

Performance Testing of Fire Protection Systems in Tunnels: Integrating Test Data with CFD Simulations.

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ABSTRACT

This paper discusses the dynamic nature of very large fire tests that were conducted in a tunnel test facility in San Pedro de Anes in Spain in 2006, and describes highlights of the FDS4 simulation of one of five tests that were simulated. The high cost of conducting large, full-scale fire tests for the evaluation of active fire suppression systems in tunnels tends to limit both the extent of the instrumentation provided and the number of tests that are conducted. Because of the turbulent complexity of large test fires in tunnels, performance criteria based on single point measurements derived from experience with much smaller test fires are not reliable measures of the overall benefits of the system. A means was sought to reduce the reliance on single point instrumentation readings, and to augment the value of the limited amount of test data by integrating the field testing with CFD modeling. In this study the NIST Fire Dynamics Simulator version 4 (FDS4), a computational fluid dynamic (CFD) model, was used to simulate a series of full-scale fire tests of water mist systems conducted in a test tunnel. The objective was to show that the CFD simulations could be at least partially validated by demonstrating a reasonable degree of agreement with the conditions measured in the tests. The model could then be used to evaluate the performance of the water mist system under conditions that were not tested. The level of agreement between the fire tests results and the results of the simulation was deemed to be good enough to establish confidence in applying the model to examine the conditions that would occur with an unsuppressed fire, which had not been tested.

KEYWORDS: computational fluid dynamics, fire suppression, fire testing, FDS, heavy goods vehicle, performance criteria, tunnels, water mist.

INTRODUCTION

A number of serious tunnel fires have occurred in Europe and North America in the last decade that resulted in significant losses of lives and property [1]. Transportation safety authorities in Europe have begun to consider the need for water-based fire protection systems (specifically water mist systems) in tunnels to improve life safety and to prevent catastrophic fire damage to the tunnel structure [2]. Before a manufacturer's water mist system design is accepted, highway safety authorities require full-scale fire testing to evaluate the performance and establish design criteria [3]. A common feature of the fire test programs has been that the test fires are much larger in scale than has been the norm for performance testing of fire protection systems in traditional industrial applications. This is largely the result of tests conducted in 2003 in the Runehamar tunnel in Norway [4], which revealed that the heat release rates from uncontrolled fires in common heavy goods vehicle (HGV) fuel loads could range from 70 to 200 megawatts (MW). This new information raised concerns about existing fire protection measures in highway tunnels that were designed based on guidelines in NFPA 502 [2] and the World Road Association (PIARC) [5], which indicated that a 30 MW design fire was considered representative of an HGV fire. The ubiquity of transport vehicles carrying loads containing a high percentage of plastic materials increases the probability that a HGV fire in a highway tunnel will exceed the capacity of ventilation systems or other tunnel safety features

that were designed based on an underestimate of fire severity. As it may not be possible to achieve life safety and property protection objectives against fires in the 100 MW range using traditional tunnel fire protection measures alone, such as ventilation and smoke extraction, the advantage of adding active fire suppression systems to limit the size of the potential fire has become evident.

Tunnel authorities require that the test fires for evaluating active fire protection systems be in the same scale as the potential fires. In the case of tunnels with heavy goods vehicle traffic, the test fires are potentially 100 MW or more [2, 3]. These test fires are 10 to 20 times larger than, for example, the largest test fire in the International Maritime Organization (IMO) [6] and Factory Mutual (FM Global) [7] water mist test protocols for machinery spaces, which is 6 MW. Very large test fires introduce a number of difficulties for approval-test programs. The large fuel arrays used, consisting of hundreds of stacked wood or plastic pallets, are not well characterized, particularly in the special conditions created by confinement in a tunnel. For reproducibility an effort must be made to purchase wood pallets that meet an industry standard, including consistency in type of wood, moisture content and weight, so that the fuel packages will be approximately comparable between tests.

The Dynamic Variability of Large Fires in Tunnels

Due to the thermal feedback to the fuel array from the tunnel ceiling and walls the burning rate of the fuel will be higher in a tunnel than under open burning conditions. Combining large scale fires with heat confinement in a well-ventilated enclosure enhances the burning characteristics of the fuel. Carvel [8] explains the difference between naturally ventilated tunnel fires and fires in the open air, suggesting there is both an enhancing effect due to the confinement of heat in the tunnel, and a diminishing effect due to reduction in the inflow of oxygen to the fire as the tunnel becomes smoke-logged. Carvel also compares the effect of natural and forced ventilation in a tunnel on heat release rate. The HRR will increase as ventilation becomes forced, and the scale of the increase will be a function of the air velocity. Ingason [9] compares the dynamics of tunnel fires with compartment fires, and fuel controlled versus ventilation controlled fires. Very large fires in tunnels are very sensitive to ventilation conditions and thermal feedback. The presence or absence of obstructions may have a very large effect on the local ventilation air movement around a large fire, which will significantly and unpredictably influence the burning rate, heat release rate and flame extensions of the fire.

Most fire test protocols for water mist systems establish pass/fail criteria based on single-point measurements, such as a thermocouple temperature reading or a heat flux value at a certain height and distance from the fire, and at a specific time relative to the activation of the system. Experience with large fire testing has shown that single-point measurements may not be consistent between apparently identical tests [10]. Local ventilation conditions may be modified by obstructions, with a large effect on heat release rate and fire growth rate as described above. Transient flame extensions create erratic readings such that it is not possible to ensure a specific condition at a point in space, such as temperature or heat flux to within one or two meters. The response of a fire to the suppression system extends over tens of minutes, rather than minutes as typically expected for test fires in the 6 MW range. Fuel packages change shape and height over the course of a fire, causing apparently illogical spatial and temporal variations in readings, at least relative to what might be imagined to be taking place based on experience with smaller, more predictable fires. It is important therefore to avoid assigning unrealistically precise performance criteria to the performance evaluation. Performance criteria should reflect overall benefits, such as stopping fire spread (propagation), the thermal management provided (cooling) as reflected in elimination of back-layering, and minimized area of direct damage to the structure [2].

High Cost of Testing Limits Instrumentation and Number of Tests

Because of the high cost of fire testing with very large fires in tunnels, decisions are made about the acceptability of suppression systems based on a limited number of sparsely instrumented tests, involving barely reproducible fires that are ten times more severe than anyone's experience. It is

proposed that CFD modeling may be used to augment the value of the limited test data and to improve the ability to understand the complex dynamics of partially suppressed fires in tunnels. If the model can reproduce the conditions measured during the tests to within a reasonable degree of agreement, the partially-validated model can then be used with increased confidence to explore other aspects of the performance that were not directly measured. The modeling exercise significantly enhances the usefulness of the limited number of tests.

The content of this paper draws from two papers covering different aspects of the fire test and modeling project which will be published in separate journals in early 2010. One of these, published in *Fire Technology*, emphasizes the practical value of augmenting the fire test results by applying CFD analysis to better understand the dynamic complexity of very large fires [11]. A second, complementary paper has been submitted to the SFPE *Journal of Fire Protection Engineering* [12] to provide more detailed information about the FDS4 modeling than was covered in the *Fire Technology* paper. This paper prepared for the 2010 ISTSS tunnel conference, presents both the practitioner’s and the modeler’s perspectives with respect to uncertainties in full-scale fire testing. As the fire testing has been described elsewhere, this paper will give highlights of constructing the CFD model using the Fire Dynamics Simulator, Version 4.0.7 (FDS4), including representing the fuel array, matching a measured heat release rate and injecting the water mist. It presents the results of one simulation, showing reasonably good agreement with full-scale test results. Results of a simulation for an un-suppressed fire, which could not be tested, are presented to illustrate the benefit of using the partially-validated model to better understand the performance of the suppression system.

DESCRIPTION OF THE FIRE TESTS

Marioff Corporation Oy of Finland conducted a program of full-scale fire test involving HGV fires in the San Pedro de Anes Tunnel Safety Test (TST) facility in Asturias, Spain in 2006. Eleven fire tests were conducted in the tunnel over a four week period [10]. The dimensions of the test tunnel are as shown in Table 1 and Figure 1. The tunnel has a rectangular cross-section with dimensions 9.50 wide by 5.17-m high.

Table 1. Dimensions and features of the TST test tunnel.

Length: 600 m	Longitudinal gradient: (-1 %)
Width: 9.50 m	Transversal gradient: 2 %
Height: 5.17 m with false ceiling	Ventilation source: 6 ceiling jet fans
Cross section (with false ceiling): 48.0 m ²	Construction: concrete
Minimum radius (S-bend): 400 m	

As shown in Figure 1, the TST test tunnel is 600-m long, with an S-bend curvature and a negative 1 percent gradient with respect to the direction of longitudinal ventilation from south to north. The tunnel is built at grade in concrete, with dimensions equivalent to a two-lane road tunnel. Figure 2 shows a 105-m section of the tunnel equipped with water mist nozzles and thermocouples for fire testing. At the mid-point of the test section a 20-m section of the tunnel ceiling was covered by a refractory lining material (Promat Promatec) to protect the concrete from the extreme heat of the test fires. The tunnel walls adjacent to the fire location were also covered with Promatec covering for thermal protection. Three lines of water mist nozzles were installed over a 72-m length, which could be activated in three 24-m long zones.

In the fire test zone thermocouples were mounted 100-mm below the ceiling at 5-m intervals along the approximate tunnel centre-line. Thermocouple trees were positioned to measure the vertical temperature profiles at four locations as shown in Figure 2. The tunnel was equipped with instrumentation at the exit portal, approximately 200-m from the fire location, consisting of oxygen gas analyzers, thermocouples and bi-directional velocity probes to allow calculation of the heat release rate (HRR) of the fires by oxygen calorimetry.

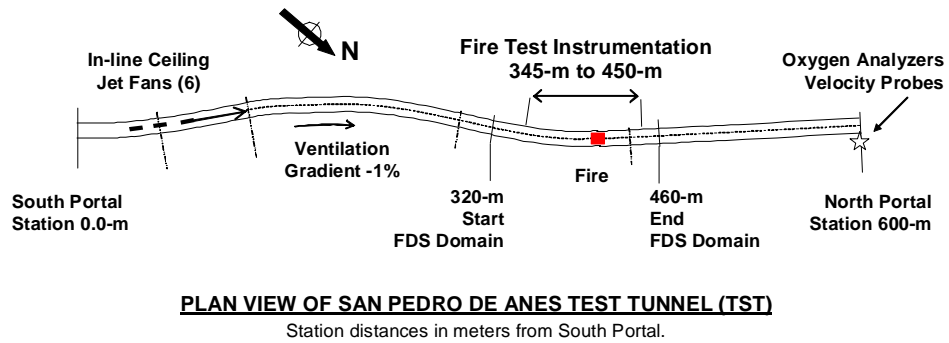


Figure 1. Sketch showing the 600-m overall length of the TST test tunnel. The instrumented zone (105-m between 345-m and 450-m), and the 140-m length of the computational domain of the FDS model between 320-m and 460-m, are indicated. The fuel arrays were typically located at 390-m.

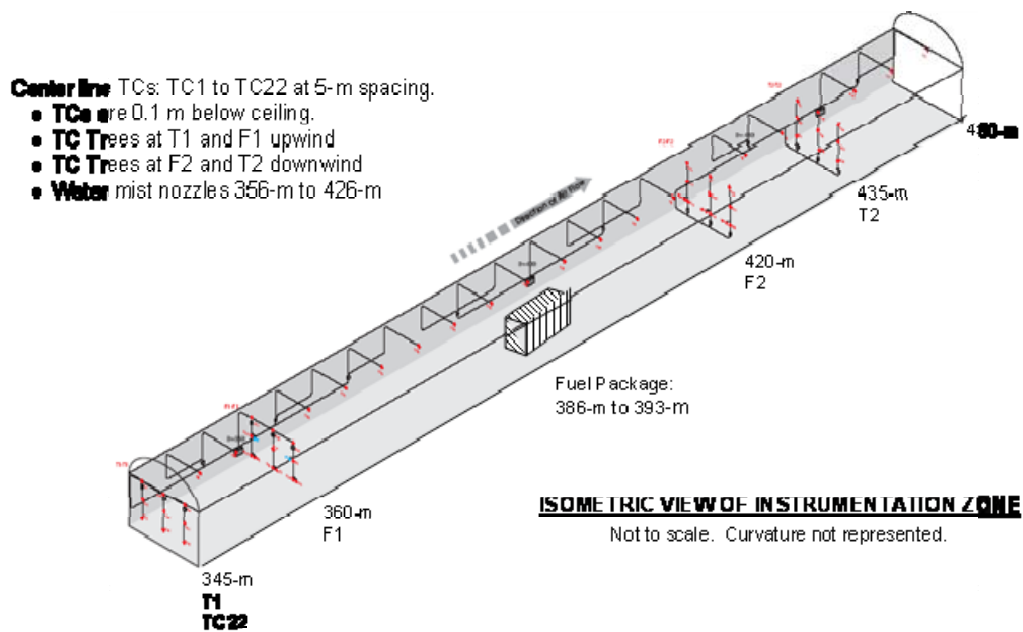


Figure 2. Isometric view of the instrumented portion of the tunnel, showing locations of thermocouples on the ceiling center-line and thermocouple trees.

The Water Mist System

The water mist system consisted of multi-jet nozzles operating at approximately 80 bar pressure in a zoned piping array. The open deluge-type nozzles manufactured by Marioff Oy, designated as 4S 1MD 6MD 1000, had a K-factor of $5.5 \text{ l/min/bar}^{1/2}$. There were three parallel lines of nozzles installed between stations 356-m and 424-m. One line was located on the center line of the tunnel, and there was one line spaced nominally 3.3-m on either side. The nozzles were spaced 4.0-m apart on each line, aligned with each other across the 9.5-m width of the tunnel. Nozzles surrounding the fire were activated manually in the tests when the fire was approximately 20 MW in size.

Wood Pallet Fuel Packages

The fuel package for Test 1 consisted of softwood Euro-pallets, Norwegian spruce, 23.9 kg each, with average moisture content of 15 percent. Pallets were arranged in stacks 14-high, placed on an elevated platform 1200-mm above the surface of the road as shown in Figure 3. The platform was constructed of wet wood pallets topped by a sheet of gypsum board. The Euro-pallets were stacked in pairs on the platform with a gap between stacks of 25-mm or less.



Figure 3. Typical fuel array using 252 softwood Euro-pallets.

Ignition was accomplished by inserting a shallow pan in the bottom pallet of each of the two upwind stacks. After establishing steady ventilation airflow velocity in the tunnel, the pans were filled with 1-L of petrol each, which was then ignited. The fires were allowed to develop and spread in the fuel package for between 5 and 7 minutes before activating the water mist system. The standard severity fires were close to 20 MW in size at the time of activation of the mist system. Because of the limited height of the tunnel, the flame height of the large fire becomes flame length extending downstream from the fuel array [9].

Effect of Water Mist on Heat Release Rate

The heat release rate (HRR) of the test fire was measured using oxygen consumption calorimetry. The methodology is well described in [4, 13]. There are numerous sources of uncertainty in the calculated values. Various researchers have estimated that a minimum uncertainty in oxygen consumption calorimetry involving measurement of the concentrations of oxygen, carbon dioxide and carbon monoxide in the calculation, under good laboratory conditions, is in the range of ± 15 percent [13, 14, 15]. There were additional factors that increased the uncertainty in the HRR calculation in the fire tests conducted in the TST tunnel, as discussed in [11]. The uncertainty in the HRR results for the San Pedro fire tests was estimated to be in the range of ± 25 percent for most tests, although less than that (± 20 percent) for Test 1 when instrumentation was in its best condition. Furthermore, due to the 200-m separation between the fire location and the oxygen sensors, there was a delay between the temperature readings immediately over the fire, and the calculated HRR, that varied depending on the air velocity in the tunnel under fire conditions. Therefore the raw data HRR plot was shifted to the left based on the known ignition and water mist activation times. Figure 4 shows a plot of the HRR versus time trace for Test 1. The plot shows the noisy measured trace as calculated, and the smoothed HRR curve. The fire growth rate was abruptly interrupted by the water mist, although the fire continued to burn at 20 MW for nearly 15 minutes before beginning to decline. The plot represents a successfully controlled fire, with a HRR less than half of what it would be without water mist. It is none-the-less a substantial fire when compared to the normal testing expectation that controlled fires will be less than 10 MW.

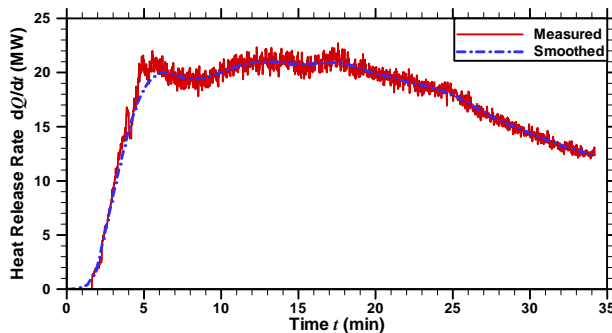


Figure 4. Measured HRR (\dot{Q}_m) plot for Test 1. The uncertainty in the measured HRR value for Test 1 is estimated to be approximately ± 20 percent.

It is desirable to know how the uncertainty in the key input variable (the HRR), manifests itself in the calculated results. Reference [12] provides a discussion of uncertainty in the calculated results of the FDS simulation, based on the methodology described in [18]. The uncertainty in the key input value for HRR (which is an experimental uncertainty) will be reflected in the output values of distance, time, velocity and temperature difference (which are uncertainties arising from the numerical simulation). Some examples from [12] of how the uncertainty in the experimental heat release rate measurement $\Delta \dot{Q}_m$, manifests itself in predicted variables of interest are shown in Table 2.

Table 2: Uncertainties in results of the simulation associated with the uncertainty in the measured maximum heat release rate.

Test Identifier	\dot{Q}_m (MW)	$\Delta \dot{Q}_m$	x_c (m)	Δx_c (m)	t_c (s)	Δt_c (s)	U_c (m/s)	ΔU_c (m/s)	$\overline{\Delta T}$
1	20	-15 - +20%	3.18	± 0.25	0.569	± 0.023	5.58	± 0.22	$\pm 13\%$
Unsuppressed	58	-15 - +25%	4.87	± 0.49	0.704	± 0.035	6.92	± 0.35	$\pm 17\%$

CFD MODELING OF THE TST TUNNEL FIRES WITH WATER MIST

The Fire Dynamics Simulator, version 4 (FDS 4.0.7), was used for all the simulations. FDS 4 is a three-dimensional large eddy simulation CFD program developed at the National Institute of Standards and Technology’s (NIST’s) Building and Fire Research Laboratory (BFRL) [19, 20]. FDS 4 is a multidimensional, multi-physics CFD model created specifically for studies related to fire protection engineering and fire science. The FDS simulations were run on a cluster of Linux computers comprised of Pentium IV single processors with 4 GB of memory each and multicore processors with access to 8 GB of memory. Each processor/core had a clock speed in the 3 GHz range. Run times ranged as long as 7 days.

A review of literature relating to CFD tunnel modeling activity is provided in reference [12]. Relevant tunnel CFD modeling work is also described in reference [17]. Most of the referenced work involved ventilation studies and fires modeled without suppression. Fire Dynamics Simulator (FDS) includes algorithms for suppression based on modeling sprinkler sprays. This study did not attempt to model the physical and chemical mechanisms by which water sprays suppress combustion, prevent or delay ignition and alter flame spread rates. The heat release rates of the fires had been measured during suppression, such that the HRR curve represents the end result of the complex suppression mechanisms. Therefore, FDS4 was applied to evaluating the cooling effects of the water mist in the presence of a sustained fire with a known heat release rate.

The modeling details are described in reference [12]. The following text describes selected elements from the work. Results from one representative simulation are presented to illustrate the level of agreement with test results. For the five simulations, the level of agreement between the measured and simulation results was deemed to be sufficient to establish confidence that the FDS4 simulation provided a conservative representation of the performance of the water mist system. The model was then used to simulate an unsuppressed fire in the tunnel; the contrast between the suppressed and unsuppressed conditions clearly demonstrates the benefit of the water mist system.

Computational Domain

Fire Dynamics Simulator (FDS) is a three-dimensional large eddy simulation CFD program developed at the National Institute of Standards and Technology (NIST) Building and Fire Research Laboratory (BFRL) [19, 20]. At the time this work began Version 5 was at an early release state. Version 4.0.7 (FDS4) was employed for the current study. To achieve an adequately small cell size, only a 140-m long section of tunnel between station 320-m and 460-m was modeled. Figure 5 illustrates the domain and Table 3 summarizes the characteristics of the computational domain.

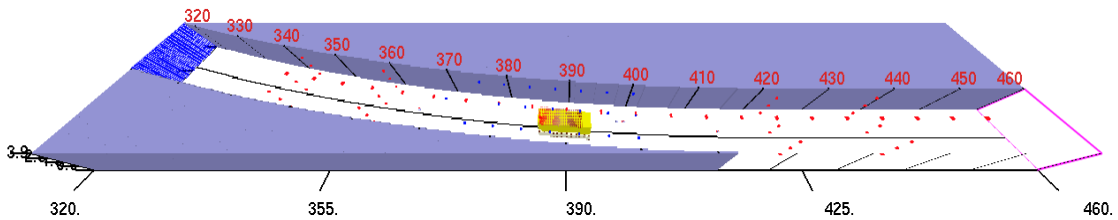


Figure 5. The computational domain for the TST test tunnel fire simulations.

The FDS4 domain was divided into cells of dimension 0.250-m × 0.230-m × 0.215-m. This was a reasonable grid-size for gas flow in the tunnel, but not sufficient to resolve flow in the pallet stacks, as the cell height was greater than the height of a single pallet (0.140-m). It should also be noted that in a spray characterization study conducted by the authors [21], it was found that the grid had to be sufficiently fine to cover the injection points of the nozzle in order to establish independent jets from each port. However, due to computational limitations, such a fine resolution grid was impossible to apply to the 140-m tunnel length. Trial simulation runs demonstrated that decreased grid-size extended computation times well beyond the 6 or 7 days of the simulations without significant improvement in the results.

Table 3: Summary of FDS4 input parameters used in the simulation series.

Category	Parameter	Value
CFD Domain	Facility	San Pedro de Anes TST Research Tunnel
	Simulation dimensions	140 m×23 m×5.17 m
Numerical	Grid dimensions	560×100×24 cells
	Cell size	0.250 m×0.230 m×0.215 m
	Total number of cells	1,344,000
	Wall boundary conditions	Concrete
	Floor boundary conditions	Concrete
	Ceiling boundary conditions	Concrete/Promat Promatec-H
	Gravity vector (-1%)	(0.0981, 0.0, -9.8095) m/s ²
Spray Nozzle	Type	Marioff 4S-1MD-6MD-(1000) water mist
	Configuration	4.0 m×3.3 m grid
	Activation criteria	Times as determined from test data

Water Mist Drop-Size Characterization

The original spray model in FDS4 is based on the spray distribution characteristic of standard sprinklers [19, 20]. High pressure water mist nozzles have a very different drop size distribution, range of velocities and spray angles than standard sprinklers. The standard spray model in FDS4 uses a composite Rosin-Rammler log-normal distribution. Equations showing the numerical representation of the composite cumulative percent volume drop size distribution curve are shown and discussed in references [11, 12]. In a study performed by the authors in 2004 [21], the composite Rosin-Rammler log-normal distribution in the FDS spray model was found to provide a poor fit to the fine fraction leg of the distribution for a high pressure water mist nozzle. To improve the fit, manipulations of the equations were performed based on drop size distribution measurements [12]. The three measured values of Dv_{10} , Dv_{50} and Dv_{90} were used, representing the drop diameters for the 10, 50 and 90 percent cumulative volume fractions of the spray, respectively, where Dv_{50} represents the median diameter d_m . For the Marioff nozzles, the measured drop size distribution gave $Dv_{50} = d_m = 89$ micron, $Dv_{10} = 35$ micron, and $Dv_{90} = 171$ micron. Figure 6 shows the resulting Rosin-Rammler/log-normal distribution for the water mist drop size characterization. It also shows the number fraction distribution, which is derived from the volumetric distribution. In determining how many drops of different sizes to inject into the domain, FDS4 utilizes the numerical distribution count.

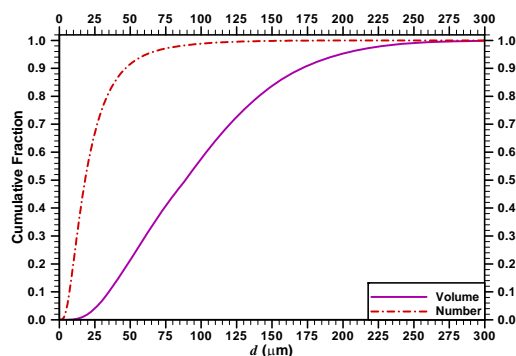


Figure 6. Cumulative volume and number fractions of the high pressure, multi-port water mist nozzle.

A full discussion of the uncertainty in the characteristic values used to represent drop diameter in sprays is beyond the scope of this paper. However, it should be said that the drop size distribution is not a constant characteristic of a spray. It varies with distance from the nozzle, spatial location within the spray, and time [22], and the interaction with a turbulent fire plume. No single measurement in a spray can be representative of the entire spray. As described in [23] it is necessary to take multiple readings of both drop size distribution and local spray density at specific locations (the centroids of equal areas), and apply statistical weighting functions to arrive at a representative distribution curve. Individual drop size distribution readings taken in a dense part of the spray cloud are given greater weight than readings taken in an equal area of a sparse portion of the spray cloud. The resulting drop size distribution curve is only statistically representative of the spray particle distribution; it is not an exact measurement. The uncertainty in the “accuracy” of the weighted-average values of Dv_{10} , Dv_{50} or Dv_{90} thus obtained can best be stated in statistical terms by assigning confidence limits, creating an envelope within which the “true” drop size distribution will lie. Given this unavoidably approximate nature of drop size distributions, concern about the smoothness of the transition between the Rosin-Rammler and Log Normal segments distributions is primarily of academic interest.

The spherical model within FDS4 was used to characterize the spray distribution pattern of a multi-port nozzle [11, 12]. A sphere with radius of 200 mm was divided into 1056 solid angles. Droplets can be introduced through any of the user-defined solid angles that make up the sphere. Required inputs are the initial droplet velocity u , and the mass flux, \dot{m}'' , through the face of each active solid

angle. The total mass discharge rate from all orifices, as a function of pressure, was provided by the “K-factor” for the nozzle. FDS4 would introduce droplets from each group of solid angles representing an orifice, according to the relative value of \dot{m}'' . Each batch of drops reflected the drop size distribution determined for the overall spray defined earlier. The initial velocity at each injection point was determined from orifice flow calculations. See ref [12] for more detail.

Activation times for the water mist spray nozzles and the operating pressure in each test were obtained from the test data. Since the water distribution piping was attached to the ceiling directly above the fire, the temperature of the water in the pipe varied in different tests, depending on the allowed pre-burn time and the flow rate in the piping. An estimate of the water temperature was made. Table 4 presents the nozzle characterization parameters used for Test 1.

Table 4. Nozzle characterization parameters used in the simulation for Test 1.

Nozzle Pressure (bar)	T_{H_2O} (°C)	4S 1MD 6MD 1000 (Test 1)		
		u (m/s)	\dot{m}''_c (a) (kg/s/m ²)	\dot{m}''_r (a) (kg/s/m ²)
100	50	123.5	51.2	199.7

a) The subscript “c” designates the center orifice; subscript “r” designates a ring orifice.

Modeling the Fuel Package and Heat Release Rate

The method employed in this study for inputting a HRR versus time plot is described in references [11, 12]. Because the nominal quarter-meter resolution in the computational domain exceeded the pallet opening dimension, the full detail of the stacked pallets could not be simulated. Instead, methods were explored by which some of the effects of flow through porous media could be obtained given that FDS has no such capabilities. In the final method adopted, denoted as the “top cell method,” the stacks of pallets were modeled as a prismoid with internal columns representing the corner and center blocks in the pallets, with wood thermal boundary conditions. Figure 7 shows a visualization of the support structure that represented the array of stacked pallets. Although the sole function of the support structure shown is to create a plane for the “top cells” where the combustion occurs, the openings allow air to flow through the core of the structure. This avoided having an otherwise solid obstacle in the center of the tunnel, which would have been an unrealistic obstruction to the air flow.

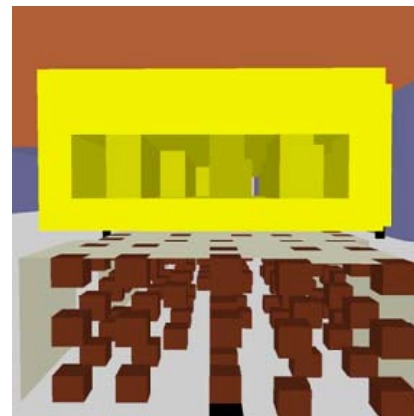


Figure 7. Representation of the pallet stacks and support platform as a porous structure.

Refer to [12] for an explanation of the progression of the fire across the top-cells. Initial trials with a full height fuel load found that not enough space was available between the top of the stacked pallets and the ceiling for a realistic flame volume. Temperatures at the ceiling did not match the experimental data. The half-height fuel load lowered the elevation of the combustion plane, which produced temperatures at the ceiling that were comparable with the test data. It led, however, to overall less drag across the pallet array than was the actual case, which had the drawback of exaggerating the flame length (downstream) under the ceiling.

FDS’s oxygen depletion algorithm was turned off. The FDS oxygen depletion algorithm examines the level of oxygen in each cell at each time step to determine whether combustion can be supported in that cell. This function would have reduced the HRR if there was insufficient oxygen in a cell. However, as noted earlier, the measured HRR inherently includes all of the suppression phenomena.

Since the goal of the simulations was to match the measured heat release rate as closely as possible, further reduction by FDS4 would have resulted in an incorrect representation of the HRR.

Figure 8 shows the result of the top-cell method simulation of the HRR for Test 1. The smoothed HRR trace obtained from the test measurement is shown as the dash-dot line. The “noisy” solid line trace represents the instantaneous HRR values calculated as the fire progressed across the top-cells of the fuel array. The mean value of the simulated HRR is within the uncertainty indicators shown. Figure 9 shows the HRR curve used for the unsuppressed fire case was taken from one of the tests (Test 10) that involved high severity fuel package with a significant proportion of HDPE plastic pallets inserted into the stacks of Euro-pallets. Test 10 also involved a minimal water mist application rate. The Test 10 fire was not controlled by the water mist, and the HRR curve peaked at 57.5 MW. The Test 10 HRR was used as the input HRR for the unsuppressed fire, using Test 1 ventilation conditions. Figure 9 shows both the experimental HRR curve simulated and the simulated curve for the unsuppressed fire. The simulation based on the top-cell method achieved an excellent match with the measured HRR, well within the uncertainty indicators.

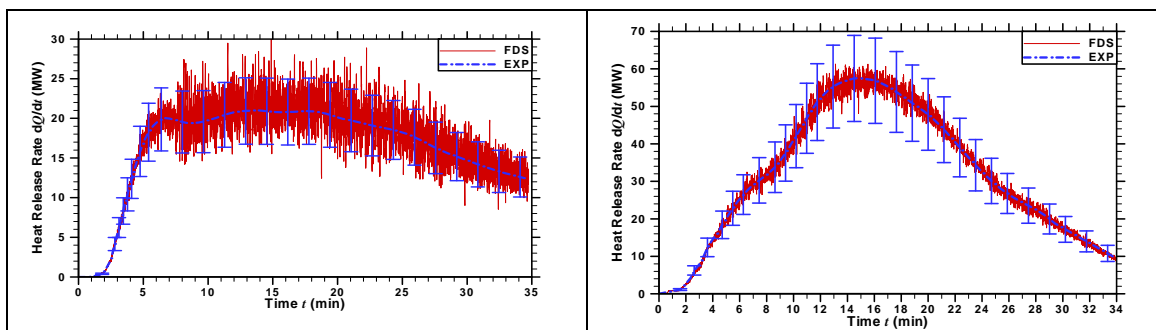


Figure 8. Comparison of HRR test data, with the FDS4 simulated HRR curve for Test 1

Figure 9. Heat release rate curve from Test 10 used as representative of an unsuppressed fire in a standard severity fuel package at 1.9 m/s ventilation air velocity.

SELECT VALIDATIONS

Center Line Temperature

Figure 10, a, b and c, shows the ceiling temperature profiles along the center line of the tunnel at different times during Test 1, as predicted by the simulation and as measured in the fire test. The lower abscissa shows the tunnel station numbers and the upper abscissa shows the ceiling thermocouple (TC) designation. The extent of the pallet array is indicated by the block above the lower abscissa. The larger rectangle denotes the area protected by water mist. Figure 10 gives three-point (2 s) averages of the temperature at the ceiling for three times, as predicted by the simulation for Test 1 and the unsuppressed fire. The first time (420 s) is indicative of the highest temperature conditions just before the water mist system came on. Each successive time period was 5 min later than the previous one, and is cooler than the profile shown for 5 minutes earlier.

Figure 10 a) shows back-layering upstream of the fire prior to activation of the mist in Test 1. In Figure 10 b) 5 minutes after activation of the mist, the back layering has disappeared. The results clearly show that the water mist eliminated back layering upstream of station 375 m, with a 20 MW fire and only 2-m/s wind velocity. The agreement of the back layering reduction in the simulation (FDS Test 01) with the experimental counterpart (Exp Test 01) in Figure 10 is very good. In the tests, the peak temperature above the fuel array occurred at C13, whereas in the simulation, the peak temperature was shifted 5-m downstream to C12. It is believed that the reason for the shift is that the half-height fuel array presented less of a barrier to air flow than the actual full-height fuel array, hence the downwind flame extension was increased, compared to the test condition. Downstream, from

C13 to C1, though, the numerical results are generally higher than the test data. The dip at C11 is due to the presence of a nozzle just below the TC. Thus, prior to activation of the water mist system, there is extremely good agreement between the simulation and the test data for regions 10 or more meters from the fire location.

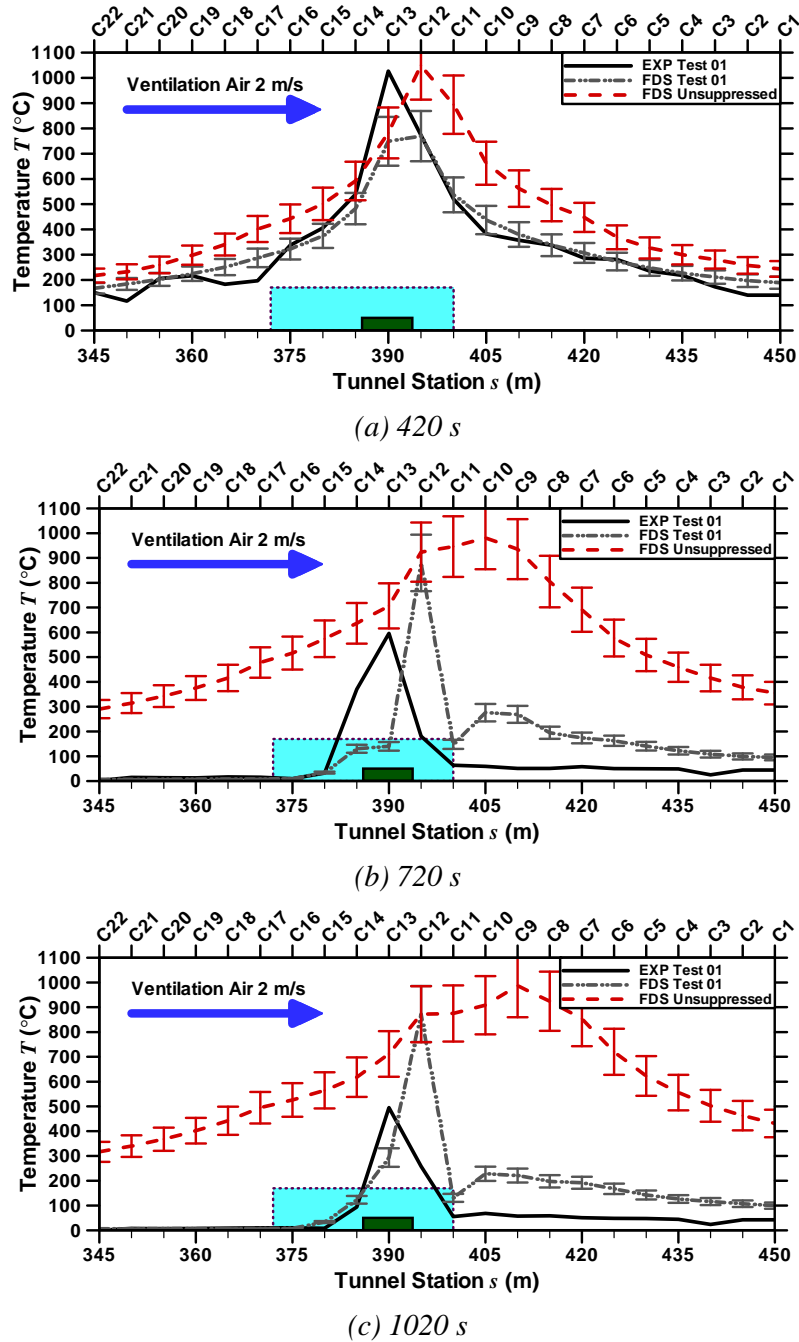


Figure 10. Three point (2 s) averages of the temperature along the tunnel center line at the ceiling thermocouple points at the indicated times for Test 1 and the unsuppressed run are compared with the experimental results. The labels along the tops of the figures are the ceiling thermocouple designations.

Otherwise, the tests recorded much better temperature reduction along the ceiling than was predicted by the model. It must be noted, though, that FDS calculates dry gas temperature while the test measurements were affected by the moist environment created by the sprays and may record a “wet-bulb” temperature expected to be lower than the gas temperature. Also note that the error bars shown in Figure 10 refer to the uncertainty in the simulation results only. They are not representative of the difference between test and prediction. There are of course uncertainties in the experimental thermocouple measurements of temperature, which are complex and are not indicated in the plots.

Immediately over the fire itself there are several differences between the simulation and the test results. The peak temperature measured (at C13 in the test) was above 1000 °C whereas the peak temperature (at C12 in the simulation) was approximately 750 °C to 850 °C (but higher at adjacent times). In the area directly above the fire, flame extensions impact directly on the ceiling. Temperatures of 800 °C or greater are deemed to represent the presence of flame. The distance from the top of the fuel package to the ceiling was only 1.9 meters, while the “flame height” of a 20 MW fire would be expected to be in the order of 10 m. In the confinement of a tunnel, flame height converts to flame length in a horizontal direction. In the test data, three thermocouples (C 12, C 13, and C14) showed the direct influence of intermittent or continuous flame.

The FDS results are conservative and tend to underestimate the cooling benefit of the water mist. They are trending correctly however. Comparison of the unsuppressed run with Test 1 shows universally worse conditions without water mist. The most dramatic difference is with the back layering. Without water mist, heat and hot gases extend both upwind and downwind of the fire, making approach from either direction hazardous. Flame spread to vehicles on either side of the fire is assured, and will have catastrophic consequences in terms of risk to life and extent of damage to the tunnel.

CONCLUSION

Full-scale fire tests to evaluate the performance of active suppression systems against very large fires in tunnels are expensive. There is seldom enough instrumentation to fully characterize the performance of the system, and the high cost of testing limits the number of tests that are conducted. Decisions about the acceptability of suppression systems are often based on a limited understanding of the complex dynamics of tunnel fires. The value of the fire tests can be greatly increased by integrating the fire test results with CFD modelling. Confidence in the model can be established by demonstrating that there is reasonably good agreement between the experimental measured values and the results of the FDS simulations. The model can then be used to examine other aspects of the performance of the suppression system that may not have been measured or tested.

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