Large scale fire tests with fixed fire fighting system in Runehamar tunnel

Haukur Ingason
Glenn Appel
Ying Zhen Li

Co-financed by the European Union
Trans-European Transport Network (TEN-T)

Fire Research

SP Report 2014:32

Large scale fire tests with fixed fire fighting system in Runehamar tunnel

Haukur Ingason
Glenn Appel
Ying Zhen Li

Abstract

Large scale fire tests with fixed fire fighting fystem in Runehamar tunnel

The report presents the main results of the large scale fixed fire fighting system (FFFS) tests that were carried out in the Runehamar tunnel in September 2013. The report describes the background and the performance of the system in the large scale fire tests, and draws necessary conclusions on the efficiency of the system. The fire load consisted of 420 standardized wood pallets and a target of 21 wood pallets. The water spray system is a deluge zone system delivering 10 mm/min in the activated zone. The detection system was simulated with use of thermocouple in the tunnel ceiling. The alarm was registered when the ceiling gas temperature was 141^{o}C. After alarm was obtained the system was activated manually after a given delay time that was varied. The protection goal of the system was to prevent fire spread to a target positioned 5 m from the rear end of the main fuel and to control the fire size so it would not exceed 50 MW in size. The system was found to perform in accordance to the given protection goals.

Key words: wood pallets, Fixed Fire Fighting System (FFFS), heat release rate, water density, time delay.

SP Sveriges Tekniska Forskningsinstitut
SP Technical Research Institute of Sweden

SP Report 2014:32
ISBN: 978-91-87461-77-4
ISSN 0284-5172
Borås 2014

Contents

Preface

The Stockholm bypass project was granted co-funding for research, including testing, from the European Union (EU) through the Trans-European Transport Network (TEN-T). The large scale tests presented in this report were performed within the frame of this EU project. The Swedish Transport Administration (STA) initiated this project and was responsible for setting up the protection goals of the system. The concept behind the system as it was tested was developed by the STA together with the fire consultancy company Brandskyddslaget AB. SP collaborated with both STA and Brandskyddslaget during the period of development of the concept.

We would like to thank those who were directly involved in the development of the concept, especially tunnel safety officer Ulf Lundström at STA, Henric Modig at Faveo Projektledning AB who was project leader of TEN-T project and Conny Becker Brandskyddslaget AB who designed the original concept of the system. The nozzles had originally the working title “T-REX”, but are now manufactured under the name of TN-25 (Tunnel Nozzle with orifice K-25) and provided for the tests by the manufacturer TYCO Fire Production Products. Also thanks to Per Slagbrand at Nordic Sprinkler who provided with material of piping and know-how in the development of the system. We would also like to thank all the technicians at SP Fire Research for their fantastic work and Reidar Stolen at SINTEF-NBL for his great work with the instrumentation and the measurements. Thanks also to Per Fiva at the Norwegian Public Road Administration in Åndalsnes who was the contact person at the Runehamar tunnel.

Summary

A new type of deluge water spray system was tested in the Runehamar tunnel in September 2013 on assignment of the Swedish Transport Adminstration (STA). The system will be installed in the Stockholm bypass when it will be in operation in 2025. The heat release rate upon activation ranged from approximately 10 MW to 30 MW in the six tests performed. In five tests the heat release rate was controlled after activation for a period of 10 – 20 minutes. After that the fire was suppressed over a period of 10 - 30 minutes, which means that the system prevented further fire spread inside the fuel. In the last test, the FFFS never operating properly due to a technical failure. This test was used as a ´free burn´ for comparison of the efficiency of the operating system.

The FFFS was able to maintain the heat release rate lower than 40 MW in all five cases, and 20 MW in four tests. After activation of the system the maximum temperatures at the ceiling were never higher than 400°C to 800°C. In the last test the maximum ceiling temperature was 1366°C, which is the same temperature as was obtained in the ´free burn´ tests carried out in Runehamar 2003.

In all the experiments the fire was controlled in the first period after activation and then suppressed with a considerable amount of fuel was still remaining. The measurements show that about one third or less was consumed, which of course is a very good performance of the system. A pile of pallets representing a target was located 5 m from end of the main fuel stack. It was used to assess the risk of fire spread to adjacent vehicles. In all cases with FFFS operating, the target was unaffected by the main fire. In the tests when the system were not able to deliver water on the fire source, the fire spread to the target, and all the fuel including the target was consumed.

The experiments show the importance of early activation of the FFFS. Despite this it was clear from the experiments that the system has a sufficient safety margin to allow delayed response while retaining the ability to fight the more severe fires produced by such a delay. The system was able to prevent the spread of the fire beyond the main fire load, and was clearly able to lower the gas temperatures in the tunnel. This has important implications for the design and safety of the evacuation. The tests show that the design fire of 100 MW as originally planned can be reduced to lower than 50 MW by the presence of a FFFS, which translates into huge savings in investment costs for the ventilation system. The experiments show that if the system activates late, an increase of toxic substances and smoke is produced, but the impact of this effect is easily mitigated by activating the system early. Further research is needed to investigate the implication of this observation in future testing.

The benefits of FFFS are primarily that they can be used to increase safety in tunnels. Such systems will be able to fight fires that are relatively large and thereby potentially prevent a major disaster. In the case of congestion and specifically when a queue is formed, the system will increase safety by minimizing the risk of propagation of a fire as it could occur.

1 Introduction

The Swedish Transport Administration (STA) plans to construct a new highway connection through the western part of Stockholm called the Stockholm bypass, due for completion in 2025. A large part of the road system will pass through tunnels. In one direction there will be just over 18 km of the total of 21 km of the motorway link that are in tunnels and in total, including ramps, about 50 km of tunnels. It is very important that adequate fire protection is in place in the tunnels since the Stockholm bypass will be a critical transportation infrastructure for the region and any disturbance in the traffic flow has the potential to cause major problems in the future. The project forecasts for 2035 show that up to 140 000 vehicles may use the Stockholm bypass every day. This traffic density indicates that there is risk of congestion in the tunnels, leading to a heightened risk of fire. Therefore, the STA has decided to test a new safety concept using sprinkler technology with large droplet side-wall sprinkler nozzles mounted in the ceiling. The working name during the development of the system was T-Rex, which was related to T for Tunnel and Rex for very large droplets.

The system consists of a pipe positioned in the middle of the tunnel ceiling, with a pair of nozzles every five meters that spray water horizontally in two directions. This means that the nozzles will be positioned back to back of each other on the central ceiling pipe. Each nozzle throws out as much water as a firefighter with a traditional firefighting hose. The uniqueness of the system is its simplicity and the fact that large droplets are thrown towards each tunnel wall. This is not a common solution for tunnels, but similar sidewall concept have been used in tunnels in Australia and US, although not with such large drops. In addition to this, the water supply for the fire brigade will be integrated into the water supply system for the FFFS. The combination of the hydrant system for fire-fighting and the FFFS is not unique as this has been applied in Australia, but it was found to be very cost saving and fits this system very well. The FFFS is a simple and robust low pressure deluge system and according to STA the investment and maintenance costs are estimated to be approximately fifty percent of a traditional deluge system. The main goal of the system is to limit fire size and prevent fire spread during the time of evacuation in congested traffic inside the tunnel system.

The purpose of the large scale tests in the Runehamar tunnel was two-fold:

1) to investigate how the activation time of the FFFS system affects their efficiency in attacking a fire in a truck trailer loaded with wood pallets; and

2) to determine the longest activation time that would be able to keep the fire under control.

There are many parameters that can affect the outcome of such tests. This includes water density in mm/min, droplet size, activation time, longitudinal ventilation velocity, fuel configuration and fuel size. Modern design fires for ventilation systems are often set to 100 MW, but if a FFFS is installed this can potentially be reduced to 50 MW, depending on the system used and the fire scenario. This lower heat release rate in turn affects the design of the ventilation system, making it perhaps possible to work with a smaller fan capacity, which affects the total investment cost. This was also one of the reasons why the STA was interested in exploring the effect of the system on the fire size. Another consequence is that the gas temperature in the ceiling near the fire and if a late activation of the system occur may be reduced from nearly 1300°C to lower than 800°C, which requires less protection for the tunnel structure. The authors want to emphasise that in order to fully realise the benefit of a lower design fire in a tunnel with a FFFS, the reliability of the systems has to be addressed first, although it will not be addressed in this report.

Prior to the large scale tests in the Runehamar tunnel, some preparatory tests were carried out to determine the spray pattern, droplet distribution and throwing length in the fire laboratory at SP. These tests were necessary as input to the planning of the large scale tests. One issue in the planning related to the fact that the Runehamar tunnel is only 9 m wide, whereas the Stockholm bypass tunnel will be on average 15 m wide. Ultimately it was determined that only one side of the system would be tested, i.e. the main pipe was mounted close to a side wall of the tunnel instead of the centre with one nozzle directed towards the fuel that was placed in the centre of the tunnel. This was a reasonable choice as the system was designed to be symmetrical and the tunnel contains several lanes implying that a real fire would be expected towards one side of the tunnel. This resulted in a lower total required amount of water for the tests (50 % relative to a real situation); however, there was a need to further reduce the water use in the tests as the water tank in the test tunnel did not have sufficient capacity for the test duration at full delivery rate. Therefore, it was decided to reduce the total length of the operating zone from 50 m to 30 m with a corresponding reduction in the water flow rate requirement. In order to investigate the influence of these deviations, the system was first tested in a model scale tunnel, at 1:4 scale [1]. In the 1:4 scale tests it was possible to study the influence of these changes. It was found that these changes lead to conservative results. The nozzles themselves were scaled by scanning the original sized nozzle and using a 3D printer technique to "print" a 1:4 scale version of the nozzle in steel.

The Runehamar tunnel is situated about 5 km from Åndalsnes in Norway. It is a two-way asphalted road tunnel that was taken out of use in the late 1980s. It is approximately 1600 m long, 6 m high and 9 m wide with a cross-section of about 47 m^2. The tunnel has an average uphill slope of 0.5 % up to about 500 m from the east portal (where the fans are located) to the west portal, followed by a 200 m long plateau and then a 900 m long downhill section with an average slope of 1 % towards the west portal. The fire was located 600 m from the east portal, i.e. on the plateau section of the tunnel. The tunnel is protected with shotcrete at the test location.

The technology for FFFS is a key feature to the safety of modern STA urban road tunnels. Therefore, it was very important that the function were properly verified through large-scale testing. Detailed information about the test-setup and the main test results are presented in the main text of the report as well in Appendix A.

2 Description of experimental set-up

2.1 Description of the water spray system

In its final design for the Stockholm bypass the FFFS will consists of a single 150 mm diameter pipe in the centreline of the tunnel ceiling, fitted with two extended coverage nozzles (K factor of 360 l/min/bar$^{1/2}$) directed horizontally towards each of the tunnel walls. The nozzle pairs are mounted every five meters and spray 375 l/min water horizontally in two directions, in total 750 l/min. The nozzles will be placed in a T-pipe down from the centre pipe with the nozzles pointing out towards the tunnel walls (back to back). Since this is a sidewall system, throwing the droplets horizontally and using gravitational forces, it will cover the entire cross-section. This means that an entire cross-section of 15 – 18 m wide tunnel will be covered with only one pipe. Each deluge section will be 50 m long and is designed to deliver 10 mm/min without use of any additives to the water. The total water flow for each deluge section is 7500 l/min. The FFFS is combined with the fire hydrant system, reducing the required number of water mains in the tunnel to only one. Thermoplastic-coated steel pipes, both outside and inside, and clamp couplings instead of welded stainless steel pipes are used. The estimated lifetime of the system is 30 years. The system can be manually operated from the traffic control centre based on detection by CCTV, or from the tunnel escape routes where the deluge valves are located. The system also starts automatically if the automatic fire detection system detects the fire (type of technology still to be decided). The sprinkler pipes are self-draining due to the risk of freezing. In winter the outside temperature is expected to drop below -20°C.

As the pipe was placed on one side in the large scale tests, see Figure 1, only the nozzles discharging water towards the tunnel centre were used. The water density in this area was the same as if the pipe was located in the centre. As the pipe was shortened to 30 m, this reduced the total water flow from 7500 l/min to 2250 l/min as the water requirement in order to deliver 10 mm/min at the 30 m section was 2250 l/min. A 600 m long ground pipe with a diameter of 140 mm (inside diameter of 127 mm) delivered the water from the water tank to the 30 m long deluge system in the ceiling. The ground pipe was connected with the ceiling pipe as shown in Figure 1. The water tank had a capacity of 230 m^3, which was enough to maintain at least 90 min delivery of water.

Figure 1 The test-setup and the water spray system after activation of the system.

The nozzles used in the tests are manufactured by TYCO and are designated as TN (Tunnel Nozzle)-25, see Figure 2 and Figure 3. Prior to the given notation by Tyco it was called T-Rex and was originally designed by Brandskyddslaget AB. A 1.1 bar water pressure at a nozzle with K-360 (l/min/bar$^{1/2}$) yields a water flow rate of 375 l/min. The coverage area was 37.5 m^2, which corresponds to water density of 10 mm/min.

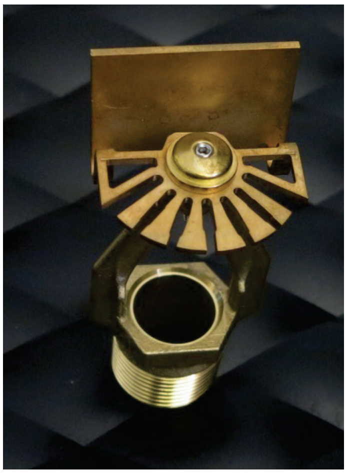


Figure 2 Nozzle TN-25 from Tyco used in the test (sometimes referred to as T-Rex). A total of six nozzles were used in the tests. The K factor was 360 l/min/bar$^{1/2}$.

Figure 3 A TN-25 was fitted with a T-coupling to 150 mm diameter pipe in the ceiling. The nozzle was mounted every five meters and spray 375 l/min water horizontally in one direction. A total of six nozzles were used in the tests.

2.2 Fire source

The fire source comprised of 420 wooden pallets placed in the center of the tunnel, 600 m from the west portal. A target consisting of a pile of 21 wood pallets was positioned 5 m from the rear end of the fuel mock-up. The target is used to evaluate the risk for fire spread. This type of test fuel mock-up is often used to simulate the pay load of a Heavy Goods Vehicle (HGV) trailer.

The wood pallets were placed on light-weight concrete slabs (Siporex) and 12 mm thick plywood boards were mounted on the top of the slabs. Ten pairs of piles each with 2 x 21 pallets were placed on the slabs, as shown in Figure 4. In order to maintain correct distance between the height of the sprinkler nozzles and the top of the fuel load, the concrete platform was 0.2 m in height. The measurements of the pallets are 0.8 x 1.2 m, i.e. the width of the fuel load was 2.4 m. Each wood pallet weighed about 24 kg and was about 0,143 m thick. The total length of the fuel load was just over 8.0 m. The total height of the fuel load was about 3 m. In total the fuel load weighed just over ten tons. This means that the potential energy content is approximately 180 GJ. The target consists of 21 pallets, giving an additional energy of approximately 9 GJ (in total 189 GJ). The moisture content in the wood pallets varied between 15 – 20%. The model scale study (1:4) showed that 420 wood pallets (1:1) was estimated to produce a peak heat release rate of about 100 MW [1].

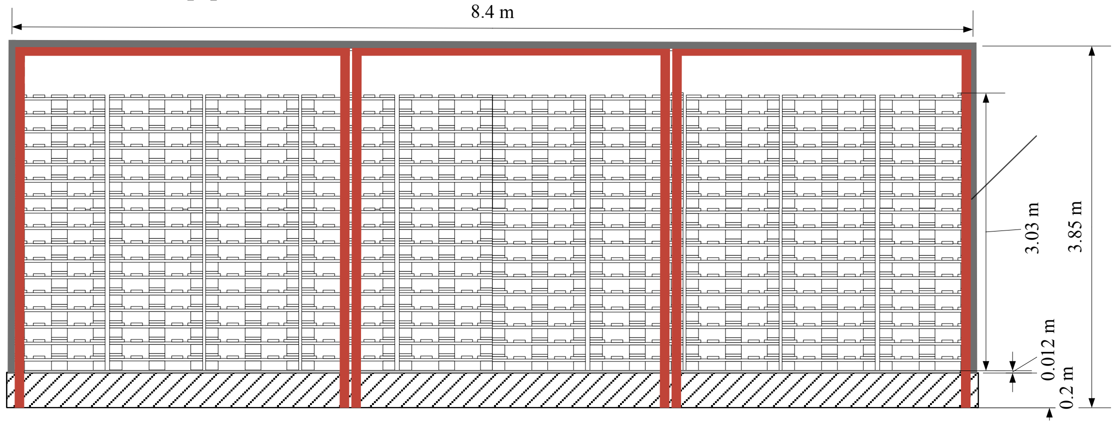
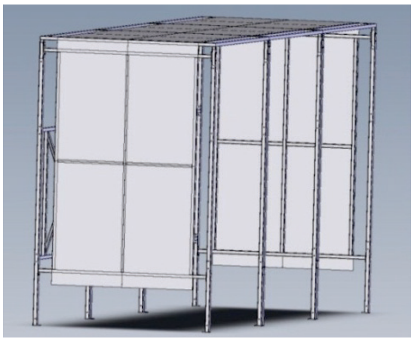


Figure 4 A side view of the fuel load which consisted of 420 standard EUR wood pallets. A steel frame to support steel sheets at the ends and the top was mounted to cover the wood pallets.

The fire source was covered with steel plates on both the front and back, and above the pallets. This arrangement makes it difficult for water to penetrate directly into the pallets, which increases the severity of the test by reducing the ability of the system to fight the fire from the top. A schematic drawing of the system is shown to the left in Figure 5 as well as a photo of the front end. Tarpaulin was only used in one test (test 4). This was not thought to be an important parameter, and it saved a lot of work by excluding the tarpaulin. The pallets were ignited just behind the front plate at the lowest pallet lever. The ignition source consisted of two rectangular heptane pools with geometries of 0.2 m×0.8 m which were placed on the bottom and at the front of the wood pallet piles. Each pan was filled with 2.5 litre heptane. Together they produced a total heat release rate of approximately 500 kW.



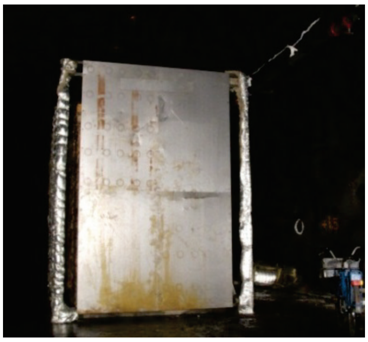


Figure 5 Steel plates on both the front and back, and above the pallets.

2.3 The mock-up set-up

The set-up of the mock-up in relation to the nozzles was planned to be in accordance to the model scale tests carried out earlier [1]. The vertical distance between the nozzles and the top of the wood pallets was 0.8 m. The horizontal distance from the wall to the wood pallets was 2.4 m, see Figure 6, whereas the horizontal distance between the nozzles and the vertical side of the wood pallets was 2 m. In the model scale tests this distance corresponded to 1.6 m. This was due to practical reasons, e.g. enough space for forklifts etc.

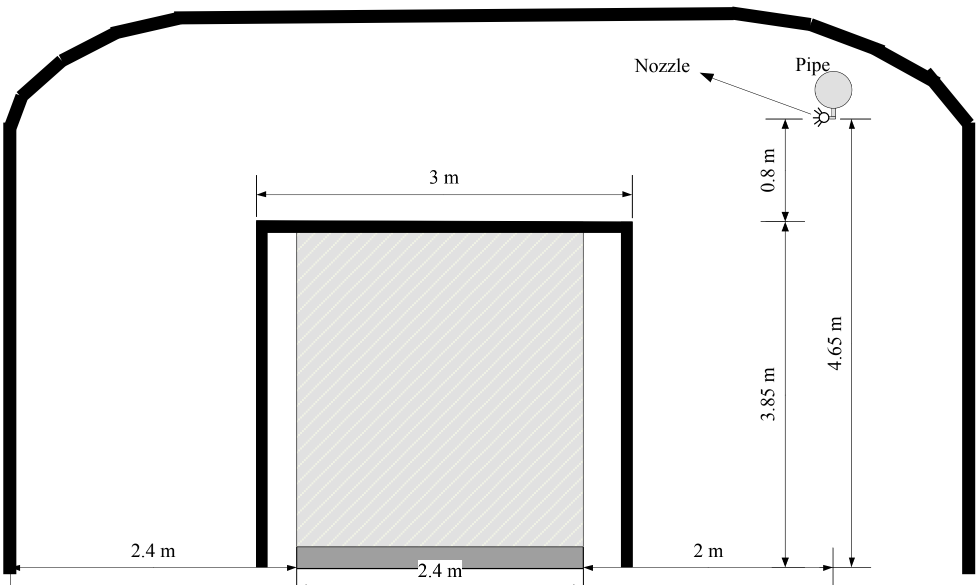


Figure 6 Cross-section of the test setup used in the large scale tests.

2.3.1 Instrumentation

The gas temperatures, gas concentrations, visibility, water flow rate and water pressure, were all registered every second. The heat release rate in MW was determined by measuring the gas and air flows about 1000 m from the fire, station marked as pile A at x=1000 m. In total, 17 thermocouples, 6 bi-directional pressure probes, 3 gas analyses (O_2, CO_2 and CO), 1 plate thermometer (PT), 2 photo/cell, 1 water pressure and 1 water flow gauge were used in these tests. Location of each instrument is given in Figure 7. All ceiling thermocouples (type K, 0.5 mm) were placed 0.3 m below the ceiling, except at Pile A. One PT was placed at x=9 m, 2 m above ground level in order to estimate the incident heat flux towards this position. One of the two photo/cell visibility instruments was placed at the measurement station (x=1000 m) and another one was placed at x= 50 m downstream. The smoke density was presented as a reduction (%) of transparency over a given length (0.4 m) and was measured 1.5 m above road surface. Note that the interval between each nozzle pair is 5 m and between the end nozzles is 25 m, corresponding to a water spray coverage length of 30 m (2.5 m for each end nozzle). The bi-directional probe and the thermocouple upstream at x=-50 m is placed at the centre of the tunnel cross-section, see Figure 7.

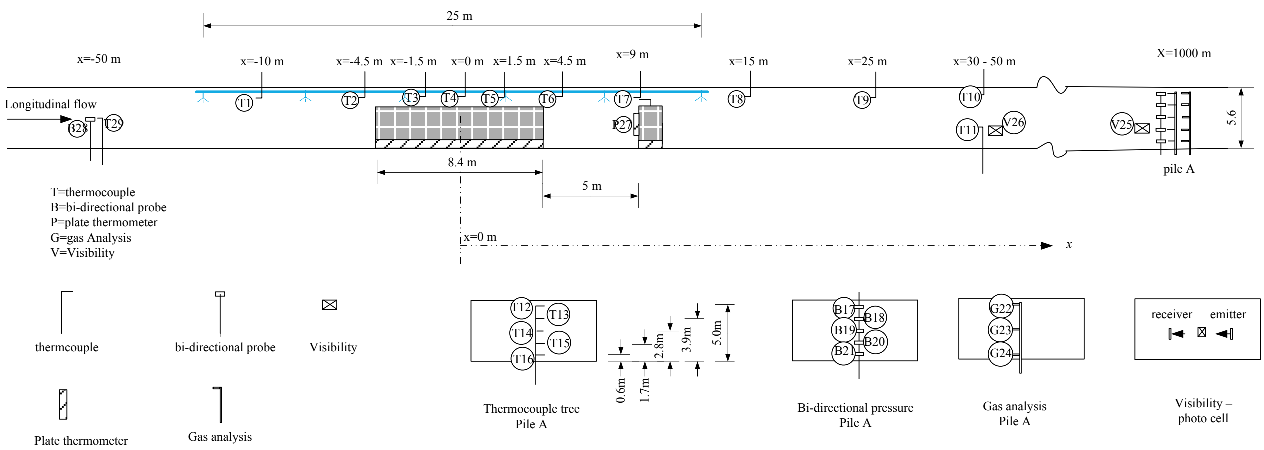


Figure 7 The layout and identification of instruments in the series of tests (dimensions in m).

Corrections for the transportation time were considered in the calculation of the heat release rate. The calculation of the heat release rate was based on an oxygen calorimetry (O_2, CO_2 and CO) and the same technique as used in reference [2] was applied.

3 Test procedure

To mimic a real detection situation, the detection temperature was set at 141°C (the first ceiling thermocouple to measure 141°C was used) and a “delay” time from detection (alarm) to activation was set in advance at two minutes for the initial test, with an additional time for each test until the system was no longer able to keep the fire under control. The additional delay times were 4 minutes and 8 minutes, respectively, for the second and third tests. The idea behind this was to simulate different manual operation times that the traffic control center needs in order to initialize the activation. First they need a confirmation that there is a fire and then a confirmation of the location. After that the system can be activated. By increasing this time continuously STA wanted to stress the system in order to find where the limits are for control of the fire. The longitudinal ventilation rate during all the tests was set at 3 m/s, which corresponds to a critical velocity for this type of tunnels. This means that no backlayering of smoke should be expected during the test.

In addition to these three tests, a test in which a tarpaulin was placed on the long sides of the fire load to simulate a covered cargo, and a test in which the front cover was removed so wind could help the fire to spread faster within the pallet stacks. In these tests the fire grew until a ceiling gas temperature of 141°C was obtained. After that additional four minutes passed before the water was turned on (activation). In the final test, the system was activated after 12 minutes, but due to the technical failure in the main pipe the water was not delivered onto the fire source. The decision for an detection temperature of 141°C is based on the results obtained in the model scale tests [1]. They showed that the heat release rate obtained within these detection periods complied well with the levels believed to be a challenge for the system. After detection and the predetermined delay time, the water flow at the pump and water tank site was activated 20 seconds prior to the expected delivery time at the nozzles 600 m from the water tank. In table 1, the test sequence and parameters varied are given.

Table 1 Test series for the STA large scale tests in Runehamar tunnel in September 2013.

Test number	Special conditions	Delay time after 141°C in ceiling (min)	Time of detection at 141°C	Time of activation after ignition (min:sec)
1		2	4:04	6:04
2		4	4:20	8:20
3		8	5:18	13:18
4	**tarpaulin**	4	14:25	18:25
5	**no steel blockage**	4	3:17	7:17
6	**”free burn”** (due to failure in one of the bolt in a coupling, very little water was delivered on the fire. Most of it bypassed the fire as the main pipe was off just behind the fire source)	12	3:48	15:48

In the last test (test 6), the water supply was originally planned to activate 16 minutes after detection, but already after 12 minutes it was realized that the situation might be too challenging for the tunnel structure. Therefore it was decided to activate the system after 12 minutes from detection. Unfortunately, nearly no water reached the fire since a bolt in one of the couplings to the main supply pipe in the ceiling broke due to the repeated mechanical loads and heating from the previous tests. In Figure 8 the failed coupling is showed. The photo was taken after the final test and all the soot on the walls and ceiling from earlier tests had burned away, leaving a large portion of white shotcrete closest to the fire place. The shotcrete exhibited no damage despite this high heat flux exposure. The maximum centerline ceiling gas temperatures were measure in the range of 1250 – 1366 ^{o}C, which corresponds to about 305 – 410 kW/m^2 incident heat flux to the walls. The same pipe and couplings had been used in all the tests. The coupling that failed was located just behind the rear end of the fuel storage. The TN-25 nozzles on the upstream side of the breaking point were not affected despite the high temperatures created in the test, most likely as some water was flowing through them and thereby cool them. Small portion of this water was flowing out of the nozzles and hit the fuel on the side closest to the pipe. Some remains of the fuel were found after the test, but most likely this did not influence the total heat release rate very much.

There was one nozzle on the section that was release from the system and was empty. The nozzle that was attached to that pipe section was slightly bent due to the high heat, see Figure 9. Any type of melting of the nozzle was not observed although the nozzle were made of brass. The melting point of brass is about 900 to 940^{0}C. The peak maximum centerline gas temperature in the area of the nozzle was measured to be about 1280^{o}C and the centerline gas temperature was over 900^{o}C during a period of 15 minutes. This was probably not enough time to heat up the solid mass to over 900 ^{o}C. However, it was high enough to soft the nozzle arms and therefore a deflection of the arms is observed in Figure 9.

Figure 8 The type of coupling that failed in the final test. The lower bolt that keeps the coupling attached to the pipes broke due to repeated heat and mechanical stressed during the test program. The main water flow bypassed the fire and flow out of the open pipe downstream of the fire.

Figure 9 The TN-25 nozzles used in the test program. After the final test (test 6) the nozzles were mounted on a table in the sequence of their position. The last nozzle downstream the fire was bended as no water cooling was available for that nozzle.

The pipe system had not only be exposed to the five tests before the technical failure with one of the coupling (just at the downstream end of the fuel load). Actually, between the first and the second test, a midnight incident occurred that may have played some role in the failure. In the first test the fire was controlled and then suppressed by the system, and about three quarters of the fuel remained. The local fire brigade made the last final extinction of the glowing embers soon after the water supply was turned off. In agreement of all partners involved in tests, it was decided to let the remains stay over the night, to be taken care of the day after. This was the traditional way of doing testing in the Runehamar tunnel.

A weather measuring station that was continuously logging, registered a significant temperature rise inside the tunnel at about midnight, about 4 hours after the last person left the tunnel. The day after it was observed that the ceiling was white when it should have been covered with soot as well as the all the remaining fuel from the first test. Everything had been consumed in the midnight fire, even the target. Luckily no damage was observed on the tunnel construction, nor the deluge system. No nozzles had been melted or deflected during the extensive heat that was created that night. There is no doubt that this incident, exposed the couplings for high thermal stress, but fortunately it was possible to continue the test program without any further delays.

4 Results

In the following a summary of the tests results are given. In Appendix A, all the measured data are given as a function of time and for each of the tests performed.

In Figure 10, all the calculated heat release rates based on mass flow rates of O_2, CO_2 and CO are shown. The expected 100 MW fire was not reached in test 6. The maximum heat release rate was measured to be 79 MW. The reason for this is believed to be the influence of the moisture content in the wood pallets on the heat release rate. Compared to the one in the model scale tests, which this estimation was based on, the moisture content was approximately half the moisture content in the large scale wood pallets. The effects of the moisture on the heat release rate can be found in reference [3]. It shows that increasing the moisture content from about 10% as was measured in the model scale tests, to about 15 - 20 % reduces the heat release rate by 15 to 25 %. This complies well with what was obtained in the final test. The effects of the water that was pouring out of the nozzles on the side of the fuel were estimated to be small.

In the first three tests the delayed activation time was successively increased from 2 minutes to 4 minutes and finally up to 8 minutes. The heat release rate at activation, Q_{act}, increased from 10 MW to 20 MW, but the system did not have any noticeable problem in controlling or suppressing the fire. Here, control means to prevent the fire to develop further and maintain it at a relatively constant level or reduce it slowly. Suppression means rapid reduction of the fire size until it becomes only small flame volumes. The heat release rate was controlled after activation for a period of 10 – 20 minutes. After that the fire was suppressed within a period of 10 - 30 minutes, which means that the system prevented further fire spread inside the fuel. The first 3 – 4 pairs of piles were consumed or damaged in the tests which mean that not more than one third of the wood pallets were consumed. In all the three tests, a portion of wood pallets fell down in the area where the fire was most intense after about 18 – 28 minutes. This exposed the wood pallets, and probably made it easier for the system to finally suppress the fire. Definitely the system prevented further fire spread within the fuel.

In test 4 with the tarpaulin the fire was controlled during a long period after activation at 16 MW. During about one hour period the heat release rate varied from 5 to 10 MW. After 80 minutes the system was shut off. The initial fire development was very slow due to the effects of the tarpaulin (oxygen limitation in the vicinity of the ignition source). For a period of about 12 minutes, not much happened, but suddenly a hole in the lower parts of the tarpaulin close to the ignition source was observed and about one minute later a new hole in the upper part were noticed. After this occurred the fire development started to accelerate and due to chimney effects inside the fuel were created resulting in a very specific spread deeply inside the fuel. At the time of activation of the system (+4 minutes) the tarpaulin had mostly fallen off, so it did not influence the performance of the system. However, the initial conditions had influenced the fire spread in the middle of the fuel, explaining this long period of relatively low heat release rate. The water did not really reach to this center of the fuel.

In the fifth test (+ 4 minutes, no wind blockage), due to the rapid fire development enhanced by the longitudinal wind velocity of 3 m/s, the activation heat release rate was relatively high, 28 MW. The system got the fire directly under control. The heat release rate was kept at a level of 30 – 40 MW for about 20 minutes. Shortly after that the fire was suppressed over the course of 20 minutes. Due to this relatively high heat release rate for a period of 20 minutes many wood pallets were consumed, although not all of them.

In the last test (+12 minutes, no water was delivered to the fuel) principally all the wood pallets were consumed. Debris of coaled wood pallets was found on the platform and the target had totally disappeared. One of the important criteria put by STA was the total heat release rate should not exceed 50 MW, after activation of the system. As can be seen in Figure 10, this criterion is met. Further, it can be observed that in four out of five tests with the system activated correctly the heat release rate is lower than about 20 MWs. This gives a certain confidence in the results and the aim of the protection.

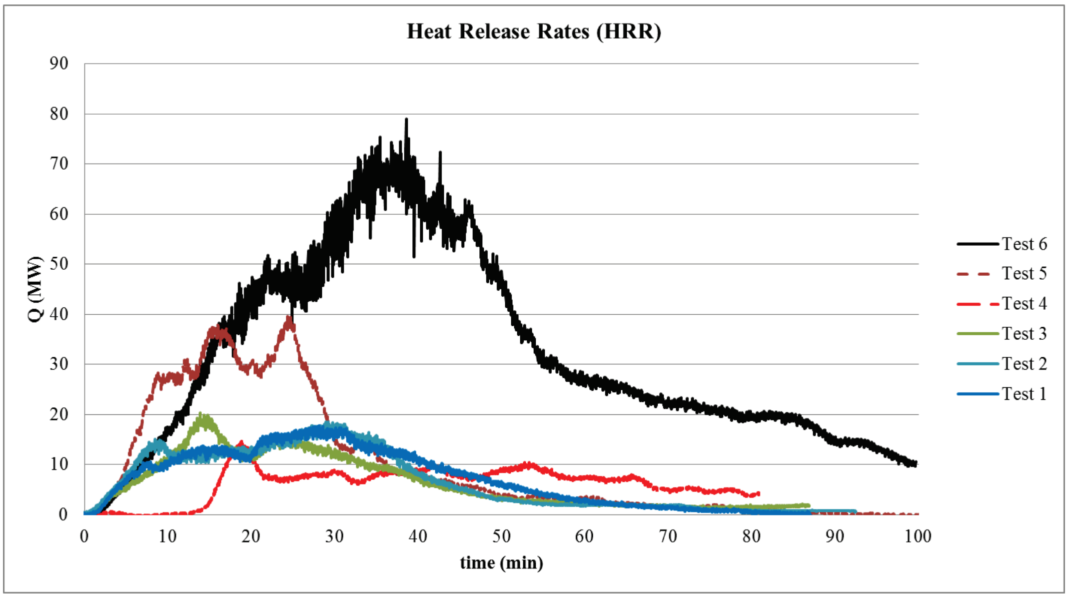


Figure 10 The measured heat release rates for test 1-6.

In the following a presentation of the measured gas temperatures at different distances is given. In Figure 11 the gas temperatures at x=0 m is given for each test. This position is at the centre of the fuel package. This position and other positions are shown in more detail in Figure 7.

In test 6, the ´free burn´ test, the temperatures at x=0 m reaches about 880°C after about 14 minutes after ignition, when the heat release rate is about 30 MW. In test 5, the test without steel protection at the end, the gas temperatures become very high early in the fire development, or about 7 minutes after ignition. This is because the flame volume hits the ceiling early, and when the temperature is at its first peak at 950°C, the heat release rate is 28 MWs. Directly after activation the temperature drops to about 750 - 800°C. In all the other tests, the cooling effects towards the ceiling are very effective after activation of the nozzles.

In the following figures, the gas temperatures are given at x=1.5 m, 4.5 m and 9.0 m, respectively, for each test. In the ´free burn´ test, test 6, the highest gas temperatures are obtained at a distance of x=4.5 m and x=9 m. This has been observed in many large scale tests, that is the maximum temperatures are obtained downstream of the centre point of the fuel. This is due the how the combustion zone moves along the ceiling. After activation these temperatures are reduced quite fast.

The maximum gas temperatures at the ceiling and presented in Figures 11-14 were never higher than 400 °C to 800 °C after activation. The highest gas temperature was measured in test 6 at x=4.5 m, 1366°C, which corresponds well to the temperatures measured by Lönnermark and Ingason [4] in the Runehamar tests in 2003.

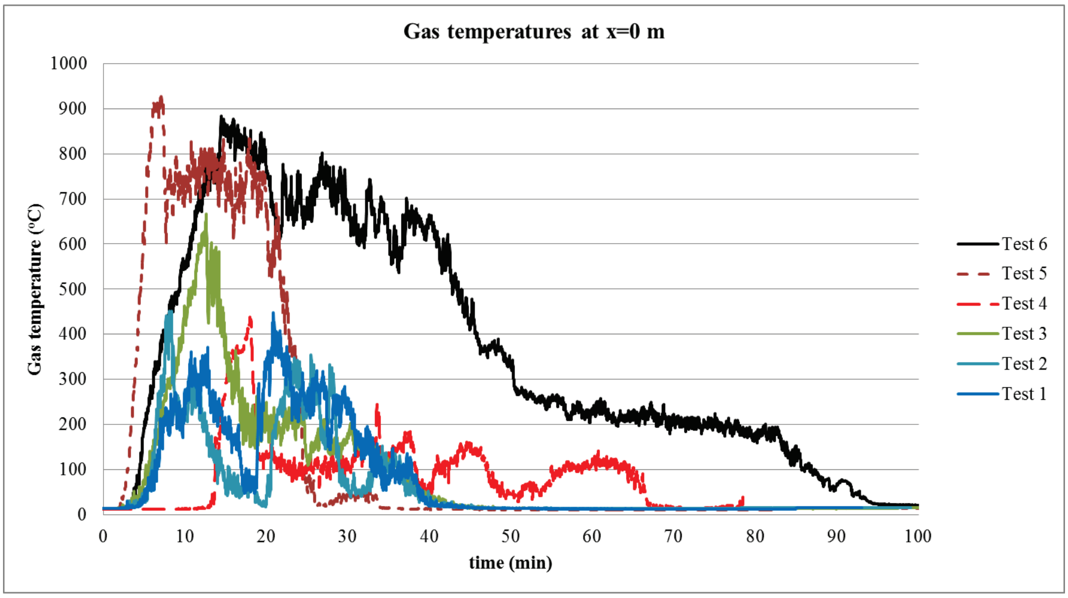


Figure 11 The measured gas temperatures in the ceiling at x=0 m for test 1-6.

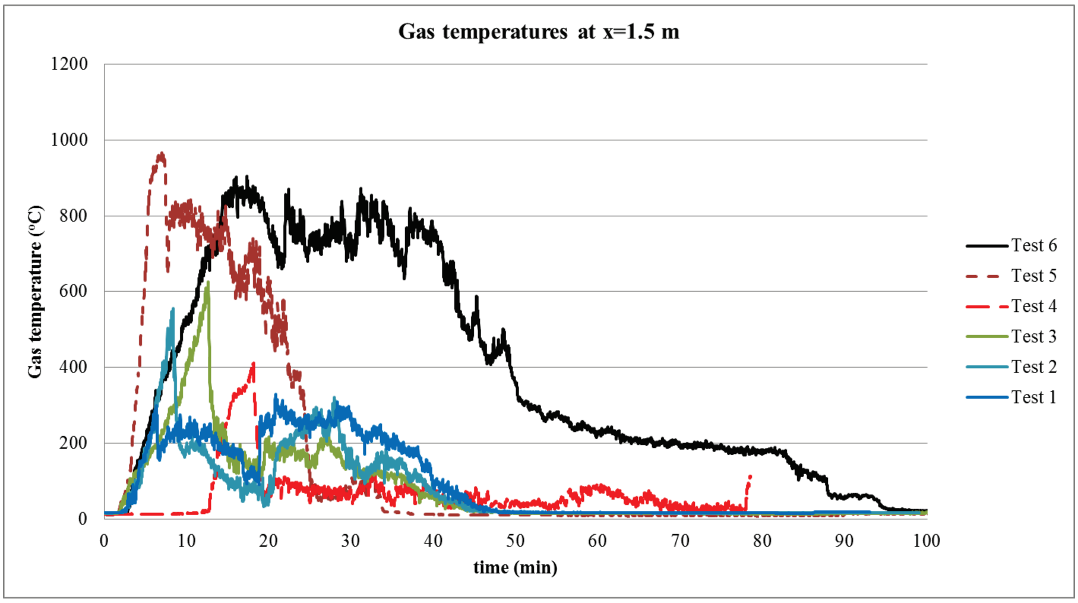


Figure 12 The measured gas temperatures in the ceiling at x=1.5 m for test 1-6.

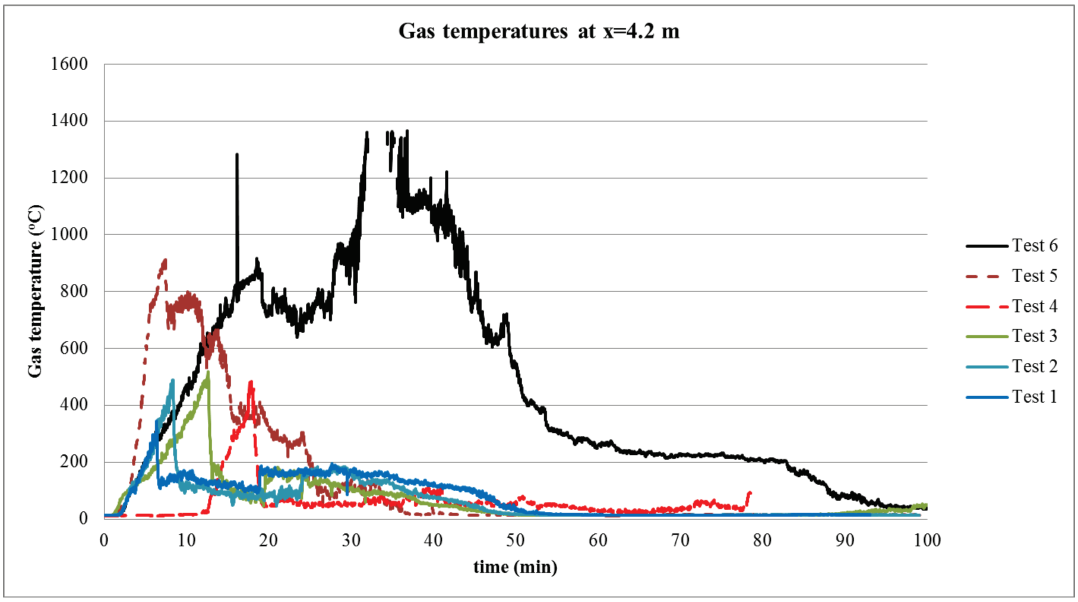


Figure 13 The measured gas temperatures in the ceiling at x=4.2 m for test 1-6.

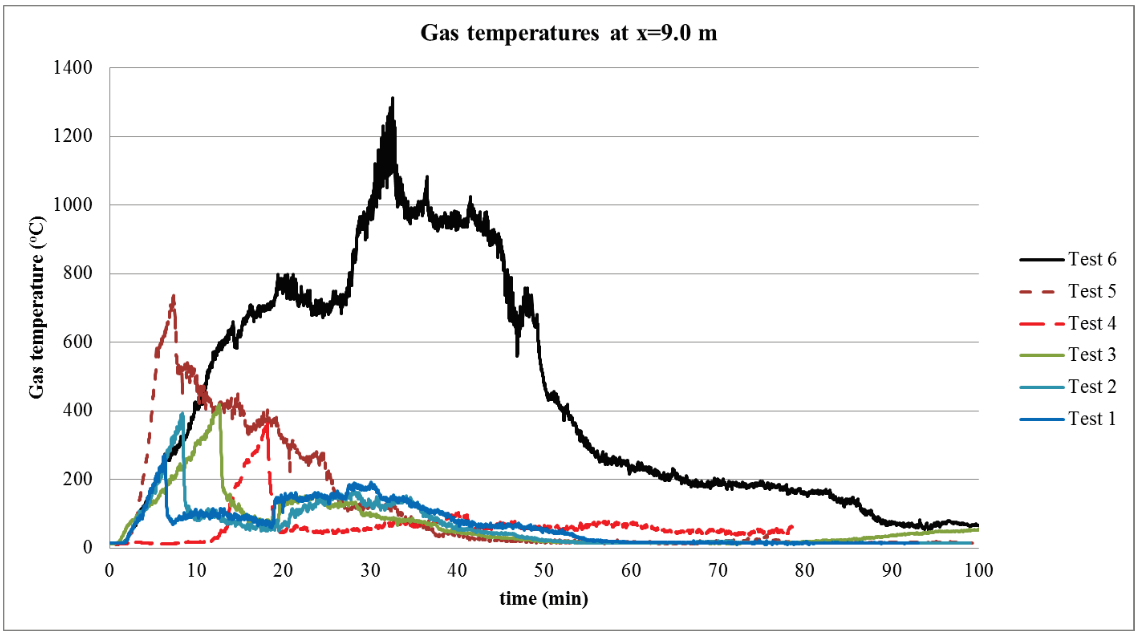


Figure 14 The measured gas temperatures in the ceiling at x=9.0 m for test 1-6.

In Table 2, a summary of the test results are given. The parameters given are the heat release rate at activation, Q_{act}, the highest ceiling temperature at activation, T_{act}, the maximum heat release rate after the system has been activated, $Q_{max\ after\ act}$ and the incident maximum heat flux to the target, q''. Followed by that there are three energy terms; E_{tot}, $E_{tot\ before\ act}$ and $E_{tot,\ after\ act}$ all given in GJ. These are integrated values from the heat release rate curves for different time periods. The total energy content of the fire load can be estimated by multiplying the mass with the theoretical heat of combustion for wood. There are 441 wood pallets, including the target, each having a weight of about 24 kg. The theoretical heat of combustion for wood can be obtained from Tewarson [5], or 17.9 MJ/kg. This means the total potential heat energy that could be released from this fuel load is 189 GJ. This value corresponds well to the value given in Table 2 for test 6.

In the last column, a value is given for equivalent number of pallets that have been consumed. This value was obtained by using E_{tot} for each test and dividing it with the heat of combustion and the weight of all the pallets. This number does not necessarily comply exactly with the ocular inspections after the tests, but gives a good indication of how many pallets were consumed. In tests 1 – 3, a very similar amount was consumed, which indicate that the system is not sensitive to the activation time for the first +8 min of the time delay. Actually, when inspecting the data it can be seen that slightly less total energy is consumed as the delay time increases. Prior to activation the consumed energy increases as expected, but after activation this energy tends to reduce slightly. Although the main mechanism of fire suppression is the surface cooling, some secondary effects such as dilution increase the efficiency of the system as the fuel gets more involved.

When physical barriers for the fuel are changed the results are influenced more dramatically. The absence of the wind shield (front steel sheet) in test 5, is an excellent example of that. Despite the dramatic change in the fire development, and 4 minutes delay, the system was able to get the fire under control and finally suppressed it. Using tarpaulin had more effects than expected, especially the initial fire development. It did not influence the outer wetting of the fuel but more how the fire spread more deep inside the fuel. One of the important criteria of the performance of the system was to prevent fire spread to an adjacent target (vehicle). The fire should not spread to a target 5 m from the end of the main fuel arrangement and the heat flux towards the target should not exceed 20 kW/m^2. In Table 2 it can be seen that the maximum heat flux at the target was far from this value. In test 6, this value was exceeded and a maximum value of q''= 39 kW/m^2 was obtained. The value of q''=20 kW/m^2, was obtained after 28 minutes into the test, at a height 2 m above the road surface. Probably the fire was ignited first at the top of the pile, and therefore most likely prior to this time.

Table 2 Summary of key heat energy parameters from the tests.

Test number	Delay time after 141°C in ceiling (min)	t_{act} (m:s)	Q_{act} (MW)	T_{act} (°C)	$Q_{max,\ after\ act}$ (MW)	q'' (kW/m^2)	E_{tot} (GJ)	$E_{tot,\ before\ act}$ (GJ)	$E_{tot,\ after\ act}$ (GJ)	Equivalent number of pallets consumed
1	2	6:04	10.2	350	17.7	0.5	37.4	1.0	36.4	89
2	4	8:20	15.0	550	18.5	0.5	36.1	4.1	32	85
3	8	13:18	20.2	680	15.2	0.6	33.0	6.0	27	78
4	4	18:25	16.3	498	11.0	0.6	39.4	1.9	37.5	93
5	4	7:17	28.0	950	39.6	2.0	57.8	3.1	54.7	137
6	12	15:48	26.2	796	78.9	39	189.7	8.9	180.8	441

In Table 3 a summary of the maximum or minimum values for gas- and optical (visibility) measurements are given. It is clear from the data that when water is applied it influences the smoke production due to cooling of the surface. Also production of incomplete combustion products such as CO is increased. The table shows that if the system activates late, an increase of toxic substances and smoke is produced, but the impact of this effect is easily mitigated by activating the system early. Further research is needed to investigate the implication of this observation in future testing.

Table 3 Maximum or minimum values for gas- and optical measurements. T_{trans} is the transparency of the laser beam.

Test number	T_{trans} x=50 m (%)	T_{trans} x=1000 m (%)	O_2 x=1000 m (%)	CO_2 x=1000 m (%)	CO x=1000 m (%)
1	-	40	20.2	0.65	0.144
2	81	49	20.2	0.63	0.128
3	89	39	20.0	0.83	0.152
4	79	37	20.1	0.71	0.110
5	42	7	18.6	2.35	0.350
6	91	90	17	4	0.039

The heat release rate upon activation ranged from approximately 10 MW to 30 MW. The heat release rate was controlled after activation for a period of 10 – 20 minutes. After that the fire was suppressed over a period of 10 - 30 minutes, which means that the system prevented further fire spread inside the fuel. The FFFS resulted in lower heat release rates than 50 MW in all five cases, which was one of the original questions postulated by the STA. The maximum temperatures at the ceiling were never higher than 400 ^oC to 800 ^oC after activation. In test 6 the maximum ceiling temperature was 1366 ^oC. In all experiments the fire was controlled in the first period after activation and then suppressed with a considerable amount of fuel still remaining. A pile of pallets stood 5 m from one end of the fire. It was used to assess the risk of fire spread to adjacent vehicles. In all cases with FFFS operating, the target was unaffected by the main fire.

5 Conclusions

The experiments show the importance of early activation of the FFFS. Despite this it was clear from the experiments that the system has a sufficient safety margin to allow delayed response while retaining the ability to fight the more severe fires produced by such a delay. The system was able to prevent the spread of the fire beyond the main fire load, and was clearly able to lower the gas temperatures in the tunnel. This has important implications for the design and safety of the evacuation. The tests show that the design fire of 100 MW as originally planned can be reduced to lower than 50 MW by the presence of a FFFS, which translates into huge savings in investment costs for the ventilation system. The experiments show that if the system activates late, an increase of toxic substances and smoke is produced, but the impact of this effect is easily mitigated by activating the system early. Further research is needed to investigate the implication of this observation in future testing.

The benefits of FFFS are primarily that they can be used to increase safety in tunnels. Such systems will be able to fight fires that are relatively large and thereby potentially prevent a major disaster. In the case of congestion and specifically when a queue is formed, the system will increase safety by minimizing the risk of propagation of a fire as it could occur.

6 Reference

1. Ying Zhen Li, et al., *Model scale tunnel fire tests with water-based fire suppression systems*, 2014, SP Technical Research Institute of Sweden: SP Report 2014:02. p. .
2. Ingason, H., A. Lönnermark, and Y.Z. Li, *Runehamar Tunnel Fire Tests*, 2011, SP Technical Research Institute: SP Report 2011:55.
3. Tran, H.C., *Experimental data on wood material*, in *Heat Release in Fires*1992. p. 357-372.
4. Lönnermark, A. and H. Ingason, *Gas Temperatures in Heavy Goods Vehicle Fires in Tunnels.* Fire Safety Journal, 2005. **40**: p. 506-527.
5. Tewarson, A., *Generation of Heat and Chemical Compounds in Fires*, in *The SFPE Handbook of Fire Protection Engineering*, P.J. DiNenno, et al., Editors. 2002, National Fire Protection Association: Quincy, MA, USA. p. 3-82 -- 3-161.

Appendix – Test results Test 1 – Test 6

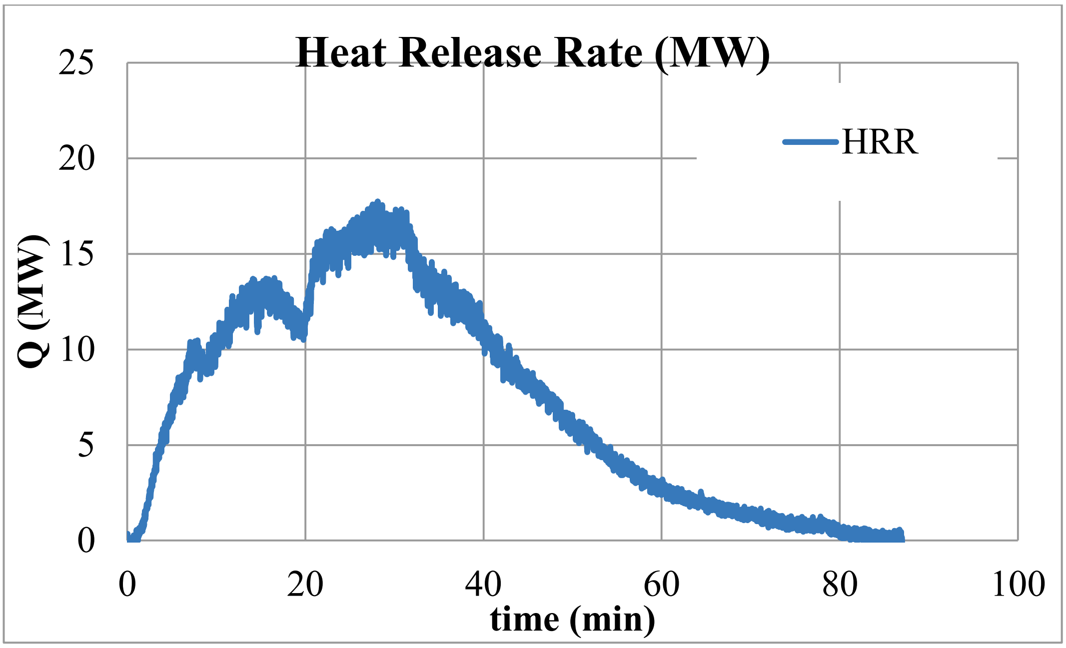


Figure A1-1 The measured heat release rate in Test 1.

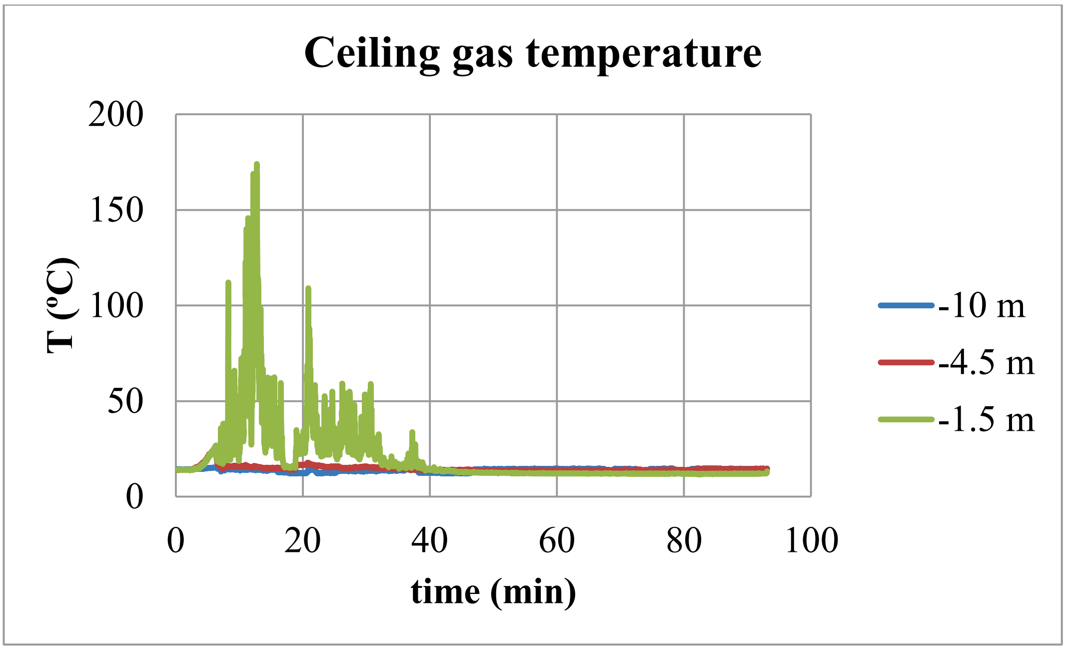


Figure A1-2 The measured gas temperature at ceiling and upstream the fire at different distances x and 30 cm below ceiling : Test 1.

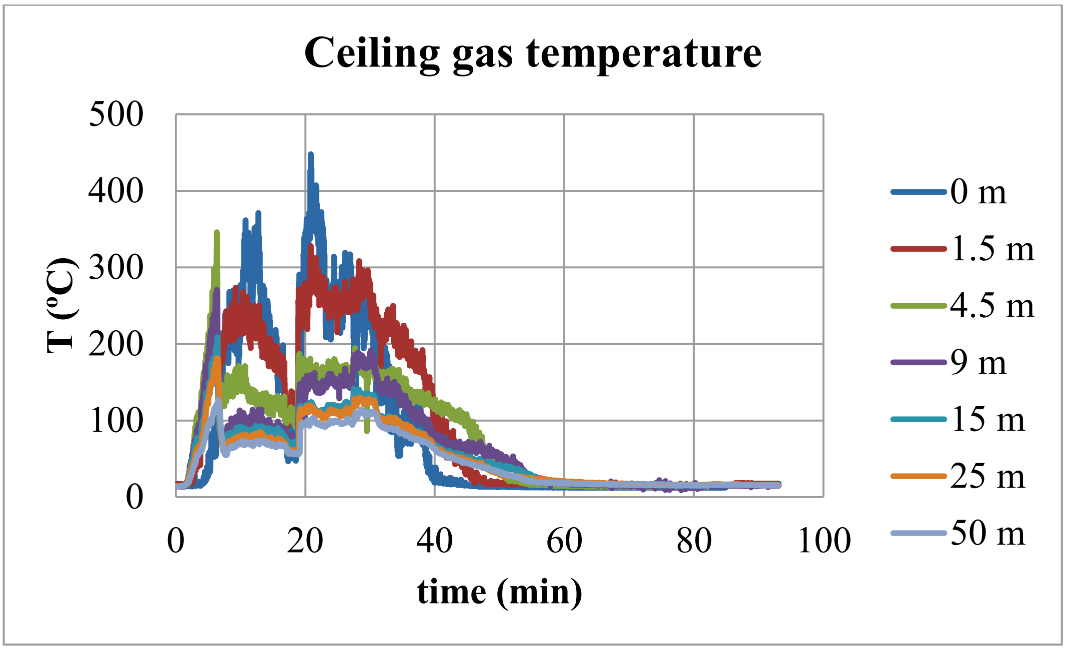


Figure A1-3 The measured gas temperature at ceiling and downstream the fire at different distances x and 30 cm below ceiling : Test 1.

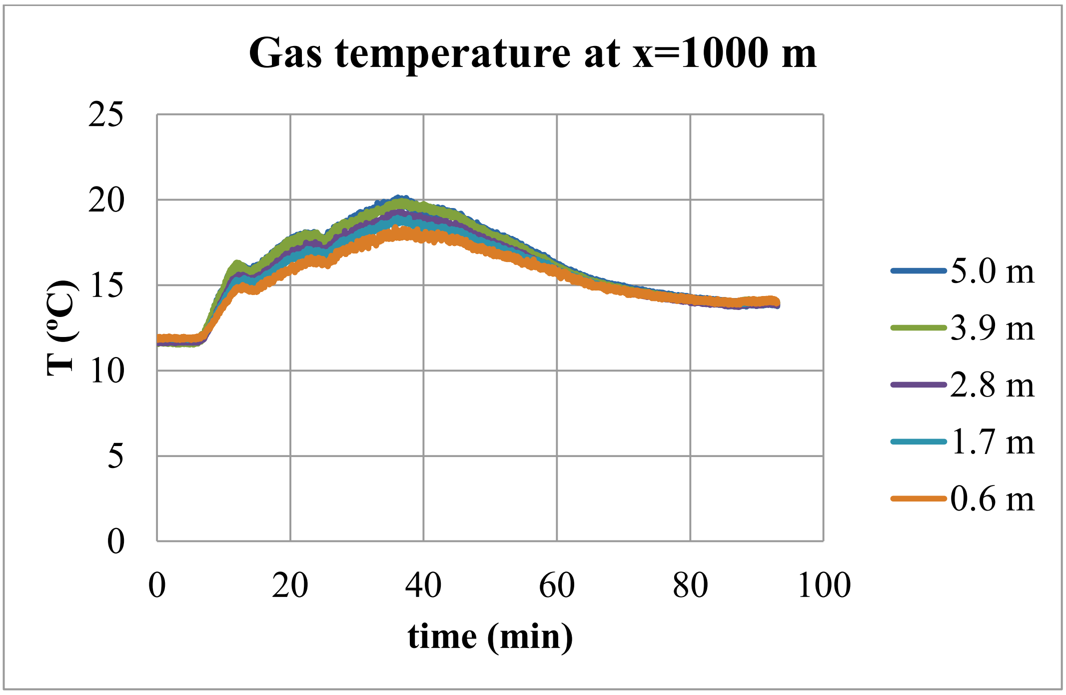


Figure A1-4 The measured gas temperature downstream the fire at distance x=1000 m and different heights above the road surface : Test 1.

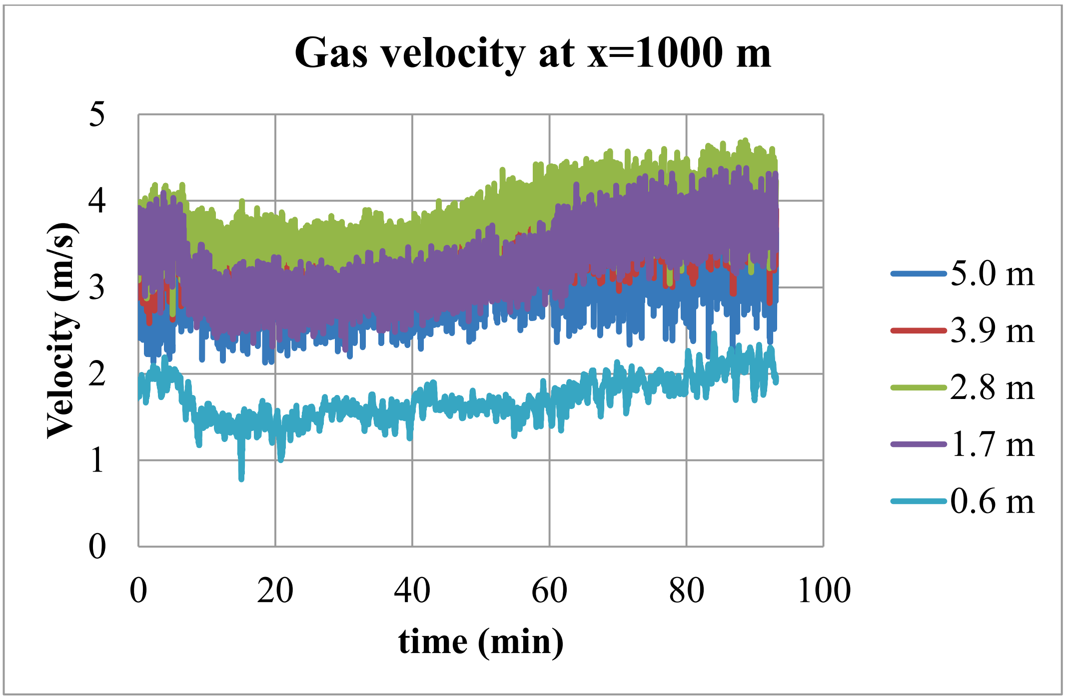


Figure A1-5 The measured gas velocity downstream the fire at distance x=1000 m and different heights above the road surface : Test 1.

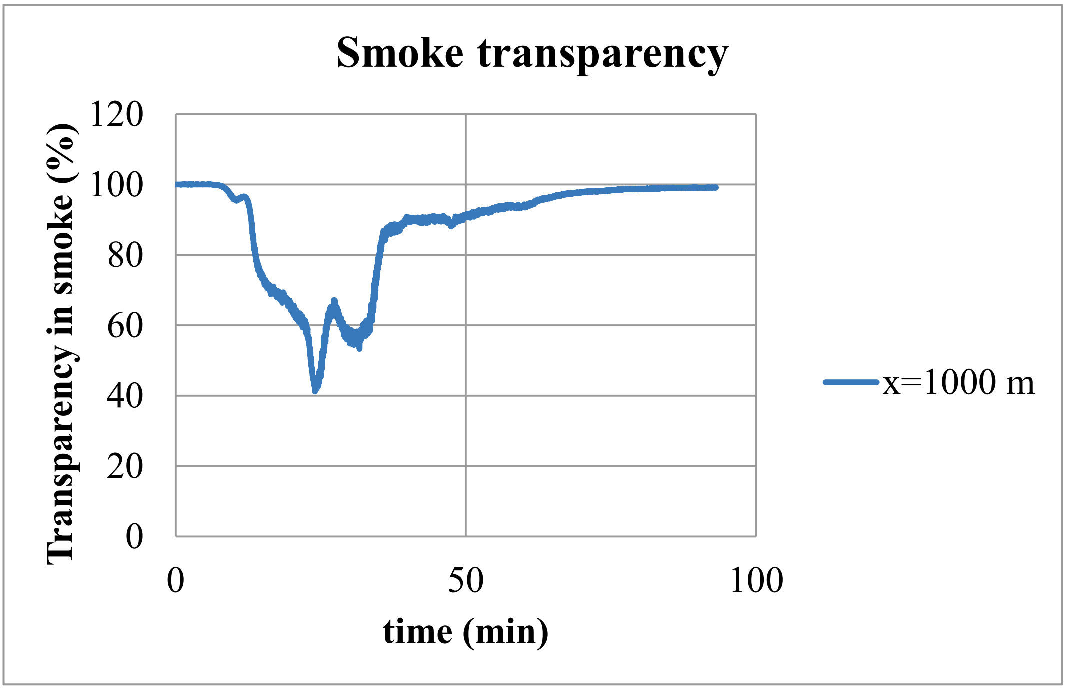


Figure A1-6 The measured smoke transparency at x=1000 m downstream the fire and 1.5 m above the road surface for Test 1.The maximum value in (%) indicate no blocking of light transmission due to smoke particles.

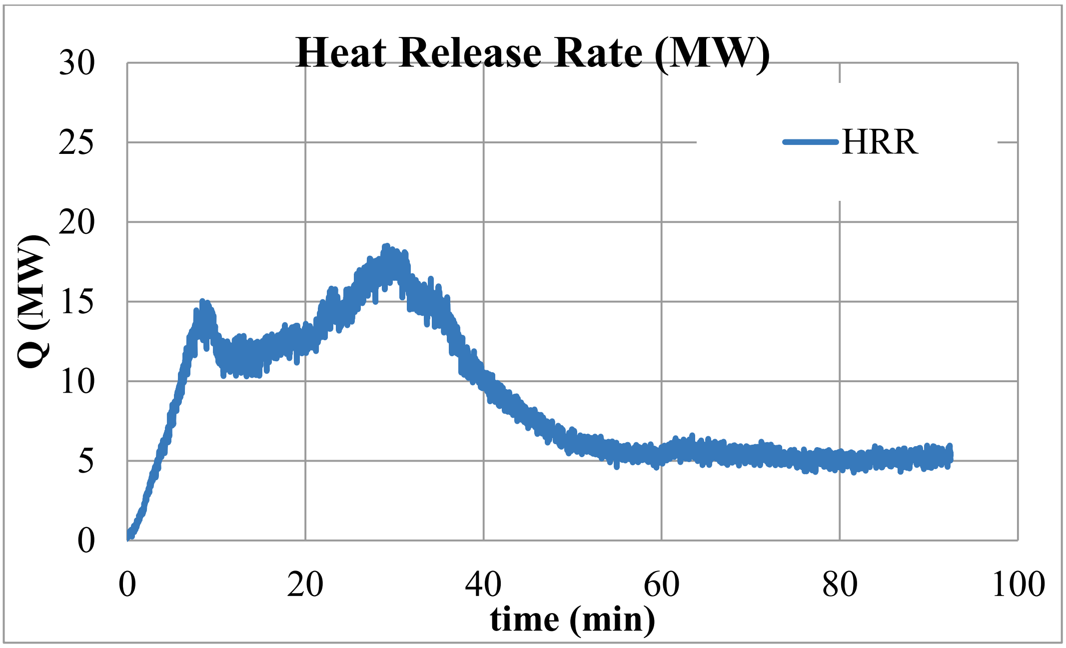


Figure A2-1 The measured heat release rate in Test 2.

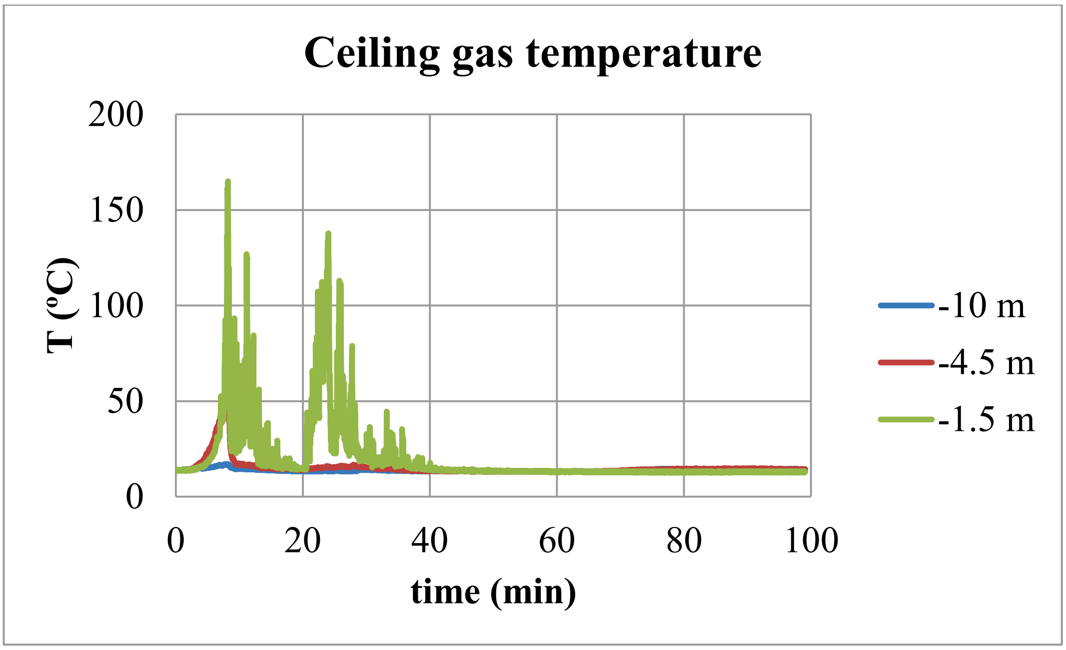


Figure A2-2 The measured gas temperature at ceiling and upstream the fire at different distances x and 30 cm below ceiling : Test 2.

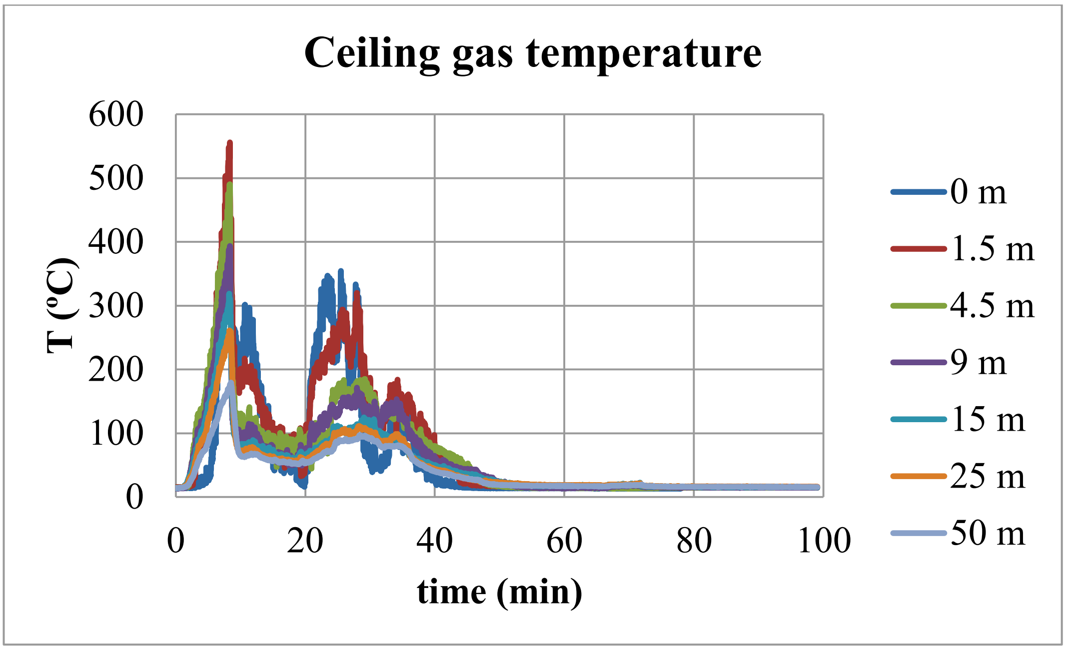


Figure A2-3 The measured gas temperature at ceiling and downstream the fire at different distances x and 30 cm below ceiling : Test 2.

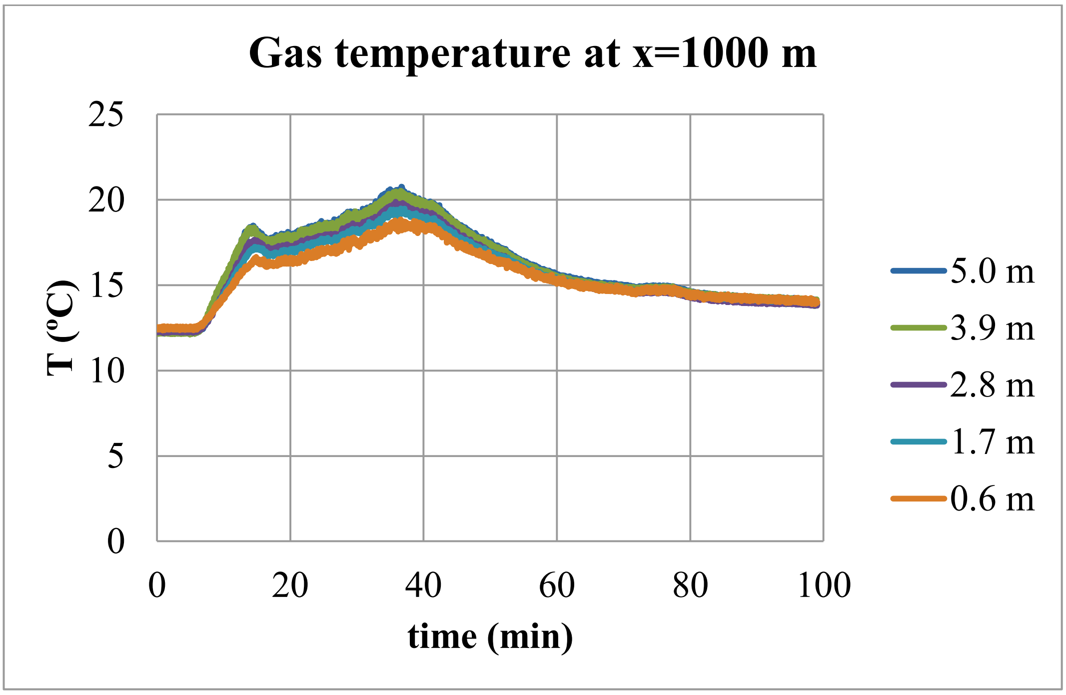


Figure A2-4 The measured gas temperature downstream the fire at distance x=1000 m and different heights above the road surface : Test 2.

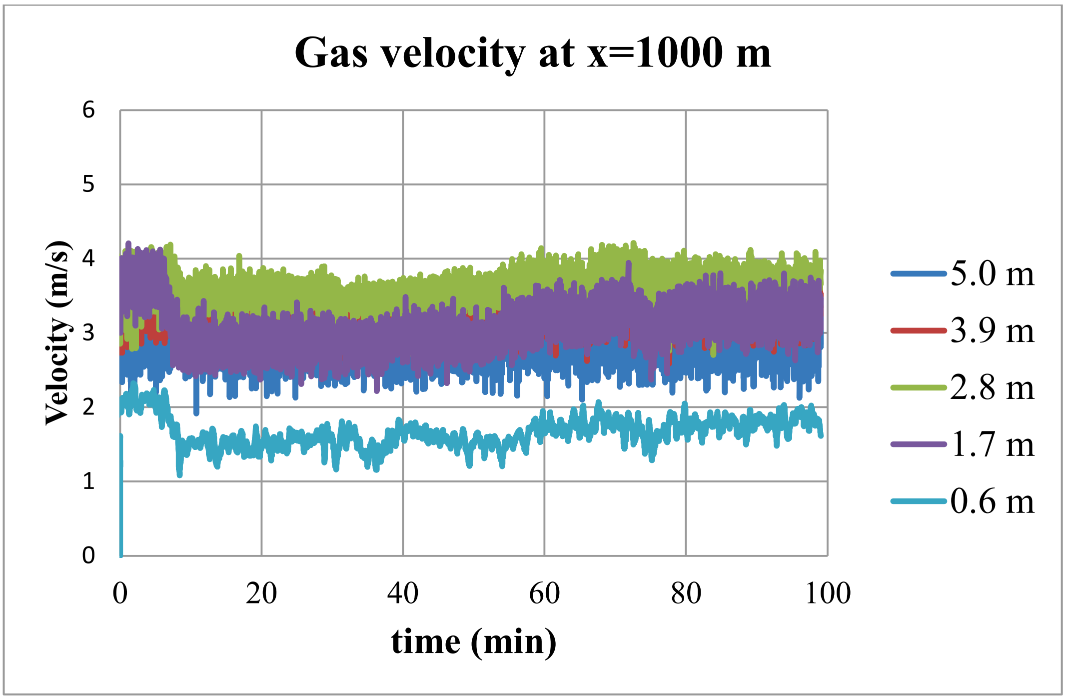


Figure A2-5 The measured gas velocity downstream the fire at distance x=1000 m and different heights above the road surface : Test 2.

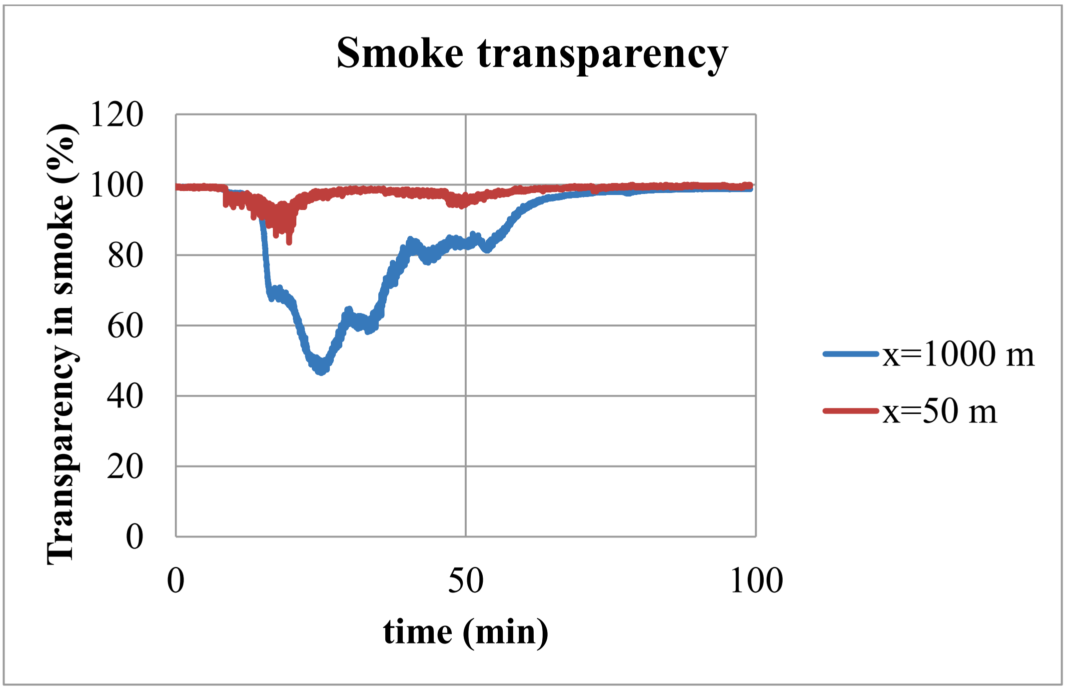


Figure A2-6 The measured smoke transparency at x=1000 m downstream the fire and 1.5 m above the road surface for Test 2.The maximum value in (%) indicate no blocking of light transmission due to smoke particles.

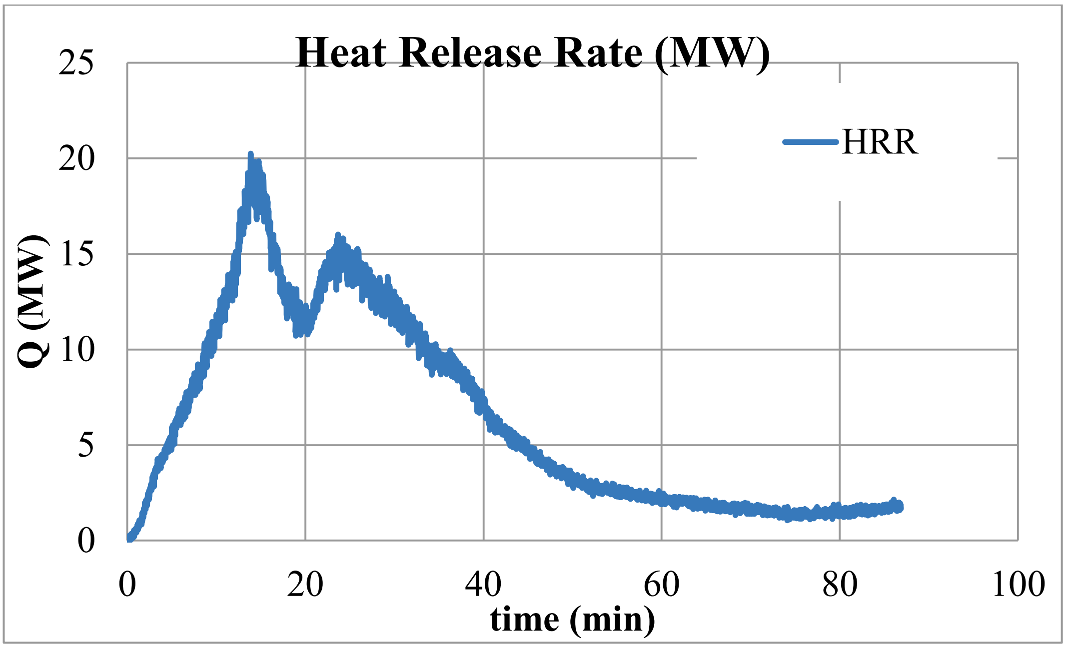


Figure A3-1 The measured heat release rate in Test 3.

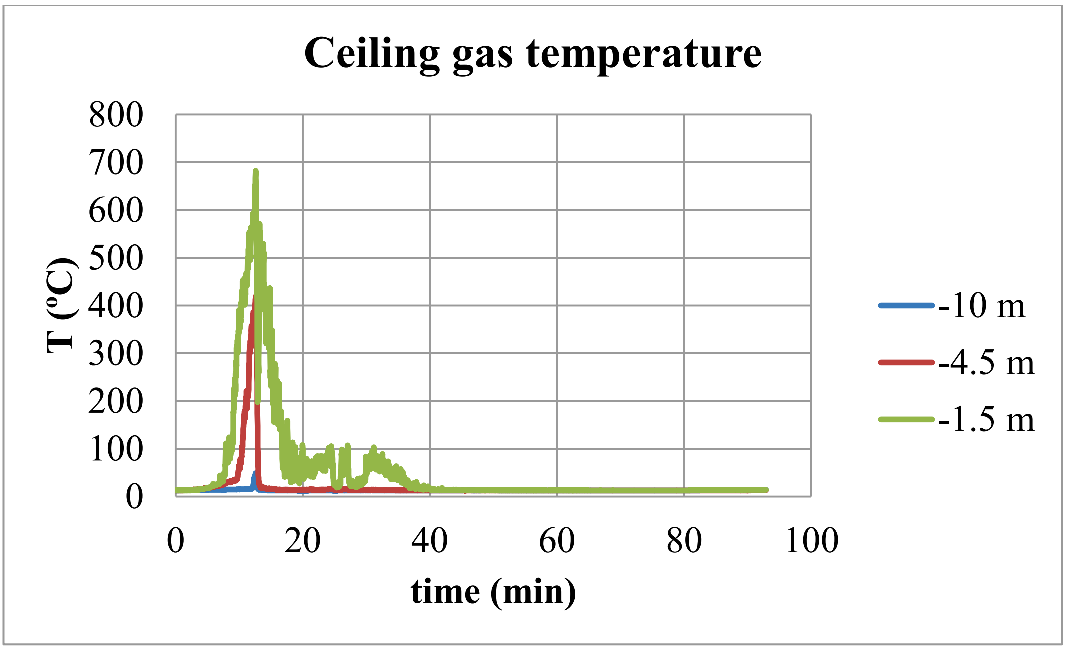


Figure A3-2 The measured gas temperature at ceiling and upstream the fire at different distances x and 30 cm below ceiling : Test 3.

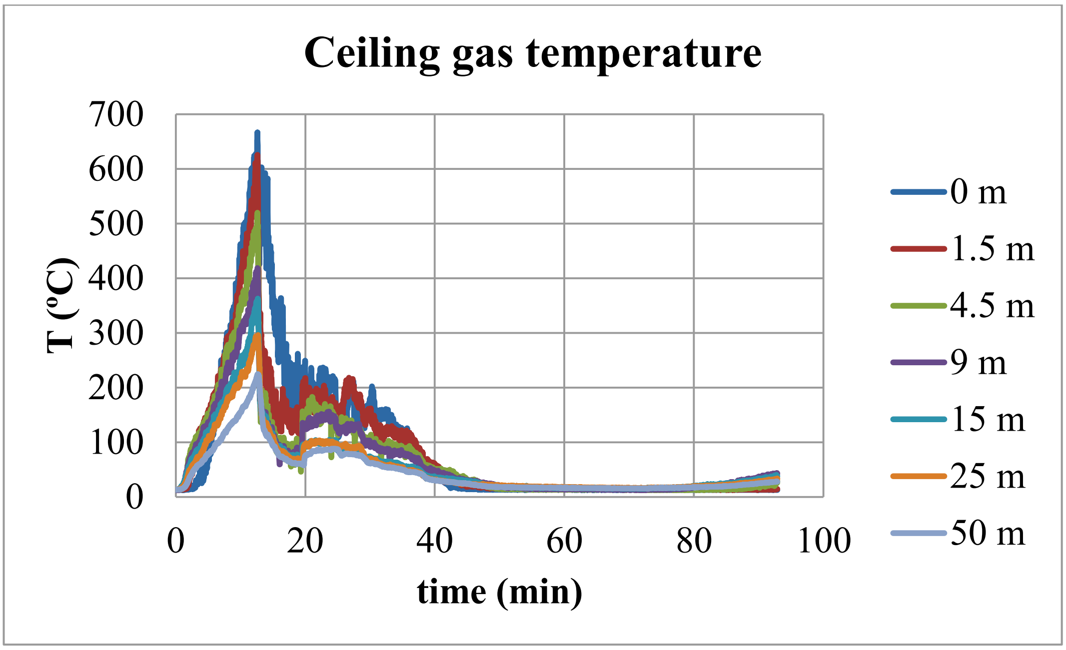


Figure A3-3 The measured gas temperature at ceiling and downstream the fire at different distances x and 30 cm below ceiling : Test 3.

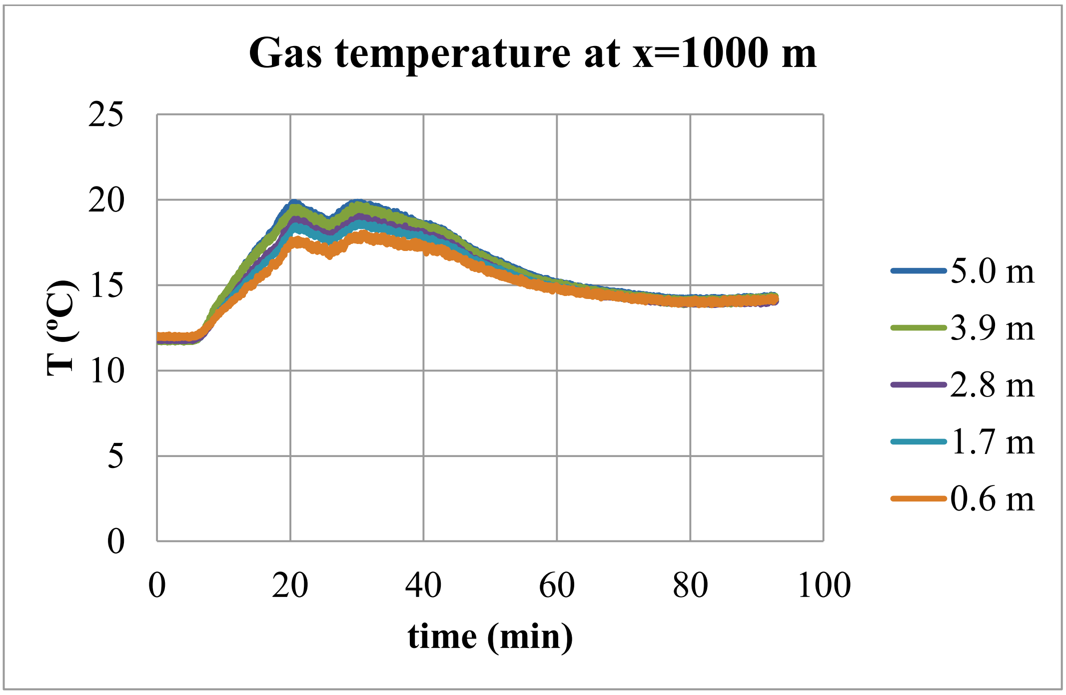


Figure A3-4 The measured gas temperature downstream the fire at distance x=1000 m and different heights above the road surface : Test 3.

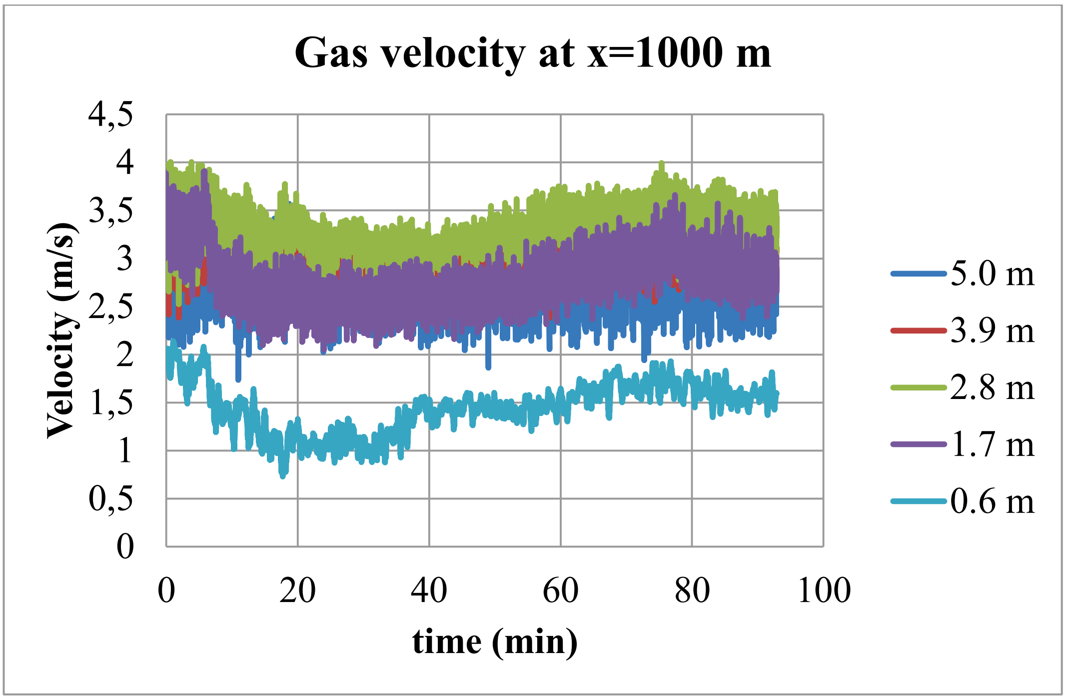


Figure A3-5 The measured gas velocity downstream the fire at distance x=1000 m and different heights above the road surface : Test 3.

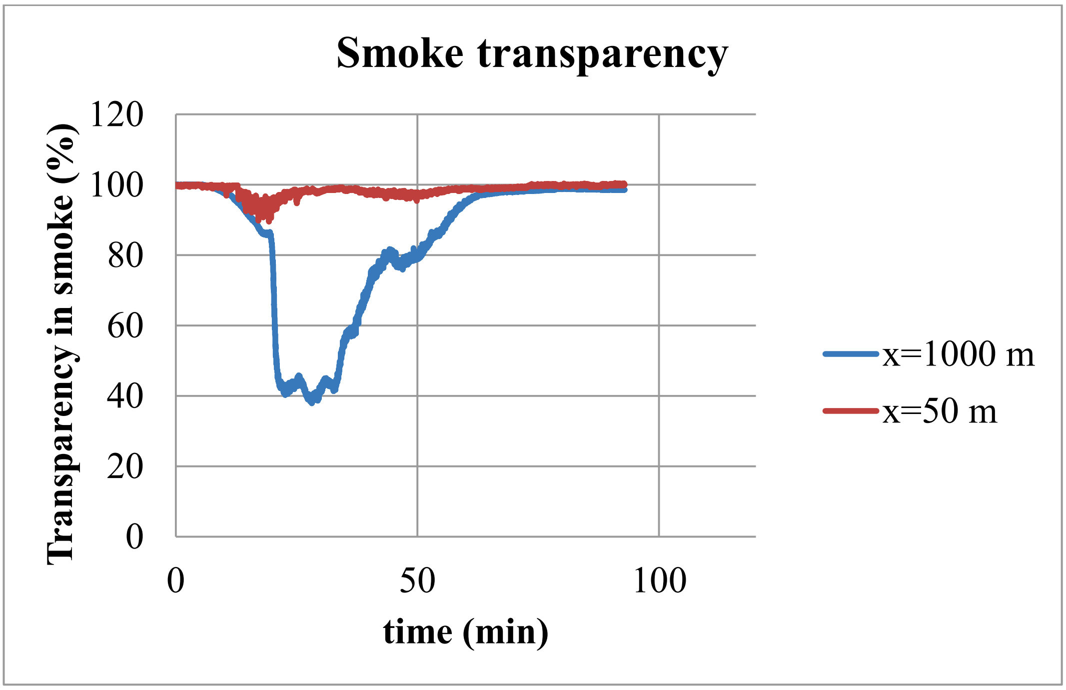


Figure A3-6 The measured smoke transparency at x=1000 m downstream the fire and 1.5 m above the road surface for Test 3.The maximum value in (%) indicate no blocking of light transmission due to smoke particles.

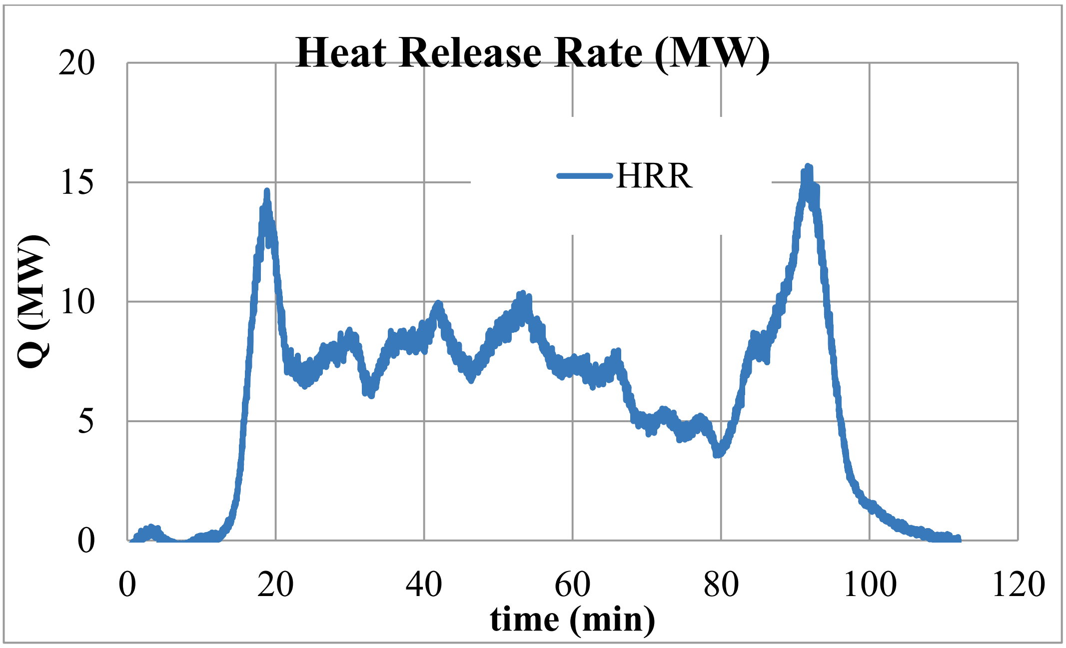


Figure A4-1 The measured heat release rate in Test 4.

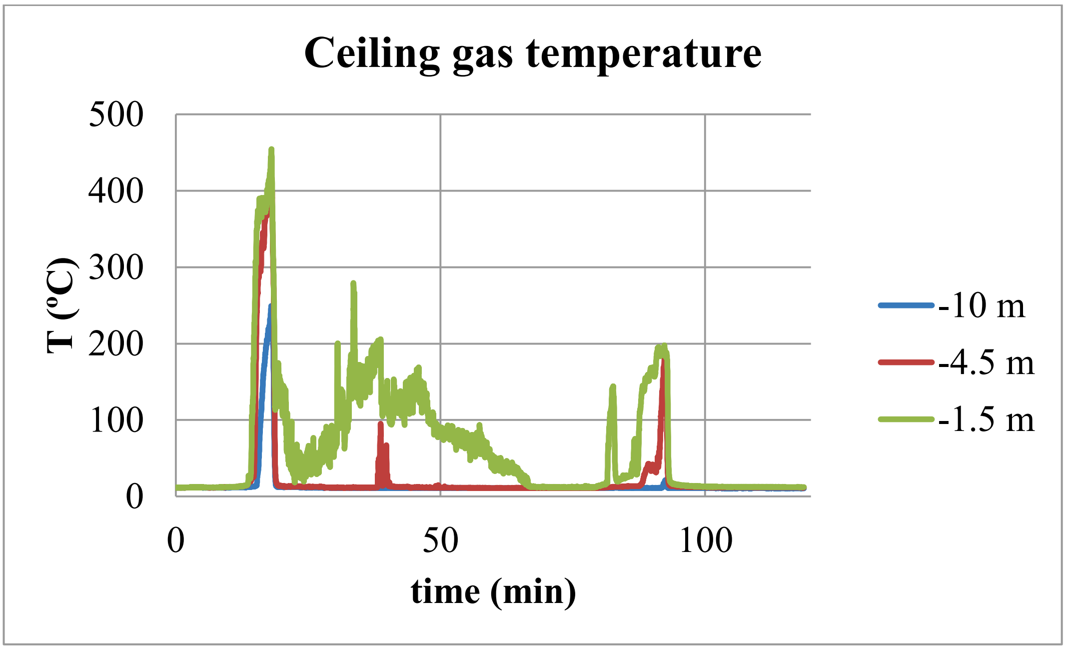


Figure A4-2 The measured gas temperature at ceiling and upstream the fire at different distances x and 30 cm below ceiling : Test 4.

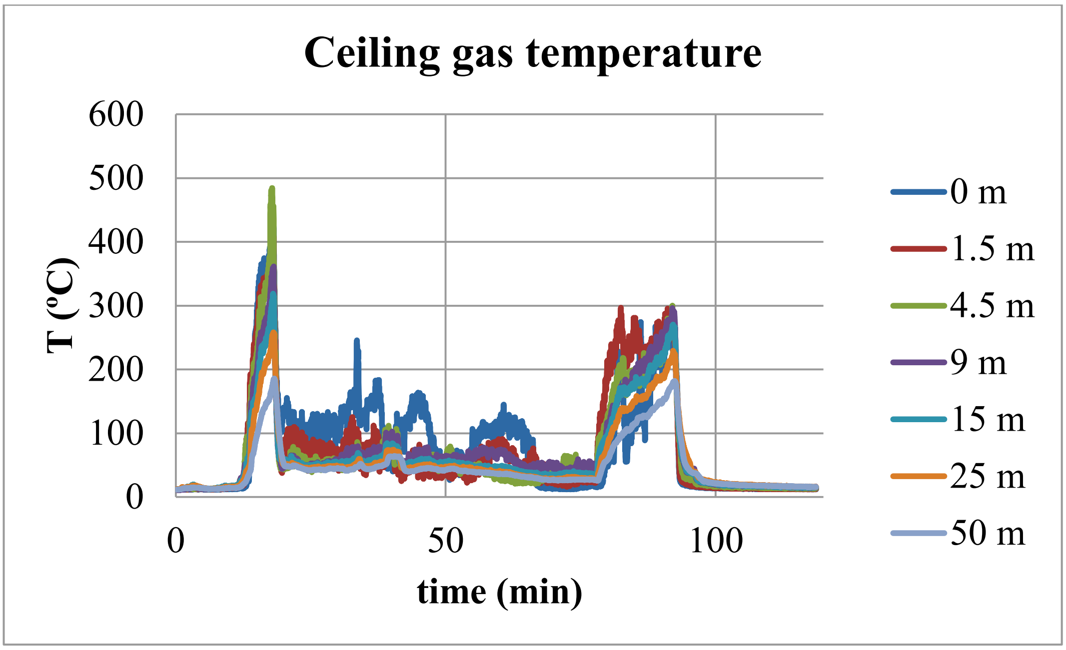


Figure A4-3 The measured gas temperature at ceiling and downstream the fire at different distances x and 30 cm below ceiling : Test 4.

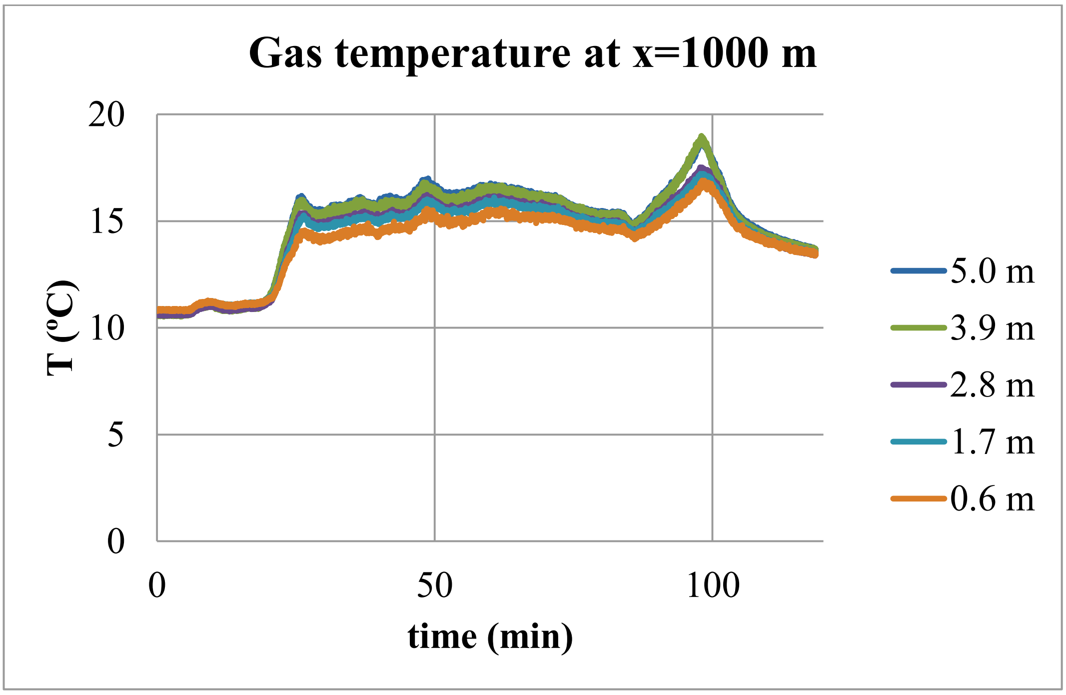


Figure A4-4 The measured gas temperature downstream the fire at distance x=1000 m and different heights above the road surface : Test 4.

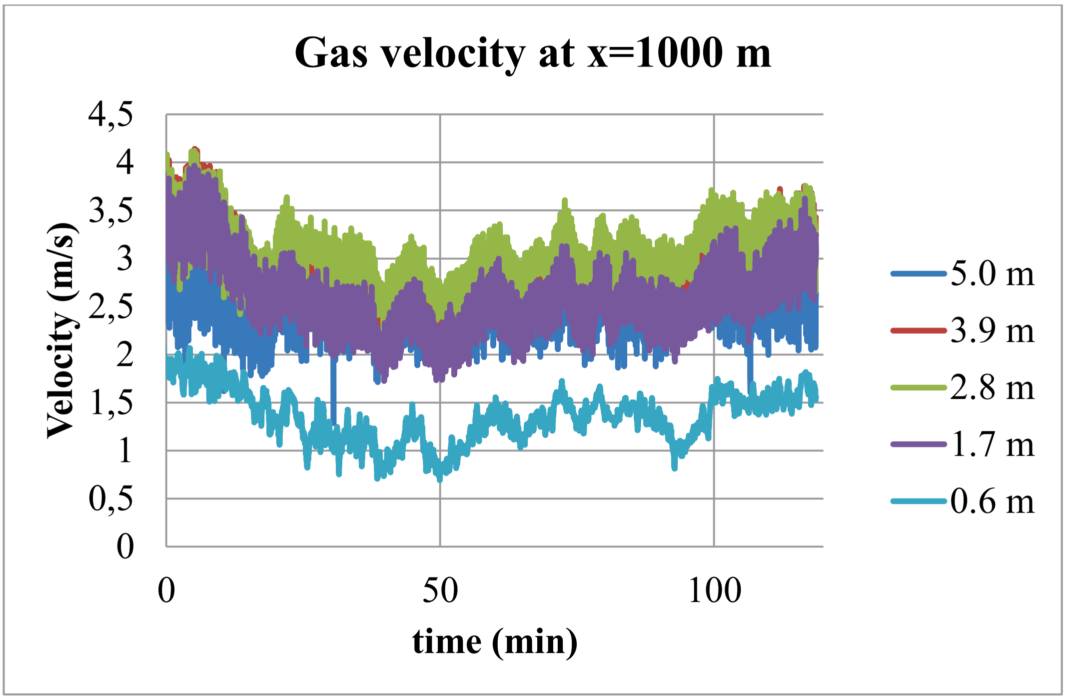


Figure A4-5 The measured gas velocity downstream the fire at distance x=1000 m and different heights above the road surface : Test 4.

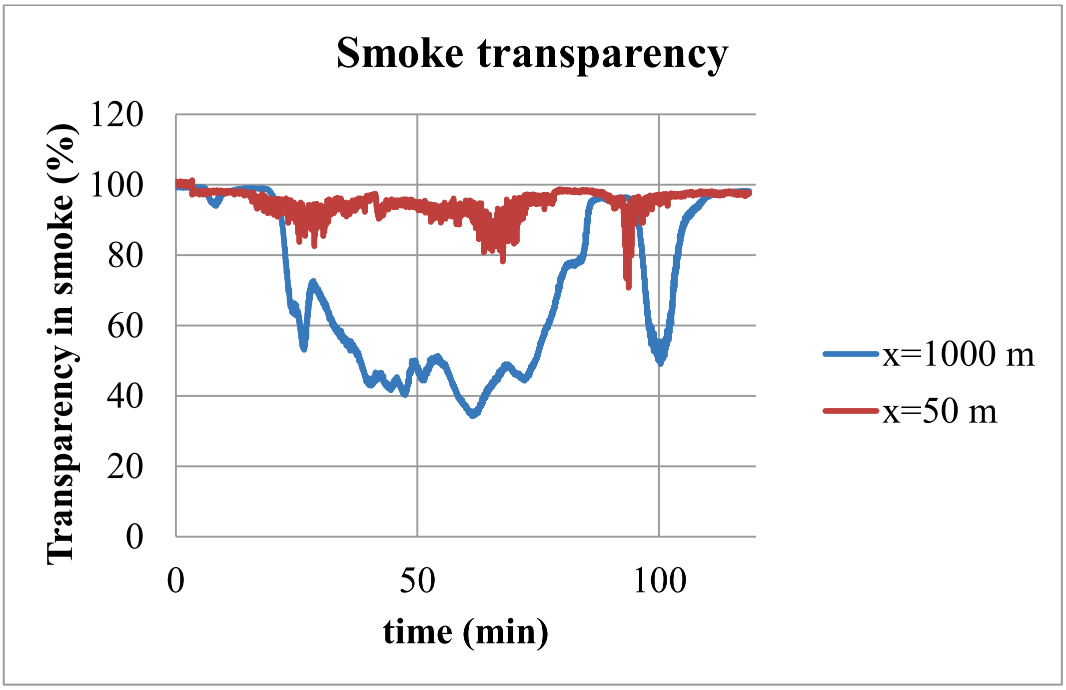


Figure A4-6 The measured smoke transparency at x=1000 m downstream the fire and 1.5 m above the road surface for Test 4.The maximum value in (%) indicate no blocking of light transmission due to smoke particles.

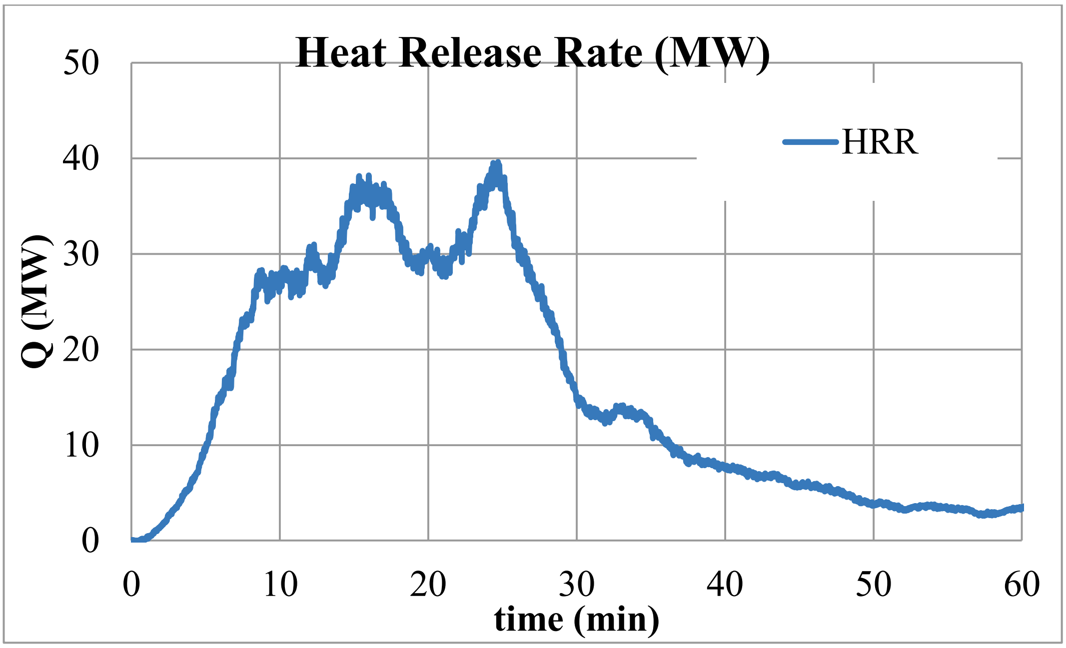


Figure A5-1 The measured heat release rate in Test 5.

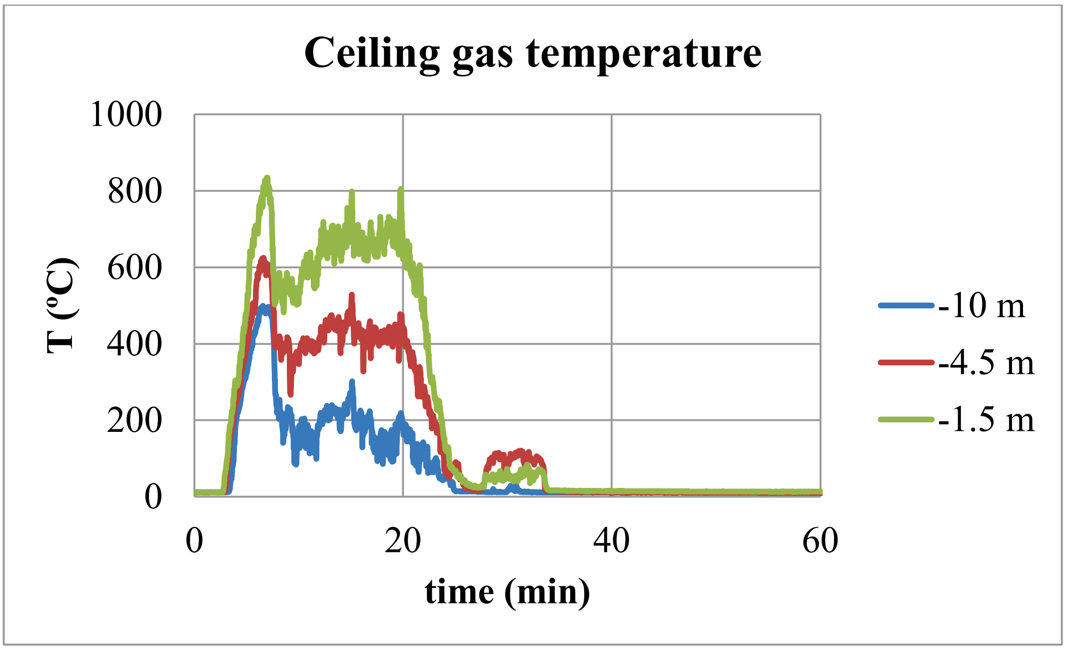


Figure A5-2 The measured gas temperature at ceiling and upstream the fire at different distances x and 30 cm below ceiling : Test 5.

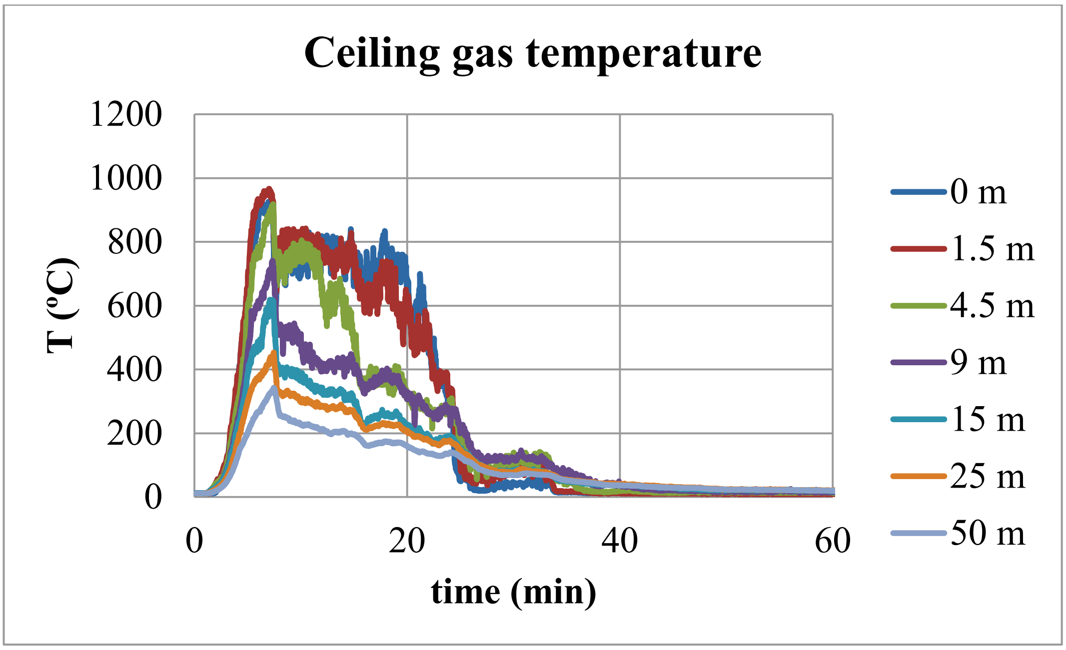


Figure A5-3 The measured gas temperature at ceiling and downstream the fire at different distances x and 30 cm below ceiling : Test 5.

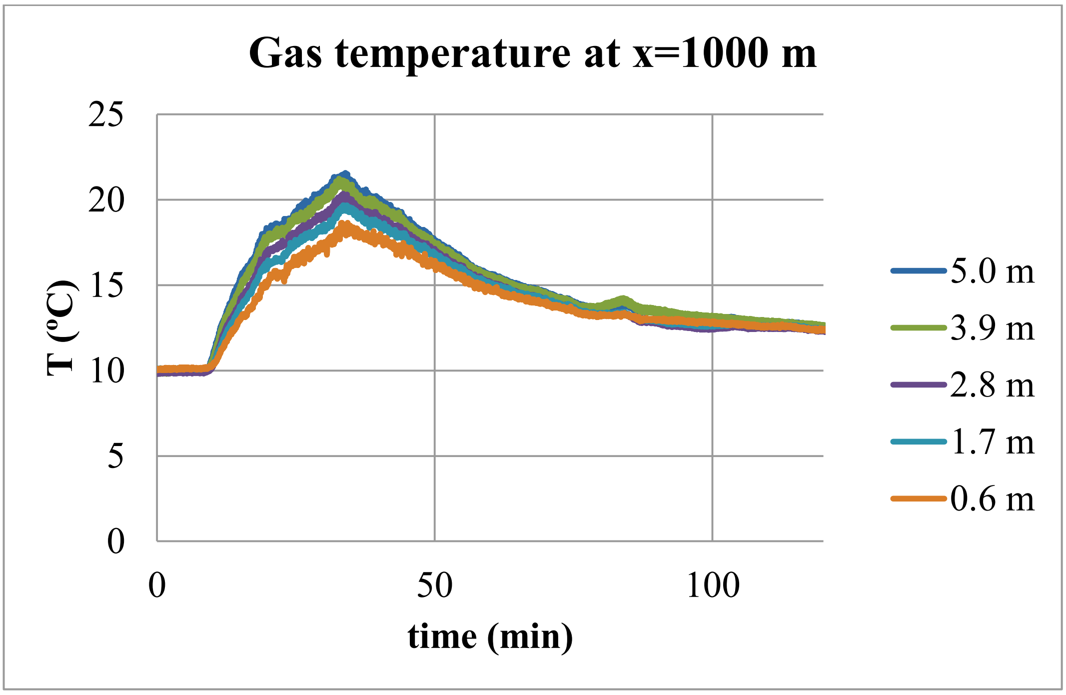


Figure A5-4 The measured gas temperature downstream the fire at distance x=1000 m and different heights above the road surface : Test 5.

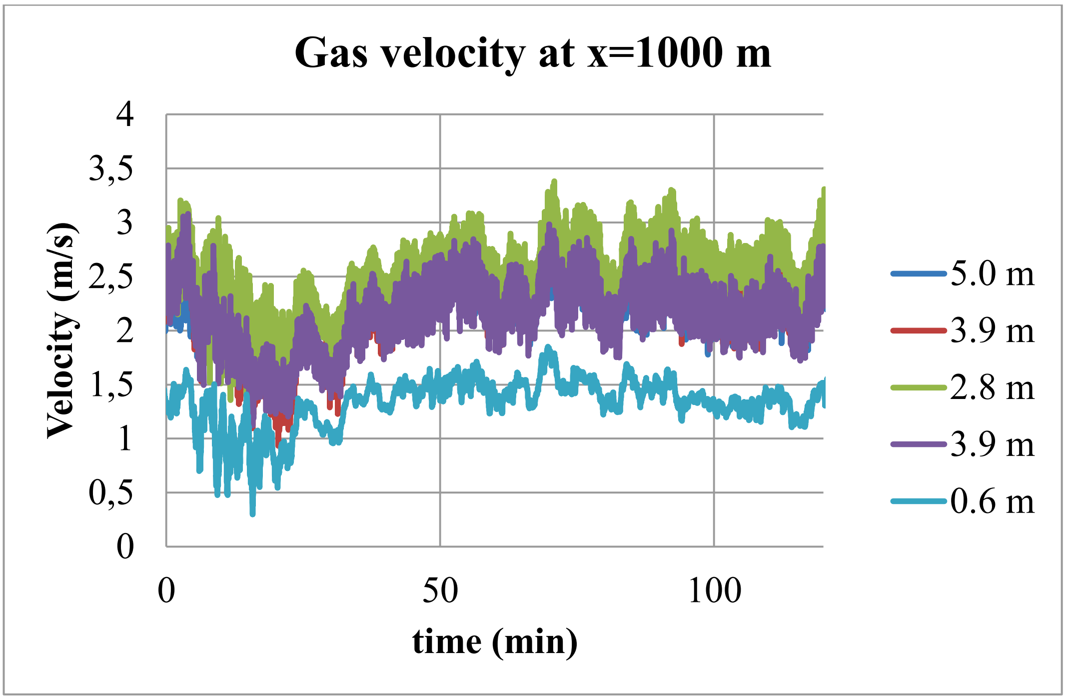


Figure A5-5 The measured gas velocity downstream the fire at distance x=1000 m and different heights above the road surface : Test 5.

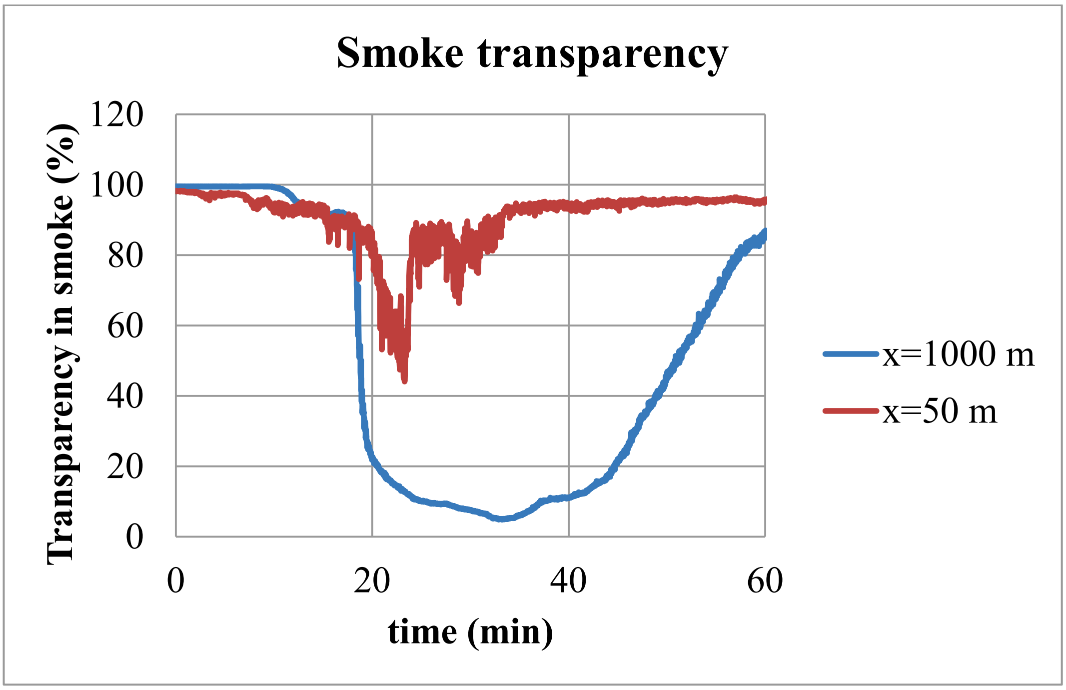


Figure A5-6 The measured smoke transparency at x=1000 m downstream the fire and 1.5 m above the road surface for Test 5.The maximum value in (%) indicate no blocking of light transmission due to smoke particles.

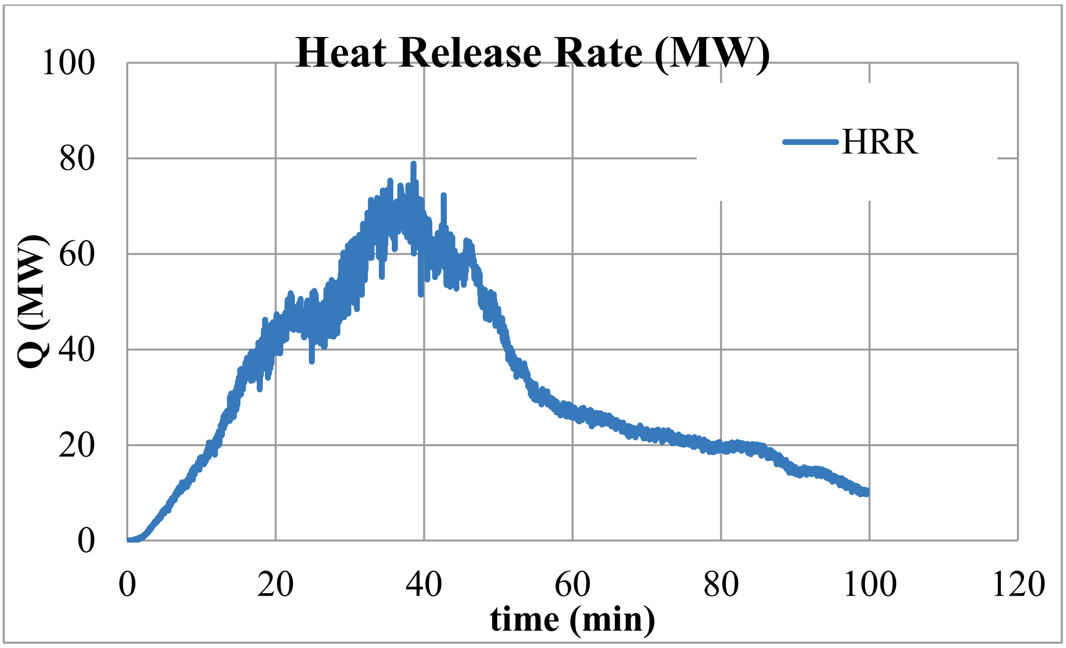


Figure A6-1 The measured heat release rate in Test 6.

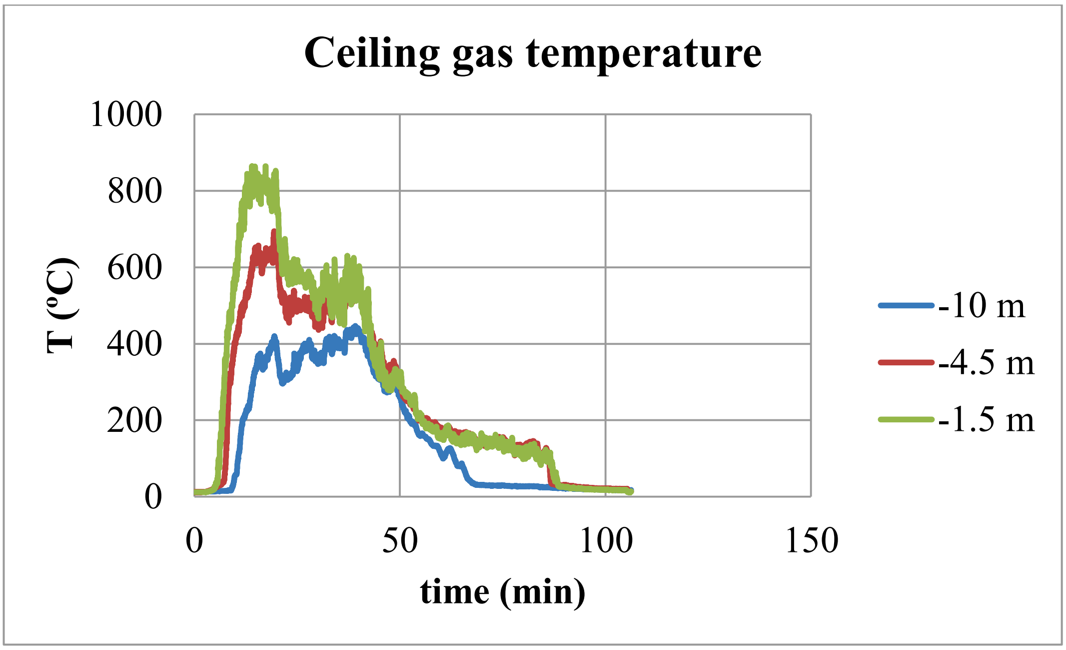


Figure A6-2 The measured gas temperature at ceiling and upstream the fire at different distances x and 30 cm below ceiling : Test 6.

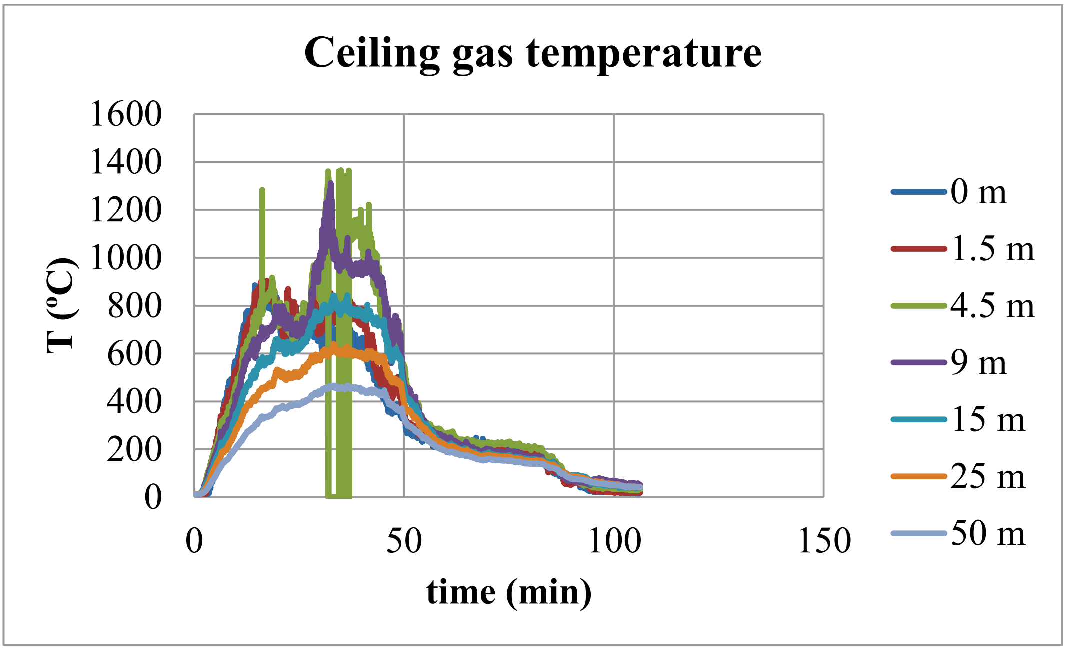


Figure A6-3 The measured gas temperature at ceiling and downstream the fire at different distances x and 30 cm below ceiling : Test 6.

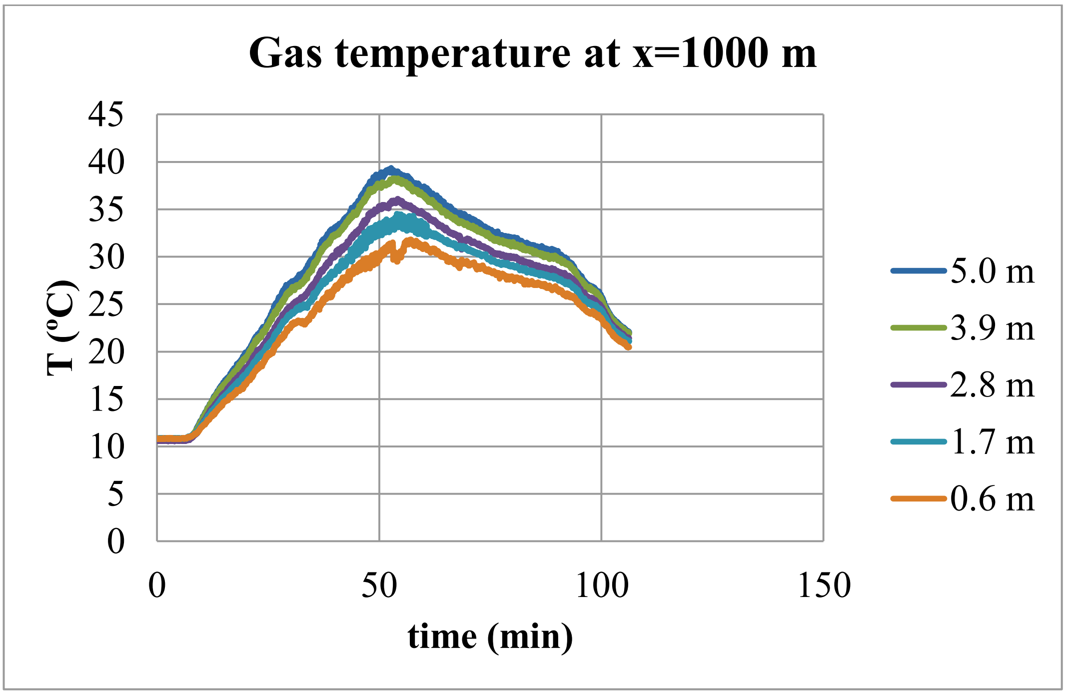


Figure A6-4 The measured gas temperature downstream the fire at distance x=1000 m and different heights above the road surface : Test 6.

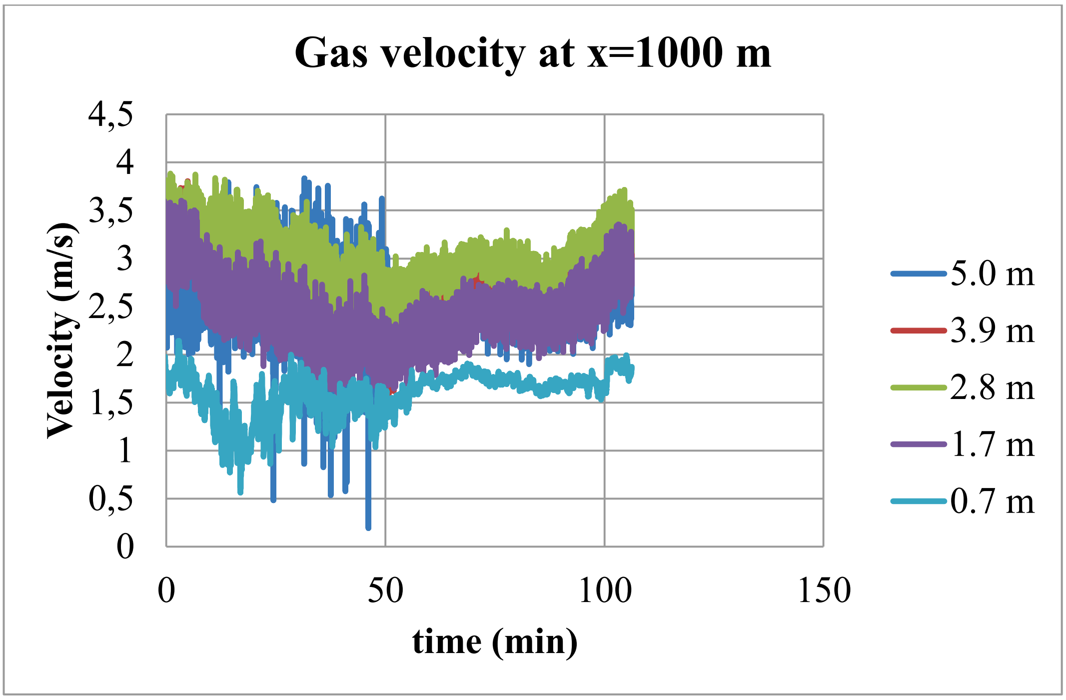


Figure A6-5 The measured gas velocity downstream the fire at distance x=1000 m and different heights above the road surface : Test 6.

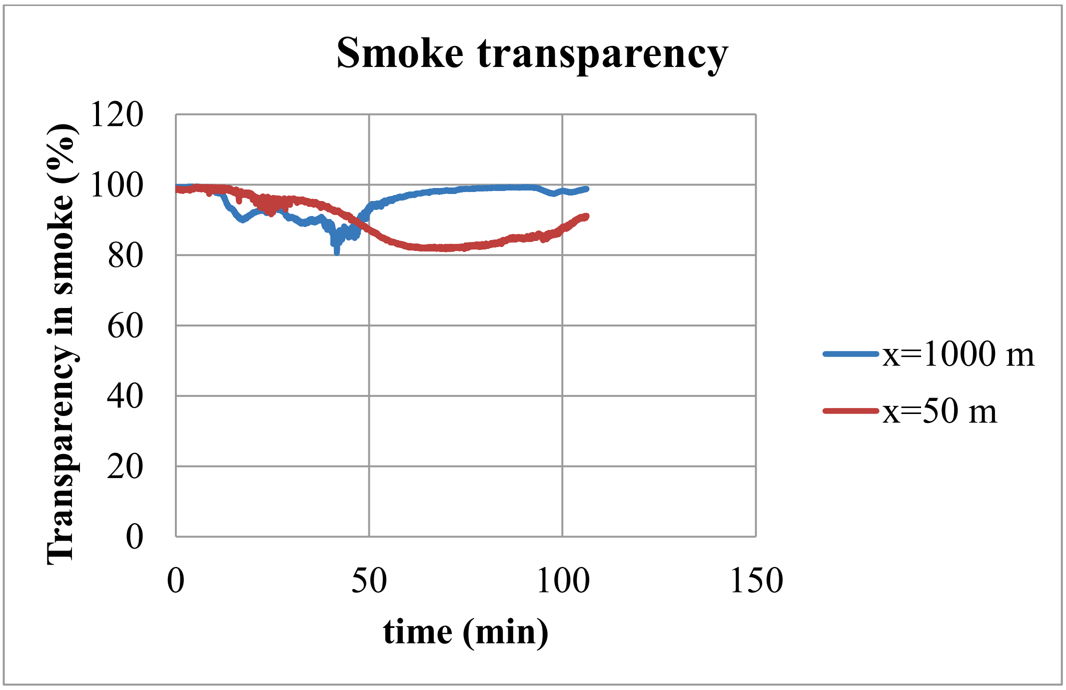
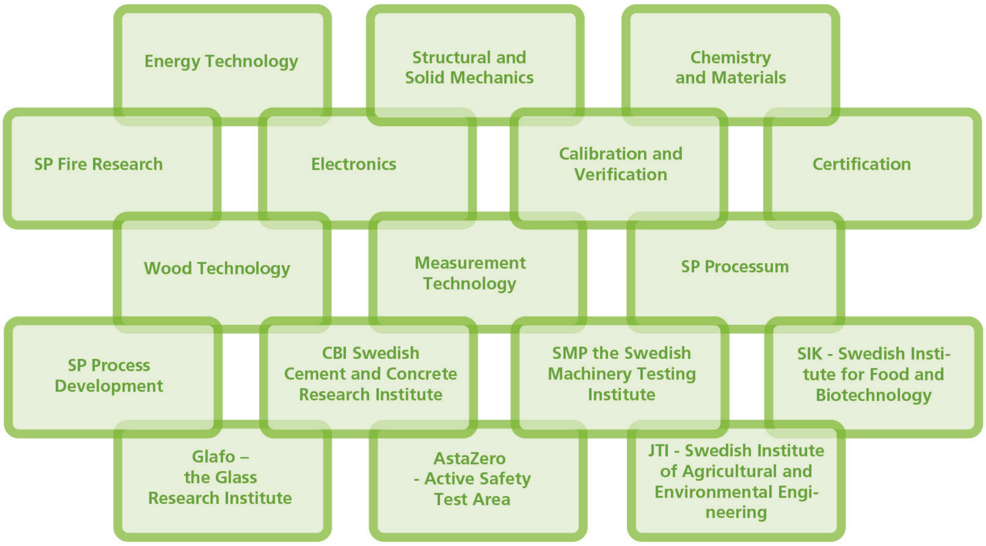


Figure A6-6 The measured smoke transparency at x=1000 m downstream the fire and 1.5 m above the road surface for Test 6.The maximum value in (%) indicate no blocking of light transmission due to smoke particles.

SP Technical Research Institute of Sweden

Our work is concentrated on innovation and the development of value-adding technology. Using Sweden's most extensive and advanced resources for technical evaluation, measurement technology, research and development, we make an important contribution to the competitiveness and sustainable development of industry. Research is carried out in close conjunction with universities and institutes of technology, to the benefit of a customer base of about 10000 organisations, ranging from start-up companies developing new technologies or new ideas to international groups.



SP Technical Research Institute of Sweden
Box 857, SE-501 15 BORÅS, SWEDEN
Telephone: +46 10 516 50 00, Telefax: +46 33 13 55 02
E-mail: info@sp.se, Internet: www.sp.se
www.sp.se

Fire Research
SP Report 2014:32
ISBN 978-91-87461-77-4
ISSN 0284-5172

More information about publications published by SP: **www.sp.se/publ**