



Analysis of Muskö tunnel fire flows with automatic sprinkler activation

Ying Zhen Li and Haukur Ingason

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Abstract

The focus of the present study is analyzing the best position of a sprinkler nozzle in a tunnel cross-section in the Muskö tunnel, south of Stockholm, Sweden. Activation of the sprinklers installed along the centerline and along the sidewall is investigated through analysis of full scale experiments and by three dimensional numerical modelling. Then the tunnel velocity is analyzed by one dimensional numerical modelling for various fire locations in the Muskö tunnel. For both activating the automatic sprinklers nearby the fire and avoiding activation of the sprinklers further downstream, the automatic sprinklers are recommended to be installed along the centerline of the tunnel. It has also been found that the tunnel velocity varies significantly with the fire location. When the fire is on the left side of the tunnel, the flow velocity mostly remains in a range of 1 m/s (positive or negative) within the first 10 minutes, which helps early activation of the automatic sprinklers. When the fire is on the right side of the tunnel, the flow velocity mostly remains within a range of -1 m/s and 1 m/s within the first 5 minutes, and the velocity mostly increases to 2 m/s at around 10 min. Therefore, the scenario for fire located on the left side is better than that for fire on the right side, especially when it is located between the middle of the right section and the right portal. As one typical case with fire on the right side, the tunnel velocity maintains at 1 m/s for the first 5 min and gradually increases to 2 m/s at 10 min. Under such conditions, the automatic sprinkler system is expected to perform well.

Key words: tunnel fire, tunnel velocity, automatic sprinkler, activation

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Preface

The research work was initiated by the Swedish Transport Administration (STA). Thanks to Ulf Lundström, Anna Niva and Audey Pules, who contributed to the discussion and preparation for this work.

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Summary

Activation of the sprinklers installed along the centerline and along the sidewall is investigated by analyzing a large scale test using automatic sprinkler and by three dimensional numerical modelling for tunnels of accurate shape. Further the fire generated tunnel velocity is analyzed by one dimensional numerical modelling for various fire locations in the Muskö tunnel.

For both early activation of the sprinklers nearby (due to higher temperatures for centered sprinklers) and avoidance of activation of the sprinklers further downstream (due to slightly lower temperatures between 10 m and 20 m), the sprinklers are recommended to be installed along the centerline of the tunnel. Especially for an automatic sprinkler system, the activation of the sprinklers upstream is extremely important. This clearly indicates that the sprinklers should be installed along the centerline. If the tunnel is rectangular and the height near sidewall is the same at the centerline, the side sprinkler may also be installed, but apparently this is not the case in this project.

It has also been found that the tunnel velocity varies significantly with the fire location. When the fire is on the left side of the tunnel, the flow velocity mostly remains in a range of 1 m/s (positive or negative) within the first 10 minutes, which helps early activation of the automatic sprinklers. When the fire is on the right side of the tunnel, the flow velocity mostly remains within a range of -1 m/s and 1 m/s within the first 5 minutes, and the velocity mostly increases to 2 m/s at around 10 min. Therefore, the scenario for fire located on left side is better than that for fire on the right side, especially when the fire is located between the middle of the right section and the right portal.

For performance of such an automatic sprinkler system in a tunnel, the early activation is of utmost importance. This period is estimated to be around 10 min, when the fire size is less than 10 MW. As one typical case with fire on the right side, the tunnel velocity maintains at 1 m/s for the first 5 min and gradually increases to 2 m/s at 10 min. Under such conditions, the automatic sprinkler system is expected to perform well.

1 Introduction

Nowadays, use of water-based fire suppression systems in tunnels has attracted much attention, and the regulations and standards are also changing with regard to its use. In Sweden, there have been several projects planned to use Fixed Fire Fighting Systems (FFFS) (see Figure 1). The use of the term FFFS in road tunnels is related to zone operated water based systems. The activation is carried out in control rooms on demand from an alarm system. If the system is using automatic thermal device, the system is usually called automatic sprinkler system as the nozzle usually comes from traditional manufacturing of sprinkler heads.

Use of automatic sprinklers is common in commercial buildings, such as high-rise office buildings, and industrial premises. The automatic sprinklers are generally activated by subsidiary thermal elements, e.g. thermal bulbs, and thus do not need other detection systems for activation. Therefore, such automatic sprinkler systems are simple and easy to use in practice. Automatic sprinklers, however, has not been used in any tunnels until now. The main concern is that the tunnel ventilation may have negative impact on activation of such sprinklers. A previous study showed that the system may fail at high ventilation, and therefore its use is only recommended for tunnels with low ventilation [1]. Indeed, the use of automatic sprinkler is attractive due to its simplicity under such ventilation conditions.

Activation of automatic sprinklers also depends on where the sprinklers are installed, e.g. along the centerline or along the sidewall. There is some difference in temperature for various locations. There have been many studies on longitudinal distribution of gas temperatures [2]. Some researchers also studies on transverse distribution of gas temperatures, but all correspond to no ventilation conditions. It can be expected that under higher ventilation, the temperature profile will be much different to that under no ventilation.

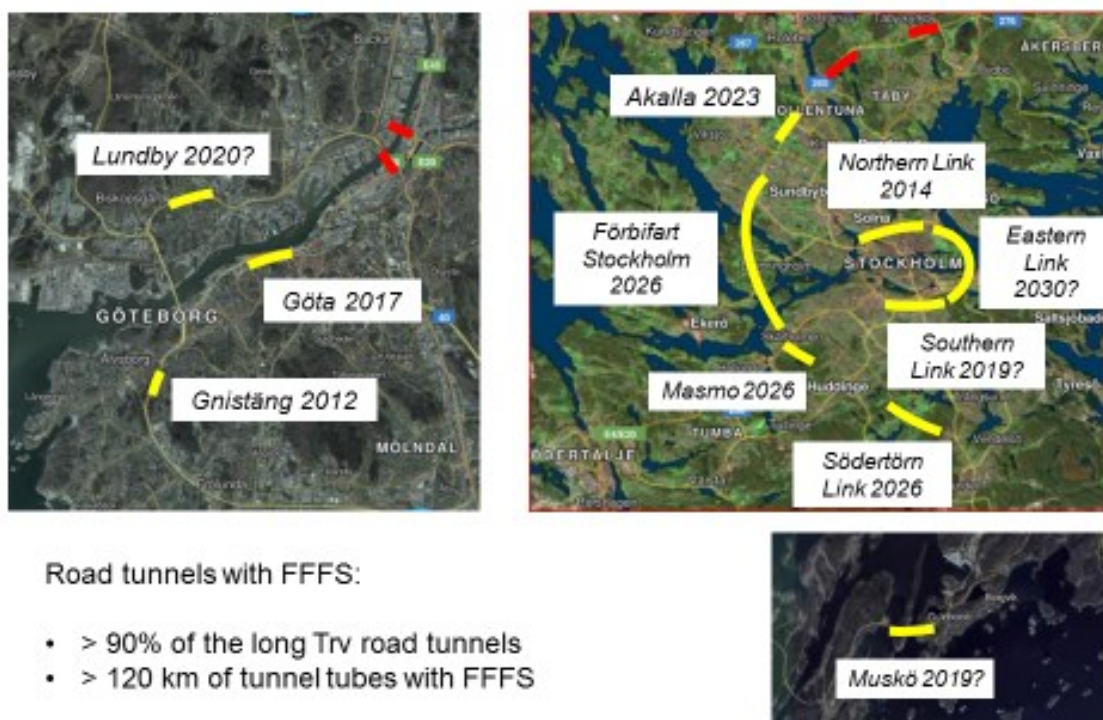


Figure 1. Planned tunnel projects and use of FFFS [3].

The key questions are:

- How large is the difference in temperature distribution across the section if the sprinklers are installed along sidewalls compared to centerline?
- How many sprinklers will be activated in a typical truck fire, assuming the fire size is the same as in Test 6 in the Runehammar tunnel?

There is an interest to install automatic sprinkler nozzles in the Muskö tunnel. Due to expected increase in traffic volume, an investigation on a simple FFFS was initiated by STA. The new sprinkler installation that is planned will be automatic. As there are no escape routes to safe regions within the tunnel, use of automatic sprinklers was considered as a solution to upgrade the existing tunnel.

There is a discussion on where to position the nozzles in relation to the cross-section. Should it be on the upper sidewall or in the center of the tunnel ceiling? Another question to ask is if the slope (5 and 7 %) of the tunnel may interfere with the activation time of the automatic nozzles chosen. An increase in velocity may influence the activation time and position of the first nozzle to activate. The use of automatic nozzles is rare and therefore need careful investigation before making any decisions. Therefore, simulations of longitudinal flows due to buoyancy effects for various fire positions are carried out.

The first step of the analysis was to investigate an existing large scale test that has been carried out. This was Test 6 in the Runehammar full scale test series carried out in June 2016 [4].

2 The Muskö tunnel

The Muskö tunnel is an existing underwater tunnel with a length of 2,912 m and bi-directional traffic flows, located 10 km south of Nynäsvägen (road 73) and 67 km south of Stockholm. The tunnel consists of several inclined sections (see Figure 2). By examining all the measured cross-section of the tunnel, the average cross-section was obtained – which is 7.7 m wide and 5.2 m high (see Figure 3). The tunnel roughness is assumed to be similar to that of the Runehammar tunnel [5], i.e. the roughness is around 0.1–0.3 m with an average value of 0.2 m. The friction coefficient is therefore around 0.06 [2]. The Muskö tunnel is a so-called subsea tunnel with a longitudinal slope of 5 to 7 %. The slope is 7 % on the Yxlö side, and 5 % on the Muskö side. A large portion of the tunnel is horizontal at the bottom. The bottom level of the tunnel is 65 m undersea. The Muskö tunnel is located 10 km south of Nynäsvägen (road 73) and 67 km south of Stockholm. It was originally built for military transportation but was open for regular traffic in 1996¹. The bottom level of the tunnel is 65 m under sea, see Figure 2. The tunnel is approximately 7–8 m wide and 4.5–5 m high.

¹ Brandskyddsdocumentation Muskötunneln, Arne Brodin 2011-04-25

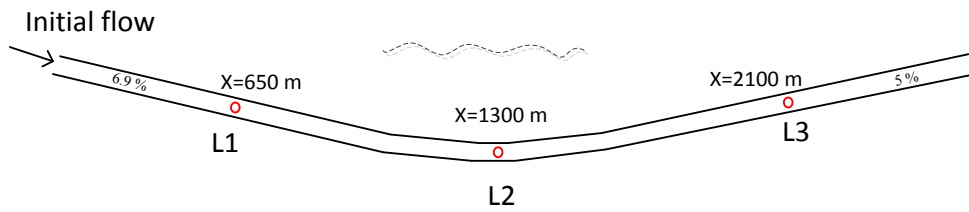


Figure 2. The profile of the Muskö tunnel.

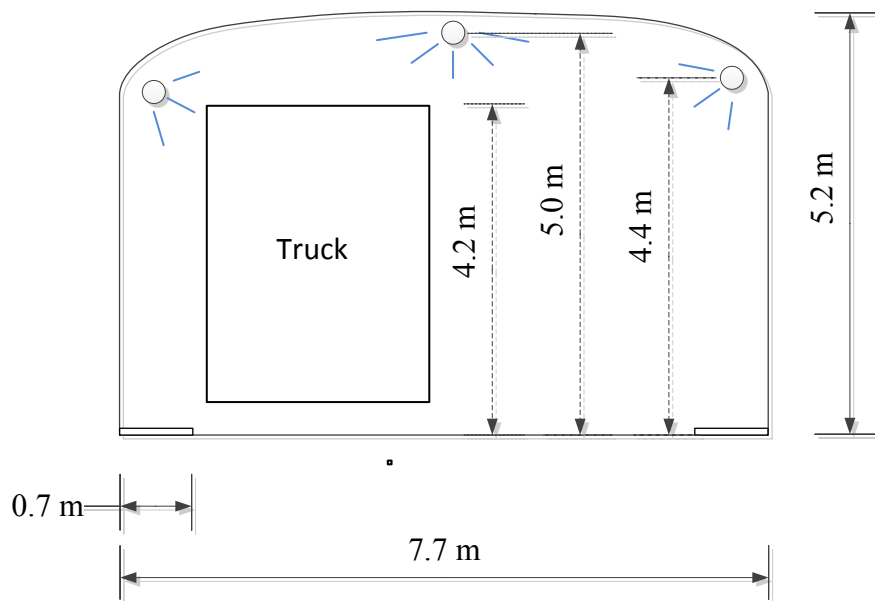


Figure 3. The cross-section of the Muskö tunnel.

To estimate the influence of meteorological conditions on the tunnel (e.g. wind), the tunnel velocity was measured during 19 - 22 February 2017. The measured tunnel velocity mostly lay between 0 and 1 m/s, and during a short period between 1 and 2 m/s. The velocity is mainly attributed to the small fans installed in the tunnel to create a small flow under normal ventilation condition. An average value of 1 m/s could be used in estimating this pressure difference. The corresponding pressure difference between the tunnel portals is around 18.5 Pa. During the measurement, the temperature in Stockholm was in a range of 1 and 7 °C. The tunnel air temperature is estimated to be around 10 °C.

3 Analysis of the large scale test nr 6 in the Runehammar tunnel

3.1 Test set up

Six large-scale tests with FFFS were carried out in the Runehammar tunnel in June 2016. The fire load consisted of 420 standardised wooden pallets and a target of 21 wooden pallets. The test setup was the same as for the tests carried out in Runehammar in 2013 [6]. Five of the 2016 tests were carried out with a 30 m long deluge zone delivering varying water densities using three different types of sidewall nozzle and an interval distance of 5 m. In total the length with nozzles were 25 m, see Figure 4. One test with 93°C glass-bulb nozzles (sprinkler head) in the same zone was also conducted. The SW-24 is an ECOH (Extended Coverage Ordinary Hazard) horizontal sidewall nozzle that uses a standard-response glass bulb, originally designed for use in ordinary hazard occupancies. The SW-24 sprinkler head used had a 3 mm-thick 93°C (green) glass bulb. This would correspond to a RTI value of $32 \text{ m}^{1/2} \text{ s}^{1/2}$, which would classify the nozzle as Quick Response.

In order to investigate the effects of position in a cross-section, Test 6 is a very good example to investigate further. The position of the nozzles used and the cross-section fits well for this investigation. Thermocouples were both located centrally at the ceiling and close to the sidewall nozzles. A detailed description of the locations and instrumentation is given below.

The nozzles were positioned at the ceiling (see Figure 4), 3.2 m from the centerline of the fuel load, and at a distance corresponding to $x = -12.5$ (N1), -7.5 (N2), -2.5 (N3), 2.5 (N4), 7.5 (N5), and 12.5 m (N6). The centerline ceiling thermocouples (type K, 0.5 mm) were placed 0.4 m below the ceiling. Thermocouples were also located close to the nozzle positions N2, N4, and N6. The thermocouples at N2, N4 and N6 were mounted 50 mm above the nozzle (see Figure 5). The bi-directional probe and the thermocouple upstream at $x = -50$ m were placed at the centerline of the tunnel cross-section.

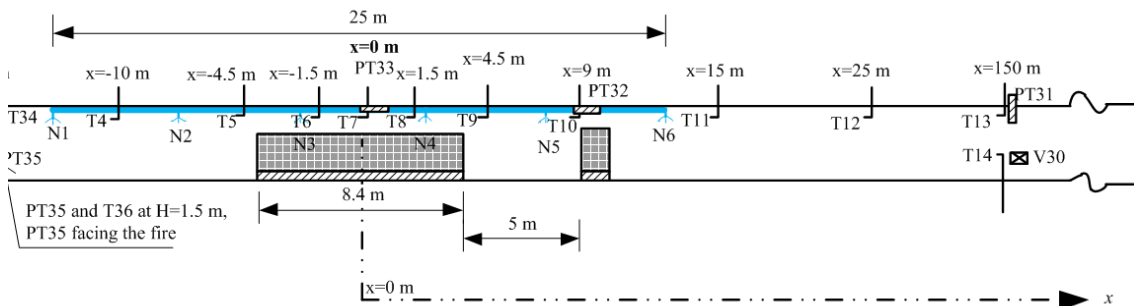


Figure 4. The layout of the instrumentation (T =thermocouples, PT =Plate Thermometer, V =velocity) and the nozzles N1-N6.



Figure 5 The nozzles were fitted with a T-coupling to a pipe with a diameter of 140 mm, located at the ceiling and close to the tunnel wall. The nozzles were mounted every 5 m, and sprayed water horizontally in one direction [6].

The important task here is to investigate the difference in gas temperatures during Test 6, both at the centerline of the ceiling and close to the nozzles. Unfortunately the thermocouples along the centerline and the nozzles did not match perfectly along the x-axis. Positions of interest here is N4 ($x=2.5$ m) and N6 ($x=12.5$ m), as for N2 ($x=-7.5$ m) there were no temperature development prior to activations of the first nozzles. This was due to the backlayering created by the 2 m/s longitudinal flow. Centerline thermocouples of interest are for comparison to N4 ($x=2.5$ m) thermocouples T8 at $x=1.5$ m and T9 at $x=4.5$ m. For comparison to N6 ($x=12.5$ m) thermocouples T10 at $x=9$ m and T11 at $x=15$ m, respectively, are used.

In Figure 6, the cross-section of the Runehammar tunnel test setup is shown. The thermocouples at the centerline were located 0.4 m below the ceiling and the thermocouples at the nozzle positions were 50 mm above the nozzles heads, which were positioned 4.65 m above the road surface (see Figure 6). The centerline tunnel height was 6 m, meaning the height up to the centerline thermocouples were about 5.6 m, whereas to the nozzle thermocouples it was approximately 5.15 m. This means that it was slightly lower at the nozzle locations and about 1.7 m from the sidewall. This difference in height and side position gives a good indication of what to expect in the Muskö tunnel, which have a similar cross-section.

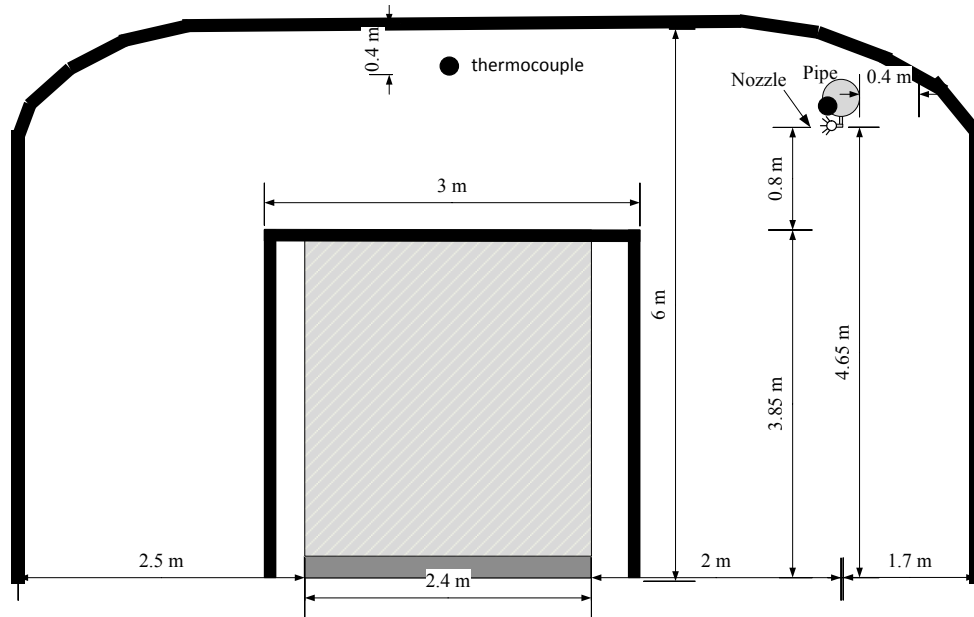


Figure 6. Cross-section of the test setup used for the large-scale tests [6]. The thermocouples are marked as a black solid circle.

3.2 Measured results from Test 6 in Runehamar

In the following graphs the gas temperatures are plotted for different locations.

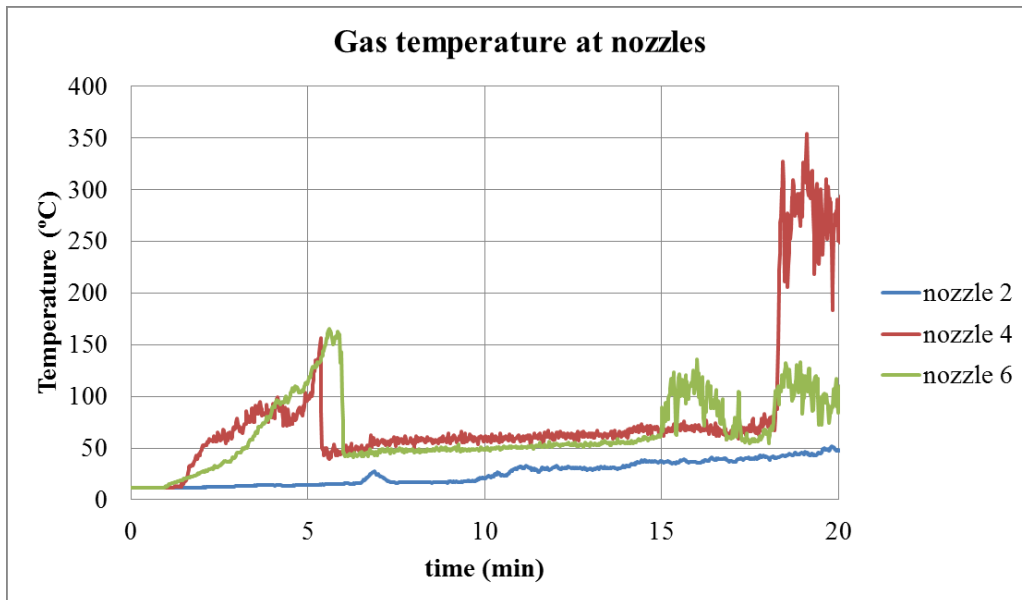


Figure 7 The measured gas temperatures at the nozzle locations N2, N4 and N6 during the first 20 minutes into the test. The first nozzle that activated was at time 5:22 min (N4), the second one was N5 after 5:45, followed by N3 at 6:47 and finally N6 at 30:56 min.

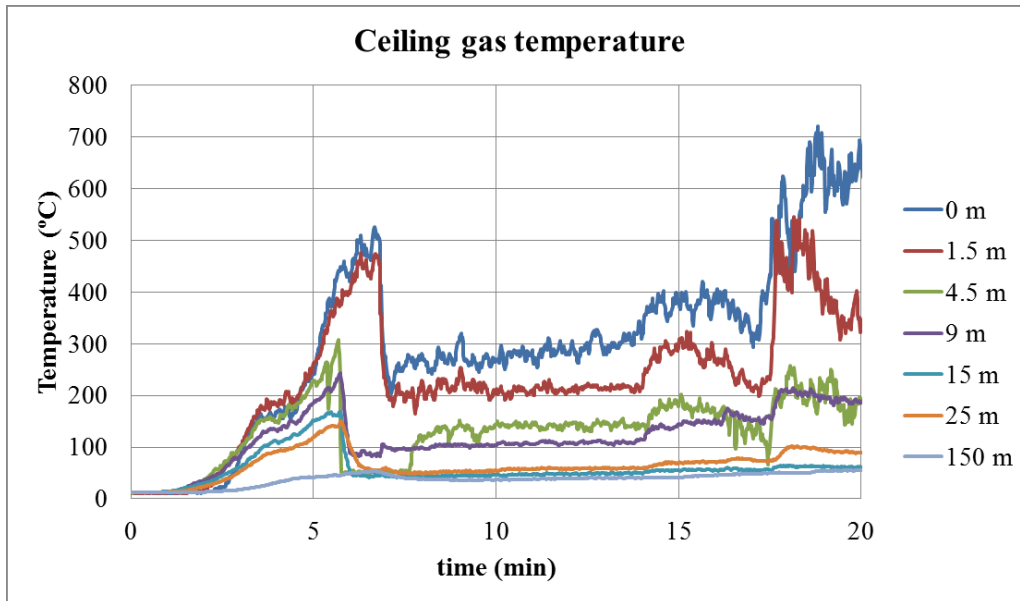


Figure 8. The measured centerline gas temperature at the ceiling (0.4 m below) for $x=0, 1.5, 4.5, 9, 15, 25$ and 150 m.

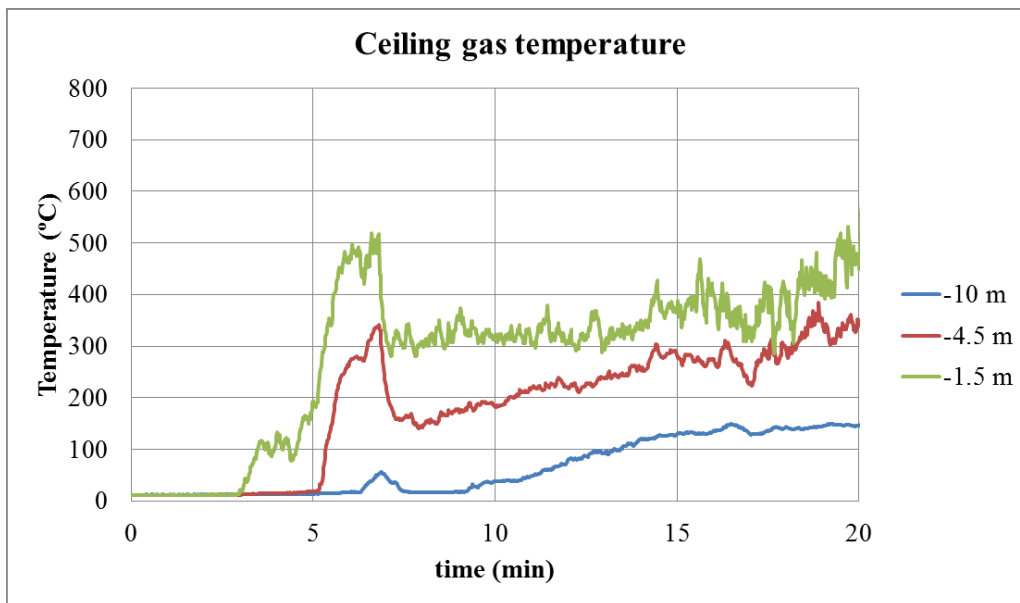


Figure 9. The measured centerline gas temperature at the ceiling (0.4 m below) for $x=-10, -4.5$ and -1.5 m.

When a glass bulb was activated, water sprayed from that nozzle and the pump was activated. This created a short pressure drop, but this was recovered as soon as the pump built up the pressure to maximum again (see Figure 10). The total backlayering after around 30 minutes was approximately 40 m.

The activation sequence of the nozzles is of particular interest here. All six sprinkler nozzles were equipped with bulbs (N1 to N6). There were also additional single bulbs mounted at various points downstream of the fire in order to indicate if, and where, the temperature rose above 93°C (the bulb temperature at which the bulbs break). The locations of these bulbs were

$x = 17.5$, 27.5 , and 47.5 m, respectively. It should be noted that no water was connected to these bulbs, and so they did not contribute by cooling of hot air after $x = 17.5$ m.

The nozzle pressure and flow measurements give a very good indication of what occurred when the first sprinkler head opened. Sprinkler nozzle N4 activated first at 5 minutes and 20 seconds where the identification of N4 was done from photos and registered a pressure gauge (see Figure 10). The pressure dropped from 5 bar (when the valve was closed) to 0.5 bar (when N4 opened). When this occurs the pump builds up the pressure again to over 6 bar and 1,000 l/min for a very short period. At 5:45 a clear change is observed in the character of the flow pattern. At this time the total flow become 750 l/min. Figure 10 shows both pressure and flow rate over the first 10 minutes. Exactly when the second sprinkler head opened is not possible to say, but it certainly took place between 5:22 and 5:45. The flow rate at this point was 750 l/min, and the water pressure was 5.5 bar, corresponding exactly to two open sprinkler heads. At 6:47, N3 activated, and at 30:56 N6 (the last sprinkler head) activated. After the test it was found that all three of the additional glass bulbs mounted downstream the sprinkler heads had been broken as well. The activation sequence of the sprinkler nozzles is summarized here:

N4; 5:22 min, N5; 5:45 min, N3; 6:47 min and N6; 30:56 min

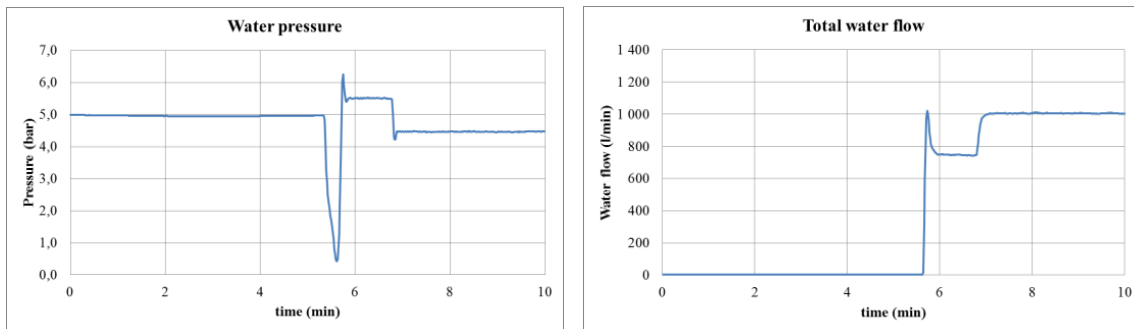


Figure 10. Water pressure during Test 6 (Left) and Water flow rate during Test 6 (Right).

The order of the activation of the first three sprinklers is quite logical. First to activate is N4 ($x = 2.5$ m) at 5:22 min which is positioned about 6.7 m ($4.2 + 2.5$ m) from the fire origin (rear end of platform). With 2 m/s one could expect the highest ceiling temperatures in this range. As can be observed in Figure 11, the gas temperature close to nozzle N4 was 156 °C when it was activated. Corresponding centerline gas temperatures are in the range of 320–260 °C (TC8 and TC9, respectively). The second one to activate is N5 ($x = 7.5$ m) at time 5:45 which is additionally 5 m downstream N4, i.e. about 11.7 m from the fire origin. Corresponding centerline temperature is in the range of 320–240 °C, (see TC9 at $x = 4.5$ m and TC10 at $x = 9$ m). The temperature difference between the side-wall and the centerline is expected to reduce further away from the fire due to mixing of warm and cold air downstream the fire source. The third one to activate N3 is the closest one to the fire which has increased in size since the first activated. The corresponding centerline temperature at activation of N3 ($x = -2.5$ m) is about 320–500 °C, see Figure 9 for $x = -4.5$ and -1.5 m. The last one to activate is N6 ($x = 12.5$ m), i.e. 16.7 m ($12.5 + 4.2$ m) downstream the fire origin, at the time 30:56 min:s. The corresponding centerline temperature is about 240 °C (see Figure 13). These measurements become more and

more difficult to rely on as the water cooling of the already activated nozzles upstream starts to influence the thermocouples more and more.

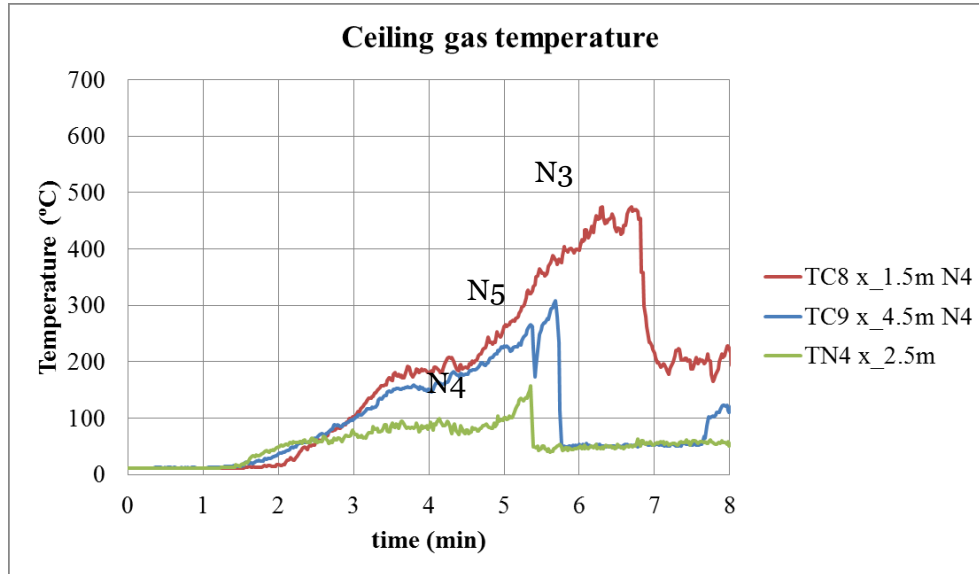


Figure 11. The centerline gas temperatures TC8 and TC9 plotted together with N4 gas temperature.

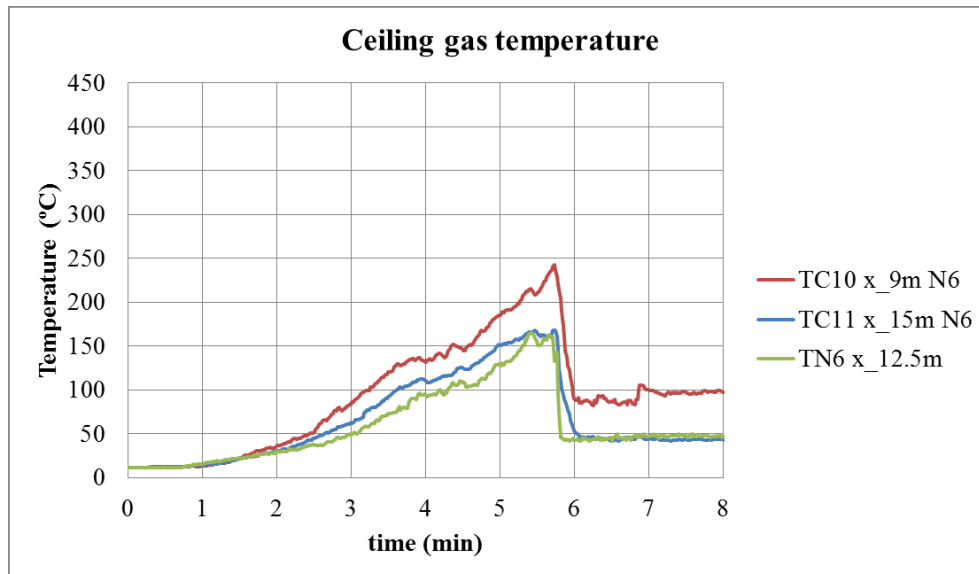


Figure 12. The centerline gas temperatures TC10 and TC11 plotted together with N4 gas temperature.

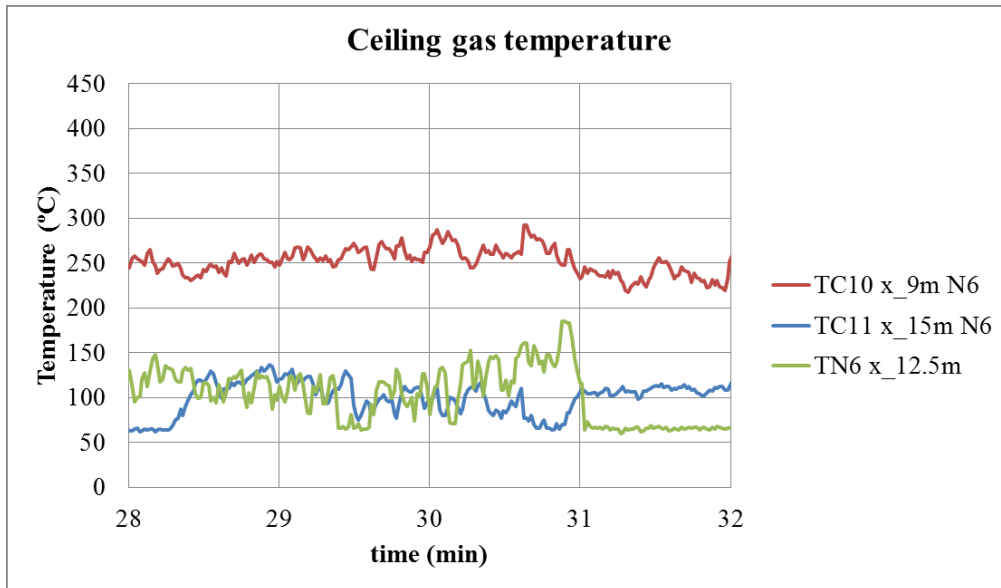


Figure 13. The gas temperature close to N6 just prior to activation.

The analysis shows numerous interesting things in the early stage of the activation period. As expected from earlier research [7], the nozzle that is slightly more than the tunnel height distance away from the origin activates first (N4), followed by one or two (N5 and N6) close to that position, but downstream them. Here only N5 activated, but as can be seen in Figure 12, it was very close the operational gas temperature of about 150 °C. These nozzles start directly to cool down the hot gases downstream and have very little impact on the fire itself. This explains why N6 operated much later. As the fire grows, the temperature increases close to the fire, and finally the one closest (N3) will operate and the entire area downstream the fire is cooled as well as the fire itself starts to reduce. This can be observed in the heat release rate curves found in the test report [4]. The fire growth rate was clearly reduced.

The difference between the centerline temperature and the sidewall temperature is highest closer to the origin of the fire (downstream origin). The difference can be over one hundred degrees Celsius or more. Further downstream, this difference is reduced as the mixing of hot air from the fire and cold air bypassing the fire is mixed. In this specific test, one could say that probably the N4 nozzle would have activated at least 2 minutes earlier if located at the centerline. Also, most likely upstream nozzles located at the centerline would have operated due to the backlayering. The single bulbs located below indicate an operational area for sprinkler of around 50 m. If these bulbs would have been connected to a water supply, this would be shorter. Considering a possible backlayering, using a 50 m long section for design of an automatic system is reasonable.

In the following, a one- and three-dimensional analysis of the effects on activation time of an automatic sprinkler system is carried out.

4 Automatic sprinkler system

The automatic sprinklers are assumed to be positioned along the centerline and at the sidewall. Two sprinklers were pre-chosen for placement at the centerline – Tyco TY9128 with K factor of 363, link temperatures of 74 or 100 °C, K factor of around 20 and operating pressure of around 0.9 bar – and one for sidewall – Tyco TY6137 with K factor of 202 and link temperatures of 93 or 100 °C , a K factor of 30–35 and operating pressure of 2.8 bar.

Each sprinkler covers an area of 7.7 m (W) × 4.6 m (L). The reason for choosing these nozzles is that they were tested concerning the water spray pattern. The results from these tests are given in Arvidson and Vylund [8].

Table 1. Parameters for possible sprinklers installed.

Sprinklers	Density	Pressure	K factor	Link temperature	RTI	Flow	Flow rate
	mm/min	bar		°C	$m^{1/2}s^{1/2}$	mm/min	L/min
Tyco TY9128	10	0.9	363	74/100	20	10	354
Tyco TY6137	10	2.4	202	93	30–35	10	354

5 Methodology

One dimensional and three-dimensional modelling was conducted. The one-dimensional modelling was carried with TunnelFireFlow to investigate the tunnel velocity for fires at various locations [9], and the three dimensional modelling was carried out using the latest Fire Dynamics Simulator (FDS) [10] to investigate the influence of installation locations on the sprinkler activation.

In this project, the fire scenario is assumed to be the same as the one in the Runehamar fire suppression test 6 in 2016 [11]. In the test 6, the performance of an automatic sprinkler system similar to the one that is planned to be installed was tested, therefore the results are considered to be a good reference. Details about these tests are found in Chapter 3 in this report. In other words, the interaction of automatic sprinkler and the fire development was not explicitly modelled but directly considered in terms of heat release rates.

6 Sprinkler activation

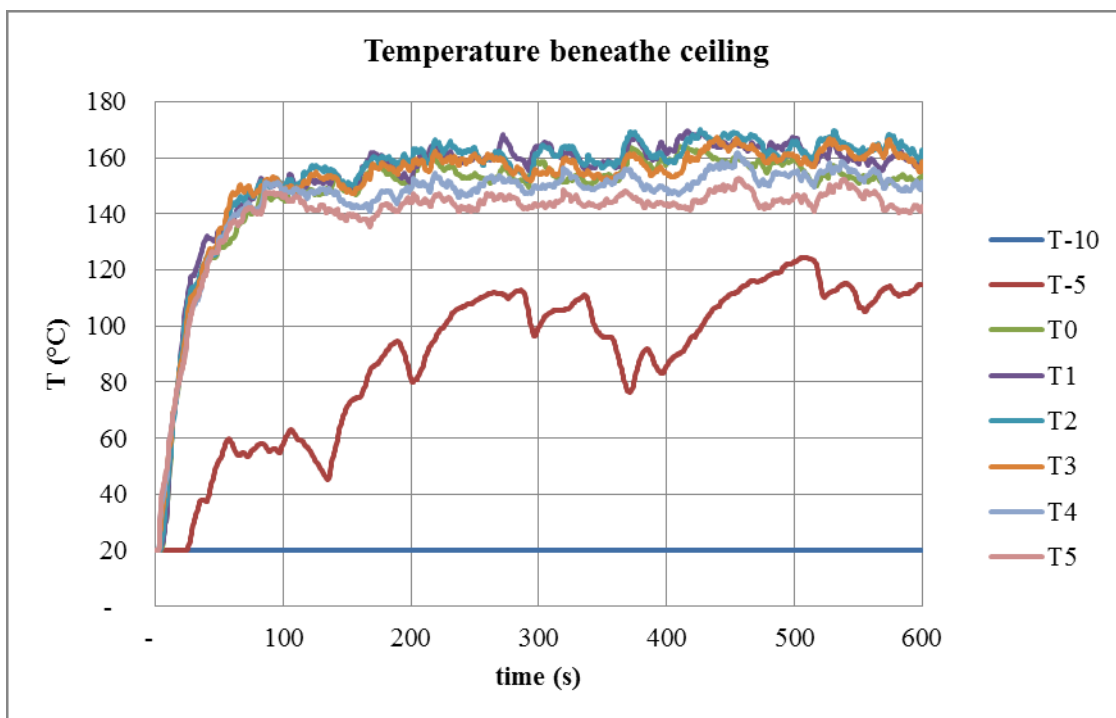
Simulations were carried out to check which position is better for early activation of the automatic sprinklers.

Two scenarios were simulated – one with a 5 MW fire and another with a 10 MW fire. The fire size was chosen based on the previous model and full scale tests. In both cases, the velocity was assumed to be 2 m/s. The sprinkler heads have a RTI of $32 m^{1/2}s^{1/2}$.

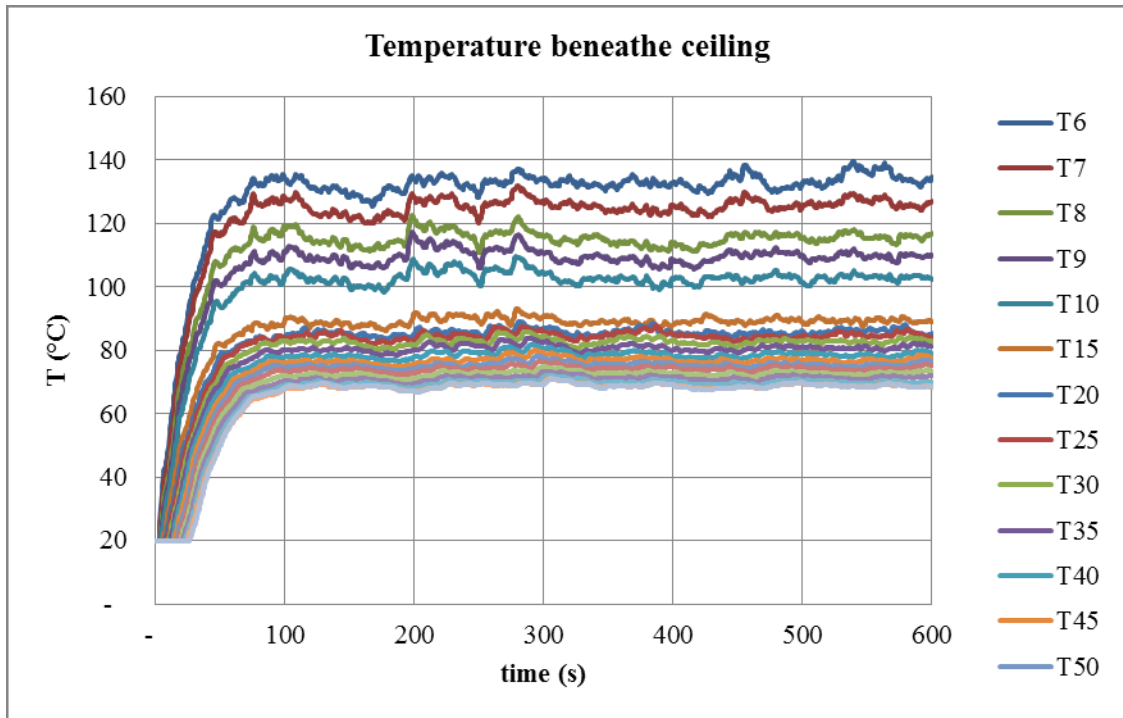
The tunnel in FDS is 100 m, with fire placed at 20 m from the upstream portal. Although the tunnel length generally does not affect the temperature distribution in such a forced flow, the upstream section is too short as the inflow may not be fully developed when it reaches the fire site. This generally results in underestimation of the backlayering length. However, this simplification is considered to have minor influence on the downstream smoke temperatures.

6.1 Activation of the sprinklers for a 5 MW fire

The temperatures of the sprinkler head along the centerline of the tunnel are shown in the following. Note that T6 means 6 m downstream and T-10 means 10 m upstream. It is assumed here that the sprinklers are installed regularly along the tunnel. There are two reasons for use of sprinkler head temperature instead of gas temperature. One is that the sprinkler head temperature is directly comparable to the activation temperature (link temperature). Another reason is that the sprinkler head temperature has less fluctuation with time, which makes comparison easier.



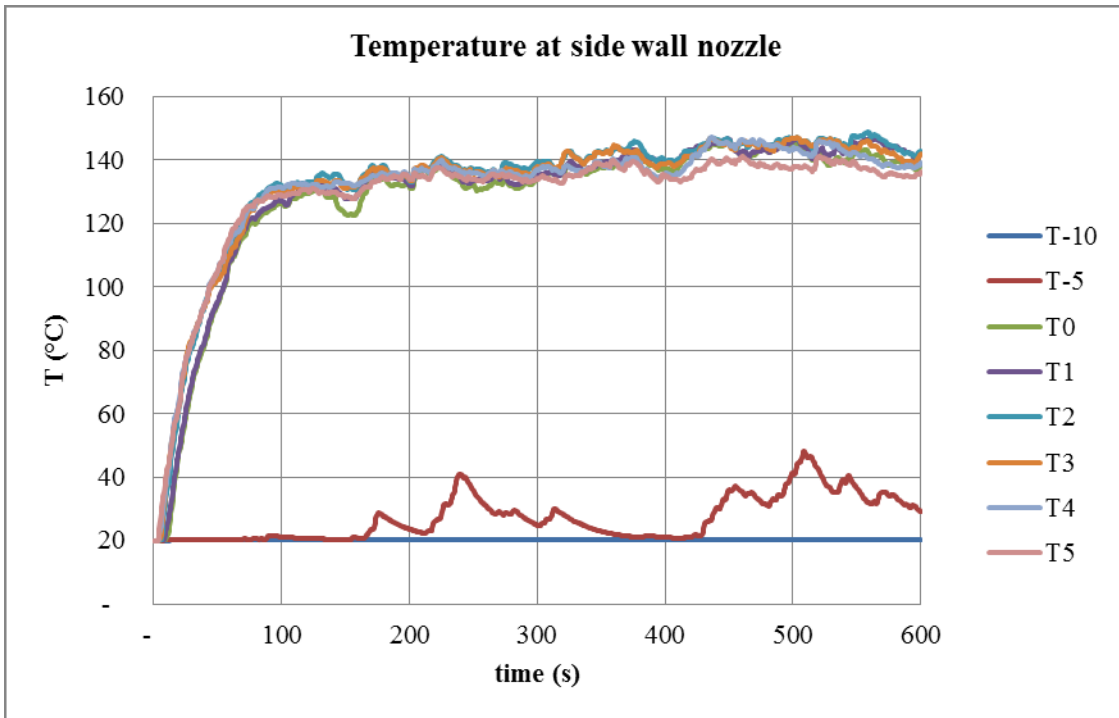
(a) -10 m to 5 m



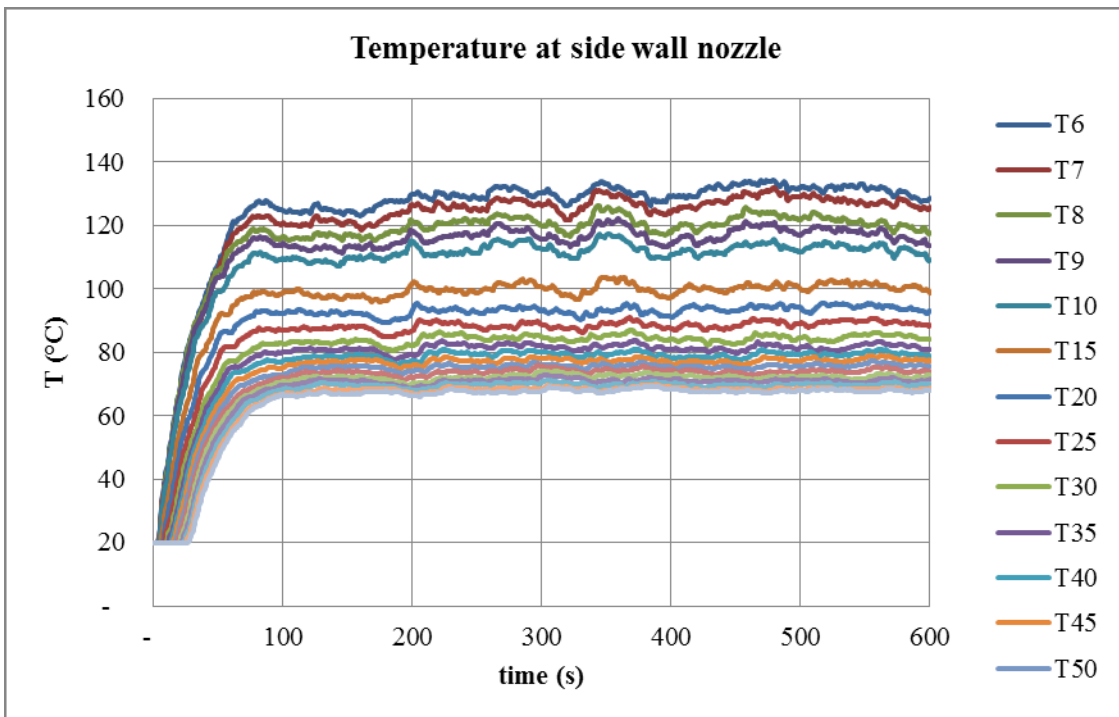
(b) 6 m to 50 m

Figure 14. Temperature along the centerline for 5 MW fire. Note that T6 means 6 m downstream and T-10 means 10 m upstream.

The temperatures of the sprinkler head along the sidewall of the tunnel are shown in the following. Compared to the previous figure, the temperatures are generally lower.



(a) -10 m to 5 m



(b) 6 m to 50 m

Figure 15. Temperature along the sidewall for 5 MW fire.

The temperature difference between the two locations is shown in the following figure.

For the upstream section, the temperatures at 5 m upstream are much greater when the sprinkler is located along the centerline. This is due to the smoke backlayering is mostly of limited depth, and lies close to the ceiling. The side sprinkler head may be slightly out of the smoke layer. This phenomenon can also be found in the results from Test 6 of the Runehamar tests in June 2016. By comparing Figure 7 and Figure 9, it can be found that the centerline temperature (Figure 9) at nozzle 2 (-7.5 m) was higher than the sidewall temperature (Figure 7), and greater than 140 °C. Therefore, the sprinkler should have been activated if the nozzle was placed along the centerline of the ceiling.

For the downstream section, the temperatures at the centerline are generally greater than at the sidewall. However, between 10 m and 20 m the temperature at the sidewall is slightly larger. In general, the temperature difference further than 10 m downstream is limited compared to the link temperature of around 100 °C. But the temperature difference closer to the fire can be significant, especially at the upstream section where the nozzle that is most important is located.

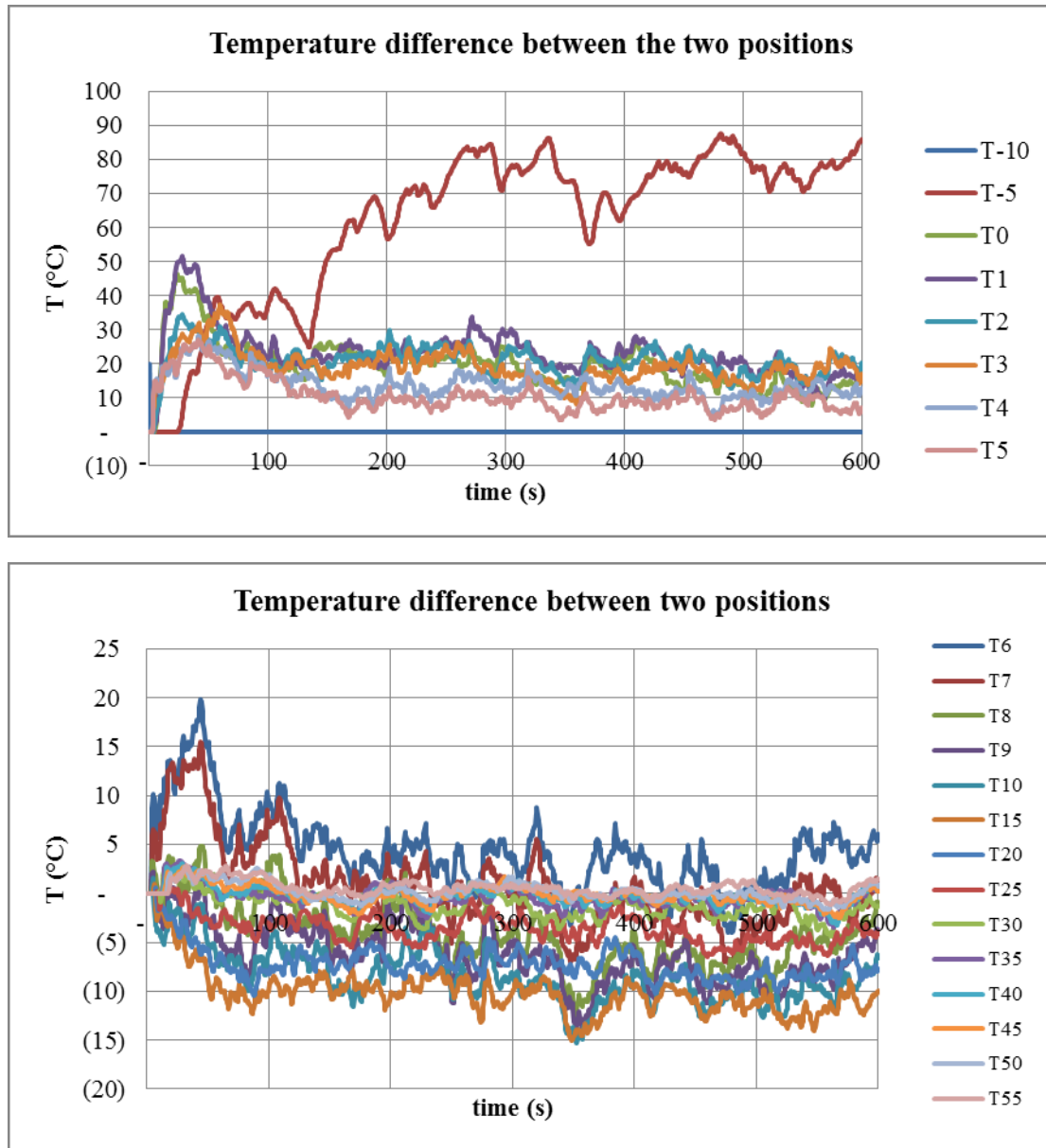


Figure 16. Temperature difference for 5 MW fire.

6.2 Activation of the first sprinklers for a 10 MW fire

The temperature difference between the two locations is shown in the following figure for a 10 MW fire. Similar trend can be found, especially for the upstream section where much higher temperatures can be found for the centered sprinkler heads.

It also shows that for the downstream section, the temperatures at the centerline are generally greater than those at the sidewall. However, between 10 m and 20 m the temperatures at the sidewall are slightly larger. In general, the temperature difference further than 10 m downstream is limited.

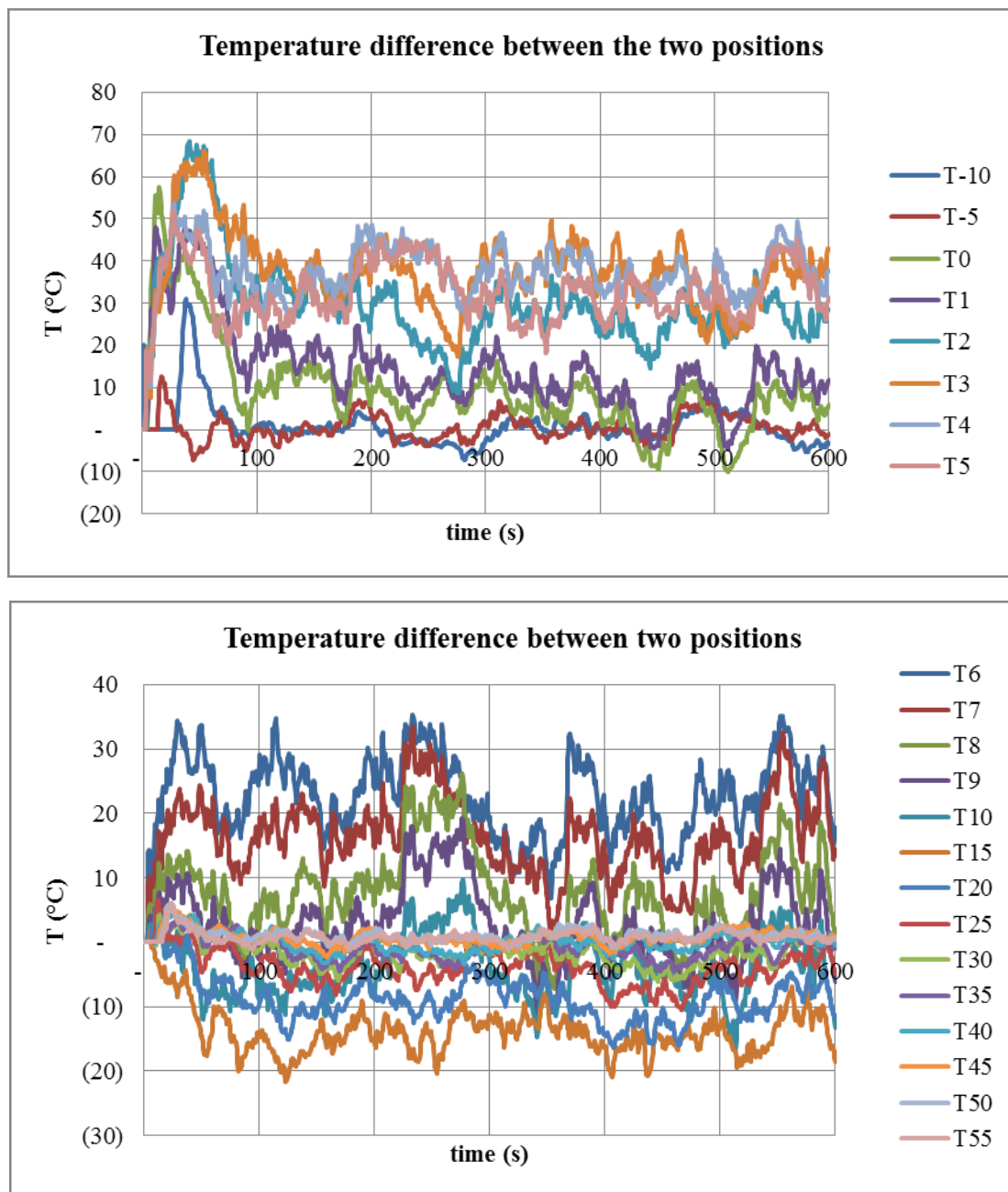


Figure 17. Temperature difference for 10 MW fire.

6.3 Summary

The comparisons clearly show that if the sprinkler heads are located along the centerline of the tunnel, the temperatures in the vicinity of the fire are obviously higher, which is better for activation. These results are in line with what was presented in Chapter 3. The trends are the same and the choice of using a center-line pipe system is well supported.

For both early activation of the sprinklers nearby (due to higher temperatures for centered sprinklers) and avoiding activation of the sprinklers further downstream (due to slightly lower temperatures between 10 m and 20 m), the sprinklers are recommended to be installed along the centerline of the tunnel.

Especially for an automatic sprinkler system, the activation of the sprinklers upstream is extremely important. This confirms that the sprinklers should be installed along the centerline.

If the tunnel is rectangular and the height near the sidewall is the same as that at the centerline, the side sprinkler may also work well, but this is not in focus here.

7 Air velocity in the Muskö tunnel

One of the aims with the study presented here was to investigate the effects of the high slope on the activation times. Note that the velocity is mainly dependent on the buoyancy force, which increases with stack height (hot tunnel length \times slope). But an increasing tunnel length also indicates increasing flow resistance. Effects of fire locations are therefore needed to be investigated.

Further, note that the initial pressure difference caused an air flow from west to east, and the buoyancy force resulted in air flow in the same direction. To obtain the largest velocity from east to west, the initial flow velocity of around 1 m/s is assumed, i.e. the corresponding pressure difference of 18.5 Pa.

7.1 Fire at L1

The tunnel velocity as a function of time for fire at location L1 is shown in Figure 18. Note that the initial pressure difference caused an air flow from west to east, while the buoyancy force may result in a reverse flow after around 7 min. The maximum tunnel velocity is around 2.5 m/s from east to west.

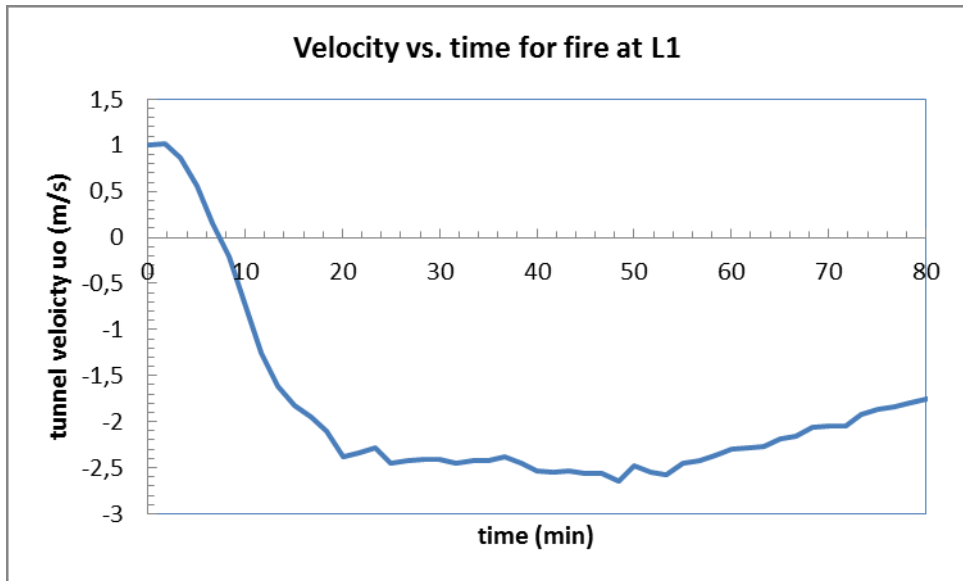


Figure 18. The velocity vs. time for fire at L1.

7.2 Fire at L2

The tunnel velocity as a function of time for fire at location L2 is shown in Figure 19.

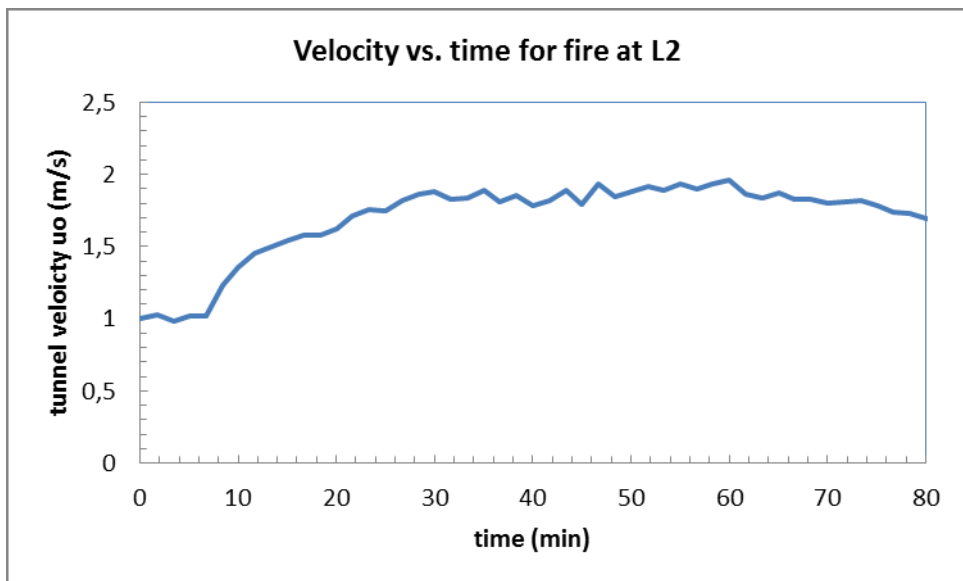


Figure 19. The velocity vs. time for fire at L2.

7.3 Fire at L3

The tunnel velocity as a function of time for fire at location L3 is shown in Figure 20.

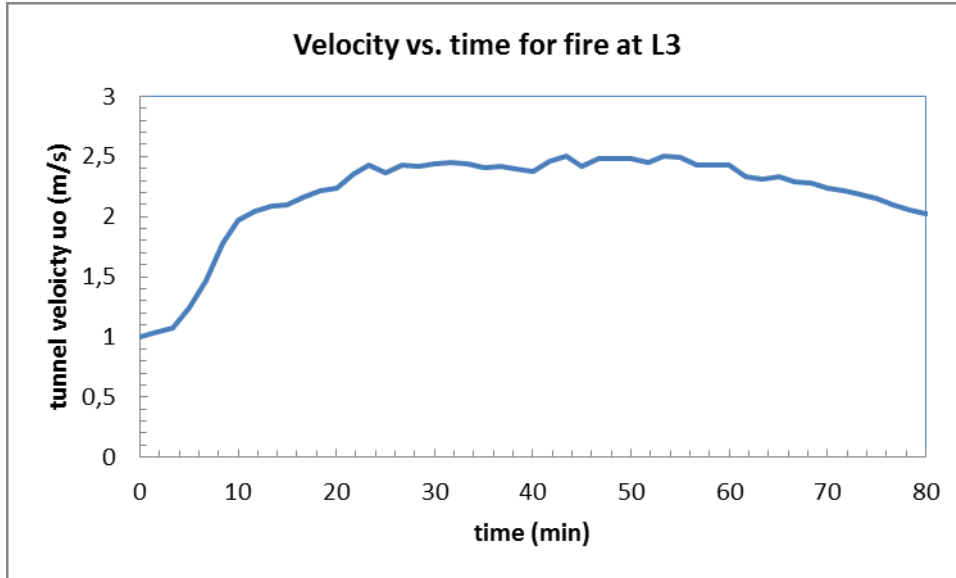


Figure 20. The velocity vs. time for fire at L3.

7.4 Fire at other locations

For various fire locations on the left side of the tunnel (6.9 % downhill), the tunnel velocities as a function of time are shown in the following figure. It shows that when the fire location is far from the tunnel center, the velocity is around 1 m/s initially, but decreases with time due to the increasing buoyancy force towards the left portal until the velocity direction reverses. The maximum velocity is obtained when the fire is located between the left tunnel portal and the middle of the left side of the tunnel. The direction is from right to left tunnel portal.

When the fire is close to the tunnel center, the velocity will always be positive as the smoke was blown to the right side of the tunnel initially, creating a strong buoyancy towards the right portal, and the velocity is lower than 2 m/s from left to right.

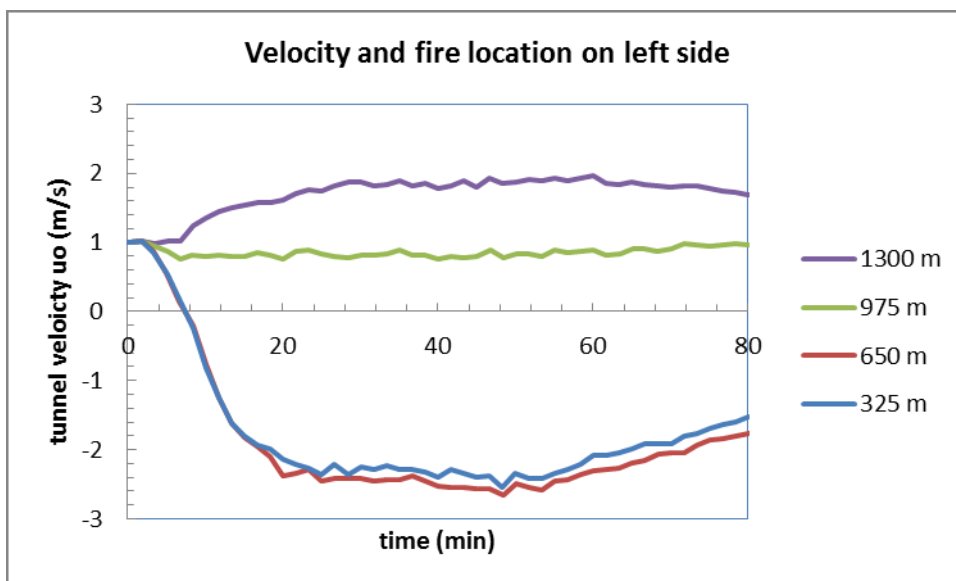


Figure 21. The velocity vs. time for various fire locations on the left side.

For various fire locations on the right side of the tunnel (5 % uphill), the tunnel velocities as a function of time are shown in the following figure. It clearly shows that all the velocities are from left to right portal. When the fire is located between the middle of the right side of the tunnel and the right tunnel portal, the velocity is higher and the maximum velocity is around 2.5 m/s.

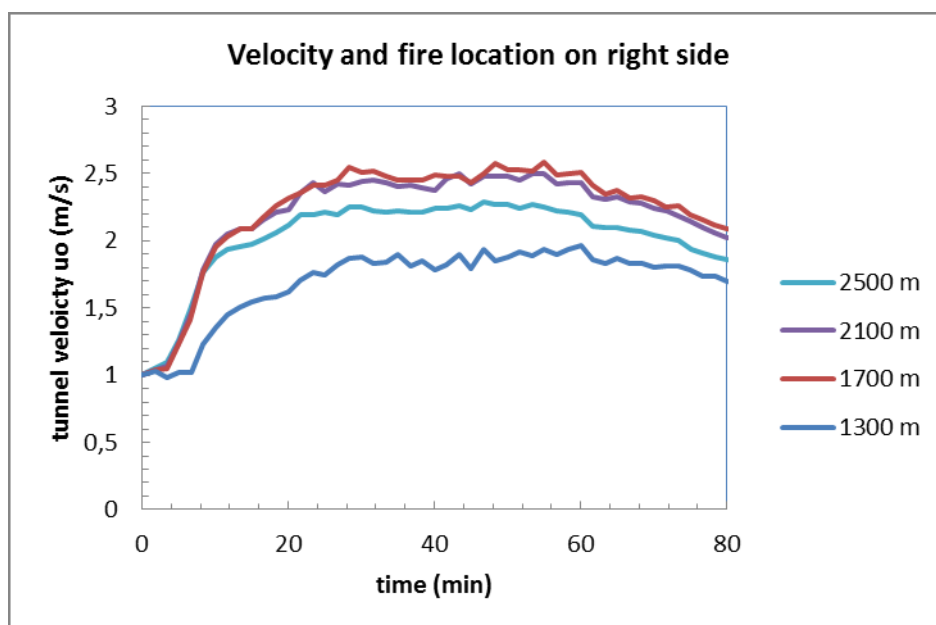


Figure 22. The velocity vs. time for various fire locations on the right side.

7.5 Summary

When the fire is on the left side of the tunnel, the flow velocity mostly remains within 1 m/s (positive or negative) during the first 10 minutes, which helps early activation of the automatic sprinklers.

When the fire is on the right side of the tunnel, the flow velocity mostly remains within a range of -1 m/s and 1 m/s within the first 5 minutes, and the velocity mostly increases to 2 m/s after about 10 min.

Note that a lower tunnel velocity indicates higher gas temperatures and better performance of automatic sprinkler systems [1]. The scenario for fire located on left side is therefore better than that for fire on the right side, especially when the fire is located between the middle of the right section and the right portal.

In any of the above cases, the activation of automatic sprinklers relies on the gas temperature or the link temperature. There is a slight difference between the gas temperature and the link temperature, but the difference is small for automatic sprinklers with low RTI. By knowing the gas temperatures, the activation time of the sprinklers may be estimated. The ceiling gas temperatures can be calculated using the MT model based on HRR [12] and velocity curves. The results for the fire location at L1, L2, and L3 are shown in Figure 23. The gas temperatures at 5 min are in a range of 300 °C and 400 °C, far above the link temperature of around 100 °C,

indicating that the sprinklers nearby the fire source may probably be activated. The temperatures at 10 min are in a range of 400 °C and 800 °C. The fire size is around 5 MW at 5 min and 12 MW at 10 min.

It is clear that for performance of such an automatic sprinkler system in a tunnel, the early activation is of utmost importance. The period is estimated to be around 10 min, when the fire size is less than 10 MW. From this point of view, the tunnel velocity of great interest to this project is 1 to 2 m/s, i.e. maintain at 1 m/s for the first 5 min and gradually increase to 2 m/s at 10 min. Therefore, the automatic sprinkler system in such cases should work well if located at the centerline of the tunnel ceiling.

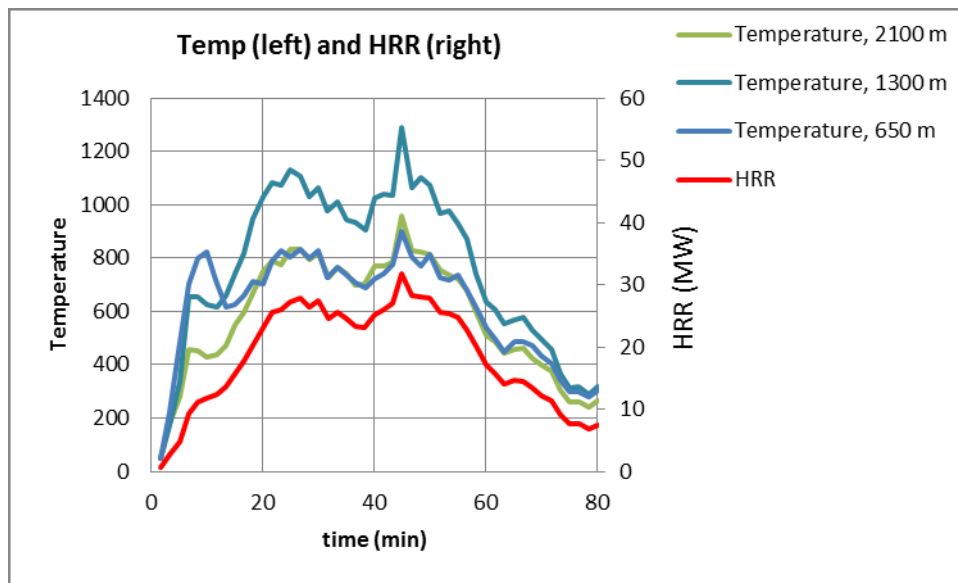


Figure 23. The estimated maximum ceiling gas temperatures for various fire locations. Right axis is only for HRR (Red).

Note that the tunnel velocity in such cases is highly dependent on the tunnel roughness. If the tunnel is smoother, e.g. with concrete lining, the friction coefficient will be much smaller. This will result in less friction loss and higher gas temperatures (less heat loss). Therefore, the tunnel velocity could be higher.

8 Conclusions

Activation of the sprinklers installed along the centerline and along the sidewall was investigated through experimental analysis of a large scale test and by three dimensional numerical modelling. Further, the tunnel velocity was analyzed by one-dimensional numerical modelling for various fire locations in the Muskö tunnel.

For both early activation of the sprinklers nearby (due to higher temperatures for centered sprinklers) and avoidance of activation of the sprinklers further downstream (due to slightly lower temperatures between 10 m and 20 m), the sprinklers are recommended to be installed

along the centerline of the tunnel. Especially for an automatic sprinkler system, the activation of the sprinklers upstream is extremely important. This clearly indicates that the sprinklers should be installed along the centerline. If the tunnel is rectangular and the height near the sidewall is the same as at the centerline, the side sprinkler may also be installed, but this is not the case in the Muskö tunnel.

It was also found that the tunnel velocity varies significantly with the fire location. When the fire is on the left side of the tunnel, the flow velocity mostly remains in a range of 1 m/s (positive or negative) within the first 10 minutes, which helps early activation of the automatic sprinklers. When the fire is on the right side of the tunnel, the flow velocity mostly remains within a range of -1 m/s and 1 m/s within the first 5 minutes, and the velocity mostly increases to 2 m/s at around 10 minutes. Therefore, the scenario for fire located on left side is better than that for fire on the right side, especially when the fire is located between the middle of the right section and the right portal.

For performance of such an automatic sprinkler system in a tunnel, the early activation is of utmost importance. This period is estimated to be around 10 minutes, when the fire size is less than 10 MW. As one typical case with fire on the right side, the tunnel velocity maintains at 1 m/s for the first 5 minutes and gradually increases to 2 m/s at 10 minutes. Under such conditions, the automatic sprinkler system is expected to perform well.

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