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Numerical and experimental investigation of carbon monoxide spread in underground mine fires

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Abstract

The primary danger with underground mine fires is carbon monoxide poisoning. A good knowledge of smoke and carbon monoxide movement in an underground mine during a fire is of importance for the design of ventilation systems, emergency response, and miners' escape and rescue. Mine fire simulation software packages have been widely used to predict carbon monoxide concentration and its spread in a mine for effective mine fire emergency planning. However, they are not highly recommended to be used to forecast the actual carbon monoxide concentration due to lack of validation studies. In this article, MFIRE, a mine fire simulation software based on ventilation networks, was evaluated for its carbon monoxide spread prediction capabilities using experimental results from large-scale diesel fuel and conveyor belt fire tests conducted in the Safety Research Coal Mine at The National Institute for Occupational Safety and Health. The comparison between the simulation and test results of carbon monoxide concentration shows good agreement and indicates that MFIRE is able to predict the carbon monoxide spread in underground mine fires with confidence.

Keywords

Mine fire; mine fire simulation; carbon monoxide spread

Introduction

Mine fires have long been and have continued to be a serious threat to the safety and health of mine workers. Unlike any fires on the surface, underground fires tend to cause worse damage to the mine due to the complicated interaction with ventilation and limited escape routes. The toxic products of combustion (POC) from a fire could quickly spread and contaminate the confined underground mine to threaten miners' lives. Two miners lost their lives due to carbon monoxide (CO) poisoning when they became separated from their crew in an evacuation from a conveyor belt fire at Aracoma Alma Mine on the morning of 19 January 2006.[1] As in this case, both the deaths are not caused by direct burns, but by

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inhalation of the toxic gases such as CO. CO can be deadly as it replaces oxygen in the bloodstream. In underground mines, the ventilation can carry the poisonous and sometimes explosive POC through the mine. Therefore, the hazard of a mine fire is not only limited to the adjacent area of the fire source but also to the entire mine. To combat this hazard, the paths along which the POC spreads must be known for the proper designation of escape routes and safe firefighting activities. Consequently, there is a high demand for mine fire simulation software to predict the fire development, POC spread, and to test and establish ventilation control strategies in an underground mine fire emergency situation. The purpose of mine fire simulation is principally to understand what areas of a mine will be affected by the fire and how badly they will be affected so as to understand impacts on egress and entrapment and therefore search and rescue and firefighting options.[2] A good knowledge of fire development and POC spread in underground coal mines during a fire is of crucial importance for the design of ventilation systems, the emergency response, and the miner's self-escape and rescuer training purposes.

MFIRE was specifically developed to simulate underground mine fires. MFIRE is an open source software originally developed in the 1970s by the United States Bureau of Mines and the Michigan Technological University. Several upgrade versions have been released over the years, including MFIRE 1.27, 1.29, 1.30, 2.0/2.01, 2.10, 2.20, and 3.0. MFIRE 3.0, the current available version, resulted from a major redesign and restructuring by the Pittsburgh Mining Research Division in 2012.[3,4] Recently, Zhou et al.[5] made several improvements to the fire modeling capabilities of MFIRE 3.0. These improvements included (1) the addition of fire source model of the *t*-squared fire and heat release rate (HRR) curve data file, (2) the addition of a moving fire source for conveyor belt fire simulations, (3) improvement of the fire location algorithm, and (4) the identification and prediction of smoke rollback phenomena.

The temperature distribution prediction in a mine fire event using MFIRE was validated using the test results from a designed test program at the Waldo experimental mine (Magdalena, NM) by the United States Bureau of Mines.[6,7] Zhou and Luo[8] improved and validated the MFIRE temperature simulation with the newly added time-dependent *t*-squared fire model using the test results from Laage and Yang[6] at the Waldo experimental mine. The comparison against the measured temperatures in a fire test at the Waldo mine proved that the MFIRE *t*-squared fire model had largely improved the degree of accuracy of temperature prediction, compared to the old MFIRE fire models. However, to the authors' best knowledge, no work has been done to validate CO prediction model neither for MFIRE nor for any other fire simulation software. The lack of validation on CO prediction in fire modeling lowers the confidence in the use of fire modeling to forecast actual toxi-city of the POC in a mine fire accident. To evaluate the CO spread model of MFIRE, several large-scale diesel fuel and belt fire tests were conducted at The National Institute for Occupational Safety and Health (NIOSH)'s Safety Research Coal Mine (SRCM). The main objective of this study is to compare the MFIRE-simulated CO concentrations to the test results for the fires of two typical mine combustibles and evaluate MFIRE's accuracy to predict the CO spread in underground mine fires.

Fire tests at the SRCM

Figure 1 shows a plan view of the SRCM, which is a full-scale underground mine used to support mine health and safety research and located at NIOSH's Bruceton campus near Pittsburgh. The SRCM is a room-and-pillar mine approximately the size of a working section, with one main intake entry and one main return entry. A Joy Axivane Series fan installed at the surface above the return shaft exhausts air from the mine. Stoppings and brattices are used in the mine to direct the airflow to where it is needed. The quantity of airflow getting into the mine is controlled by the main fan and a door at the main return entry.

Full-scale diesel fuel and belt fire tests were conducted in the mine to evaluate the contaminant spread model in MFIRE. The fire sources were placed at the main intake entry 10 m in-by the portal. A digital load cell was placed under a metal tray containing the burning material to measure the mass loss rate in all the tests. The measured mass loss rates were used to calculate the fire intensity in terms of HRR for all the tests. Eight monitoring stations throughout the mine (as shown in Figure 1) were equipped with various sensors. Airflow velocity, CO, CO_2, and other parameters were monitored and measured at each station throughout the fire tests. The CO sensors used in the tests are diffusion-type electrochemical sensors. Each CO sensor was calibrated before each test.

In the diesel fuel fire test, 7.6 L (2 gal) of No. 2 diesel fuel in a 0.8 m by 1.1 m (32 in by 44 in) pan was ignited using an acetylene burner. In the conveyor belt test, the belt was cut into 48 pieces sized 7.6 cm × 7.6 cm (3 in × 3 in) which were placed on a metal plate with eight electrical strip heaters in between, as shown in Figure 2. During the test, the electrical heaters were first turned on. The belt was heated and underwent smoking, and eventually flaming. For the diesel fuel fire test, the fire was allowed to burn until the fire was self-extinguished. For the belt fire test, the fire was manually extinguished using water after the burning was observed to be declining continuously.

Fire simulations using MFIRE

Construction of mine ventilation network model

A calibrated and well-tuned mine ventilation network model is the first critical element for MFIRE to achieve acceptable mine fire simulation results. To predict mine ventilation network airflow distribution with great accuracy, a thorough and comprehensive ventilation survey was conducted to obtain the frictional pressure drop and the corresponding airflow rate for each of the main branches of the ventilation network.

In general, there are two practical methods to measure the pressure drop along a branch in a mine ventilation survey, namely, the gauge and tube method and the barometric method. The gauge and tube method connects the two measuring stations along a branch using a length of pressure tubing and measures the pressure drop between the two measuring points with two pitot tubes directly connected to a manometer, while the barometric method measures the absolute pressure using barometers (altimeters) at the assigned measuring locations along a branch. Each method has its advantages and is accurate under certain circumstances.[9]

Although a barometric survey can be accomplished by a single person but a gauge and tube survey requires at least two people, the gauge and tube method was selected to measure the pressure drops in this study due to its higher accuracy. In the SRCM, 21 airflow measuring stations were established to take the measurements of airflow velocities, temperatures, and relative humidity, and 13 pressure measuring stations were established for the pressure differential measurements using the gauge and tube method in order to more accurately calculate and evaluate the resistances of the airways. Using the basic mine ventilation information, the calculated resistances of entries through the pressure–airflow survey, and the performance curve of the SRCM main fan, the SRCM ventilation network model was developed and tuned. Comparison of the MFIRE ventilation model result against the measured airflow rate at each airflow measuring location shows that a very good agreement was achieved after calibrating and tuning the SRCM ventilation model.

Determination of the HRRs and the fire parameters

One of the most important input variables to a mine fire simulation program is the fire intensity in terms of HRR. It can be used to estimate the size and growth rate of a mine fire event. It can also be used to assess the effectiveness of the fire suppression system in the firefighting efforts and the available egress time for fire evacuation. However, it is impractical to measure the HRR of the fire directly in this study. Instead, the HRR, q, was calculated using the measured fuel mass loss rate, m, and the heat of combustion, H_c, of the burning materials following equation (1)

$$\dot{q} = \dot{m}H_c \quad (1)$$

The fuel mass was measured using a digital load cell every 0.4 s during each fire test. An example of the measured total mass of the burning belt with the metal plate and the strip heaters over time is shown in Figure 3. Based on this measured mass history, the belt mass loss rate throughout the belt fire test was derived and is plotted in Figure 3 as well. The scale for the fuel mass loss rate is on the right side of the figure, and some negative mass loss rates were obtained at the early stage of the test. The heat of combustion for the tested belt and diesel fuel was determined from the proximate analysis and ultimate analysis of the fuels conducted in a geochemical testing lab. The heat of combustion values of the tested belt and diesel fuel are 24.6 MJ/kg and 42.3 kJ/kg, respectively. Approximately, 13.4 lb diesel and 7.1 lb belt were consumed in the fire tests.

Applying equation (1), the HRR curves were obtained for the diesel fire test (shown in Figure 4) and the belt fire test (shown in Figure 6). It should be noted that the HRR curve in Figure 6 and the mass loss rate curve in Figure 3 look different for the first 6 min because the mass loss rate data containing negative values for that period are not reliable and were removed from the HRR calculation.

The proper estimation of the HRR evolution is among the first priorities of a fire modeler.[8] To appropriately model a given fire situation, MFIRE offers five types of fire source models: (1) fixed heat input fire, (2) oxygen-rich fire, (3) fuel-rich fire, (4) t-squared fire, and (5) HRR curve fire. Details about these five fire source models can be found in the literature.

[5,8,10] The first three fire source types (fixed heat input, oxygen rich, and fuel rich) were initially defined in MFIRE 2.20.[11] Zhou and Luo[8] later added a *t*-squared fire model to the upgraded MFIRE 2.30. The HRR curve fire was added to the MFIRE recently.[5] Among the five types of fire sources, the *t*-squared fire is the most suitable to simulate the test fires at SRCM due to the combination of fewer required input parameters and relatively accurate simulation results.[8]

During the growth phase of many fires, the HRR can often be characterized by simple time-dependent polynomial or exponential functions. Extensive research and analysis show that the energy release rate varies with the second power of the time measured from an ignition reference time, t_i, as[12]

$$\dot{q} \propto \left(t - t_i\right)^2 \quad (2)$$

Typically, a mathematical representation is shown as follows

$$\dot{q} = \alpha t^2 \quad (3)$$

where $\dot{q}$ is the HRR (kW), α is a coefficient (kW/s2), and t is the time (s).

The *t*-squared fire model developed by Zhou and Luo[8] for MFIRE is shown in Figure 7.

The *t*-squared fire model consists of an increasing HRR during the fire growth period, a simplified constant HRR for the fully developed fire period (also known as the steady period), and a declining HRR for the decay period. A four-piece equation (4) is applied to represent the HRR curve for different time periods

$$\dot{q}(t) = \begin{cases} 0, & t \le t_0 \\ \dfrac{\dot{q}_{\max}(t - t_0)^2}{(t_1 - t_0)^2}, & t_0 < t \le t_1 \\ \dot{q}_{\max}, & t_1 < t \le t_2 \\ \dfrac{\dot{q}_{\max}(t - t_3)^2}{(t_2 - t_3)^2}, & t_2 < t \le t_3 \end{cases} \quad (4)$$

where $\dot{q}$ is the HRR (kW),$\dot{q}_{\max}$ is the HRR at fully developed stage (kW), t is the time, t_0 is the time of ignition delay, t_1 is the start time of the steady fire period, t_2 is the end time of the steady fire period, and t_3 is the end time of the decay period. It can be seen from equation (4) that five parameters including four time period variables (t_0, t_1, t_2, t_3) and the peak HRR $\left(\dot{q}_{\max}\right)$ need to be determined to input a *t*-squared fire in MFIRE. Based on the HRR curves (Figures 3 and 4) obtained for the diesel fuel and belt tests, the input parameters of the two fires are determined and listed in Table 1. With the specified *t*-squared fire parameters, the input curves of the diesel fire and the belt fire tests are compared with the measured HRR curves in Figures 5 and 8, respectively. This indicates that the *t*-squared fire input can represent the measured HRR values.

Estimation of CO production rate in MFIRE

MFIRE is a computer simulation program that performs normal ventilation network planning calculations and dynamic transient-state simulation of ventilation networks under a variety of conditions including the influence of natural ventilation, fans, fires, or any combination of these. It logically comprises four parts: (1) a conventional flow network calculation, where it performs the basic network balancing without considering heat or mass transfer; (2) a temperature calculation to establish the reference temperature distribution before a non-steady state (transient-state) simulation; (3) a transient-state simulation that follows changes in ventilation step by step to produce a continuous description of the temperature distribution, smoke, and contaminant spread throughout the ventilation system during a fire event; and (4) a quasi-equilibrium simulation to predict the state of the ventilation system after a relatively long period of time (defaulted to 5 h in MFIRE) as the fire reaches a quasi-steady state.[12] The CO production and spread are simulated in parts (3) and (4). The CO production rate determines the amount of CO produced by the fire and, therefore, the concentration of CO throughout the mine ventilation network.

In MFIRE, there are two approaches for quantifying the production rate of CO. One approach is to specify a constant CO production rate. The other approach is to employ a built-in production constant (β), which is the CO volume production rate per Btu of the heat released. This can be expressed as

$$F_{r(cp)} = \dot{q} \times \beta \quad (5)$$

where $F_{r(cp)}$ is the CO production rate for the combustion product of interest, expressed in ft^3/min, $\dot{q}$ is the HRR in Btu/min, and β is the production rate constant for the combustion product of interest in ft^3/Btu.

The values of β were experimentally derived by Egan[13] for a variety of mine combustibles, such as coal, transformer oil, and conveyor belts, for both flaming combustion and smoldering combustion. In the first approach, the CO production rate is a pre-calculated value using a constant HRR and CO production rate constant, and then entered as a constant to MFIRE. Throughout a certain fire simulation, the CO production rate is kept the same during the fire development. However, the second approach takes into account the effect of fire development with variable HRR. With an entered CO production rate constant (β), the CO production rate becomes a function of the HRR of the fire. If a time-dependent fire source model (such as *t*-squared fire) is employed in the simulation, the CO production rate varies with time as the HRR of a *t*-squared fire varies with time.

Results and discussion

Two fire simulations were conducted with MFIRE to simulate the diesel and the belt fire tests using the *t*-squared fire models listed in Table 1. For each fire simulation, the airflow simulation was conducted first using MFIRE's conventional mine ventilation simulation part to match the measured airflows at each station using the installed airflow sensor. The CO production rate constants for the tested diesel and belt fires were initially determined based on the recommended values by Egan[13] and then carefully adjusted according to the measured CO concentrations. The CO production rate constants used for the diesel and the belt fire simulations were 0.000045 ft^3/Btu and 0.00024 ft^3/Btu, respectively. The simulation results were output every 45 s which is consistent with the data acquisition interval of the CO sensors. After the initial processing of the measured CO concentration data, it was found that sensor stations 1, 6, and 7 produced better quality CO concentration data than the other sensor stations for both diesel and belt fire tests. These three stations were those closest to the fire sources and produced the largest readings from the CO sensors by comparison to the other stations in each test. For these reasons, only these stations were considered for this study.

Figure 9 displays the comparisons of the measured and simulated CO concentrations at sensor stations 1, 6, and 7 for the belt fire test. It can be seen from the figure that a good agreement between the measured and simulated CO concentration at each sensor station was achieved in this study. The simulated peak CO concentrations were consistent at the three stations with a value of 63 ppm. However, the measured peak CO concentrations at these three sensor stations varied from 57 to 71 ppm. MFIRE always assumes that CO thoroughly mixes with air immediately after it is produced from the fire. With this assumption, the same CO concentration is carried by air passing the sensor stations 1, 6, and 7. This can explain why nearly the same peak value occurred at these three locations in the simulation. In reality, CO is slightly lighter than air and cannot diffuse evenly into airflow immediately. The CO concentration distribution at the measuring station was not uniform, while the CO concentration was measured at a single location below the roof. In addition, the sensor response and measurements were also affected by airflow.[14] Despite the slight difference in the peak values, the simulated and measured CO concentrations at these three sensor stations agreed well.

The comparisons of the simulated and measured CO concentrations at sensor stations 1, 6, and 7 for the diesel fire test are shown in Figure 10. Similar to the case of the belt fire test, the simulated CO concentrations at these three sensor locations matched the measured values.

Conclusion

In order to evaluate the CO spread model of MFIRE, large-scale fire tests using diesel fuel and conveyor belt were conducted at NIOSH's SRCM. CO concentrations were measured during the fire tests at eight sensor stations in the mine. A ventilation network model was created and tuned using the ventilation survey results. The HRRs, calculated based on the measured mass loss rate data during the tests, were used to generate fire source input parameters for MFIRE simulations using the *t*-squared fire model. The results indicate that the *t*-squared fire model can represent the real fire scenario. The comparisons between the measured and simulated CO concentrations at different sensor stations demonstrate that MFIRE can predict CO spread in underground diesel and belt fires accurately and, therefore, may find use as an effective tool for mine fire emergency and mine rescue training.

To thoroughly validate the CO spread model of MFIRE, more research work needs to be done under various conditions in the future. The future tests include the tests with different test materials such as coal and hydraulic oil, with different ventilation conditions, and with a large range of HRRs.

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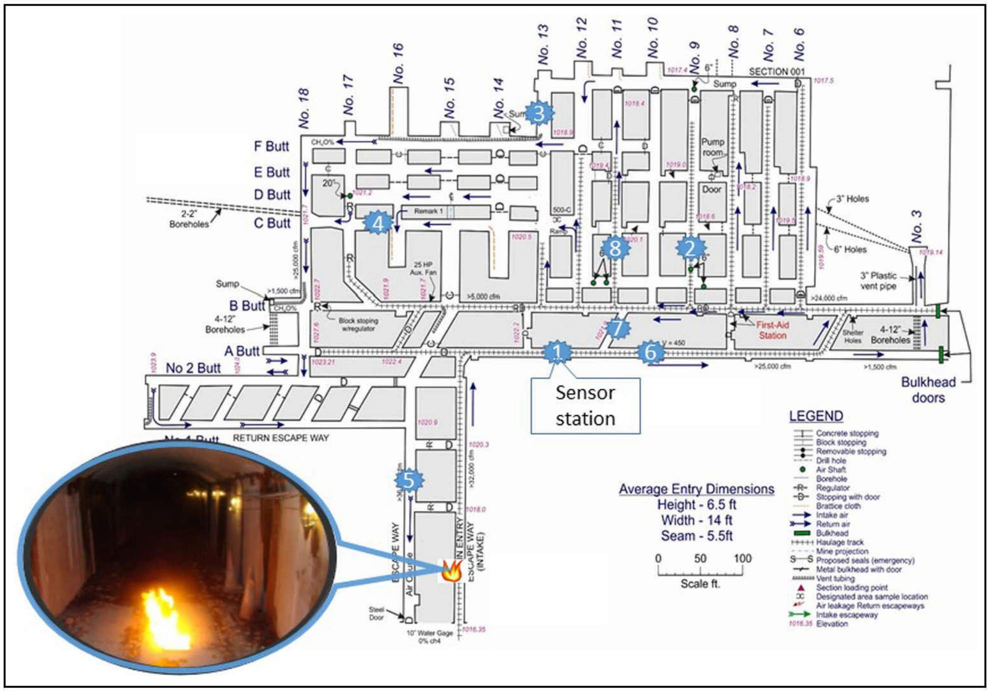

Figure 1.
SRCM mine map and the CO monitoring locations.

Figure 2.
Fire sources of the diesel and belt tests.

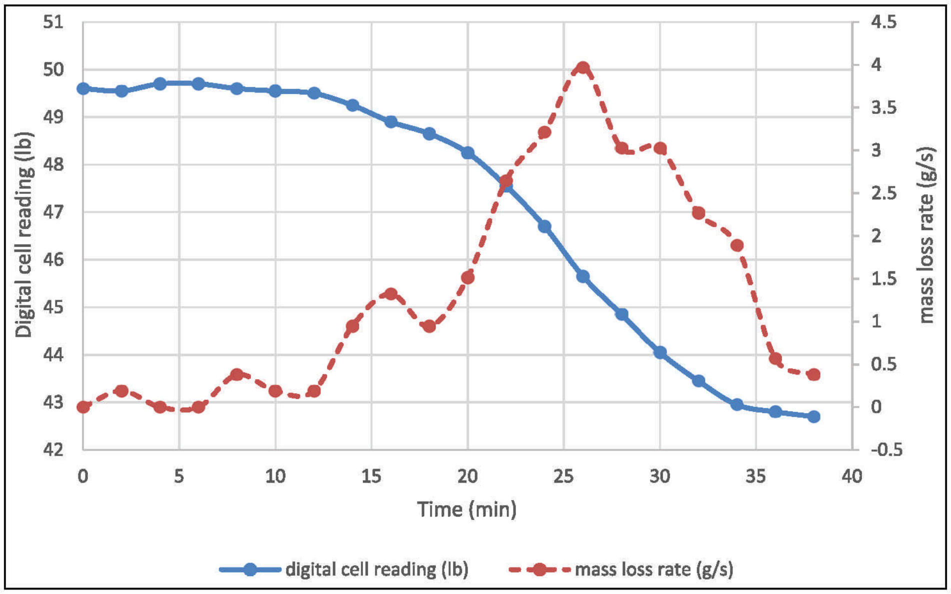

Figure 3.

The measured mass and the mass loss rate of the belt test.

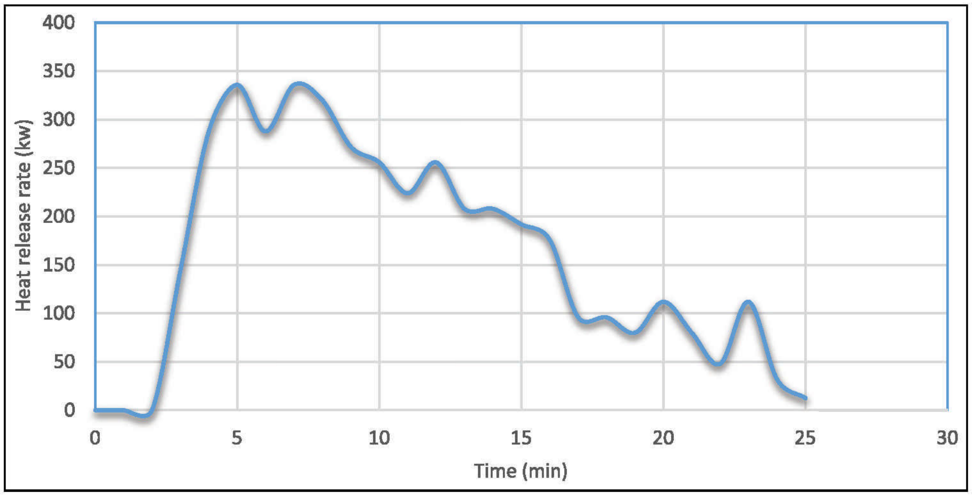

Figure 4.
Measured HRR of diesel fire test.

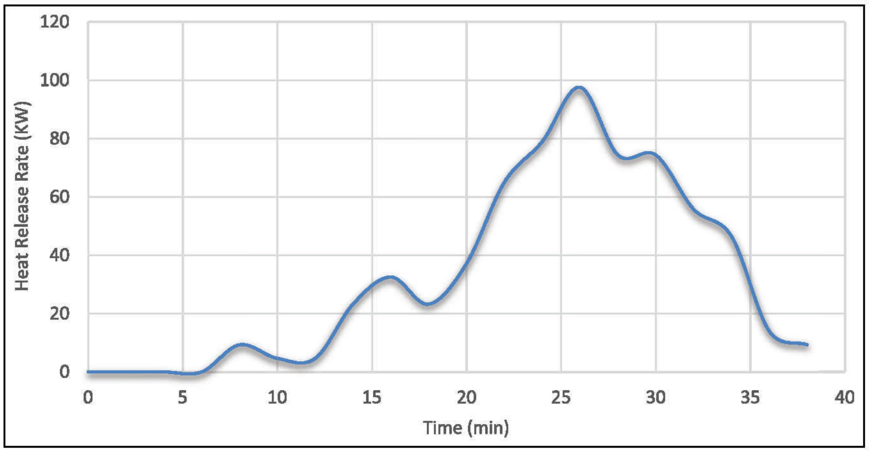

Figure 5.
Measured HRR of belt fire test.

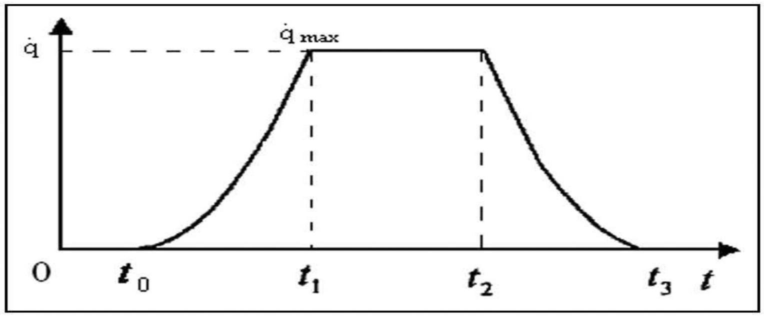

Figure 6.
Idealized *t*-squared fire curve with HRR versus time.
Source: Adapted from Zhou and Luo.[8]

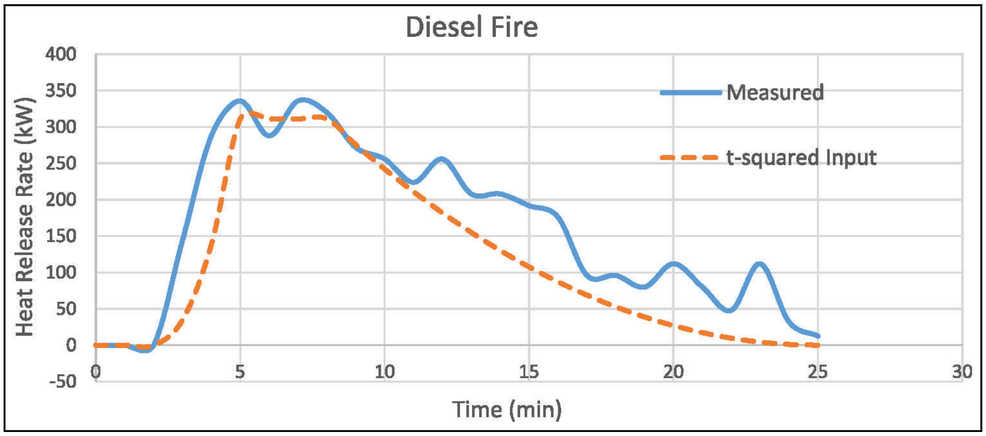

Figure 7.

The measured HRR and the *t*-squared fire input for diesel fire test.

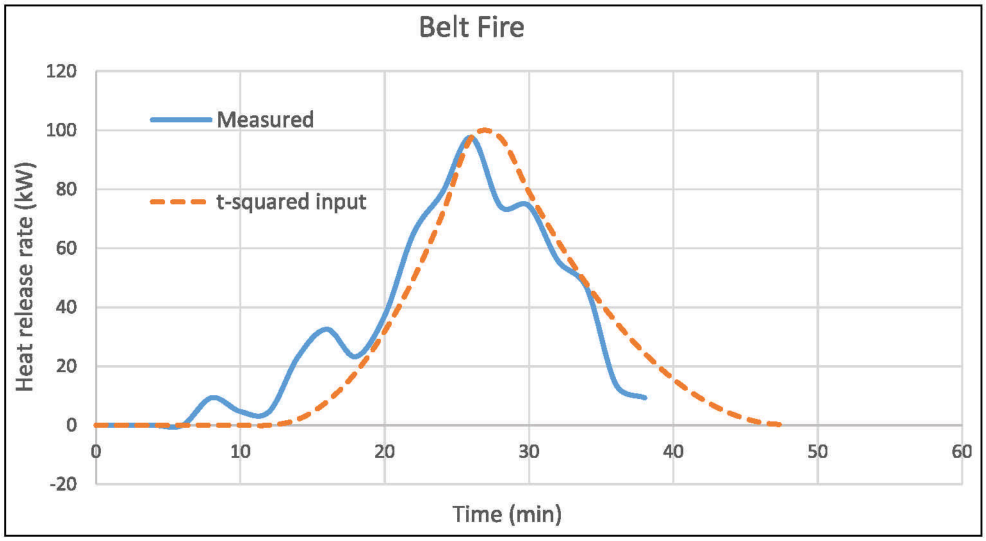

Figure 8.
The measured HRR and the *t*-squared fire input for the belt fire test.

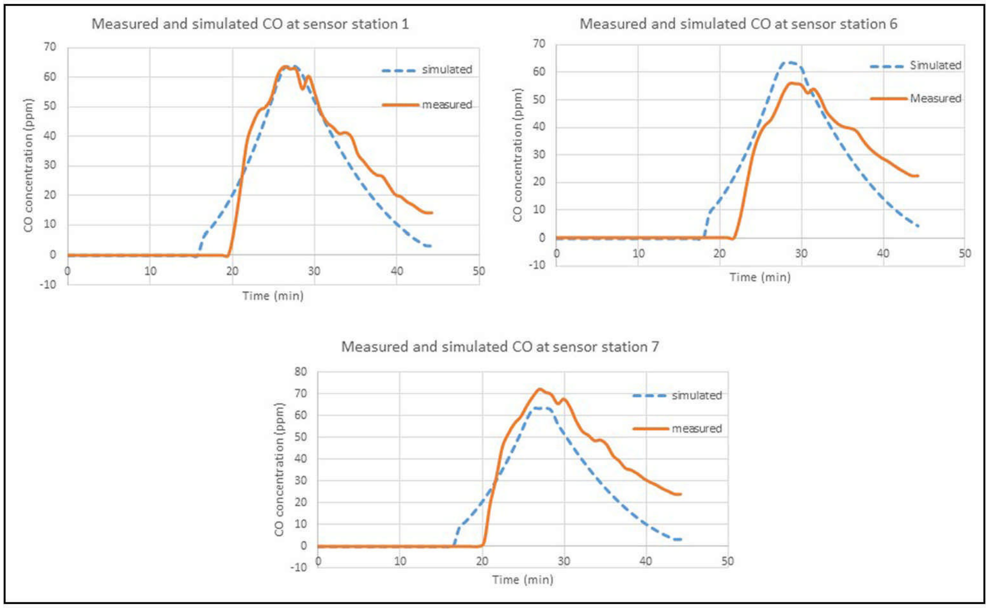

Figure 9.
Simulated and measured CO concentrations of the belt fire test.

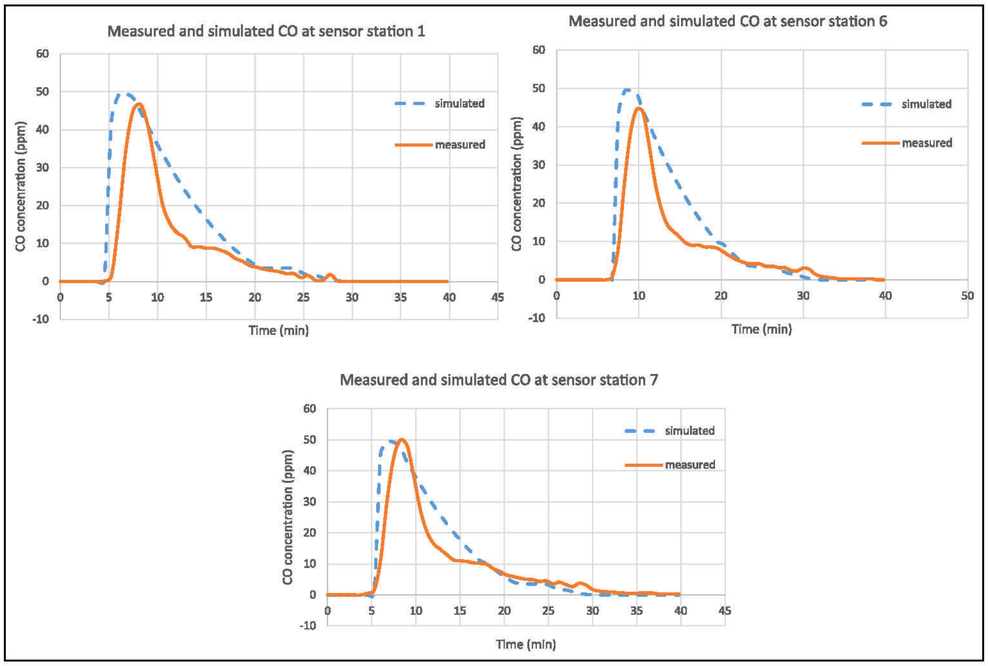

Figure 10.

Simulated and measured CO concentrations of the diesel fire test.

Table 1.

t-squared fire input of the fires.

	Diesel fire	**Belt fire**
Peak HRR, kW	311	97.5
Time of ignition delay (t_0), min	2	12
Start time of steady period (t_1), min	5	26
End time of steady period (t_2), min	8	28
End time of decay period (t_3), min	25	48

HRR: heat release rate.