The Effect of Nozzle Design on the Fire Heat Release Rates in Tunnel Deluge Systems

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A series of full-scale tunnel fire experiments were carried out at the TST Tunnel in Spain to assess the performance of deluge fire suppression systems to potential fire heat release rates in excess of 200 MW. The experiments included consideration of a standard deluge nozzle, a directional nozzle and a free burning test. The fire suppression tests were undertaken with a nominal discharge rate of 12 mm/min, which is the standard adopted for tunnel deluge systems in Singapore. The fire load comprised a simulated trailer truck containing 104 plastic pallets (20%) and 390 wooden pallets (80%) and was shielded by metal plates at the ends and along its roof. An air velocity of approximately 5 m/s was applied to simulate the operation of the road tunnel ventilation system. Two fire zones, each 25 m in length, were activated in each fire suppression test.

The results indicated that both the standard nozzle and the directional nozzle achieved a substantial reduction in fire heat release rates, when activated within 4 minutes of fire detection. However, the directional nozzle reduced the peak fire heat release rate from 242 MW to 31 MW, while the peak suppressed fire heat release rate for the standard nozzle was 43 MW. The reason for the improved performance of the directional nozzle is due to its improved water spray pattern compared to the standard nozzle.

1 INTRODUCTION

There are currently seven road tunnels in Singapore: Chin Swee Tunnel and Kampong Java Tunnel which together form the Central Expressway (CTE) Tunnels, Fort Canning Tunnel, Kallang-Paya Lebar Expressway (KPE) Tunnel that will be directly connected to the Marina Coastal Expressway (MCE) Tunnel, Sentosa Gateway Tunnel and Woodsville Tunnel. Other tunnels including the North-South Corridor Tunnel (2.1 km of semi-tunnel and 10.2 km full tunnel) are currently being designed. All of these tunnels are provided with emergency ventilation systems to control the movement of smoke during a fire, in accordance with NFPA 502 requirements. Three of the existing tunnels (MCE, Sentosa Gateway Tunnel and Woodsville Interchange Tunnel) have water-based deluge systems installed, to suppress the growth of fire. Both directional and standard deluge nozzles are used in these existing tunnels (Table 1). The CTE and KPE Tunnels will have a low-pressure water mist system (WMS) installed.

No.	Tunnel	Nozzle Type	Discharge Density (mm/min)
1	Woodsville Interchange	Standard	21
2	Marina Coastal Expressway	Directional 180 degrees	12
3	Sentosa Gateway Tunnel	Directional 180 degrees	12

Table 1: Nozzle Types in Existing Singaporean Tunnels

There are currently regulations prohibiting vehicles carrying hazardous materials from entering the road tunnels [Ref. 1]. The Singapore Civil Defence Force (SCDF) has implemented a Hazmat Transport Vehicle Tracking System (HTVTS) to ensure the regulations are followed. The HTVTS has the ability to track the location of the hazmat vehicles and immobilise these vehicles remotely in the event of a violation. It controls the throttle of the vehicle, restricting the fuel injection to the engine and forcing the driver to slow down and stop. Police personnel are then dispatched to the incident [Ref. 2]. The current regulation in Singapore prohibits long vehicles such as very heavy goods vehicles (VHGV) trailers from entering the road tunnel as part of the fire safety measures to control and minimise the risk of such long vehicles catches fire in the road tunnel.

One of the main objectives of the large scale fire test programme is to assess whether VHGV trailers could be allowed to drive through the road tunnels without increasing the fire risk with the implementation of fire suppression systems in the road tunnels.

As part of the tunnel upgrade project, a large scale fire test programme was conducted in the Tunnel Safety Testing (TST) facility at “San Pedro de Anes”, Spain. The large scale fire test programme involved assessments of the magnitude of the heat release rates generated by a simulated VHGV trailer fire with water mist and deluge systems, and also without any fire suppression. Two types of deluge systems, with standard and directional nozzles, were tested as described in section 3 below. Table 2 shows the schedule of the fire tests conducted in this part of the large scale fire test programme. Figure 6 shows nozzle and pipe orientations for the deluge system tests.

Date	Test Description	Fire Suppression / Cooling System	Activation time (after detection time)
8th May 2018	Deluge - Directional nozzle	2 zones of deluge system (upstream and above fire) supplied by 3 water pipes	4 min
		Zone 1 and 2: 180 Directional (K:80) nozzle	
24th Sept 2018	Deluge – standard nozzle	2 zones of deluge system (upstream and above fire) supplied by 3 water pipes	4 min
		Zone 1 and 2: 15mm K:80 deluge nozzle	

Date	Test Description	Fire Suppression / Cooling System	Activation time (after detection time)
3rd Oct 2018	Free-burning	½ zone of WMS cooling system to protect the tunnel structure, 18 m downstream of fire. 3 water pipes over fire zone (not activated)	Not applicable

Table 2: Large Scale Fire Test Schedule

2.0 LARGE-SCALE TUNNEL FIRE TEST PROGRAMME

The large scale fire tests were conducted in the “San Pedro de Anes” test tunnel facility in Spain in May to October 2018 (see Table 2). The test tunnel is a two-lane road tunnel built of concrete, with a lower gallery for emergency and services, and with at-grade emergency exits [Ref. 3].

The test tunnel has an overall length of 600 m and its cross section can be modified from a horseshoe shape to a rectangular shape by erecting walls and ceiling. For the large scale fire tests, the cross section of 450 m length of the tunnel was modified into a rectangular shape. The dimensions of the rectangular test section were approx. 9.0 m wide and 5.2 m high with a longitudinal gradient of 1%. Jet fans at the south end tunnel portal were used to generate a longitudinal air velocity of about 5 m/s in the tunnel for all the tests.

Figure 2 gives an overview of the test tunnel and positions of the fuel load, jet fans and measurement stations. The position of the sensors in the test tunnel is shown in Figure 3.

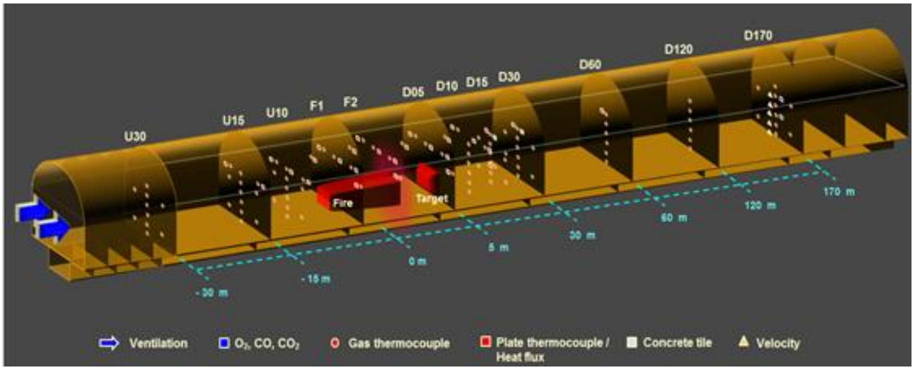


Figure 1: Measurement Locations in Test Tunnel

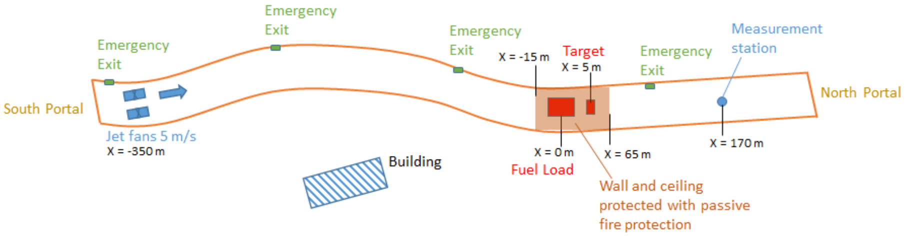
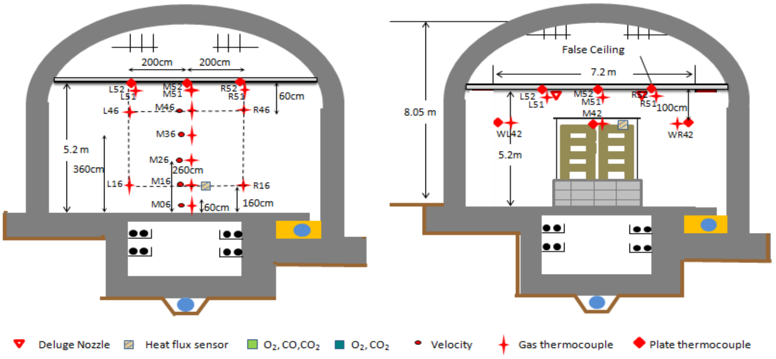
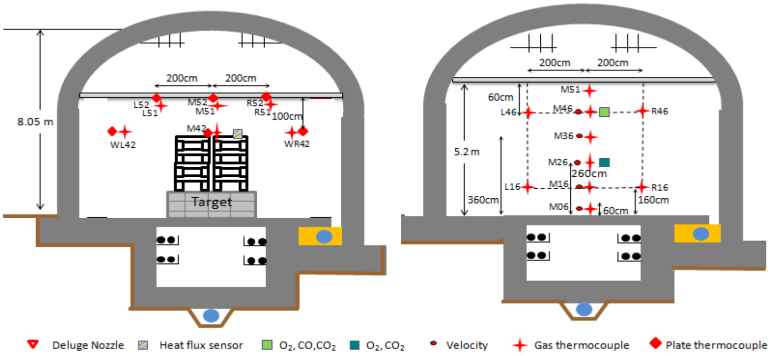


Figure 2: Plan View of the Test Tunnel



U10 Location X = -17 m
Fire Location X = 0 m



D5 Location X = 12 m
D170 Location X = 177 m

Figure 3: Cross-section of the test tunnel and instrumentation setup

A typical VHGV trailer fully loaded with pallets was used as the fuel load for the large scale fire test (Figure 4). The fuel load consisted of 494 pallets, with 390 wooden pallets (80%) and 104 plastic pallets (20%). The pallets were arranged in 26 stacks, with each stack consisted of 19 pallets, and placed on top of 1 m high concrete hollow blocks. The pallets were housed in a steel frame secured by wire mesh on the sides to prevent the pallets from falling off. The steel frames supported the 1 mm thick steel roof cover and plastic tarpaulin sheet on both sides. The upstream and downstream sides of the pallets were covered by 1 mm thick steel plates. The pallets used for the tests were Euro pallets and the size of each pallet was 1.2 m × 0.8 m [Ref. 4].

The fire source was 2 trays (0.35 m × 0.70 m each) containing about 2.5 litres of gasoline each. The trays were placed inside one of the pallet located at the upstream edge of the fuel load as shown in Figure 4. To assess the risk of fire spread to a downstream position, a target comprising two stacks of 19 pallets was placed 5 m downstream from the edge of the fuel load (Figure 4).

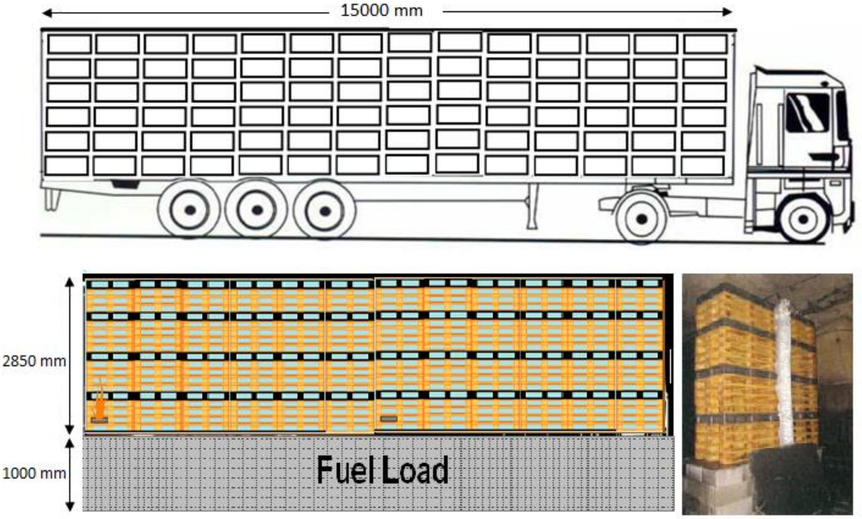


Figure 4: Photographs (upper-VHGV) and (lower – fuel load arrangement)

Two types of fire suppression systems were tested as part of the large scale fire tests: water mist and deluge systems. Only the deluge tests are reported in this paper, while a companion paper reports on the water mist tests (Ref. 5). These two systems were designed to activate and discharge water simultaneously in two zones (zones 1 and 2 in Figure 5). The length of each suppression zone was 25 m, and the overall area of the suppressed zones was 50 m (length) by 9.0 m (width). The deluge nozzles were arranged to be 1 m above top of pallets.

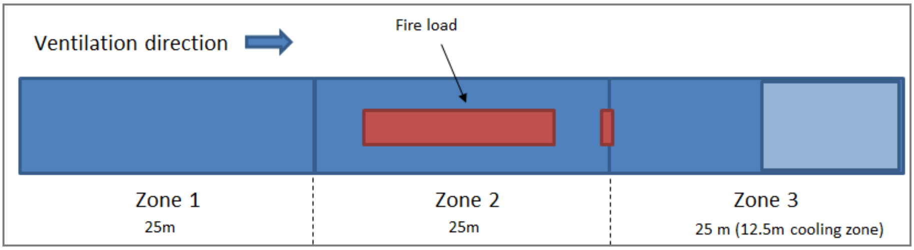


Figure 5: Fire Suppression Zone Layout

3.0 Nozzle Types

Two types of deluge nozzles were used in the tests:

- 15 mm K80 standard nozzle, nominal K factor: 80 l/min/√bar,

- 180-degree directional spray nozzle, nominal K factor: 80 l/min/√bar

For the fire tests involving deluge nozzles, standard and directional pendent spray nozzles (open version) having a K-factor (metric) of 80.6 and installed in a spacing grid of 3m x 3m, were employed. A supply pressure of 1.8 bar at the nozzles ensured 108 l/min flow rate per nozzle, and therefore a water density of minimum 12 mm/min (see calculation below).

Nozzle spacing : 9 m^2 (3m x 3m)
Water density : 12 mm/min (l/min/m^2)
K-factor : 80.6 (metric)
Flow per nozzle needed : 9m^2 x 12 l/min/m^2 = 108 l/min
Pressure at nozzle : (108 l/min / 80.6 l/min/√bar)^2 = 1.8 bar

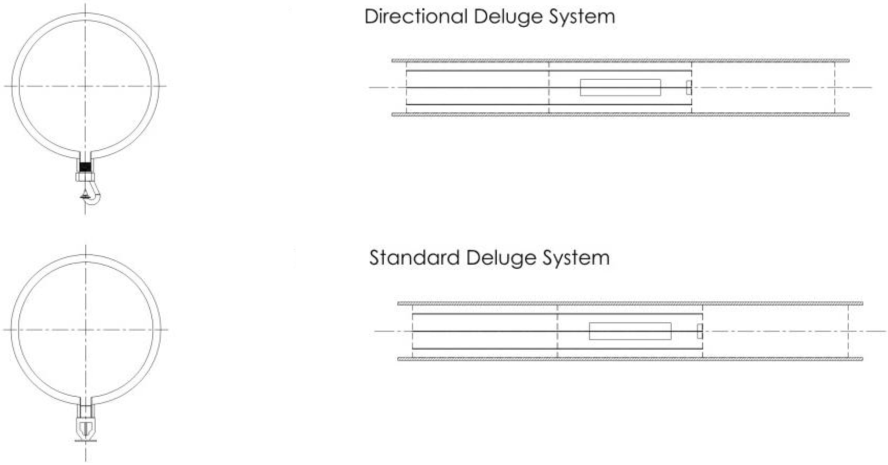


Figure 6: Nozzle and Pipe Orientations for Deluge Tests (Left: Nozzle Orientation, Right: Plan View of Pipes and Fire-Load)

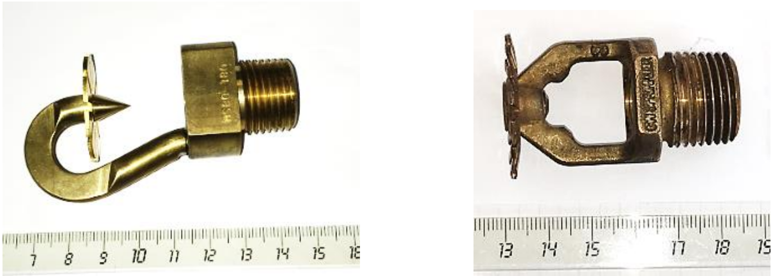


Figure 7: Left: 180 degree directional nozzle, Right: 15mm K80 standard nozzle

Figure 8 and Figure 9 show the spray patterns for the standard and directional nozzles, as measured by the manufacturers, with the fuel load and the tunnel cross-section superimposed. As can be seen from Figure 9, the directional nozzle delivers the water droplets with a spray pattern of approximately 180 degrees, and has smaller “dead zones” (i.e. areas which the water droplets do not reach) compared to the standard nozzle (Figure 8). The “dead zones” occur at higher elevations, where hot gases may be present due to thermal buoyancy. In addition, a substantial proportion of the water delivered by the standard nozzle is not available to cool the hot gases, because it is sprayed onto the walls due to the wider spray pattern.

The spray patterns provided by the manufacturers relate to quiescent conditions, whereas these tests were conducted with an air velocity of approximately 5 m/s. Despite the distortion of the spray patterns due to the oncoming airflow. the differences between the two types of nozzles due to the “dead zones” and the proportion of water wetting the walls are still present.

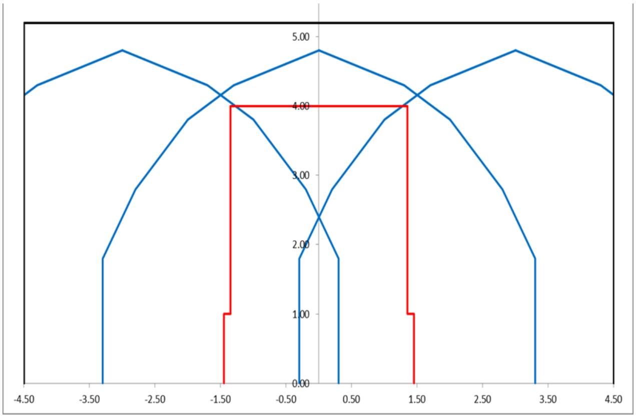


Figure 8: Spray envelopes (blue) for standard nozzle in cross section of tunnel with fuel load (in red)

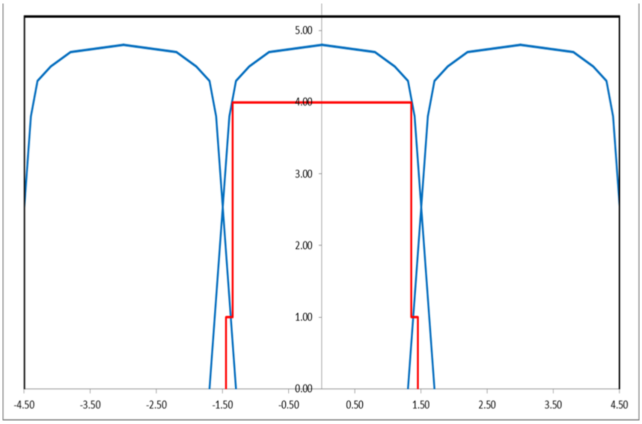


Figure 9: Spray envelopes (blue) for directional nozzle in cross section of tunnel with fuel load (in red)

4.0 Heat Release Rate Estimate

There are several methods of estimating the heat release rate (HRR) of a fire. The most common methods make use of either the mass loss rate or oxygen depletion calorimetry where the HRR is calculated based on the measured mass loss rate or amount of oxygen consumed respectively.

For fire tests with deluge systems, the use of the mass loss rate method is not practical because the water flow during the activation of the deluge system will disturb the measurement of the mass loss of the fuel load and will therefore affect the accuracy of the HRR estimation. As such, this method was not considered for the large scale fire test.

The oxygen depletion method uses the energy produced by the amount of oxygen consumed to determine the heat generated (for a specific group of combustibles). There are three different methods: a) Method 1 - measure the oxygen concentration only, b) Method 2 - measure the oxygen and carbon dioxide concentration only, and c) Method 3 - measure the oxygen, carbon dioxide and carbon monoxide concentrations. Method 3 is the most accurate [Ref. 6]. For this fire test programme, Method 3, where the oxygen, carbon monoxide and carbon dioxide concentrations were measured, was used to improve on the accuracy of the HRR estimates.

The HRRs for the tests were calculated according to the “basic equations” 2 and 3 given in the paper by Dlugogorski et al [Ref. 6]. The “basic equations” take into account the influence of the water vapour content and they correspond mathematically to the equations derived by Janssen and Parker [Ref. 6]. However, in contrast to the equations of Janssen and Parker, the “basic equations” do not require calculations of the molecular flow rate nor do they require the humidity of the incoming air, and as such, they are easier to use.

For convenience the “basic equations” are given below [Ref. 6]:

$$\dot{q} = n^{e}_{total}(1 - X^{e}_{H2O})\left[0.5(E - E^{co})X^{e,d}_{co} + E(X^{i,d}_{o2}\frac{1 - X^{e,d}_{o2} - X^{e,d}_{co2} - X^{e,d}_{co}}{1 - X^{i,d}_{o2} - X^{i,d}_{co2}} - X^{e,d}_{o2})\right] \quad \text{Eq. (2)}$$

From Dlugogorski et al [Ref. 6], the total molar flows rate for an ideal gas:

$$n^{e}_{total} = m^{e,d}_{air} / (M^{e}_{total} \times M^{i,d}_{air})^{0.5} \quad \text{Eq. (3)}$$

As the total molecular weight M^{e}_{total} differs from $M^{i,d}_{air}$ the relation in Eq. (3) is used to compute n^{e}_{total} with:

$$M^{e}_{total} = X^{e}_{H2O}M_{H2O} + (1 - X^{e}_{H2O})(X^{e,d}_{N2}M_{N2} + X^{e,d}_{O2}M_{O2} + X^{e,d}_{CO2}M_{CO2} + X^{e,d}_{CO}M_{CO}) \quad \text{Eq. (4)}$$

The required ‘exhaust’ mass flow rate of dry air and ‘exhaust’ molar fractions of H_2O vapour and dry O_2, CO_2 and CO gasses were determined from the air velocities, temperatures and concentrations measured at 170 m downstream from the fire location, taking into account the travelling time of the combustion products.

The required molar fraction of dry N_2 at exhaust is determined with the following equation:

$$X^{e,d}_{N2} = 1 - X^{e,d}_{O2} - X^{e,d}_{CO2} - X^{e,d}_{CO} \quad \text{Eq.(5)}$$

The measured air velocities, temperatures and concentrations at positions M16, M26 and M36 (see Figure 3) were used to establish the contribution of the HRR at the lower 2/3 portion of the tunnel cross section. The remaining portion of the estimated HRR at the upper 1/3 portion of the tunnel cross section were measured at positions M46 and M51 (see Figure 3) in the tunnel. The molar fractions of O_2 and CO_2 of the incoming air were set at 0.2095 and 0.00041 respectively.

Given the uncertainty in the measurements and the observed air velocity, temperature and concentration profiles at the downstream location D170M, a relative error of approximately ±10% in the calculated value of the HRR is expected.

5.0 Measurement Results

The measured fire heat release curves for the tests are shown in Figure 10. Table 3 gives a tabulation of the peak HRR and integrated calorific energy for the tests.

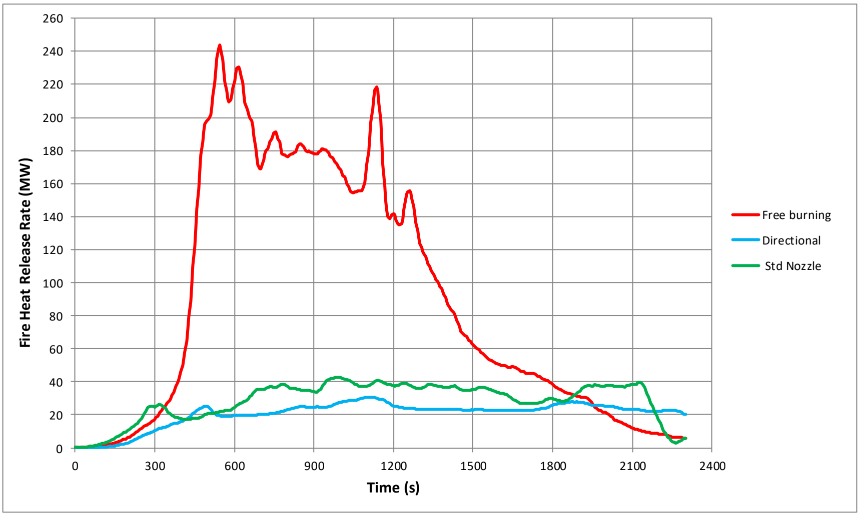


Figure 10: Measured fire heat release rates, with and without fire suppression

Fire Test	*Discharge density (mm/min)*	*Approximate activation time (min)*	*Time to peak (min)*	*Peak HRR Q_{total} (MW)*	*Integrated calorific energy (GJ)[a]*
Standard nozzle	12	4	16.3	42.6 [b]	51
Directional nozzle	12	4	18.5	30.7 [b]	35
Free-burn	NA	NA	9	243	194

Note: [a] Calorific energy is based on 30 minutes burning duration
[b] Peak fire heat release rate after deluge system activated

Table 3: Peak Fire Heat Release Rates and Integrated Calorific Energy

6.0 DISCUSSION OF RESULTS

With no fire suppression system operating, the fire heat release rate reached a peak value of 243 MW. This is a very high value, but it is comparable with the 2003 UPTUN measurements [Ref. 7]. The pallet stack in the current measurements is estimated to weigh 10,998 kg in total with a total energy content of 203 GJ. In the 2003 UPTUN tests, which also used a materials mass ratio of 80% cellulose to 20% plastic, the pallet stack weighed 10,911 kg with a peak fire heat release rate of 202 MW.

The measured total and convective HRR are shown in Figure 10 and Figure 11. The peak fire heat release rates were significantly lower with activation of the fire suppression system, when compared with the free burning test. Standard deluge nozzle suppressed the peak fire heat release to 42 MW (of which a third is convective), while directional nozzles reduced the peak fire heat release rate to 31 MW (of which a quarter is convective). The proportion of convective fire heat release rate is reduced by the use of directional nozzles, which is an added benefit. However, directional nozzles are typically more expensive than standard nozzles.

The higher efficiency of the directional nozzle is also supported by its lower integrated calorific energy of 35 GJ compared to 51 GJ of the standard nozzle. It is believed that the better suppression and gas cooling capacity of the directional nozzle is caused by its more efficient (narrow) spray pattern as discussed in section 3.0 of this paper.

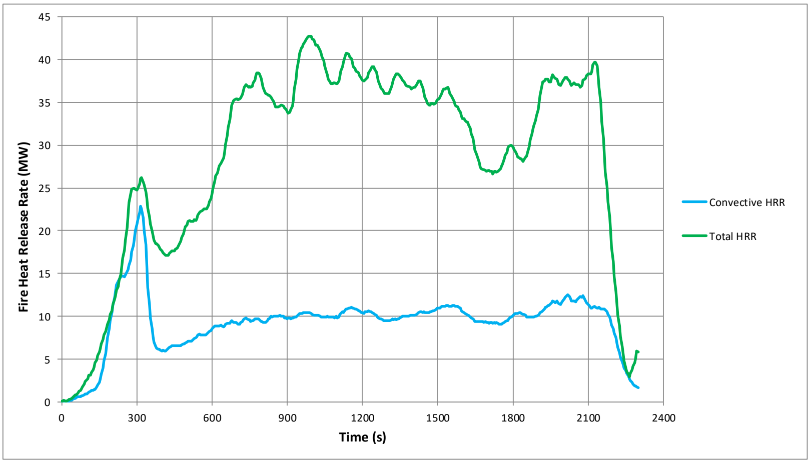


Figure 11: Total and convective fire heat release rates for standard nozzle

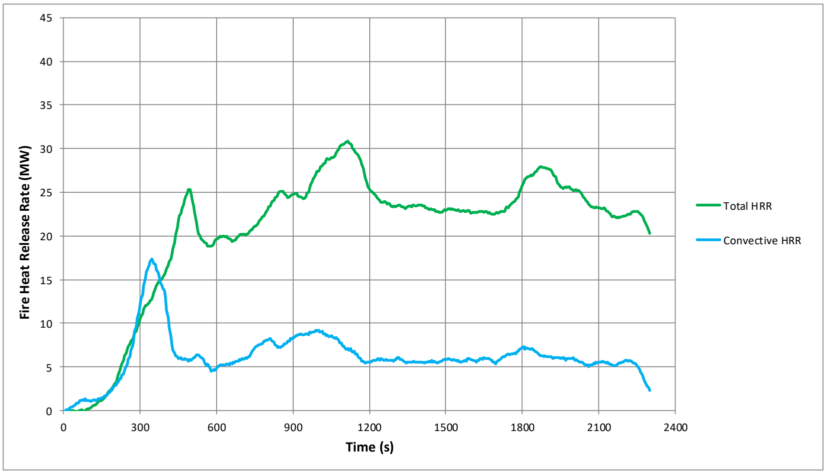


Figure 12: Total and convective fire heat release rates for directional nozzle

7.0 CONCLUSION

This paper describes the test setup and results of the large scale fire test programme for road tunnel with deluge system operation. The heat release rates of a very heavy goods vehicle (VHGV) trailer fire in a tunnel with and without deluge system operation are presented. The peak heat release rate of a VHGV trailer without operation of the fire suppression system was measured as approximately 243 MW. The test results show that for a fixed water discharge rate of 12 mm/min, there is a significant reduction in the fire heat release rates, depending on the type of deluge nozzle. Standard deluge nozzle suppressed the peak fire heat release to 42 MW (of which a third is convective), while directional nozzles reduced the peak fire heat release rate to 31 MW (of which a quarter is convective). In both cases, the convective heat release rate at the peak was only a fraction of the total heat release rate, which should significantly assist the control of the smoke via mechanical ventilation.

8.0 ACKNOWLEDGEMENTS

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9.0 NOMENCLATURE

E = heat of combustion per kmol of consumed oxygen (419.2 MJ/kmol of O_2)

E^{co} = heat of combustion of CO per kmol of consumed oxygen (563.2 MJ/kmol of O_2)

M = molecular weight (kg/kmol)

$\dot{n}$ = molar flow rate (kmol/s)

s = seconds (sec)

T = temperature (K)

Rh = relative humidity (%)

$\dot{q}$ = heat release rate (MW)

X = mole fraction (unitless, corresponds to volume fraction for ideal gases)

Superscripts

e = refer to exhaust conditions

d = refer to dry gas

i = refer to incoming air

Subscripts

CO = refer to carbon monoxide

CO_2 = refer to carbon dioxide

H_2O = refer to water

N_2 = refer to nitrogen

O_2 = refer to oxygen

total = refer to total (e.g molar flow)

10.0 REFERENCES

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Ref. 4: Report on Full-Scale Tests Conducted by Efectis at the TST test tunnel facility in 2018.

Ref. 5: “Heat Release Rates of Heavy Goods Vehicle Trailer in Tunnels with Fixed Water-based Fire Fighting Systems” by M K Cheong, G Louis, L W Lim, M Thong, A Palle, A D Lemaire, T Rakovec and E Ferad, 18th International Symposium on Aerodynamics, Ventilation and Fire in Tunnels, Athens, Greece, 2019.

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