

SMOKE STRATIFICATION IN A MINE DRIFT WITH MULTIPLE OBJECTS DOWNSTREAM

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Abstract: *The smoke behaviour and smoke stratification of a fire in a mine drift will be one of the decisive factors affecting the risk to mining personnel during a fire. This paper studies the smoke stratification in a mine drift with multiple objects downstream of the fire, at varying distances and number of objects. Data for the study was provided from earlier model-scale fire experiments and CFD modelling was performed for in-depth analysis of specific phenomena. It was found that at considerable downstream distances from the fire, the smoke stratification differences were significant, reflecting the high impact of multiple objects. With an increasing distance between the objects downstream, an increased degree of mixing and decreased stratification occurred. With an increasing distance between the burning object and the second object, the smoke layer will descend further before encountering the object and the smoke stratification on the upstream side of the second object will decrease. The increased mixing of the hot gases flowing from the burning object will have a more significant effect on the overall stratification due to the higher temperatures. An increasing number of objects downstream will not by itself lead to increased stratification, with shorter distances between the objects and an increasing number of objects, the smoke stratification may instead be retained for a longer distance. An increasing flow velocity will result in decreasing stratification found foremost downstream of the burning object, as the tilt of the plume will increase and interact increasingly with the second object.*

Keywords: stratification, mine drift, longitudinal ventilation, fire, obstacle, underground mine

1. Introduction

The smoke spread from a fire in an underground mine will in most cases pose the greatest risk to the personnel underground. The smoke spread in a mine section will largely be described by the stratification of the smoke. In turn, the smoke stratification will describe characteristics such as when and at what distance the smoke layer will descend and reach the floor, at what distance from the floor will the smoke layer be found and will the conditions allow for a safe evacuation. The degree of smoke stratification will be a crucial factor when evaluating the possibility of evacuation, fire suppression operation etc.

The fuel distribution as well as the distribution of non-combustible items in a mine is distinguished by its discontinuity [1]. Multiple islands or pockets of items and equipment can be found underground, but in between one will find long and extensive mine drifts, ramps etc., containing no material. Places with multiple large items or equipment would include for example parking drifts with several vehicles parked, a ramp with several vehicles in a queue or a storage facility with multiple piles of items. With multiple items or equipment found downstream of a longitudinal ventilation flow, changes in the turbulence and the occurrence of eddies are likely to occur. These phenomena will change the flow field along the mine drift or the mine section, which in turn will affect the smoke stratification and smoke spread.

This paper focuses on the occurring smoke stratification in a mine drift with a burning item and multiple larger objects found downstream, partially obstructing the ventilation flow. How will a varying distance between the objects influence the smoke stratification? How will the number of objects influence the smoke stratification? To investigate the smoke stratification in an underground mine drift with longitudinal ventilation flow and multiple

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objects downstream, experimental data from model-scale fire experiments were applied as these experiments provided essential data. Furthermore, supplementary CFD modelling was performed to investigate in-depth certain phenomena observed from the experimental data. The purpose of the paper is to investigate the impact of multiple objects downstream, at varying distances, number of objects and longitudinal flow velocity on the smoke stratification. With increased knowledge of the occurring smoke stratification underground, the safety of the personnel underground and the fire and rescue personnel would increase during the initial and critical evacuation phase of a fire as well as the later phases when fire suppression may take place. The findings of the paper will also have bearing on tunnel fire safety, with a fire scenario with multiple vehicles caught downstream of the fire.

The smoke stratification in underground mines have earlier been investigated and analysed primarily aimed at the upstream smoke stratification and the downstream smoke stratification in a mine drift with a single mining vehicle on fire and accounting for the rough rock surface.

Applying data from duct fire experiments, where no obstacles were present downstream, where the fire position was on the floor and where the duct surface could not be related to the rough rock surface of a mine drift, Newman [2] studied the occurring smoke stratification. Based on the experimental data, a correlation between the local temperature stratification and the local mass distribution of a chemical compound was presented. Furthermore, Newman applied the local Froude number (Fr) to divide the occurring smoke stratification into three different regions depending on the degree of stratification. Fletcher et al [3] conducted CFD simulations on a tunnel fire, where the turbulence and radiation effects on the stratification and backlayering were studied. The changes in the downstream temperature profiles - and thus also the stratification - for downhill tunnels and varying inclination angles were studied by Atkinson and Wu [4]. The stratification was found to decrease for increasing inclination angles. Haddad et al [5] performed experiments in a model-scale tunnel, investigating the smoke stratification beneath the ceiling where the horizontal fire source locations were varied. Hansen [6] studied the smoke stratification in a mine drift with a burning mining vehicle, investigating the influence of the rock surface roughness, rock surface material and the impact of the vehicle body. In the study, proposed correlations were found to successfully predict the smoke stratification in a mine drift with a burning mining vehicle. It was found that non-stratified conditions could be expected at much shorter distances in a mining environment with rough rock surfaces compared with a tunnel environment with smoother surfaces. Rock surface materials with low volumetric heat capacities were found to cause longer distances to non-stratified conditions.

In the following, earlier performed model-scale fire experiments are described and the resulting stratification data are presented. The data is used when analysing the horizontal and vertical temperature differences along the mine drift, describing the differences in stratification. The analysis was supplemented by CFD modelling to investigate in-depth certain phenomena observed from the experimental data.

This study is limited to the downstream smoke stratification in a mine drift with no inclination.

2. Smoke stratification in an underground mine

The smoke stratification in a mine section, along a ramp etc. will be influenced by several different parameters. With an increasing longitudinal ventilation flow, the smoke stratification downstream will decrease as opposed to a scenario with lower ventilation velocity where the stratification will be higher. A higher heat release rate will result in a higher stratification downstream as the gas temperatures and vertical temperature gradients will increase. An increase in the height of the mine drift as well as the distance to the fire will decrease the stratification, due to increased cooling and decreased vertical temperature gradients. An increasing surface roughness of the surrounding rock surface will increase the heat losses and cooling, resulting in a decreased smoke stratification. Any surrounding rock surface material with low volumetric heat capacity will result in higher stratification. A larger, burning item will increase the turbulence of the flowing gases and increase the cooling of the fire gases, resulting in a decreased stratification. Figure 1 displays an example of stratification in a mine drift with a burning mining vehicle.

Based on fire experiments in a duct and where the fire was positioned on the floor, Newman [2] defined three regions with different degree of smoke stratification and where the local Froude number (Fr) was used as criterion. The local Froude number is calculated using:

$$Fr = \frac{u_{avg}}{\sqrt{\frac{\Delta T_{cf}}{T_{avg}} g \cdot H}} \quad (1)$$

where u_{avg} is the average fire gas velocity [m/s], ΔT_{cf} is the temperature rise between near the ceiling and near the floor [K], T_{avg} is the average fire gas temperature [K], g is the acceleration of gravity [m/s²] and H is the ceiling height of duct or mine drift [m].

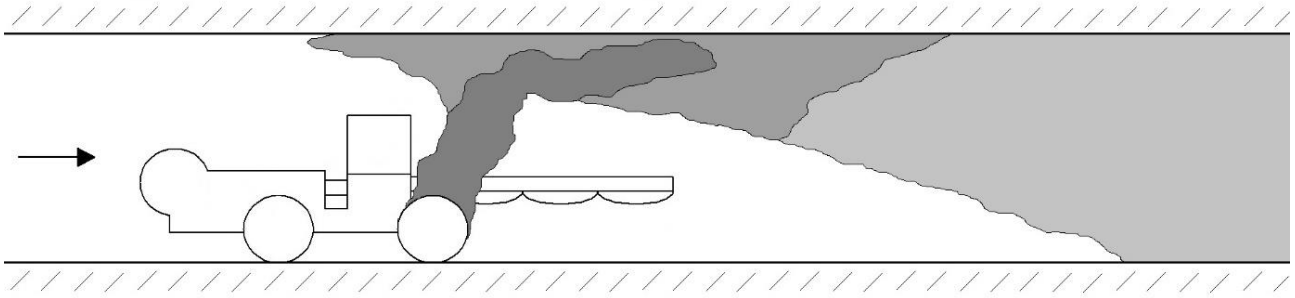


Figure 1. The smoke stratification in a mine drift with a burning mining vehicle and longitudinal ventilation flow

The criterion and description of each region were as followed:

- Region I ($Fr \leq 0.9$): severe stratification.
- Region II ($0.9 < Fr < 10$): intermediate stratification.
- Region III ($Fr \geq 10$): negligible stratification.

Hansen [6] found that based on full-scale experiments with a burning mining vehicle in an underground mine drift, the risk of over predicting the distance to when region I transitions to region II is significant if applying the criterion by Newman where the induced turbulence and mixing was not included. Instead, based on the full-scale experimental data the following criterion for region I was proposed:

$$\frac{Re^{0.694}}{Fr^{0.669}} > 15,000$$

where Re is the Reynolds number, which is connected with turbulence and would therefore include the occurring phenomena in the mine drift.

Furthermore, the smoke stratification can be linked to the ratio of ΔT_{cf} to ΔT_{avg} . Applying the data points from full-scale experiments and performing a regression analysis, Hansen [6] proposed the following correlation:

$$\frac{\Delta T_{cf}}{\Delta T_{avg}} = 0.112 \cdot 10^{-3} \cdot \frac{Re^{0.694}}{Fr^{0.669}} \quad (2)$$

where ΔT_{avg} is the average gas temperature rise relative to ambient [K].

The temperature difference at ceiling level will also be of high interest with respect to the smoke stratification, as it will be a driving force for the smoke stratification. Depending on whether the point of interest is situated in region I or II, the correlation for the temperature difference between the ceiling temperature and the ambient temperature (ΔT_h) will be different. For region I, Hansen [6] proposed the following correlation based on a regression analysis:

$$\Delta T_h = 1.77 \cdot 10^{-4} \cdot \Delta T_{avg}^{1.09} \cdot \left(\frac{u_{vehicle} \cdot D_h}{\nu} \right)^{0.757} \cdot \left(\frac{g \cdot H}{T_{avg} \cdot u_{vehicle}^2} \right)^{0.364} \quad (3)$$

where $u_{vehicle}$ is the accelerated ventilation flow velocity when passing the burning mining vehicle or other burning object [m/s], ν is the kinematic viscosity [m²/s] and D_h is the hydraulic diameter of the mine drift or duct [m].

For region II, the following correlation was proposed [6]:

$$\Delta T_h = 0.06 \cdot \Delta T_{avg}^{1.32} \cdot \left(\frac{u_{vehicle} \cdot D_h}{\nu} \right)^{0.211} \cdot \left(\frac{g \cdot H}{T_{avg} \cdot u_{vehicle}^2} \right)^{0.102} \quad (4)$$

As no data corresponding to region III was obtained during the full-scale experiments, Hansen [6] did not propose any correlations for region III. For further reading on the smoke stratification in a mine drift with a burning mining vehicle, see study by Hansen [6].

2.1. Objects downstream of the fire

A single burning, larger object in a mine drift where a longitudinal ventilation flow is present, will cause an increased turbulence due to changes in the flow field when the object and the rough rock surface interacts with the ventilation flow. An increased turbulence will in turn increase the mixing of the gases and thus

decrease the stratification. The interactions will consist of the accelerated flow - when passing the object due to restricted cross-sectional area – and the occurrence of flow separation, eddy formation etc. downstream of the object and along the rock surface caused by the construction of the object and the rough rock surface structures. The accelerated flow of gases will be marked by a stabilized boundary layer and minimized energy dissipation. The decelerated flow of gases – occurring at the flow separation – will be marked by instability and large energy dissipation. The fire will add further to the turbulence by increased flow velocities (caused by the decreasing gas densities of the heated gases), increasing gas temperatures causing increased irregularities in the flow field, and the outflow of hot fire gases from wheelhouses, vehicle cabs etc into the passing ventilation flow. Figure 2 displays a single object with accelerated flow at the object, and flow separation and eddy formation downstream of the object.

Several objects downstream of the fire object will add further to the changing flow field along the mine drift. Downstream of the burning object a separation of the flowing gas from boundary surface is expected with the occurrence of asymmetric flow fields with a recirculation zone containing eddies. The eddies will not be steady but highly transient: forming, dissipating, and re-forming. An adjacent object further downstream may be in the path of the eddies or within the recirculation zone depending on the distance. The impact on the flow fields and the smoke stratification will therefore largely depend on the distance between the individual objects. The likelihood of the occurring eddies will increase with an increasing height/width-to-length ratio of the object, the length being the dimension of the object in the direction of the ventilation flow. The dimensions of the burning object as well as the objects further downstream will thus be of interest when analysing the smoke stratification. With a decreasing distance between the objects downstream, the question arises whether the individual objects may possibly start to act more and more as a single, continuous object with a lower height / width-to-length ratio with less occurrence of eddies, retained acceleration of the gases, less instability and retained smoke stratification for a longer distance?

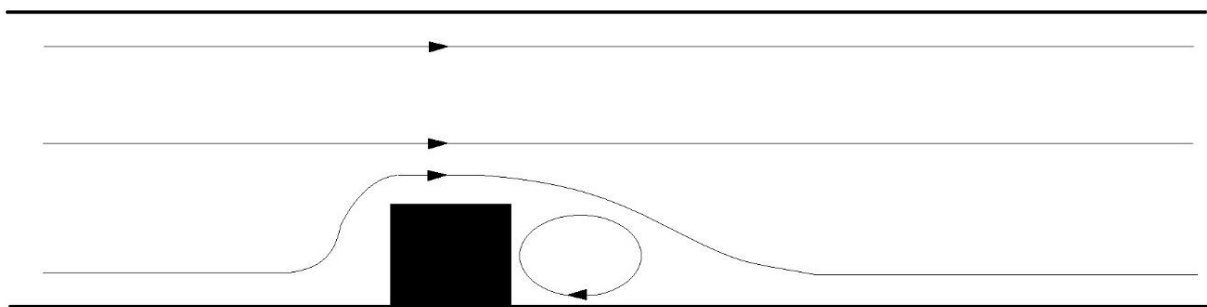


Figure 2. A single object in a mine drift with accelerated flow at the object, and flow separation and eddy formation downstream of the object

3. Methodology

3.1. Model-scale fire experiments

3.1.1. Model-scale experiments with varying distance between fuel items

Twelve fire experiments were performed in a model-scale mine drift, where the number of individual fuel items, the distance between the fuel items, and the longitudinal flow velocity were varied. The main objective of the experiments was to study the fire spread between individual fuel items, but the extensive collection of data from the experiments allowed for an analysis of the downstream smoke stratification as well. During the experiments either a single pile or four piles of wooden pallets were applied, where each pile consisted of five scaled down pine pallets. Each scaled down pallet had an overall dimension of 0.3 m by 0.2 m by 0.036 m (L × W × H). Out of the twelve experiments, three experiments included a single pile of pallets and the remaining nine included four piles. In one of the experiments including four piles, only the first pile took part in the fire (i.e., experiment #2). In the remaining eight experiments, all four piles burned. The individual free distances between the piles of pallets were varied in the nine experiments. The first pile was always positioned at the same location, which was the platform seen above the letter ‘W’ in figure 3. Three different and constant longitudinal flow velocities were applied during the experiments: 0.3 m/s, 0.6 m/s and 0.9 m/s respectively. The ventilation flow was established using a blower fan at the entrance to the model-scale mine drift. Table 1 contains data on the different experiments regarding number of piles, free distances,

and flow velocities. Experiment #12 included a single pile and with a flow velocity of 0.9 m/s. As no experiment was conducted with multiple piles and with a flow velocity of 0.9 m/s, experiment #12 was omitted in the ensuing analysis.

Table 1. Data on the piles of wooden pallets used in the model-scale fire experiments.

Exp #	Longitudinal flow velocity [m/s]	Number of piles	Arrangement of piles of pallets – free distance [m]			Average free distance between piles [m]	Distance between pile #2 and pile A [m]	Distance between pile #4 and pile B [m]
			Pile #1 and #2	Pile #2 and #3	Pile #3 and #4			
1	0.3	1	-	-	-	-	-	-
2	0.3	4	0.6	0.9	0.9	0.8	0.45	2.35
3	0.6	4	0.4	0.7	0.6	0.57	0.65	3.05
4	0.6	1	-	-	-	-	-	-
5	0.6	4	0.5	0.7	0.8	0.67	0.55	2.75
6	0.6	4	0.5	0.8	0.9	0.73	0.55	2.55
7	0.6	4	0.5	0.8	1.1	0.8	0.55	2.35
8	0.6	4	0.5	0.8	1.3	0.87	0.55	2.15
9	0.6	4	0.6	0.8	1.1	0.83	0.45	2.25
10	0.6	4	0.7	0.8	1.1	0.87	0.35	2.15
11	0.6	4	0.7	0.9	1.1	0.9	0.35	2.05
12	0.9	1	-	-	-	-	-	-

The model-scale mine drift had a length of 10 m, a width of 0.6 m and a height of 0.4 m, being in scale 1:15. The surface material along the mine drift consisted of either Promatect boards or window glazes, and therefore had smooth surface characteristics. The following parameters - having bearing on the ensuing analysis - were either measured or calculated from the experiments:

- fire gas temperatures, using either single thermocouples along the ceiling of the mine drift or thermocouple piles. Thermocouple piles A and B were equipped with thermocouples at different heights to give a picture of the vertical temperature distribution.

- The centreline flow velocity was calculated at the inlet and at pile B, using the measured centreline temperature from the thermocouple and the pressure difference from the bi-directional probe at the point of interest.

See figure 3 for the layout of the model-scale mine drift in question and the position of thermocouples and probes. For a further detailed description of the experiments, see Hansen and Ingason [7].

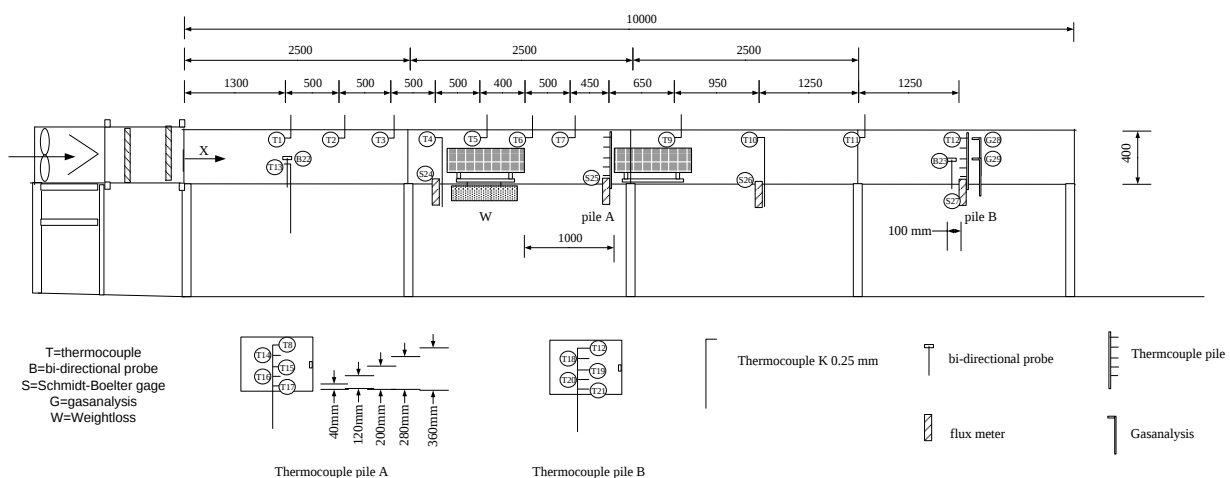


Figure 3. The model-scale mine drift and the position of thermocouples and probes [7]

3.1.2. Model-scale experiments with constant distance between fuel items

Another twelve fire experiments were carried out by Ingason in model-scale tunnel in scale 1:23 [8]. The aim of the experiments was to study the effect of different ventilation rates on the fire growth rate, fire spread, flame length, gas temperatures, radiation, and backlayering.

Out of the twelve experiments, three experiments were selected where all parameters were kept constant except for the number of fuel items. In the experiments one, two and three wood cribs were used respectively as fire load. The free distance between the wood cribs was 0.65 m in the experiments containing two or three cribs. A drawing of a wood crib can be seen in figure 4.

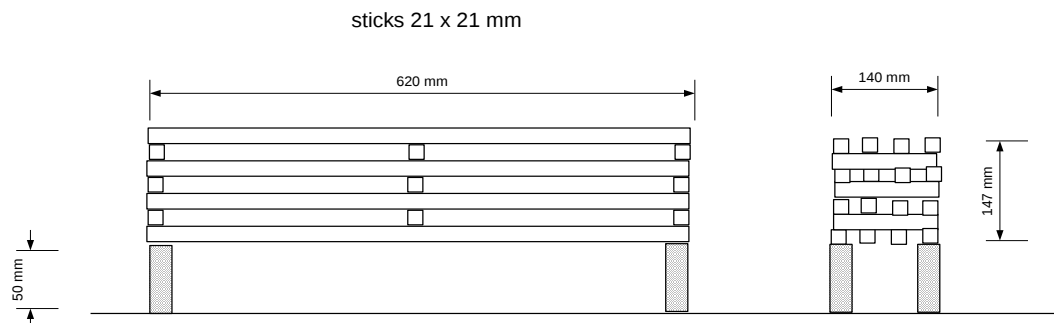


Figure 4. Drawing of a wood crib used in the experiments [7]

The model-scale tunnel was 10 m long, 0.4 m wide and 0.3 m in height. The height between the top of wood crib and the tunnel ceiling was 0.1 m. Same as for the experiments in a model-scale mine drift, the surface material along the tunnel had smooth surface characteristics. The longitudinal flow velocity was 0.6 m/s in all three experiments and a blower fan was positioned at the tunnel entrance. Input data from the experiments are listed in table 2.

Table 2. Data on the model-scale tunnel experiments.

Experiment #	Longitudinal flow velocity [m/s]	Number of wood cribs	Distance between wood cribs [m]
1	0.6	1	-
3	0.6	2	0.65
4	0.6	3	0.65

The instrumentation in the tunnel was similar to the mine drift instrumentation with individual thermocouples positioned along the ceiling and two thermocouple piles (with five individual thermocouples at different heights). The distance between the centre of the platform (onto which the first crib was positioned) to thermocouple T4 was 0.855 m, to thermocouple T5 was 2.105 m, to thermocouple pile A was 3.355 m, to thermocouple T11 was 4.605 m and to pile B 5.855 m.

For further description of the experiments and the instrumentation, see Ingason [8].

3.2. CFD modelling of phenomena of interest along the mine drift

The ability to model complex geometries and transient fire characteristics make CFD models suitable for modelling common fire features such as ventilation flows and heat transfer. In a CFD model, the modelled domain is divided into a three-dimensional mesh of multiple cells, where the fundamental laws of fluid mechanics and heat transfer found in the laws of conservation mass, momentum and energy are applied. See for example Yeoh and Yuen [9] for further reading on CFD modelling.

CFD modelling was applied in an earlier study when investigating the throttle effect in a model-scale mine drift [10]. Version 6.7.5 of the Fire Dynamics Simulator (FDS) was selected as CFD model due to its ability to model low-speed, thermally driven flow typical of fires [11]. One of the key parameters influencing the throttle effect is the temperature stratification in the model-scale mine drift. The modelled results were validated against the experimental results from model-scale fire experiments [7].

Figure 5 displays the average gas temperature at thermocouple pile B of experiment #1 (see table 1) and as can be seen the modelled temperature matches the measured temperature very well during the initial four minutes of the experiment. During the following minutes the CFD model over predicts the average temperature when comparing with the measured results. The initial match between the modelled and experimental results are due to the over prediction of the lower thermocouples in the thermocouple pile being cancelled by the under prediction of the uppermost thermocouple. Due to the difficulties to accurately predict the thermal stratification, Hansen [10] recommended using the CFD model mainly for qualitative analysis. The ensuing modelling results are thus predominantly applied with a qualitative approach during analysis.

The ensuing simulations were based on input data from the validation study of Hansen [10] as well as a modelling study on the influence of blower fan versus exhaust fan on the throttle effect [12]. The measured heat release rates of the individual model-scale fire experiments [7] were used as input when modelling the burning pile of wooden pallets applying the heat release rate per unit area (HRRPUA) model. The HVAC (Heating, Ventilation and Air Conditioning) feature of FDS was applied to sections prior to and after the mine drift to decrease the computational time of the simulations. Slice files and vector files were used as output data to investigate certain phenomena observed from the model-scale experiments. The slice files reproduced the planar temperatures and flow velocities along the length of the model-scale mine drift. The vector files also contained the gradients and thus also specified the direction of the velocity change. The temperature vector files contained velocity vectors coloured on the temperature contour. The selected mesh grid size in the study was 0.02 m, which is in line with the earlier modelling study on the throttle effect [10].

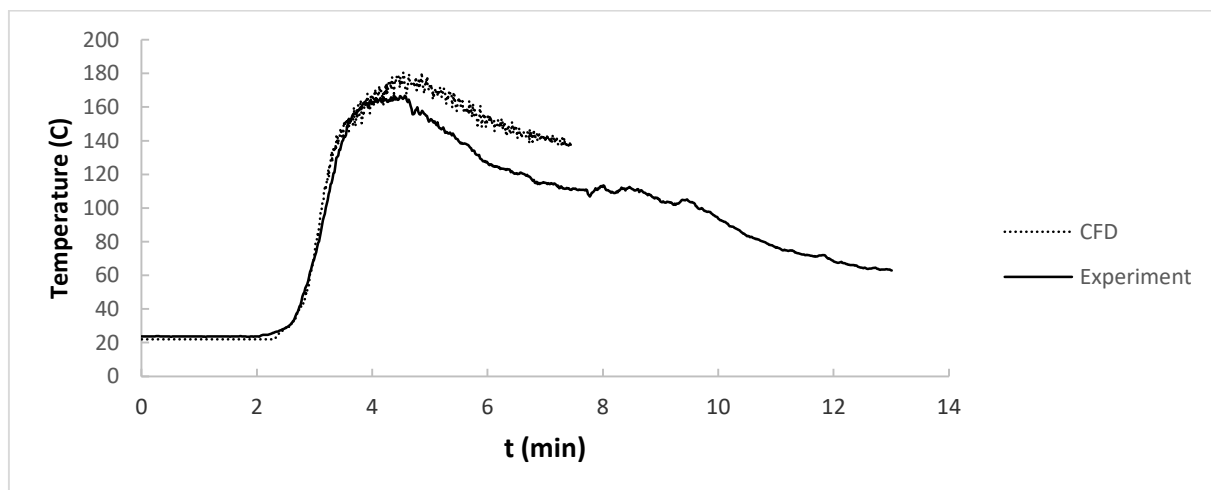


Figure 5. The measured and modelled average temperature at pile B – experiment #1 [10]

4. Results and discussion

In the following, the results and analysis on the differences in smoke stratification for varying number of objects, distance between objects, and longitudinal flow velocity can be found.

Additionally, comparison and discussion on the equivalent full-scale lengths and heat release rate is provided.

4.1. Model-scale experiments with varying distance between fuel items

When studying the data from the experiments, it was found that for experiment #5 the ignition time of the second pile was longer (111 s) compared to experiment #9 (110 s) despite a shorter distance between the first pile and the second pile (see table 1). Also, the measured heat flux along the mine drift was very low in experiment #5 and the average temperature at pile B the lowest of all experiments. The fire spread and fire growth of experiment #5 was inexplicably slow and experiment #5 was therefore excluded in the analysis.

4.1.1. Distance between objects

The following experiments were included in the analysis with identical longitudinal ventilation velocity but varying distances between piles of pallets (see table 1): #3, #6, #7, #8, #9, #10 and #11. The comparison between the experiments was carried out until the point in time where the earliest ignition of the second pile was recorded, as the heat release rate would thereafter differ between the experiments. Using the temperature difference at ceiling level as an indicator of the smoke stratification degree, ΔT_h was calculated at pile A, pile B and along the ceiling. The temperature difference at ceiling level for the highest thermocouple of pile A can be found in figure 6 and for pile B in figure 7.

At the time of the earliest ignition of the second pile, the maximum temperature difference between the experiments at pile A involved experiments #3 and #11 with a difference of approximately 110°C. The maximum temperature difference at pile B also involved experiments #3 and #11 with a difference of 60°C. These temperature differences are significant and reflect the high impact on the smoke stratification. When comparing figure 6 and figure 7, some of the experiments seem to be grouped together. Experiments #10 and #11 with the lowest temperatures, followed by higher temperatures for experiments #6 and #9, and for experiments #7 and #8. The highest temperatures were measured for experiment #3.

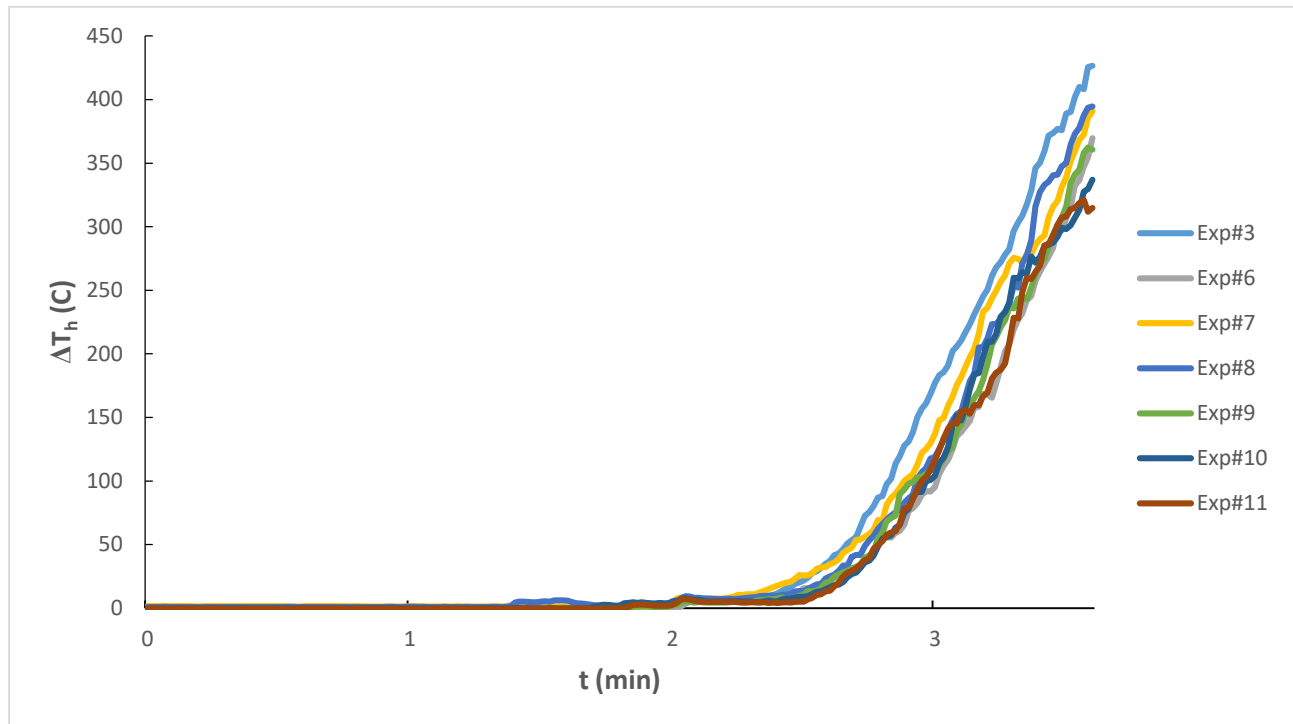


Figure 6. The temperature difference at ceiling level at pile A

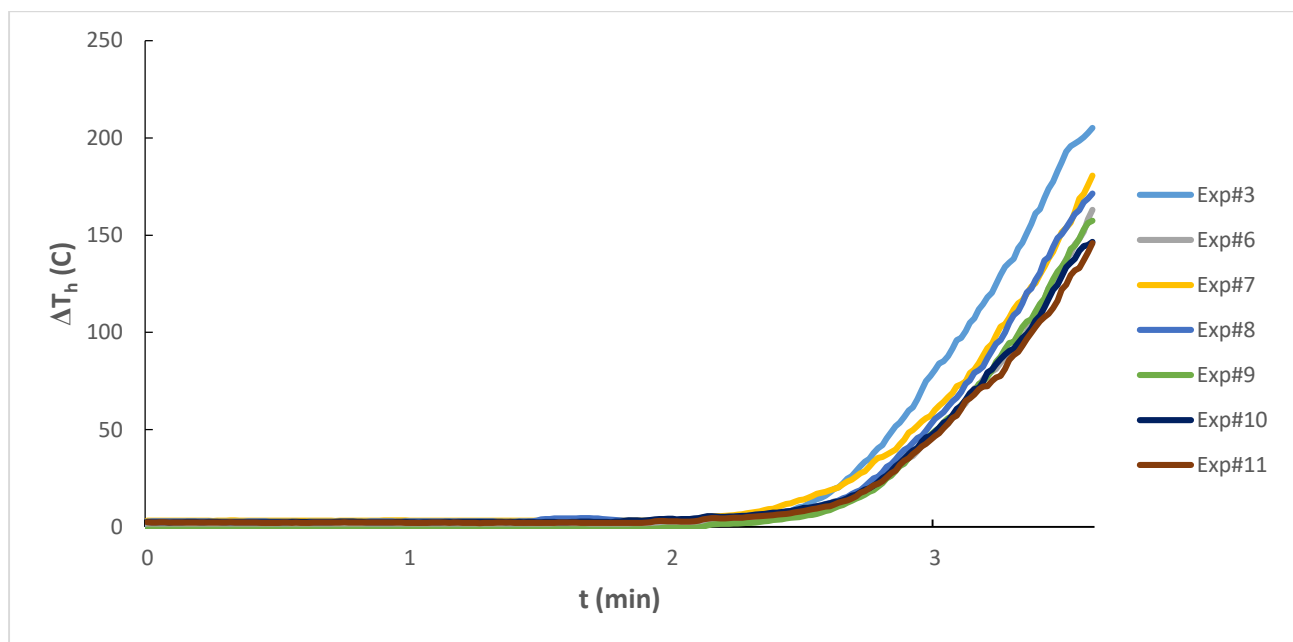


Figure 7. The temperature difference at ceiling level at pile B

Studying the data in table 1 and figures 6 and 7, for the same number of objects downstream the average distance could partially explain the variations in ΔT_h (i.e., an increasing average distance will lead to a decreasing ΔT_h and decreasing smoke stratification). Still, the average distance will not fully explain the variations if looking at the data for experiment #8. The individual distances between the objects would thus also have to be included in the analysis as the distance between the burning pile and the adjacent pile downstream seems to follow the variations in ΔT_h . An increasing distance between the burning object and the adjacent object downstream could possibly contribute to a higher degree of mixing of the flowing fire gases, a higher degree of cooling at the ceiling level and a decreasing smoke stratification.

Figure 8 displays the temperature difference at ceiling level at thermocouple T7, which is positioned 0.45 m upstream of pile A. In the case of experiments #3, #6, #7 and #8, the thermocouple was positioned downstream of the second pile of pallets. In experiments #9, #10 and #11, the thermocouple was positioned above the second pile. At the time of the earliest ignition of the second pile, the maximum temperature

difference was between experiment #3 at approximately 640°C and experiment #11 at approximately 410°C, resulting in a temperature difference of 230°C. ΔT_h for the other experiments were in descending order: experiment #8 at ~540°C, experiment #7 at ~500°C and experiments #6, #9 and #10 at ~450°C. With an increasing distance between the first – burning – pile of pallets and the second pile, the smoke layer will descend further down, the mixing will increase and the ceiling temperature decrease. The shorter distance in experiment #3 influences the output considerably, with considerably higher ΔT_h measurements. The second pile in experiment #3 had little effect on the stratification due to the short distance.

At the position of pile A (see figure 6), the flow of smoke and fire gases has passed the second pile amply in all experiments and the effect of the second pile is more visible. The highest temperatures are still measured for experiment #3 (~430°C) with the shortest distance to adjacent pile, and the lowest for experiments #10 and #11 (~340°C and ~320°C respectively) with the largest distances to the next pile downstream. The effect of the larger distance to the second pile in experiment #10 compared with experiment #9 can be seen when comparing figure 8 with figure 6. At thermocouple T7 (figure 8) the flowing gases has not yet passed the second pile in experiment #10, but further downstream the full impact of the second pile can be seen in the separation of the temperature curves for the two experiments (figure 6).

Figure 9 displays the temperature difference at ceiling level at thermocouple T10, which is positioned 1.6 m downstream of pile A. At T10 in experiment #3, the flowing gases had passed the fourth pile of pallets with ample distance. In experiments #6 and #7, T10 was positioned immediately downstream or directly above the fourth pile. In the remaining experiments, T10 was positioned downstream of the third pile with ample distance. At the time of the earliest ignition of the second pile, the maximum temperature difference was between experiments #7 and #8 at approximately 320°C and experiment #11 at approximately 240°C, resulting in a temperature difference of 80°C. ΔT_h for the other experiments were in descending order: experiments #3 and #6 at ~300°C, experiment #9 at ~280°C and experiment #10 at ~260°C. The flowing gases at the ceiling level of experiment #3 have undergone a larger degree of mixing and decrease of stratification at this position compared with the other experiments, as the flowing gases have passed the fourth pile of pallets in experiment #3. The lesser degree of mixing in experiments #6 and #7 despite the near vicinity of the fourth pile was due to that mixing predominantly takes place on the downstream side of the pile where the flow undergoes a retardation and instability is a common feature. Thus, the full effect of the fourth pile in experiments #6 and #7 will not be distinguished at T10. The second shortest distance between the first pile and the second pile in experiments #6, #7 and #8, and that one pile remains downstream in these experiments can thus be seen in the higher or equivalent ΔT_h measurements compared with experiment #3. The impact of the larger distances between the piles in experiments #10 and #11 is very evident in figure 9 and the temperature difference compared with experiment #9 remain.

At the position of pile B (see figure 7), the flow of smoke and fire gases has passed the fourth pile amply in all experiments, the effect of the multiple objects has now stabilized and the temperature and stratification results will reflect the situation at 30 to 45 m downstream of the last object if transferring to full-scale conditions. Experiment #3 stands out with the significantly highest ΔT_h (~205°C) and the highest degree of stratification and with a temperature difference of ~60°C compared with experiments #10 and #11. Experiments #6, #7, #8 and #9 have since T10 undergone an increased mixing caused by the fourth pile of pallets. If comparing the distances of experiment #8 with experiment #10 in table 1 – having an equivalent distance between the first and fourth pile, but shorter distance between the first and second pile and longer distance between the third and fourth pile – the significance of the distance between the first and second pile is again highlighted, where a shorter distance will lead to a higher degree of stratification. The distances between the piles of pallets of experiments #6, #7 and #8 are identical except for the distance between the third and the fourth pile, but the temperature measurements seen in figure 7 are inconclusive with respect to the impact of the distance between the third and fourth pile. Possibly, the impact is less and insignificant.

4.2. Model-scale experiments with constant distance between fuel items

The ignition times of the individual wood cribs were not listed in the report by Ingason [8]. The heat release rate curve of experiment #1 – involving only a single wood crib – was subtracted from the heat release rate curves of experiments #2 and #3 to pinpoint the time of ignition of the second wood crib. The point of ignition was defined as the point in time when the heat release rate started a continuous increase.

The analysis was carried out using data until the ignition of the second wood crib took place.

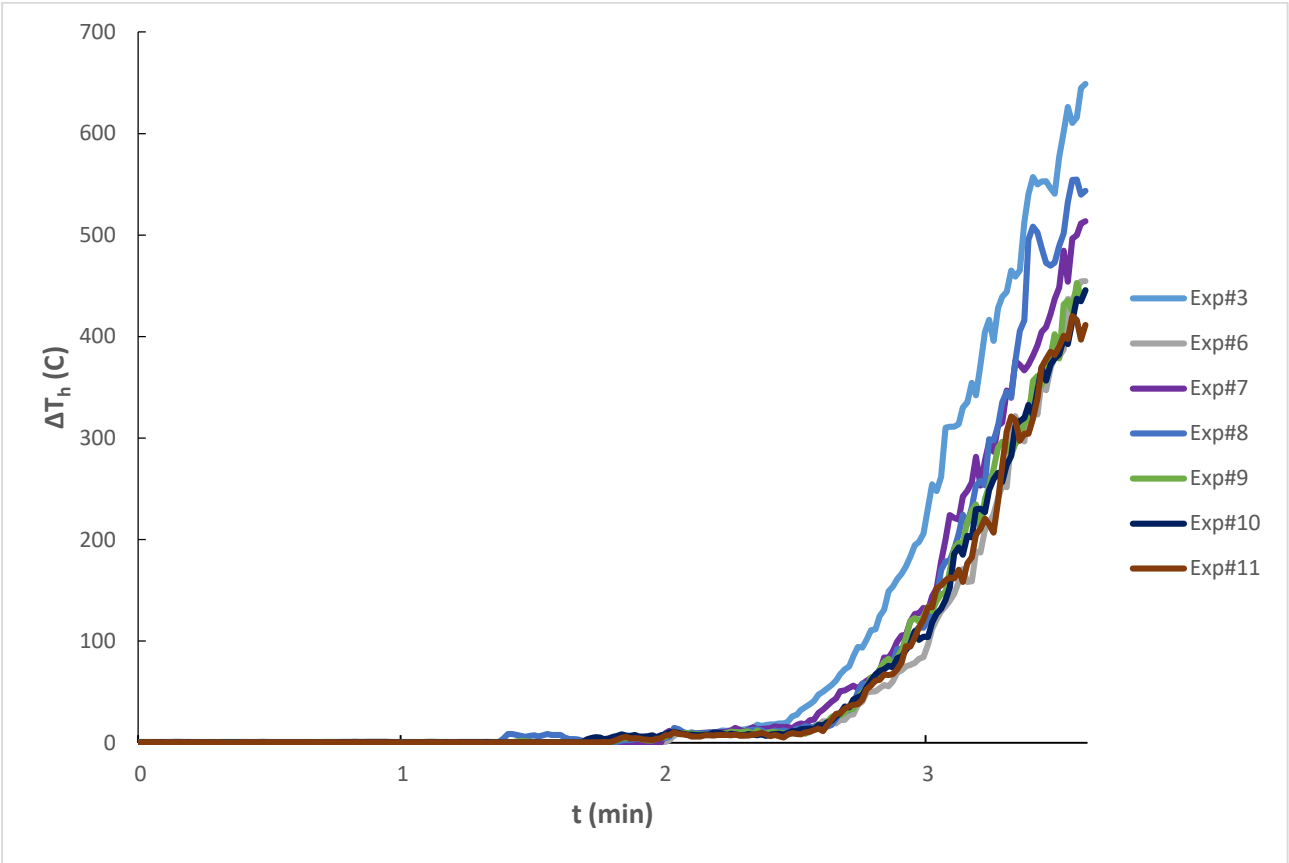


Figure 8. The temperature difference at ceiling level at thermocouple T7

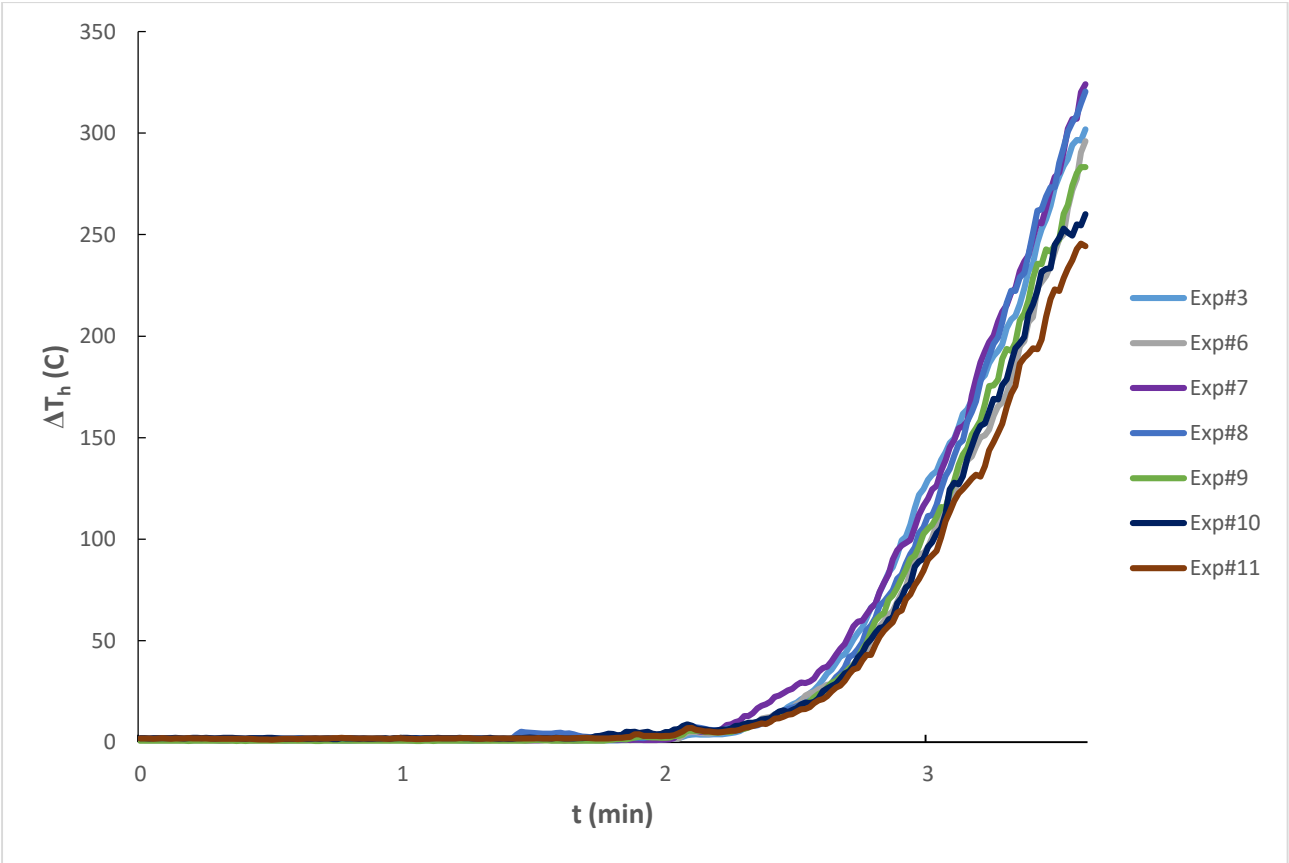


Figure 9. The temperature difference at ceiling level at thermocouple T10

4.2.1. Number of objects

The three experiments in table 2 were included in the analysis with identical distances between objects (wood cribs) but with varying number of objects.

Immediately downstream of the second wood crib, the ΔT_h of the three experiments - at the ignition of the second wood crib - was found to be at similar levels but with slightly higher temperature difference for experiment #1 involving a single wood crib. At 0.505 m (thermocouple T5) downstream of the third wood crib, the ΔT_h of the three experiments starts to clearly diverge as seen in figure 10 and display different degrees of stratification. The experiments involving multiple wood cribs can be seen to have a larger degree of stratification at this distance. Further downstream, the ΔT_h of experiment #4 undergoes a larger degree of mixing and cooling compared with experiment #3. At 4.255 m (pile B) downstream of the third wood crib, experiment #3 displays the highest ΔT_h of the three experiments and experiment #1 the lowest as seen in figure 11. Multiple objects would seem to lead to an increased degree of stratification compared with a single burning object, but an increasing number of objects downstream will not by itself lead to increased stratification if studying the results in figure 11.

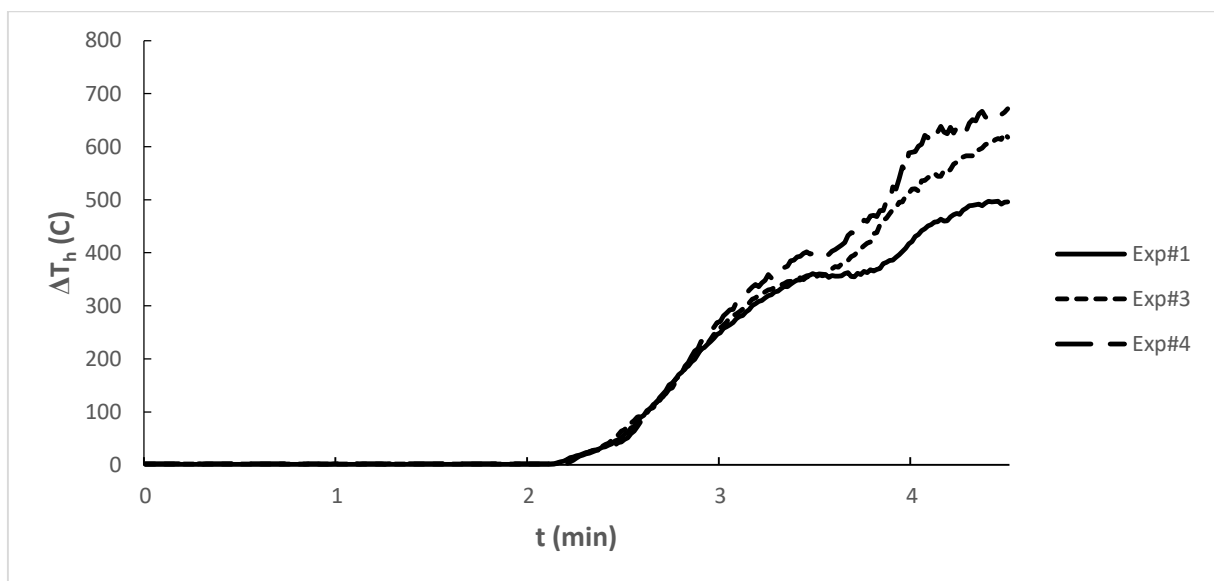


Figure 10. The temperature difference at ceiling level at 0.505 m downstream of the third wood crib

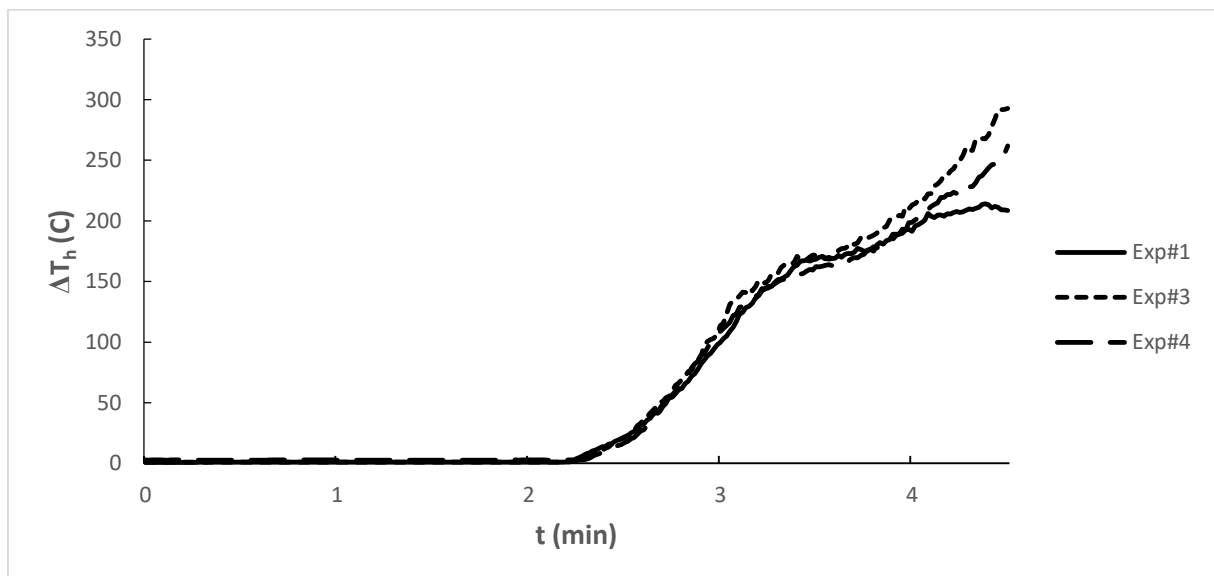


Figure 11. The temperature difference at ceiling level at 4.255 m downstream of the third wood crib

From the experiments conducted by Hansen and Ingason [7], the following experiments and comparisons were included (see table 1): experiment #1 was compared with experiment #2, and experiment #4 was compared with experiments #3 and #11. In the experiments involving multiple objects, the free distance between the objects were varied.

When comparing experiment #1 and #2, the entire time period was included as only the first pile of pallets burned in experiment #2 and the heat release rates would thus be similar. At thermocouples T8 (0.45 m downstream of the second pile in experiment #2) and T9 (positioned above the third pile) the temperature difference at ceiling level was higher for experiment #1 as experiment #2 experienced increased mixing when the gas flow passed piles of pallets. From thermocouple T10 (positioned above the fourth pile) and further downstream, the differences between experiments #1 and #2 was negligible except for the later part of the decaying phase (figure 12 displays the temperature differences at ceiling level 2.35 m downstream of the fourth pile of pallets).

In experiments #3 and #4, the degree of stratification was larger in experiment #4 compared to experiment #3 during the passage of the multiple piles of pallets. Further downstream at ample distance from the fourth pile, the degree of stratification is larger in experiment #3 as seen in figure 13. When comparing experiments #4 and #11 (see figure 14), the degree of stratification was larger in experiment #4 at all measuring points at ceiling level throughout the mine drift. The difference between experiments #3 and #11 was the individual distances between the piles of pallets. Comparing with experiment #4 – containing only the burning pile – the impact of the distances versus the number of objects is clearly seen. With shorter distances between the objects and an increasing number of objects, the smoke stratification will be retained for a longer distance.

The main and most significant difference between experiments #1 and #2, and the other experiments in this analysis is the longitudinal flow velocity. A flow velocity of 0.3 m/s in experiments #1 and #2 is only 50% of the flow velocity of the other experiments at 0.6 m/s. A lower longitudinal flow velocity would decrease the impact of multiple objects on the stratification.

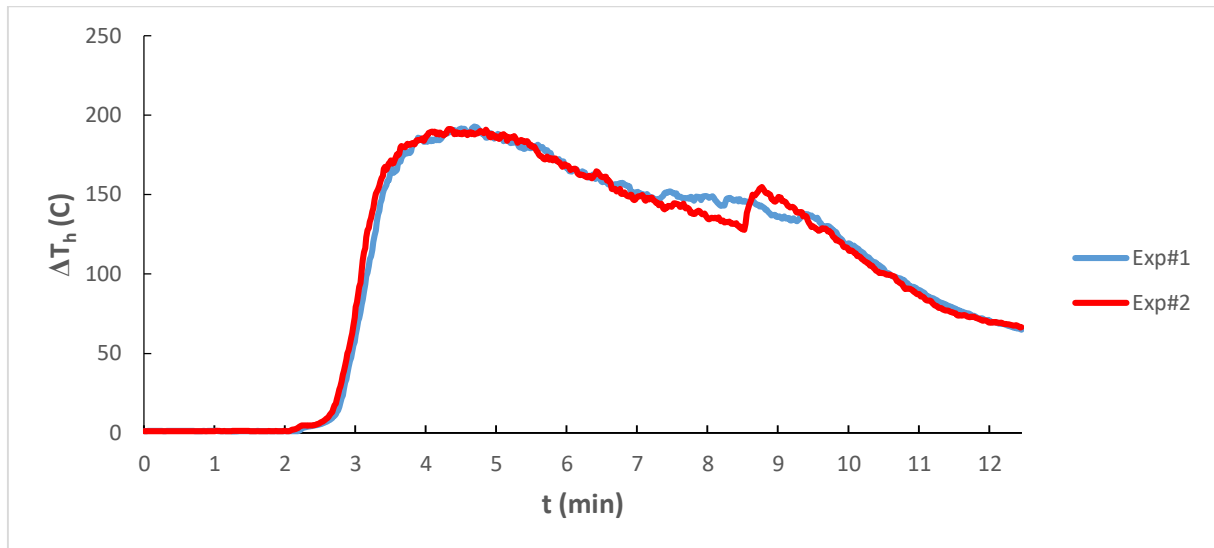


Figure 12. The temperature difference at ceiling level at 2.35 m downstream of the fourth pile of pallets

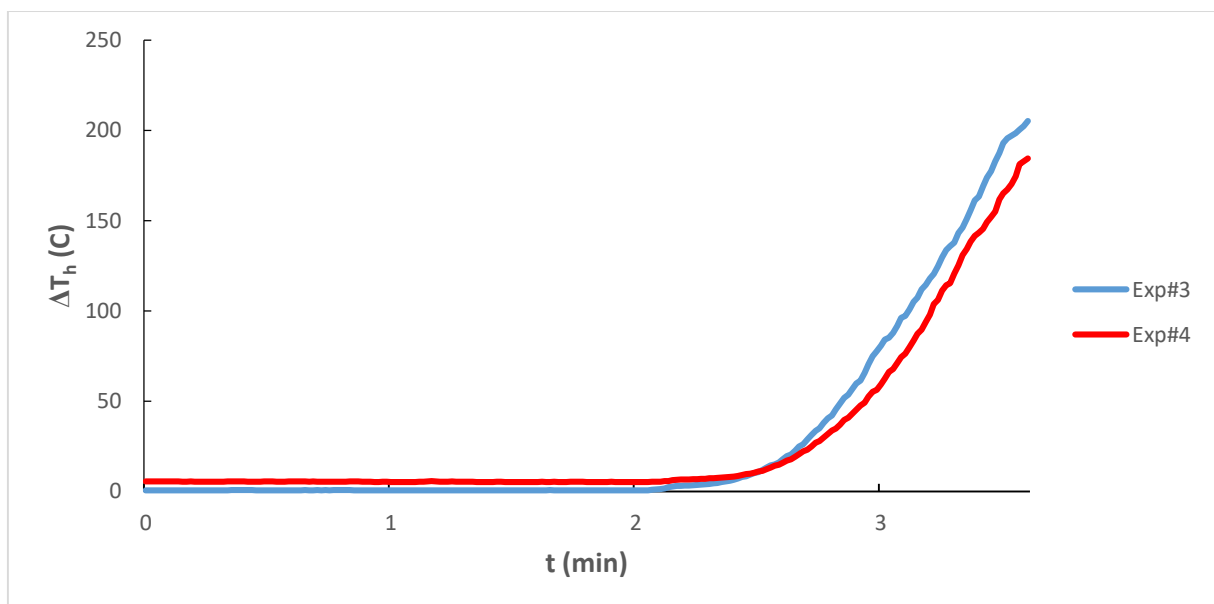


Figure 13. The temperature difference at ceiling level at thermocouple T12

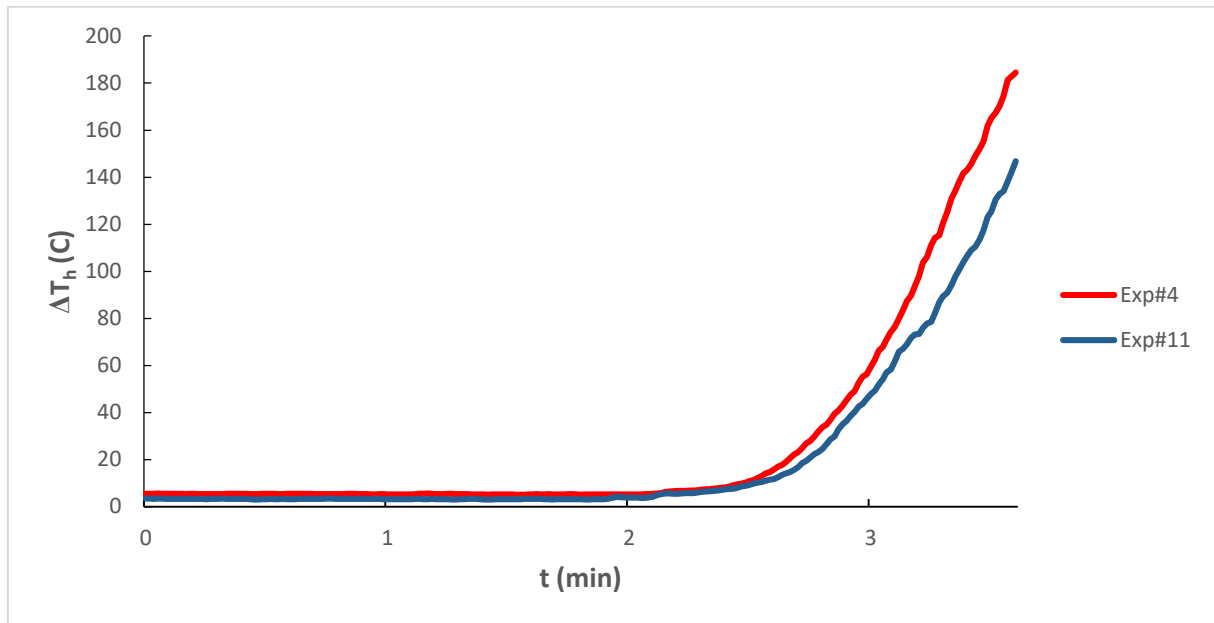


Figure 14. The temperature difference at ceiling level at thermocouple T12

4.3. CFD modelling results

The output results along the model-scale mine drift were taken at the same point of time – i.e., $t = 270$ s – to obtain the temperature field and velocity field at the same heat release rate and at a point of time where a higher heat release rate would result in differences which are more easily detected. The measured heat release rate from experiment #4 was applied in all simulations, as only the first pile of pallets participated in the fire in the simulations. The other piles of pallets downstream were modelled as inert objects. Total simulation time was 300 s, including a pre-ignition period of 120 s.

4.3.1. Varying the distances between the objects downstream of the burning object

To investigate occurring phenomena if applying different distances between the individual objects downstream of the burning object, the following distances were applied: 0.2 m, 0.4 m, and 0.6 m. In each simulation a constant distance between the objects was applied.

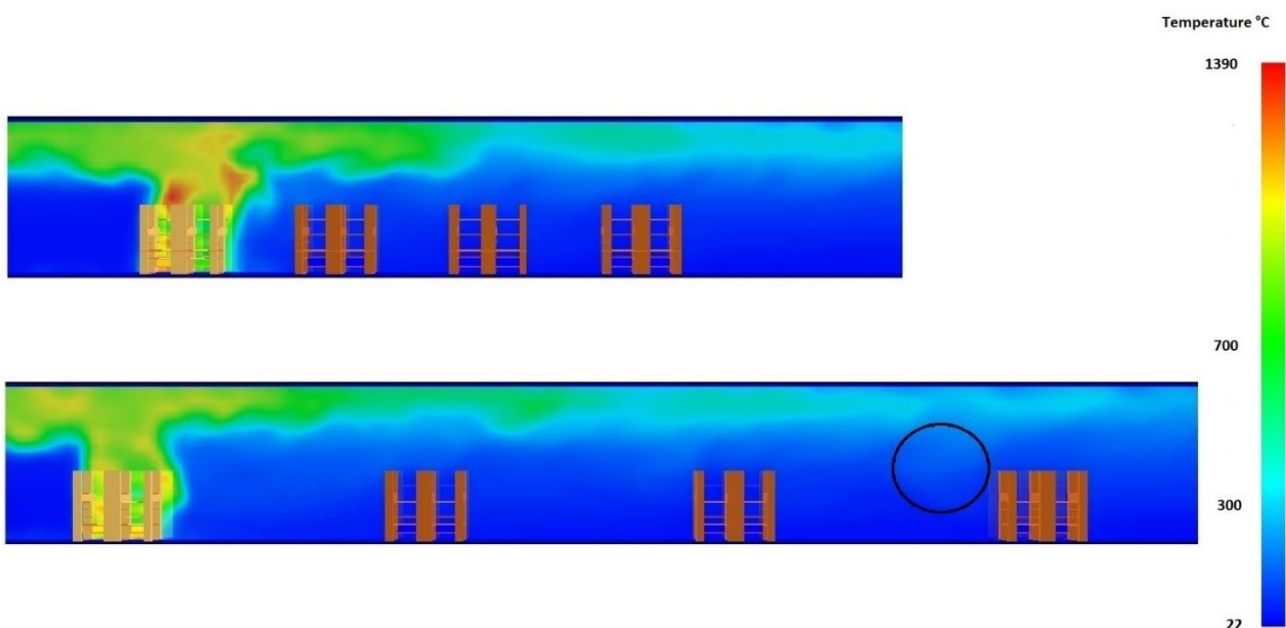


Figure 15. The temperature slice results for the 0.2 m distance (top) and the 0.6 m distance (bottom)

In the simulations it was seen that with a longer distance between the objects downstream, an increased degree of mixing occurred. The decrease in stratification was due to more and more mixing occurring on the upstream side of each object, adding to the mixing taking place downstream of each object due to the retardation and instability occurring at this position. The explanation of the increased upstream mixing can be found in figure 2, where the flow downstream of the object and the occurring eddies will start to fill up the volume between the two objects more and more with increasing distance and thus with increasing distance a larger portion of the flow of gases will hit the downstream object head on, resulting in increased mixing. Figure 15 displays the resulting temperature slice for a 0.2 m distance versus a 0.6 m distance. The increased mixing can foremost be seen on the upstream side of the piles (encircled area indicates the upstream side of the fourth pile with mixing of gases with higher temperature). As seen in figure 15, the mixing between the second and third pile in the 0.2 m case was insignificant, which is in line with the earlier observation from experiment #3 where the second pile had little effect on the stratification due to the short distance. Will the individual objects with decreasing distance start to act as a single, continuous object with less eddies, less instabilities, retained acceleration of the gases etc? Eddies will still occur on the downstream side of the objects and with ensuing instability, and the decrease in mixing will foremost be due to the lack of mixing upstream of each object and the shorter distance between objects decreasing the distance where mixing will take place.

4.3.2. Varying the distance between the burning object and the adjacent object downstream

With an increasing distance between the first – burning – pile of pallets and the second pile, the flowing gases will descend further down before encountering the second pile, the mixing on the upstream side of the second pile will thus increase and the stratification decrease. The increased mixing of the hot gases flowing from the first pile will have a more significant effect on the overall stratification due to the higher temperatures, compared with objects further downstream where the hot gases will be flowing at the ceiling level and will be less affected by the objects downstream. Figure 16 displays the temperature results for a 0.2 m and a 0.6 m distance between the first and second pile, where more mixing – temperature gradients - can be seen to take place in the 0.6 m case (encircled area). The earlier observation from the model-scale experiments regarding the influence of the distance between the first and second pile was therefore confirmed in the simulations.

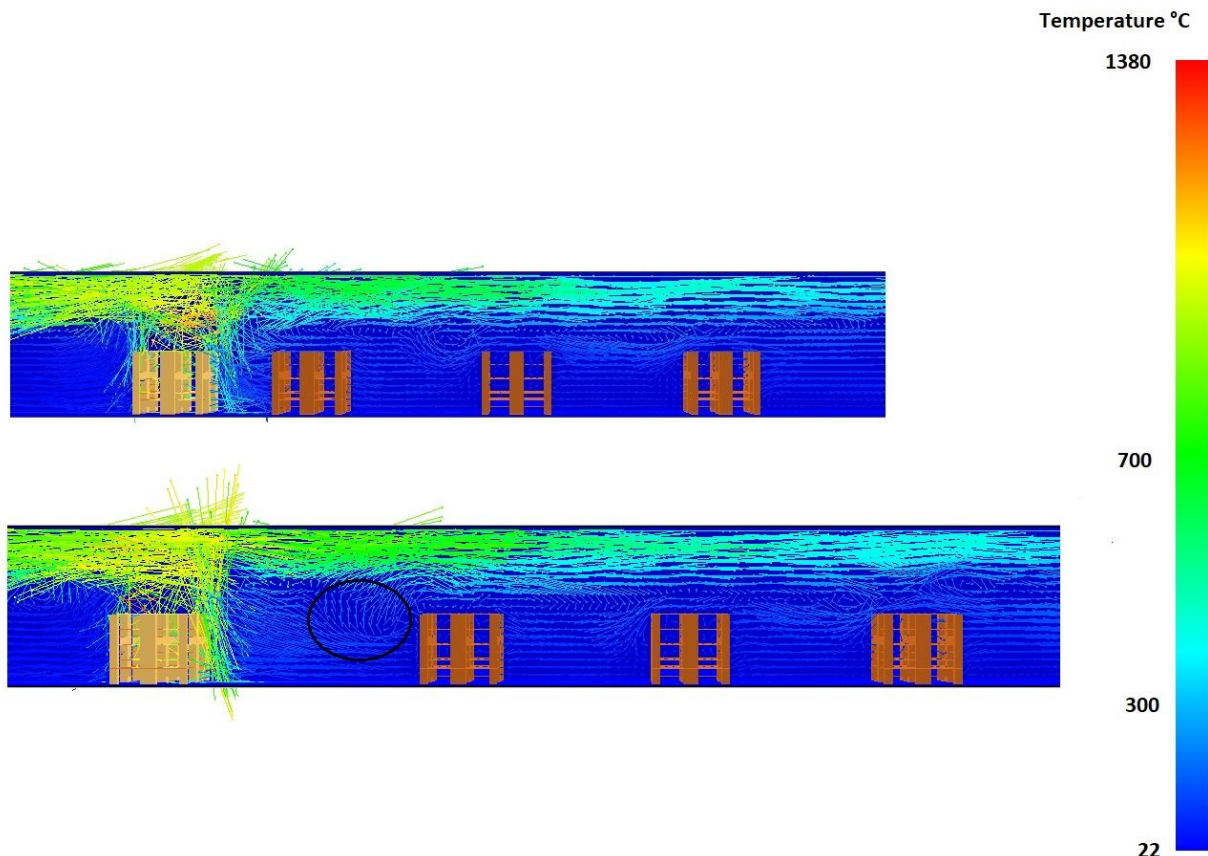


Figure 16. The temperature results for the 0.2 m distance between the first and second pile (top) and the 0.6 m distance (bottom)

4.3.3. Varying the distance between the third and fourth object downstream

With an increasing distance between the third pile of pallets and the fourth pile, the flowing gases will descend further down before encountering the fourth pile, the mixing on the upstream side of the fourth pile will thus increase and the stratification decrease. Still, the impact on the stratification will be less compared with a varying distance between the first, burning pile of pallets and the second pile. Figure 17 displays the temperature slice for a 0.4 m and a 0.8 m distance between the third and the fourth pile, where a lower degree of stratification and an extended region with mixing (encircled area) can be seen in the 0.8 m case.

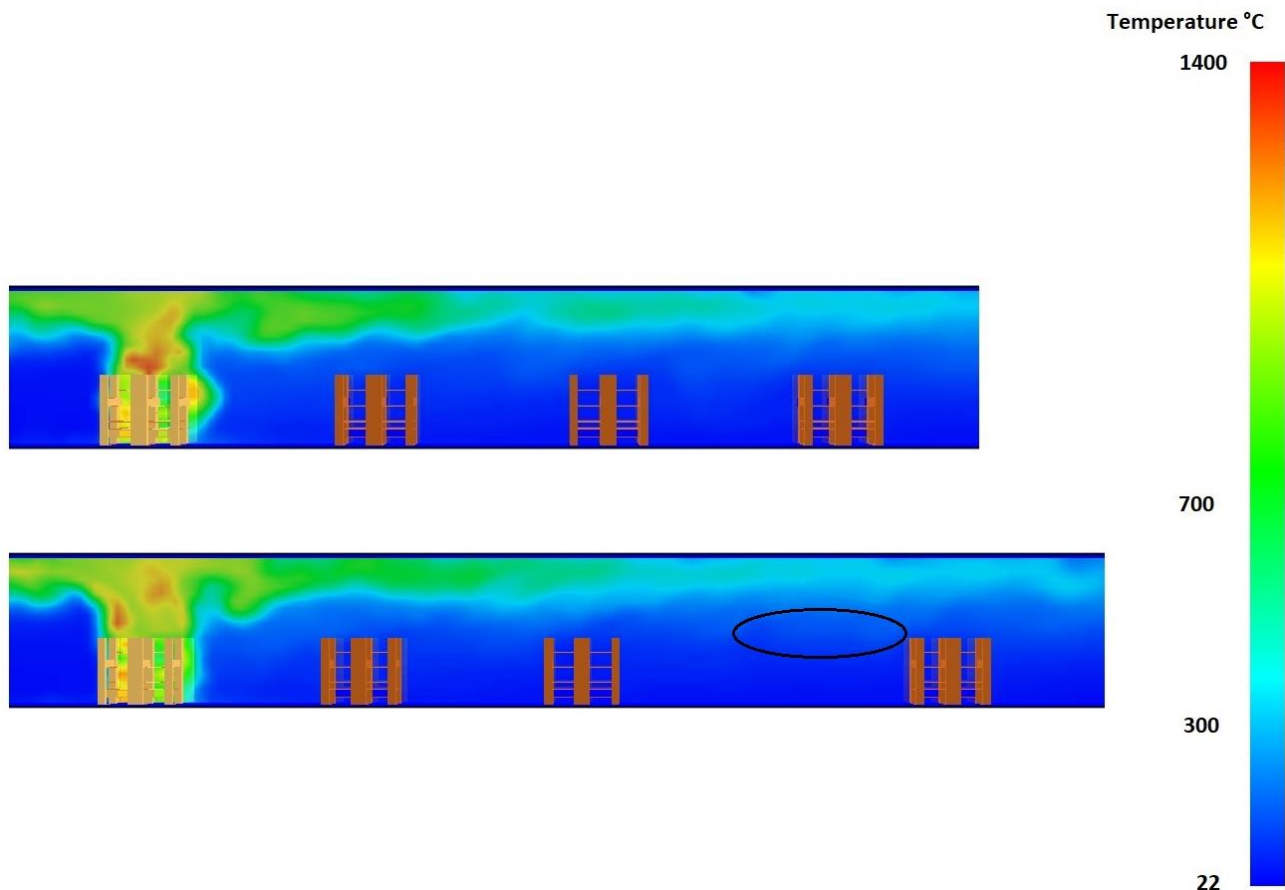


Figure 17. The temperature slice results for the 0.4 m distance between the third and fourth pile (top) and the 0.8 m distance (bottom)

4.3.4. Varying the longitudinal flow velocity

An increasing longitudinal flow velocity resulted in increased mixing and decreasing stratification in the simulations. The increased mixing was foremost found downstream of the first pile – of burning – pallets, as the tilt of the plume increased and interacted increasingly with the second pile downstream. Figure 18 displays the temperature slice for the 0.6 m/s and the 1.2 m/s flow velocity case. The distance between the individual piles was 0.4 m in both cases. As mentioned earlier, a lower longitudinal flow velocity would thus decrease the impact of multiple objects on the stratification.

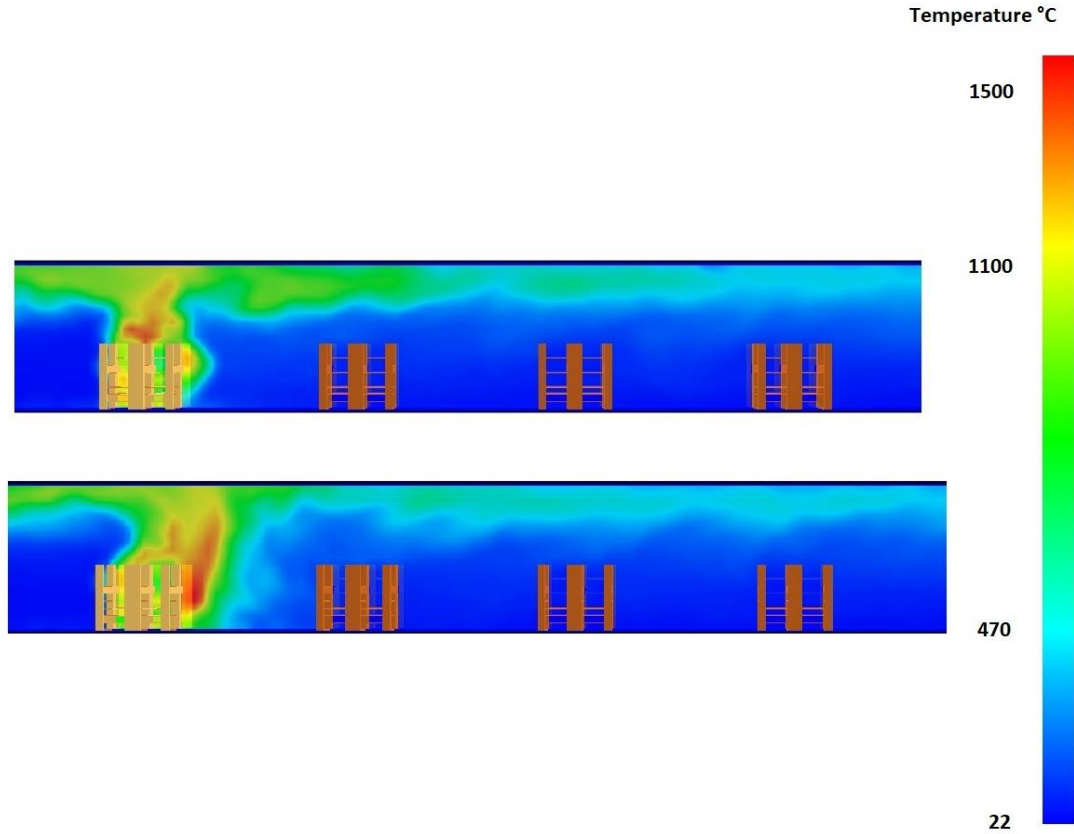


Figure 18. The temperature slice results for the 0.6 m/s flow velocity (top) and the 1.2 m/s flow velocity (bottom)

4.4. Full-scale dimensions and heat release rate

The theory of dimensionless groups allows for a translation of the model-scale results, as a well-defined similarity exists between the model-scale results and the corresponding full-scale results [13-15]. Equations (5-6) contain the scaling models for the heat release rate and the flow velocity. The index F seen in equations (5-6) relates to the full-scale (i.e., 15 in the case of the model-scale experiments with varying distance between fuel items [7]) and the index M relates to the model-scale (i.e., 1 in this case). A model-scale length of 1 m would therefore be equivalent to 15 m in full-scale, when comparing the results from the model-scale experiments by Hansen and Ingason [7].

$$\text{Heat release rate:} \quad \dot{Q}_F = \dot{Q}_M \cdot \left(\frac{L_F}{L_M}\right)^{5/2} \quad (5)$$

$$\text{Flow velocity:} \quad u_F = u_M \cdot \left(\frac{L_F}{L_M}\right)^{1/2} \quad (6)$$

where $\dot{Q}$ is the heat release rate [kW], u is the flow velocity [m/s] and L is the length [m].

The equivalent full-scale distance between the first pile of pallets and the second pile in experiment #3 would be 6 m. This distance was found to result in decisively different smoke stratification compared with cases with longer distances and even the case with only a single, burning object in the model-scale mine drift. In a mine drift or a road tunnel, the distance between objects would most likely be less than 6 m and thus a retained smoke stratification could be expected for a longer distance.

The maximum temperature difference at thermocouple pile A was 110°C (experiment #3 versus experiment #11). The equivalent full-scale distance between the burning pile of pallets and thermocouple pile A would be 18.75 m. The equivalent full-scale distance between the burning pile of pallets and thermocouple pile B (with a maximum temperature difference of 60°C) would be 80.25 m. Thus, at significant distances from the fire, the differences in temperature and thus also smoke stratification would be considerable for the different scenarios with various distances between the objects downstream of the fire.

The equivalent full-scale height of each pile of pallets would be 2.7 m, which approximately corresponds to the height of larger mining vehicles but will be somewhat lower than the heavy goods vehicles found in road tunnels. A lower degree of stratification – for otherwise identical conditions – could therefore be expected in road tunnels.

The equivalent full-scale heat release rate at the time when the earliest ignition of the second pile of pallets would take place is approximately 88 MW, which is a substantially high heat release rate for a fire in a mine drift. This heat release rate would likely involve several larger vehicles or larger amounts of flammable liquid.

4.5. Further research

The fire experiments which this study is based on, were conducted in model-scale mine drifts with similar cross-sectional dimensions and distances between top of the objects and the ceiling. Different ceiling heights versus different heights of objects will affect the smoke stratification downstream as an increasing height of the object and a decreasing distance between the object and the ceiling will increase the likelihood of the occurring eddies downstream of the object. Higher objects and longer distances to adjacent objects will also increase the mixing – thus decreasing the stratification – on the upstream side of the objects. Further research into the impact of various heights and distances between the objects downstream and the mine drift ceiling would be of interest.

The longitudinal flow velocity in the conducted fire experiments had similar magnitudes in a majority of the experiments. A further study on the smoke stratification with multiple objects downstream and with various flow velocities would be of interest.

A fire scenario in a mine drift or a tunnel with multiple objects downstream would most likely involve objects of varying heights. The flow field in a mine drift with objects of various heights would be highly affected, with increasing complexity. Further research into this issue is justified and of high interest.

5. Conclusions

The smoke stratification in a mine drift with a longitudinal ventilation flow and with several objects downstream of a burning object was analysed, applying data from model-scale fire experiments, and performing CFD modelling. The focus of the study was to investigate the impact of multiple objects on the smoke stratification in a mine drift, at varying distances, number of objects and longitudinal flow velocities. It was found that:

(1) Even at considerable downstream distances from the fire, the temperature differences were significant and thus also the smoke stratification differences. This reflects the high impact of multiple objects on the smoke stratification.

(2) With an increasing distance between the objects downstream, an increased degree of mixing occurred. The decrease in stratification was due to more and more mixing occurring on the upstream side of each object, adding to the mixing taking place downstream of each object due to the retardation and instability occurring at this position.

(3) With an increasing distance between the first – burning – object and the second object downstream, the smoke layer will descend further down before encountering the object, the mixing on the upstream side of the second object will thus increase and the stratification decrease. The increased mixing of the hot gases flowing from the burning object will have a more significant effect on the overall stratification due to the higher temperatures, compared with objects further downstream where the hot gases will be flowing at the ceiling level and will be less affected by the objects downstream.

(4) An increasing number of objects downstream will not by itself lead to increased stratification, with shorter distances between the objects and an increasing number of objects, the smoke stratification may instead be retained for a longer distance.

(5) An increasing longitudinal flow velocity will result in increased mixing and decreasing stratification. The increased mixing will foremost be found downstream of the first – burning – object, as the tilt of the plume will increase and interact increasingly with the second object downstream.

The findings of the study will increase the knowledge of the occurring smoke stratification underground, which would increase the safety of the personnel underground and the fire and rescue personnel during the initial and critical evacuation phase of a fire as well as the later phases when fire suppression may take place. The findings of the study will also have bearing on tunnel fire safety, with a fire scenario with multiple vehicles caught downstream of the fire.

Acknowledgments

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