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Water spray suppression of leaked oil fires: A numerical study

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ABSTRACT: Equipment fires caused by hot surface ignition of leaked oil in mines can be a serious safety concern to miners and mining operations. A water spray fire extinguishing system is an effective and economical means of fire extinguishment in the suppression of flammable liquid pool and spray fires. This paper investigated numerically the effectiveness of water spray systems on suppressing leaked oil fires. The parameters studied include ventilation air velocity, spray droplet size, and spray flow rate. Results from the study indicate that ventilation can be an effective side measure to reduce the fire temperature, with the optimal sprinkler droplet size at around 300 or 400 μm for the size of fire studied. Water flow rate also has a significant effect on fire suppression. The results can be used to design effective suppression techniques for mine equipment fire

1 INTRODUCTION

Mine equipment fires remain one of the biggest threats to miner health and safety in metal/nonmetal mines. From 2009 to 2018, 177 fires and 43 fire-related injuries were reported for metal/nonmetal mines in the United States, including both underground and surface mines. Out of those 177 fires, 54% involved mine equipment [MSHA 2018]. Fire suppression techniques, including fire sprinkler and spray in a mine environment need to accommodate the uniqueness of mine fires. Hansen and Ingason [2013] conducted full-scale fire experiments using a wheel loader and a drilling rig in an underground mine. Heat release rates for two mining vehicle fires were calculated based on measured data of gas concentrations of oxygen, carbon monoxide (CO) and carbon dioxide (CO_2), measured gas velocity and temperatures. The calculated peak heat release rate of the loader fire was 15.9 MW, occurring approximately 11 min after ignition, and the rate was 29.4 MW for the drilling rig fire, occurring approximately 21 min after ignition.

Li and Ingason [2018] investigated the effect of a fire suppression system on the production of key combustion products, including CO and soot, through a series of scaled-model tunnel fire tests. The results show that the fire suppression system type has an influence on the production of combustion products, especially for cellulose fuels. In the case that the fire is not effectively suppressed—e.g. when the water application rate is too low, or activation is too late—the CO concentration could be higher, and visibility could be worse than the free-burn test.

Computational Fluid Dynamics (CFD) has been proven to be a useful tool to investigate water-based sprinkler fire suppression behaviors. Yuan and Smith [2017] investigated the water spray characteristics in the suppression of conveyor belt fires and found that the initial spray particle velocity at 20 m/s is the most effective in reducing the belt surface temperature.

In this paper, a numerical model was developed using the Fire Dynamics Simulator (FDS), which was developed by National Institute of Standards and Technology (NIST) [McGrattan 2010], to investigate the suppression effectiveness of different spray droplet particle sizes, spray flow rates, and ventilation velocities on a heptane oil fire. Results from this work could be used to help design effective fire suppression techniques and systems for equipment fires in metal/nonmetal mines.

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2 NUMERICAL MODEL

A numerical model of a water sprinkler fire suppression was built using the FDS version 6.7. The simulation domain was a 2m x 3m x 3m (length x width x height) cubicle. The model includes the following components. Heptane is the fuel of the leaked oil fire and drips from the fuel nozzle to a pan on the floor shown in the Figure 1. The pan has a size of 1m x 0.5m x 0.1m (length x width x depth). The fuel nozzle was 0.5 m above the pan. The fuel flow rate from the nozzle was 2 liters per minute (LPM). In the simulations, fuel was released from the nozzle for 30 seconds before it was stopped, which produced 1 liter of heptane oil in the pan. Fire is immediately initiated in the pan. The sprinkler was activated right after 30 seconds. Total simulation time was 100 seconds. The water sprinkler was placed at the ceiling of the cubicle and right above the fuel nozzle. Ventilation was also applied to the simulation domain from the left side. Five sides of the domain remained open during the simulations. One temperature measuring point at 1 m above the fuel pan was used to measure the temperature of the flame during simulations. Three key parameters were considered and varied in the study: the water flow rate of the sprinkler, the water droplet size, and the ventilation velocity.

In the simulations, three water flow rates were used—50 LPM, 100 LPM, and 200 LPM. The sprinkler angle was set to (30°, 45°) for all the cases. In FDS, sprinkler angle (30°, 45°) directs the water spray through a band between 30° and 45° of the orientation vector, which is facing down. Water droplet size is another factor that influences fire suppression effectiveness. In the numerical model, the distribution of the water droplet sizes can be described in a Cumulative Volume Fraction (CVF), given in equation 1 [Lawson 1988].

$$F(d) = \begin{cases} \frac{1}{\sqrt{2\pi}} {}_0^d \frac{1}{\sqrt{2\pi}} e^{-\frac{[ln(x/d_m)]^2}{2\sigma^2}} dx \; d \le d_m \\ 1 - e^{-0.693\left(\frac{d}{d_m}\right)^{\gamma}} d > d_m \end{cases} \tag{1}$$

Where d_m is the median droplet diameter, γ and σ are empirical constants equal to 2.4 and 0.6, respectively. The median diameter of the water droplet is a function of the orifice diameter and water droplet properties, as shown in equation 2.

$$\frac{d_m}{D} = C\left(\frac{\rho_d u_d^2 D}{\sigma_d}\right)^{-1/3} \tag{2}$$

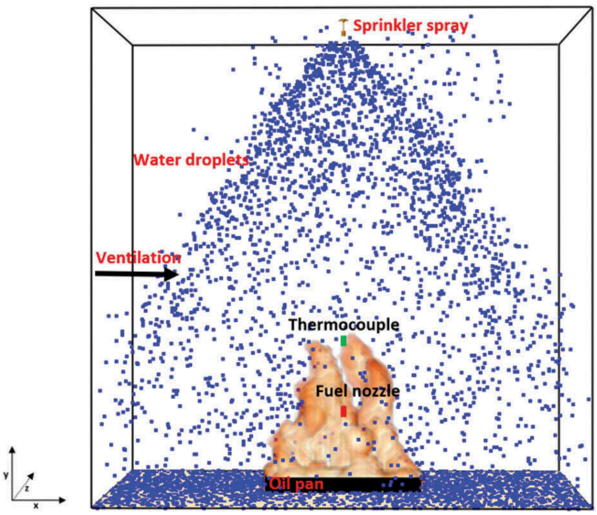

Figure 1. Numerical model schematic.

Where D is the diameter of the sprinkler orifice, C is a constant, and ρ_d, σ_d, and u_d are the water density, surface tension, and droplet initial velocity, respectively [Sheppard 2002]. In the simulation work, several droplet sizes were selected ranging from 200 mm to 700 mm. Ventilation air velocity in a mine could affect the fire behavior and suppression effectiveness. The coupled effect of ventilation and sprinkler suppression is considered in this paper. Table 1 summarizes the simulation conditions used in this study.

Grid size is a critical parameter in numerical simulations. In FDS, the grid size near the fire should be less than 1/10 of the characteristic length D^* to achieve a grid independence [McGrattan 1998], which is written as:

$$D^* = \left(\frac{\dot{Q}}{\rho_a c_p T_a \sqrt{g}}\right)^{2/5} \tag{3}$$

Where $\dot{Q}$ is the heat release rate (HRR) of the fire; ρ_a, c_p, T_a are the density, specific heat, and temperature of the ambient air; and g is the gravitational acceleration. In the simulations, the HRR is calculated around 600 kW, which will render the D^* to be around 0.8 m; the grid size of the simulation thus needs to be less than 0.08 m so that grid independence can be achieved. Therefore, a grid size of 0.03 m was chosen for the current study. The total mesh number of the model is 486,000 (60*90*90).

3 SIMULATION RESULTS AND DISCUSSIONS

3.1 *Effect of water flow rate*

To examine the effect of flow rate on the fire suppression, three sprinkler water flow rates were used in the simulations as described in the above section. The other two parameters remained the same: ventilation velocity at 0 and water droplet size of 500 μm. Comparisons were made between the free burn case and the three sprinkler flow rate cases in Figure 2. Temperature slices were taken at the center of the pool pan at t=70s simulation time. Distinctions can be observed for the peak temperatures of the fires. In the case of free burn, peak fire temperature reached around 900 °C. In the case of 200 LPM water flow rate, the peak temperature recorded at 1m above the pool was the lowest, and at t=70 s the flame was almost extinguished.

Temperature evolution at 1 m above the pool pan and the time to cool at the location are plotted in Figure 3A and 3B. Time to cool is defined as the time from simulation starts to the time when temperature starts to drop steadily. It can be observed from Figure 3A that peak temperature generally goes down with increasing water flow rate. For the free burn case, after about 80s, the temperature starts to decrease, indicating the fuel level has significantly reduced. The time to cool for the cases with suppression decreases with the increase of water flow rate, indicating increasing suppression effectiveness with increasing suppression water flow rate.

3.2 *Effect of droplet size*

Six droplet sizes were chosen to investigate the influence of droplet size on the effectiveness of fire suppression. Temperature slices at 1m above the pool center for each case are plotted and compared at t=80s, shown in Figure 4. Notice that temperature slice

Table 1. Simulation conditions.

Case NO.	Ventilation velocity (m/s)	Droplet size (μm)	Water flow rate (LPM)
1, free burn	0	No suppression	No Suppression
2-7	0.5, 1.0, 1.5, 2.0, 2.5,3.0	500	100
8-10	0	500	50, 100, 200
11-15	0	200, 300, 400, 600, 700	100

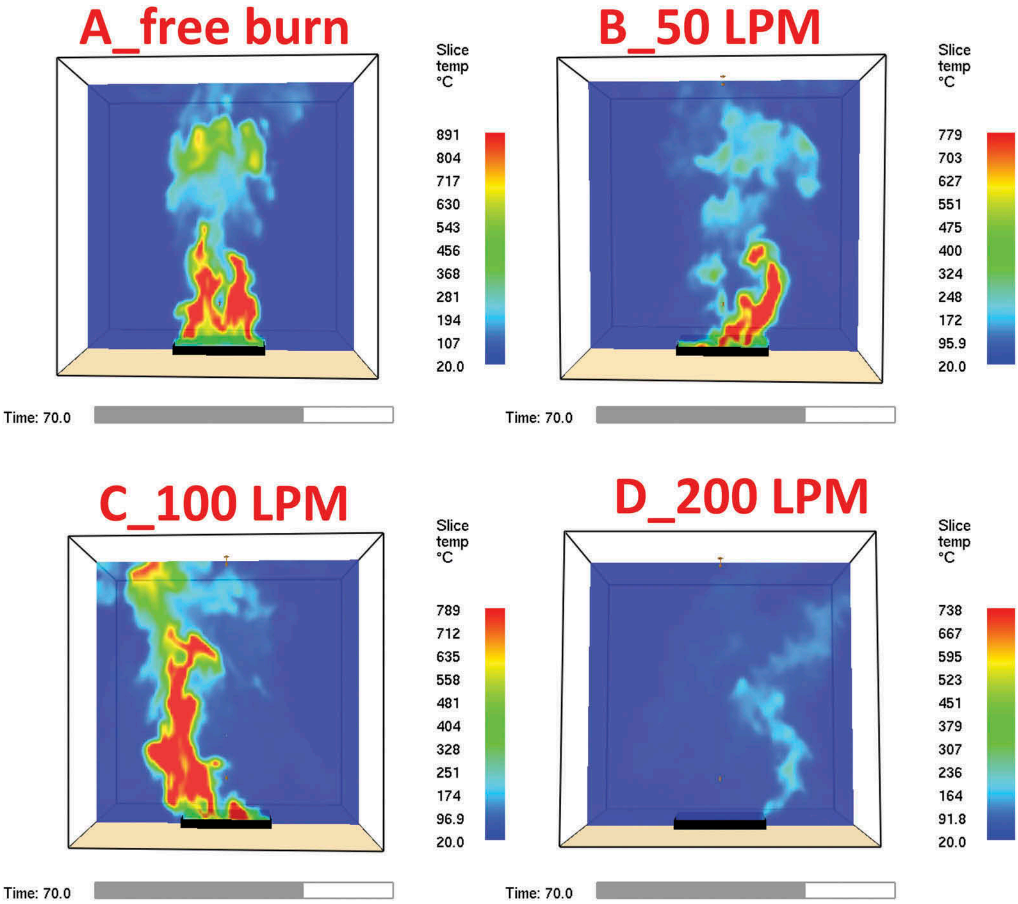

Figure 2. Effect of different sprinkler flow rates on fire suppression with no ventilation: A – free burn, B – 50 LPM, C – 100 LPM, D – 200 LPM.

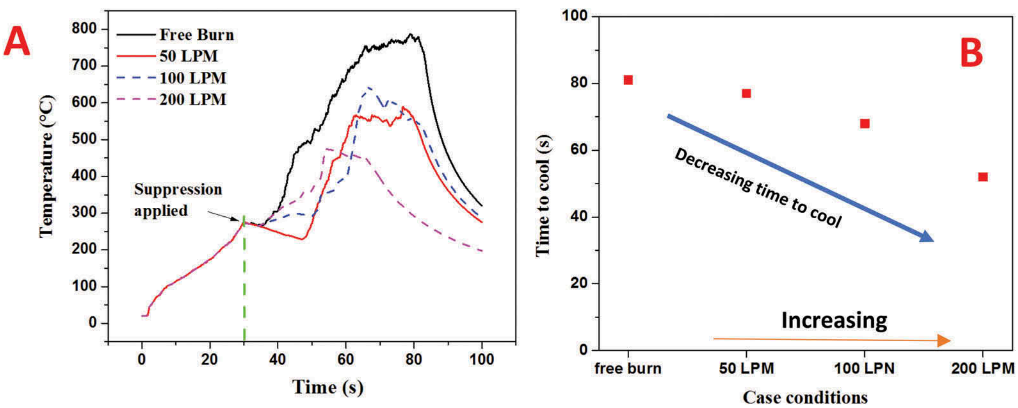

Figure 3. Temperature evolution (A) and time to cool (B) under different suppression water flow rates.

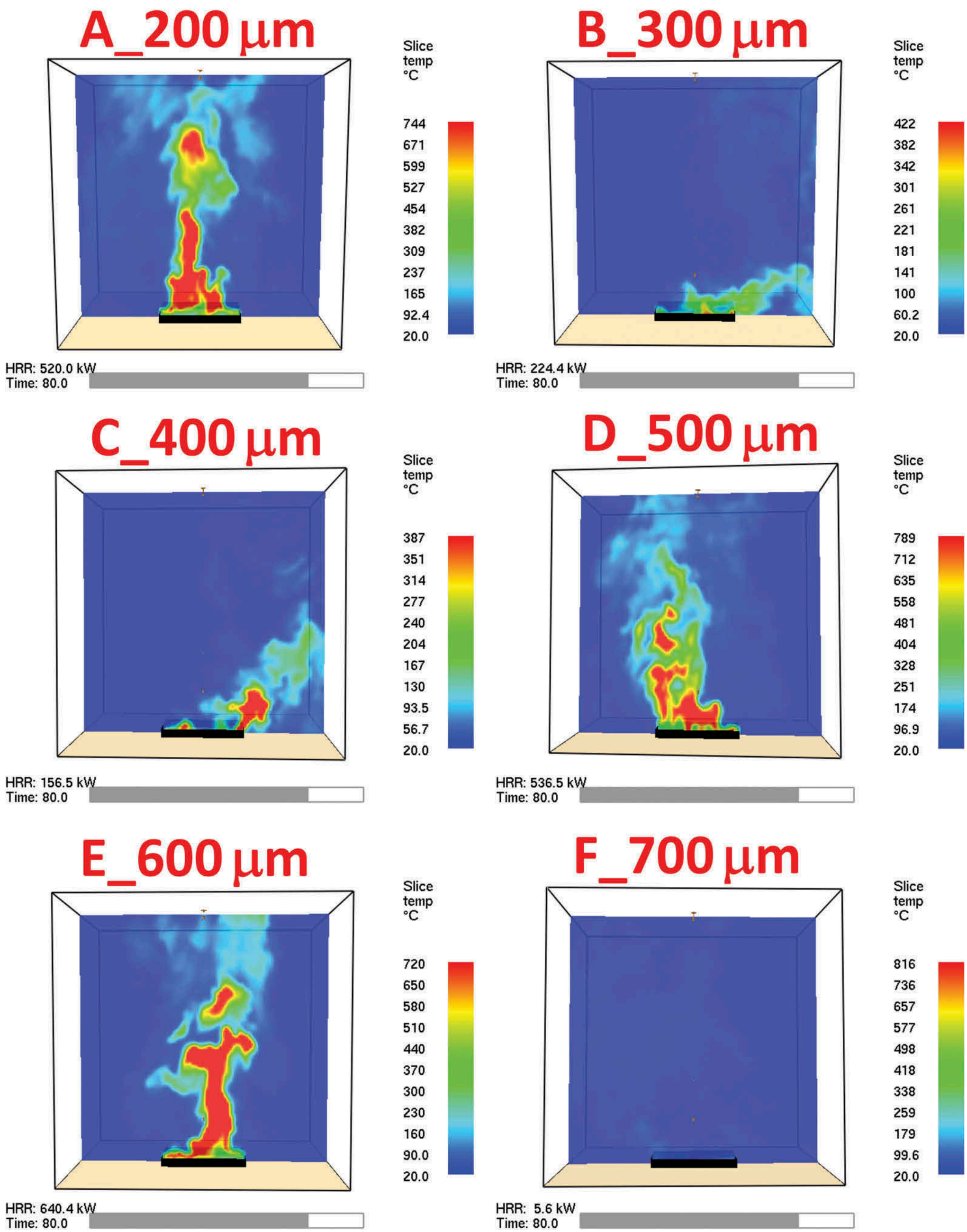

Figure 4. Effect of droplet sizes on fire suppression: A – 200 μm, B – 300 μm, C – 400 μm, D – 500 μm, E – 600 μm, F – 700 μm.

provides only instantaneous information on the flame behavior, which is turbulent in nature. Observations can be made that for a droplet size of 300 μm, 400 μm, and 700 μm, fire extinguishing effect is more obvious than for the other cases. Figure 5 plots the temperature evolution and the peak temperature of the different droplet size cases. Distinctions can be observed for cases with droplet sizes of 300 μm and 400 μm compared to other cases. After suppression was applied at t=30s, the cases with droplet sizes of

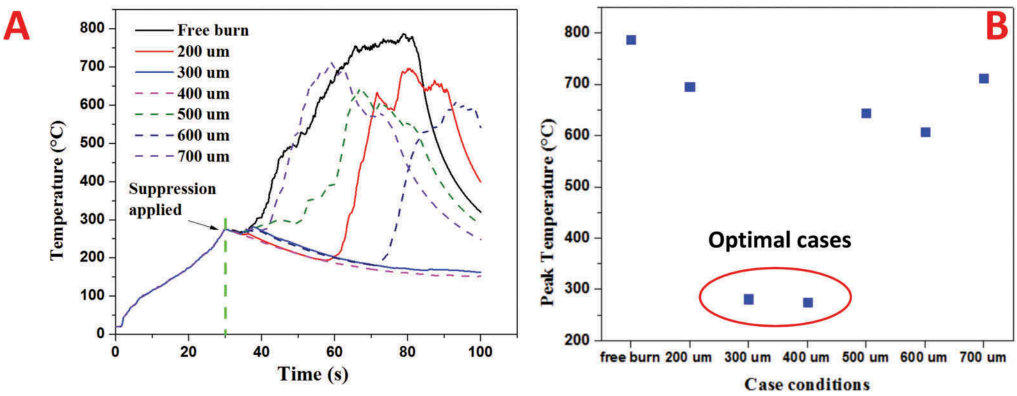

Figure 5. Temperature evolution (A) and peak temperature (B) under different droplet sizes.

300 μm and 400 ám saw a temperature drop consistently, while other cases saw an opposite trend and fluctuations. The peak temperatures for cases with droplet sizes of 300 μm and 400 μm were also far lower than other cases shown in Figure 5B. A possible explanation is that if the water droplet size is too small, the sprinkler spray becomes water mist and buoyant force from the flame plume will prevent the mist from landing onto the fire pool, thus the fire suppression effect is compromised. For larger droplet size cases, the number of water droplets per unit volume is smaller than for other cases, and it becomes harder for the spray to suppress the whole flame and the suppression effect becomes less effective.

3.3 *Effect of ventilation*

Six ventilation velocities were used to investigate the coupled effect of ventilation and water spray on fire suppression. Temperature slices for each case were captured and compared in Figure 6 at t=80s. Obviously, with higher ventilation velocity, the flame will be tilted further, and with openings on 5 sides, fire plume and smoke will be pushed out. Figure 7 shows the temperature evolution and the peak temperature at 1m above the pool pan. It can be seen from the figures that with ventilation, temperatures at this location were well controlled below 150 °C. Figure 7B shows the comparison of peak temperature of ventilation cases to the free burn case. The peak temperature of free burn can reach as high as 800 °C, while for cases with ventilation, a significant temperature drop can be observed. With higher ventilation velocity, peak temperature generally decreases. When ventilation velocity is over 1.5 m/s, temperature seems to stay stable, indicating that the effect of higher ventilation on fire suppression can become diminished beyond a certain value.

4 CONCLUSIONS

A series of numerical simulations were performed using FDS to investigate the effects of water flow rate, water droplet size, and ventilation velocity on leaked oil water based fire suppression. Results from this study indicate that ventilation velocities greater than 1.5 m/s can be an effective measure to contain oil fires. The optimal sprinkler generated water droplet size is around 300 μm or 400 μm with which a significant temperature drop can be achieved. Flame turbulence and temperature were also greatly reduced with higher water flow rate. The results from this study can be used to design efficient fire suppression techniques for mine fires that are caused by hot surface ignition of leaked oils.

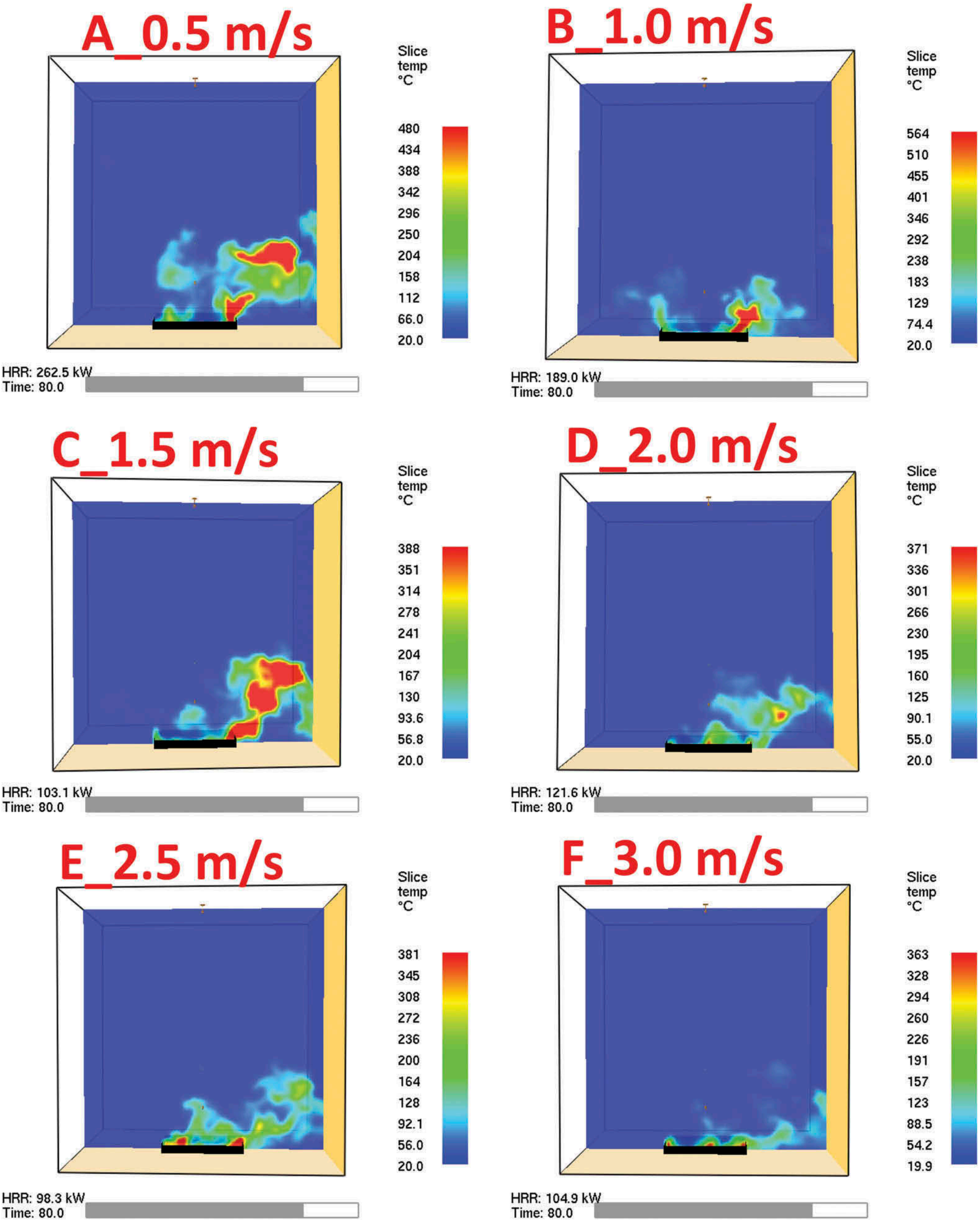

Figure 6. Ventilation velocity effect on fire suppression: A – 0.5 m/s, B – 1.0 m/s, C – 1.5 m/s, D – 2.0 m/s, E – 2.5 m/s, F – 3.0 m/s.

DISCLAIMERS

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

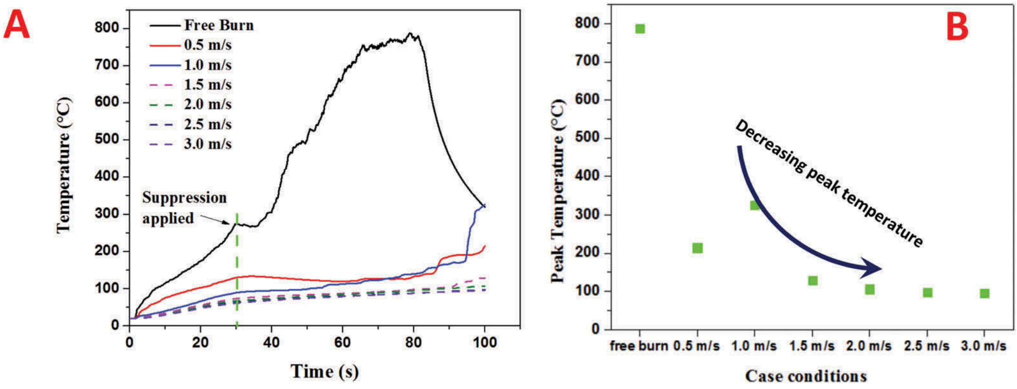

Figure 7. Temperature evolution (A) and peak temperature (B) under different ventilation velocities.

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