*Fifth International Conference on CFD in the Process Industries*
*CSIRO, Melbourne, Australia*
*13-15 December 2006*

# THE APPLICATION OF COMPUTATIONAL FLUID DYNAMICS TO THE IMPROVED PREDICTION OF DUST EMISSIONS FROM SURFACE QUARRYING OPERATIONS

**Stephen SILVESTER, Ian LOWNDES, Joseph DOCX, Sam KINGMAN**

School of Chemical, Mining and Environmental Engineering, University of Nottingham, Nottingham, UK

## ABSTRACT

The extraction and processing of minerals from surface quarries can produce significant fugitive emissions as a result of attrition and re-entrainment processes. Dust generation, liberation, re-entrainment and dispersion present serious environmental, health, safety and operational issues. The initial re-entrainment and subsequent dispersion of fugitive dust presents a process complicated by the combination of man-made topography, natural topography and the dynamic nature of emissions unique to these sites. These factors impact upon the accuracy and reliability of established gaussian plume based models where accurate source characterisation is imperative. This paper presents a study on the potential benefits of using CFD as a means by which emissions sources can be more accurately characterised and subsequent localised dispersion modelled with due regard to the localised turbulence and secondary flows typical of these sites. Atmospheric flow field data is provided via CFD simulations performed on a UK case study site. Blasting emissions are modelled through lagrangian particle tracking incorporating a dynamic momentum source representing the initial blast front. Haul truck emissions are characterised through the simulation of a CAT777D dump truck and assessment of the dispersion of re-entrained particulates in the immediate vehicle wake zone. The results are compared to conventional gaussian plume based models and site field study data.

## NOMENCLATURE

| | |
|---|---|
| *U(z)* | Velocity at height z |
| z | Height |
| z0 | Surface roughness |
| $U_*$ | Friction velocity |
| *K* | Von Karman's constant 0.4 |
| *k* | Turbulent kinetic energy |
| $\varepsilon$ | Turbulent dissipation rate |

## INTRODUCTION

The surface minerals extraction industry poses significant environmental impact upon neighbouring residential areas in addition to on site personnel in terms of exposure to fugitive dust, in particular PM10s (QUARG, 1996). Efforts to reduce these emissions via the implementation of improved processing equipment, shrouds, water treatments etc have led to significant reductions in recent years. However, with increased pressure from governmental environmental agencies research in this area remains highly active. For purposes of planning it is often necessary to perform predictive modelling to forecast potential future emissions such that regulatory approval may be gained. It is therefore essential that any modelling carried out to perform such a task can be relied upon since inaccuracies may lead to planning alterations or even rejection. This paper explores the potential usage of CFD for the purposes of improving the understanding of the initial dispersal of fugitive dust produced from in pit blasting and haulage traffic within the locality of the source (in pit). The approach investigates the possibility of the complimentary use of CFD modelling for the purposes of improving long range gaussian plume modelling. Similar themes have been raised in recent studies (Brown and Fletcher, 2003; Riddle et al, 2004). The work is carried out in response to a related reported study (MIST, 2004) whereby methods using conventional modified gaussian plume based models were found to under perform in close proximity to the source when applied to ground emissions from a surface extraction site.

## BACKGROUND

### The Site

This investigation is based upon the topography of a limestone surface extraction facility located in Derbyshire, UK.

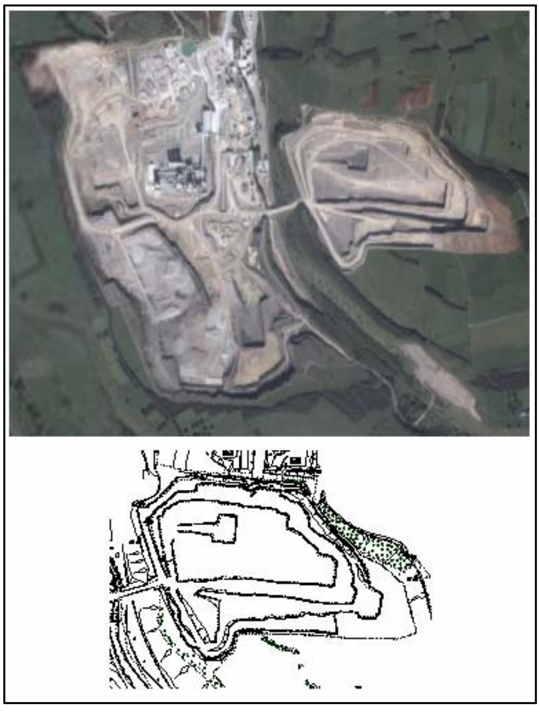

**Figure 1**: Site topography and survey detail.

The site in its entirety is referred to as 'Tunstead' and is comprised of two adjoined quarries, Tunstead, the larger of the two, and 'Old Moor', a relatively new extraction. This paper will focus upon the Old Moor section, hereafter referred to as 'the site'. The site operates a typical blast and haul methodology; typically a blast event occurring daily will liberate 20,000 to 60,000 tonnes of limestone for processing within the site comminution circuit. The site is typical of UK based extraction facilities being located close to residential settlements and bordering a national park. For these reasons, site particulate emissions are of significant concern to the operators who have come under increased pressure from government environmental agencies to proactively monitor, reduce and forecast emission events. Figure 1 illustrates the site survey contour map.

### Site Emissions Monitoring

The site sampling study to which this paper draws reference to is an on going programme conducted at the site collecting deposition data, meteorological data and haul road emission and road surface material characteristics. Pit activity in terms of blasting location and haul truck movements are accurately logged and used within long term gaussian plume models using UK ADMSv3.

Data from a perimeter network of sampling gauges and subsequent modelling using ADMS according to the methodology adopted in Appleton et al 2006 demonstrated consistent over prediction of particulate deposition from in pit blasting and haul road usage (MIST 2004). Figure 2 illustrates the results of the plume based modelling studies for a single month.

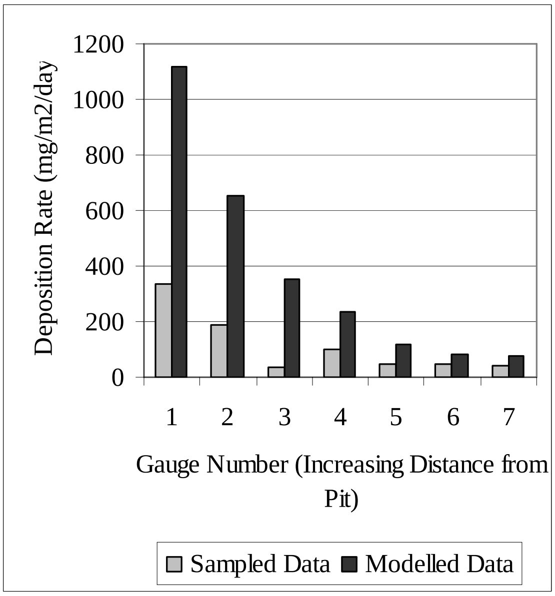


**Figure 2**: Single month plume modelling and sampling results.

This over prediction is attributed to two factors. Firstly, the Emission Factors (EF) used for the ADMS modelling are extracted from United States Environmental Protection Agency (USEPA) and MQEQ documentation (USEPA, 1998; MDEQ, 2002). These factors represent the best available data for these purposes; they are however accepted as guidance. This combined with the application within a UK surface pit creates significant uncertainty as to their application. The second factor concerns the limited ability of gaussian plume based models to sufficiently resolve the complex turbulent flow regimes occurring at ground level in the locality of in pit emissions (detachment of boundary layers, reversals etc). These flow regimes are complicated by the nature of surface pit topography being composed of a series of vertical steps in addition to the dynamic characteristics of blasting and vehicle movements. The success of any plume based simulation depends upon the accurate characterisation of the source. In this case, the initial dispersion of the emission source whilst still in pit must be more accurately studied since the complex turbulent flow regimes at ground level may serve to increase in pit residence time thus decreasing the total emission liberated from the pit boundaries. Since plume models do not resolve these characteristics it is suggested that this factor in part is responsible for the demonstrated over predictions. In order to improve the modelling of surface pit emissions it is necessary to address both the EF quantitative uncertainty and the resolution issues described above. The work presented here is focussed upon the resolution issue, an understanding of which will allow subsequent consideration of the source EF.

## OBJECTIVES

The objectives of this study are summarised as follows;

- Conduct parallel emissions simulations using a CFD lagrangian approach incorporating an approximation of a blast emission and a conventional gaussian plume model approach.

- Conduct a CFD simulation of a haulage truck under measured operating conditions incorporating emissions represented via lagrangian tracking using a site sample based size distribution and compare the normalised decay rate to site sampled data.

## METHODOLOGY

### Application of Gaussian Plume Methods for Comparative Analysis

To provide a quantitative and qualitative comparison and reference for the CFD simulation of the quarry air flow regime and lagrangian emissions modelling of a blasting event a commercially available plume dispersion model, UK ADMS v3, was employed. UK ADMS is a modified gaussian plume dispersion model designed for regulatory use in modelling the dispersion of pollutants within the Atmospheric Boundary Layer (ABL) typically up to ranges of 60km from source. It has been subjected to numerous validation tests and is widely used within industry and academia for planning, environmental monitoring and research. The ADMS model allows sources to be defined geometrically as point, line, area or volume and is capable of incorporating the influence of complex ground topography on plume dispersion via the calculation of flow and turbulence fields using linearised analytical solutions of momentum and continuity on a maximum grid size of 64x64. This enables plume predictions to be modified in accordance with large scale ground topography as typified by hilly terrain and is of particular importance for the modelling of ground sources such as those encountered within the surface extraction industry.

A single blast event liberating a typical 25,000 tonnes was modelled using ADMS. Meteorological input data was defined in terms of wind direction (westerley) and speed at a height of 10m ($5ms^{-1}$) in accordance with the Pasquill-Gifford neutral stability class D (surface heat flux = 0). The emission source geometry was defined as a three dimensional block volume source of 70m normal to the face, 80m in width and 20m in height.

In accordance with the methodology developed in (Appleton et al, 2006) derived from the work of MDEQ (2002 and EPAQS (2000) four particle sizes were defined as 2.5, 10, 30 and 75μm at mass fractions of 0.05, 0.45, 0.3 and 0.2 respectively applying an assumed uniform limestone density of $2{,}600kgm^{-3}$. The quantity of dust released from the blast event was defined using an EF as proposed by MDEQ (MDEQ, 2002) of 0.038 $kgt^{-1}$ for PM10 particulates assuming a 50% fraction of Total Suspended Particulates (TSP). It has been assumed that TSP can be taken as <PM75 and as such the EF used for this work is equal to twice the value defined for PM10 leading to a total emission release of 1900kg. For the purposes of modelling this release was entered as an average rate over one hour of 4.71e-3 $gm^{-3}s^{-1}$ as required by the ADMS solver. The model was run and the results recorded and plotted in terms of total surface dry deposition in units of $gm^{-2}$ based upon the output rate averaged over one hour.

#### CFD modelling of Quarry Activity Emissions

The site topography is typified by a complex series of interconnected ramps, vertical faces and benches. Beyond the site perimeter the site topography is sharply contrasted by the naturally undulating slopes of the surrounding unworked countryside. Survey data measured at 4m intervals across the site detailing position and elevation was used to create the domain surfaces. This data was filtered in two passes, the first to reduce the data to the primary vertical levels representing the elevations of the site, the second to eliminate redundant vertices in the horizontal planes. Since the focus of the study was on the Old Moor section of the site the upstream Tunstead section was replaced with flat terrain. In practice the upstream Tunstead topography would be included to allow a more realistic inflow condition, however, since this study is intended as a direct comparison with an alternative modelling approach this was precluded in the interests of practicality. The total domain measured 2km x 2km. The Gambit pre-processor was used for all domain geometry, meshing and boundary definitions. The height of the domain extended to 500m above the surrounding topography.

The entire domain was meshed using an unstructured approach utilising a prismatic boundary layer (0.5m, expansion factor – 1.2) on all horizontal surfaces and size functions on all vertical surfaces. The total size of the mesh was in the order of 2.5 million cells. In order to accommodate the emission from the blasting event the geometry of a post blast rubble pile was incorporated at the foot of the B5 blast face, figure 3. This enabled a transient forward momentum to be applied to an emission emanating from the surfaces of the blast rubble pile.

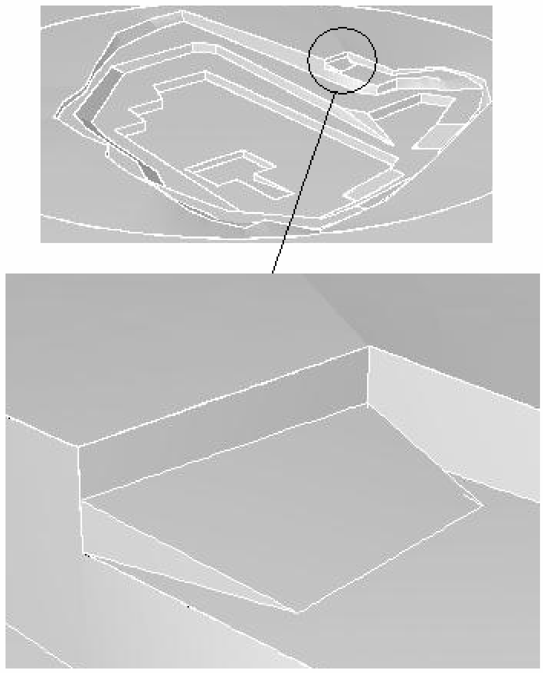

**Figure 3**: Detail of domain surfaces and B5 blast face.

#### *Boundary Conditions and Solver Settings*

The domain mesh was divided into four primary boundaries, an inlet, outlet, symmetry conditions for the top and sides and a single wall representing the quarry and surrounding topography ground. An inlet velocity profile was defined according to the logarithmic profile defined as;

$$U\left(z\right) = \frac{u_*}{k} \ln\left(\frac{z + z0}{z0}\right)$$

1
)

All ground surfaces were defined using a roughness height of 0.1m in accordance with the recommendations of the ADMS user guide (CERC, 1999). In line with the studies of Riddle et al (2004) the Reynolds Stress Model (RSM) was used owing to its demonstrated ability to maintain TKE and dissipation profiles to a greater extent than the standard two equation $k\varepsilon$ model.

The applied momentum source was intended to approximate the initial forward 'pulse' of air associated with the blast front and the collapse of fragmented material onto the quarry ground causing the emission to be initially carried away from the face prior to the momentum decaying and subsequently reverting to the background flow regime. No measurements were found in the literature suitable for any kind of estimation of the magnitude of this momentum likely due to the impracticalities and risk involved in such a study although qualitative studies have been published (Jones et al 2003).

To obtain an estimate, video footage of a blast occurring at the B5 face was used under similar weather conditions. The video was taken parallel to the blast face using a digital mini-dv camera operating at 30 Frames Per Second (FPS) at a distance of approximately 200m. Figure 4 details frame captures from the video at time intervals of 0.4s from the initial appearance of the dust cloud.

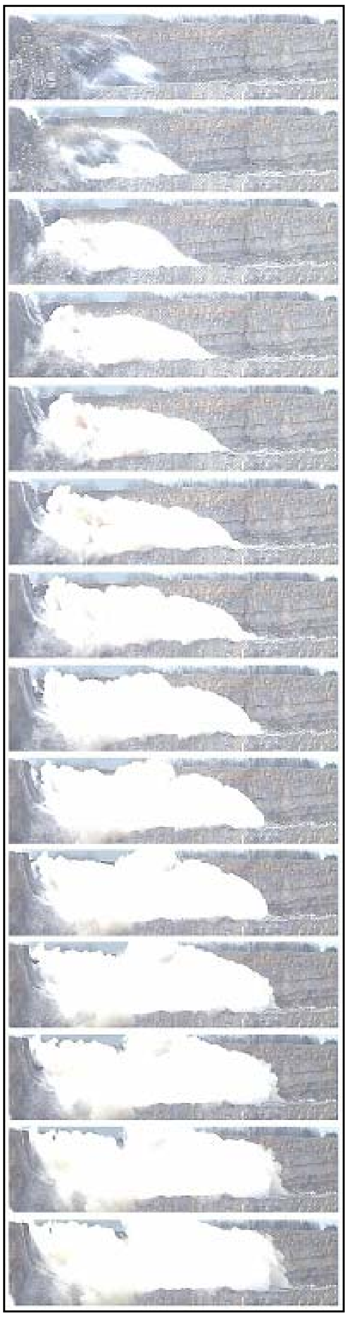

**Figure 4**: B5 blast cloud progress.

The velocity of the dust cloud was measured by consideration of the horizontal extent of the cloud at the respective time intervals. Figure 5 illustrates this data as cloud horizontal velocity over time. At a time of 5s a combination of the increased dispersion and reduced rate of forward velocity of the cloud prohibited any further useful measurements to be made though the measurements up to this point were sufficient to establish the initial velocity of the cloud and subsequent decay. A momentum source derived from the velocity measurements was applied by ramping the value up to the measured maximum and down to zero symmetrically over a period of 2s using an initial time step of 0.02s increasing to 0.1 after the momentum source had been applied.

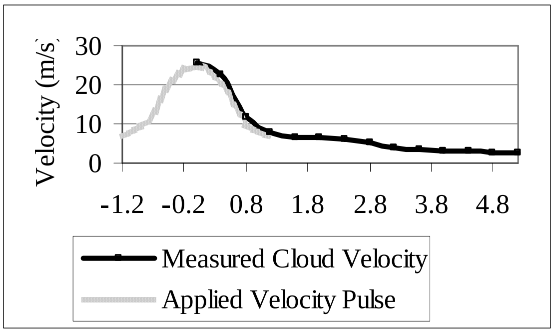


**Figure 5**: B5 blast cloud velocity.

The emission was defined using the Discrete Phase Model (DPM). Four particle sizes were used, 2.5, 10, 30 and 75µm in accordance with the ADMS reference case and assuming spherical drag laws. The emission for the transient case was defined on the surfaces of the B5 blast rubble pile. Turbulent diffusion was incorporated via the stochastic tracking method utilising the Discrete Random Walk (DRW) method. A total of 320,000 particles were injected into the domain.

The model was initially solved in the steady state and subsequently as a transient case incorporating the emission and approximated blast momentum. Results data was obtained in terms of total particulate surface deposition. To obtain comparable surface deposition values a User Defined Function (UDF) was employed to record surface particle impacts and associated particle diameter per surface unit area ($m^2$). The UDF also applied weighting to the recorded surface deposition to reflect the particle mass fractions and total emission rate employed within the ADMS model.

#### CFD modelling of Haulage Truck Emissions

The modelling of a site haulage truck, a CAT777D, was undertaken in order to evaluate the ability of the RANS based stochastic DRW model to accurately represent the qualitative decay curve in emission concentration in the immediate locality of the road (<30m). The geometry of the truck was created by reference to the CAT777D technical specifications documentation and represents the primary surfaces acting to influence flow.

The domain measured 350m x 150m and extended 500m in height. The geometry was meshed using an unstructured approach employing prismatic cells for the surface boundary layer using an initial size of 0.1m and expansion factor of 1.2. The truck surfaces were meshed using a size function of 0.1 and expansion factor of 1.2. Figure 6 illustrates the truck geometry. The final mesh comprised approximately 2.4 million cells.

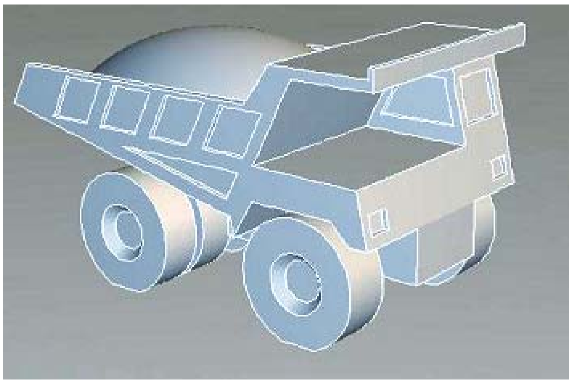

**Figure 6**: Haulage truck geometry.

### *Boundary Conditions and Solver Settings*

As with the site models the RANS RSM model was used to accommodate for the turbulence field. The domain was split into an inlet, outlet, truck surface (wall), wheels (wall) and symmetry surface applied to the top. To reflect the measured conditions of the sampling data a log law profile was applied to the inlet side of the domain in conjunction with a uniform vector parallel to the road representing the vehicle speed of 8.33ms$^{-1}$ taken as a mean operating speed from site measurements. The applied cross wind was based upon a log law curve fit to the measured cross wind at a height of 2m acting perpendicular to the road. Inlet values of TKE (k) and dissipation ($\varepsilon$) were obtained via a simulation of the domain minus the truck geometry and truck speed vector to allow the profile to converge to a fully developed state.

Road emissions were defined as injections on the wheel tyre surfaces. A particle size distribution was applied using data obtained from a road sampling exercise taken during the experimental sampling study, figure 7.

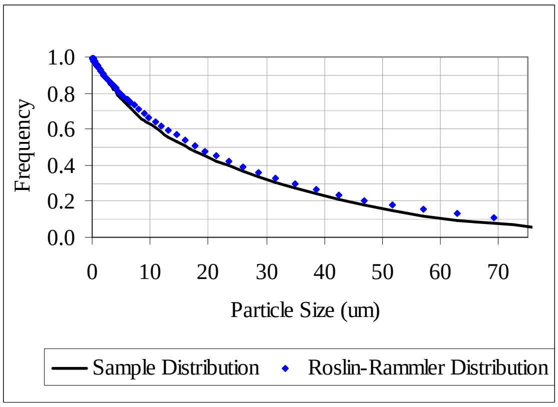


**Figure 7**: Road surface silt sizing distribution and curve fit Roslin-Rammler data.

The model was solved in the steady state and results data was obtained in terms of the emission concentration data at coincident points to the sampling locations used in the acquisition of the experimental sampling data.

All CFD simulations were conducted using Fluent v6.2.16 and solved on a 3.4 GHz 4 GB RAM Pentium based machine running SUSE Linux v9.

## RESULTS

### In Pit Emission Simulation

The results data from the CFD model of the in pit blasting emissions was plotted directly using a pixel map function employed through the application of the 'Surfer' data visualisation application. Figure 8 illustrates the resulting images for the Fluent model and the ADMS model.

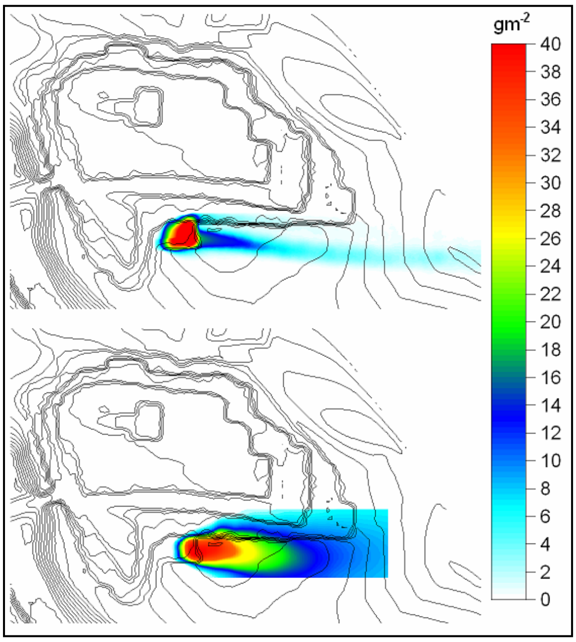


**Figure 8**: Fluent (top) and ADMS (bottom) surface deposition results data.

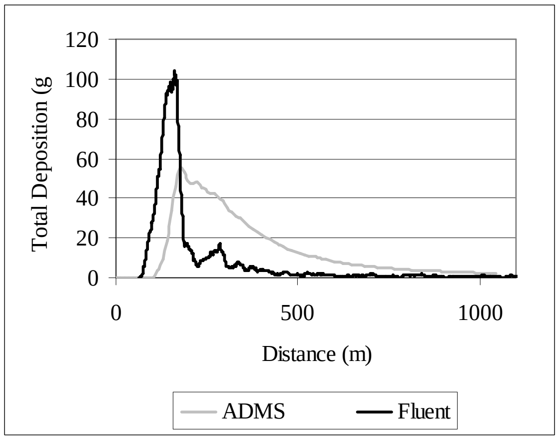


**Figure 9**: Fluent and ADMS surface deposition data plotted from blast face centre point outward along plume axis.

Two characteristic differences can be clearly observed relating firstly to initial emission confinement and secondly downstream plume spread. As can be seen in figure 8, the prediction of the Fluent model demonstrates clear terrain effects whereby the emission is deposited in high concentrations in the vicinity of the pit faces and subsequently drops off significantly. The latter stages of the emission development are markedly different in terms of horizontal plume spread. The Fluent model predicts only marginal horizontal spread downstream of the emission point with the deposition pattern occupying a clearly defined 'band'. This echoes some of the conclusions drawn by Riddle et al (2004) whereby the RSM turbulence model was found to predict lower turbulence levels near ground as compared to the ADMS model which may in turn be responsible for reduced downwind plume spread. In contrast, the ADMS model predicts a much wider downstream plume spread. Figure 9 details a slice through the horizontal surface deposition data taken from the centre of the B5 blast face. The fluent results clearly demonstrate a higher deposition rate in the vicinity of the blast area and demonstrate a clear spike coinciding with the region of the face. Subsequent to this a sharp drop can be observed leading to lower deposition beyond the face compared to the ADMS results.

### Haulage Truck Emissions Model

The results from the CFD simulation of the haulage truck emissions were plotted in terms of total concentration along lines parallel to the road located at coincident heights and distances as the points used for the acquisition of the site sampling data. Site sampling data was representative of the average of three consecutive periods of sampling. Both the fluent simulation data and the sampling data were normalised with respect to the concentration recorded at the sampling point nearest to the road side to enable a comparison of the concentration decay rate to be made. Figure 10 illustrates the normalised concentration data obtained from the fluent simulation and the site sampling data.

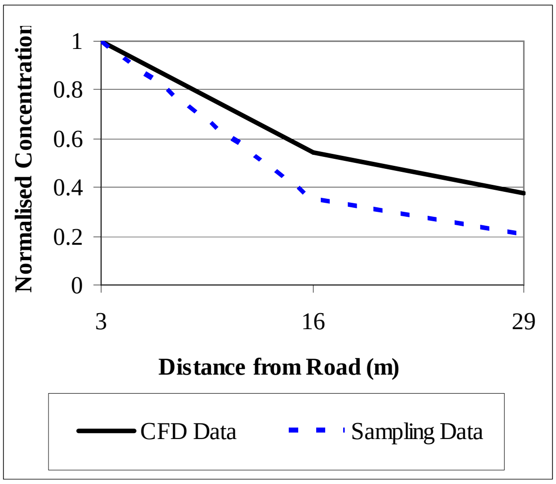


**Figure 10**: Normalised CFD total concentration attenuation profile compared to site sampling data.

The normalised concentration profiles detailed in figure 10 indicate that the CFD model predicts a slightly lower rate of decay than that obtained through the sampling study data. Given that the RSM turbulence model has been demonstrated to predict lower levels of ground turbulence than conventional plume based models this may suggest that these lower levels, as with the blasting case, may be responsible for a reduced dispersion and hence concentration in the near wake of the truck.

## CONCLUSIONS

The CFD modelling of the in pit blasting event clearly demonstrates the effects the vertical pit faces have on particulate deposition. The inclusion of the blast induced momentum used in the CFD model is a simple approximation and should be subject to further investigation to identify a range of sensitivity. In addition, further simulation studies would benefit from focussing on small scale localised flows in and around the blasting face rather than encompassing the entire pit. The haulage truck simulation indicates a higher level of concentration in the immediate roadside wake compared to that measured indicating an under prediction wake attenuation. It is noted that the model prediction of downstream plume spread was significantly reduced compared to that of the ADMS model. For longer range dispersion and deposition studies the ADMS model is clearly superior in terms of economy and validation. However, to realise these benefits it is clear that CFD methods will play an increasing role in the characterisation of ground sources during the initial stages of dispersion where the accurate resolution of ground effects is of greatest importance.

## REFERENCES


QUARG., (1996), "Airborne particulate matter in the United Kingdom", Third report of the quality of urban air review group, Department of the environment, UK, 30.

Jones, T., Morgan, R. and Richards, (2003), "Primary blasting in a limestone quarry", Mineralogical Magazine, **67**, 2, 153-162.

CERC., (1999), "ADMS user guide", CERC ltd, Cambridge, England, CB2 1SJ.

United States Environmental Protection Agency (USEPA), (1998), "Unpaved haul roads", AP-42, **I**, 13.2.2.

Riddle, A., Carruthers, D., Sharpe, A., McHugh, C. and Stocker, J., (2004), "Comparisons between Fluent and ADMS for atmospheric dispersion modelling", Atmospheric Environment, **38**, 1029-1038.

Appleton, T.J., Lowndes, I.S., Kingman, S.J. and Silvester, S.A. (2004) "The development of a modelling strategy for the simulation of fugitive dust emissions from in pit quarrying activities: A UK case study", Int. J. Mining, Reclamation and Environment, **20**, 1, 57-82.

MIST, (2004), "MA 4/1/002 - Cleaner quarries: Methods to reduce the environmental impact of quarry operations", Minerals industry sustainable technology programme, MIRO, UK.

Brown, D.F. and Fletcher, D.F. (2003) "CFD prediction of odour dispersion and plume visibility alumina refinery calciner stacks", 3rd Int. Conf. on CFD in the Minerals and Processing Industries, CSIRO, Melbourne, Australia.

Michigan Department of Environmental Quality (MDEQ), (2002). "Emission calculation fact sheet", Accessed at http://www.deq.state.mi.us/documents/deq-ead-caap-maers-EmissionCalculation-mineralproductprocesses.pdf on 15/11/03.