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Numerical modeling of water spray suppression of conveyor belt fires in a large-scale tunnel

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ABSTRACT

Conveyor belt fires in an underground mine pose a serious life threat to miners. Water sprinkler systems are usually used to extinguish underground conveyor belt fires, but because of the complex interaction between conveyor belt fires and mine ventilation airflow, more effective engineering designs are needed for the installation of water sprinkler systems. A computational fluid dynamics (CFD) model was developed to simulate the interaction between the ventilation airflow, the belt flame spread, and the water spray system in a mine entry. The CFD model was calibrated using test results from a large-scale conveyor belt fire suppression experiment. Simulations were conducted using the calibrated CFD model to investigate the effects of sprinkler location, water flow rate, and sprinkler activation temperature on the suppression of conveyor belt fires. The sprinkler location and the activation temperature were found to have a major effect on the suppression of the belt fire, while the water flow rate had a minor effect.

1. Introduction

A conveyor belt fire in an underground mine can lead to a catastrophic situation. For example, on January 19, 2006, an underground mine conveyor belt fire occurred at the Aracoma Alma No. 1 mine, located in Logan County, West Virginia. Two miners were fatally injured when they became separated from their crew while trying to escape from the fire.

Some mines use belt air to provide additional air quantity to working sections that would otherwise not be possible without such a system. If a mine uses belt air at the mining face and the belt catches fire, the toxic gases and smoke produced from the burning of the belt are carried to the face, exposing miners to potentially hazardous levels of toxic gases such as CO, HCl, SO_2, H_2S, and NO_x. Also, the smoke produced from the burning belt limits visibility for the miners, making it much more difficult to escape from the mine. Therefore, it is important to suppress and control the belt fire in a timely manner in order to prevent the fire from causing any harm to the miners and ensure they can evacuate safely from the mine.

The U.S. Code of Federal Regulations (30 CFR 75.1101-7, and 8) requires a fire suppression system in underground coal mines to protect the conveyor belt entry and the first 50 ft of belting from the drive. These regulations were promulgated prior to the permitted use of belt air at the face. When water sprinkler systems are used, the suppression process of a belt fire is complicated by the interaction between the airflow, the flame spread over the belt, and the water spray in the entry. Some large-scale experiments were conducted by NIOSH to evaluate the effects of air velocity, water sprinkler activation temperature, and a limited water application time on the effectiveness of water sprinkler fire suppression systems to extinguish conveyor belt fires (Rowland et al., 2011; Teacoach et al., 2011).

Several novel fire suppression systems such as fire-fighting foam, fire gel, and water mist systems have been evaluated

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for the suppression of conveyor belt fires in underground coal mines (Teacoach and Thomas, 2013). To develop a more effective fire protection system for the conveyor belt entry in an underground mine, more systematic engineering data are needed. These data should include the effects of sprinkler location, water flow rate, sprinkler activation temperature, water droplet size, water droplet velocity, spray angles etc. Although full-scale experiments can be conducted to obtain engineering data to develop guidelines for performance-based designs for the installation of mine fire suppression systems, these tests are both expensive and time-consuming. Computational Fluid Dynamic (CFD) modeling is well adapted to this situation and can provide insights into the complicated interaction between the conveyor belt fires and the mine ventilation airflow. These interactions have a direct impact on the performance of the fire suppression systems. Such modeling can be completed in a short time and at comparatively low cost and can be used in conjunction with full-scale experiments to develop more effective engineering designs for installation of mine fire suppression systems.

CFD is the application of numerical techniques to solve the Navier–Stokes equations for fluid flow. CFD modeling has been widely used in simulating the interaction between water spray or mist and a fire. Novozhilov et al. (1997, 1999) simulated the extinguishment of a wood fire with a water spray. They developed a relatively comprehensive model, combining the water spray model with a fire extinction model. Prasad et al. (1999, 2002) simulated water mist suppression of small-scale methanol liquid pool fires and large-scale compartment fires. Parametric studies were performed to optimize various water mist injection characteristics for maximum suppression. Hua et al. (2002) conducted a CFD study on the interaction of water spray with a fire plume. The effects of several important factors such as spray pattern, water droplet size, and water spray flow rate on the fire suppression mechanism were investigated. Their simulation results indicate that CFD modeling has the capability to reasonably capture the interactions between the water spray and the fire plume, taking in account the effects of momentum exchange, heat and mass transfer, as well as chemical reactions. Yao and Chow (2005) developed a thermal model to study the extinguishment of a polymethyl methacrylate (PMMA) fire by water spray. The effects of droplet size and velocity, external radiant heat flux, and specimen configuration on fire suppression were investigated. Yoon et al. (2007) conducted a computational study of the effect of water spray characteristics on the suppression of a large-scale (2 m × 2 m) pool fire in a 10 m × 10 m × 10 m compartment. Nmira et al. (2009) investigated the efficiency of water mist systems in mitigating thermoplastic fires in a tunnel numerically. A parametric study was carried out to study the effects of ventilation rate, nozzle location, injection mass flow rate, and droplet size on the performance of water mist systems. Trelles and Mawhinney (2010) used the National Institute of Standards and Technology (NIST) Fire Dynamics Simulator (FDS) program to investigate a large-scale pallet stack fire in tunnels protected by water mist systems. An algorithm was developed to allow the fire to spread along the top of a series of pallet loads and the measured heat release rate (HRR) was reproduced. Blanchard et al. (2013) conducted experimental and numerical studies of the interaction between water mist and fire in an intermediate test tunnel. An extensive numerical study using FDS was conducted to quantify each mechanism involved in interaction between water mist and hot gases. Finally, Jenft et al. (2014) conducted numerical simulations with FDS to study the suppression of a pool fire using water mist.

Although much research has been done to model fire suppression using water spray or water mist, limited research has been conducted specifically to simulate the suppression of conveyor belt fires using water spray. The purpose of this study is to simulate the water spray suppression of conveyor belt fires in a large-scale tunnel with ventilation. The flame spread over the conveyor belt was modeled to reflect the real development of the belt fire. The CFD model was calibrated using large-scale experimental results. The calibrated model was used to investigate the effects of sprinkler location, water flow rate, and sprinkler activation temperature on the suppression process. The simulation results can be used to design more effective fire protection systems for the conveyor belts used in underground coal mines.

2. Modeling of water spray suppression

To simulate the water spray suppression of conveyor belt fires, the flame spread over the conveyor belt needs to be modeled first. In a previous study (Yuan et al., 2014), the flame spread over the conveyor belt in a large-scale tunnel was simulated using FDS. Thermogravimetric analysis (TGA) data for the conveyor belt was used to determine the kinetic properties for modeling the pyrolysis process of the conveyor belt burning. The CFD model was calibrated using large-scale conveyor belt fire test results. The comparison between simulation and test results showed that the CFD model was able to capture the major features of the flame spread over the conveyor belt.

In the current study, FDS is again used to simulate the water suppression of conveyor belt fires. FDS has previously been used to simulate the performance of water spray and mist fire suppression systems successfully (Vaari et al., 2012; Sikanen et al., 2014). To simulate water spray suppression of belt fires, some spray characteristics need to be specified as input for the simulations. Those characteristics include sprinkler activation temperature, sprinkler response time index (RTI), water flow rate, droplet diameter, droplet initial velocity, and spray angles. The sprinkler activation temperature and RTI value were obtained from the sprinkler manufacturer. The water flow rate was calculated based on the K-factor value of the sprinkler and the operating pressure used in the test using the equation:

$$\dot{m} = K\sqrt{P} \tag{1}$$

where $\dot{m}$ is the water flow rate in liter/min (Lpm), K is the K-factor for the sprinkler in Lpm/bar$^{0.5}$, and P is the operating pressure in bar. A water spray usually consists of spherical droplets with various sizes. The size distribution of water droplets can be expressed in terms of its Cumulative Volume Fraction (CVF), a function that relates the fraction of the liquid volume transported by droplets less than a given diameter. The CVF for a sprinkler may be represented by a combination of log-normal and Rosin–Rammler distributions (McGrattan et al., 2010):

$$F(d) = \begin{cases} \dfrac{1}{\sqrt{2\pi}} \displaystyle\int_0^d \dfrac{1}{\sigma d'} e^{-\dfrac{[\ln(d'/d_m)]^2}{2\sigma^2}} dd' & (d \le d_m) \\ 1 - e^{-0.693\left(\dfrac{d}{d_m}\right)^{\gamma}} & d > d_m \end{cases} \tag{2}$$