Principle Roles of Mine Fire Simulation in Mine Management and Emergency Planning

Jon Fox[a], John Bowling[a], Steven Schafrik[b]

[a] *Mine Ventilation Services, Clovis, California, USA*
[b] *Virginia Center for Coal and Energy Research, Virginia Tech, Blacksburg, Virginia, USA*

Safety personnel and ventilation engineers need a tool for the design of credible fire scenarios and appropriate emergency response procedures. A validated ventilation network model with measured site-specific parameters is a necessary starting point for development of underground fire simulations. MineFire, based on the NIOSH MFIRE program, is an engineering tool used to simulate fire dangers. The MineFire tool combines the visualization and network editing tools familiar to ventilation engineers with fire simulation capabilities and result visualizations. Employing the evaluation tools one can develop realistic emergency procedures, including escape route planning and emergency response to maintain the health and safety of the underground workforce. This paper covers the three principle roles of mine fire simulations: 1. ventilation system design and evaluation, 2. operator training and 3. Emergency preparedness planning. Practical working knowledge contained in the MineFire program will be great for planning mining ventilation networks and the dynamic responses to fire events that will greatly improve emergency   preparedness.

Keywords: Mine Design, Training, Emergency Preparedness, Mine Rescue, Mine Fire

1. Introduction

Most of the major mine disasters throughout the history of mining have been caused by explosions and/or fires and both causes remain among the greatest potential hazards in mining. The greatest hazard of mine fires is the poisonous and sometimes explosive combustion products which are carried through the mines by the ventilation airflow. Additional hazards occur due to interaction of the source fire with the airflow passing through the ventilation network. The volume expansion of the air as it passes through the fire has a constriction or throttle effect [1]. Density differences in non-horizontal communicating airways create buoyancy effects similar to chimney drafts. In order to educate mine ventilation engineers about these non-steady state interactive effects, the United States Bureau of Mines (USBM) undertook a software development project known as MFIRE [2].

The MFIRE program was developed in FORTRAN at the Michigan Technological University, under a contract from the former USBM. MFIRE performs normal ventilation network planning calculations, and dynamic transient state simulation of ventilation networks under a variety of conditions. MFIRE simulates a mine's ventilation system and its response to altered ventilation parameters such as the development of new mine workings or changes in ventilation control structures, external influences such as varying outside temperatures, and internal influences such as fires. The original version of MFIRE allowed ventilation networks of up to 500 branches and 10 fans.

MFIRE performs the transient-state simulation of a mine ventilation system as a stepped series of short-duration steady-state calculations with output from the initial step becoming the input for the next time step. The heat transfer model is constructed on the basis of the energy balance of airflow to pre-calculate time-dependent air temperatures at different locations. Given data that describes the geometry of the mine network, airway resistances, dimensions, characteristic curves of fans and characteristics of the fire or thermal event, the program will provide tabular representations of various predicted ventilation, contaminant, and temperature parameters as well as graphical representation of the ventilation system and fume front propagation over selected time increments.

Following the disbanding of the USBM, the National Institute of Occupational Safety and Health (NIOSH) took over the project and contracted a software developer to rewrite the FORTRAN into C++ code that handles all input and output operations. Currently with release at version 3.0.2.0, the NIOSH software does not provide graphical interpretation of simulation results [3].

Mine Ventilation Services, Inc. (MVS) began development of MineFire in 2003 using the source code from MFIRE version 2.2, which was modified by MVS solely to increase the number of junctions and fans available and to run in the Windows operating environment [4]. This calculation kernel was then adapted into the user-friendly interface of MVS' VnetPC ventilation network software package. MineFire is designed to assist with the prediction of spread of contaminants, heat, or other changes in air density. The latest version has removed all network boundaries for ventilation models. The only limitation now is a maximum of 20 data points for a fan curve definition.

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2. Program Description

MineFire performs steady-state ventilation network simulation and dynamic-transient-state modeling of ventilation networks under a variety of conditions. The program simulates a system's response to altered ventilation parameters such as: the introduction of fire to the system, varying outside temperatures, changing ventilation control structures, and development access for new mine workings.

MineFire requires a number of parameters in addition to those input into the VnetPC model. The modeler uses the k-factor resistance type for setting up the ventilation network, or assigns calculated resistance values for each branch. Length, perimeter, and area parameters must be defined for each branch of the model in order for the transient-time utilities in MineFire to function properly.

Not all MineFire parameters must be entered for successful simulations. In a fire simulation, conductivity, diffusivity, and rock temperature are recommended parameters for each branch in the model and may be defined as average values (Fig. 1).

Fig. 1. Contaminant Data - Simulation Parameters Tab

Variable parameters and modeling boundary conditions required for model execution must be defined. A range of acceptable values are entered with validation rules applied to help maintain accuracy of simulation results.

2.1 Conductivity

This variable is the thermal conductivity for the rock mass. The number is used by the program to define the thermal transfer to or from the air mass as it travels through the airway. This will affect airflows in the mine. An understanding of which rock type defines a branch is needed for detailed models. A theoretical average or general value for the rock mass may also suffice. Where the rock type in the model is uniform, large numbers of branches will have the same value. The units for conductivity are Btu/hr×ft×°F or W/m×°C.

2.2 Diffusivity

Rock diffusivity is obtained through laboratory testing of core samples, or from tables. It defines how quickly heat moves between the rock mass and the air as air moves through a branch. The units for diffusivity are ft²/hr. or m²/sec.

2.3 Rock Temperature

This variable uses the average temperature of the rock at a given network location and is based upon local borehole measurements or derived through known regional geothermal gradients. Sample measurements are taken in numerous key locations throughout the mine and this data is applied to those network junctions respectively. This data may be averaged as necessary.

2.4 Fan Data

Fan characteristic curves are defined by entering between two and twenty pairs of pressure - airflow quantity points. Fan characteristic curves must be defined by at least two points for the MineFire program to provide accurate results. This allows the program to correctly apply the effects of the changing natural ventilation pressure (NVP) with respect to the fan characteristic curves.

Model domain parameters are defined that control the simulation execution. These parameters govern iterative calculation characteristics, the fan curve fitting algorithm, and simulation timing conditions. Additional atmospheric parameters are defined to provide boundary conditions for temperature and reference density. The modeler determines parameters for time span, time step increment and allowable error between calculation iterations in order for the simulation to properly converge.

Contaminant source parameters are established for each proposed fire location for simulation. The airflow quantity for the fire source airway is used together with the mass of combustible materials to calculate contaminant production and heat generation from the fire. Diligent estimation of each fire source includes characteristics for both oxygen-rich and fuel-rich fire propagation.

A timeline is developed which most realistically represents the anticipated sequence of an underground mine fire. Time table events simulate conditions and actions which could be expected to occur during a mine

fire. These discrete events describe changes to the ventilation network such as reversal of main fans, closing of fire doors or the introduction of an emergency fan. The modeler decides the starting time and event duration, entering these discrete events sequentially into the time table (Fig. 2) tab of .

Fig. 2 Contaminant Data - Time Table Tab

Important simulation results such as changes to fume front propagation, temperature rise and contaminant concentrations over the simulation timespan are displayed graphically in VnetPC. Subsequent analyses of the simulation reveal district locations susceptible to airflow reversal and/or recirculation. Visual display of simulation results allows mining engineers to optimize design of escape routes, plan locations of refuge chambers as mining production changes and effectively communicate those requirements to key safety personnel.

3. Program Assumptions

Sound risk assessment is essential to developing credible scenarios for fire simulations. Hazard analyses are conducted to identify the potential frequency of the hazard, number of people affected, potential spread of contaminants, cost of damage, and seriousness of each hazard. Accounting for actual and estimated fire source materials reflects the worst-case scenario. Once potential sources are identified, the magnitude of associated risks are evaluated to determine if they are tolerable or not. Each intolerable hazard is simulated using a realistic ventilation model, developed for a typical mining layout or for the development stage of worst-case ventilation.

Development of a ventilation model that uses realistic resistance values, in either k-factor or practical resistances calculated from measured field data is required for MineFire. All fixed quantities are removed and all fans have curves to sufficiently represent anticipated operating points. The modeler takes into account the surface atmospheric conditions and incorporates them into the models.

A solid understanding of the NVP being applied to the ventilation network is also a requisite. Worst-case scenarios reflect maximum driving (or retarding) NVP and account for those forces appropriately in the model's respective airways. The effects of NVP are handled in MineFire with the insertion of an effective fixed pressure fan in the relevant airway. In this way, the effect of the conversion of thermal energy to mechanical work is represented as an effective fan pressure that is independent of airflow rate.

Development of a representative mine ventilation network model involves a considerable amount of effort. It is suggested the ventilation model being used as the basis for the fire model be developed from a ventilation survey of the mine workings. This is accomplished by using data from ventilation surveys together with information determined from known airway dimensions and characteristics. MVS has attempted to provide the user with explanations, reference material and sources, along with procedures for determining some of the input parameters. It is up to the user to envision credible scenarios according to specifics of the ventilation system or design in question.

4. Program Limitations

Fire behavior is very difficult to predict and nondeterministic; fire is energetic chemical reaction(s) with very chaotic inputs. The results of a simulation will only be as good as the inputs. Input data relating to fires is more complex. Heat release rates are calculated based upon which type(s) of fuel is (are) burning and available oxygen in the airflow at the hazard's location. The location of the fire in a main intake/exhaust airway or area of low flow is important in determining whether to assume an oxygen-rich or fuel-rich fire [5], which helps the user determine which parameters to use in the fire simulation. Contaminants are determined based on the stoichiometric reaction of the combustible materials.

MineFire does have several limitations. One of the most important of these is that it treats airways as one-dimensional: MineFire assumes instantaneous and complete mixing of airstreams at junctions and assumes uniform distribution of contaminants within a given transverse cross-section of the airway (e.g., no smoke layering). Additionally, the program assumes the fuel source burns indefinitely after ignition and ramp-up time: there are no time table events for ramp-down or burn-out of the fire. The program also does not directly deal with the impacts of a combustible ore, such as coal, adding fuel to the fire; nor does it deal with issues

surrounding burn-through of stoppings or doors. These conditions are characterized by adding time table events to simulate the fire moving to adjacent entries or change in fuel type. Localized thermodynamics of the fire and associated chemical reactions are also ignored. Thus, it does not contend with the issues of stratified (laminar) flow, either in the direction of bulk flow or reverse flow.

As with any time-based numerical modeling, the MineFire solution kernel uses results from the preceding time step to compute the following time step solution. Improper simulation parameters for time span, time step increment and allowable error between iterations lead to solution divergence. Very small errors in accuracy introduce compounded errors in the final stages of the simulation [6].

Successful fire simulation requires a series of interdependent decisions from the user in order to converge as expected. These decisions govern the simulation algorithms, and hence the quality of results. Understanding the model time domain conditions and applying sound judgment to those conditions requires considerable experience. Experience of the modeler ultimately limits the development of a fire simulation with credible results.

5. Program Additions

In order to balance ventilation network meshes, the summation of all pressure drops around a closed circuit will equal zero [7]. Synchronized psychrometric and pressure measurements along loop boundaries with surface readings will help the engineer account for NVP and accurately balance meshes. MineFire allows the user to introduce a differential NVP at any junction where these adjustments are accounted for in the model to balance individual circuits. In this way, balanced mesh loops will better handle the dynamic nature of fire modeling while allowing for airflow reversal and adjusting associated upstream airflow perturbances.

MineFire also adds two new curve fitting algorithms to better simulate changes to fan operating points during fire events, Gaussian and constant pressure fan [4]. The MFIRE program has had two fan curve fitting methods built in with an optional parameter. The program includes the Least Squares method and a Spline method of curve fitting. These methods are used for interpolation of data points between the data points entered by the user. The optional parameter defines how to handle points that are beyond the extents of the user entered points, referred to here as the projection points. The projection points can be calculated using one of these three rules:

1. The end point slopes are continued indefinitely

2. Right most value is held constant

3. Left most and right most values are held constant.

Fan curve fitting method must be specified for individual fans, but the projected points method is consistent for all fans.

Experience shows that the most useful fitting method is the Least Squares method with projection points using the option to extend the fitted slope indefinitely. However, when the models are increasing in size and complexity, this combination of methods can yield data results that are beyond a reasonably fitted fan curve. An example graph of the internal calculations is show in Fig. *3*.

In this case, the constant slope moving away from the inputted data allows the simulation routine to ask for unreasonable data from the fan curve. This example includes all data requests, including those in intermediate iterations. A new data table report was added to the program that will report all requested flowrates for each fan calculation and the pressure that was determined via the fitting method. Considering this data for very large and complex models it was determined that a new fitting method should be developed.
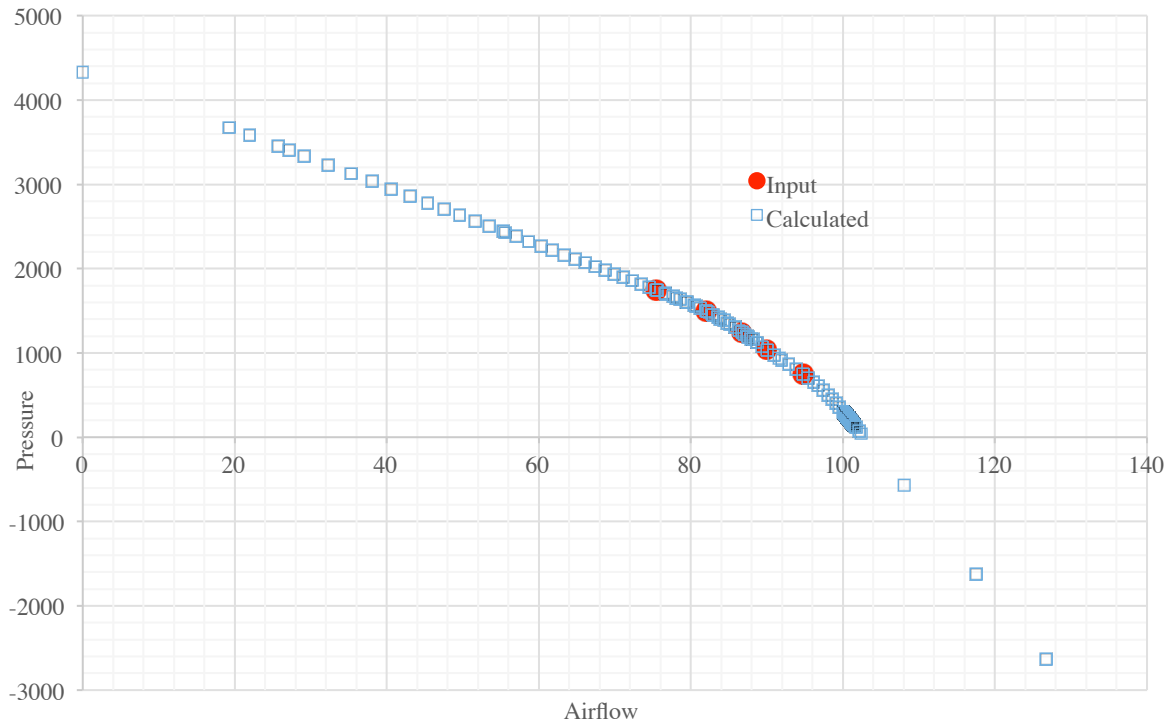
Fig. 3 Example of Fan Curve Fit with inputted data points and calculated data from MineFire simulation

Using the Polynomial fit method established in R. Sedgewick's "Algorithms in C", a new regression model was added [8]. There were several adaptations to the Sedgewick example to make the fit work faster by parallelizing the execution of the code. In addition, the three optional parameters are not necessary for the new curve fit. For values going to the right, they are not allowed to intersect the X axis and are not allowed to return a Y value that is larger than the previous Y value. For values going to the right, the X axis intercept is the furthest value allowed providing that all Y values calculated are increasing. This provides for an inconsistent slope beyond the inputted values, but does not include data that can easily be regarded as unreasonable.
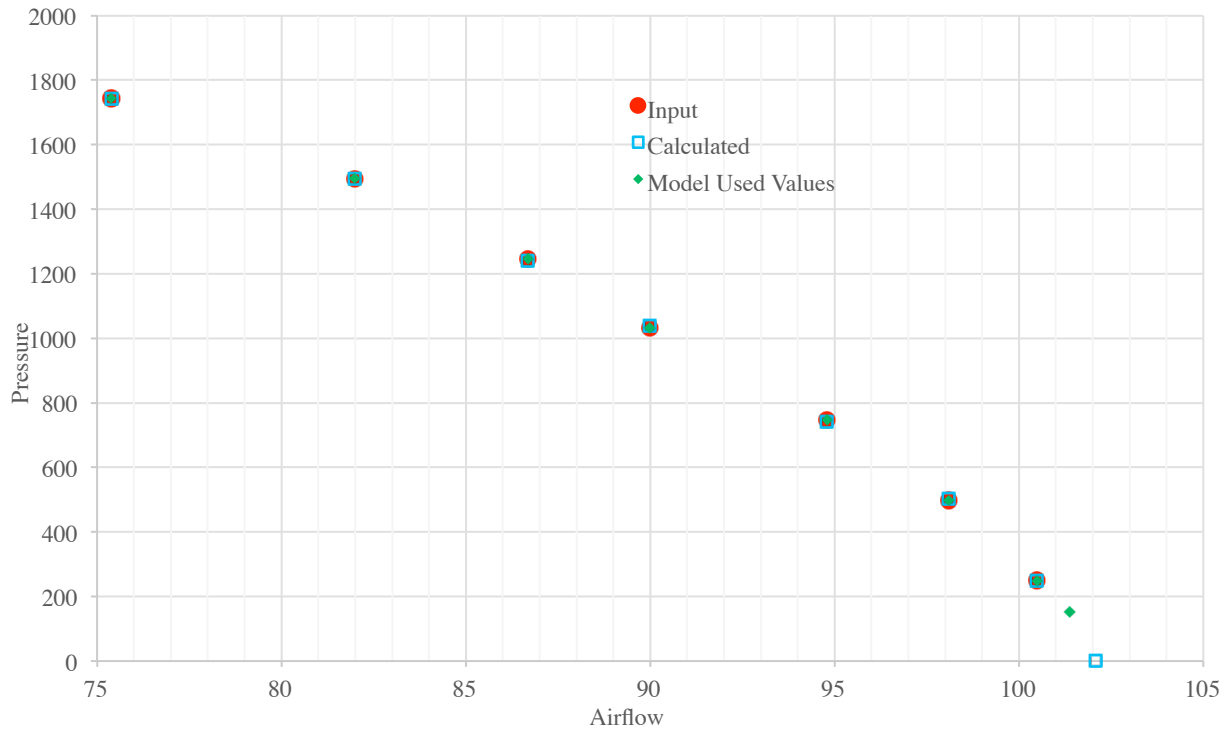

Fig. 4 Example of New Fan Curve Fit

Fig. 4 shows an example of this new fan curve fit. In this example, the user inputted points are shown along with points that are calculated specifically to demonstrate the difference between the fitted curve and

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the inputted data. The equation governing this fit is reported to the user and in future versions of the software the user will be able to input or override the equation.

Calculated points are also shown that is on the right hand most side of the curve, as well as one of the data points that was used in a solution to the model and is outside of the user inputted points. We have found that this fitting method will not work for all fans, but the new data that is available to the user will allow the expert to make better decisions about the fitting method that works best for their model.

6. Practical Applications

MineFire is a comprehensive engineering tool for ventilation engineers, upper management and emergency responders to evaluate the effects of fires on a mine ventilation network. MineFire is employed in three principle roles:

1. System design and evaluation – design stage efforts, in which potential fire hazards and fuel sources are known, such as maintenance shops and fuel bays. This allows mine safety and engineering personnel to consider the overall impacts of fire control procedures on the mine ventilation system for planning efforts, procedure development and training purposes.
2. Operator training – graphical display of simulation results provides immediate feedback necessary for miners to visualize effects of fire spread. The effects of a credible fire scenario and fire control measures are evaluated interactively.
3. Emergency preparedness – development of effective emergency response plans involves careful examination of potential risks and effective response to terminal hazards. Evaluating an existing mine plan for likely shortcomings in egress will be improved with the use of comprehensive fire modeling.

7. Modeling Fire Scenarios for Emergency Preparedness Plans

Ventilation engineers and officers should consider integral participation in their emergency preparedness planning team, alongside delegates from upper management. Development of emergency preparedness plans should include dressed rehearsals of simulated fire hazard mockups to give the planning team a tangible event to design around. The ability to quickly communicate the tasks required to control underground fire shows the necessary steps, the order in which these steps need to occur and an efficient timeline for these tasks. Describing accepted firefighting efforts in sufficiently granular detail, along an acceptable timeline, is paramount when gathering "buy-in" from first responders and upper management to a credible fire simulation.

Miners play an important role in developing the mine-related aspects of the plan. Including a diverse team during the initial review stages of an emergency preparedness plan provides a broad perspective on those issues relevant to each person's department or function. Problem solving is quantitatively better since people with different backgrounds, experience and expertise view problems from different perspectives.

Representatives from upper and middle management need to set aside sufficient budget and sit alongside rescue team members during the early phases so that all team members understand the benefits of mock emergency response exercises. If a mine does not have a fire brigade, the mining company should consider additional, more in-depth firefighting training for their rescue team members.

Training in fighting conveyor belt and other large equipment fires using fire hoses, nozzles and other related equipment [9]. Should a mine operator want to conduct this more intense training, they will need to equip rescue team members with appropriate personal protective equipment including fire fighter turnout gear, hoods, gloves and other related items.

Understanding necessary changes to ventilation controls and the timing of early responses to fire events greatly improves emergency preparedness. First responder teams benefit greatly from the use of MineFire as a prediction tool in training exercises. Animated playback of a fire simulation can be invaluable during emergency training.

Development of fire models for each working section gives each production team a sense of stewardship when reviewing firefighting procedures. Displaying animated results of the advance of noxious fumes from a simulated fire event to crew members will impart the urgency of response required to minimize the growth rate of a fire.

Working section firefighting brigades, and particularly production foremen, should become involved during review of fire simulation results amongst the emergency response team. Since many early firefighting response actions depend upon managing ventilation controls, section foremen need to understand the appropriate order of events for optimum mitigation.

Miners that are well informed of supplies necessary to fight a fire are more likely to keep those supplies in order and readily available in their section. Once the foreman understands the sequence of events to effectively modify the existing ventilation network in a firefighting exercise, critical supplies are more likely to remain at the ready [10].

8. Conclusion

This paper presented a use case for the NIOSH update MFIRE program with MVS's modifications and a robust graphical interface. Ventilation experts using this program will be able to build and analyze credible

fire scenarios. This can be done in conjunction with regular mine ventilation modeling and analysis work in the same frontend program.

MVS has made several modifications to the NIOSH MFIRE program. They allow the user to make modifications to the NVP at various points in the model. This is a very nice feature for overcoming some limitations in the Hardy-Cross solver. The user also has a new fan curve fit method that is very accurate. To improve the accuracy, the internal fan curve calculations are now made available to the modeler in an intuitive manner allowing the expert to make better decisions about the fans that are deployed in the mine. New reporting capabilities have been added that put more data into the model mesh available to view and in table views.

While adding features to the MineFire program, it was of great concern to MVS that the additional features not preclude a user from running the model in current or future version of the NIOSH produced MFIRE. As long as a user does not take advantage of new features such as the new fan curve fit or the NVP editor, an XML file that is compatible with the NIOSH version of the program can be created. Other differences between the two programs are model size and number of fan curve points.

An example mine was presented that shows how all of these proven features of MFIRE have been incorporated into MineFire and how the new features can be utilized. This was also performed with a significant speed-up of the execution time. With proper planning and appropriate usage of MineFire, mine emergencies can be mitigated altogether or can be responded to in an efficient manner.

Acknowledgments

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