CFD MODELING OF FIRE SPREAD ALONG COMBUSTIBLES IN A MINE ENTRY

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Abstract

A computational fluid dynamics (CFD) program was applied to fire spread along combustibles in a ventilated mine entry. The rate of flame spread was evaluated for the ribs and roof of a coal mine entry; timber sets; and a conveyor belt. The CFD program models char forming materials with temperature dependent thermal properties. The program solves three dimensional time dependent flow equations with a mixture fraction model for the gas phase reactions. Radiant heat exchange is evaluated for non-scattering gas. The CFD program predicted a flame spread rate of 0.0145 m / s for an actual coal mine fire in which the estimated flame spread rate was 0.0086 m / s. This overestimated flame spread rate was a possible consequence of the presence of inert materials in the mine entry's roof and ribs. CFD fire spread rate predictions of 0.043 m / s and 0.73 m / s bounded the measured value of 0.27 m / s for fire spread along Douglas Fir timber sets in a tunnel.

Introduction

Fires in a mine create a hazardous environment for mine personnel due to toxic gas and low visibility. The primary toxic gas emission is carbon monoxide (CO). Fire spread expands the emissions source. Important for controlling the spread of a fire over combustible surfaces is an understanding of how rapidly the fire will spread. Fire spread in a coal mine will depend upon the thermal and physical properties of the material, the imposed ventilation, and the entry dimensions. Coal mine solid combustibles include coal, conveyor belts, and wood supports which can undergo the complex process of char formation. These fuels, because of their physical distribution, can result in fire spread over considerable distances in a coal mine. Liquid combustibles, such as diesel fuels and transformer fluids, will generally be limited to a localized region, although their combustion products can be transported by ventilation for extensive distances. Past research [1] on fire spread has generally been limited to one dimensional ignition models which do not consider the char formation process within the solid, and the buoyancy generated flow. With high speed computational capability, it is possible to model fire spread in a mine entry with particular attention to the entry dimensions, air ventilation velocity, fuel combustion properties, and char formation process. From this capability relationships between fire spread velocity and ventilation for a particular mine entry configuration can be developed. This information can be used to develop measures to control fire spread and to project CO and smoke emissions and their transport through the mine ventilation network.

Fire Spread Model

To simulate the spread of a fire in a mine entry a fire dynamics simulator (FDS) [2] based upon computational fluid dynamics (CFD) was used. This CFD program is suitable for defining the geometry of a mine entry and the combustible fire sources, and the time dependent evolution of heat and mass from the ignited combustibles. In this simulator the Navier-Stokes equations for multi-component gas flow are solved numerically. Gas phase combustion is predicted with a mixture fraction model. Radiant heat transfer is solved with a radiative heat transport equation for an emitting and absorbing, but non-scattering, gray gas. A radiation band model for methane, its combustion products, and soot is used to model the blackbody radiation absorption coeffcients. In practice, the radiation intensity integrated over a wavelength band is solved. Over the wavelength of 1-200 μm, the number of bands is from 6 to 10. Turbulence is simulated in the flow with a large eddy simulation (LES) method. One advantage of the LES method over the standard κ- ε is the instantaneous characterization of the turbulent flow eddys. The κ- ε model represents a time average of the fluid dynamics equations, and loses the irregular characteristics of the gas phase flame. Another advantage is the greater spatial and temporal accuracy of the LES method. The κ- ε model requires the specification of algebraic wall functions, which are not required with the LES method.

Most mine combustibles undergo combustion by a gas phase reaction of the volatiles generated by the pyrolysis of the material. The pyrolysis front advances as a reaction front into the solid fuel leaving behind a char layer. Version 4 of the FDS includes a pyrolysis model in the CFD model for the fire simulation. This option is employed in the present study. The significant parameters for this process are the thermal conductivity, specific heat, and density of both the unreacted coal and the char. The thermal conductivity and specific heat will be temperature dependent quantities. The surface materials of the tunnel are assumed thermally thick. In the code, the material temperature is computed through a one-dimensional heat conduction equation. For the release of volatiles, the heat of pyrolysis, or vaporization, H_p must be specified. The mass burning rate, which defines the release rate of volatiles, is approximated by an Arrhenius rate equation in the FDS. The maximum burning rate is associated with a specified pyrolysis temperature. Combustion of the volatiles with the oxygen is defined by the stoichiometric fuel – oxygen mass balance. The heat of combustion provides the energy for preheating of the solid external surface through radiative and convective heat transfer. Heat transfer internal to the fuel is controlled by the temperature dependent thermal diffusivity of the solid. For all tunnels, a uniform velocity is assigned at the inlet and atmospheric pressure is assigned at the exit. At the tunnel walls, the gas velocity has slip as given by the CFD code. This implies that no wall function is used near a wall to accommodate the no-slip boundary condition.

Convective and radiative heat transport to the fuel surface downwind from an initiating heat source will increase the fuel surface temperature to the pyrolysis temperature. In the CFD application the initiating heat source can be a localized high temperature surface, or an input surface energy flux per unit time. Since the flame spread is associated with the emission of pyrolysis gases, the leading edge of the fuel surface, which is at the pyrolysis temperature, is used to define the flame front. Temporal movement of the pyrolysis temperature along the fuel surface defines the flame propagation.

Coal Fire Spread

A fire spread CFD model application with the FDS was made to the 1990 fire at Mathies Coal mine [3]. In appendix K of the MSHA investigation report [3] it is stated that the fire spread a distance of about 900 ft in about 9 hours. The corresponding average flame spread rate is about 1.7 fpm (0.0086 m/s). The entry for the simulation was 7 ft high and 14 ft wide. The ribs and roof were coal, and the floor was assigned the value for an inert material. The ventilation air reported for the entry was 6000-8000 cfm. For the simulation purposes a ventilation of 7000 cfm was assigned, which is a linear air velocity of 71.4 fpm (0.363 m / s). The FDS was used to model the fire spread along the mine entry roof and ribs, which were a continuous coal surface. Temperature dependent specific heat and thermal conductivity of coal and coke values reported by Merrick [4,5] were used. The mass density of coal, 1,330 kg / m^3, and coke, 850 kg / m^3, were reported by Lee et al [6]. The heat of combustion for the coal was 31,300 kJ / kg based upon a bituminous coal [7]. The stoichiometric coal - oxygen reaction was represented in the gas phase by

$$CH_{0.74}O_{0.08} + 1.145O_2 \rightarrow CO_2 + 0.37H_2O + \nu_{CO}CO + \nu_{soot}SOOT \quad (1)$$

The stoichiometric coefficients, ν, for CO and SOOT are related to the carbon available in the fuel. The pyrolysis front advances with an endothermic heat of reaction. There is considerable variation in the literature values for the heat of pyrolysis, H_p. Values from Mahajan et al [8] indicate a value of 209 kJ / kg, and value reported by Hertzberg et al [9] indicates a value of 1,300 kJ / kg. To investigate the sensitivity of the simulation to the heat of pyrolysis, both cases were evaluated. For the simulations conducted the thermally inert floor was assigned the FDS library values for fire brick. Initiation of the fire occured by some event for which the details are not known. The MSHA report [3] concluded that the most likely fire source was that a roof fall caused energized trolley wire to make contact with steel rails, creating a high resistance electrical arc, which ignited the fallen coal. For the purpose of the simulation, two virtual heater elements 5 m long, 20 cm wide, and 60 cm high, were suspended near the entrance, and maintained at 1,600 °C for 2,000 s. These radiant heaters supplied thermal energy to the coal surfaces to initiate the fire development. The pyrolysis temperature of the coal was 525 °C, based upon [9]. When the surface temperature of the coal reached the pyrolysis temperature, the flame front was considered to have reached that location. For the simulation the entry length was limited to 151 m, which is approximately 53 hydraulic diameters. The coal was assumed to be moisture free. Typical inherent moisture content for Pittsburgh Seam coal is less than 5 pct. Figure 1 shows the centerline roof temperature at selected locations downwind from the entrance for a 209 kJ / kg heat of pyrolysis. The intersection of the temperature curves with the 525 °C isotherm defines the flame movement.

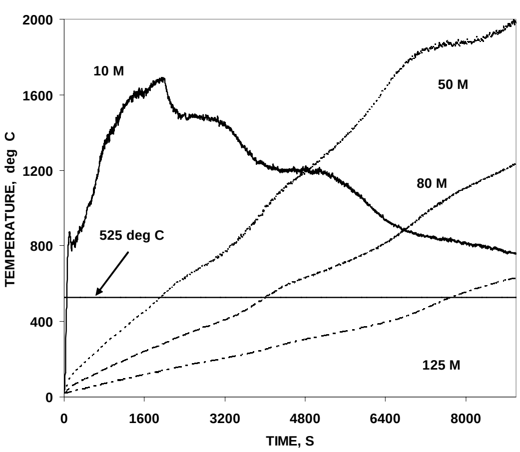

Figure 1. Centerline roof coal temperature

Figure 2 shows the nearly linear increase in flame position, as defined by the pyrolysis temperature, with time. Also shown in figure 2 is the nearly linear increase of flame position with time for the 1,300 kJ / kg heat of pyrolysis. Both sets of data are well represented by the nearly linear flame spread increase with time, as defined by the pyrolysis temperature at the centerline of the roof, of 0.0145 m/s, which is to be compared with the 0.0086 m / s observation determined from [3]. Presence of moisture in the coal, with its 2,470 kJ / kg heat of vaporization, would retard the propagation of the pyrolysis temperature along the coal surface. This effect was demonstrated for the heat of pyrolysis equal to 1,300 kJ/kg and three different moisture contents of the coal. For 0 and 5 pct mass fraction of moisture content in the coal the fire propagation displacements along the tunnel were relatively close as shown in figure 3. At an increased moisture content of 10 pct the fire propagation ceased at about 2,830 s, as shown in figure 3.

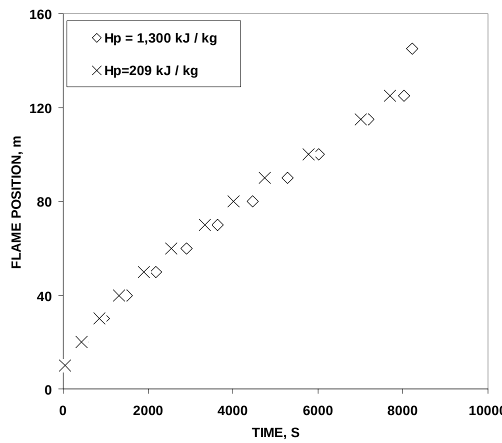

Figure 2. Effect of heat of pyrolysis on flame propagation

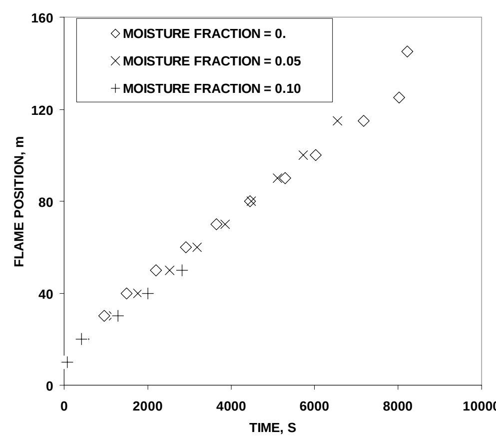

Figure 3. Effect of moisture content on flame spread

The predicted flame spread rate with the CFD application of 0.0145 m/s was higher than the estimated average flame spread rate of 0.0086 m/s for the Mathies mine fire. This can be accounted for by the presence of inert materials in the mine rib and roof. Inert materials such as shale would affect the expected emissions of pyrolysis gases and the heat release from the propagating fire, and the thermal properties of the fuel.

The effect of ventilation on flame spread rate is important for understanding mine fire control. For a moisture fraction of 0.05 and a heat of pyrolysis, H_p, of 1,300 kJ / kg, simulations were made for air flows of 0.363 m /s, 0.454 m / s, and 0.544 m / s. Figure 4 shows a a comparison of the flame spread with time for these three air flows. The flame spread rates are nearly linear. The flame spread rates based upon a linear interpolation of the data in figure 4 are summarized in Table 1.

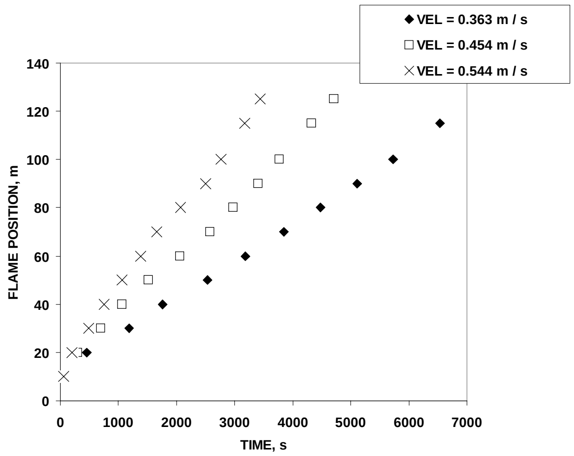

Figure 4. Effect of ventilation velocity upon flame spread

Table 1. Flame spread vs air flow

Air flow, m / s	Flame spread rate, m / s
0.363	0.0156
0.454	0.0235
0.544	0.0320

For the range of air flows considered, a linear fit between flame spread rate V_f and air flow V_a is established with an R square value, coefficient of correlation, equal to unity.

$$V_f = 0.0904V_a - 0.0173 \quad (2)$$

A linear dependence of flame spread upon ventilation was reported by Roberts and Blackwell [10] for wood lined ducts 0.3 m by 0.3 m square cross section. The constant term in the flame spread rate relationship is a consequence of the nonlinear effects such as radiant heat transfer. When the flame had advanced to the 115 m position along the entry, the fire heat release rates were 16 MW, 19 MW, and 22 MW for the three air flows. For air flows less than 0.326 m / s, continuous flame propagation could not be established for the same source fire intensity and duration. The flame ceased propagation about 1,500 s after the source fire was extinguished for a ventilation velocity of 0.326 m / s, with propagation not extending to the 70 m station.

The dominant mode of heat transfer to the coal surface was radiant energy. The radiant energy transfer dominated the convective heat transfer. For example, at the 50 m and 100 m locations along the tunnel roof, the ratio of the radiant heating to convective heating was approximately one order of magnitude when the flame front reached these locations.

Fire Characteristic

Roberts and Blakwell[10] analyzed the propensity of a fire in a fuel lined roadway to transition from an oxygen rich mode into a fuel-rich mode. The characteristic parameter R for the transition was defined by

$$R = KAB/(\rho Q) \quad (3)$$

Where A = fuel burning area
B = fuel surface burning rate
K = air / fuel ratio from stoichiometric equation
ρ = air density (1.2 kg / m^3)
Q = volumetric air flow

Roberts [10] showed that if R exceeded a critical value of approximately 0.4, the fire is expected to transition from an oxygen rich state to a fuel rich state. An evaluation was made of R to compare the value at the termination of the heat source for a ventilation velocity of 0.363 m/s in a coal lined fire tunnel for the two values of heat of pyrolysis. For a coal fire the value of K was 11.27. The coal was moisture free. The CFD predictions for burning rate along the ribs and roof of the entry were used to evaluate the terms A and B in equation 3. A heat of pyrolysis of 209 kJ / kg resulted at 1,000 s in a R value 2.56, and at 5,000 s in a R value 3.49. After the external heat source was turned off at 2,000 s the fire continued to be fuel rich. At an increased heat of pyrolysis of 1,300 kJ / kg the R values at 1,000 s and 5,000 s were 2.39 and 2.96 respectively. The continued propagation of the fire for these cases was associated with a fire intensity which was about 16 MW for each fire.

Timber Set Fire Spread

Another combustible source in a mine is timber sets, which are used for roof supports. Warner [11] investigated the effect of timber set spacing on fire propagation in a ventilated timbered roadway. Fire spread experiments were conducted in a 53 m long tunnel with a cross section 4.57 m wide and 1.83 m high. Each timber set consisted of an overhead element at the roof supported by a leg element on each rib. The linear air flow was 1.78 m/s. A kerosene ignition fire source near the entrance had an effective heat release rate of 3,194 kW/ sq m, with a total heat release rate of 12 MW. Mineral wool was used as a thermal insulation on the tunnel sides and roof to protect the tunnel exposed surfaces. Fire brick, with a thermal diffusivity about three times that of rock wool, provided thermal insulation to the tunnel floor. An application was made with the FDS to the results reported in [11] for the evaluation of fire spread along Douglas Fir timber sets in a ventilated entry. Thirteen Douglas fir timber sets, each 0.30 m by 0.30 m square, were formed by two vertical sections along the tunnel wall, with a cross beam along the roof connected to the vertical beams. The separation distance between the timber sets was 2.34 m. The moisture content of the wood was 18 pct. Thermal and physical properties for Douglas Fir wood and char reported by Parker [12], and Hostikka and McGrattan [13], were used in the simulation. The heat of vaporization of 1,820 kJ / kg is specified in [14] for Douglas Fir. Figure 5 shows a comparison of the CFD predicted and measured flame spread rate. The flame spread in [11] was defined by the temperature immediately behind the roof timber and approximately 2 cm below the beam reaching 538 °C. The measured flame propagation in figure 5 is nearly linear with time with an approximate rate of 0.27 m / s. The CFD prediction can be broken into two approximately linear segments with time. For the initial 1.1 minutes the flame propagation rate is approximately 0.73 m / s, followed by an 0.043 m / s propagation rate for an additional 3.4 minutes propagation to the end of the tunnel. Figure 6 shows a comparison of the measured gas temperature with the CFD predicted gas temperature at the ninth timber set, approximately 18.6 m downwind from the first timber set. The agreement between the CFD prediction and measured gas temperature is very good during the temperature increase and decrease. The maximum temperature is overestimated with the CFD program.

Conveyor Belt Fire Spread

CFD simulations were made for fire spread along a conveyor belt in a fire tunnel for which experimental data are available [15]. The dimensions of the tunnel are 28 m x 3.6 m x 2.4 m with the conveyor belt suspended horizontally 1.2 m above the floor as shown in Figure 7. The conveyor belt is 1.5 m wide by 10 m long.

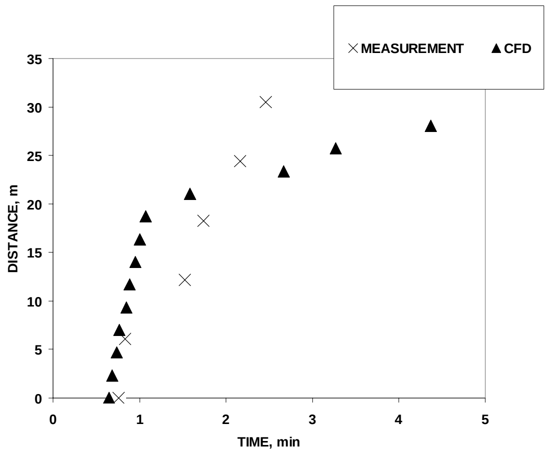

Figure 5. Comparison of CFD predicted flame spread with measured values for Douglas fir timber sets

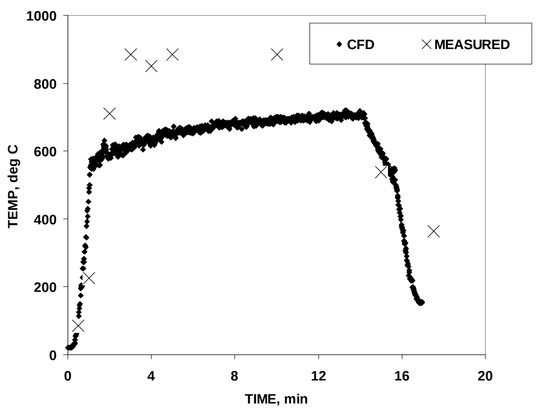

Figure 6. Comparison of CFD predicted gas temperature with measured values at Douglas fir timber set

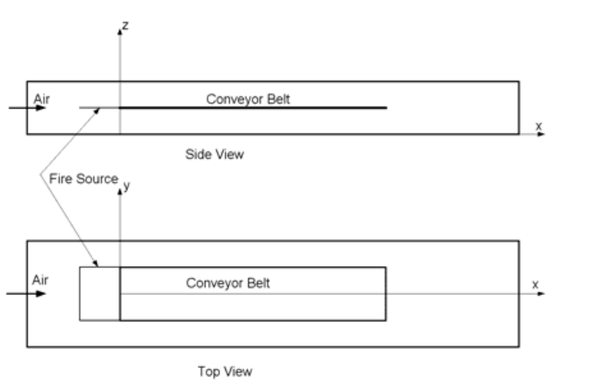

Figure 7. Schematics of a tunnel (not to scale) for conveyor-belt fire spread.

Typical time-temperature traces obtained from the thermocouples along the centerline of the sample are shown in Figure 8. The flame is assumed to spread to the front where the material surface temperature reaches the ignition temperature. The air speed was 4. m / s. Sample plots of the flame front, X_{ig}, with different source-fire intensities from 500 to 1,000 kW / m^2 are shown in Figure 9.

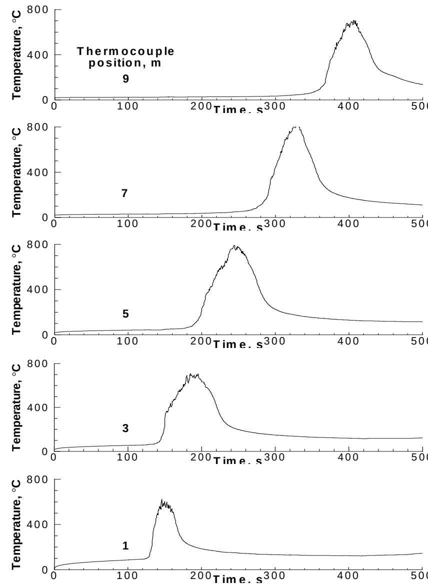

Figure 8. Time-temperature traces of fuel surfaces thermocouples at distances from 2 m to 10 m

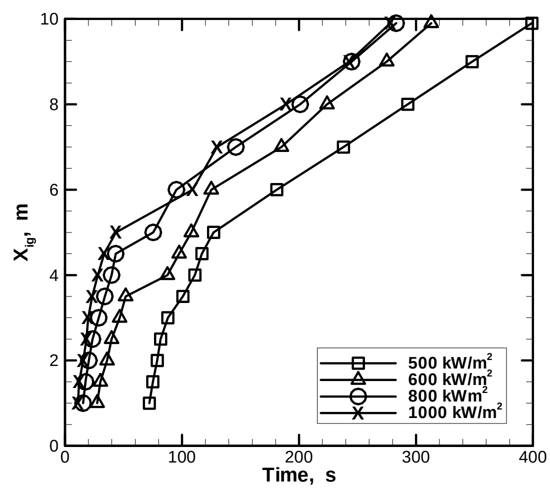

Figure 9. Flame front versus time for different source-fire strength.

The source fire area was 0.75 m^2, and the air speed was 4 m / s. For this case, the flame-spread rates are insensitive to the source-fire intensity. Figure 10 shows the flame-spread rate as a function of the air speed entering the tunnel. Although the CFD results show a much stronger effect of the air speed on the flame-spread rate than the experimental results, the agreement with experimental values of Lazzara and Perzak [15] is good for air speeds between 0.8 and 1.8 m/s. The experimental results of Green et al [16] are also shown in the figure, for which the CFD predictions are less favorable.

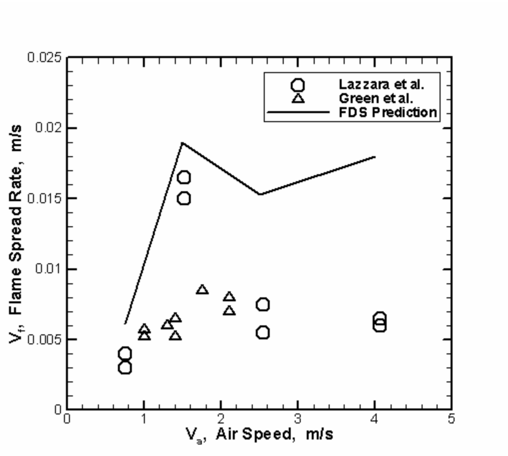

Figure 10. Flame-spread rate as a function of the air speed at the tunnel inlet

Conclusions

1. Fire propagation along a fuel surface which undergoes pyrolysis with char formation can be accounted for with a CFD model which predicts the spatial advance of the pyrolysis temperature along the fuel surface.

2. The observation that a coal mine fire propagated with an average spread rate of 1.7 fpm (0.0086 m / s) was simulated with the CFD program to yield a flame propagation rate of 2.9 fpm (0.0145 m / s). Based upon the sparse information with regard to the unobserved mine fire, the result is reasonable. The presence of inert materials in the mine roof and ribs, which were coal for the model computations, would moderate the effective flame spread rate.

3. CFD analysis showed the coal lined tunnel flame spread rate was relatively insensitive to the heat of pyrolysis, but strongly sensitive to the coal moisture content and the ventilation. A linear dependence of flame spread rate upon imposed ventilation was predicted with the CFD computations for a moisture fraction of 0.05.

4. CFD prediction of flame spread in a tunnel lined with Douglas Fir timber sets initially overestimated the measured fire propagation rate, and subsequently underestimated the measured flame propagation rate. The measured fire propagation rate was 0.27 m / s. The CFD fire spread rate prediction was 0.73 m / s for an initial linear fire spread rate, which was followed by a 0.043 m / s fire spread rate.

5. CFD prediction of the dependence of flame spread along a conveyor belt upon air speed showed good agreement with measurements of Lazzara and Perzak [15] for air speeds less than 2 m/s.

CFD modeling provides an important tool to facilitate the dependence of fire spread upon the material properties, inlet air flow, and entry dimensions for applications to fires in mines. The extent of the fire spread can be used to project the smoke and CO emissions, and their transport through the mine network. Additional CFD investigations need to be undertaken to determine the effect of flame spread upon ventilation. With this capability, an analytic method can be provided for mine fire emergency planning.

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