UDC 550.34.01:504.3.054

I.S. Lowndes, **S.A. Silvester**, **S.W. Kingman**, *Prof.,* **D.M. Hargreaves**
Process and Environmental Research Division, University of Nottingham, UK

IMPROVED MULTI-SCALE COMPUTATIONAL MODELLING OF FUGITIVE DUST DISPERSION FROM SURFACE MINING OPERATIONS

Abstract. *The extraction and processing of minerals from surface mines and quarries can produce significant fugitive emissions as a result of site activities such as blasting, unpaved road haulage, loading, primary crushing and stockpiling. Uncontrolled fugitive dust emissions can present serious environmental, health, safety and operational issues impacting both site personnel and the wider community. Simulation technology is finding increasing use for the purposes of advanced warning of potential problem emissions in addition to providing a basis for future planning applications where demonstrable compliance with regulatory requirements are necessary. The initial re-entrainment and subsequent dispersion of fugitive dust presents a process complicated by the combination of the in pit topography, the surrounding natural topography and the dynamic nature of emissions from these sites. These factors impact upon the accuracy and reliability of the conventional Gaussian plume based computational prediction methods employed for regulatory compliance and IPPC applications. This paper proposes that optimal modelling of open pit emissions may be more accurately achieved by the use of a multi-scale predictive modelling approach utilising computational fluid dynamic (CFD) methods for high resolution near source dispersion and conventional Gaussian based methods for far field dispersion modelling.*

This paper presents a numerical based flow and dispersion analysis of a typical UK based open pit utilising CFD in conjunction with a conventional Gaussian plume based methods. Typical operating emissions and meteorological conditions are obtained from long term data records collected at a large operating quarry extraction operation in the UK. Emissions are modelled using a Lagrangian framework within conventional atmospheric boundary layer (ABL) profiles expressed as functions of turbulence and velocity parameters under assumed neutral conditions. Results are presented in terms of the impact of site topography on in pit retention as compared to the Gaussian based method.

Keywords: *dust dispersion, CFD, surface mines.*

1 Introduction

As open pit mines and quarries become deeper and more productive the potential to produce greater pollutant emissions including fugitive dust emissions will increase. To maintain and enhance the health and safety of the extractive and transport operations and to minimise off site dust emissions it is necessary to design effective mitigation measures to minimise fugitive dust emissions, and to maximise the ventilation of the pit opening to dilute, disperse and remove fugitive dust from the workings. The principal tool available to environmental engineer is to use the shape of the excavation and the surrounding topography to harness the penetration of the natural wind systems to maintain the air exchange rates within the mine opening. The determination of the internal ventilation regime within the open pit is a complex process as the driving natural wind system will change subject to diurnal and seasonal changes in its strength and direction, which are dictated by the local wind systems and the differential heating of the earths surface by the sun.

The background local wind system may be modelled by the construction of a three dimensional velocity profile called the atmospheric boundary layer (ABL). The ABL model requires the definition of the surface roughness of the surrounding topology, a measured reference height velocity above the terrain and the determination of the thermal stability of the atmosphere. The strength and the direction of the resulting downwind ABL will be influenced by the topography of the terrain surrounding the open pit and the shape and depth of the excavation. The internal microclimate is created by a combination of: the degree the external ABL penetrates the mine opening; the in pit topography; and the diurnal heat exchanges between the sun, the internal surface of the pit and the atmosphere. These internal ventilation flows will be responsible for the initial dilution, dispersion of any fugitive dust emissions within the open pit. In turn, the amount of air exchange affected between the internal ventilation regime and the mainstream ABL flowing over the mine opening will determine the degree of off-site fugitive dust emission experienced.

Dust dispersion rates may be attenuated by low airflow exchange rates caused by the recirculation of local ventilation flows or containment by thermal inversions. The retention of ambient dust levels will potentially decrease visibility and increase the exposure of workers.

2 Atmospheric flow over complex terrains

The prediction of local wind field over complex terrain with hills, valleys and open pit mines provides information that is critical to assess the prediction of pollutant dispersion in the atmosphere [13]. The global circulation or mesoscale models of atmospheric flow are nor suitable for such purposes for two reasons: (a) They are based on the hydrostatic approximation in which a balance is assumed between the pressure and gravity fields in the vertical direction, and (b) The hydrostatic assumption (appropriate and convenient for length scales of the order of 100 kilometres) is not required to address local wind effects within valleys and surface openings such as mines and quarries. Pressure changes due to inertial effects in the vertical direction cannot be neglected at the local scales. And secondly, the mesoscale models are not able to resolve variations in topography in the vertical direction that are important to the prediction of local wind patterns within open pit mines that typically involve flow separations and recirculation eddies [5] on surfaces of varying roughness. For the purposes of predicting local wind patterns, it is necessary to use microscale models. These are usually based on the numerical solution of the Reynolds-averaged Navier -Stokes (RANS) equations and a turbulence model in a boundary-fitted coordinate system that follows the local terrain.

3 Dust dispersion models for surface mining operations

A recent research project [17], collated a comprehensive review of the fugitive dust emissions that may be generated from surface mining operations and summarises the range of conventional mitigation technologies and strategies that may be applied to control these emissions. This report presents a summary of the potential dust sources and mitigation strategies, and also presents a detailed overview of the current UK and International environmental and health and safety legislation governing mineral dust emissions. In addition [19] has recently produced a comprehensive review of the dust dispersion models that have been developed or applied to the prediction of dust from surface mining operations including quarries. The dust dispersion models used to predict emissions from surface mining operations are generally adapted from existing regulatory industrial air pollution models.

A major challenge to the modelling the dispersion of fugitive dust emissions from deep surface mines or hard rock aggregate quarries is the influence of the in pit meteorology. As most Gaussian plume dispersion models have been developed to model downwind dispersion of dust from sources across a flat or undulating terrain, these models cannot account for the influence that the complex flow regimes that exist within quarry openings. As fugitive dust emissions within a quarry are transported and dispersed by the local airflow field within the quarry, there is a need to develop transport and deposition models that reproduce the local effects produced by these flows.

The airflow regime within a deep quarry opening is produced by the combined action of the mechanical shear of the atmospheric boundary layer across the surface opening and the thermal buoyancy forces created by the differential heating of the quarry surface by the passage of the sun during the day. In addition, the occurrence of thermal temperature inversions at night may also assist trapping the dispersion of the dust emissions from within the quarry. The combination of these forces creates: (1) an external flow field across the surrounding terrain and across the interfacial quarry opening that is governed by the atmospheric boundary layer (ABL), and (2) an internal flow field driven by the combination of the mechanical shear of the atmospheric boundary layer across the surrounding terrain and the airflow within the quarry opening, and the thermal effect created by the differential heating of the internal quarry surfaces by the sun (see Fig. 1). To improve the understanding and modelling of these processes requires the adoption of a multi-scale modelling approach; this is discussed in a following Section 6.

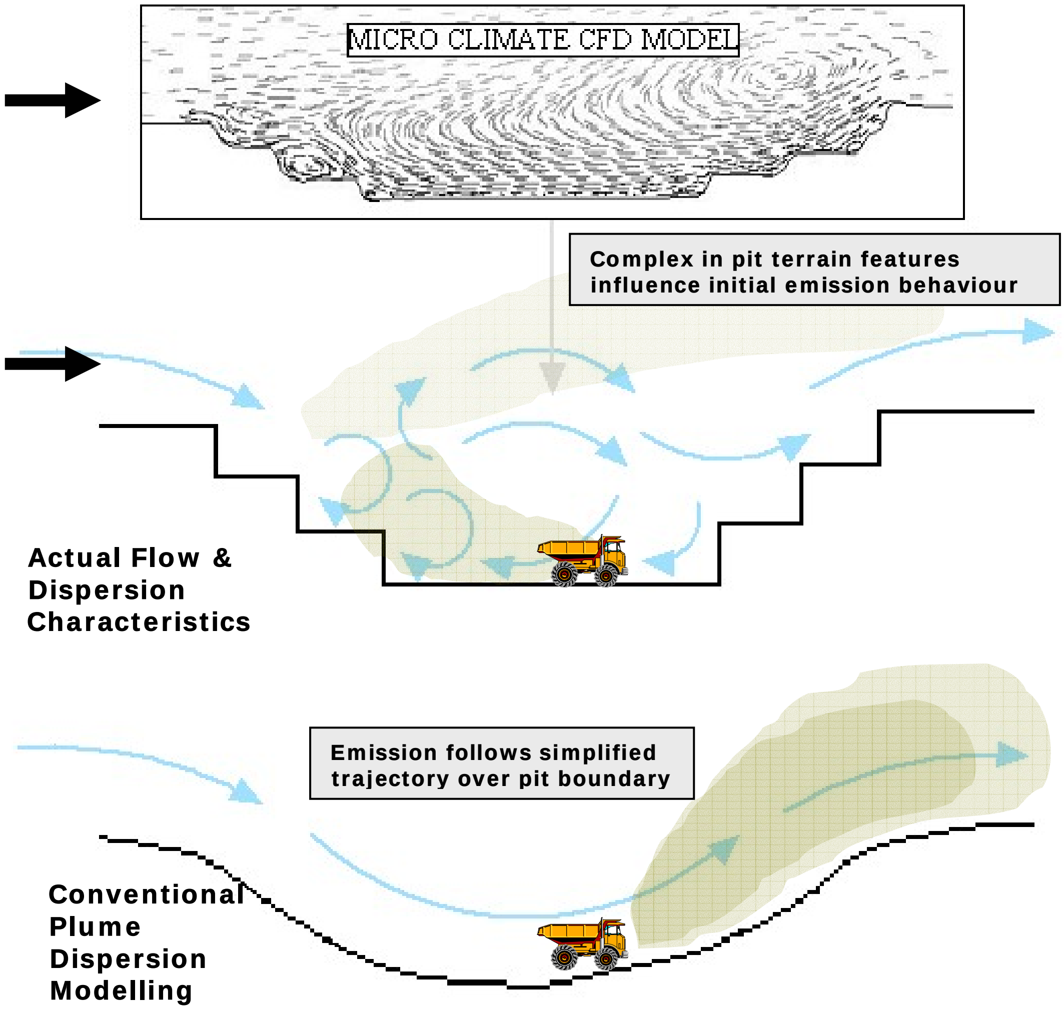

Fig. 1 – The influence of in-pit micro climate on dust dispersion.

Thus, a fugitive dust emission within a quarry will be transported and dispersed by this locally generated flow field. The creation of this chaotic, and often recirculatory in-pit flow regime within the quarry will increase the residence time of the entrained dust particles within the confine of the quarry. As the deposition of particles is governed by Stokes Law, any increase in the dust residence time within the quarry may allow either; (1) allow the settlement of many of the dispersed dust particles or (2) increase the probability of their removal by impaction on the internal surfaces of the quarry. Consequently, only a fraction of the fugitive dust emitted and dispersed within the confines of the quarry will cross the interfacial layer defined between the quarry opening and the atmospheric boundary layer to be dispersed and potentially deposited downwind across the surrounding terrain. The fraction of the dust emission which crosses the interfacial layer between the quarry opening and the ABL will form an equivalent areal emission source whose downstream dispersion may be modelled by conventional Gaussian plume models.

This paper presents a summary of a selection of the results from a series of recent fugitive computational fluid dynamics studies conducted by the team of researchers at the University of Nottingham. These studies were validated using field meteorological and dust deposition data collected at an extensive UK limestone quarry in the UK. The full details of these field validated computational fluid dynamic studies are contained within a series of recent research papers that have been submitted to a number of peer reviewed technical journals.

The field study quarry, Old Moor is located within the Tunstead Quarry Works operated by Tarmac Ltd, north of Buxton in Derbyshire, UK. The investigation has considered mineral extraction and comminution operations at the Tarmac Ltd operated Tunstead and Old Moor Quarries in Derbyshire, UK (‘the site’). The majority of the site is located on the boundary of the Peak National Park; the boundary of the Park bisects Old Moor in a general North-South direction. There are 6 designated Sites of Special Scientific Interest (SSSIs) located within approximately 2 km of the site. The quarries are physically separated by a 50 m deep valley that is known as Great Rocks Dale. All comminution circuits and mineral stockpiles are contained within the boundaries of the Tunstead site. The mineral deposits are exposed for extraction by overburden removal and then by blasting. Overburden at the site is minimal, and is removed and stored for future use in restoration and rehabilitation. Bench blasting is carried out in both quarries, typically up to 5 times per week. Further details of the quarrying and mineral transport and processing operations at the works may be found in the research papers [4,13,17,18,21].

4 The modelling of the near pit and in–pit topography

The terrain immediately surrounding the boundary of the Old Moor quarry is undulating farm grazing land. The in pit quarry topography of the quarry is characterised by a complex series of interconnected ramps, vertical faces and working benches. Detailed site elevation survey data at 4 m grid spacing was able to delineate the detailed topography of the working pit and surrounding terrain. This data was used to construct the surface topography of the model domain within the Gambit pre-processor model used by the commercial Fluent™ software used to construct the flow and dust dispersion simulations. The size of the total model domain constructed was approximately 4 km x 4 km. The model was capable of being rotated to allow for the ease of simulation of the direction of the simulated atmospheric boundary layer to represent the mean average wind sped and direction. The rectangular domain mesh was divided into four primary flow boundaries, a background flow inlet and outlet and two boundary walls to define the flow across the quarry opening.

5 The modelling of the ABL

The inlet ABL velocity profile was defined using a logarithmic profile. All ground surfaces were defined using a roughness height of 0.1 m in accordance with the recommendations of the ADMS user guide [3]. Following the studies of Riddle et al [18] the Reynolds Stress (RSM) turbulence flow model was used as it is demonstrated to maintain the turbulent kinetic energy (TKE) and dissipation. The modelled ABL was allowed to develop from inlet boundary across the surrounding terrain before it crosses the open surface of the quarry. The simulated velocity profiles and directions corresponded to the principal flow conditions determined from the meteorological record recorded on site. For all of the initial flow models constructed neutral thermal stability class conditions were assumed, which correspond to stability class D on the Pasquill-Gifford scale.

6 Fugitive dust emission and dispersion models

In accordance with the dust sampling and modelling methodology developed in [4], four particle sizes 0.05, 0.45, 0.3 and 75 μm, at mass fractions of 0.05, 0.45, 0.3 and 0.2 respectively were used to simulate fugitive dust emission sources within the quarry. The quantity of dust released from each individual or collection of fugitive dust emission events modelled (e.g. bench blasting, loading, truck haulage etc.) were calculated using the emission factors defined by the US EPA AP-42 fugitive dust emission models [1,2].

7 The simulation of the natural ventilation of the quarry excavation: the generation of recirculation airflows

To simulate the natural ventilation regime promoted within the surface quarry excavation, a series of models simulation were performed to replicate the micro climate that is produced within the quarry opening subject to the predominant seasonal prevailing wind directions and speeds identified from the meteorological record. The results of such a simulation are illustrated on Fig. 2. This dark shaded volumes on the leeward and windward

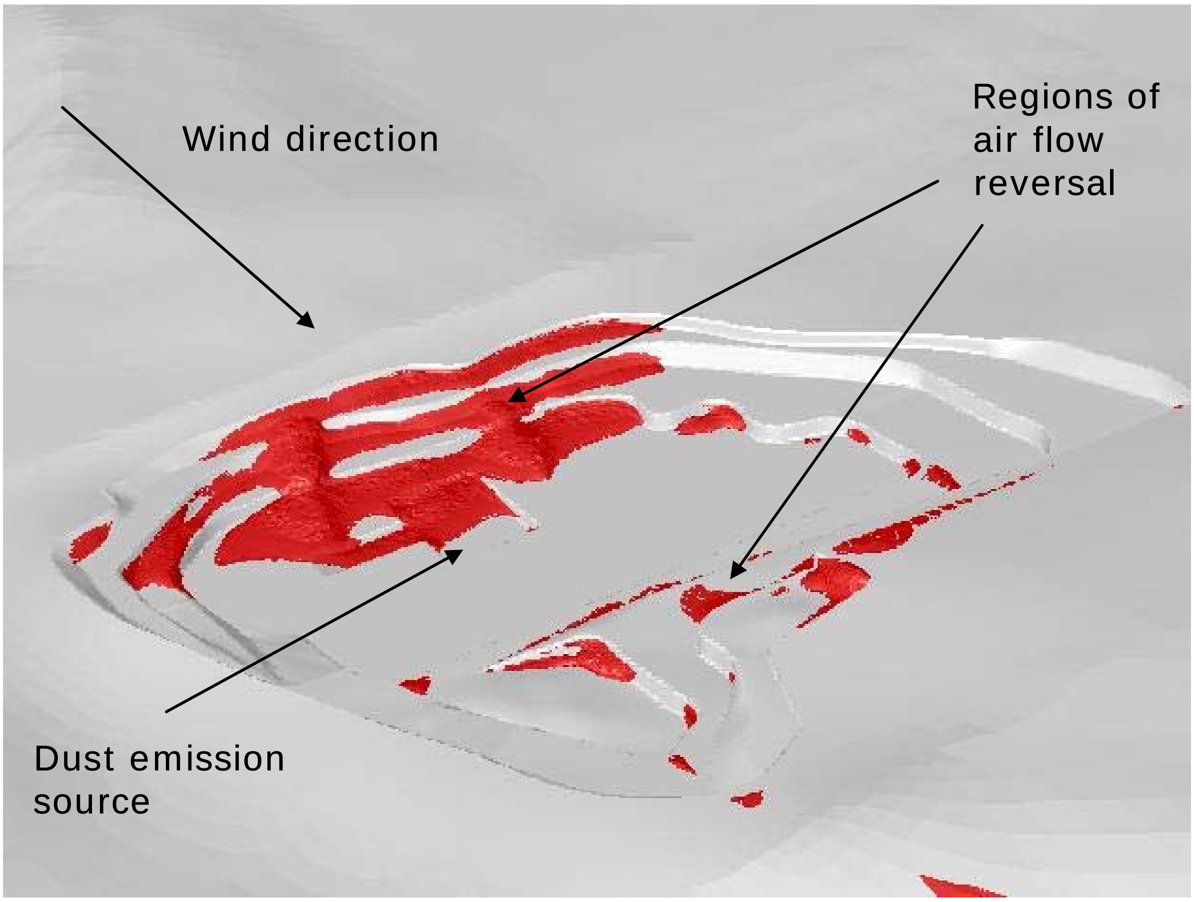

Fig. 2 – The creation of recirculation flow zones within the pit opening.

slopes of the quarry represent the areas of recirculatory flows, counter to the normal background ABL flow regime, that are produced by the interaction of a north westerly prevailing wind and the in pit topology. The results of these simulations are consistent with the findings of the previous two dimensional modelling studies of Baklanov [6,7,8] and other Russian scientists.

The generation of these recirculatory airflows is observed to create micro climates that are observed to influence the emission, dispersion and deposition of dust emitted within the quarry opening. As outlined earlier in the paper, conventional Gaussian plume models used to estimate fugitive dust emission and deposition for regulatory purposes, employ modified emission models for shallow open pit mines to replicate the resultant retention of fugitive dust emission from the open pit opening. However, it is suggested that the use of a more sophisticated in pit ventilation models would more accurately represent the true in pit dust dispersion and deposition regime, and determine the true fraction of the original emission that is transported out of pit to be dispersed by the background ABL.

8 The influence of the in pit topology to deposition

Figure 3 illustrates the influence that the downwind surface topology can have on the dispersion and deposition of fugitive dust emissions. The modelled stationary areal dust source is located at the lowest elevation of the quarry. The modelled prevailing wind direction crosses the quarry opening from a westerly direction. The influence that an increase in the detail of the in pit topology has on the dispersion and deposition of the fugitive dust source is illustrated by comparing the results of successive simulations that increase the density of the in pit domain mesh. From an examination of the dust deposition simulation results shown on the figures, starting at the top left hand side and moving in a clockwise direction, it is observed that as the detail of the topology including the elevation changes increases, the greater is the degree of near source deposition.

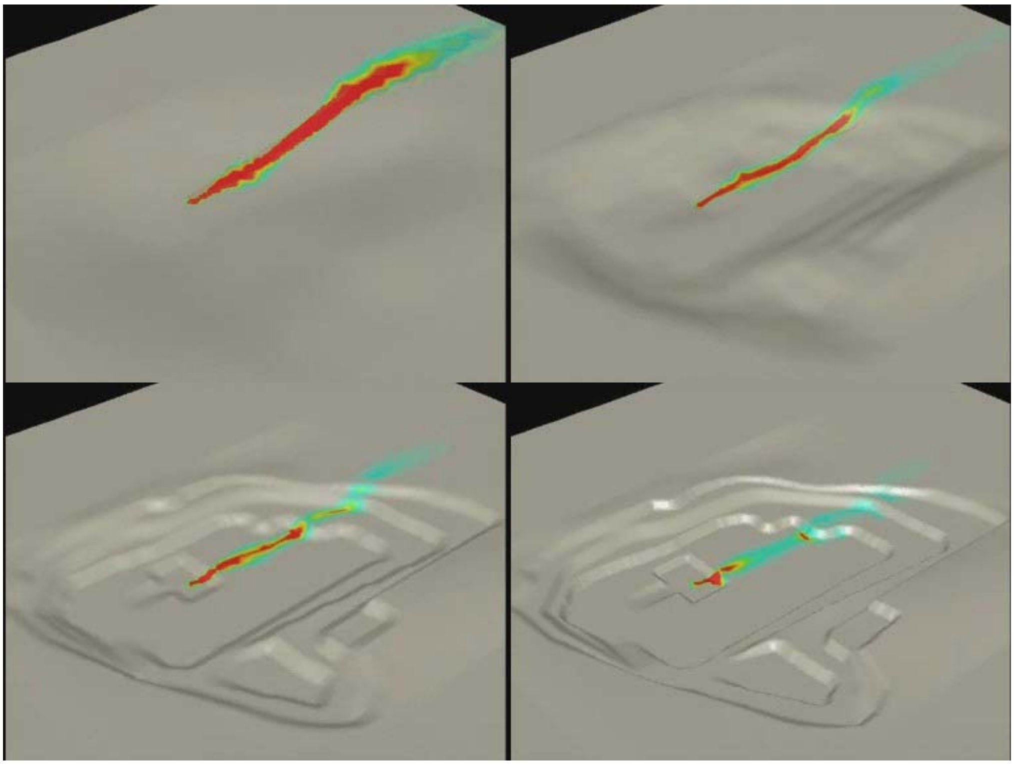

Fig. 3 – The influence of increased topography detail on dust deposition

Consequently, it is concluded that under neutral stability conditions that the combination of the prevailing wind direction and speed together with the in pit topography create an in pit ventilation regime and micro climate that will greatly influence both the dispersion and deposition of fugitive dust sources within the confines of the surface opening.

The influence of the microclimate may both contain or enhance or attenuate the dispersion and hence dilution of the fugitive dust that may decrease the visibility within the open pit, or may attenuate the fugitive dust emissions within the opening due to the increased impaction and removal afforded by the recirculatory ventilation flows induced within the quarry.

9 The development a multi-scale modelling approach

An analysis of the results of this and the series of previous recent research studies conducted at the University of Nottingham conclude that it would be sensible to consider the adoption of a multi-scale modelling approach to assessment of the emission, dispersion and deposition of fugitive dust from in pit fugitive dust sources.

A number of recent research studies have concluded that the use of the US EPA AP-42 dust emission models for large open pit and quarry operations, together with the in pit dust retention models together with conventional Gaussian plume dispersion models can produce over predictions of off site emission and deposition. These studies have also concluded that these methods are unable to replicate the true nature of the in pit fugitive dust emissions, dispersion and deposition. The use of a more complex three dimensional field validated computational model, may allow the improved simulation of these events, which could allow the mine operator to predict the occurrence of in pit reduced visibility.

It is therefore proposed the development of a three scale modelling approach.

The development of improved dust emission models to more accurately represent the emission characteristics of the various stationary and mobile in pit fugitive dust sources, including unpaved road truck haulage models.

The development of a simplified, less complex three dimensional computational fluid dynamic model, that allows the engineer to more accurately predict the influence of the generated in pit microclimate has on the dispersion and deposition of fugitive dust within the open pit workings.

The development of an interface between the model described in (2) above, with which to determine an areal emission factor dust through a defined area across the mine opening and the transference of the determined areal dust emission to the background ABL, the resultant far field downwind dust dispersion to solved by a conventional Gaussian plume dispersion model.

References

1. *Anon* (1995) USEPA, AP-42, Compilation of air pollution factors, Vol 1: Stationary point and area sources, Chapters 13.2.4, Aggregate handling and storage piles, Research Triangle Park, NC, USA.
2. *Anon* (1998) USEPA, AP-42, Compilation of air pollution factors. Vol 1: Stationary point and area sources. Chapter 13.2.2: Unpaved roads, Research Triangle Park, NC, USA.
3. *Anon* (1999) ADMS User Guide. CERC Ltd, Cambridge, UK.
4. *Appleton, T.J., S.W. Kingman, I.S. Lowndes and S.A. Silvester* (2006) The development of a modelling strategy for the simulation of fugitive dust emissions from in-pit quarrying activities: a UK case study. International Journal of Mining, Reclamation and Environment, 20, 1, pp 57–82.

5. *Atkinson, B.W.* (1995) Introduction to the fluid dynamics of mesoscale flow fields, in Diffusion and Transport of Pollutants in Atmospheric Mesoscale Flow Fields. Kluwer Academic Publishers, Dordrecht, pp.1–20
6. *Baklanov, A.A*. (1984) Determining the propagation of impurity in the atmosphere of a pit on the basis of mathematical models. Soviet Mining Science, 20(5), pp. 402–407.
7. *Baklanov, A.A*. (1986) A method of evaluating the energy characteristics of the air in an open pit mine. Soviet Mining Science, 22(1), pp. 66–70.
8. *Baklanov, A.A*. (1995) Numerical modelling of atmosphere processes in mountain cirques and open pits. Proceedings of International Conference on Air Pollution, Porto Carras, Greece, pp. 231–238.
9. *Baklanov, A.A. and O.Yu. Rigina* (1994) Research of local zones atmosphere normalization by artificial currents. Proceedings of the 2nd International Conference on Air Pollution, WIT, Computational Mechanics Publications, pp. 553–561.
10. *Belousov, V.I.* (1985) Natural dynamic ventilation of open mines. Soviet Mining Science, 21(3), pp. 264–267.
11. *Belousov, V.I.* (1990) Ventilation of open-pit mines by controlling the boundary layer of the wind stream. Soviet Mining Science, 25 (3), pp. 267–270.
12. *Bukhman, Y.Z, A.L. Kazakov and V.I. Belousov* (1976) Manual to open pit ventilation in USSR nonferrous metallurgy (in Russian). Izd. VTsM SSSR, Moscow.
13. *Docx, J., S.W. Kingman, E.H. Lester, I.S. Lowndes, S.A. Silvester and T. Wu* (2007) An investigation into unpaved road emissions from a UK surface limestone quarry using cylindrical adhesive pad collectors and image analysis. International Journal of Mining, Reclamation and Environment, 21, 1, pp. 1–18.
14. *Kim, H. G., V.C. Patel and M.L. Chuong* (2000) Numerical simulation of wind flow over hilly terrain. Journal of Wind Engineering and Industrial Aerodynamics, 87, pp. 45–60.
15. *Nikitin, V.S. and N.Z. Bitkolov* (1975) Mine Ventilation (in Russian). Nedra, Moscow.
16. *Peng, X. and G.R. Lu* (1995) Physical modelling of natural wind and its guide in a lrge open pit, Journal of Wind Engineering and Industrial Aerodynamics, 54/55, pp. 473–481.
17. *Petavratzi, E., S.W. Kingman and I.S. Lowndes* (2007) Assessment of the dustiness and the dust liberation mechanisms of limestone quarry operations, Chemical Engineering and Processing, 46, pp. 1412–1423.
18. *Petavratzi, E., S.W. Kingman and I.S. Lowndes* (2005) Particles from mining operations: A review of sources, effects and regulations. Minerals Engineering, 18, pp. 1183–1199.
19. *Reed, W.R.*(2005) Significant dust dispersion models for mining operations. *NIOSH IC 9478*, Pittsburgh, PA, USA.
20. *Riddle, A., D. Carruthers, A. Sharpe, C. McHugh and J. Stocker* (2004) Comparisons between Fluent and ADMS for atmospheric dispersion modelling. Atmospheric Environment, 38, pp. 1029–1038.
21. *Silvester, S.A., I.S. Lowndes and S.W. Kingman* (2006) The application of computational fluid dynamics to the improved prediction of dust emissions from surface quarrying operations. Proceedings of the Fifth International Conference on CFD in the Process Industries, CSIRO, Melbourne, Australia, pp. 1–6.

Усовершенствованная многомасштабная вычислительная модель распространения летучей пыли при эксплуатации карьеров

Аннотация. *Добыча полезных ископаемых из карьеров и открытых выработок и их первичная переработка может сопровождаться выделением значительного количества летучих веществ в результате таких действий, как горные взрывные работы, транспортировка по грунтовым дорогам, погрузка, первичное дробление и аккумуляция запасов. Неконтролируемые выбросы летучей пыли могут* *представлять серьезную опасность для окружающей среды, здоровья, безопасности и работоспособности людей, как находящихся в непосредственной близости от места разработок, так и вдали от них. С целью предварительного предупреждения потенциально опасных выбросов, также как и для разработки программ по будущему планированию, которые должны отвечать требованиям регламентирующих документов, все более широко применяют технологии моделирования. Вторичное вовлечение пыли на начальном этапе и последующее ее распространение представляют собой процесс, усложненный топографией внутри открытых выработок, топографией окружающей местности и динамикой выбросов из мест разработок. Эти факторы влияют на точность и надежность стандартных вычислительных прогностических методов, в основе которых лежит гауссова модель факела, и которые используются для регламентирующих инструкций и программ в проекте IPPC ("Комплексный контроль и предупреждение загрязнения"). В данной статье предполагается, что оптимальное моделирование выбросов из открытой выработки наилучшим образом может быть достигнуто при применении многомасштабной прогностической модели, использующей методы вычислительной гидродинамики (ВГД) для зоны с высоким разрешением вблизи источника и стандартную гауссову модель для дальней зоны. В данной статье представлен анализ численного моделирования атмосферных потоков и рассеяния примеси для типовых открытых выработок Великобритании. Характерные параметры выбросов и метеорологических условий были получены из данных долгосрочных записей, собранных на действующих открытых выработках Великобритании. Выбросы были смоделированы лагранжевой схемой для типичных профилей в пограничном слое атмосферы, выраженных как функции характеристик скорости параметров турбулентности при нейтральной стратификации. Представленные результаты получены с учетом влияния топографии местности на удерживающую способность шахты, в отличие от метода, базирующегося на гауссовой модели факела.*

Ключевые слова: *распространение пыли, вычислительная гидродинамика, карьеры*