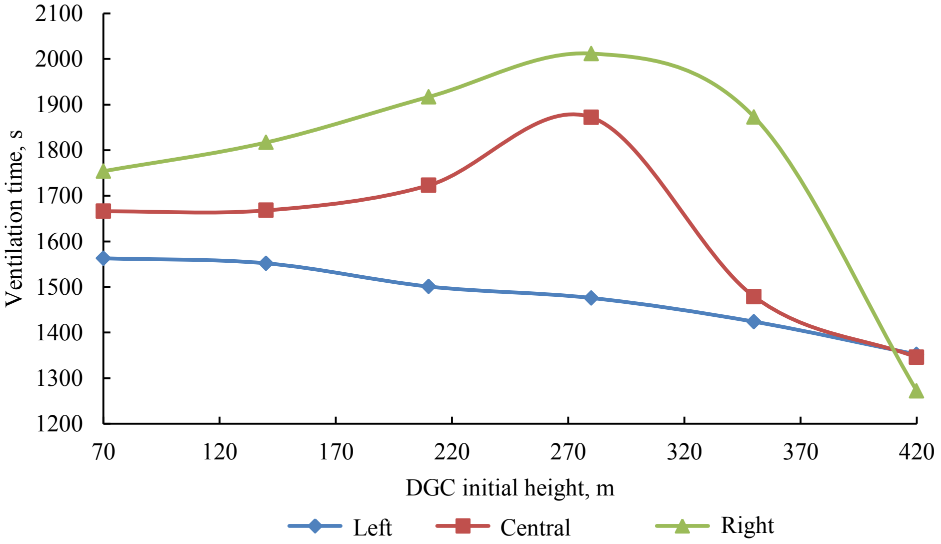

Figure 3. The dependence of the ventilation time on the initial height of the dust and gas cloud for different locations of bulk explosions
Рисунок 3. Зависимость времени проветривания от начальной высоты пылегазового облака (ПГО) для разных местоположений массовых взрывов

Graphs of Figure 4 illustrate the dynamics of air contamination near the upper edge of the open pit down the flow (air contamination in the point with 2000 m coordinate is controlled (Figure 1)) under DGC initial height variation. Figure 4, *a* complies with the left, (while Figure 4, *b* with the central and Figure 4, *c* with the right) location of bulk explosions.

The undulating "behavior" of curves (with different heights of peaks) is common for all situations and testifies to the fact that the contamination leaves the open pit not at one blow (as probably expected). This process, along with the convection-diffusion mechanism, also includes the recirculation conditioned by the physics of the process, i.e. the manifestation of vortex formation.

In Table 2 estimated values of time are presented, which comply with the first peaks of air contamination for three locations of bulk explosions under DGC initial height variation.

For left and central locations, typical is the reduction in the time of reaching the first peak of contamination with the growth of DGC initial height (Table 2), which cannot be recorded for the right location. In this case, with the growth of DGC initial height, the contamination peak access time increases, and starting with height of 280 m time reduction is predicted, which complies with the maximum level of air contamination.

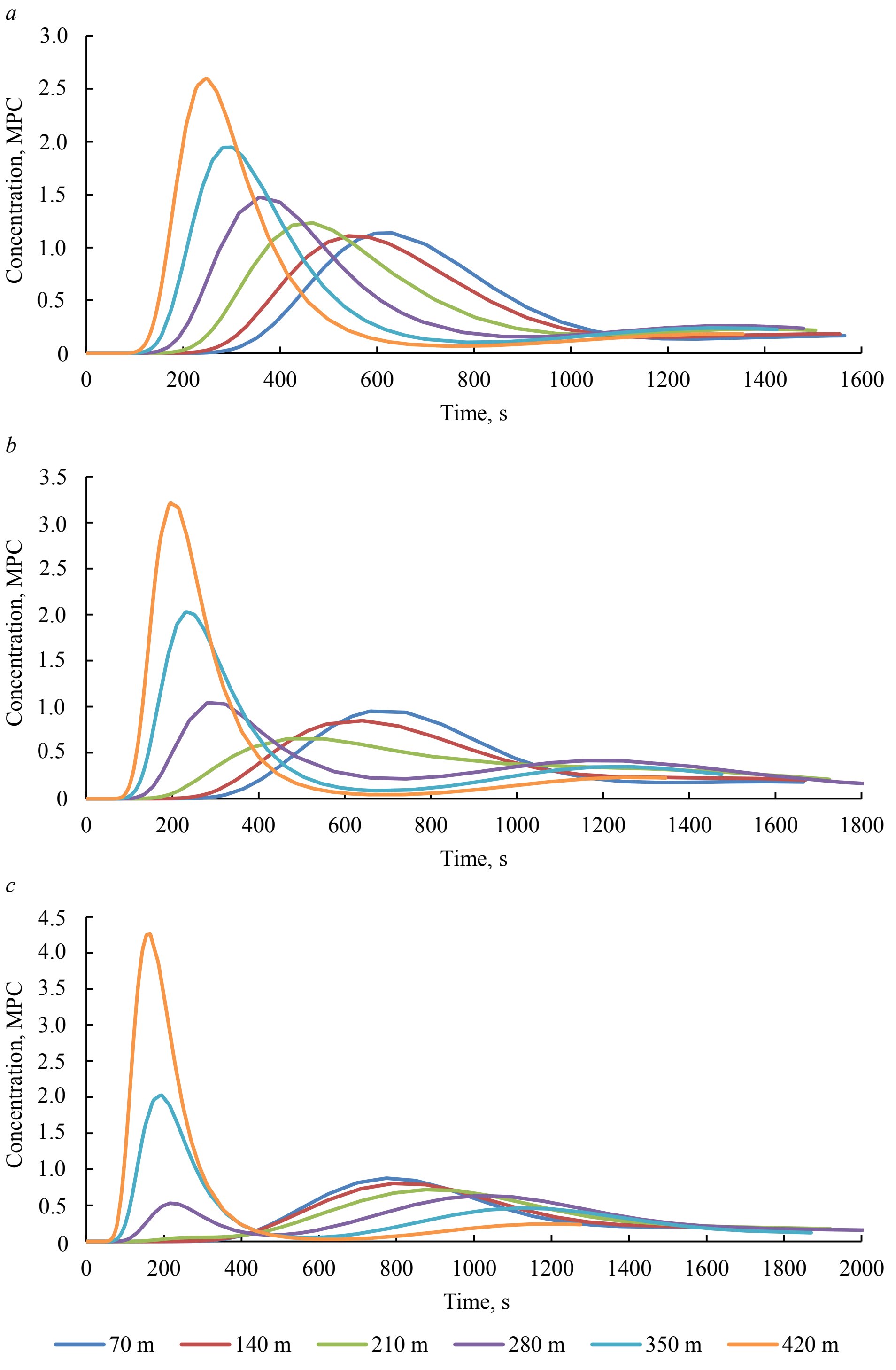

Figure 4. Dynamics of atmospheric contamination at the monitoring point with variations in the initial height of the dust and gas cloud for the left – *a*, central – *b* and right – *c* locations of bulk explosions
Рисунок 4. Динамика загрязнения атмосферы в точке мониторинга при вариации начальной высоты ПГО для левого – *a*, центрального – *b* и правого – *c* местоположений массовых взрывов

The analysis of contamination spatial distribution along the windward pit edge has revealed that within the whole period of ventilation, contamination distribution is close to regular. Notably, the slight growth of contamination (about 7.5% for 100 m) is recorded towards the open pit.

Comparative analysis of contamination peaks does not make it possible to entirely agree with the authors of paper [23]. The indicated paper concludes that DGC lift reduction prevents contaminants from leaving the borders of the open pit space. As can be seen from Figure 4 and Table 2, this rule is not realized in all situations.

For the left location of bulk explosions particularly, the first peak of air contamination at the pit wall under the DGC initial value of 70 m is higher than the first air contamination peak at the pit edge under the DGC initial value of 140 m.

Table 2. The time of reaching the first peak of atmospheric contamination at the monitoring point for three locations of bulk explosions with a variation of the initial height of the dust and gas cloud, s

Таблица 2. Время достижения первых максимумов загрязнения атмосферы в точке мониторинга для трех местоположений массовых взрывов при вариации начальной высоты ПГО, с

Initial height of the DGC center, m	Bulk explosions location		
	left	central	right
70	630	660	775
140	540	640	795
210	465	470	880
280	360	285	215
350	300	235	195
420	250	200	165

For the central location of bulk explosions, the chain of first peaks reduction is 70–140–210 m. In the instance of the right location, the same chain is even longer: 70–140–210–280 m.

It must be emphasized that the obtained results comply with the accepted model approximations. It seems rather obvious that the research should be continued to create a more realistic model, aerothermodynamic first of all. It can be a CFD model where the approximation of the incompressible fluid is supplemented by the heat transfer equation and convection (buoyancy) and background stratification parameters [24–27]. In this case and when solving the convection-diffusion equation of contamination transfer, the gaseous DGC heating factor may be taken into account.

Conclusions. By the numerical modeling method, the effect of bulk explosions location and the DGC initial height on the time of open-pit ventilation and the upper pit wall air contamination level down the wind was studied.

The modified 2D computer model has been used that makes it possible to calculate the open pit air aerodynamics in the approximation of the incompressible fluid applying the standard k–ε turbulence model and the processes of the gaseous component contamination by solving the nonstationary convection-diffusion equation of impurity transfer before contaminants reach the MPC in the area of modeling.

Open-pit natural ventilation time has been analyzed as well as the air contamination dynamics of the upper edge of the pit down the wind when varying two parameters of the model, namely bulk explosion locations and the initial lift of DGC under the fixed values of the gaseous component initial concentration in the cloud and the speed of the incoming wind flow. The complex and diversified nature of pit ventilation for various locations of bulk explosions has been recorded. For the recirculation scheme of ventilation, bulk explosion locations shifted to the windward side of the pit are the longest.

The air contamination dynamics has been analyzed at the upper edge of the open pit down the wind. The undulating character of contaminant loss has been predicted (with different heights of peaks) conditioned by the presence of vortex formation in the open pit. It has been shown that the reduction in the DGC lift does not always ensure the reduction in the contamination level at the upper edge of the open pit down the wind.

The ways have been mapped of the CFD model development by supplementing the approximation of the incompressible fluid with the heat transfer equation and the parameters of convection (buoyancy) and background stratification.

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Information about authors:

Pavel V. Amosov – PhD (Engineering), leading researcher, Institute of North Industrial Ecology Problems KSC RAS. E-mail: p.amosov@ksc.ru; https://orcid.org/0000-0002-7725-6261

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Численное моделирование процесса проветривания карьера при вариации местоположения пылегазового облака

Амосов П. В.[1]

[1] Институт проблем промышленной экологии Севера КНЦ РАН, Апатиты, Россия.

Реферат

Цель работы. *Оценка влияния местоположения массовых взрывов и начальной высоты пылегазового облака на время естественного проветривания карьера и уровень загрязнения атмосферы верхнего борта карьера вниз по ветровому потоку.*

Методика. *Компьютерное моделирование аэродинамики и переноса газовой компоненты в двухмерной геометрии выполнено с помощью программы COMSOL. Для вычисления аэродинамических характеристик применялось приближение несжимаемой жидкости с привлечением стандартной (k–ε)-модели турбулентности. Процесс распространения газовой компоненты промоделирован посредством численного решения конвективно-диффузионного уравнения переноса загрязнений. Численные эксперименты при фиксированной начальной концентрации газовой компоненты и скорости набегающего ветрового потока выполнены для трех местоположений массовых взрывов и шести значений начальной высоты (от 70 до 420 м с шагом 70 м) пылегазового облака.*

Результаты и их анализ. *Получены пространственные распределения аэродинамических характеристик модели и газовой компоненты загрязнений на момент достижения уровня ПДК в области моделирования. Выполнен анализ расчетного времени естественного проветривания карьера и динамики загрязнения атмосферы верхнего борта карьера вниз по ветровому потоку. Отмечен сложный и разнообразный характер процесса проветривания карьера для различных местоположений массовых взрывов. Спрогнозирован волнообразный характер выноса загрязнений (с разной высотой максимумов), обусловленный наличием в карьере вихреобразования.*

Выводы и область применения. *Для рециркуляционной схемы проветривания наиболее продолжительными являются ситуации местоположения массовых взрывов, смещенных к наветренному борту карьера. Показано, что уменьшение высоты подъема пылегазового облака не всегда обеспечивает снижение уровня загрязнения на верхнем борту карьера вниз по потоку.*

Ключевые слова: *карьер; массовый взрыв; проветривание; высота подъема; пылегазовое облако; загрязнение; численное моделирование.*

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Сведения об авторах:

Амосов Павел Васильевич – кандидат технических наук, ведущий научный сотрудник Института проблем промышленной экологии Севера КНЦ РАН. E-mail: p.amosov@ksc.ru; https://orcid.org/0000-0002-7725-6261

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