

CFD MODEL VALIDATION OF POLLUTANT TRANSPORT IN OPEN PIT MINE UNDER AIR INVERSION

K. V. Raj, Univ. of Alaska Fairbanks, Fairbanks, AK
S. Bandopadhyay, Univ. of Alaska Fairbanks, Fairbanks, AK

ABSTRACT

The development and advancement of computational fluid dynamics (CFD) has made it possible to better understand pollutant flow and distribution in deep open pit mines. Open pits located at higher latitudes, especially in the Arctic and sub-Arctic, face a unique problem due to atmospheric temperature inversion, which is prevalent during much of the winter. A three-dimensional CFD model of an actual open pit mine in the Arctic was developed to analyze the problem of pollutant growth during inversion, and mitigation of the pollutants through improved ventilation schemes.

Due to the availability of mine-specific data, such as contaminant concentrations and coordinates of sampling locations, the actual 2013 pit geometry was used for model validation. Concentrations predicted by the selected realizable $k-\epsilon$ turbulent model are compared to measured pollutant concentrations at the open pit. Pollutant concentrations at selected locations showed differences, but remained within the same order of magnitude in most cases.

INTRODUCTION

Computational fluid dynamics (CFD) has emerged as a useful tool for ventilation modeling in underground mines (Edwards and Hwang 1999, Purushotham and Bandopadhyay 2009, Wala et al. 1998, Xu et al. 2011). Application of CFD in open pit mines has been limited, however, since most open pit mines located at lower latitudes do not encounter considerable ventilation problems. Open pits located at higher latitudes, especially the Arctic and sub-Arctic, face a unique problem due to atmospheric temperature inversion, which is prevalent during winter. A number of Russian researchers have tried to understand the air inversion and resulting pollutant transport problem by modeling air flow phenomena in open pit mines (Baklanov and Burman 1996, Baklanov 1984, Baklanov 1995, Belousov 1985, 1989, 1995). Much of their work, however, was based on numerical models and methods of finite difference. Baklanov (2000) applied a modified $k-\epsilon$ and a $k-l$ CFD model to air flow phenomena on various terrains. More recently, Choudhury (2011) used the COMSOL CFD package for modeling pollutant transport for an idealized open pit mine. Collingwood et al. (2012a, 2012b) used a two-dimensional model for fluid flow and contaminant transport at an Arctic open pit mine. The authors have also previously presented work on CFD modeling of an actual open pit mine at high latitude (Bandopadhyay et al. 2014, Raj et al. 2015a). However, the CFD work done by the above-cited researchers lacked model validation with field-measured data.

Validation of a developed model is important in assessing the quality and accuracy of the predicted results. In general, experiments are done numerous times in controlled environments to assess the validity of collected data. There are two types of assessments used in CFD simulations: (1) verification and (2) validation. Model verification is checking the accuracy of the computer codes during the implementation phase of a real-world problem, within the specific limits of accuracy (Oberkampf and Trucano 2002). Since, the pollution transport model presented in this paper used the commercial ANSYS-FLUENT CFD package, verification is not needed as the program has been tested widely, and verified numerous times.

For validation of the CFD model presented in this paper, the realizable $k-\epsilon$ model was selected. Simulated pollutant concentrations

are compared with measured values obtained by monitoring the actual mine concentrations.

DATA FOR MODEL VALIDATION

Due to the cost and time involved, it was not possible to monitor pollutant concentrations at numerous locations for validation of the model. It was decided, therefore, to monitor pollutant concentrations at three locations in the open pit, and compare the measured concentrations with model-predicted values. The extent of agreement between the two sets of data form the basis for model validation. Based on the toxicity of various gaseous pollutants in the open pit, nitrogen dioxide (NO_2) was selected for monitoring. Simulation results presented previously by the authors (Bandopadhyay et al. 2014, Raj et al. 2015a) were based on the 2010 pit geometry and correspond to 2010 pit data collected from the same open pit mine. For validation purposes, however, additional pollution concentration data, equipment locations, and information regarding the extended geometry of the 2013 pit (Figure 1) were collected and used for modeling. The reasons for selecting the 2013 pit geometry and corresponding data were (1) to examine the effect of aspect ratios on the pollutant transport and parameterization of turbulence variables, and (2) to reduce the influence of boundary effects on the simulation results. One of the major objectives of using the extended pit in the model was to understand the various physical phenomena occurring within the pit, thus, it was necessary to have the domain boundaries far away from the open pit.

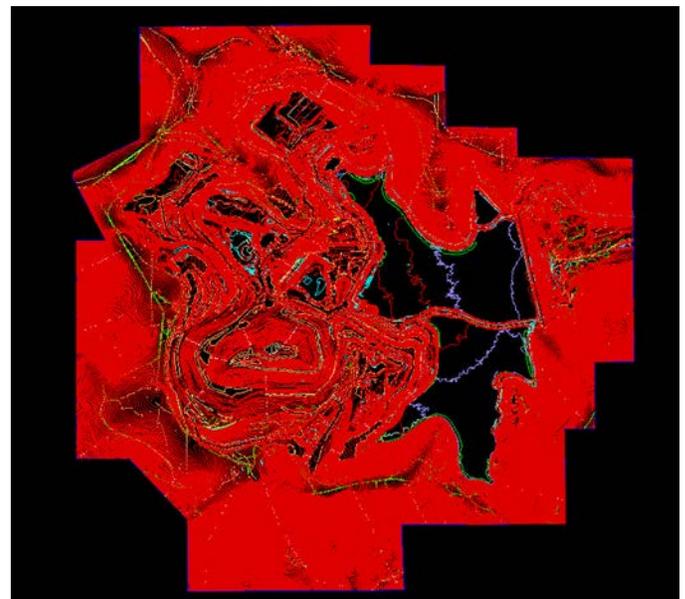


Figure 1. Contour Data Collected from the Selected Open Pit Mine.

SAMPLING PROCEDURES FOR POLLUTION CONCENTRATIONS

The selected mine has collected data during various times of inversion, including measurement locations, time-varying pollutant concentrations, and temperature at the pit rim and pit bottom. However, the methods for sample collection at the mine are not very

systematic, and pollution data are not collected at regular intervals. Often, relevant information (such as temperature and the location of temperature measurement) is not recorded. The collected data includes NO₂, NO and CO concentrations at several locations, in addition to the temperature at the pit bottom and pit rim. During the time of inversion, if there is any visible sign of brown haze (Figure 2) in the pit, the mine management starts to measure pollutant concentrations and temperature at the selected sampling points (Figure 3). The deepest point of observation is the 213 m (700 ft) Bench, which is one of the production benches; other sampling locations are the 286 m (940 ft) Bench and the Lift Station, which is located on the ramp. With the first visible sign of brown haze, which generally corresponds to approximately 1 part per million (Waggoner et al. 1983), measurements are initiated at the bottommost part of the pit (213 m Bench). As the concentration rises to 4 ppm, the haul trucks are pulled out of the pit. The shovel and drill machine, however, keep idling. If the concentration at the 213 m Bench is approximately 5 ppm, no further measurements are taken at that location, however, measurements are taken at the 286 m Bench, which is at a higher elevation. Similarly, if measurements at any locations are around 5 ppm, further measurements are subsequently taken only at higher bench elevations in the pit.



Figure 2. Pit under Inversion with Brown Haze.

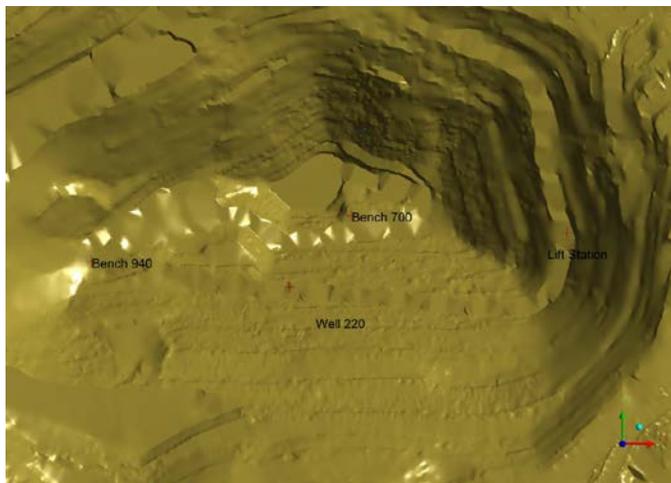


Figure 3. Sampling Locations for Collecting Data during Inversion.

Measured pollution concentration data collected during an inversion on January 3, 2011, following the established procedure, were used for model validation. The data, which are available from 7:45 AM onward, are provided in Table 1. The data collected at 7:45 AM is not included in Table 1. This initial data point was not used for model validation, since the model-predicted values would be affected by initial bias. There is no time sequence in the collected data, i.e. data are not collected at any regular interval. From Table 1, it is evident that around 7:45 PM, the pollutant concentration at the 213 m

Bench level is around 5 ppm, therefore, no data was collected at that location at 7:57 PM and beyond. The time referred to in the text is the Alaska Standard Time (AKST).

Table 1. NO₂ Concentration Data Collected from the Mine during Inversion.

Date	Time of the day (AKST)	Bench 700 (213 m)	Bench 940 (286 m)	Lift Station
January 3 rd 2011	10:15 AM	3.50		2.80
January 3 rd 2011	1:20 PM	3.60		2.50
January 3 rd 2011	3:30 PM	4.00		0.00
January 3 rd 2011	4:30 PM	4.30		
January 3 rd 2011	7:45 PM		4.80	4.10
January 3 rd 2011	9:40 PM		4.90	1.50
January 3 rd 2011	11:00 PM			2.50
January 4 th 2011	0:05 AM			2.60
January 4 th 2011	1:20 AM		4.90	0.90
January 4 th 2011	2:43 AM	4.5	4.50	0.20
January 4 th 2011	3:50 AM		4.90	0.20
January 4 th 2011	4:55 AM		5.00	0.20
January 4 th 2011	5:05 AM		4.90	0.70
January 4 th 2011	6:00 AM	4.7	4.20	0.00

Management personnel from the selected mine have provided the 2013 pit geometry (Figure 1), as well as access to the mine dispatch system for identifying precise locations of pollutant sources, such as trucks, shovels and drill-machines, which provided realistic data for the simulation run. The exact sampling locations, as well as contaminant concentrations and spatial coordinates of those locations, are significant information for validating the simulation model.

Figure 4 is a plot of the temperature and dew point, and indicates the absence of clouds over the Fairbanks area at the time of measurements.

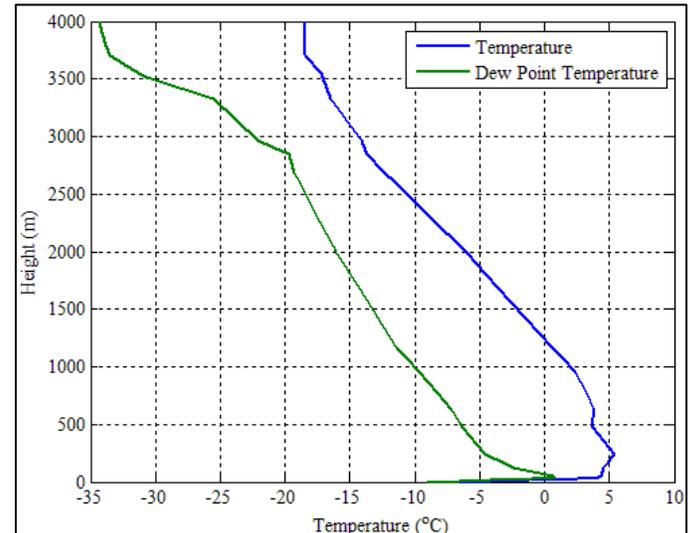


Figure 4. Temperature and Dew Point Variation with Altitude at 3:00 AM, January 3, 2011.

Apart from the information from the selected mine, it is equally important to have realistic boundary conditions in the simulation for the inlet velocity and inlet temperature, which vary with altitude and time. Since, the model is an atmospheric model developed using the CFD tool, one of the major challenges is its reproducibility. Validation of the data collected from such experiments is also challenging due to various phenomena occurring at different time and spatial resolutions.

INCORPORATING VARIABLE BOUNDARY CONDITIONS IN THE MODEL

The atmospheric boundary layer (ABL) forms the lowest layer of the earth atmosphere. It can reach up to 3 km in depth depending on solar heating and frictional drag at the surface, and it responds rapidly to changes in surface forcing. Turbulence is characteristic of ABL, and

generated as a result of both sensible heat fluxes (thermal forcing) and wind shear (mechanical forcing). During the day, where buoyancy dominates the production of turbulence the ABL is referred as a convective boundary layer (CBL). At nights when the surface cools through the emission of longwave radiation, the ABL becomes stratified. In these conditions, the thermal stratification works to inhibit vertical motion, and any turbulence is generated mechanically through wind shear (Raj et al. 2015b). This turbulence is much weaker than that of the CBL resulting in a much shallower boundary layer, and the ABL in this state is characterized as the stable boundary layer (SBL). It is within the ABL that most release of pollutant takes place. The mixing of pollutant in the ABL is governed by the state of turbulence with different wind speeds and surface heat fluxes.

As discussed in the previous section, wind velocity and air temperature are both space and time dependent. It is important to incorporate such variability in the model domain, via appropriate boundary conditions. The velocity and temperature at the velocity-inlet boundary are functions of height, more precisely, within the first hundred meters of the atmospheric boundary layer (ABL). According to Stull (1988), the wind velocity follows a logarithmic wind profile under neutral conditions (Equation 1). More information, however, is required to define the inlet velocity, such as the friction (shear) velocity (u_*) and the aerodynamic roughness length (z_0). The constant k is Darcy friction factor constant, with a value of 0.41, and z is the reference height, which is generally known. The aerodynamic roughness length for various terrain types are available in the literature (Stull 1988). The friction velocity, however, is difficult to obtain, as it requires some experimental data for velocity at the site. Due to the non-availability of wind velocity data at the mine, the friction velocity is calculated using the wind profile power law (Equation 2).

$$u_z = \left(\frac{u_*}{k}\right) \ln\left(\frac{z}{z_0}\right) \quad (1)$$

$$u_z = u_r \left(\frac{z}{z_r}\right)^\alpha \quad (2)$$

The wind profile power law generally provides a good estimate of wind velocity within the boundary layer. In Equation 2, u_r is the reference velocity at a reference height, z_r , and the exponent α depends on the stability of the atmosphere. The value of α is taken as 1/7, assuming a neutral, stable atmospheric condition. Since the wind velocity at the mine is unknown, an approximation was made using data from a weather station located close to the mine. Collected wind velocity and temperature data from the weather station are assumed to be representative of the mine air velocity and temperature fields for the (inlet) boundary conditions. The velocity, u_r , at the reference height was obtained from the same weather station; the weather station elevation of 690.67 m (2266 ft) is the reference height, used in the model. Equation 3 was used to develop the vertical temperature profile at the inlet boundary:

$$T = T_0 + L \cdot z \quad (3)$$

Where, T is the temperature at height, z , L is the lapse rate and T_0 is the reference temperature. A lapse rate of -6.5°C per kilometer was used for the simulation. Varying temperature and velocity profiles are incorporated in the ANSYS-FLUENT simulation model by introducing two user-defined functions (UDFs). The input vertical temperature and velocity profiles are presented in Figure 5 and Figure 6. The initial elevation is 457 m (1500 ft) above sea level, located at the east wall boundary of the model domain.

It is important to recognize that the wind and temperature profiles not only vary with height, but also with respect to time. Thus incorporation of temporal variability into the boundary conditions makes the simulation model behave closer to the real system. For this purpose, a time varying temperature and velocity distribution was adopted at the velocity-inlet boundary, where both the temperature and velocity are the function of height.

EQUIPMENT LOCATIONS AND DISPATCH

The mine dispatch data indicates that five shovels and two drill machines were operating in the pit on January 3, 2011, along with a number of trucks that were deployed according to production need.

Based on the dispatch data, the model includes a shovel, a drill machine, and five trucks located at the pit bottom, near the 213 m Bench (Bench 700). The actual coordinates of the shovel and drill machine were therefore incorporated by creating a set of UDFs with an on and off switch at intervals of 4, 8 and 12 minutes. Locations of other equipment are above the inversion level and did not contribute to the pollution load, therefore, those equipment are not included in the validation model. Various contaminant sources present in the pit are shown in Figure 7 and the three locations where pollutant samples were collected are presented in Figure 8.

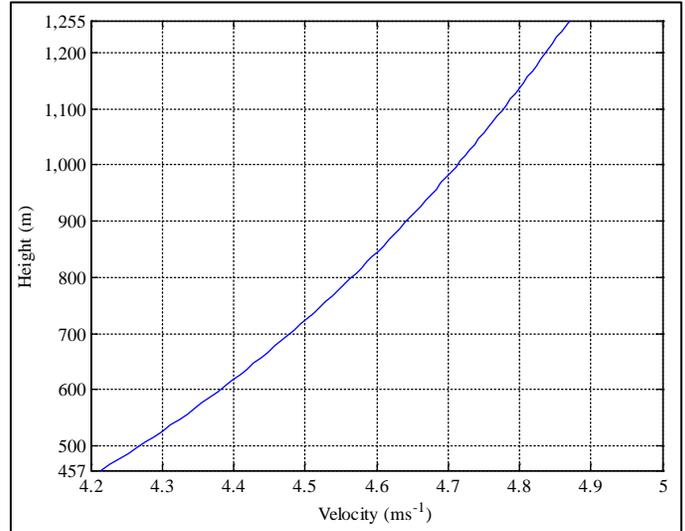


Figure 5. Vertical Velocity Profile at the Inlet Boundary.

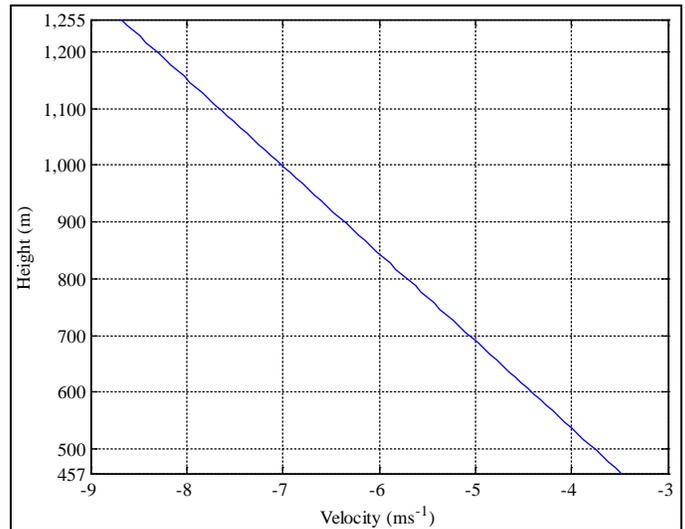


Figure 6. Vertical Temperature Profile at the Inlet Boundary.

SIMULATION USING REALIZABLE K-E MODEL

The realizable $k-\epsilon$ model simulation run was performed for a period of 24 hours, starting at 7:45 AM on January 3, 2011, along with its time-varying boundary conditions. The results presented in the following section are from the simulation. Time steps were manually adjusted during the simulation. Initial time steps were kept to a low value (0.001 second) to ensure model convergence. Once convergence was achieved, the time step was increased gradually. The maximum time step was fixed to 5 seconds, where model convergence was reached.

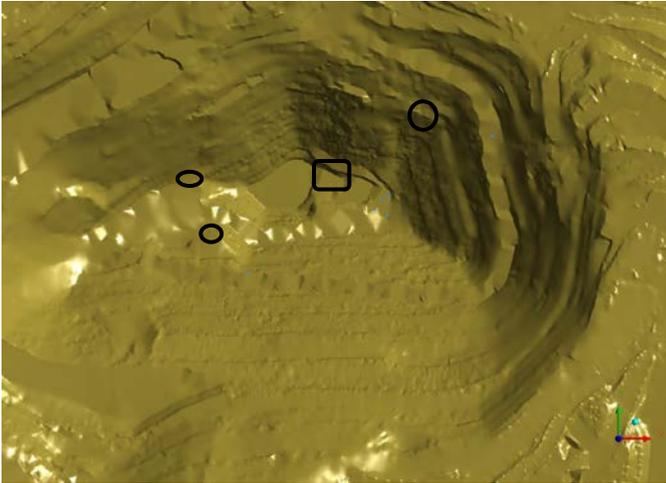


Figure 7. Pollutant Sources Placed at Different Locations in the Pit.

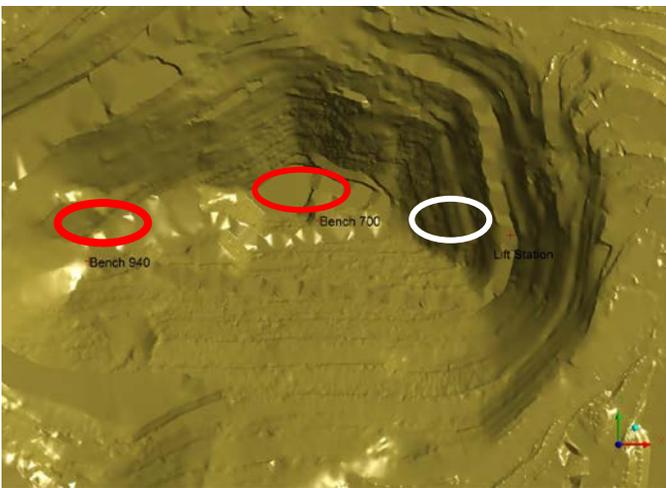


Figure 8. Sampling Locations during Inversion at the Open Pit.

SIMULATION RESULTS

Figure 9 shows the five lines for plotting vertical profiles located in the open pit domain. Lines 1 through 4 are within the pit and Line 5 is located on the pit rim. Line 1 extends from the bottom most part of the pit to the top of the model domain and Line 2 is near continuously operating equipment. Along the lines, temperature, and velocity are plotted at different time intervals (Figures 10 through 19).

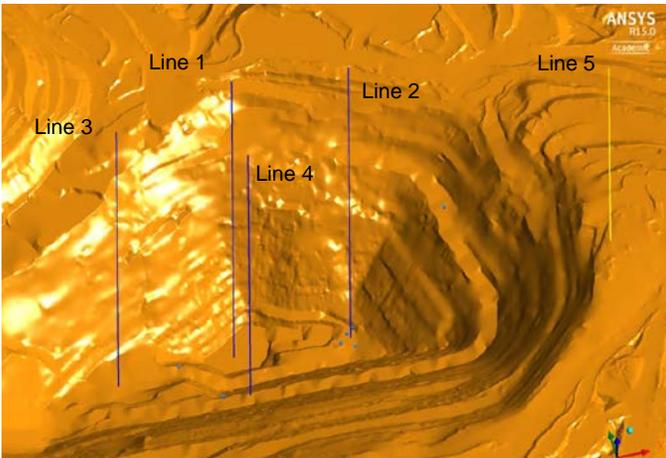


Figure 9. Different Lines for Sampling Simulated Data.

Vertical profiles of temperature and wind velocity for the simulated stable boundary layer (SBL) from the model agree well with observations by other researchers (Hartmann and Wendler 2005) and show a small vertical gradient below the capping inversion. This is due to the large amount of turbulence, especially in the vertical direction. The simulated turbulence structure shows the dominance of vertical velocity variance within the mixed layer, while horizontal variances dominate within the SBL. After several hours of cooling the SBL shows a strong, surface-based temperature inversion (Figure 10).

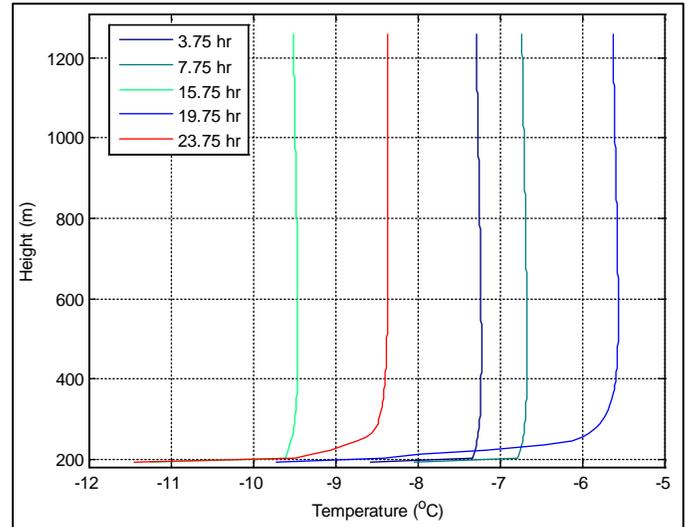


Figure 10. Temperature Profile along Line 1 at Various Time Intervals.

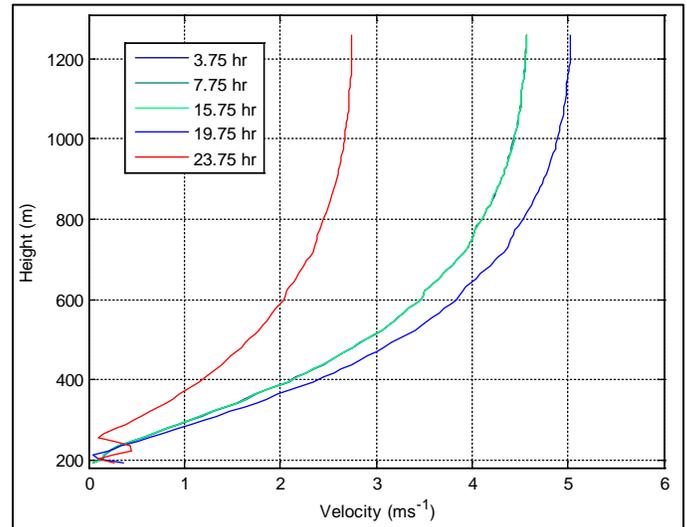


Figure 11. Velocity Profile along Line 1 at Various Time Intervals.

Line 2 is located near operating equipment and heat released from the equipment is captured in the temperature profile (Figure 12). A sudden jump in the magnitude of the temperature during the initial time period can be observed at the lower level of the pit. However, in the later part of the simulation the sudden jumps in temperature are not visible as the trucks were turned off after 16 hours, thus no heat release.

COMPARISON WITH MEASURED DATA

Simulated results of pollutant concentration for a volume cell in a computational domain are for the Reynolds Averaged value and cannot be readily compared with the measured data (a point in time) or evaluated without further time averaging. However, it is not obvious what time period should be used for time averaging.

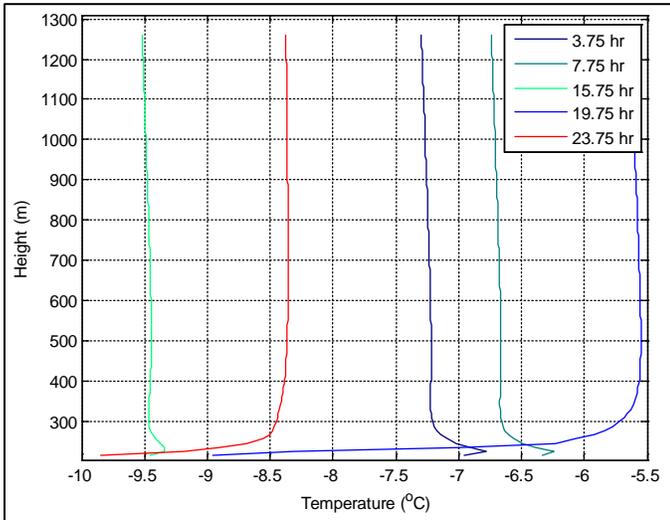


Figure 12. Temperature Profile along Line 2 at Various Time Intervals.

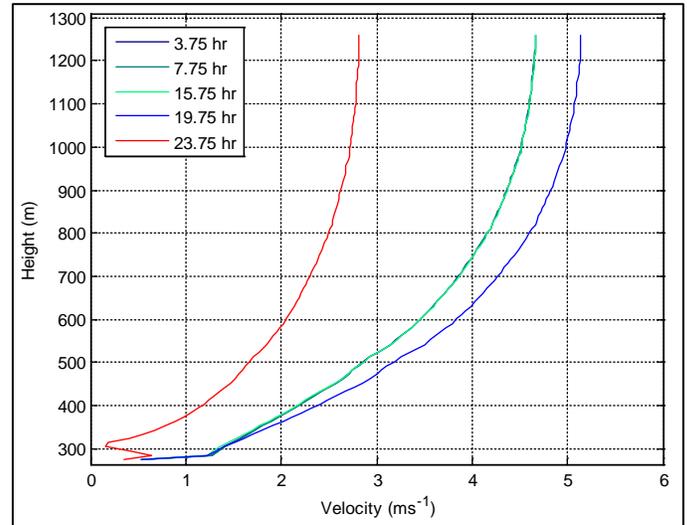


Figure 15. Velocity Profile along Line 3 at Various Time Intervals.

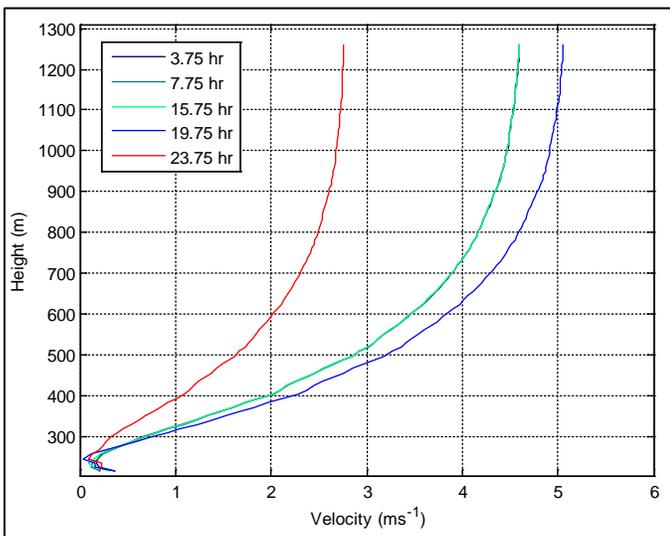


Figure 13. Velocity Profile along Line 2 at Various Time Intervals.

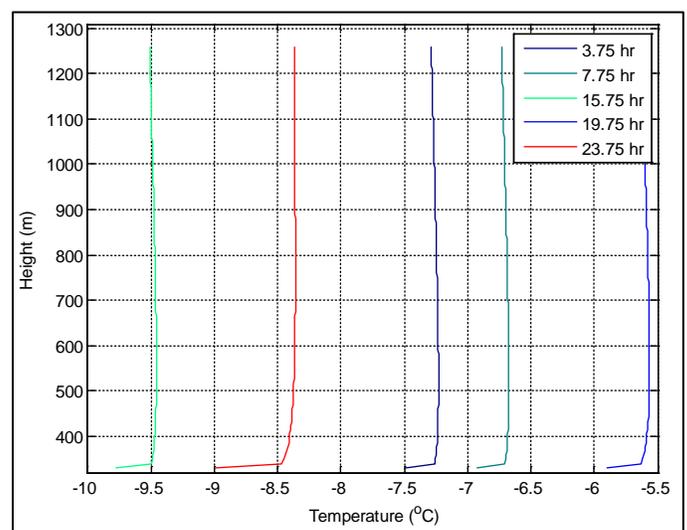


Figure 16. Temperature Profile along Line 4 at Various Time Intervals.

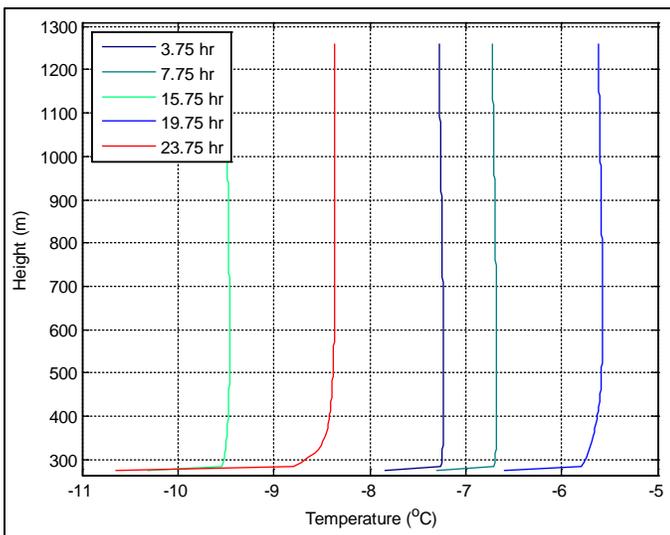


Figure 14. Temperature Profile along Line 3 at Various Time Intervals.

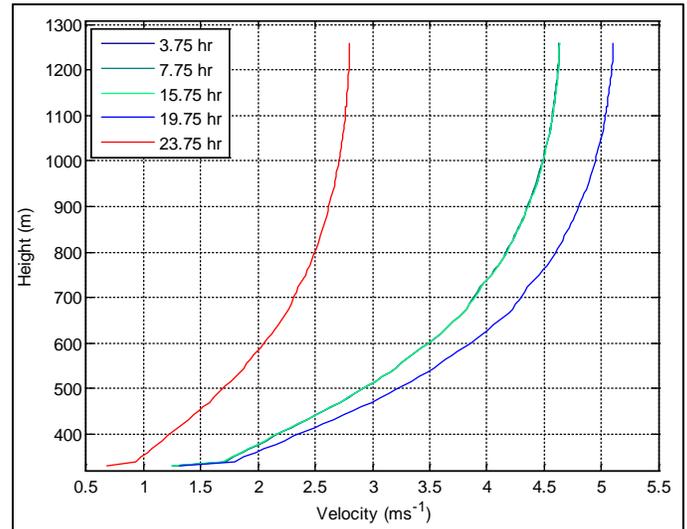


Figure 17. Velocity Profile along Line 4 at Various Time Intervals.

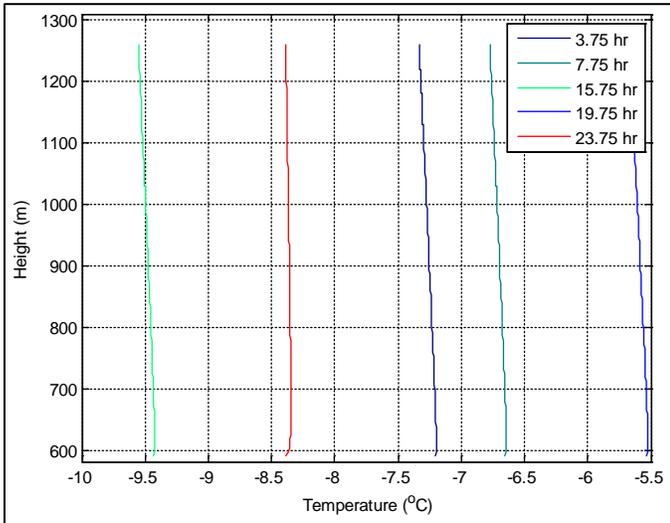


Figure 18. Temperature Profile along Line 5 at Various Time Intervals.

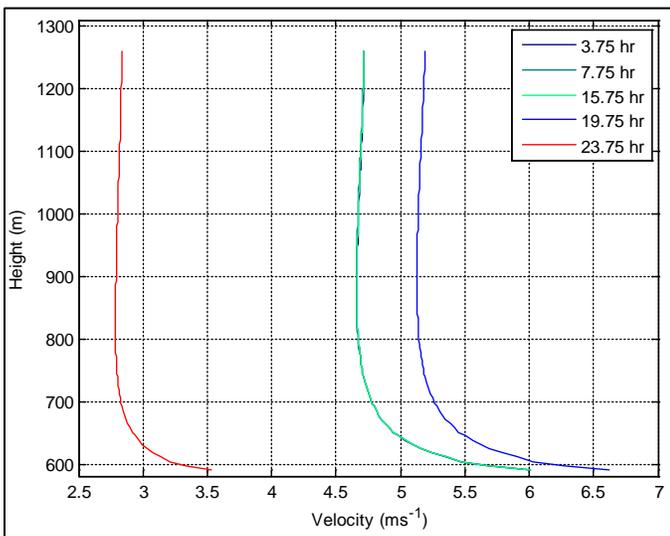


Figure 19. Velocity Profile along Line 5 at Various Time Intervals.

The threshold limit value (TLV) for pollutants in the mining environment is time-averaged on an 8-hour shift. For comparison, the data were divided into groups of 8 hours for averaging. Each averaged data value was compared with the simulated data averaged over the same time frame and a percentage difference was computed. The measured data are provided in Table 2, averaged over a period of eight hours.

Table 2. Comparison of Measured Data and Simulation Model Predicted Data.

	Bench 700			Bench 940			Lift Station		
	Actual Time Averaged Value	Simulated Time Averaged Value	Percentage difference (%)	Actual Time Averaged Value	Simulated Time Averaged Value	Percentage difference (%)	Actual Time Averaged Value	Simulated Time Averaged Value	Percentage difference (%)
First 8-hour average	3.85	4.93	21.89				1.77	1.82	2.85
Second 8-hour average				4.85	4.39	-10.48	2.68	0.38	-607.59
Third 8-hour average							0.44	0.31	-41.39

Table 2 presents a comparative assessment of the actual and simulated data averaged over a period of 8 hours. The data shown are

NO₂ values, since the concentration of NO₂ is the limiting factor for mine operation during an inversion.

From table 2, it can be seen that at Bench 700, for the first 8-hour period, the model over-predicts by approximately 22 percent. For the Lift Station, the model over-predicts only by 3 percent. It is known that Reynolds-Averaged Navier-Stokes (RANS) models under-predict flow fields, and thus, the CFD profiles are confirmed to over-predict pollutant concentrations.

In the second 8-hour period, concentration data from Bench 700 were not collected, as it was assumed that the NO₂ concentration was higher than 5 ppm. The simulated averaged value at Bench 940 underestimates the pollution concentration by approximately 10 percent, whereas, at the Lift Station, the concentration is under-predicted by 600 percent. The low simulated value of NO₂ at the Lift Station can be due to mixing of pollutants by the air mass at the leading edge of the pit rim. In the final 8 hours of simulation, the pollutant concentration data is only available for comparison from the Lift Station and is around 41 percent below the actual value.

The variation in transport and dispersion of pollutants in the SBL depends strongly on height, due to the strong wind shear and variation in the strength of turbulence. The height dependence of wind velocity and direction of transport is clearly evident. There is no strong variation in dispersion with height, however, within the middle portion of the SBL near the Lift Station, there is much larger dispersion due to higher wind velocity (velocity at Line 2). The temperature profile (temperature plot of Line 2) indicates that the inversion is very weak and there is probably stronger wind shear. This leads to a significantly reduced pollutant concentration at that location.

For the first 8-hour period, trucks were passing by the Lift Station, thus, releasing pollutants and additional heat in the open pit. Pollutants released from incoming and outgoing trucks are reflected in the measured data at the Lift Station. Whereas, in the model domain, the trucks were placed on the ramp at fixed locations. In effect, the pollutants and heat released by the trucks are dispersed in the model domain. Once the concentration reached 5 ppm in the pit, trucks were withdrawn, which was accomplished in the model by turning trucks off in the UFDs.

SUMMARY AND CONCLUSION

Model validation is an important step in assessing the quality and accuracy of simulation results. Validation of a CFD model for air flow and contaminant transport in an open pit mine is presented. The model was able to capture the inversion phenomena in the open pit reasonably well.

In terms of contaminant concentrations, measured and simulated NO₂ concentrations are within reasonable agreement for most of the sampled locations, despite ever changing atmospheric conditions and complex topography.

In a way, the RANS turbulent models are all problem-dependent, which is a large drawback of the RANS model. Some of the differences between model-predicted values and measured concentrations are probably due to the possibility that important unsteady phenomena are present in the flow over the selected open pit mine, such as intermittent flow separation in the windward side of the pit. This results in unsteady turbulence, which could not be modeled with a high degree of certainty by the RANS simulation.

This model is a good candidate for prediction of pollutant transport under neutral atmospheric conditions, and can be extended to the SBL. The effect of boundary conditions noticeably influences model results of the computational domain.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the National Institute for Occupational Safety and Health (NIOSH) for the financial support from a NIOSH Research Contract # 200-2009-31968. The authors would also like to acknowledge Mr. Chris Pritchard of NIOSH for his valuable suggestions and feedback on the research. Assistance provided by

the ANSYS technical support staff and mining engineers at the selected open pit mine is also gratefully acknowledged.

REFERENCES

- Baklanov, A., and J. Burman. (1996) "Numerical Modelling of Three-Dimensional Flow and Pollution Transport over Complex Terrain During Stable Stratification." In *Air Pollution Modeling and Its Application XI*, edited by S.-E. Gryning and F. Schiermeier, 665-666. Springer US.
- Baklanov, A. A. (1984) "Determining the Propagation of Impurity in the Atmosphere of a Pit on the Basis of Mathematical Modeling." *Soviet Mining* no. 20 (5):402-407.
- Baklanov, A. A. (2000) "Application of CFD Methods for Modelling in Air Pollution Problems: Possibilities and Gaps." In *Urban Air Quality: Measurement, Modelling and Management*, edited by R. S. Sokhi, R. San José, N. Moussiopoulos and R. Berkowicz, 181-189. Springer Netherlands.
- Baklanov, A. A., Lukovsky, V.D., Rigina, O. Yu. (1995) "Contemporary Notions about Ventilation of Open Pit Mines." *Russian Academy of Sciences*.
- Bandopadhyay, S., K. V. Raj, and R. V. Ramani. (2014) A Three-Dimensional CFD Model of Pollutant Transport in a Deep Open-Pit Mine under Arctic Air Inversion. In *Proceedings of the Tenth International Mine Ventilation Congress*, edited by G. F. von and M. Biffi. Sun City, South Africa: The Mine Ventilation Society of South Africa.
- Belousov, V. I. (1985) "Natural Dynamic Ventilation of Open Mines." *Journal of Mining Science* no. 21 (3):264-267.
- Belousov, V. I. (1989) "Ventilation of Open-Pit Mines by Controlling the Boundary Layer of the Wind Stream." *Soviet Mining* no. 25 (3):267-270.
- Belousov, V. I. (1995) "Breeze Circulation in Open-Pit Mines." *Journal of Mining Science* no. 31 (3):216-220.
- Choudhury, A. (2011) *Multiphysics Modeling of Gaseous Contaminant Transport in Deep Open Pit Mines under Arctic Air Inversions*, Mining and Geological Engineering, University of Alaska Fairbanks, Fairbanks.
- Collingwood, W., K. V. Raj, and S. Bandopadhyay. (2012a) "CFD Modeling of Air Flow in an Open Pit Mine." *Mining Engineering* no. 64 (2):44-50.
- Collingwood, W., K. V. Raj, and S. Bandopadhyay. (2012b) CFD Modeling of Pollution Transport in Open Pit Mines under Arctic Air Inversion. In *Proceedings of the 14th U. S. /North American Mine Ventilation Symposium*, edited by F. Calizaya and M. Nelson. Salt Lake City, Utah: University of Utah.
- Edwards, J. C., and C. C. Hwang. (1999) CFD Analysis of Mine Fire Smoke Spread and Reverse Flow Conditions. In *Proceedings of the 8th US Mine Ventilation Symposium*, edited by J. C. Tien. Rolla, MO: University of Missouri-Rolla.
- Hartmann, B., and G. Wendler. (2005) Climatology of the winter Surface Temperature Inversion in Fairbanks, Alaska. In *8th Conference on Polar Meteorology and Oceanography*, edited by V. Alexeev. San Diego, CA: American Meteorological Society.
- Oberkampf, W. L., and T. G. Trucano. (2002) "Verification and validation in computational fluid dynamics." *Progress in Aerospace Sciences* no. 38 (3):209-272.
- Purushotham, T., and S. Bandopadhyay. (2009) Estimation of Shock Loss Coefficient Values for Mine Ventilation Configurations using CFD Simulations. In *Proceedings of 9th International Mine Ventilation Congress*, edited by D. C. Panigrahi. New Delhi, India: Oxford & IBH Publishing Company.
- Raj, K. V., S. Bandopadhyay, and R. V. Ramani. (2015a) "Turbulent Models for Pollutant Transport in Open Pit Mines under Stable Boundary Layer." *Transactions of the Society for Mining, Metallurgy, and Exploration* no. 336.
- Raj, K. V., G. J. Fochesatto, and S. Bandopadhyay. (2015b) Air Temperature Inversions and its Impact on Natural Ventilation in Open pit Mines. In *Proceedings of the 15th North American Mine Ventilation Symposium*, edited by E. Sarver, S. Schafrik, E. Jong and K. Luxbacher. Blacksburg, VA: Department of Mining and Minerals Engineering.
- Stull, R. B. (1988) *An Introduction to Boundary Layer Meteorology*. Netherlands: Kluwer Academic Publishers.
- Waggoner, A., R. Weiss, and N. Ahlquist. (1983) "The Color of Denver Haze." *Atmospheric Environment* (1967) no. 17 (10):2081-2086.
- Wala, A. M., J. C. Yingling, and J. Zhang. (1998) Evaluation of the Face Ventilation System for Extended Cuts with Remotely Operated Mining Machines using Three-Dimensional Numerical Simulations. In *SME Annual Meeting*. Orlando FL: SME.
- Xu, G., J. Bowling, K. Luxbacher, and S. Ragab. (2011) Computational Fluid Dynamics Simulations and Experimental Validation of Tracer Gas Distribution in an Experimental Underground Mine. In *SME Annual Meeting*. Denver, CO: SME.