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Improvement of the Mine Fire Simulation Program MFIRE

Lihong Zhou

Dissertation submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Doctor of Philosophy
in
Mining Engineering

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Keywords: fire simulation, t-squared fire, conveyor belt fire, smoke rollback

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ABSTRACT

Fire represents one of the most severe hazards to underground mines. A good understanding of the interaction between a mine fire and the mine ventilation network would be very crucial for fire emergency planning and hazard control. MFIRE, an underground mine fire simulation program developed in 1980's, is a tool that can be used to simulate the impacts of a mine fire event to a mine ventilation network. However, the lack of the abilities to simulate some of the important mine fire phenomena realistically hindered its wide applications. This research has been carried out to improve the MFIRE program. The new program, named as MFIRE 2.30, incorporated the following improvements to make it more useful in mine fire simulation:

- A time-dependent fire model, a t-squared fire, is introduced and incorporated into MFIRE. The t-squared fire model was validated with a fuel fire test conducted in 1990. It has been shown that predicted temperatures of the t-squared fire model agreed well with the measured temperatures.
- Smoke rollback is a phenomenon in underground mine fire and it could hinder the firefighting efforts and endanger the fire fighters. A semi-empirical model based on a large-scale experiment conducted in a real coal mine entry has been selected to identify the smoke rollback in MFIRE 2.30. The distance of smoke rollback is also estimated and output as an important result of MFIRE 2.30.
- A moving fire source model to represent a conveyor belt fire has been proposed based on experimental studies on belt fires. The model predicts the flame spread rate along the conveyor belt based on the airflow velocity and the thermal properties of the conveyor belt. Two types of moving fire, a constant spread rate moving fire and non-constant spread rate moving fire were defined. The proposed model has been incorporated into the MFIRE 2.30 program. In addition, a fire can start at any location in a branch, not only at the starting junction of a branch as prescribed in the original MFIRE program.

In order to facilitate the continued support and development of the MFIRE program, the program is recoded using an object-oriented programming (OOP) language, Visual C++ (Note: the original MFIRE was coded in FORTRAN 77). A public database interface has been created for the flexible data access. Graphi-

cal user interfaces were also provided for easy data input and display of the program outputs.

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This dissertation is dedicated to the memory of my mother, Shuxiu Dong and my grandmother, Dongliu Shi.

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LIST OF SYMBOLS

A	cross sectional area of tunnel
a	growth factor
a_1	growing factor of growth period
a_2	decaying factor of decay period
C_{o_2}	oxygen concentration downstream from the fire
C_p	specific heat of air at constant pressure
Fr_r	Froude number for a flow ventilating a fire
g	acceleration due to gravity
g_a	increasing rate of air temperature due to auto-compression of air
H	height of tunnel
$\bar{H}$	hydraulic height of tunnel
h	convective heat transfer coefficient
K_1	defined as $Fr_c^{-1/3}$, Fr_c is critical Froude number
L	length of airway or control volume
$\dot{m}$	mass loss rate of the fuel in combustion
P	airway perimeter
$\dot{q}$	heat release rate (HRR)
$\dot{q}_{\max}$	maximum heat release rate

$\dot{q}_{in}$	energy entering the control volume per unit time
$\dot{q}_{out}$	energy leaving the control volume per unit time
$\dot{q}_{generation}$	energy generation inside the control volume per unit time
$\dot{q}_{convection}$	convection energy transported through wall surface per unit time
$\dot{q}^*$	dimensionless heat release rate
q_c	heat of combustion
q_f	heat generated per cubic feet of oxygen consumed
q_t	total heat released
q_i	heat flowing into the junction from the i th airway connecting the junction
Q	airflow rate
Q_i	airflow rate of the i th airway
ρ	density of airflow (average density of upstream in Equation (4.2)).
ρ_i	air density of the i th airway
ρ_f	average density of the fire-site gases
R	coordinate in radial direction
R_i	Pseudo resistance
R_0	hydraulic radius of airway
t	time

t_0	time of ignition delay
t_1	the end time of steady period
t_2	the end time of fully developed fire period
t_3	the end time of decay period
T_a	air temperature
T_{a0}	air temperature at $t=0$
T_{ae}	air temperature at the end of an air segment
T_{ave}	average airflow temperature
T_0	temperature of the approach air.
T_r	rock temperature
T_{rv}	virgin rock temperature
T_f	average temperature of the fire-site gases
T_j	air temperature in junctions
T_w	wall temperature
V	velocity of the approach air
V_a	airflow velocity
V_{ax}	maximum airflow velocity
V_c	critical velocity of smoke rollback
V_c^*	dimensionless critical velocity

V_f	flame spread rate
V_{fx}	maximum flame spread rate
ψ	coefficient of age
λ	thermal conductivity of rock
β	slope angle of airway

CHAPTER 1 INTRODUCTION

1.1 Mine Fire Accidents

Fire in underground mines has long been a concern for workers. A mine fire produces gases and heat which can be carried by airflow traveling through the confined and connected mine ventilation system. The liberated gases can be poisonous or explosive and the released heat can disturb the ventilation system. Worst of all, an uncontrolled mine fire could ignite the available fuels (e.g., methane, coal dust, wood) on its propagation path and probably result in a severe mine disaster. The majority of deaths arising from mine fires and explosions are caused, not by burning or blast effects, but by the inhalation of toxic gases, in particular, carbon monoxide. There are two major differences between underground fires and those that occur in surface structures. The first concern is the long distance, often several kilometers, for the miners to travel in passageways that may be smoke-filled. Secondly, the ventilation routes are bounded by the confines of the airways and workings, causing closely coupled interactions between the airflows and behavior of the fire (McPherson, 1993). Unlike fire accidents on the surface, the limited numbers of evacuation routes in an underground coal mine may slow down the evacuation process, and cause worse damage and a larger threat to miners' lives.

A mine fire can occur at any time and impose hazards to health and safety of miners. Statistics from the Mine Safety and Health Administration (MSHA) indi-

cate that 137 reportable fires¹ occurred in underground coal, metal, and nonmetal mines from 1991 to 2000 in the United States. Those fires caused 2 fatalities and 34 injuries (Ronald et al., 2000). The statistic data combined by Alexander (2006) based on some published statistical analysis of coal mine fires has shown that there were still about 10 reportable fires in 2001 even though the number of reportable fire have decreased from 1950 to 2001 as shown in Figure 1.1.

Figure 1.1 Underground Coal Mine Fires 1950-2001 (Alexander, 2006)

The most recent fatal underground mine fire with two fatalities happened on January 19, 2006, at Aracoma Alma Mine No. 1 in Logan County, West Virginia. Although the number of fires and injuries is relatively low, fires that occur in confined spaces have potentially catastrophic consequences. In 1984, a fire at the Wilberg Coal Mine in Utah caused 27 deaths, while a fire at the Sunshine Silver

¹ A fire has to be reported to MSHA within 15 minutes if it causes a death or severe injury or is not extinguished within 10 minutes of discovery in an underground coal mine according to 30CFR 50.20. The data presented was based on the former 30 minute reporting standard.

Mine in Idaho in 1972 killed 91 miners. The mine fire at Roch-la-Moliere (France) killed 48 miners in 1928 and has been a classic and often-quoted example. In addition to the safety problems, mine fires can also cause significant production losses and place huge financial burdens on the mining companies. For example, the February 2005 fire in Buchanan Mine of Consol Energy, Inc. in Virginia idled the mine for nearly 4 months and caused \$23.3 million in property damage (PBT, 2005).

1.2 Fire Computer Modeling

Fires in underground coal mines have more chances to start and less certainty of being controlled because of the confined environment and the existence of abundant combustible materials, such as belt, diesel, wood, unlimited coal, etc. Fire modeling in the laboratory as well as on a computer is the best choice to simulate a fire scenario and obtain good knowledge about a fire event.

A mine ventilation system is often treated as a complicated network with hundreds, even thousands of branches, junctions, various controls and multiple fans. An underground mine fire may develop and spread under the influence of the mine ventilation system, and therefore disturb or disrupt the air movements in the network. A coal mine fire is not only affected by the nature and amount of available flammable materials but also the ventilation system arrangement. In a mine fire event, a good knowledge of the fire development, its dynamic effects on the mine ventilation system, and its thermal, gaseous and solid combustion products would be very helpful to safely and effectively extinguish the fire as well

as safely and quickly evacuate the miners when the fire is growing or out of control.

The first computer simulator (Greuer, 1977) for the interaction of mine fires and mine ventilation systems focused on the assessment of these disturbances. In 1981, a computer program, named MTU/BOM was developed at Michigan Technological University. The program takes into account the mutual influences of fire intensities and ventilation conditions and can determine the distribution of products of combustion (POC) from a mine fire in a multilevel mine with several operational fans (Greuer, 1981). The program was modified later (Chang et al., 1990) to accommodate dynamic state modeling of the fire and make it work on the transient-state modeling problem. The resulting program, MFIRE, could provide some useful information for fighting a mine fire as well as planning the fire evacuation routes (Chang et al., 1990). The program allows the simulation of the mine ventilation system in its normal steady state condition and in its transient state after a mine thermal event or fire begins. In addition to estimating the air quantity and pressure distributions in the steady state condition from a regular mine ventilation network analysis program, MFIRE also outputs information about the propagation of time dependent air temperature and concentrations of gases (including mine gases or products of combustion) in the mine.

Besides MFIRE, two other numerical methods for fire computer modeling including Computational Fluid Dynamics (CFD) was widely used in surface and underground fire simulation research. The idea of studying a fire numerically dates back to the beginning of the computer age. Although the fundamental

conservation equations governing fluid dynamics, heat transfer and combustion were first proposed over a century ago, practical mathematical models of fire were only created recently due to the inherent complexity of the problem. CFD provides a new, efficient, reliable, and economical approach for fire research and has become an essential fire research tool. Before the advent of CFD simulation, fire study was limited to experimental investigation and empirical correlation. Due to its expense and practical difficulty, experimental data are usually very limited, if not unavailable. With the limited experimental data as validation base, a properly validated CFD simulation tool can provide much more information and thus extensively extrapolate the limited experimental data. With new developments in modeling techniques and the rapid increase of computing power, it is expected for CFD simulation to continuously gain popularity in mine fire research. In recent years, CFD modeling has been used to investigate smoke movement, concentration and temperature distribution caused by a fire in a mine entry. Hwang and Edwards (2001) have applied CFD to investigate smoke rollback in a mine entry. A CFD program was also applied to the simulation of a buoyant roof layer generated by a hydrocarbon fire source in a mine entry (McGrattan et al., 2007). Compared with MFIRE, a CFD representation of fire scenario is based on a 2- or 3-dimensional analysis, while MFIRE treats the ventilation system and fire source as one dimensional. Although the CFD method has contributed to mine fire research, its limitations are also significant. It can only cover one or a couple of entries due to the limitation in computer memory and processor speed at the current time. It's impossible to use CFD in investigating the propagation of a fire

at the scale of the entire mine including hundreds or even thousands of airways. A CFD program can provide detailed fire simulation information in a limited length of entry which has been isolated from a complete ventilation system. But it cannot represent what influence a mine fire may impose to the entire ventilation system.

Since the intrinsic interplay between fire and airflow usually drives an originally stable airflow pattern to change drastically, toxic fumes may be brought to even remote regions, thereby suffocating miners. It's hard to make the right decision about evacuation without knowing the ventilation pattern under the thermal disturbance of a mine fire. When a fire occurs out-by the working place, immediate evacuation of miners from the potential hazard areas should always be the first action. Therefore, it is very important and necessary to predict how the smoke will spread in an underground ventilation system to make the right decision for fire evacuation and rescue. All these predictions within a confined ventilation system can only be conducted by a network fire modeling software such as MFIRE as opposed CFD or zone models. An accurate prediction of the fire impacts on a mine ventilation system could be very valuable during efforts to fight fires, evacuate miners, prevent methane or coal dust explosions, and or regain control over the mine ventilation. In summary, the program MFIRE is a useful and unique tool for gaining a good understanding about the fire effects on the mine ventilation system and cannot be replaced by CFD or Zone modeling methods.

MFIRE was initially developed in 1990 (Chang et al.) and improved slightly in

1995 (Laage et al.) when it was released as MFIRE 2.20. Since then, no improvement has been made to MFIRE. However, research in fire dynamics as well as computer technology has developed very quickly since then. Some of these new findings and developments should be incorporated into MFIRE to improve the mine fire simulation program. The main objective of this dissertation is to incorporate some new research achievements including a time-dependent fire model, smoke rollback identification, and a moving fire source into the MFIRE program.

1.3 Outline the Dissertation

The complete work carried out in this research has been organized in 7 chapters commencing with Chapter 1 introducing mine fires, mine fire modeling and the scope of present work. Chapter 2 includes a thorough review of the literature related to the mine fire modeling and the mine fire simulation program MFIRE.

Chapter 3 deals with the improvement of fire source modeling of MFIRE. The fire model in the original MFIRE program is simplified to a point fire source with a constant heat release rate (HRR). Such simplified treatment makes it easy to incorporate the fire event into a network representation of the mine ventilation system. In reality, such over-simplification is unable to describe adequately a mine fire. Consequently, it would provide an inaccurate simulation of temperature distribution, air flow, etc. in each airway. Therefore, fire model in the original MFIRE should be improved to make it capable of representing the fire more realistically. A time-dependent fire, t-squared fire is introduced and incorpo-

rated into the improved MFIRE program. The calibration study has also been done at the end of this chapter.

In Chapter 4, the smoke rollback phenomenon is discussed. It is a well known fact that the smoke generated by a fire event would not evenly spread in an airway space and may not travel with the main airflow at the same pace. Smoke layers are normally formed within some distance from the fire site and the layer in the upper portion of the airway could even travel backwards against the main airway flow to some distance. This phenomenon is called smoke rollback, and it presents threat to firefighters because it may affect visibility and distribute products of combustion (POC). It should be noted that a good understanding of the smoke rollback is particularly important for planning and implementing a successful fire fight strategy. Since the airflows in airways are represented as one-dimensional quantities in a ventilation network, the current version of MFIRE is incapable of modeling the smoke rollback phenomenon. A one dimensional network only allows the possibility of identifying the complete airflow reverse. Obviously, this is not consistent with the reality since fires are most likely to occur within the airways and so do the smoke rollback phenomena. In this research, a method was developed to identify whether smoke rollback exists in the airway(s) with fire event(s) based on the fire intensity, airflow velocity and physical dimensions of the entry.

Chapter 5 discusses the moving fire source modeling, which can represent conveyor belt fire. Because it imposes a major safety and health risk to miners, a belt entry fire has always been a great concern in fire detection and prevention. A

fire can start anywhere along the conveyor system and can spread quickly to other areas. The burning of the belt rubber materials in confined a belt entry may produce a large amount of carbon monoxide (CO) that is actually responsible for more deaths in mine fire accidents than heat. Because of the fast moving nature of a belt fire, the detectors installed in the belt entries often have trouble detecting the fire. The hazard associated with a moving belt fire should be adequately understood and modeled in mire fire studies. However, MFIRE 2.20 and the previous versions lack the ability to define a moving fire source and thus is incapable of simulating a moving belt fire. Therefore, a method to simulate a moving fire source should be developed with the consideration of the influence of airflow velocity and the belt's flammability characteristics. The hazard associated with a belt fire could be better understood.

Chapter 6 deals with recoding MFIRE from FORTRAN to Visual C++. MFIRE was written originally in FORTRAN to run in the DOS environment. MFIRE is in danger of being unsupported by current and new computer technology and unable to run in the new Windows Vista 64 environment. Also, its unfriendly data input and output format and environment also limit its application in the mining industry. An object oriented programming language, VC++, will be employed to recode MFIRE. Friendly graphical user interfaces with schematic and tabular views will also be designed and provided for easy data input and display of the program outputs.

In chapter 7, an example from the manual book of MFIRE 2.20 is employed to illustrate the new features of the improved MFIRE program.

In summary, this research has contributed to improve the ability to simulate mine ventilation system under the influences of mine fires. Such ability could be used to improve mine safety. The major works made for such improvements are: (1) improved fire models in MFIRE using a time-dependent fire, t-squared fire, (2) developed a method to recognize smoke roll back condition and to estimate the extent of rollback (3) developed a method to simulate moving fire source such as conveyor belt fire, and (4) incorporated the improvements to a upgraded program that is written in Visual C++. The new version of MFIRE upon the mentioned improvements is named as MFIRE 2.30².

² In this paper, MFIRE 2.30 refers to the improved MFIRE; MFIRE 2.20 is the latest version released in 1995; MFIRE refers to all the original MFIRE not including MFIRE 2.30.

CHAPTER 2 LITERATURE REVIEW

2.1 Fire Modeling

The use of mathematics and science as applied to fire-related dynamics began in the early 1940's (Gorbett, 2008). Mathematical models are sets of mathematical equations that describe the behavior of a physical system. Computer fire modeling has been used to design and analyze fire protection systems (i.e. sprinkler systems, detection systems), evaluate the effects of fire on people and property, estimate fire risks, and assess post-fire reconstruction (Gorbett, 2008). Mathematical fire modeling can be arranged into the following four categories based on the types of calculations performed: hand calculations, zone models, computational fluid dynamics models (CFD) and network models. Each method will be discussed separately in the following sections.

2.1.1 Hand Calculation

Basic hand calculation typically was algebraic equations developed from experimental correlations and are utilized to estimate the effects of simple fire phenomena for simple configurations. Even though these calculations are basic, they can often provide a quick, reliable prediction of the fire phenomena for a given scenario. In fact, the upper level mathematical equations found in the more advanced computer fire models (zone and CFD) are similarly based on these hand calculations and experimental correlations. These hand calculations are often implemented via spreadsheet software (e.g. Microsoft Excel) as a collection of

calculations for ease of use and repetition. The most popular collection is known as Fire Dynamics Tools (FDTs) which was created and is still supported by the U.S. Nuclear Regulatory Commission (Gorbett, 2008).

2.1.2 Zone Models

Zone fire models are a type of computer software utilized for evaluating enclosure fire dynamics. It is based on a conceptual representation of the compartment fire process, and is an approximation to reality. The zone modeling approach emerged in the mid-1970s when the effort to study the developing fire in a compartment intensified. The zone model simply represents the system as two distinct compartment zones: an upper volume (or upper layer) and a lower volume (or lower layer). The fire plume and resulting collection of hot gases and combustion products would form the upper zone. The ambient air and entrained air outline the lower zone. The interface between the two zones constantly changes height based on the increasing collection of hot gases in the upper zone, which subsequently descends the upper zone (Gorbett, 2008). Zone models, from a mathematical standpoint, therefore consider two separate control volumes. The upper zone is considered as a control volume that receives both mass and energy from the fire. This upper zone loses its energy by convection or mass movement of gases through openings, by radiation to the floor, and by conduction and radiation to its contacting surfaces.

Figure 2.1 Schematic view of zone models (Gorbett, 2008)

This two-zone approach has evolved from observation of such layering in real-scale fire experiments. The upper and lower zones were deemed relatively uniform in temperature and composition. Distinct phenomena were discerned that could be studied in isolation, enabling better predictions of their roles in the compartment fire system (Quintiere, 1995). Thus, the zone models can produce a fairly realistic simulation under many common and important conditions.

The relative physical and computational simplicity of the zone models has led to their widespread use in the analysis of fire scenarios. Zone model based software packages CCFM.VENTS and CFAST (Jones et al., 2005) from the National Institute of Standards and Technology (NIST) are still used widely to study compartment fires.

2.1.3 Computational Fluid Dynamics (CFD)

The rapid growth of computational power and the corresponding maturing of computational fluid dynamics (CFD) have led to the development of CFD based “field” models applied to fire research problems (McGrattan et al., 2007). The

use of CFD models has allowed the description of fires in complex geometries and the incorporation of a wide variety of physical models. CFD is the most advanced and sophisticated fire modeling technique to predict fire growth and compartment temperature.

Figure 2.2 Schematic of CFD model (Gorbett, 2008)

CFD models separate a compartment into hundreds to thousands of tiny cubes or calculation cells based on user inputs (as shown in figure 2.2). CFD models are more calculation intensive than their zone model counterparts. These models calculate each cell using higher level mathematics to specifically relate energy transfer and flow of fluids to each other. The basic laws of mass, momentum, and energy conservation are applied in each cell and balanced with all adjacent cells. The input requirement for CFD models is very demanding and requires expertise in defining the correct input parameters and assessing the feasibility of the calculated results (Gorbett, 2008). On the other hand, the out-

puts are much more detailed, providing the variables in all points of the compartments, such as temperature, velocity and concentration of chemical species. Fire Dynamic Simulation (FDS) based on CFD from NIST is the most commonly used compartment fire simulator (McGrattan et al., 2007). Other CFD-based commercial software packages such as Fluent and PHOENICS can also be used to study fire scenarios.

2.1.4 Network Model

In the realm of computational heat and mass transfer, a network model represents the lowest level of abstraction for a multiple volume prototype. In a network model, each control volume of interest is represented as a single node. In some sense, this could be referred to as a one-zone model. A control volume is either a compartment or a heating, ventilation and air conditioning (HVAC) system plenum. Heat and mass transfer occur by defining branches between nodes. These branches represent flow paths for the transfer of mass, energy, and momentum between nodes (Floyd et al., 2005). Some of the existing network models with potential usage for multiple compartment fire are shown as below:

- **CONTAM:** It is an HVAC network model developed by NIST (Dols et al., 2000). It supports the computation of buoyant flows and HVAC system flows within a building. However, it doesn't contain any models for combustion-related phenomena.
- **FIRAC:** It was developed by Los Alamos National Laboratories. It is capable of predicting the dispersion of radionuclide through a complex ventilation system (Nichols and Gregory, 1986)

- **MELCOR:** It was developed by US Nuclear Regulatory Commission to simulate the post accident response of reactor containment systems (Gaunt et al., 2000).
- **FSSIM:** It is a software tool from Hughes Associates. It is capable of simulating fire and smoke spread through very large structures, including complex HVAC system. Simulations of buildings containing thousands of rooms with multiple HVAC systems are easily achieved with FSSIM (Floyd et al., 2005).

The application of Network model to the mine fire simulation can be dated back to 1970s (Greuer, 1973). It is even earlier than the existence of network modeling of compartment fire. One of the most important reasons is that the mine ventilation system itself is a very complicated network and network analysis has been used in ventilation design and management widely since 1950s. Of greatest concern in a research on mine fire is the fire-generated ventilation disturbances. Of course, the research about fire in these network systems should focus on the mutual influence of fire intensity and the ventilation network. A mine fire network model treats a ventilation system as a closed network with a great number of airflow branches and nodes. With the combination of the fire dynamics and the mine ventilation network, the fire network model is able to simulate fire growth and smoke spread in a complex ventilation system. MFIRE, MineFire from Mine Ventilation Service (MVS, 2000), and VentGraph from Strata Mechanics Research Institute of The Polish Academy of Sciences (SMRI) are the three

most popular software tools for the mine fire network modeling and they will be discussed in detail in Section 2.3.

2.2 Development of Mine Fire Simulation Program

2.2.1 Mine Ventilation Network Analysis

A ventilation network schematic is a graphical representation of a ventilation system and consists of a set of junctions and interconnecting lines called branches or airways which denote major or significant airflow routes. The solution for the airflow distribution in a mine ventilation system as a result of mine fans, thermal forces, and flow resistances is a formidable mathematical problem. A large set of equations formulated explicitly based on Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL) are solved iteratively by the Hardy Cross method (Hartman et al., 1997).

Before the mid 1950's there were no practical means of conducting detailed and quantitative ventilation network analysis for complete mine systems. Ventilation planning was carried out either using hydraulic gradient diagrams formulated from assumed airflows or, simply, based on the experience and intuition of the ventilation engineer. Attempts to produce physical models of complete mine ventilation systems using air or water as the medium met with very limited success because of difficulties from scale effects (McPherson, 1993). In the late 1950's, digital computers became commercially available and the first network calculations with digital computers were performed for waterworks in the United States. The first ventilation network calculations were reported in Belgium in 1958 and in Germany in 1959 (Laage et al., 1995). Ventilation simulation programs for main-

frame digital computers had begun to appear in 1960's (McPherson 1964, Hartman and Wang, 1967). These proved to be much more versatile, rapid and accurate, and their employment soon dominated ventilation planning procedures in major mining countries. Coupled with continued improvements in ventilation survey techniques to provide the data, ventilation network analysis programs resulted in unprecedented levels of flexibility, precision and economics in the planning, design and implementation of mine ventilation systems (McPherson, 1993).

Throughout the 1970's, network programs were developed for large centralized mainframe computers. Their initial use by industry tended to be inhibited by the often pedantic procedures of data preparation together with the costs and delays of batch processing. In the 1980's, the enhanced power and reduced cost of microcomputers led to the evolution of self-contained software packages that allowed very easy interaction between the user and the computer. These incorporated the use of graphics. Ventilation engineers could, for the first time, conduct multiple planning exercises on large networks entirely within the confines of their own offices. The complete processing of data from survey observations through to the production of plotted ventilation plans became automated. Personal computers, printers and plotters proliferated in mine planning offices. Together with the ready availability of software, these led to a revolution in the methodologies, speed and accuracy of subsurface ventilation planning (McPherson, 1993).

Up to date, mine ventilation network analysis software is still a very essential tool for a mining engineer to design or optimize a ventilation system. It can quantify the distribution of airflows together with the locations and duties of fans and

other ventilation controls required to achieve acceptable environmental conditions throughout the system during the design phase of a new underground mine. Similarly, throughout the life of an underground operation, mine ventilation network modeling can help plan ahead in order for new fans, shafts or other airways to be available in a timely manner for the efficient ventilation of extensions of the mine workings. As any operating mine is a dynamic system with new workings continually being developed and older ones coming to the end of their productive life, ventilation planning should be a continuous and routine process (McPherson, 1993). Therefore, mine ventilation network modeling software is a routine tool for mining engineers.

VnetPC, Ventsim, Vuma and MVSAS are the most used ventilation network modeling software package in the United States, Australia, South Africa and China. The current versions of these software packages run under Windows environment. The programs require input information that describes the geometry of a ventilation network, airway resistances or dimensions, and the locations and characteristic curves of fans. Then they will perform the solution process and output the predicted airflows, pressure drops, air power losses in airways, and fan operating states. The core of all the programs, to solve a set of specially formulated linear and non-linear equations, is basically the same. The differences exist in how the mass conservation law is introduced and observed, how the fan characteristics are simulated, and how the thermal drafts are considered.

2.2.2 Mutual Influences between a Mine Ventilation System and the Fire

It is well known that heat generated by a mine fire, especially a severe open fire in a mine can affect the stability of a ventilation system by buoyancy (natural draft changes) and throttling. These effects can cause changes in the quantity of ventilating air currents and sometimes result in smoke rollback along the roof of airways for a short distance and even a complete reversal of airflow direction. In a gassy mine, significant airflow changes could lead to the possibility of carrying the explosive mixtures back to the fire zone and result in even more hazardous conditions.

(1) The choke or throttling effect

Heat generated by an underground mine fire can increase the temperature of the air and then thereby expand its volume. The expansion of the volume is also due to gas expansion as well as the addition of products of combustion (POC) such as fire gases and evaporated water. These expansions attempt to take place in both directions along the airway. The tendency of volume expansion against the prevailing airflow direction can cause airflow reduction. This is known as choke or throttling effect (McPherson, 1993).

According to McPherson (1993), the choke effect is analogous to increasing the resistance of the airway. For the purposes of ventilation network analyses based on a standard value of air density, the raised value of this "pseudo resistance", R_t , can be estimated with the square of the absolute temperature (T), as shown in the Equation (2.1). Litton et al. (1987) have also produced an estimate of the increased resistance in terms of the carbon dioxide evolved from a fire.

$$R_t \propto T^2 \quad (2.1)$$

(2) Buoyancy (natural draft) effects

The decreased air density due to the volume expansion under the influence of fire makes the heated air more buoyant. It causes local effects and changes in the magnitude of natural ventilating energy. The buoyancy effect causes the mixture of hot air and POC to rise and flow preferentially along the roof of the airway. Strong buoyancy effect in a level airway could also cause smoke rollback.

Friel et al. (2006) discovered that smoke from diesel-fuel fires of 500 KW and 660 KW HRRs in a return airway can develop into smoke rollback events without causing a complete air flow reversal. The roof layer formed a counter flow to the primary airflow in the two mine-fire experiments. In the experiments, smoke even penetrated into an intake airway and created a hazardous atmosphere in the intake airway upwind from the fire. Poor visibility conditions of less than 13 m were created by the smoke in the intake airway downwind from the smoking leaking crosscut. Smoke rollback will be discussed in more detail in Chapter 4.

Buoyancy effects have significant influence in shafts or descensional airways where airflow moves downwards through the inclined airways. In a descensional airway, the expanded hot air and POC tend to flow upward which causes a buoyancy force to oppose the ventilation force. With sufficient fire intensity, the buoyancy force could even overcome the ventilation force to induce a complete airflow reverse. In this case, the reversed airflow may bring POC to the adjacent parallel airways and make the fire event more hazardous (Gillies, et al., 2004).

These airways maybe the primary or secondary escape way which if contaminated could endanger escaping miners or fire fighters.

Diagonal airways between two parallel airways could be subjected to airflow reversal and the possibility depends on the pressure imbalance between the connected airways. Wala and Stoltz (1999) have shown that connections of diagonal airways can result in catastrophic events, such as methane explosion. Smoke reversal caused by buoyancy effects could lead to a severe accident once it flows into a diagonal airway.

2.2.3 Mine Fire Simulation

In order to study the fire-generated disturbances to the mine ventilation system in a mine fire event, ventilation engineers developed a large number of manual calculation methods to detect potentially unstable airways for airflow reversals. When analog and digital computers became available for ventilation planning, they were almost immediately applied to this problem. The expected fire-generated ventilating pressures were manually inserted into the network simulations, with their constant values usually obtained from experience or from approximation. In such an approach, the mutual influences of fire intensities and ventilation conditions were not taken into account. If gas concentrations were calculated at all, they were only calculated for the cases where no recirculation existed. All calculations were, as in conventional network calculations, based on steady-state conditions or based on the assumption that the ventilation system is time independent (Laage et al., 1995).

The researchers at the Michigan Technological University first solved this problem with steady-state analysis, and the resulting program became known as the MTU/BOM code. A new program MFIRE came into being by improving the MTU/BOM code with providing transient-state modeling capability that is required to deal with the dynamic nature of mine fires. MFIRE is useful for the analysis of ventilation networks under the influences of natural ventilation, fans, fires, or any combination of these. MFIRE also preserves the common features of traditional mine ventilation programs to simulate a mine's ventilation system and its response to changes in the mine system, ventilation control structures, as well as external and internal influences. Its extensive output enables detailed and quantitative analysis about the influences of these alterations to the ventilation system (Laage et al., 1995).

Since the original development of MFIRE, a number of fire simulation packages have been developed to perform numerical modeling of mine fires, such as MineFire, Ventgraph, etc. MineFire (Figure 2.3) was built from MFIRE 2.20 code released by the U.S. Bureau of Mines (USBM) in 1995. VentGraph, as shown in Figure 2.4, is mine fire simulation software from SMRI in Poland. Both MineFire and VentGraph can provide a dynamic representation of the fire's progress (in real time) and utilizes a color-graphic visualization of the spread of combustion products, oxygen and temperature throughout the ventilation system, which are the most fundamental features of fire simulation software. They are both capable of simulating fire progress after some fire control strategies such as hanging brattice or check curtains, breaching stoppings, and changing fan characteristics are

applied during the simulation session.

From the standpoint of fire modeling, MineFire is the same as MFIRE except for modifications made by its developer Mine Ventilation Service (MVS, 2005) were to increase the number of branches and fans available. In MineFire, the calculation kernel of MFIRE was adapted into the user-friendly interface of MVS's VnetPC ventilation software package, which allows MFIRE be able to run in a MS-Windows environment like any other Windows-based software (MVS, 2005).

Compared with MineFire or MFIRE, one of VentGraph's unique features is that it can simulate the consequences of the usage of some suppression strategies such as the Polish developed jet engine unit, the Gorniczny Agregat Gasniczy (GAG) (Gillies et al., 2005). Simulations using VentGraph can be undertaken to gain better understanding of how inertisation units or systems interact with the complex ventilation behavior underground during a substantial fire. Validation studies on VentGraph have been performed by Wala et al. (1995) using data gathered from a real mine fire.

Neither MineFire nor VentGraph is capable of identifying the smoke rollback phenomena or simulating a moving fire such as a conveyor belt fire, which will be done in this research.

Figure 2.3 Main view of MineFire (MVS, 2000)

Figure 2.4 An application example of VentGraph (Gillies and Wu, 2004)

2.3 The MFIRE Program

2.3.1 Program Structure

In order for MFIRE to perform mine ventilation network analyses under normal mining operational conditions and under fire influences, the program MFIRE logically consists the following four sections (Chang, 1987).

(1) **Network calculation section:** perform the basic network balancing without considering heat/mass transfer.

The beginning of the MFIRE code is a network calculation for the pre-fire state, to ascertain that the input data are correct. The network calculation part performs airflow rates and pressure-loss calculations as a result of fans, branch resistances and ventilation network connection patterns and controls. In other word, MFIRE is capable of not only mine fire simulation but also conventional mine ventilation simulation.

(2) **Temperature calculation section:** Establish reference temperature distribution before the non-steady state (transient-state) simulation.

In the network calculation section, no thermal event is involved. However, temperature distribution such as mean temperature in each airway and temperature at each junction needs to be known in order to evaluate natural ventilation pressure and choke effects. In the temperature section, the temperature distribution is calculated based on the airflow distribution obtained from the network calculation section. The calculation of temperature starts at a node with known temperature, normally, at the surface or a place in the intake airways. Starting with the known temperature at the starting node, the tem-

perature calculation is performed for all branches leaving this node. Next, find the junctions where the conditions of all entering airways are known. Then assuming that the entering air currents are mixed thoroughly at the junction and the calculations of temperature and gas concentration are performed for all airways leaving this junction. The process is interrupted when recirculated air enters a junction. The mean temperature of each branch and the temperature at each junction are two essential parameters to be evaluated in the temperature section. The detailed process is presented in the flowchart shown in Figure 2.5.

(3) **Transient-state simulation section:** calculation changes in the ventilation step by step to offer a continuous snapshot on the ventilation pattern.

A transient process in the ventilation of a mine can be induced by a mechanical disturbance (e.g., change of fan operating state) and thermal disturbance. In the transient state simulation (or non-steady state simulation) of MFIRE, users can specify a series of time increments within a time period of interest. This follows with the airflow in the system divided into corresponding air segments. With the aid of a heat transfer model, the temperature distribution in a system can be obtained in an airway-by-airway advancing process. As a subsequent step, the natural ventilation pressures around meshes can be evaluated according to the calculated air temperature distribution (Chang, 1987). The results at the present time define the initial conditions for the next time increment. The procedure is repeated through all successive time segments to produce a series of ventilation states of the mine to show the process of

transient ventilation. The schematic flowchart of transient simulation section is shown in Figure 2.6.

(4) **Quasi-equilibrium simulation Section:** This simulation predicts the ventilation pattern at a quasi-steady state condition. The ventilation system reaches a more or less steady state condition after a relatively long period of time has elapsed from the starting of a fire. The processing procedure is similar with that of the temperature calculation.

In summary, MFIRE starts with a network solution process for the pre-fire state. Then, a reference temperature distribution in the mine without a fire is determined in the temperature calculation section. The transient state of a mine ventilation system under the influence of a fire event is simulated with a time-stepped iterative solution algorithm. In each timed step, the temperature distribution is determined and the resulting natural ventilation pressures are considered in the network solution process. The resulting temperature and state of the ventilation system at a given time step are then used for the next iteration until the total simulation time exceeds the time span specified by the user.

Figure 2.5 Flowchart of temperature section of MFIRE

Figure 2.6 Flowchart of transient state simulation section of MFIRE

CHAPTER 3 IMPROVEMENT OF FIRE SOURCE MODELING

3.1 Introduction

Whether a definition of a fire source is close to the real fire scenario determines the accuracy of a fire simulation. In the MFIRE program, three types of fire sources were originally defined: a fixed heat release fire; an oxygen rich fire and a fuel rich fire. However, all of these fire models were simplified to a point fire source with a constant heat release rate (HRR). Such a simplified treatment makes it easy to incorporate the fire event into the network representation of the mine ventilation system. Obviously, it is difficult for this treatment to describe a dynamic mine fire adequately which in turn results in inaccurate simulation of temperature distribution, air flow, etc. Therefore, the fire source models in MFIRE should be improved to make it capable of describing a fire event more accurately.

3.2 Fire source Models

3.2.1 Heat Release Rate

The HRR is one of the most important parameters characterizing the energy intensity of a fire scenario. It can be used to estimate the size and growth rate of a mine fire event. It can also be used to assess the impact of the fire suppression system in the firefighting efforts and the available egress time for fire evacuation. It is the primary variable that determines the contribution to the fire hazards from combustible materials and is also a critical parameter for evaluating the fire prop-

erty of a material. The importance of HRR is shown in the following two aspects. First, it is directly related to mass loss rate. The toxicity level of a burning material is a function of the release rate of toxic gases defined as the product of the total mass loss rate and the yield of these gases. The generation of most other undesirable fire products tends to increase with increasing HRR. Smoke, toxic gases, temperatures and other fire hazard variables generally march step-in-step with HRR as HRR increases (Karlsson and Quintiere, 2000). Second, the HRR is the driving force for the fire, which can be viewed as an engine driving the fire. This tends to occur in a positive-feedback way: heat makes more heat. Higher HRR also indicates a higher threat to human life because it induces higher temperature and higher heat flux which are both lethal to occupants.

One of the most important tasks in fire simulations is to estimate the HRR-time relationship. The HRR in real fires is seldom available and can only be estimated at best. Some experiments have been conducted under controlled laboratory conditions to monitor the HRR evolution process (Jahn et al., 2009). The proper prediction of the HRR evolution is therefore among the first priorities of a fire modeling effort to study the fire development.

3.2.2 Compartment Fire Development Process

Fire is a complex physical and chemical phenomenon that strongly interacts with nature. Fire research involves a number of disciplines such as fluid mechanics, heat and mass transport, and chemical kinetics. The development of a fire is considered to be governed by a general principle even though it is a complex process. The following five stages are commonly used to describe the develop-

ment process of a fire (Walton and Thomas, 1995) and are illustrated in Figure 3.1.

- Ignition
- growth
- flashover
- fully developed fire
- decay

The ignition stage is the period during which sufficient ignition energy is provided to the combustible materials to start a flame fire. It can be considered as a process that produces an exothermic reaction characterized by an increase in temperature greatly above the ambient.

Following the ignition, the fire may grow at a slow or a fast rate depending on the type of combustion, the type of fuel, interaction with the surroundings, and access to oxygen. The growth period of a fire could be very long, and it may die out before subsequent stages are reached. The growth stage can occur very rapidly, especially with flaming combustion. In such cases, the fuel is flammable enough to allow rapid flame to spread over its surface, the heat flux from the burning of the first fuel package is sufficient to ignite adjacent fuel packages, and sufficient oxygen and fuel are available for rapid fire growth (Karlsson and Quintiere, 2000). Fires with sufficient oxygen available for combustion are said to be fuel-controlled or oxygen rich.

Flashover is the transition from the growth period to the fully developed stage in fire development. At this point, a sufficient amount of the solid or liquid are va-

porized to start a rapid combustion process. The formal definition from the International Standards Organization is given as “the rapid transition to a state of total surface involvement in a fire of combustible material within an enclosure” (ISO, 1996).

At the fully developed stage, the heat released is at its greatest and the temperature in the tunnel is often very high. During this stage, the fire is often limited by the availability of oxygen. More fuel is frequently pyrolyzed than can be burned with the oxygen available in the compartment. This is called ventilation-controlled burning (Walton and Thomas, 1995). The pyrolysis rate of the burning objects is affected significantly by the environment.

The decay stage starts as either the fuel or the oxygen depletes, the HRR diminishes and thus the average temperature declines. The state of the fire may change from ventilation controlled to fuel controlled during this period.

As it is mentioned before, the HRR is an essential characteristic that quantitatively describes “How big is the fire?” It is the rate at which the combustion reactions produce heat (Babrauskas, 2002). The HRR during a fire varies with time and is therefore a time dependent parameter. It increases at a certain rate during the growth period and reaches to the highest value in the fully developed period and then declines in the decay period. A fire can be completely described in terms of HRR and the production of combustion gases. Figure 3.1 shows an idealized variation of HRR with time during various fire periods.

Figure 3.1 Idealized description of fire development stages

3.2.3 Fire Source Definition in MFIRE

As previously stated, three types of fire sources are defined in MFIRE. They are: a fixed heat input fire, an oxygen rich and a fuel rich fire (Chang et al., 1990). In the oxygen rich fire case, air passing through the fire zone is not completely consumed and the air downstream from the fire still contains high oxygen concentrations.

In the fuel rich case, the fire zone is so large and so hot that the entire quantity of air passing through the fire zone is heated to a temperature sufficient to cause pyrolysis of the fuel. The heated air passing through the fire zone pyrolyzes any fuel it contacts. The pyrolyzed fuel burns intensely until all available oxygen in the air stream is depleted. Fuel continues to pyrolyze, but cannot burn

due to the lack of oxygen. Pyrolyzed, but unburned, fuel remains in the downstream air, the reason it is called a fuel rich fire (Laage et al., 1995, Chang, 1987)

Whether an oxygen rich or a fuel rich fire results depends on the type of combustible material, its quantity, mine entry size, ventilation and ignition source. A fire is more likely to develop into a fuel rich one if the air velocity is small, the size of the airway is small, or the fire intensity is large. For a given fuel loading and ventilation rate, a fuel rich fire burns more intensely than an oxygen rich fire. Fuel rich fires propagate faster, produce higher temperature and higher concentrations of combustion products (possibly in the explosive range), and consume more oxygen. For these reasons, fuel rich fires represent a far greater hazard than oxygen rich fires. Fortunately, fuel rich fires are extremely rare events. It is estimated that less than 0.1% of mine fires reach the fuel rich state (Laage et al., 1995, Mitchell, 1996).

A mine fire was defined in MFIRE by inputting fire properties which include HRR, oxygen consumption, and production rate of products of combustion (POC). In MFIRE, certain assumptions (Chang et al., 1990) are made to define a fire source analytically including: (1) for oxygen rich and fuel rich fires, MFIRE assumes complete combustion and therefore the combustion products are carbon dioxide and water, (2) an amount of 437 BTU of heat are produced for each cubic foot of oxygen consumed, and (3) a nominal ambient oxygen concentration of 21%.

Based on the above assumptions, The HRR of an oxygen rich fire is determined by the concentration of oxygen contained downstream from the fire. HRR can then be obtained by Equation (3.1).

$$\dot{q} = 437(0.21 - C_{o_2} / 100)Q \quad (3.1)$$

Where:

$\dot{q}$ heat release rate (But/min)

C_{o_2} oxygen concentration downstream from the fire (%)

Q airflow rate in the airway containing the fire source (ft³/min)

The HRR in a fuel rich fire is defined by the airflow rate through the fire zone and a user-defined heat release per cubic foot of oxygen (HTPO2) delivered to the fire. For fuel rich fire cases, MFIRE assumes all oxygen passing through the fire zone will be consumed completely before it gets downstream. The oxygen concentration downstream is zero. The amount of oxygen consumption per minute will be the product of the concentration of oxygen upwind (assumed 21%) and the airflow rate. Therefore, the HRR of fuel rich fire is determined by Equation (3.2).

$$\dot{q} = 0.21q_f Q \quad (3.2)$$

Where:

q_f Heat generated per cubic feet of oxygen consumed (Btu/ft³ O₂)

For fixed heat input fires, the HRR is inserted directly into the MFIRE input data specified by the users. Normally, the user finds it necessary to calculate

values for these parameters using fundamental combustion data for the fuel or fuels involved in the simulated fire.

Among these three types of fire defined in MFIRE, none of them is time dependent. Obviously, the fixed heat input fire only requires a constant HRR no matter what kind of fire it really is. Even though oxygen rich and fuel rich fires obtain HRR value using oxygen consumption, the input oxygen concentration and specified heat generation are constant without varying with time. The HRRs for these two types of fires are still constant and time independent which differ considerably from the reality. As discussed in section 3.2.2, HRR is time dependent. Hence, in order to improve the fire definition in MFIRE 2.30, a more accurate and time dependent HRR model needs to be found and incorporated in MFIRE 2.30.

3.2.4 Time Dependent Fire Source - t-Squared (t^2) Fire Model

The HRR during the growth phase of many fires can often be characterized by simple time dependent polynomial or exponential functions. Extensive research and analysis show that the HRR varies with the second power of the time measured from an ignition reference time (Alpert, 2002), t_0 , as

$$\dot{q} = \alpha (t - t_0)^2 \quad (3.3)$$

Typically, a mathematical representation is shown as follows:

$$\dot{q} = a(t - t_0)^2 \quad (3.4)$$

Where:

a growth factor

t time

A typical t-squared fire curve (Schifilliti, 1986) is shown in Figure 3.2. High HRR doesn't normally occur as soon as the fuel is ignited. A time period with a low HRR can be defined as the ignition reference time. This curve shows the HRR for a burning foam sofa varying with time. The growth stage, the fully developed fire stage and the decay stage are seen very clearly in this curve. The HRR for the growth phase can be represented by Equation (3.5) with an ignition reference time of 80 seconds.

$$\dot{q} = 0.1736 (t - 80)^2 \quad (3.5)$$

Figure 3.2 HRR history for a burning foam sofa (Schifilliti, R.P., 1986)

This relationship has been found to fit well with the growth rates exhibited by various different commodities (Karlsson and Quintiere, 2000). The t-squared fire

has been used extensively in the U.S. in compartment fire simulation research. The National Institute Standard Technology (NIST) developed a computer compartment fire simulation program Consolidated Model of Fire and Smoke Transport (CFAST) (Jones et al., 2005). This program is based on the zone models and employs a t-squared fire as its primary fire model.

In NFPA 72 (National Fire Protection Act), four fire HRR models based on Equation (3.4) were used as the basis for the evaluation. These fire HRRs histories were chosen to be representative of actual fire situations involving different commodities and geometric storage arrangements. These idealized fire energy release rates are (Evans, 1995)

Slow,	$\dot{q} = 0.00293t^2$
-------	------------------------

Medium,	$\dot{q} = 0.01172t^2$
---------	------------------------

Fast,	$\dot{q} = 0.0469t^2$
-------	-----------------------

Ultrafast,	$\dot{q} = 0.1876t^2$
------------	-----------------------

3.2.5 Implementation of a t-squared Fire in MFIRE

HRR, the most critical input parameter for fire simulations, is normally obtained by experiment, either a full scale or bench scale test. A large amount of research has shown that the growth phase of many fires can be characterized by a HRR increasing proportionally with a power of time measured from the ignition reference time. A t-squared fire model will be defined and incorporated into MFIRE 2.30 program.

3.2.6 Theoretical t-squared Fire Model

In order to develop a reasonable representation of the HRR curve during a fire, the “standard” fire HRR development curves (as shown in Figure 3.3) at the growth stage, fully developed stage and decay stage can be simplified as shown in Figure 3.3. The fuel is assumed to be ignited at $t=0$ and time from $t=0$ to $t=t_0$ is the ignition reference time. The HRR in both the growth period (from t_0 to t_1) and the decay period (from t_2 to t_3) increase and decrease as square of the time, respectively. In order to achieve an analytical solution describing the physical processes, the HRR in the fully development fire period is simplified to a constant value.

Figure 3.3 Idealized t-squared fire curve with HRR vs. time

Using different value of growth and decay rates combined with a maximum HRR profiles as peak value means that the curve has to be represented with different mathematical expressions for different time periods. In order to represent the entire fire development process, a four-piece equation (Equation (3.6)) is applied to represent the HRR curve for different time periods.

$$\dot{q}(t) = \begin{cases} 0 & t \leq t_0 \\ a_1(t - t_0)^2 & t_0 < t \leq t_1 \\ \dot{q}_{\max} & t_1 < t \leq t_2 \\ a_2(t - t_3)^2 & t_2 < t \leq t_3 \end{cases} \quad (3.6)$$

Where:

$\dot{q}$ heat release rate (KW)

a_1 growing factor of growth period (KW/s)

a_2 decaying factor of decay period (KW/s)

$\dot{q}_{\max}$ maximum heat release rate (KW)

t time (s)

t_0 time of ignition delay (s)

t_1 the end time of steady period (s)

t_2 the end time of fully developed fire period (s)

t_3 the end time of decay period (s)

3.2.7 Determination of Growing Factor and Decaying Factor

There are seven unknown variables that need to be specified in Equation (3.6) in order to describe the complete HRR development curve. They are: the growing factor (a_1), decaying factor (a_2), maximum HRR ($\dot{q}_{\max}$) and time period variables (t_0, t_1, t_2, t_3). Among these variables, it's easy to determine maximum HRR and time periods from a given HRR curve. Once these five variables are known, the growing factor and the decaying factor can be determined using Equation (3.7) and (3.8), respectively.

$$\alpha_1 = \frac{\dot{q}_{\max}}{(t_1 - t_0)^2} \quad (3.7)$$

$$\alpha_2 = \frac{\dot{q}_{\max}}{(t_2 - t_3)^2} \quad (3.8)$$

It should be noted that it is not necessary for the growing factor and the decaying factor to be the same in a fire scenario. It is very common that fires grow much faster than the decay, this showing a larger growing factor than the decaying factor in a fire.

MFIRE 2.30 allows the users to input the t-squared fire data after the above t-squared fire model is incorporated in the program. Figure 3.4 shows the input view of the t-squared fire in MFIRE 2.30. The unit system used in MFIRE is the Imperial system. Therefore, the input parameters for the t-squared fire in MFIRE 2.30 are in imperial units as shown in Figure 3.4. Specification of the t-squared fire is completed after users specify the maximum HRR and four time period variables.

Figure 3.4 t-squared fire input card

3.3 Air Temperature Evaluation in MFIRE 2.30

The temperature distribution is the most important output parameter in mine fire simulation programs. MFIRE 2.20 presents the temperature distribution in a mine by outputting temperatures at each junction, temperature at the end of each airway, average temperature of each airway, and temperature of fume front. MFIRE 2.30 program will inherit the temperature modeling algorithm of MFIRE stated in the previous chapter with the following two exceptions:

- The time independent fire source models are replaced with time dependent fire source model -- t -squared model.
- The convection heat transfer is taken into account while evaluating air temperature in the branch with a specified fire source.

3.3.1 Air Temperature Evaluation in Fire Branch

As mentioned in Section 2.3.1, the reference temperature distribution is calculated in the temperature part based on the airflow distribution obtained from the network solution without considering the thermal event. Once a fire source is placed in an airway, the fire-generated thermal forces (throttling and natural draft effects) are then determined and inserted into a new network calculation. Air temperature is then evaluated starting from the fire branch. The schematic for determining the heat transfers and temperature variations in a fire branch is shown in Figure 3.5.

Figure 3.5 Control volume in an airway

A fire branch is treated as a control volume and the law of general energy conservation is applicable and the heat balance is expressed by Equation (3.9). All parameters involved in this section are all in imperial units in order to keep consistent with those used in MFIRE program.

$$\dot{q}_{in} + \dot{q}_{generation} = \dot{q}_{out} + \dot{q}_{convection} \quad (3.9)$$

Where

- $\dot{q}_{in}$ Energy entering the control volume per unit time (*Btu* / min)
- $\dot{q}_{out}$ Energy leaving the control volume per unit time (*Btu* / min)
- $\dot{q}_{generation}$ Energy generation inside the control volume per unit time (*Btu* / min)
- $\dot{q}_{convection}$ Convection energy transported through wall surface per unit time (*Btu* / min)

In the control volume the only energy generation source is fire. The amount of generated heat is described by the HRR that is defined as a time-dependent t-squared fire source using Equation (3.6) in MFIRE 2.30.

$$\dot{q}_{generation} = \dot{q}(t) \quad (3.10)$$

In the event of a mine fire, the average air temperature is much higher than the rock temperature. The heat transfer by conduction due to rock temperature gradient and energy exchange by convection due to the temperature differences between the airway walls and the moving air flow must be considered (Laage and Yang, 1991). However, the heat transfer by conduction and convection was neglected in MFIRE program while evaluating the air temperature of the fire airway. In MFIRE 2.30, conduction and convection heat transfer are taken into account. These two processes occur on the airway surface where there is neither heat generation nor heat storage. The heat energy balance on the wall surface is expressed as Equation (3.11).

$$\dot{q}_{conduction} = \dot{q}_{convection} \quad (3.11)$$

The convection heat loss through the wall surface is determined by Newton's Cooling Law:

$$\dot{q}_{convection} = PLh(T_{ave} - T_r) \quad (3.12)$$

Where

- P airway perimeter (ft)
- L length of airway or control volume (ft)
- h convective heat transfer coefficient ($Btu / ft^2 \cdot min \cdot ^\circ F$)
- T_{ave} average airflow temperature ($^\circ F$)
- T_r rock temperature ($^\circ F$)

In the fire branch, the energy needed to increase the air temperature from T_{ao} to T_a can be calculated with Equation (3.13) if potential and kinetic energy changes are neglected.

$$q_{increase} = \rho Q C_p (T_a - T_{ao}) \quad (3.13)$$

Where

ρ density of airflow (lb / ft^3)

C_p specific heat of air at constant pressure ($Btu / lb \cdot ^\circ F$)

T_a air temperature ($^\circ F$)

T_{ao} air temperature at $t=0$ ($^\circ F$)

Also, we know from Equation (3.9), the energy increase in the flowing air in unit time is:

$$\dot{q}_{increase} = \dot{q}_{in} - \dot{q}_{out} = \dot{q}_{generation} - \dot{q}_{convection} \quad (3.14)$$

Therefore, the energy conservation of the fire airway can be expressed as:

$$\rho Q C_p (T_a - T_{ao}) = \dot{q}(t) - PLh(T_{ave} - T_r) \quad (3.15)$$

The specific heat of air at constant pressure is described as:

$$C_p = a + bT_{ave} \quad (3.16)$$

In MFIRE 2.30, the specific heat of air is evaluated with coefficients a and b being designated 0.2376 and 0.000024, respectively. The average air temperature T_{ave} can be expressed by:

$$T_{ave} = \frac{T_a + T_{ao}}{2} \quad (3.17)$$

Submit Equation (3.16) and (3.17) to (3.15), then we can obtain the air temperature at the end of fire airway is:

$$T_a = -\frac{a}{b} - \frac{PLh}{2\rho Qb} + \sqrt{\left(\frac{a}{b} + \frac{PLh}{2\rho Qb}\right)^2 + \frac{2A}{b}} \quad (3.18)$$

Where

$$A = \frac{b}{2}T_{a0}^2 + \left(a - \frac{PLh}{2\rho Q}\right)T_{a0} + \frac{\dot{q}(t) + PLhT_r}{\rho Q}$$

However in MFIRE 2.20, Equation (3.19) is employed to evaluate the air temperature at the end of fire airway (Chang, 1989).

$$T_a = -\frac{a}{b} + \sqrt{\left(\frac{a}{b} + T_{a0}\right)^2 + \frac{2\dot{q}}{b\rho Q}} \quad (3.19)$$

Comparing Equation (3.18) in MFIRE 2.30 and Equation (3.19) from MFIRE 2.20, both used to calculate the air temperature in fire airway, two aspects of difference can be seen. They are:

- (1) In Equation (3.18), the heat released by fire is described as a function of time, $\dot{q}(t)$ and therefore is a so called “time dependent” fire model. However, in Equation (3.19), a constant value q is employed to represent the HRR. As described previously, a time dependent fire model is more accurate than the time independent fire model.
- (2) Since heat transfers by convection and conduction can not be ignored because of large temperature gradient in the rock and between air and rock, Equation (3.18) takes into account these heat transfers but Equation (3.19) did not.

3.3.2 Air Temperature Evaluation in Junctions

A mixing process takes place at a junction when airflows enter it from the connecting airways. Such a process is controlled by numerous factors, mainly the airway connection pattern and respective airflow velocities. As it takes a very short period of time for air to pass a junction, molecular diffusion is not significant in the process (Chang, 1989). MFIRE 2.20 assumes that the airflows meet in a junction and are thoroughly mixed and no heat transfer exists in the junction. MFIRE 2.30 uses the same equation to determine air temperature in junctions as the original MFIRE, as shown in Equation (3.20).

$$T_j = -\frac{a}{b} + \sqrt{\left(\frac{a}{b}\right)^2 + \frac{2\sum_i q_i}{b\sum_i \rho_i Q_i}} \quad (3.20)$$

Where

T_j air temperature at junction i (°F)

q_i heat flowing into the junction from the i th airway connected to the junction (Btu)

ρ_i air density of the i th airway (lb/ft³)

Q_i airflow rate of the i th airway (ft³/min)

3.3.3 Air Temperature Evaluation along Airways (Chang, 1989)

The technique employed by MFIRE 2.20 in transient-state fire simulation divide airflow into several air segments according to a user specified time interval. Each air segment is considered as a control volume which advances with the

flow through the ventilation system. To advance air segments in a time increment, the airflow and temperature distribution in the current time interval are necessary.

In MFIRE, the air temperature at the end of an air segment can be determined by Equation (3.21).

$$T_{ae} = T_{rv} + (T_{a0} - T_{rv}) \exp\left(\frac{\lambda PL \psi}{Q \rho C_p R_0}\right) - \frac{g_a L \sin \beta}{2} \left(1 + \exp\left(\frac{\lambda PL \psi}{Q \rho C_p R_0}\right)\right) \quad (3.21)$$

Where

T_{ae} air temperature at the end of an air segment ($^{\circ}F$)

T_{rv} virgin rock temperature ($^{\circ}F$)

R_0 hydraulic radius of airway (ft)

g_a increasing rate of air temperature due to auto-compression of air ($^{\circ}F / ft$)

β slope angle of airway

λ thermal conductivity of rock ($Btu / ft^2 \cdot min \cdot ^{\circ}F$)

ψ coefficient of age defined by a dimensionless function (as shown in Equation (3.22)).

$$\psi = \frac{hR_0}{\lambda} \frac{T_w - T_a}{T_{rv} - T_a} = R_0 \frac{\left(\frac{\partial T}{\partial R}\right)_{R=R_0}}{T_{rv} - T_a} \quad (3.22)$$

Where R is a coordinate in the radial direction. The term $\left(\frac{\partial T}{\partial R}\right)_{R=R_0}$ represents the rate of temperature change at $R=R_0$. ψ is not a constant but a function of time and heat transfer parameters instead. ψ decreases with time at a decreasing

rate. When time approaches the infinity, the wall temperature T_w will approach the air temperature T_a and the limit value of ψ is zero. The coefficient of age can be obtained from the corresponding geometrical and heat transfer parameters at any particular moment of time.

3.4 Calibration and Case Study

3.4.1 Experiments

Six fire experiments were conducted at the Waldo Mine to validate MFIRE's calculation of temperature distribution in an airway due to a mine fire during the week of March 19, 1990 (Laage and Carigiet, 1991; Laage and Yang, 1991). Wood was used in three tests, while diesel fuel was used in the other three tests.

The Waldo mine is owned by American Smelting and Refining Company (ASARCO) and leased to the New Mexico Institute of Mining and Technology for research and education purposes. The Waldo mine is located in the mountains near Magdalena, NM. Sixteen levels were mined in the lead-zinc-copper limestone replacement orebody from the late 1800's until ore reserves were exhausted in 1949. In 1983, New Mexico Tech leased the Waldo mine and began rehabilitation work on the 3rd, 6th, 8th, and 9th levels.

A fire site was selected in the Waldo Tunnel on the 9th level. A pan was constructed to contain the fires. For the diesel fires, fuel was placed in a second round pan 0.71m (2.33ft) in diameter and 0.05m (0.16ft) high inside the containment pan.

Three holes were bored into the roof over the fire location. Each hole was instrumented with four K-type thermocouples at depths of 0.038m, 0.076m, and

0.114m. The thermocouples were secured by wedging rock core and chips around them and filling the voids with plaster of paris.

Air temperatures near the center of the drift were measured downwind from the fire with K type thermocouples at 0.61m (2ft), 2.13m (7ft) and 3.05m (10ft) and with Analog Devices 590 temperature sensing transducers at 6.10m (20ft), 15.24m (50ft) and 60.50m (198ft). Single point temperature measurements were taken near the roof with the Analog Devices 590 at 60.9m (200ft), 91.4m (300ft), 121.9m (400ft), 152.4m (500ft), 182.9m (600ft), and 213.4m (700ft) downwind from the fire.

To monitor the experiment a video camera was mounted to the roof in an environmental enclosure and the video signal was sent to the mine office for remote reviewing. The data acquisition system was fed to a portable computer in the mine office. A remotely activated water suppression system was installed and tested to extinguish the fire for the contingency of some unexpected event. From these experiments, temperature profiles were developed as functions of time and distance from the fire in this airway. The experiments were described in detail in the Open File Report "Waldo Mine Fire Experiments of March 1990" by Laage and Carigiet (1990).

3.4.2 Simulation of Test 3

Laage and Yang (1991) discussed test 3 and the measured temperatures were compared with the simulated temperatures of MFIRE for various locations downwind of the fire. In this chapter, MFIRE 2.30, with the t-squared fire model, is used to simulate test 3. The calculated temperatures from MFIRE 2.30 are com-

pared with the measured temperatures and the MFIRE simulation results published by Laage and Yang (1991).

Test 3 used a light diesel fuel with a heat content of 12.75 Kw.hr/Kg (19,739 Btu/lbs) and specific gravity of 0.78. The air temperature inside the mine remained constant at 11.7 deg C (53°F). The measured air flow rate was 662 m³/min (23,378 ft³/min). A total of 5.68 liters (1.5 gallon) of diesel fuel were used and the combustion lasted 12 minutes and 50 seconds (Laage and Yang, 1991).

As previously discussed, definition of a t-squared fire model in MFIRE 2.30 requires the specification of maximum HRR and time period variables.

(1) Determination of time period variables

The temperature profiles have been given along the experimental airway at the different distances downwind from the fire (Laage and Carigiet, 1990). The temperature profile related well with the HRR directly. Temperature and the rate of temperature change increase as HRR increases. According to the temperature profile, the development stages of fire can be seen very clearly. The temperature profile at the site closest to the diesel fuel fire (2 ft downwind of fire) is chosen to be a reference for determining time periods t_0 , t_1 , t_2 and t_3 .

(2) Determination of maximum HRR

The most common way of representing a fire is by choosing a maximum HRR from a design table provided by the National Fire Protection Association (Ingason, 2009). In this experiment, the fuel type, combustion duration and ignition condition were all known. In this case, it would be more accurate that to cal-

culate the maximum HRR according to experiment than to choose it from the design table.

With the assumption that the diesel fuel in this test combusted completely, the total released heat can be obtained by Equation (3.23)

$$q_t = \dot{m}q_c t \quad (3.23)$$

Where

q_t total heat released

$\dot{m}$ mass loss rate of the fuel in combustion

q_c heat of combustion

In this example, mass loss rate $\dot{m}$ is determined as 5.75 g/s (0.76 lbs/min) by using the known volume and specific gravity of the fuel.

Therefore, the total released heat in test 3 is

$$\dot{Q} = 5.75 \times 10^{-3} \text{ kg} / \text{s} \times 45900 \text{ KJ} / \text{kg} \times 770 \text{ s} = 203,222 \text{ KJ} = 192,468 \text{ Btu}$$

The total released heat should be the same no matter what fire model is applied. For the t-squared fire model, the total released heat might be expressed as Equation (3.24).

$$\dot{Q} = \int_{t_0}^{t_1} a_1 t^2 dt + \dot{q}_{\max} (t_2 - t_1) + \int_{t_2}^{t_3} (\dot{q}_{\max} - a_2 t^2) dt \quad (3.24)$$

The growth factor a_1 and the decay factor a_2 can be expressed by maximum HRR $\dot{q}_{\max}$ and time period variables (t_0 , t_1 , t_2 , t_3) according to Equation (3.7) and (3.8). Equation (3.25) can be carried out after integrating Equation (3.24) and submitting Equation (3.7) and (3.8) into Equation (3.24).

$$\dot{Q} = \frac{t_1^3}{3(t_1 - t_0)^2} \dot{q}_{\max} + (t_3 - t_1) \dot{q}_{\max} - \frac{(t_3^3 - t_2^3)}{3(t_2 - t_3)^2} \dot{q}_{\max} \quad (3.25)$$

Therefore, Equation (3.25) is solvable with only one unknown $\dot{q}_{\max}$. A maximum HRR calculator was designed in MS Excel and the input parameters of the fire model in test 3 is shown in Figure 3.6. MFIRE 2.30 requires input, performs calculations, and produces output in imperial units which is the same as MFIRE 2.20. The units used in the calculator are English Units. The maximum HRR is calculated as 31,607.95 Btu/min in test 3.

qmax Calculator for t-squared fire					
Tlead (t0)	=	120	s	=	2.00 min
Tmax (t1)	=	660	s	=	11.00 min
Tsteady(t2)	=	700	s	=	11.67 min
Tdecay(t3)	=	1120	s	=	18.67 min
Total Heat	=	192468	Btu		
qmax	=	517.80	Btu/s	31067.95	Btu/min

Figure 3.6 Max. HRR calculator and input parameters of fire model

3.4.3 Comparison of Results

The results of the t-squared model and the comparison with measured temperatures and the original MFIRE simulation are shown in the following figures. It should be noted that the simulated temperatures by MFIRE and the experiment data in the following figures are from Laage and Yang (1991).

From Figure 3.7 to Figure 3.14, the measured temperatures, simulated temperatures as simulated with MFIRE 2.30 with t-squared fire model (marked as t2 Model), and the original MFIRE were graphed and compared with each other at 6.1m (20ft), 15.2m (50 ft), 30.5m (100 ft), 61m (200 ft), 91.4m (300 ft), 121.9m (400 ft), 152.4m (500 ft), and 182.9m (600 ft) downwind of the fire, respectively.

Temperature profiles for MFIRE calculated by Laage and Yang (1991) in all of the figures show a long duration of constant value. It is obvious that this fire is not a constant heat output type fire. As modeled by MFIRE, the constant temperature output from the original MFIRE results from the time-independent fire source model. The predicted temperatures from the t-squared fire model have great agreement with the observed temperature from the experiment in Figure 3.7 and Figure 3.8. From Figure 3.9 to Figure 3.14, the predicted peak temperatures are 10 to 15 degree larger than the observed peak temperature. The tendency of predicted temperatures still fit very well with the observed temperatures. The difference between the peak temperatures can be explained by the assumption in the t-square model that the fuel was combusted completely. If this is the difference, then it is reasonable that the predicted temperatures are higher than the experimental temperatures. In addition, MFIRE 2.30 and the previous MFIRE only consider the “dry” condition. However, water in the branches where the fume travels through can absorb a large amount of heat as it is evaporated, which will cause less heat to be transferred downwind. The heat loss resulted from water evaporation is ignored in the MFIRE 2.30 and the previous MFIRE.

This also can explain why the peak temperatures from MFIRE 2.30 and the original MFIRE are much higher than the observed temperatures.

Figure 3.7 Diesel fuel test 6.1m (20ft) downwind of fire

Figure 3.8 Diesel fuel test 15.2m (50ft) downwind of fire

Figure 3.9 Diesel fuel test 30.5m (100ft) downwind of fire

Figure 3.10 Diesel fuel test 61.0 m (200ft) downwind of fire

Figure 3.11 Diesel fuel test 91.4 m (300ft) downwind of fire

Figure 3.12 Diesel fuel test 121.9 m (400ft) downwind of fire

Figure 3.13 Diesel fuel test 152.4 m (500ft) downwind of fire

Figure 3.14 Diesel fuel test 182.9 m (600ft) downwind of fire

3.5 Summary

- The heat release rate (HRR) is an essential variable in fire simulations. The HRR is a time dependent variable and varies with time during a mine fire event. However, the HRR of a fire in the MFIRE 2.20 program only provides a constant heat input and therefore it is time independent. A time dependent fire model needs to be developed and incorporated into MFIRE program.
- A step-wise time-dependent mathematical equation is introduced to represent the HRR curve for growth, fully developed and decay periods.
- MFIRE 2.30, the improved MFIRE, takes into account the heat transfer by conduction due to rock temperature gradient and that by convection due to the temperature differences between the airway walls and mine air. Such heat transfers were ignored in MFIRE 2.20. The updated equation which evaluates air temperature in junctions is therefore derived and presented in this chapter, and is also incorporated in MFIRE 2.30.
- A method of defining a t-squared fire with reference to determining maximum HRR and the variables of the time periods is discussed in this chapter.
- In order to incorporate the t-squared fire model into MFIRE 2.30, a user input interface has been created for the users to define a mine fire source using the maximum HRR and time period variables.
- The temperature profiles obtained from the MFIRE 2.30 with the t-squared fire model are compared with the observed temperatures in a

test conducted in the Waldo mine in 1991 and that from the original MFIRE program. It is shown that the t-squared fire model applied in MFIRE 2.30 improves the fire simulation to a large extent.

CHAPTER 4 IDENTIFICATION OF SMOKE ROLLBACK

4.1 Introduction

During an underground mine fire, a large amount of smoke and toxic gases can be produced. Inhalation of the fire-generated toxic combustion products can be injurious and fatal to miners, and the heat released can induce roof and rib collapse. At the early stages of a fire such as the ignition and growth period, smoke produced by the fire will initially be transported downwind side of the fire. Once the fire has developed to a sufficient intensity, the buoyancy force generated by the fire could overcome the inertial forces of ventilation to cause smoke to migrate upwind along the roof counter to the positive ventilation (Edwards et al., 2006). Miners refer to smoke flowing along the roof against the ventilating air current as “smoke rollback” (Mitchell, 1996). Smoke rollback is a fatal and dangerous threat to miners and firefighters. Smoke rollback may prevent firefighters from getting close enough to fight a fire effectively. Also, the rollback not only contains smoke but also hot gases which can directly bring flame from the fire back onto the firefighters. The rollback smoke is hot enough to loosen resin bolts and destabilize roof. According to Edwards et al. (2006), the reversed smoke may also leak through stoppings into adjacent airways and thereby further endanger miners.

Smoke rollback, as a dangerous threat to fire fighters’ lives, needs to be recognized and therefore approaches need to be found to prevent or reduce it. In

the event of a mine fire or smoke emergency, a main concern is to keep an evacuation path free of smoke and hot gases. Predicting the occurrence of a smoke rollback in an underground fire is also necessary for the preplanning and implementation of ventilation changes during mine fire fighting and rescue operations.

4.2 Critical Velocity

Experimental and numerical studies have been conducted to show that smoke rollback can be prevented by maintaining a sufficient velocity of the airflow to the mine fire. The minimum air velocity required to prevent smoke rollback is called the critical velocity.

The term “critical velocity” is usually applied to judge if smoke rollback occurs in a tunnel. Critical velocity has become one of the prime criteria for the design of tunnel ventilation systems. A few reports (Mitchell, 1996; Kennedy, 1996; Edwards and Hwang, 1999; Wu and Bakar, 2000; and Edwards et al., 2006) use the critical air velocity to identify the occurrence of a smoke rollback. There are mainly two approaches to obtain the value of critical velocity for various tunnels. The first approach is based on semi-empirical equations obtained from the Froude number preservation combined with experimental data. The second approach is based on dimensionless HRR. Also, a rule of thumb is presented by Mitchell (1996) to estimate the critical air velocity in a mine entry. A detailed description of these approaches is given below.

4.2.1 Mitchell's Rule of Thumb

Mitchell (1996) presents a simple relationship for estimating the critical velocity for smoke rollback in relation to the entry height.

$$V_c = 100\sqrt{H} \quad (4.1)$$

Where:

V_c critical velocity of smoke rollback (*ft* / min)

H entry height (*ft*)

4.2.2 Theory Based on Froude Number Preservation

The Froude number is defined as the ratio of gravity (buoyancy) forces to pressure forces. The Froude number is applicable to situations where turbulent conditions prevail and viscous forces can be neglected. Since the airflow in a tunnel in most cases is fully turbulent with very insignificant viscous effects, the use of Froude number to define critical velocity dates back to 1960's (Thomas, 1968).

One definition of the Froude number is from Lee et al. (1979) as:

$$F_r = \frac{gH(\rho - \rho_f)}{\rho V^2} \quad (4.2)$$

Where:

F_r Froude number

g acceleration due to gravity

ρ average density of upstream

ρ_f average density of the fire-site gases

H height of tunnel

V velocity of the approach air

Lee et al. (1979) stated that if the Froude number is kept at or below a certain critical value, smoke and hot gases from the fire will not rollback. That is because the lower the Froude number, the weaker the buoyancy forces become. Their scale-model tests in ducts show the critical value of the Froude number ranges from 4.5 to 6.7. The Froude number may varies with the size and condition of experiment facility.

Based on the Froude number, Thomas (1968), Hinkley (1970), and Heselden(1976) have proposed the relationship between the ventilation velocity and the heat release rate from the fire. The equation of critical velocity derived by Kennedy et al. (1996) as shown in Equation (4.3) has become the most popular equation used by fire researchers.

$$V_c = K_1 \left(\frac{gH\dot{q}}{\rho C_p A T_f} \right)^{1/3} \quad (4.3)$$

Where

K_1 defined as $Fr_c^{-1/3}$, and Fr_c is the critical Froude number

A cross sectional area of tunnel

T_f average temperature of the fire-site gases

T_f is estimated from the enthalpy conservation equation (as shown in Equation (4.4))

$$T_f = \frac{\dot{q}}{\rho C_p A V_c} + T_0 \quad (4.4)$$

Where T_0 is the temperature of the approach air. The critical velocity can be determined by solving Equation (4.3) and Equation (4.4) simultaneously using

iteration. The value of K1 is set to 0.61, calculated based on a modified Froude number of 4.5, with reference to scale model tests by Lee et al. (1979). It indicates from Equation (4.3) that the ventilation velocity, tunnel geometry, and fire intensity are the most essential factors which determine if a smoke rollback occurs along the roof into the fresh air.

4.2.3 Equations Based on Dimensionless Analysis

Oka and Atkinson (1995) derive an equation calculating the critical velocity based on their small-scale experimental results with a dimensionless analysis. The following general expressions were reported for the critical velocity in their model

$$V_c^* = \begin{cases} V_{\max}^* (0.12)^{1/3} (\dot{q}^*)^{1/3} & \text{as } \dot{q}^* \leq 0.12 \\ V_{\max}^* & \text{as } \dot{q}^* > 0.12 \end{cases} \quad (4.5)$$

Where V_c^* and $\dot{q}^*$ are the dimensionless critical velocity and dimensionless HRR which determined by Equation (4.6) and Equation (4.7) respectively.

$$V_c^* = \frac{V_c}{\sqrt{gH}} \quad (4.6)$$

$$\dot{q}^* = \frac{\dot{q}}{\rho_0 T_0 C_p g^{1/2} H^{5/2}} \quad (4.7)$$

$V_{\max}^*$ is 0.35 which depends on the various burners in the smaller models. It indicates from Equation (4.5) that the critical velocity varies as the one-third power of the HRR at low HRR (the dimensionless HRR lower than 0.12 in this case) and the critical velocity is independent of fire intensity at higher HRR. Wu and Bakar (2000) also obtain a similar conclusion with their small scale tests except that the

replacement of tunnel height H with the hydraulic tunnel height $\overline{H}$ which is defined as the ratio of 4 times the cross-sectional area to the tunnel wetted perimeter (Equations (4.8) and (4.9)).

$$V_c^* = \frac{V_c}{\sqrt{g\overline{H}}} \quad (4.8)$$

$$\dot{q}^* = \frac{\dot{q}}{\rho_0 T_0 C_p g^{1/2} \overline{H}^{5/2}} \quad (4.9)$$

The critical dimensionless HRR is determined as 0.20 in Wu and Bakar's (2000) tests rather than 0.12 proposed by Oka and Atkinson (1995) (Equation (4.10)).

$$V_c^* = \begin{cases} 0.40(0.20)^{1/3} (\dot{q}^*)^{1/3} & \text{as } \dot{q}^* \leq 0.20 \\ 0.40 & \text{as } \dot{q}^* > 0.20 \end{cases} \quad (4.10)$$

According to Wu and Bakar's (2000) analysis, the difference of critical dimensionless HRR in Oka and Atkinson's (1995) equations and Wu and Bakar's (2000) equations indicate that this value is related with the dimensions of the experimental facility. It is considered that the influence of fire intensity on the critical velocity is still not certain and it may vary with the geometry of test models.

Five diesel fuel fire experiments were conducted in NIOSH's (National Institute for Occupational Safety and Health) Pittsburgh Research Laboratory (PRL) Safety Research Coal Mine (SRCM) to determine the critical air velocity for preventing smoke rollback (Edwards et al. (2006)). This is the first time that the critical velocity is tested in a real size mine entry of 2.06 m (6.76 ft) high and 2.91 m (9.55 ft) wide. The fire intensity varied from 50kW to 300kW. The experimental

results showed a dependence of the dimensionless critical velocity upon the dimensionless HRR to the one third power, which can be expressed as:

$$V_c^* = 0.92\dot{q}^{*0.3} \quad (4.11)$$

Where V_c^* and $\dot{q}^*$ are defined by the Equations (4.8) and (4.9) respectively.

4.3 Control of Smoke Rollback

4.3.1 Objective of Identifying Smoke Rollback

The equations about the critical velocity presented previously show that the entry dimension, fire intensity and airflow rate determine if a smoke rollback occurs. Airflow rate is the only one which can be controlled and adjusted among these three factors for a real mine fire case. According to Edwards et al. (2006), the use of ventilation to control the movement and dilution of smoke associated with an underground mine fire has been recommended but not quantified.

Based on the relationship between air velocity and smoke rollback, we can see that the larger the air velocity, the less chance of the smoke roll back. As noted by Mitchell (1996), increasing air velocity is the most positive way to reduce smoke rollback and the easiest way is to hang brattice across the bottom half of the entry as close to the fire as possible. Practically, two miners may advance the brattice slowly while holding it across the bottom half the entry. Mitchell's approach to reduce smoke rollback is about increasing the air velocity at the top of the entry by reducing the cross sectional area of the entry. Also, hanging a brattice across the bottom half the entry can force the air to flow toward the smoke. The turbulence caused by the sudden change of the cross-sectional area

can force back the smoke much larger than an even distributed airflow. It is obvious that the air velocity of an entry equals the airflow rate divided by the cross sectional area. Air velocity will double if the cross sectional area is reduced by half. However, in a mine ventilation system, the air velocity won't follow the above principle since blocking the bottom half of the entry would increase the resistance and thereby reduces the quantity of air. The explanation is that we are dealing with a complicated ventilation network consisting of hundreds, even thousands of branches which can affect each other to certain extents. Reducing cross sectional areas definitely can increase airflow velocity in a single airway; however, it may not work in a ventilation network. For example, with 9,000 ft³/min in a 90 ft² entry, the velocity would be 100 ft/min. The velocity would not equal to 200 ft/min after hanging brattice across the bottom half of entry. The reason is that the air velocity will not maintain 9,000 ft/min because the brattice has increased the resistance which would cause less air to flow in the airway. Mitchell (1996) also realized this possible problem and suggested to drop the brattice if smoke still rolls back while blocking the bottom half of the entry. In most cases, blocking the bottom half of the entry may be effective in reducing the smoke rollback. However, it is also possible that it will worsen the smoke rollback because of the complicated interaction between the resistance change and the airflow change in a mine ventilation network. How and how much the change of resistance will affect airflow distribution depends on the airway connection pattern, the adjacent resistances of the airway and even the performance of the

main fan. A software tool of ventilation network simulation can answer this question directly.

Therefore, a mine ventilation network needs to be studied and the effects of reducing cross sectional area in an entry needs to be understood before taking any action to reduce or prevent smoke rollback in an entry. It is not too complicated to determine how the change of resistance in the fire airway has an impact on the air quantity of the fire airway even all airways via ventilation network analysis program. MFIRE, based on ventilation network analysis, is capable of conducting such calculations and providing a quantified relationship between airway resistance and airflow rate. MFIRE can help to make a decision if a ventilation control method should be chosen to prevent smoke rollback.

It is known that an underground mine fire can change airflow dramatically particularly in the fire branch because of the throttling and buoyancy effects. The airflow velocity is an important parameter to be used to identify if a smoke rollback occurs. The previous experiments (Lee et al., 1979; Oka and Atkinson, 1995; Kennedy, 1996; Wu and Bakar, 2000) about smoke rollback are for the purpose of road tunnel which only has one single airway and is not in a ventilation network. A fire doesn't have an effect on the airflow rate in a tunnel as much as in an underground entry since a road tunnel is open to the atmosphere, and the pressures of its two ends is kept constant. Edwards et al. (2006) shows that the airflow velocity varies from 0.8 m/s to 1.8 m/s in experiment C with the 304 kW fire conducted in a real size coal mine in the SRCM. Therefore, airflow changes during an underground fire must be considered for identifying possible

smoke rollback. One of MFIRE's important advantages is to dynamically predict airflow change in each branch of a mine ventilation network during the fire. The critical velocity equations mentioned previously mean nothing without knowing the real airflow velocity. It is very necessary to incorporate these or one of these equations in MFIRE to identify smoke rollback in an underground coal mine fire.

A sufficiently intense fire relative to the airflow rate could induce a complete airflow reversal in an airway. Such a situation can be modeled accurately by MFIRE (Chang et al., 1990). When the smoke rollback in an airway is out of control with increasing fire intensity and lower air velocity, the entire airflow of the airway reverses its direction. That is the reason that steady ventilation airflow to the fire should be maintained and cannot be reduced during a mine fire fighting process. The complete airflow reversal is the last stage of smoke rollback and it is hard to control. Complete airflow reversal has more chance to be avoided if the early stage of smoke rollback³ is identified and controlled successfully. Complete airflow reversal in an airway can be treated as one-dimensional because the increasing production of smoke totally blocks the airflow and generally only one-direction of flow occurs in the airway. Different from the complete airflow reversal, a normal smoke rollback should be treated as at least a two dimensional⁴ problem with airflow flowing in the normal direction along the lower section of an airway and smoke flowing to the opposite direction in upper section of the airway. MFIRE 2.20, based on a one-dimensional model, can directly si-

³ In this paper, smoke rollback refers to the early stage of smoke rollback and complete airflow reversal refers to the last stage of smoke rollback.

⁴ Three dimensional is more accurate.

simulate the complete airflow reversal but cannot simulate the smoke rollback in an airway.

In this research, no effort was made to extend a one-dimensional network model to a two-dimensional model for the purpose of identifying smoke rollback in an airway. However, since the influence factors and the quantified expression of smoke rollback are already known, the efforts are made to incorporate the proven research findings to the new MFIRE program to identify the smoke rollback in an airway.

4.3.2 Comparison of equations

An equation about critical velocity among the equations described in Section 4.2 will be chosen to apply in MFIRE to identify smoke rollback. The equations will be named by their proposers' name respectively in order to eliminate confusion in description such as Mitchell's equation (1996), Kennedy's equation (1996), Oka and Atkinson's equation (1995), Wu and Bakar's equation (2000) and Edwards et al.'s equation (2006).

Mitchell's equation is simple to apply and is especially useful in the events of mine fire fighting and rescue. However it only considers the height of a tunnel ignoring the important factor of fire intensity in determining the critical velocity. Many experimental studies (Lee et al., 1979; Oka and Atkinson, 1995; Wu and Bakar, 2000; and Edwards et al., 2006) have proved that the critical velocity is dependent on fire intensity and varies with the one-third power of fire intensity at lower fire HRR. Mitchell's equation is only applicable for the extreme large fire intensity at which the critical velocity is independent of fire intensity. Therefore,

Mitchell's empirical equation should not be considered in this research. However, it should be noted that Mitchell's equation is very practical for emergency evacuation and rescue without the need of complex calculation. It is applicable for the high fire intensity at which the critical velocity is independent of the fire intensity.

All the above equations about critical velocity are semi-empirical and based on experimental data collected by their developers. This is the reason that the critical dimensionless HRR at which the critical velocity starts to become independent of fire intensity is 0.12 in Oka and Atkinson's equation and 0.20 in Wu and Bakar's equation. The deviation of these two values is caused by the difference between their experimental results. Without finding out the particularities of these corresponding experiments, it is hard to decide which method is the best to be used to identify the smoke rollback in the new program.

After a thorough comparison of the experimental facilities and results, it is determined to use Edwards et al.'s equation with some minor corrections for identifying the smoke rollback in an underground coal mine entry. The reasons for such selection follow:

(1) Tunnel size

Kennedy's equation is based on Froude number preservation and some coefficients are determined according to the scale model tests conducted by Lee et al. (1979). Oka and Atkinson's equation is obtained based on small scale tunnels with hydraulic height 0.32m. The hydraulic height of experimental tunnels employed in Wu and Bakar's tests varies from 0.18m, 0.25m, 0.26m, 0.33m and 0.40m, respectively. Edwards et al.'s experiments were conducted in a real mine

entry which is 2.06m high and 2.91m wide. Real size experiments no doubt can provide more accurate results than scale test.

(2) Wall roughness

Edwards et al.'s experiments are the first and the only series of experiments which were conducted in a coal mine entry. All the others were either conducted in a road tunnel (Massachusetts Highway Department, 1995) or small scale-model tunnels (Oka and Atkinson, 1995 and Wu and Bakar, 2000) of which the wall is much smoother than the mine entry wall. The wall roughness can introduce additional turbulence which can definitely have impact on fire development and smoke rollback.

(3) Shape of experimental tunnel

A coal mine entry is normally rectangular in shape while Oka and Atkinson's (1995) and one of Wu and Bakar's (2000) experimental tunnel have arc-shaped roofs. Hot smoke floats up to the upper arch area during a tunnel fire. The shape of the roof could have a significant influence on smoke rollback. A flat roof entry is almost universal entry in American coal mines.

Considering the above three points, Edwards et al.'s experiments conducted in a real size coal mine entry are expected to be the closest to a real coal mine fire. Therefore, the semi-empirical equations about critical velocity based on these experiments are determined to be most suitable to identify smoke rollback in a coal mine entry.

Even though Edwards et al.'s equation appears to be the suitable one to be incorporated to the improved MFIRE 2.30, the equation itself should be carefully

inspected. The fire intensity and the tunnel geometry are two factors to have significant influence on the critical velocity in an airway as being confirmed in the previous equations. Slight differences occur among those equations and they are discussed from the following two aspects:

(1) The effect of tunnel geometry

Kennedy's equation and Oka and Atkinson's equation employ the tunnel height as the characteristic length. Wu and Bakar (2000) have conducted a series of experimental tests using five model tunnels with different shapes but the same height to study the relationship between the critical velocity and the tunnel geometry. Their study demonstrates that the magnitude of the critical velocity varied significantly with the tunnel cross-sectional geometry. At a given height, the critical velocity varies with the tunnel width. Ideally, it is better to use a single characteristic length, not its height and width, to represent the geometry of the tunnel in the analysis of the critical velocity. Hydraulic tunnel height defined as the ratio of four times the cross-sectional area to the tunnel wetted perimeter is introduced to replace tunnel height in Oka and Atkinson's equations. Edwards et al. (2006) also applied the hydraulic tunnel height to their equations.

(2) The effect of fire intensity

All the equations have considered the effect of fire intensity and shown that the critical velocity varies with one-third power of the fire intensity except that Edwards' equation has slightly difference with the power of 0.3. Both Oka and Atkinson's equation and Wu and Bakar's equation have shown two regimes of variation of critical velocity against the heat released from the fire. At low rates of

HRR, the critical velocity varies as the one-third power of the HRR, however at higher rates of heat release; the critical velocity becomes independent of fire HRR. Kennedy's equation and Edwards et al.'s equations show only one regime of variation of critical velocity against fire HRR. In other words, Edwards et al.'s equation indicate that the value of critical velocity varies with 0.3 power of HRR from the fire and is not independent of fire HRR at higher HRR. However, Wu and Bakar's tests (2000) showed that, as the fire size increases to the point where the flame length exceeds the tunnel height, the critical velocity becomes much more weakly dependent on the HRR. Oka and Atkinson's experiments and equations also make the same conclusion. Why Edwards et al.'s experiments don't make the conclusion that the critical velocity is independent of the HRR at high HRR needs to be investigated before Edwards' equations are applied to MFIRE 2.30.

Wu and Bakar (2000) have investigated the fire plume distribution at critical velocity conditions and to explain why the critical velocity becomes independent of fire intensity when fire size increases to a critical level. The velocity profiles and temperature distributions inside the tunnels were examined both by detailed experimental measurement and CFD simulations. It was found that when the fire HRR is small, all persistent and intermittent flames lay low inside the tunnel, with only the buoyant smoke flow reaching the ceiling. In this case, the critical velocity is to the one-third power of the fire intensity. When the HRR increases to a certain level, the intermittent flames reach the ceiling and occupy the upper part of the tunnel. The intermittent flames have the feature of a constant flow speed;

therefore, the buoyancy force in the rolling back smoke is not sensitive to the HRR.

In Edwards et al.'s experiments, the maximum fire intensity is 304 kW with dimensionless fire intensity of 0.038. However, the critical dimensionless fire intensities in Oka and Atkinson's equation and Wu and Bakar's equation is 0.12 and 0.20, respectively. The significantly lower dimensionless fire intensity in Edwards et al.'s experiments can explain why there is only one regime of critical velocity against the heat released rate from the fire. The fire intensities employed in Edwards et al.'s experiments are relatively small compared with the tunnel size. In other words, the fire intensity of Edwards et al.'s experiment is not large enough to approach the independent relationship between critical velocity and fire intensity. Assuming the critical dimensionless fire intensity is 0.20, using Wu and Bakar's value, the fire intensity will be not less than 1.4 MW in order to test the independence of critical velocity and fire intensity according to the Froude scaling rule (shown as Equation (4.12)).

$$\frac{\dot{q}_{scaling}}{\dot{q}_{model}} = \left(\frac{\overline{H}_{scaling}}{\overline{H}_{model}} \right)^{5/2} \quad (4.12)$$

Based on the above analysis, it is agreed that the critical velocity is independent of fire intensity as the fire size exceeds a certain value. Therefore, it is necessary to expand Edwards et al.'s equation from one regime to two regimes.

4.3.3 The Correction of Edwards' Equation

Oka and Atkinson's, and Wu and Bakar's equations can be expressed in one form:

$$V_c^* = \begin{cases} V_{\max}^* (\dot{q}^*_{critical})^{-1/3} (\dot{q}^*)^{1/3} & as \quad \dot{q}^* \leq \dot{q}^*_{critical} \\ V_{\max}^* & as \quad \dot{q}^* > \dot{q}^*_{critical} \end{cases} \quad (4.13)$$

Similarly, considering the two regimes equations, Edwards et al.'s equation can be rewritten as

$$V_c^* = \begin{cases} V_{\max}^* (\dot{q}^*_{critical})^{-0.3} (\dot{q}^*)^{0.3} & as \quad \dot{q}^* \leq \dot{q}^*_{critical} \\ V_{\max}^* & as \quad \dot{q}^* > \dot{q}^*_{critical} \end{cases} \quad (4.14)$$

Where $V_{\max}^* (\dot{q}^*_{critical})^{-0.3} = 0.92$

4.4 Implementation of Smoke Rollback Identification in MFIRE 2.30

4.4.1 Identification Equations

Substituting Equation (4.8) and (4.9) into Equation (4.14) yields the following equation (4.15):

$$V_c = \begin{cases} 0.92 \frac{g^{7/20}}{\bar{H}^{1/4}} \left(\frac{\dot{q}}{\rho_0 T_0 C_p} \right)^{0.3} & as \quad \dot{q}^* \leq \dot{q}^*_{critical} \\ 0.92 (g\bar{H})^{1/2} (\dot{q}^*_{critical})^{0.3} & as \quad \dot{q}^* > \dot{q}^*_{critical} \end{cases} \quad (4.15)$$

The above equation is employed by MFIRE 2.30 to identify smoke rollback in an airway. While applying the equation, the HRR, $\dot{q}$, in Equation (4.15) is required to be replaced with the function of $\dot{q}(t)$ defined as Equation (3.6) if the t-squared fire model is chosen by users. Otherwise, the constant HRR can continue to be used. The critical dimensionless HRR is left as a variable requiring the user to specify because the value is not determined in Edwards' experiments.

For the practical purposes, the improved MFIRE 2.30 uses a default value of 0.20 to the variable of $\dot{q}_{critical}^*$ as recommended in Wu and Bakar's equation (Equation (4.10)).

4.4.2 Determine Smoke Rollback Length

The extent of smoke rollback along the roof into the oncoming fresh air is also dependent on the ventilation velocity, airway dimensions, and fire intensity. Although the instability of the smoke reversal makes it difficult to define with great certainty the extent of smoke reversal for different ventilation velocities, a reduction of the data with dimensionless variables makes the trend more apparent in Edwards et al.'s article (2006). For the smoke reversal length, L_r , achieved for different ventilation velocities V_{in} and the HRR $\dot{q}$, a pair of dimensionless variables, X and Y , can be defined as

$$X = \dot{q} / (AV_{in}^3 \rho_0) \quad (4.16)$$

$$Y = \frac{gL_r}{C_p(T_f - T_0)} \quad (4.17)$$

Where T_f is average temperature of the fire-site gases in degrees K, which can be determined by Equation (4.4). Regressions studies (Edwards et al., 2006) showed that X and Y satisfy the simple relationship $Y = 0.0238\ln(X) - 0.0479$ with $R^2 = 0.68$.

After submitting Equation (4.16) and (4.17) into the above relationship yields the expression about smoke rollback length, L_r is

$$L_r = [0.0238 \ln \left(\frac{\dot{q}(t)}{AV_{in}^3 \rho_0} \right) - 0.0479] \frac{C_p (T_f - T_0)}{g} \quad (4.18)$$

4.4.3 Implementation of Smoke Rollback Identification

Function Criticalvelocity() in MFIRE 2.30 and some other updated functions from MFIRE 2.20 are responsible for smoke rollback identification. At each time interval, the critical velocity and real airflow velocity of the fire branch will be calculated employing Equation (4.15) according to whether the dimensionless HRR is smaller or larger than the critical dimensionless HRR. MFIRE 2.30 is capable of providing information about branch ID and the time for a smoke rollback to occur, and the length of smoke rollback. Some necessary data about smoke rollback are output into a table in the database and a warning message (as shown in Figure 4.1) was popped out to warn users that a smoke rollback occurs at the same time.

Figure 4.1 Warning of smoke rollback

The implementation of the smoke rollback computer modeling makes it possible to quantify the effect of ventilation controls on smoke rollback, particularly for an emergency plan. For example, MFIRE 2.30 can be employed to estimate the effect of the smoke rollback prevention method recommended by Mitchell (1996) that hangs brattice across the bottom half of the entry as close to the fire as possible by reducing the cross sectional area of the fire branch to half and a local resistance produced by brattice added to the original resistance. MFIRE 2.30 then can evaluate if the brattice works for a certain coal mine and the critical velocity also will be output at each time stage as a reference of emergency plan. A detailed example will be discussed in Chapter 7.

4.5 Summary

- Critical velocity is used to identify the occurrence of a smoke rollback. Equations determining critical velocity are semi-empirical with the value of some coefficients obtained from experimental studies.
- Some previous research has shown that the critical velocity varies as about one-third power of fire intensity at low HRR, and it is independent of fire intensity at higher HRR. The critical dimensionless fire intensity is defined to determine which principle the critical velocity will follow.
- A few equations about critical velocity are compared according to their test models and the expression of the equations themselves. Edwards et al., (2006)'s equation was chosen to identify smoke rollback in an underground coal mine fire after expanding it from one regime to two regimes.
- The reasons for selecting Edwards et al.'s equation are based on two main categories. At first, Edwards et al.'s equation is carried out based on a real size mine entry with actual wall toughness while the other experiments are all conducted in scale-models with smooth walls. Secondly, the rectangular entry, common in US coal mines, is used in Edwards et al.'s experiments. The testing tunnels in the other experiments are arc types, the typical shape of a road tunnel. All the above factors are believed to have a significant influence on smoke rollback.
- Edwards et al.'s equation only deals with one regime of smoke rollback due to the fact that only "small" scale fires were experimented. Improve-

ments have been made to Edwards' equations borrowing some of the findings from the other researchers.

- The improved Edwards et al.'s equation was incorporated into MFIRE 2.30 to identify the smoke rollback. The combination of MFIRE program with smoke rollback identification make it possible to evaluate the effect of smoke rollback prevention methods in an underground coal mine fire.

CHAPTER 5 CONVEYOR BELT FIRE SIMULATION

5.1 Introduction

Belt entry fires have always been a great concern in fire detection and prevention and they impose a major safety and health risk to miners. The combination of friction caused between the high speed belt and defunct support structures and flammable material can and has resulted in heating and/or ignitions. From 1980 to 2005, there were 63 reportable belt entry fires accounting for about 15-20% of the total numbers of fires in underground coal mine, according to MSHA (2007 (b)). A recent underground coal mine conveyor belt fire occurred in the Aracoma Alma Mine No.1 in West Virginia on January 19, 2006. The MSHA Investigation Report (2007(a)) indicates that the fire occurred in the 9 Headgate longwall belt takeup storage units when the frictional heating ignited accumulated combustible materials. Two of 29 miners working underground at that time became separated during evacuation and were found dead two days later.

A fire can start anywhere along the conveyor belt and can spread quickly to other areas often making the belt fires more hazardous than other types of mine fires. As the belt fire progresses and extends to other combustibles, the combustion in a confined mine space often produces a large amount of CO to elevate the concentrations of toxic gases to potentially lethal levels.

Since June, 2004, the underground coal mine ventilation safety standards Code of Federal Regulations, Title 30, Part 75 allows the use of a conveyor belt

entry as an intake air course to ventilate working areas. An increasing number of mines are either using or petitioning to use the belt entry air to ventilate active work areas. It was believed by operators that using the belt entry as an intake entry will allow them to deliver more air to the work areas. However, one of the critical problems is that a belt fire may spread along the belt entry quickly and the generated CO and smoke can then be carried by airflow into active working areas. Both are major causes of deaths to miners working in these active areas. The Technical Study Panel on the Utilization of Belt Air and the Composition and Fire Retardant Properties of Belt Materials in Underground Coal Mining (TSP, 2007) recommended more research be conducted about development of guidelines for improved escape way design in various ventilation situations. Fire simulation software including MFIRE will provide a useful tool for this kind of research.

5.2 Belt Fire Hazards

5.2.1 Causes of Belt Fire

In a belt entry, there are abundant sources of fuel (coal, the belt, trash, lubricants, wood posts), sources of ignition (frictional heating, sparks from welding or malfunctioning electrical components) and an abundant source of air. Therefore, the belt entry has a high probability for a fire to occur.

The Risk of a conveyor belt fire is compounded by the fact that coal dust and coal fines accumulate on and around the rollers, the steel frame and the belt itself. Thus when a belt roller becomes damaged or broken, heating can occur in close proximity to the fuel source – the coal dust accumulations. The combina-

tion of friction caused by high speed belts and flammable material can and has resulted in heating and/or ignitions.

Inadequate maintenance of the belt conveyor system is a contributing factor to the causes of belt fires, resulting in the accumulation of fuels and creation of sources of ignition. The most common source of ignition is frictional heating (Lazzara, 1990). It can occur if idler rollers seize or if the belt becomes misaligned. There are thousands of load-bearing rollers for each mile of belt. If any one breaks or seizes, a belt continuing to pass over the roller can cause frictional heating. Frictional heating has also occurred if belts become misaligned and rubbed against adjacent structures, rib, roof, or floor. Heat generated by friction may be sufficient to ignite grease, accumulated coal dust, the belt itself, or other combustible materials. Other sources of ignition include sparks from welding or from malfunctioning electrical equipment. Fuel for combustion can be the belt, coal or coal dust, lubricants, or other combustible materials such as wood, trash, etc. Since freshly cut coal is carried by the belt, float coal dust is common in belt entries. If it is not removed on a regular basis, it may become fuel for a fire. If the ribs of a belt entry are not adequately rock-dusted, the coal that constitutes these ribs may also ignite.

Based on MSHA data (2007 (b)), the number of conveyor belt reportable fires between 1980 and 2005 was 63 with the frictional heating, flame cutting and welding, and electrical malfunctions being the primary causes. Frictional ignitions are a common source of belt fires, accounting for approximately 20% of all belt fires (Lazzara, 1990).

In order to reduce the fire hazard from conveyor belts, fire –resistant conveyor belts are required in U.S. underground coal mines. The current U.S. flammability test for acceptance of fire-resistant belts for underground coal mines is specified in the Code of Federal Regulations (CFR) and is conducted by the Department of Labor, MSHA Approval and Certification Center (MSHA, 2009).

5.2.2 Development Stages of a Belt Fire

Typical fires in belt entries develop in the following three distinct stages (Litton et al., 1991):

(1) Early smoldering stage

The early smoldering stage may take a few minutes or a few hours before the flame starts. Heat produced by overheated equipment or friction between the belt fabric and drive roller due to belt slippage, or friction between the belt and structure or other object such as steel post, wood crib or coal can accumulate to the point of flaming. The duration depends upon many factors, such as, the temperature of the overheated equipment, the quantity of coal involved, the size of coal, and the proximity of the source of heating to the exposed surfaces of the coal pile. A large amount of smoke and CO are produced during this stage.

(2) Early flaming stage

A small coal fire starts once the coal is ignited by overheated equipment or friction. The coal fire intensity begins to increase at a rate which depends on the air velocity and the surface area of coal available for burning. The small coal fire may subsequently ignite the conveyor belt once the temperature exceeds the ignition point of the belt.

(3) Combined coal and conveyor belt fire

The fire increases in intensity to the point of sustained belt flame spread. Once the belt is ignited, the flame will begin to spread over the surface of the belt in the vicinity of the source of the coal fire. Previous works (Litton et al., 1991, Verakis and Dalzell, 1988, Edwards and Hwang, 1991) have shown that the rate of spread along the belt was affected by the air velocity and the flame-spread characteristics of the belt material. The flame will spread more quickly along a poorer flame-resistant belt than a better flame-resistant belt.

5.3 Impact of Air Velocity on the Belt Fire Spread

Research and experimental studies on the fire hazard of conveyor belts have been conducted over many decades. Most research about conveyor belt fires focused on the flammability of the belts and the impact of ventilation on the fire.

Conveyor belts as a typical solid combustible can result in a fire that spreads over a considerable distance in a coal mine, unlike any liquid combustibles such as diesel fuels, and will generally be limited to a localized region. MSHA investigation report (1991) stated that a fire spreads a distance of about 900 ft in about 9 hours. The corresponding average flame spread rate is about 0.0086 m/s (1.67 ft/min).

Several large-scale conveyor belt fire tests were conducted at air velocities of 1.3 m/s and 3.1 m/s (256 and 610 ft/min) by Shepherd and Jones (1952). Their test results show that the rate of burning and completeness of combustion increased with increasing air velocity, but the spread of fire along the belt was slow. Mitchell et al. (1967) conducted large-scale fire tests in a mine entry at air veloci-

ties of 1.0 m/s and 2.6 m/s (200 and 512 ft/min). They found that the flame spread rate was significantly greater for rubber than for neoprene or polyvinyl chloride belts. Mitchell and other researchers continued their investigations, examining the relations between the flame propagation and air velocity, belt width, and cross-sectional area of the test apparatus (Mitchell et al., 1967). They found that, among other matters, air velocity greater than 0.5 m/s (100 ft/min) increased flame propagation but belt width seemingly has no impact. The propagation is affected by the cross-sectional area of the test gallery to some degree. Of relevance to the use of belt entries for ventilation, they suggested that “In practice, consideration might be given to limiting air flow in belt installations.”

Another large-scale conveyor test (Litton et. al, 1991; Hwang et. al, 1991) conducted in the former U.S. Bureau of Mines’ above ground fire gallery located at Lake Lynn Laboratory showed airflow velocity has a significant impact on the rate of CO and smoke production. The test (Hwang et al., 1991) also indicates that the burning zone remains approximately the same length and the flame spread rate along the conveyor belt depends strongly on air velocity and propagates steadily. The following two figures show the propagation of the front and the rear of the burning zone at two different air velocities.

Figure 5.1. Front and rear of burning zone (A) flame spread at $V_a=0.76 \text{ m/s}$ (B) flame spread at $V_a=1.52 \text{ m/s}$ (Source: Hwang et al., 1991)

Large-scale conveyor tests conducted by MSHA (Verakis, 1991) have shown that the flammability characteristics of conveyor belts are significantly affected by the airflow and the composition of the belt. The highest flame spread rates, significant smoke rollback and combustion products occurred when airflow was 1.5 m/s . The approximate air velocity is also obtained by Yuan and Litton (2006) and Hwang et al. (1991). The experimental results (Yuan and Litton,

2006) about flame front velocity vs. air velocity for two kinds of conveyor belt samples are shown in Figure 5.2.

Figure 5.2 Flame front velocity vs. air velocity (source: Yuan and Litton, 2006)

From the curve of flame front rate and the air velocity shown in Figure 5.2, we can see that the flame spread rate peaked at a certain air velocity, approximately 1.5 m/s in Yuan and Litton's tests, and then decreased as the air velocity increased further. The experimental studies conducted by Hwang et al. (1991) and Verakis and Dalzell's (1988) have also shown the similar pattern between the imposed airflow velocity and the flame spread rate. When the air velocity increases, more oxygen is brought to the burning belt fire to increase the heat generated by the fire. However, the higher air velocity would also carry more heat away from the source. A balance occurs between the amount of oxygen supplied and heat carried away result in the curve shown in Figure 5.2.

5.4 Definition of Moving Fire Source

The previous cases show that the conveyor belt fire is a moving fire instead of a stationary fire. The imposed hazards and effects to the surrounding environments will differ from a stationary fire. A moving fire source can not be adequately described by a stationary fire model defined in the current fire simulation programs (e.g., MFIRE, MineFire and VentGraph). Even with the addition of a time-dependent (t-squared fire) fire model to the original MFIRE, the fire model is still stationary. Therefore, it is necessary to create a new definition for a moving fire source for the accurate simulation of a conveyor belt fire and incorporate it into MFIRE 2.30.

5.4.1 Dealing with Fire Source Location

One of the most important issues to define a moving fire is the exact location of the fire source at any time during the simulation. However, MFIRE 2.20 assumed that the fire source always locates at the starting junction of the fire source branch no matter how far the fire source is actually from the starting junction. This assumption makes it simple to trace each control volume in the transient state simulation. The starting junction of the fire source branch is taken as the starting point of the first control volume as shown in Figure 5.3.

Figure 5.3 Schematic diagram of the fire branch assumption

For a relative short airway, this assumption won't have any significant influence on the simulation results such as temperature distribution. However, if a fire occurs in a very long airway particularly nearby its end node, this assumption will definitely result in inaccuracy in the simulation output. In fact, we all know that the most dramatic thermal phenomena including temperature changes, oxygen consumption, smoke and toxic gases emission take place nearby the fire source. Moreover, this old assumption has to be eliminated when a moving fire source such as a conveyor belt fire is considered in this chapter. Unlike a stationary fire source defined in MFIRE 2.20, a moving fire source can move along a designated route at a certain speed. A distance from the starting junction of fire branch to the actual fire source (as shown in Figure 5.4) has to be specified by users in order to eliminate the old fire source location assumption. Now the actual fire source is the starting point of the control volumes which can describe the detailed change downwind of the fire source in the fire branch.

Figure 5.4 New definition of fire branch

5.4.2 Assumptions of Moving Fire Source in MFIRE 2.30

The cited experimental studies have shown that the flame will spread along a belt at a determined propagation rate based on the air velocity and the construction material of the conveyor belt during a conveyor belt fire event. Defining a moving fire model in MFIRE 2.30 needs the following simplifications and assumptions:

- (1) A conveyor belt fire is considered as a point fire source without considering the length of the burning zone although it indicates from Figure 5.1 the burning zone has its own width. The larger the flame spread rate, the wider the burning zone is. Truly simulating a burning zone actually is at least a two-dimensional problem, which could not be dealt with in a one-dimensional network problem.
- (2) No heat is released from the burned conveyor belt area where the flame front has passed by. The residual heat released from the burned area is still an unsolvable problem for fire scientific researchers.

- (3) The conveyor belt is the only fuel involved in a moving fire. The combustion of coal on the conveyor belt, wood supports and any other combustible fuel won't be considered in the moving fire model. Based on the discussion about the stages of conveyor belt fires in Section 5.2.2, a fire on a loaded conveyor belt definitely will get involved with the coal. However, no experiment has been done for a conveyor belt fire with coal on it so far. The parameters of the flame spread rate along a belt combined with coal are still unknown.
- (4) All the conveyor belt fires occur at the stationary belts. In reality, the conveyor belt will be stopped and warnings will be issued if a fire or thermal event is detected by CO detectors. The fire on a running conveyor belt rarely happens.

5.4.3 Definition of Flame Spread Rate

Compared with the definition of a stationary fire, the flame spread rate is the most important parameter needed to specify a moving fire source. As it was discussed before, the flame spread rate is mainly determined by the flame-spread characteristics of the belt materials and the airflow velocity. However, no analytical equation has ever been derived to define the flame spread rate. At present, two types of flame spread rate are considered. They are: 1) a constant flame spread rate without considering any influence of airflow velocity; and 2) a non-constant flame spread rate varying with airflow velocity.

(1) Constant flame spread rate

The constant flame spread rate refers to a flame spreading at a constant rate without being affected by airflow velocity during its spreading process. Users are required to determine this value based on the flammability property of a conveyor

belt. The constant spread rate moving fire is a simplified moving fire source model. It can be applied to a stationary fire with the flame spread rate being given as zero.

(2) *Non-constant flame spread rate*

It has been demonstrated that the flame spread rate is affected by airflow velocity. In order to describe the relationship without any analytical equation available, the basic principle about flame spread rate and airflow velocity obtained from experimental studies can be simplified as the graph shown in Figure 5.5. For a particular conveyor belt, the flame spread rate follows a linear relationship with airflow velocity. Two discontinuous equations (as shown in Equation (5.1)) can be established if the maximum flame spread rate V_{fx} and the corresponding airflow velocity V_{ax} are known. The variable V_{ax} in experiments performed by Verrakis and Dalzell (1988), Hwang et al. (1991), and Yuan and Litton (2006) are all determined to be around 1.5 m/s. However, the maximum flame spread rate V_{fx} varies with the composition of the conveyor belt materials. For example, the values of V_{fx} are 7.0 cm/s and 9.5 cm/s for two SBR belts, respectively as shown in Figure 5.5. A conveyor belt with poor flame-resistant properties will have a larger maximum flame spread rate than one that with good flame-resistant properties.

$$V_f = \begin{cases} \frac{V_{fx}}{V_{ax}} V_a & (V_a \leq V_{ax}) \\ 2V_{fx} - \frac{V_{fx}}{V_{ax}} V_a & (V_{ax} < V_a \leq 2V_{ax}) \\ 0 & (V_a > 2V_{ax}) \end{cases} \quad (5.1)$$

Figure 5.5 Idealized Relationship between flame spread rate and airflow velocity

Figure 5.6 and Figure 5.7 show the input screens for the user to define the two moving fire sources in MFIRE 2.30. In both input forms, the fire source branch ID, exact fire location in the branch, fire source model (i.e., t-squared fire model or MFIRE's original fire model), and the possible traveling route need to be specified. The only difference between the input parameters of these two moving fire is the flame spread rate. It is easily understood that a constant spread rate moving fire needs a fixed flame spread rate. However, the maximum flame spread rate and the corresponding airflow velocity need to be specified in a non-

constant spread rate moving fire in order to determine the influence that airflow velocity imposes on the flame spread rate of a conveyor belt fire.

Define Moving Fire Source

Fire source branch ID:

Location: distance from starting node ft

Flame spread rate ft/min

Fire source type

Possible traveling route (ID1,ID2,.....)

OK Cancel

Figure 5.6 Constant spread rate moving fire input screen

Non-Constant Spread Rate Fire

Fire source branch ID:

Location: distance from starting node ft

Fire source type

Possible traveling route (ID1,ID2,.....)

Graph showing Flame Spread Rate (V_f) vs Airflow Velocity (V_a). The graph shows a triangular relationship with a peak at V_{fx} and V_{ax} , and a zero spread rate at $2V_{ax}$.

Max.Flame spread rate V_{fx} ft/min

Airflow Velocity V_{ax} ft/min

OK Cancel

Figure 5.7 Non-constant spread rate moving fire input screen

5.4.4 Advancement of Fire Source

The moving fire source will induce a few issues in the transient state fire simulation. Contrary to a stationary fire model, the moving fire source will deal with not only the advancement of each air segment but also the advancement of the fire source itself in a complex ventilation network.

A conveyor belt fire, considered as a moving fire, will only spread along the belt entry that can be divided into several branches in the expression of a mine ventilation network. It is possible that the moving fire moves out of its original branch during its spreading process. A potential traveling route of a moving fire needs to be specified with branch IDs in sequence. For example, Branches A, B, C connected one by one in a ventilation network are used to specify a long belt entry into three parts. A belt fire occurs in Branch A first and potentially spreads into Branch B and then C. In this case, Branch B and C must be input as the traveling routes of the moving fire. Otherwise, MFIRE 2.30 will recognize that once the fire has moved through Branch A, it will cease further advancement and the fire source will stay at the ending junction of Branch A for the rest of the time intervals. At each time interval, the fire source is advanced according to its flame spread rate and its new location in a branch is determined. A new fire branch with corresponding properties is recognized once a moving fire flows into the next designated “traveling” branch. Therefore, the original fire branch changes back to a normal branch.

The advancement of the air segment mainly employs MFIRE's original techniques. The process of a moving fire simulation in MFIRE 2.30 can be described briefly as shown in Figure 5.8.

Figure 5.8 Flowchart of moving fire simulation

5.5 Summary

- A conveyor belt fire, as a moving fire source, was not defined in the original MFIRE and other mine fire simulation programs. In order to simulate the effects of such a fire source, a moving fire model is proposed and incorporated into a fire simulation program for the first time.
- The development of the moving fire source models is based on research findings that the flame spreads along the conveyor belt at a certain rate, the length of the burning zone remains nearly constant and the flame spread rate is mainly affected by airflow velocity and belt material.
- Several experimental studies have found that the maximum flame spread rate of a conveyor belt fire occurs when the airflow velocity is about 1.5 m/s. The definition of the moving fire models took into account these research findings. Two types of moving fires can be modeled in the new MFIRE program. One is a moving fire with a constant flame spread rate without considering the effects of airflow velocity. This kind of moving fire can also be applied to simulate a stationary fire by inputting zero spread rate. The other type of moving fire is a variable spread rate based on the mathematic expression carried out to represent the relationship between the flame spread rate and airflow velocity.
- The original MFIRE assumes that a fire source is always at the starting junction of a branch. This assumption is replaced with the exact location of a fire source within a branch, because the location of a moving fire needs to determine at each simulated time interval.

- The moving fire source model in a coal mine fire is not only applicable for a conveyor belt fire but also for any other solid combustible in an underground mine such as coal and wood support, along which a fire can spread at a certain rate.

CHAPTER 6 RECODE MFIRE WITH VISUAL C++

6.1 Introduction

The previous versions of MFIRE (versions 1.27, 1.29, 1.30, 2.0/2.01, 2.10 and 2.20) were written in FORTRAN 77 and compiled with Microway FORTRAN for the Intel 80386 based computers with an 80387 math co-processor (Laage et al., 1995). MFIRE 2.20, written in FORTRAN 77 and running under the DOS operation system, is the most recent version released in 1994. FORTRAN is quickly losing support in the newer and more popular operating systems currently in use since it is difficult to update and not easily maintained in the current computer environment. An updated MFIRE is urgently needed to run under the popular Windows operating system.

6.2 Object-Oriented Programming (OOP) and Microsoft Visual C++

Object-Oriented Programming is a programming paradigm that uses "objects" – data structures consisting of data fields and methods together with their interactions – to design applications and computer programs. Programming techniques may include features such as information hiding, data tion, encapsulation, modularity, classification, polymorphism, and inheritance. It was not commonly used in mainstream software application development until the early 1990s. Many modern programming languages including C++, JAVA and Python now support OOP. Object-oriented programming was developed as the dominant programming methodology during the mid-1990s, largely due to the

influence of C++. Its dominance was further enhanced by the rising popularity of graphical user interfaces (GUI), for which object-oriented programming seems to be well-suited (Wikipedia, 2009).

“Class” is a very important concept and term in OOP. A class is a programming language construct that is used as a blueprint to create objects of that class. This blueprint describes the state and behavior that the objects of the class all share. Fundamentally, it encapsulates the state and behavior of the concept it represents. It encapsulates state through data placeholders called attributes (or member variables or instance variables); it encapsulates behavior through reusable sections of code called methods. A class has both an interface and a structure. The interface describes how to interact with the class and its instances with methods, while the structure describes how the data is partitioned into attributes within an instance.

All similar objects or those having the same attributes (or data structure) and behavior (or operation) are grouped together. A new object also can be formed using classes that have already been defined, which is called inheritance. Inheritance is intended to help reuse existing code with little or no modification. The new classes, known as derived classes, inherit attributes and behavior of the pre-existing classes, which are referred to as base classes.

Microsoft Visual C++ (often abbreviated as MSVC) is a commercially integrated development environment (IDE) product engineered by Microsoft for the C, C++, and C++/CLI programming languages. C++ is an extension of the programming language C produced in the early 1980s by Stroustrup (1986) at

Bell Laboratories and supports object-oriented programming. In this research, Microsoft Visual C++ 6.0 released in 1998 was employed in rewriting the MFIRE 2.30 code.

6.3 Structure of MFIRE 2.30

In general, MFIRE 2.30 has three functional sections: Graphical Users Interface (GUI), database section and fire simulation section. Their communication patterns can be seen clearly from the chart in Figure 6.1.

Figure 6.1 Structure of MFIRE 2.30

The data required by the fire simulation are input via the GUI, and then saved in the corresponding table in the database taking advantage of ActiveX Data Objects (ADO) which is a set of Component Object Model (COM) objects for accessing data sources. The fire simulation process will start reading data via ADO from the database as the simulation reacts, to the command for conducting the fire simulation. After the calculation is accomplished, the results will be sent and saved in the database and then displayed in GUI.

One of the significant advantages of the structure of MFIRE 2.30 is its reusability. The GUI section and fire simulation process are connected via database

and section GUI is able to be separated easily from the other two parts. If any other applications intend to use the fire simulation, database is the only object needs to deal with without knowing the detailed process of fire simulation. Fire simulation part is enclosed in a "black box" with the database as its interfaces. A third party, such as Virtual Reality, can use the fire simulation calculation without knowing its codes by just communicating with the database.

6.3.1 Graphical User Interface (GUI)

As opposed to old text-base interfaces, today's major operating systems provide a graphical user interface. Applications typically use the elements of the GUI that come with the operating system and add their own graphical user interface elements and ideas. Obviously, the text-base interface of MFIRE 2.20 is outdated in the current popular operating systems. The GUI shown in the MFIRE 2.30 is developed based on the Mine Ventilation System Analysis Software (MVSAS) which is software for conventional mine ventilation network simulation. MVSAS GUI employed in this research is the first version. The author of this dissertation has participated in the design to development, and co-copyrighted with two other developers. The main view and main menu of the Chinese version of MVSAS are shown in Figure 6.2.

Three aspects (listed below) of this program updating for this thesis are made (other than converting Chinese to English).

- (1) Adding input and output parameters to include thermal features. Since MVSAS is only a conventional ventilation network simulation program, it did not involve any input and output data relating to thermal characters

such as conductivity, diffusivity, rock temperature, average temperature of each branch and temperature at the ending junction of each branch. The MFIRE 2.30 GUI provides a means for the input and output of all this data which is essential to fire simulation.

(2) Adding three input forms for all the three fire source models including: the moving fire source, original MFIRE fire source and the t-squared fire source model activated from “Execute” menu.

(3) Adding the fire simulation control data input form to MVSAS. For example, maximum iterations, time span and time increment of simulation, criteria of warning, and accuracy of some parameters.

Figure 6.2 Main view of MVSAS

Figure 6.3 Main view of MFIRE 2.30

6.3.2 Database Design

The data in MFIRE 2.20 were input from an ASCII text file which is very typical under the DOS operating system. Text files only store actual data but do not contain any format information. One of the biggest problems with text files is that retrieving data requires reading the entire text file from beginning to end. In a large text file, this makes retrieving data slow and clumsy. MS Access is a random-access type database which consists of records that can be accessed in any sequence. Converting the text files to database files has numerous advantages primarily because it is much faster to display the select data than when

opening a database than opening a text file. Therefore, the input and output data in MFIRE 2.30 are managed using a database created with MS Access.

Generally, four categories of input data are required by MFIRE 2.30, they are:

- (1) *Branch data*: consists of data representing basic physical characteristics of each branch including branch ID, starting junction and ending junction of the branch, resistance, airflow rate and branch type specified by: normal branch, fan branch or fixed quantity branch. If no resistance is input, the friction factor, length, perimeter, cross-sectional area of the branch required to calculate the resistance are required. In a fire simulation, conductivity, diffusivity, and rock temperature are also requested for input. Methane concentration may be used for gas flow simulations, as in a coal mine, and the user would enter methane emission rates or methane rates per unit area.
- (2) *Junction data*: contains junction temperature and elevation in preparation for the natural ventilation calculation, as well as methane concentration in the case of a gassy mine. Also, consideration must be given the types of junctions. Users need to specify if a junction is in the atmosphere.
- (3) *Fan data*: the fan characteristic curve is the most essential input data for mine ventilation network analysis and mine fire simulation. Ten sets of air quantity and pressure obtained from a fan curve are required to represent the fan curve because the curve cannot be entered directly.

Other data such as fan location and method of fitting the fan curve are also needed.

- (4) *Fire data*: MFIRE 2.30 not only keeps the fire models (fixed-heat input fire, oxygen-rich fire, fuel-rich fire) of MFIRE 2.20 but also adds two new fire models: t-squared fire and moving fire.

Only the output data for transient state fire simulation is discussed here even though MFIRE 2.30 is capable of conducting a normal mine ventilation analysis like MFIRE 2.20. Since transient state fire simulation is conducted at each time interval specified by users, a large number of transient state output data are produced in a simulation case. Similarly to the input data, the transient state output data are categorized into three groups as shown below.

- (1) *Branch data*: Besides basic data about branch characteristic, airflow rate, average temperature of the branch, and temperature at the ending of branch at every time interval are the most important output data for transient state fire simulation.
- (2) *Junction data*: Consist of temperature and methane concentration at every time interval.
- (3) *Air segment data*: Since a time span is divided into a series of time increments in the transient state fire simulation, the airflow in the system is traced by dividing it into air segments. The branch by branch temperature updating process in each air segment is in fact a process of segment by segment data point advancing and updating. Air segment

data record the location, temperature, airflow, mass and length of each air segment at every time interval.

- (4) *Smoke rollback data*: These data contain the time occurring smoke rollback, actual velocity of the smoke rollback branch, critical velocity, and rollback length.

A total of seven tables (shown as Figure 6.4) are created under the categories of input and output data. Fire data are not managed in database but input directly from dialogs which will be illustrated in Chapter 7.

Figure 6.4 Database design

6.3.3 Build ADO Applications

ActiveX Data Object (ADO) is an application program interface from Microsoft that lets a programmer writing Windows applications get access to a relational or non-relational database from both Microsoft and other database providers. Like Microsoft's other system interfaces, ADO is an object-oriented programming interface. It is also part of an overall data access strategy from Microsoft called Universal Data Access.

An open connection to a data source needs to be created through a derived class of class CDaoRecordset representing a set of records selected from a data source. Through this connection, a database is accessed and manipulated. The procedure and method of building a connection to Microsoft Access database in this effort will be illustrated using an example of Table Air Segment next. The Table Air Segment stores data which describe characteristics of each air segment. The table contains a total of nine fields with four of them representing the air segment's length, mass, temperature of ending point, and gas concentration and the other records such as the time, the airway containing the air segment, and the numbers and the order of air segment in a given airway. A new class, CCVoutput, is derived from CDaoRecordset and represents all fields of Table Air Segment in the Microsoft Access database. From class CCVoutput's declaration (Listing below), we can see that the member variables that correspond to the fields in the table have been claimed.

```

////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
///

class CCVoutput : public CDaoRecordset
{
public:
    CCVoutput(CDaoDatabase* pDatabase = NULL);
    DECLARE_DYNAMIC(CCVoutput)
// Field/Param Data
   //{{AFX_FIELD(CCVoutput, CDaoRecordset)
    longm_ID;
    longm_Timecost;
    longm_order;
    longm_airway;

```

```

    longm_No_of_CV;
    floatm_CV_distance;
    floatm_CV_temperature;
    floatm_CV_concentration;
    floatm_CV_mass;
    short    m_IFinbranch;
    /}}AFX_FIELD

// Overrides
// ClassWizard generated virtual function overrides
//{{AFX_VIRTUAL(CCVoutput)
public:
    virtual CString GetDefaultDBName();
    virtual CString GetDefaultSQL();
    virtual void DoFieldExchange(CDaoFieldExchange* pFX);
//}}AFX_VIRTUAL
#ifdef _DEBUG
    virtual void AssertValid() const;
    virtual void Dump(CDumpContext& dc) const;
#endif
};

////////////////////////////////////
///

```

In the main application of MFIRE 2.30, the function to write air segment data to Table Air Segment is defined with the declaration of class CCVoutput as a member variable of the main application. The class CCVoutput derived from CDaoRecordset class inherits a large number of member functions from CDaoRecordset. SomeRecordset navigation functions including Find, FindFirst, FindLast, FindNext, and FindPrev; and Move, MoveFirst, MoveLast, MoveNext, and MovePrev and data update functions including AddNew, Cancel, Update, Delete,

Edit, and Update are employed to manage and write calculated air segment data to Table Air Segment. Figure 6.4 shows an example of output of air segments. Similarly, the other tables in the database can be written and read via DAO.

Time	order	airway	No of CV	IFinbranch	CV distance	CV temperature	CV
30	2	3	1	1	127.5315	63.74573	
30	4	12	1	1	29.13399	62.13097	
30	5	13	1	1	7.513591	63.00826	
60	2	3	2	1	254.7805	62.14228	
60	2	3	2	1	127.0256	65.158	
60	4	12	2	1	88.33491	60.66575	
60	4	12	2	1	30.02135	61.98986	
60	5	13	2	1	24.0089	62.65988	
60	5	13	2	1	8.340902	63.36496	
90	2	3	3	1	380.8331	61.23627	
90	2	3	3	1	253.3446	62.97773	
90	2	3	3	1	126.3107	72.08685	
90	4	12	3	1	149.2696	60.20187	
90	4	12	3	1	90.98975	60.60337	
90	4	12	3	1	32.93193	64.57943	

Figure 6.5 an example of air segment table

6.3.4 Classes of Fire Simulation

There are totally of 139 classes including all classes from MVSAS that have been created in MFIRE 2.30. 36 of the 139 classes are newly created in this project. Some of them are in charge of dialogs, some are for data access. The most important class is “Ventilate” which is defined to deal with all functions and variables for mine fire simulation.

About 8,600 lines of code contained in MFIRE 2.20 which is written in Fortran 77 are translated into Visual C++ 6.0. All the variables and functions of MFIRE 2.20 are enclosed in Class Ventilate as its member variables and mem-

ber functions. The newly added variables and functions in this class are used to define t-squared fire, smoke rollback and moving fire. A complete description of these variables and functions is beyond the scope of the dissertation.

6.4 Summary

- Visual C++, an Object Orientation Programming Language, is used to rewrite the 8,600 lines of MFIRE code which was written in FORTRAN 77.
- A MS Access database including three input data tables and four output data tables is created to store and manage all the data for MFIRE 2.30.
- ActiveX Database Object (ADO), an object-oriented programming interface, is employed to access database from its main application.
- A brief Graphical Users Interface is also created based on a Chinese version Mine Ventilation Simulation and Analysis System (MVSAS).

CHAPTER 7 ILLUSTRATIVE EXAMPLES OF MFIRE 2.30

7.1 Introduction

Incorporating various mathematical models developed in this research, a new mine program, MFIRE 2.30, has been developed for mine fire simulation. The updated program greatly enhances the mine fire simulation capabilities of its previous version MFIRE 2.20 by expanding its applications. It runs under the Windows Operating System. The following examples serve as an introduction of these new features of MFIRE 2.30.

7.2 Case study

7.2.1 Description of Case

A multilevel mine fire case with complete input and output data was provided in the User's Manual for MFIRE (Chang et al., 1990). There are a total of 49 branches and 34 nodes with the main fan installed in Branch 45 and a fire assumed in Branch 4 in this case. Among all the junctions, Junction 1, 3, 4, 27, 33, and 34 are in the atmosphere. A fixed input fire provided 50,000 Btu/min of heat and 200 ft/min of pure products of combustion to the network. The schematic ventilation network is shown as Figure 7.1.

Figure 7.1 Multi-level of mine ventilation network layout

7.2.2 Data Completion

Before conducting the multi-level mine fire simulation using MFIRE 2.30, the following parameters need to be determined first:

- Schematic ventilation network
- Branch data: friction factor, length, cross sectional area or resistance, etc.
- Junction Data: temperature, elevation and Junction type
- Fan curve
- Fire source: maximum HRR, time periods for t-squared fire and HRR or oxygen concentration, or heat released per unit volume of oxygen consumed.

- f. Thermal properties of rock: thermal diffusivity, thermal conductivity and average temperature, etc.

The input data in the case study are all the same as the data employed in the example from the User's Manual for MFIRE (Chang et al., 1990) except the fire source parameters in Section 7.4 since the fire models are new to MFIRE 2.20.

Figure 7.2 The input network of the example

7.3 MFIRE 2.20 Fire Model

MFIRE 2.30 still keeps the fixed heat input fire, oxygen rich fire and fuel rich fire models of MFIRE 2.20 for users experienced with these fire models. The input view of fire models of MFIRE 2.20 is shown in Figure 7.3. The view is activated by choosing menu Execute -> Define Fire -> Fire Model from MFIRE.

The data shown in the following screen define a fixed heat input fire which is employed in the multi-level mine ventilation example with a fume production rate

of 285 ft³/min, fume concentration of 100%, and heat influx of 50,000 Btu/min. Oxygen concentration downstream of the fire is the variable used to specify an oxygen rich fire. Fume production and heat generated per cubic feet of oxygen consumed are the two variables to specify a fuel rich fire.

Parameter	Value	Unit
Contaminant in Branch	4	
Fume Production Rate	285	cfm
Fume Concentration	100	%
Heat Influx	50000	Btu/min
Oxygen Con. Downstream	0	%
Fume Production	0	ft ³ /ft ³ O ₂
Heat Generation	0	Btu/ft ³ O ₂
Reference Flow Rate	0	cfm

Figure 7.3 MFIRE 2.20 Fire models input screen

Some control data need to be determined before a fire simulation starts. One of the control data input screens is shown in Figure 7.4.

Simulation Control Card

Starting Junction (Atmosphere)

Junction ID:

Temperature: Degree F

Accuracy

Fume: %

Methane: %

Temperature: %

Warning Criteria

Pressure Drop: in.w.g

Methane Con.: %

Fume Con.: %

High Temperature: Degree F

Time Span to Quasi-equilibrium: hours

Buttons: Set Default, OK, Cancel

Figure 7.4 Control data input screen

The simulated results of MFIRE 2.30 for this case totally converge with the results provided in the Manual book of MFIRE (Chang et al., 1990). The comparisons between the predicted average temperatures at each branch from the original MFIRE (Chang et al., 1990) and MFIRE 2.30 are shown in Figure (7.5) and (7.6). The relative errors have also been calculated and shown in the following figures. The maximum relative error of 0.74% occurs at the temperature estimation of Branch 39 at time 120 seconds. Most of the relative errors are below 0.4%

which is acceptable for the temperature evaluation in a coal mine. The deviation is not avoidable because the difference existing of the declarations of variables between FORTRAN language and C++ language.

Figure 7.5 The predicted temperatures of branches at t=0 second

Figure 7.6 The predicted temperatures of branches at t=120 second

7.4 T-squared Fire

The HRR of a conveyor belt tested in a full scale fire test (Wachowicz, 1997) was employed to be a reference for determining parameters of a t-squared fire in this case.

The HRR curve shown in Figure 7.7 is a typical t-squared fire with maximum HRR of about 6 MW. The time period variables were determined as $t_0=0s$, $t_1=500s$, $t_2=1200s$ and $t_3=2200s$. The fire source was set 10 ft away from Junction 6 in Branch 4. The final t-squared fire parameters can be input through the input form shown in Figure 7.8.

Figure 7.7 HRR of a conveyor belt vs. time (source: Wachowicz (1997))

Figure 7.8 Input parameters of t-squared fire in the example

The total simulation time for the transient state is set as 45 minutes with time increment of 30 seconds. At time $t=210$ seconds, as shown in Figure 7.9, the fumes have advanced into branches 3, 12 and 13. At time $t=2,160$ seconds (Figure 7.10), fumes have reached Branch 33 and Branch 37 by passing branches 3, 7, 8, 11, 12, 13, 18, 19, 22, 23, 27, 28, 34, 35, and 36.

The simulation results show that the left side of the mine is directly endangered by a mine fire in Branch 4. Most of the branches are full of fumes at about 2,000 seconds after the fire ignition. However, the right side of the mine is free from smoke.

Figure 7.9 Fire in Branch 4 at $t=210s$

Figure 7.10 Fire in Branch 4 at t=2160s

7.5 Smoke Rollback Identification

In this case, smoke rollback could occur in branch 4. The determined critical velocity is less than the actual velocity before time $t=120$ seconds. At time $t=120$ seconds, the critical velocity is 282 ft/min while the actual velocity is 274 ft/min. According to the rollback identification equations presented in Chapter 5, there will a smoke rollback occurring in the vicinity area of this fire source at time $t=120$ seconds (as shown in Figure 7.11).

Figure 7.11 Velocities and rollback length in Branch 4

We have discussed Mitchell's recommendation (1996) about prevention of smoke rollback in Section 4.3.1, which refers to increase airflow velocity by reducing the cross-sectional area of the fire branch. In order to test Mitchell's recommendation, a new case was created by adding a local resistance which was produced by hanging brattice across the bottom half of the entry as close to the fire in Branch 4 as possible. In this case, the original cross-sectional area of Branch 4 is 50 ft². The hanging brattice can be treated as a regulator with the orifice area of 25 ft², and then the local resistance created by hanging brattice can be calculated with some related equations about the resistance of a regulator (Hartman et al., 1997). Half of the original cross-sectional area of Branch 4 is used to calculate the actual airflow velocity since it is recommended to place the brattice as close to the fire as possible. The predicted results about the critical velocity and the actual velocity of Branch 4 are shown in Figure 7.12. It shows

that hanging brattice doesn't increase the airflow velocity as intended but actually results in reduced air velocity. The brattice has increased the resistance and thereby reduces the quantity of air in this airway. From the standpoint of the air velocity, Mitchell's recommendation would not work for Branch 4 in this network. It should be noted that the consequence of the turbulence generated by reducing the airflow passing area to the smoke rollback is beyond the capability of the MFIRE program because it is a two or three dimensional problem. A CFD model is recommended to investigate the effect of the turbulence in the future research.

Figure 7.12 Velocities and rollback length after blocking half bottom

The incorporation of the identification algorithm of smoke rollback into MFIRE program can provide not only warning information but also quantitative information about its prevention method.

In this case, after finding out the reducing cross-sectional area of Branch 4 would not be able to prevent smoke rollback, an alternative controlling method should be sought and tested. In the ventilation network shown in Figure 7.1, if the resistance of Branch 5 is increased, it could force more air to flow in Branch 4. The approach is tested in MFIRE 2.30 by adding an extra resistance to Branch 5. In this case, the additional resistance to Branch 5 was set to be the same as that produced by hanging a brattice across the bottom half of the entry as well. The simulation results shown in Figure 7.13 have demonstrated that the increase in resistance in Branch 5 will help to increase airflow velocity in Branch 4 even though it cannot totally prevent smoke rollback. The maximum length of smoke rollback was reduced from 9 feet to 7 feet after applying the ventilation control in Branch 5. It should be noted that this controlling method will work for a fire with relatively small intensity.

Similarly, MFIRE 2.30 can be used to test and evaluate any other ventilation control approaches to see if it is applicable for reducing smoke rollback.

Figure 7.13 Velocities and rollback length after blocking Branch 5

7.6 Moving Fire Case

A case of moving fire is illustrated with setting a fire 10 ft from the starting junction of Branch 4. A fixed flame spread rate of 1.9 ft/min is specified. It was shown from the simulation results that the fume advancing route is the same as that in a stationary fire case as discussed in Section 7.4 but the former advances a little bit quicker. For example, the fume advancing route of the moving fire at the time of 2160 s is shown in Figure 7.14. Compared with Figure 7.8, one of significant differences in Figure 7.14 is that fumes have flowed into Branch 39 while fumes of a stationary fire were still in Branch 33 at the same time as shown in Figure 7.10.

Figure 7.14 A moving fire in Branch 4 at t=2160s

If we set an observation spot in Branch 3 which is the closest branch to the fire branch, the observed average temperatures of both stationary fire and moving fire are shown in Figure 7.15. It indicates that the average temperature in the branch in the moving fire case is generally a little bit higher than that in the stationary fire case. Figure 7.15 also shows that as a moving fire is advancing closer to Branch 3, the influence for the moving fire on Branch 3 is getting larger and larger. Any other branches in the route will also have the same phenomena as shown in Figure 7.15. The more detailed description of the simulation results is not presented here to avoid lengthy writing.

Figure 7.15 Temperatures of Branch 3 for moving fire and stationary fire

7.7 Fire source Location

In MFIRE 2.20 or earlier versions, fires were always assumed to occur at the starting junction of a branch. In order to make it more realistic, MFIRE 2.30 makes it possible to place a fire at any location in a branch. Three fires located at 1 foot, 100 feet and 199 feet apart from the starting junction of Branch 4 (a 200 ft long airway) are simulated. The comparison of the resulting average temperatures of Branch 3 is shown in Figure 7.16. The closest fire to Branch 3 is the fire at the end of Branch 4 and the highest temperature is about 330 degrees which is about 250 degrees higher than that in the fire at the starting junction of Branch 4. However, such a large difference would be ignored in MFIRE 2.20 or earlier versions. For example, a fire actually existing at the end of a branch would be treated as that at the starting part of the branch in MFIRE 2.20 or earlier versions.

It is obvious that the resulting temperature using such treatment would be less accurate if the fire source is located far away from the starting junction, especially if the fire branch is very long. By specifying the actual fire location, MFIRE 2.30 has improved the simulation capability.

Figure 7.16 Temperature of Branch 3 for fires at different location of Branch 4

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This research was aimed at improving the mine fire simulation software MFIRE version 2.20. Four improvements have been made and incorporated into a new version of MFIRE 2.30. Compared with the latest version of MFIRE 2.20, the following improvements have been made based on the research findings:

- (1) Fire models: Heat Release Rate (HRR), the most important parameter describing a fire source, is also the most critical input variable to a fire simulation. The time-independent HRR model in MFIRE 2.20 which defines either a fixed heat fire, oxygen-rich or fuel-rich fire is believed to be over simplified. The HRR of a fire in growth and decaying periods can be simply well characterized by functions of the second power of time, which is called a t-squared fire. A t-squared fire model is a time-dependent fire model. A multi-staged equation is created to represent a t-squared fire with the value of HRR in the fully developed period being simplified to a constant value. Such a time-dependent t-squared fire model has been incorporated into MFIRE 2.30. One of the experimental study cases conducted to validate the original MFIRE program in 1990 is selected to validate the new defined t-squared fire in MFIRE 2.30. Comparisons are made among the predicted temperatures by the original MFIRE, MFIRE 2.30 and the measured tem-

peratures at several points downwind from the fire. It has been demonstrated that the predicted temperatures from the MFIRE 2.30 agreed better with the testing data than those from the original MFIRE. While upgrading fire models, the equations evaluating temperatures in a fire branch is also improved by considering the conduction and convection heat transfer.

(2) Smoke rollback is a threat to miners and firefighters during an underground coal mine fire event. Its occurrence depends upon fire intensity, airflow velocity and airway dimension and size. Four semi-empirical smoke rollback identification equations derived from experiments are discussed and compared with respect to their testing facilities, and fire intensities. Based on the comparison, a corrected equation based on Edwards et al.'s experimental studies in a real size coal mine entry is employed to identify smoke rollback in MFIRE 2.30. The correction is made to Edwards et al.'s equation by adding fire intensity independence relationship description at high HRR. At each simulating interval, smoke rollback identification is performed in MFIRE 2.30 and a warning message is also displayed once a smoke rollback occurs. All the essential data about smoke rollback are output and stored in a database for further application.

(3) Conveyor belt fire, as a moving fire source, not defined in MFIRE 2.20 or its earlier version as well as any other mine fire simulation programs, is incorporated into MFIRE 2.30 as the first attempt ever in this aspect. The incorporation of a conveyor belt fire is based on research findings such as the

flame would spread along the conveyor belt at a certain rate which depends on airflow velocity with a constant burning zone length. Several experimental studies have shown that the flame spread rate of a conveyor belt fire will occur as the airflow velocity is about 1.5 m/s. Two types of moving fire models can be defined. One is the moving fire with constant flame spread rate independent of airflow velocity. This kind of moving fire can be applied as a stationary fire with spread rate of zero. The other type of moving fire is non-constant spread rate that is dependent on the airflow velocity. MFIRE 2.20 and earlier versions assumed that a fire source is always at the starting junction of a branch. In MFIRE 2.30, the fire source could be placed at any location of the fire branch.

- (4) Visual C++, an Object Orientation Programming Language, is used to rewrite the 8600 lines of original MFIRE code which was written in FORTRAN. The new program is called MFIRE 2.30. A MS Access database including three input data tables and 4 output data tables is created to store and manage all the data for MFIRE 2.30. ActiveX Database Object (ADO), an object-oriented programming interface, is employed to access database from the main application. A brief Graphical Users Interface is also created based on a Chinese version Mine Ventilation Simulation and Analysis System (MVSAS).

In summary, MFIRE 2.30 has the following improvements (Table 8.1) compared with MFIRE 2.20 which is the latest released version of MFIRE.

Table 8.1 Comparison of MFIRE 2.20 and MFIRE2.30

Category	MFIRE 2.20	MFIRE 2.30
Platform	DOS	Windows
Programming Language	FORTRAN 77	Visual C++
Data storage	Text file	MS Access database
GUI	NO	YES
Fire models	Time-independent fire	Time-independent fire and time-dependent fire
Convection and conduction heat transfer in fire branch	NO	YES
Smoke rollback identification	NO	YES
Location of fire source	Starting junction of a branch	Exact location
Moving fire	NO	YES

8.2 Recommendations for the Future Research

Based on the conclusions carried out in this research, the following work is recommended for any future studies:

- (1) The HRR curves of the common combustible materials in underground mine fire need to be collected or tested if not available. Some research need to be conducted to identify different combustible materials used in mines, classify various mine fires in both coal and metal and nonmetal mines, and for-

simulate fire heat release rate changes with the time, designing numerical algorithm.

- (2) The estimation of critical velocity of the smoke rollback in an inclined airway differs from that in a level airway discussed in this research. The experimental or numerical study is recommended to be conducted to determine the relationship between the slope of the inclined airway and the critical velocity.
- (3) A small scale fire experiment is recommended to ascertain the fire intensity independence at the high heat release rate of the fire based on Edwards et al.'s experiments. The critical fire intensity needs to be determined in the test.
- (4) The principle of the flame spread on a conveyor belt with coal on it needs to be studied. The impact of airflow velocity on the belt combined with coal also recommended to be investigated.
- (5) MFIRE 2.30, MFIRE 2.20 and the previous versions only consider the dry condition. How the humidity affect the heat transfer need to be studied, and the achievements need to be incorporated into the MFIRE program.

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