Revista Minelor – Mining Revue
ISSN-L 1220-2053 / ISSN 2247-8590
vol. 32, issue 1 / 2026, pp. 66-76

THE INTERACTION OF MULTIPLE FIRES IN A MINE DRIFT – EFFECTS OCCURRING UPSTREAM OF THE FIRES

Rickard HANSEN[1*]

[1]Sustainable Minerals Institute, The University of Queensland, Brisbane, Australia, rickard.hansen@uq.edu.au

DOI: 10.2478/minrv-2026-0006
received – 05.01.2026 / revised – 19.01.2026
accepted – 16.02.2026 / published – 24.03.2026

Abstract: *The fire gas behaviour involving multiple fires in a mine drift with longitudinal ventilation was analysed, focusing on the phenomena occurring upstream of the fires. The analysis was based upon experimental data from model-scale fire experiments. Multiple fire source scenarios will for identical heat release rates result in higher upstream fire gas temperatures at the ceiling level and longer backlayering distances compared to a single fire source scenario. The explanation of the higher upstream fire gas temperatures can likely be found in the changed flame behaviour downstream of the multiple fire sources. Correlations for the upstream ceiling fire gas temperature - accounting for the conditions in a mine drift with multiple burning objects - were proposed. The results of the analysis will improve the understanding of, and the mitigation measures taken when facing multiple fire sources in a mine drift.*
Keywords: *Multiple fires, mine drift, fire gas temperature, backlayering, upstream, dimensional analysis*

1. Introduction

In an underground mine multiple individual fires may occur simultaneously and in the same mine section due to for example a major fire spreading to adjacent fuel items further downstream or due to arson activities. In the case of a major fire spreading to adjacent items, a shorter distance between the fires can generally be expected to allow for a fire spread to occur. Whereas in the case of arson fires, longer distances between the individual fires could also be the case. The fire behaviour, smoke spread, etc. for multiple individual fires in a mine drift with longitudinal ventilation flow may differ significantly compared with a fire scenario involving only one fire source. Fire scenarios with multiple individual fire sources in a mine drift will generally result in severe fire behaviour and a major risk to the miners and the fire and rescue personnel.

This paper investigates the interaction between multiple fires in a mine drift, where the multiple fires start to influence the fire gas temperatures and extension of backlayering upstream of the fires. How will the multiple fire behaviour and distance between the fires affect the fire gas temperatures and the extension of backlayering? Improved understanding and knowledge of the fire behaviour and the smoke behaviour when facing multiple fire sources in a mine drift is needed to improve mitigation measures taken when addressing the safety of mining personnel and rescue personnel underground. Data from earlier model-scale fire experiments were applied and analysed when conducting the study [1].

This paper is aimed at investigating the interaction between multiple fires and their impact on the upstream region – i.e. upstream of the fires - in a mine drift with longitudinal ventilation.

Several studies have been conducted on flames merging from multiple fires in tunnels or mine drifts. Model scale fire experiments in a model scale tunnel with two propane burners and with no forced longitudinal ventilation were conducted by Wan et al [2]. During the study it was found that the distance between the gas burners had a more significant effect on the merging of flames and resulting flame length in the open space case than in a tunnel scenario. Model scale fire experiments involving two pool fires and with no forced longitudinal ventilation were performed by Ji et al [3]. It was found that the mass loss rate of the

[*] Corresponding author: Rickard Hansen, Ph.D. eng., Sustainable Minerals Institute, The University of Queensland, Brisbane, Australia, rickard.hansen@uq.edu.au

fires initially increased and subsequently decreased with increasing distance between the fires. The mass loss rate of two pool fires in a tunnel was found to be higher than for the open space case. Shafee and Yozgatligil [4] studied the effects of multiple fire sources in a tunnel on the burning rate and heat release rate characteristics of the fires. Pool fires were used as fire sources in a model scale tunnel with longitudinal ventilation flow. Hansen [5] performed fire experiments in a model scale mine drift with forced longitudinal ventilation flow and using solid fuel items (i.e., scaled down wooden pallets) for multiple fire sources. During the study foremost the flame mergence between the individual fire sources was studied. During the study it was also found that a scenario involving several individual fires in a mine drift may in severe cases lead to flames tilted horizontally and filling up the entire cross section, leading to earlier ignition, higher fire growth rates, higher fire spread rate and severe fire behaviour. Longer flame lengths may also result due to decreased air entrainment. Applying data from fire experiments in a model scale mine drift with multiple fires and longitudinal ventilation flow, Hansen [6] studied the average fire gas temperature downstream of multiple fires. During the study a model to predict the average fire gas temperature was developed and validated against the experimental results.

No earlier study has investigated the interaction of multiple fire sources in a mine drift with respect to resulting fire gas temperatures and backlayering upstream of the fires.

In the following, the general fire behaviour of a single fire source and multiple fire sources are outlined and discussed, performed model scale fire experiments are described, and the results of the model scale experiments are presented and analysed with respect to the interaction between the multiple fire sources and their impact on the surroundings.

2. Single fire source and multiple fire sources

2.1 The fire behaviour of a single fire source in a mine drift

The fuel distribution in mine drifts generally describes isolated fuel items found in the lower regions. Thus, limiting the risk of fire spread and the risk of multiple individual fire sources. Still, mine areas with continuous fuel distribution can be found for example in mine drifts used as parking areas for mining vehicles.

The general openness, the cooling effect of the surrounding rock surface and the general non-continuous fuel distribution in a mine drift will decrease the likelihood of a flashover. Still, the risk of high intensity fires is still an issue given for example the high fuel load on mining vehicles.

The dominating fire spread mechanisms during a fire in a mine drift will foremost vary with distance from the fire. In the near vicinity of the fire, the flame radiation will dominate among the fire spread mechanisms. With increasing distance from the fire, the convective heat transfer mechanism will increase in importance.

The longitudinal ventilation flow in a mine drift will greatly affect the fire and smoke behaviour. A low ventilation velocity will lead to a higher degree of smoke stratification in the vicinity of the fire and with increasing ventilation velocity the stratification will decrease further downstream of the fire. An increased heat release rate will increase the degree of smoke stratification overall. An increased mine drift height will decrease the smoke stratification overall.

Furthermore, as the heat release rate increases, a counter-current flow of fire gases at the ceiling level, known as backlayering, may occur. The backlayering of hot fire gases will cool down as they mix with the cooler ventilation air flowing in the opposite direction, causing them to descend towards the floor and move back towards the fire.

The characteristics of the mine drift will also have an impact on the fire behaviour. In the region closest to the fire, the surrounding rock will re-radiate heat back to the fire, which in turn will increase the heat release rate of the fire due to increased incident heat flux. Further downstream of the fire the surrounding rock will instead have an increased cooling effect on the fire gases, which in turn will lead to a decreased smoke stratification and a lower risk of ignition. Furthermore, an increase in the mine drift height will decrease the risk of ceiling impingement of flames, which in turn will decrease the risk of ignition further downstream.

2.2 The fire behaviour of multiple fire sources in the open

The occurrence of multiple fire sources is common during wildfires and extensive research has been conducted to identify and explain various phenomena and interactions that may occur specifically for multiple fires in the open.

When the distance between the individual fire sources is sufficiently small, interaction between the fires may occur. Sugawa and Takahashi found through experiments that flames of multiple fire sources could interact over distances four times their diameter [7]. Instead of the fire diameter, Baldwin applied the flame length as threshold and found – based on small-scale fires as well as full-scale fires in the open - that flame interaction would occur if

the distance between the individual fires was less than 0.22 times the flame length [8]. Based on small-scale fire experiments, Delichatsios found the distance to be less than 0.33 times the flame length [9].

The interaction may consist of several different effects. Based on fire experiments with multiple fires, Huffman et al [10] and Kamikawa et al [11] found that the burning rate of each individual fire increased with decreasing distance between the fires as the flames merged due to increased incident heat flux at the fuel surfaces. It was also found that for merged flames, the burning rate was higher for cases with longer distance between the fires. The latter observation was explained by more air being entrained, increasing the combustion efficiency. With decreased combustion efficiency comes increased flame lengths, where a substantial increase in the flame length will occur as the flames merge. After the flames have merged, Chigier and Apak [12] discovered that further decreases in distance between the fires will have little effect on the flame length.

2.3 Multiple individual fire sources in a mine drift

Given the frequently sparsely distributed fuel items along a mine drift, the fuel conditions are unfavourable for multiple fire sources. Nevertheless, arson fires could overcome the unfavourable fuel conditions and arson fires generally include two specific characteristics: the use of an accelerant and multiple fires ignited simultaneously. An earlier study on arson fires in manufacturing and storage premises - these types of premises will at least partially resemble mining operations at fixed facilities - in New Zealand revealed that 723 arson fires occurred between 1996 and 2006 [13]. The number represented 11% of the total number of fires that occurred in this property category. This percentage number is identical with the percentage of fires being arson in industrial properties 2017-2021 in the US [14]. An earlier statistics study on fires in the Australian mining industry only listed two fires attributed to arson between 2014 and 2017, but an underestimation of arson fires is probable as few fires undergo a thorough fire investigation where arson would have been detected [15].

During fire experiments with multiple piles of wooden pallets along a model-scale mine drift with longitudinal ventilation flow, it was found that higher fire gas temperatures and flames across the entire cross section of the mine drift may occur and with flames tilted horizontally. These conditions will cause earlier ignition, higher fire growth rate, higher maximum heat release rate, increasing fire spread rate and more severe fire behaviour [5]. Furthermore, the measured flame lengths showed increasing and longer flame lengths with each ignited fuel item further downstream, due to decreasing air entrainment. Even though this study gives some insights in the fire behaviour of multiple fire sources in a mine drift with longitudinal ventilation flow, further studies of upstream phenomena typical for mining fires – such as backlayering - are warranted.

3. Methodology

3.1 Performed model scale fire experiments

A brief summary of the model scale fire experiments conducted is presented below. For a more detailed description of the wooden pallets, experimental procedures, and heat release rate results, please refer to Hansen and Ingason [16].

Hansen and Ingason conducted a series of model scale mine drift fire tests, completing a total of 12 tests in a 1:15 model scale tunnel, which measured 10 meters in length, 0.6 meters in width, and 0.4 meters in height [1]. The parameters evaluated during the tests included the distance between piles of wooden pallets and the longitudinal ventilation rate, with velocities of 0.3 m/s, 0.6 m/s, and 0.9 m/s. The purpose of the study was to examine the impact of varying distances between the wooden pallet piles on fire spread under different longitudinal ventilation conditions. A sketch of the model tunnel is provided in figure 1, and figure 2 details the positioning of thermocouples, probes, and instruments.

The fire load used in the experiments consisted of scaled-down softwood pallets made from pine, with each pile containing five individual pallets. Three reference tests were conducted with a single pile of pallets, while the remaining tests included four piles of wooden pallets positioned at varying distances from one another.

During the experiments, the following parameters were measured or calculated:

- The ignition times of adjacent piles were recorded manually.

- The total heat release rate was calculated.
- Fire gas temperatures were measured, with most thermocouples placed along the ceiling. Two sets of thermocouples were also located 4.65 m and 8.75 m from the inlet opening to measure temperatures at different vertical positions, allowing for the calculation of an average fire gas temperature. The sets are displayed as pile A and B in figure 2.
- Gas concentrations were measured at the end of the tunnel.
- Heat fluxes were measured at multiple positions at the floor level.
- The centreline flow velocity was calculated at two positions – upstream of the fires and downstream of the fires - based on the measured centreline pressure difference.

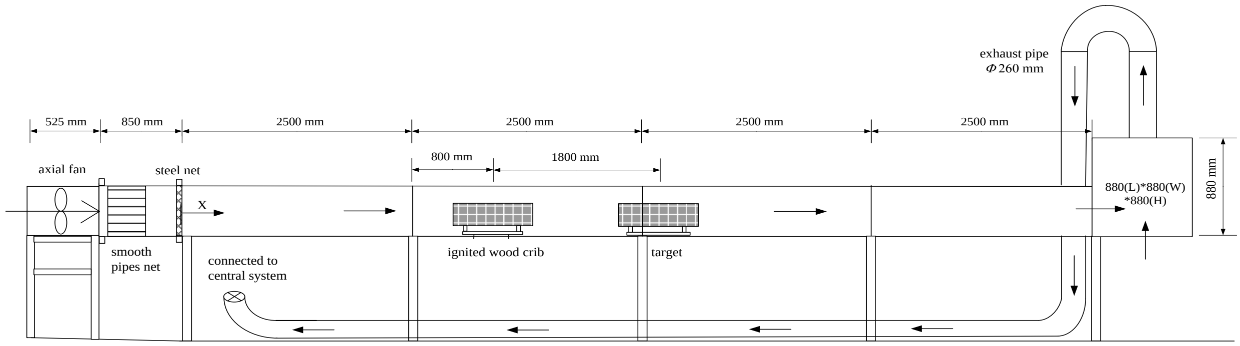

Fig.1. A schematic drawing of the model tunnel [17].

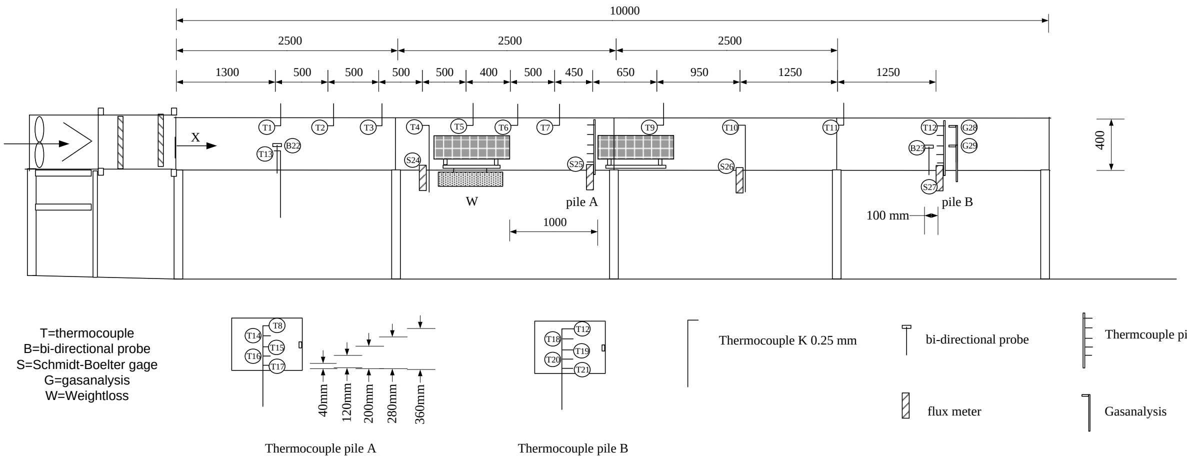

Fig.2. Position of thermocouples, probes and instruments [17]

All experiments were documented visually with a video camera, capturing the fire behaviour along the long side of the tunnel. This side of the tunnel was fitted with a fire-resistant window glaze, enabling visual observations of ignition times. Refer to Table 1 for the results from the model scale experiments. Experiment #2 involved four piles of wooden pallets, but only the initial pile was engaged in the fire and was not included in the analysis. Experiments #1 and #12 contained only a single pile of wooden pallets and were performed with different ventilation velocities and were therefore not included in the analysis. Experiment #4 contained a single pile of wooden pallets and was used for reference and comparison with the other multiple fires scenarios. The ignition time for the first pile of wooden pallets was established at 0 seconds.

Table 1. Results from the model scale fire experiments

Experiment #	u [m/s]	Number of piles	Free distance between the piles [m]	Maximum heat release rate [kW]	Ignition times of second, third and fourth pile [s]
	0.6	4	0.4; 0.7; 0.6	504	96; 129; 150
4	0.6	1	-	154	-
5	0.6	4	0.5; 0.7; 0.8	467	111; 164; 183
6	0.6	4	0.5; 0.8; 0.9	488	105; 149; 176
7	0.6	4	0.5; 0.8; 1.1	485	96; 139; 180
8	0.6	4	0.5; 0.8; 1.3	479	99; 140; 195
9	0.6	4	0.6; 0.8; 1.1	461	110; 162; 190
10	0.6	4	0.7; 0.8; 1.1	454	130; 183; 224
11	0.6	4	0.7; 0.9; 1.1	464	134; 196; 235

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3.2 Scale modelling

The use of model scale fire experiments is advantageous as it facilitates cost-effective fire experimenting, with the results applicable to full-scale systems based on the theory of dimensionless groups. A clear similarity is established between model scale and full-scale experiments. The model scale mine drift was geometrically scaled using a 1:15 ratio. The scaling models for the heat release rate, flow rate, time, energy content, mass, and temperature are detailed in table 2, where L is the length [m] and ΔH_c is the heat of combustion [kJ/kg]. The index - F - corresponds to the full scale (15 in this case), while the index - M - corresponds to the model scale (1 in this case). The effects of the thermal inertia of the materials involved, turbulence intensity, and radiation were not considered.

Table 2. List of scaling models [17]

Unit	Scaling model	Equation number
Heat release rate [kW]	$\dot{Q}_F = \dot{Q}_M \cdot \left(\frac{L_F}{L_M}\right)^{5/2}$	(1)
Velocity [m/s]	$u_F = u_M \cdot \left(\frac{L_F}{L_M}\right)^{1/2}$	(2)
Time [s]	$t_F = t_M \cdot \left(\frac{L_F}{L_M}\right)^{1/2}$	(3)
Energy [kJ]	$E_F = E_M \cdot \left(\frac{L_F}{L_M}\right)^{3} \cdot \frac{\Delta H_{c,M}}{\Delta H_{c,F}}$	(4)
Mass [kg]	$m_F = m_M \cdot \left(\frac{L_F}{L_M}\right)^{3}$	(5)
Temperature [K]	$T_F = T_M$	(6)

4. Results and discussion

In the following analysis, the temperatures at the ceiling level and the temperature and flow velocity at one position mid-height upstream of the initial fire were applied and investigated. For the fire experiment involving a single pile of wooden pallets, only the measurements up to the maximum heat release rate were included. For the fire experiments involving multiple piles of wooden pallets, only measurements starting from the ignition of the second pile of pallets were included in the analysis as the data prior to this would only represent a fire scenario involving a single pile.

4.1 Fire gas temperatures at the ceiling level, upstream of the fires

When examining the fire gas temperatures at the ceiling level, it was found that it was foremost at the thermocouple positioned furthest away from the fire – i.e., T1 which was positioned 2 m upstream of the fire (see figure 2) – where the most distinct temperature differences could be detected. Thus, the temperature measurements at thermocouple T1 were focused on in the ensuing analysis.

Figures 3-5 display the temperature measurements at thermocouple T1 for different time segments: between the ignition of the second and third pile of wooden pallets, between the ignition of the second and fourth pile of wooden pallets, and between the ignition of the second pile of wooden pallets and the attainment of the maximum heat release rate for the multiple fire experiments. The temperatures are depicted as a function of the heat release rate at the time of the temperature to facilitate the detection of any temperature differences as other influencing parameters were kept constant during the experiments (i.e., flow velocity and mine drift dimensions). Temperature differences are most discernible in figure 4 (temperature measurements between the ignition of the second and fourth pile of wooden pallets), where experiments #10 and #11 resulted in significantly higher temperatures and experiment #4 (single pile of pallets) resulted in the lowest temperatures. The maximum heat release rate for experiment #4 was approximately 150 kW.

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The temperature results from the other experiments tend to clump together in between the temperatures of experiments #4, #10 and #11, but where temperatures from experiments #8 and #9 are frequently found among the higher temperatures. Experiments #4, #10 and #11 represent the extremes of the experiments, with no distance between piles (i.e., experiment #4 with a single pile) or with the longest total distances between the first and second pile and between the second and third pile (i.e., experiments #10 and #11). Overall, multiple fire sources will for identical heat release rates result in higher upstream fire gas temperatures at the ceiling level and longer backlayering distances compared to a single fire source scenario.

Why do we see higher upstream ceiling temperatures for multiple fire sources scenarios compared to a single fire source scenario? The explanation can likely be found in the changed flame behaviour downstream of the multiple fire sources. With multiple fire sources, flame merging and longer flame lengths will result which in turn will influence the flame radiative fraction of the total heat release rate. Following upon this, a larger convective fraction of the total heat release rate will result which in turn will increase the fire gas temperatures upstream of the fire and increase the backlayering distance. Both upstream fire gas temperatures and backlayering are the outputs of the convective heat release rate.

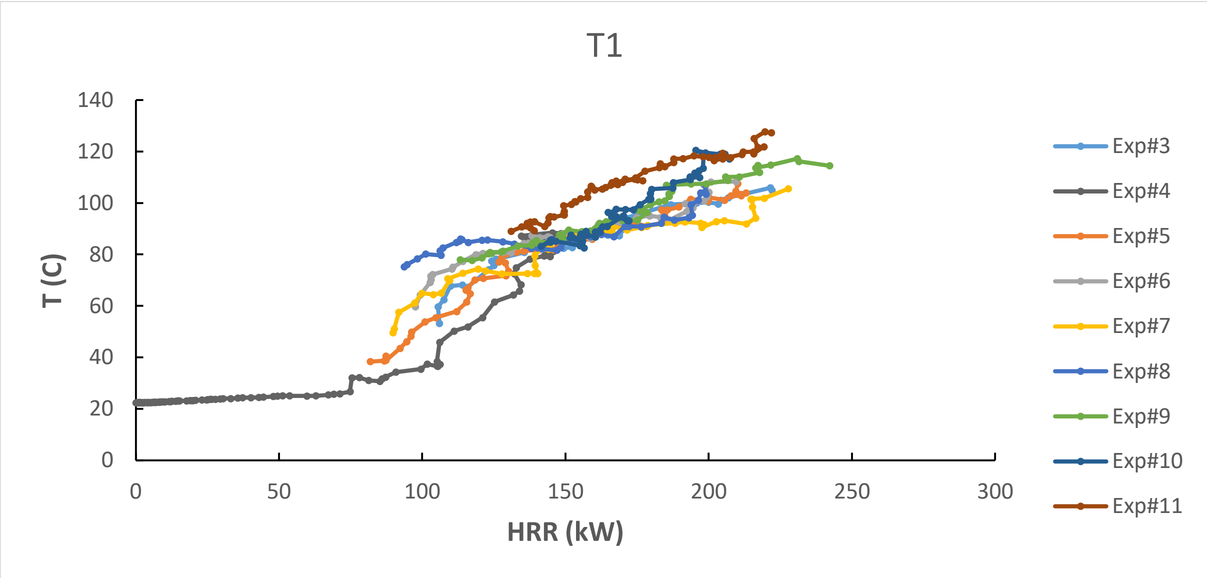

Fig.3. The fire gas temperatures at the ceiling level 2 m upstream of the closest fire, including temperatures between the ignition of the second and third pile of wooden pallets for the multiple fire experiments

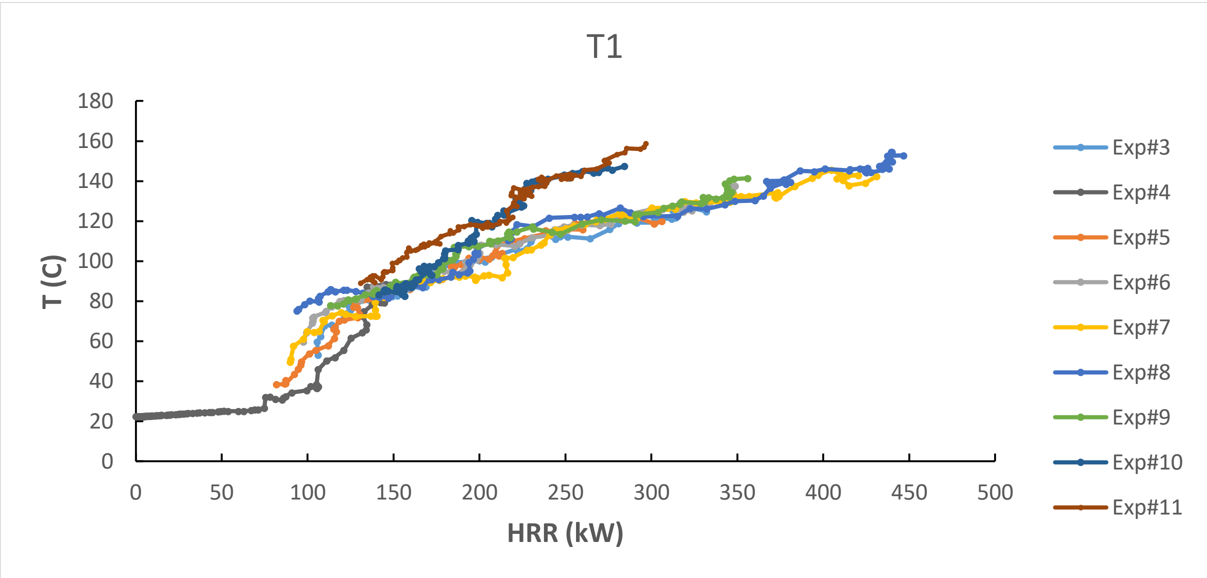

Fig.4. The fire gas temperatures at the ceiling level 2 m upstream of the closest fire, including temperatures between the ignition of the second and fourth pile of wooden pallets for the multiple fire experiments

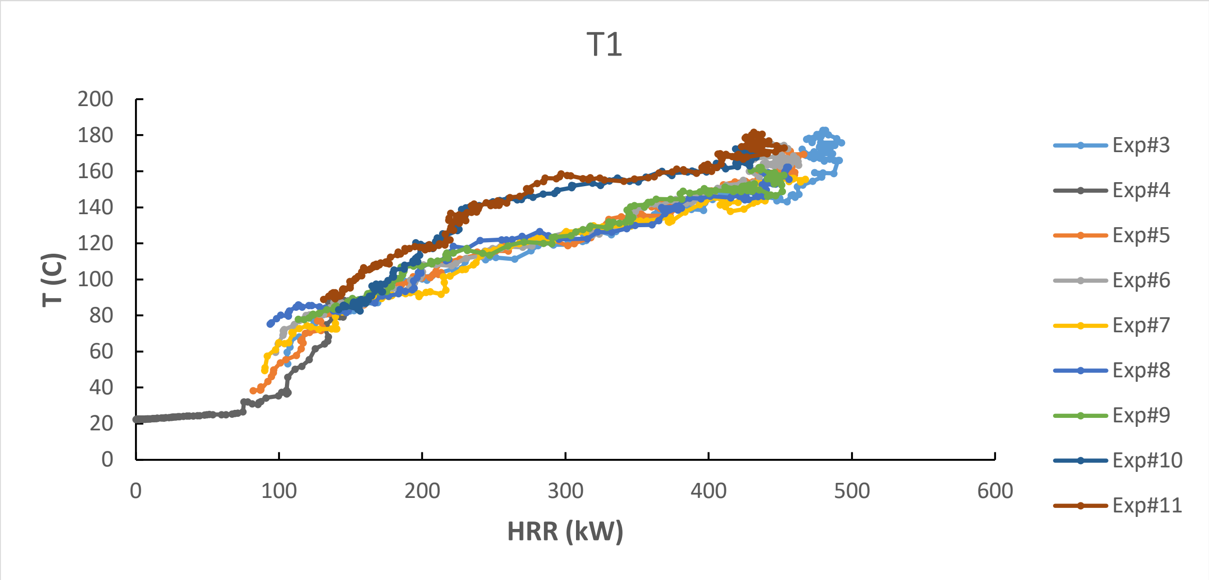

Fig.5. The fire gas temperatures at the ceiling level 2 m upstream of the closest fire, including temperatures between the ignition of the second pile of wooden pallets and the attainment of the maximum heat release rate for the multiple fire experiments

4.2 Centreline flow velocities and temperatures, upstream of the fires

When examining the centreline flow velocity upstream of the fires (see figure 2 for the position of the probe) as a function of the heat release rate, no differences between the different experiments involving multiple fire sources could be detected.

The upstream centreline flow velocity was constant at the early stages of the experiments and increased for the higher heat release rates. This was expected as the gas temperature at the probe increased for the higher heat release rates, resulting in decreased gas densities and increased gas flow velocities.

The centreline temperature measurements displayed similar result as the ceiling temperature measurements, i.e., higher upstream fire gas temperatures compared to the single fire source scenario.

4.3 Dimensional analysis - extension of hot fire gases upstream/backlayering

Backlayering distance – i.e., the length of the reversed smoke flow upstream of the fire - can be described by the following correlation by Thomas [18-19]:

$$\frac{L_b}{H} \propto \left(\frac{g\cdot\dot{Q}}{\rho_a\cdot c_p\cdot T_a\cdot u^3\cdot H}\right)^{1/3} \tag{7}$$

where L_b is the backlayering distance [m], H is the mine drift height [m], g is the acceleration of gravity [m/s^2], ρ_a is the ambient density [kg/m^3], c_p is the specific heat of air at constant pressure [kJ/kg·K] and T_a is the ambient temperature [K].

As can be seen in equation (7), if increasing the heat release rate, the backlayering distance will increase as well. The fire gas temperature will in turn be dependent on the heat release rate, with increasing temperatures with increasing heat release rates. Thus, an increase in the fire gas temperatures will result in an increased backlayering distance.

In the ensuing dimensional analysis, the extension of hot fire gases at the ceiling level, upstream of the fires will be investigated, which can also be – given the reasoning above – related to the backlayering distance.

Performing a dimensional analysis on the extension of the fire gases at the ceiling level, upstream of the fires, the following governing parameters of the fire as well as the surrounding conditions were included based upon earlier studies on fire gas temperatures at ceiling level in mine drifts with longitudinal ventilation flow [18-20]: $\dot{Q}$, $u_{c,upstream}$, H, $\rho_{upstream}$, c_p, T_a, g, x

$$T_{ceiling} = f\left(\dot{Q}, u_{c,upstream}, H, \rho_{upstream}, g, c_p, T_a, x\right) \tag{8}$$

where $T_{ceiling}$ is the fire gas ceiling temperature upstream of the fires [K], $u_{c,upstream}$ is the centreline flow velocity upstream of the fire [m/s], $\rho_{upstream}$ is the gas density upstream of the fire [kg/m^3], x is the distance between the individual fire sources [m].

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The normalized fire gas temperature:

$$\frac{T_{ceiling}}{T_a} = f\left(\frac{\dot{Q}}{\rho_{upstream} \cdot c_p \cdot T_a \cdot g^{1/2} \cdot H^{5/2}}, \frac{u_{c,upstream}^2}{g \cdot x}\right) \quad (9)$$

Equation (9) shows that the normalized fire gas temperature is a function of the normalized heat release rate and the upstream flow velocity normalized by the distance between fire sources and the gravitational constant.

Temperatures from the ignition of the second pile to the ignition of the third pile of pallets

Proceeding with the work using equation (9) to investigate the upstream, ceiling fire gas temperatures at thermocouple T1, measured between the ignition of the second pile until the ignition of the third pile of wooden pallets, the following correlation finally resulted from the regression analysis:

$$T_{ceiling} = T_a \cdot \left(2.28 + 0.194 \cdot ln\left(\frac{\dot{Q}}{\rho_{upstream} \cdot c_p \cdot T_a \cdot g^{\frac{1}{2}} \cdot H^{\frac{5}{2}}}\right) - 0.085 \cdot ln\left(\frac{u_{c,upstream}^2}{g \cdot x}\right)\right) \quad (10)$$

The measured experimental upstream fire gas temperatures were plotted in figure 6 as a function of the corresponding fire gas temperature calculated by equation (10). An R^2 value of 0.85 resulted from the regression analysis. The plot in Figure 6 shows that the upstream fire gas temperature at the ceiling level can be well described by equation (10). A total of 383 data points is included in figure 6.

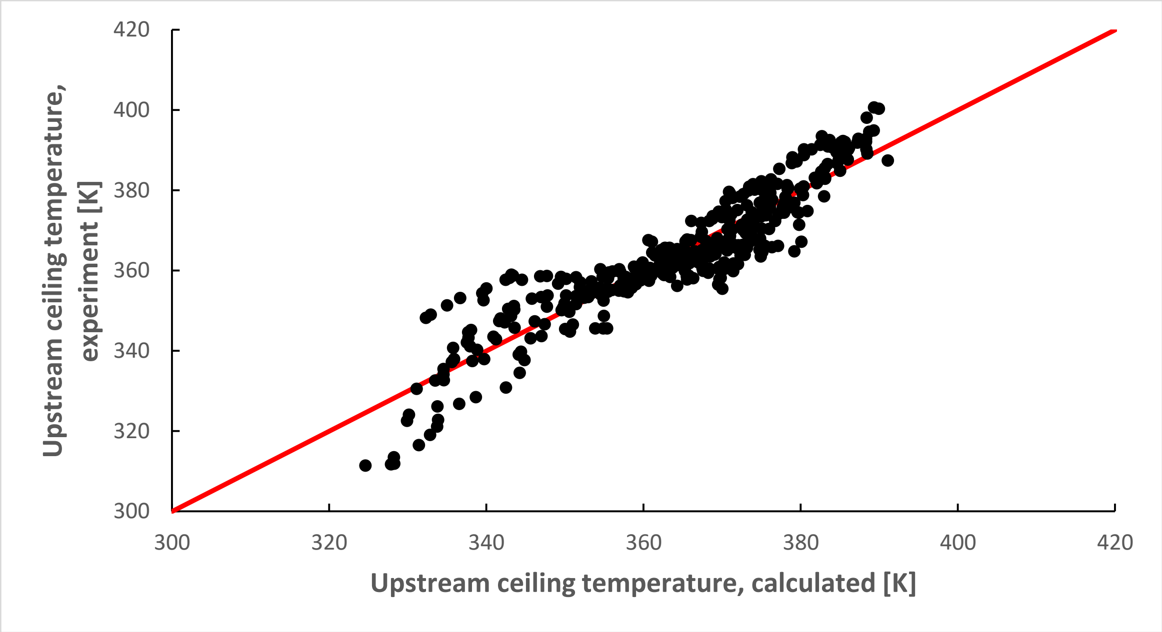

Fig.6. The scatter plot of the experimental upstream ceiling temperature versus the calculated. Based on data between the ignition of the second pile until the ignition of the third pile of wooden pallets

Temperatures from the ignition of the second pile to the ignition of the fourth pile of pallets

Performing a similar analysis for the ceiling fire gas temperatures at thermocouple T1, measured between the ignition of the second pile until the ignition of the fourth pile of wooden pallets, the following correlation finally resulted from the regression analysis:

$$T_{ceiling} = T_a \cdot \left(1.90 + 0.199 \cdot ln\left(\frac{\dot{Q}}{\rho_{upstream} \cdot c_p \cdot T_a \cdot g^{\frac{1}{2}} \cdot H^{\frac{5}{2}}}\right) - 0.222 \cdot ln\left(\frac{u_{c,upstream}^2}{g \cdot \bar{x}}\right)\right) \quad (11)$$

In the analysis the average distance between the three first piles of wooden pallets (i.e., the first, second and third piles) was used when describing x.

Figure 7 displays the measured experimental upstream fire gas temperatures as a function of the corresponding fire gas temperature calculated by equation (11). An R^2 value of 0.92 resulted from the regression analysis. The plot in Figure 7 shows that the upstream fire gas temperature at the ceiling level can be very well described by equation (11). A total of 656 data points is included in figure 7.

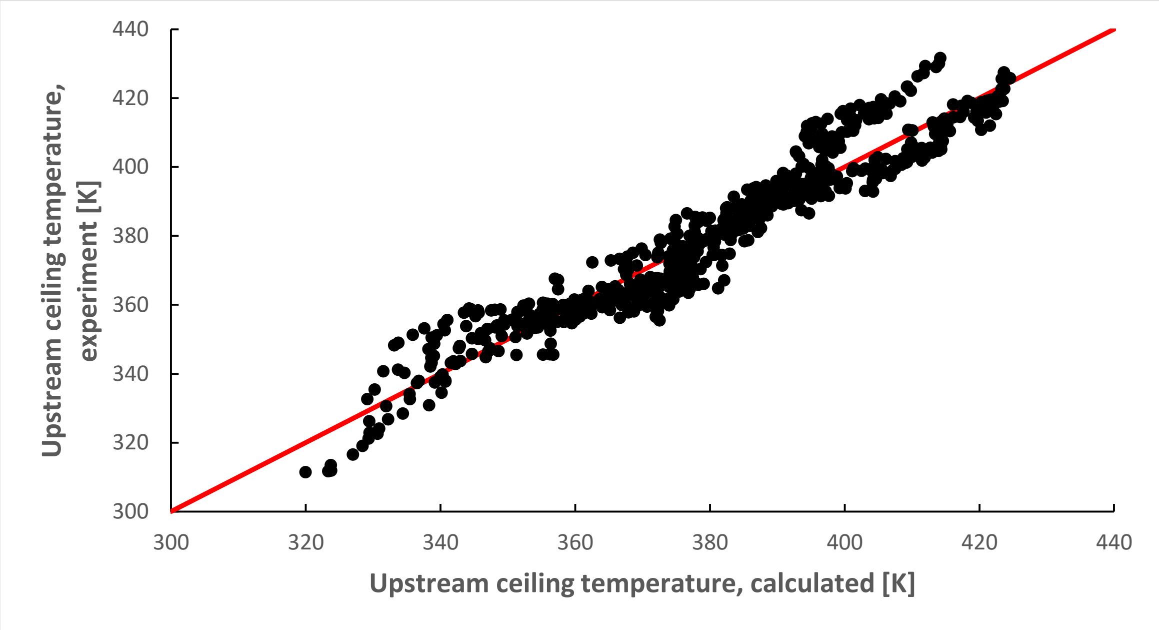

Fig.7. The scatter plot of the experimental upstream ceiling temperature versus the calculated. Based on data between the ignition of the second pile until the ignition of the fourth pile of wooden pallets

4.4 Full-scale values

Applying applicable equations found in table 2, the longitudinal ventilation velocity of the model-scale experiments corresponded to a full-scale velocity of 2.32 m/s, which is within the range of ventilation velocities encountered in underground mines. The peak heat release rate of each pile of wooden pallets corresponded to approximately 131 000 kW, which is a very severe fire intensity typically found in fires involving multiple, larger mining vehicles or larger accumulations of combustible goods. The model-scale distances between the piles corresponded to 6 m in full-scale (model-scale 0.4 m), 7.5 m (0.5 m), 9 m (0.6 m), 10.5 m (0.7 m), 12 m (0.8 m), 13.5 m (0.9 m), 16.5 m (1.1 m) and 19,5 m (1.3 m). The full-scale distances represent distances that are found when fuel items are not adjacent but sufficiently short distances for a possible arson fire scenario where fuel items are ignited along the mine drift. Individual arson fires are generally set with a shorter distance between them to minimize detection.

5. Conclusions

The fire gas behaviour involving multiple fires in a mine drift with longitudinal ventilation was analysed, focusing on the phenomena occurring upstream of the fires. Based on fire experiments in a model-scale mine drift it was found that:

- Multiple fire source scenarios will for identical heat release rates result in higher upstream fire gas temperatures at the ceiling level and longer backlayering distances compared to a single fire source scenario.
- The explanation of the higher upstream fire gas temperatures can likely be found in the changed flame behaviour downstream of the multiple fire sources. With multiple fire sources, flame merging and longer flame lengths will result which in turn will influence the flame radiative fraction of the total heat release rate. Following upon this, a larger convective fraction of the total heat release rate will result which in turn will increase the fire gas temperatures upstream of the fire and increase the backlayering distance.
- No differences in the upstream flow velocity between the different experiments involving multiple fire sources could be detected. The upstream centreline flow velocity was constant at the early stages of the experiments and increased for the higher heat release rates. This was expected as the gas temperature at the probe increased for the higher heat release rates, resulting in decreased gas densities and increased gas flow velocities.
- The centreline temperature measurements displayed similar result as the ceiling temperature measurements, i.e., higher upstream fire gas temperatures compared to the single fire source scenario.
- A regression analysis was performed and resulted in proposed correlations which matched the experimental results very well and successfully accounted for the conditions in a mine drift with multiple burning objects.

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The findings of the analysis would improve the understanding of and the knowledge of the fire behaviour and the smoke behaviour when facing multiple fire sources in a mine drift and improve mitigation measures taken when addressing the safety of mining personnel and rescue personnel underground.

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