The Energy Budget in Suppressed Tunnel Fires

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There has been substantial interest in the use of fire suppression systems to reduce risks to tunnel structures, improve life safety and to enhance road network integrity. A key factor in delivering these benefits is the reduction in heat release rates from fires through the deployment of fire suppression, as reported in our companion paper to this Symposium. However, it is this paper's contention that fire suppression provides another dimension in the delivery of risk-reduction benefits: namely, that a significant proportion of the residual fire heat release rate is absorbed through a benign process of heating and evaporation of water, rather than through convection or radiation.

Measurements were undertaken during the course of medium-scale fire tests using stacks of wooden (80%) and plastic (20%) pallets. This combination of combustibles was considered to be representative of HGV loads in Singapore. The fire heat release rates were estimated using the oxygen depletion calorimetry method, based on sensors installed within a smoke exhaust hood. A low-pressure deluge system with discharge density in the range of 8-12mm/min was used in the tests. Results from the medium-scale fire tests and also from full-scale fire tests suggest that the convective heat transfer rate is generally no more than 50% of the suppressed fire heat release rate. This finding may allow a reduction in the capacity of longitudinal ventilation systems for smoke control.

1 INTRODUCTION

The Land Transport Authority of Singapore (LTA) has recently undertaken a research project to explore the benefits of water based suppression systems for tunnels. The LTA sought insight into full or partial substitution by a fire suppression system of other fire safety measures such as passive fire protection or a high capacity ventilation system.

The fire suppression systems investigated by the project are:

- Water-based deluge systems;
- Low pressure water supply (up to ~5 bar);

- Coverage area of at least $9m^2$ per nozzle;
- Water coverage rates of 8 to 12 mm/min;
- Generic nozzles, with the view to be independent of any one supplier.

The research project included both full-scale fire tests in a tunnel (reported in a companion paper to this symposium) and laboratory tests. The latter tests were undertaken with the objective of optimising the fire suppression system for the fuel type specified by LTA (comprising 80% wood and 20% plastic pallets by volume).

The laboratory tests provided an opportunity to investigate the energy budget in suppressed fires, in order to estimate the relative proportions of energy dissipated through convection, evaporation, heating up of water and other losses. This paper reports specifically on the measurement set-up and conclusions of the experimental study in relation to the energy budget in suppressed fires.

2 PREVIOUS WORK

There is very limited information in the literature with regards to the energy budget in suppressed fires. Writing about mist rather than low-pressure deluge systems, Wighus (1995) defined the term 'spray heat absorption ratio' (SHAR), which relates the rate at which heat is absorbed by evaporation of a given mass of water (Q_w), to the rate at which heat is given off by a fire (Q_f):

$$SHAR = Q_w / Q_f \qquad \text{(Equation 1)}$$

Wighus reported that, for optimised application of mist to an unconfined propane flame, the spray heat absorption ratio can be as low as 0.3, but is more likely to be about 0.6 for more realistic machinery space conditions. As noted by Mawhinney and Back (2008), in the absence of reignition surfaces, only enough heat has to be absorbed from the flame to drop the temperature to the limiting adiabatic flame temperature; it is not necessary to drop the temperature of the compartment or the fuel to ambient.

3 TEST SET-UP

3.1 Geometry

The laboratory test setup was built inside the Efectis laboratory in the Netherlands, and is indicated in Figure 1 and Figure 2.

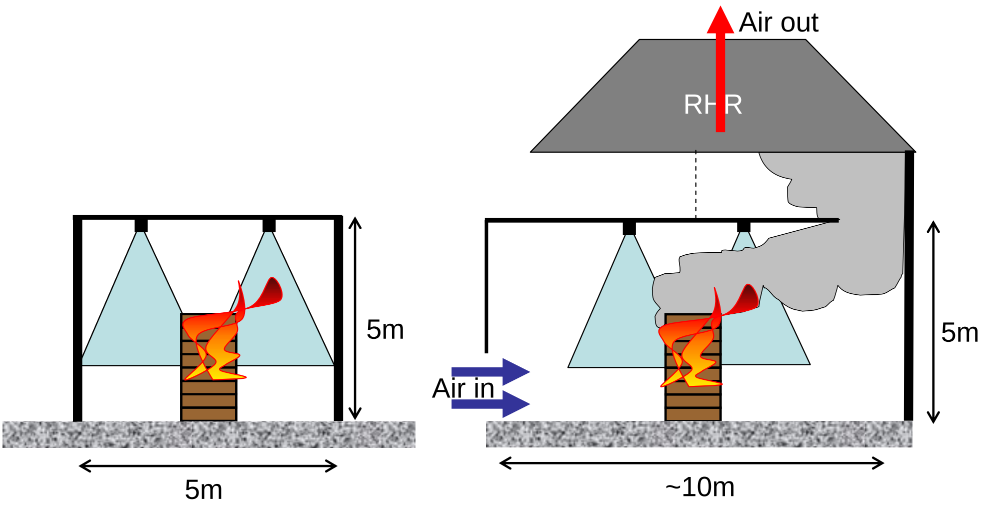


Figure 1 – Test setup

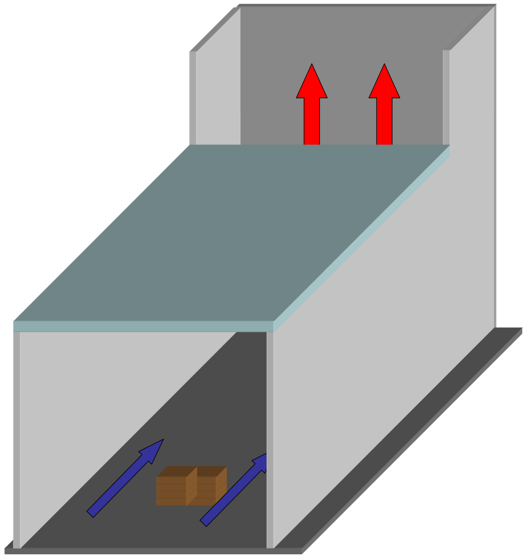


Figure 2 – Simplified 3D model of the test setup

The test setup is constructed inside the laboratory and has a roof of steel/rockwool sandwich panels. The walls are made of a fire resistant fabric. Locally the sandwich panels are protected by ceramic blanket (Test 1) or fire protection boards (from Test 2 onwards). A picture of the test setup is shown in Figure 3.

Figure 3 – Photo of the test setup before the tests

3.2 Fuel type and stacking

The fire load in the laboratory fire tests consists of wooden and plastic pallets, with the number of plastic pallets equalling 20% of the total number of pallets. In order to sufficiently represent the fuel layout as in the large scale tunnel tests, the same stacking height (relative to the nozzles) was used as in the large scale tunnel tests. A pallet stack height of about 3m from the floor was used, and the top of the pallet stack was thus 2m below the sprinkler nozzles.

In Test 1, a pallet stack of 19 pallets was set up, including 4 plastic pallets. From test 2 onwards pallet stacks of 15 “semi-pallets” were set up, including 3 plastic pallets.

In the tests early collapse of the pallet stack was prevented by fixing wooden strips to the pallet stack, as shown in Figure 4 and Figure 5.

Additionally, in test 1 a ‘thermal mirror’ was used to shield the fire source and increase the fire development in the early stage. From test 2 the thermal mirror was left out.

In order to investigate the behaviour of covered and uncovered HGV load, depending on the specific test an uncovered or covered pallet stack was created using a 1mm aluminium plate as cover on top of the pallet stack (without covering on the sides of the stack). The objective of including a covered pallet stack is to investigate the most realistic worst-case scenario for the suppression system.

Figure 4: Full Europallet including dimensions and picture of the test setup

Figure 5: “Semi-pallets” including dimensions and picture of the test setup

3.3 Fire suppression system

The installed suppression system included 4 nozzles in the ceiling for all tests. The nozzles were installed in a 3m x 3m grid around the fire source. This is shown, including the position of the pressure sensor, in Figure 6.

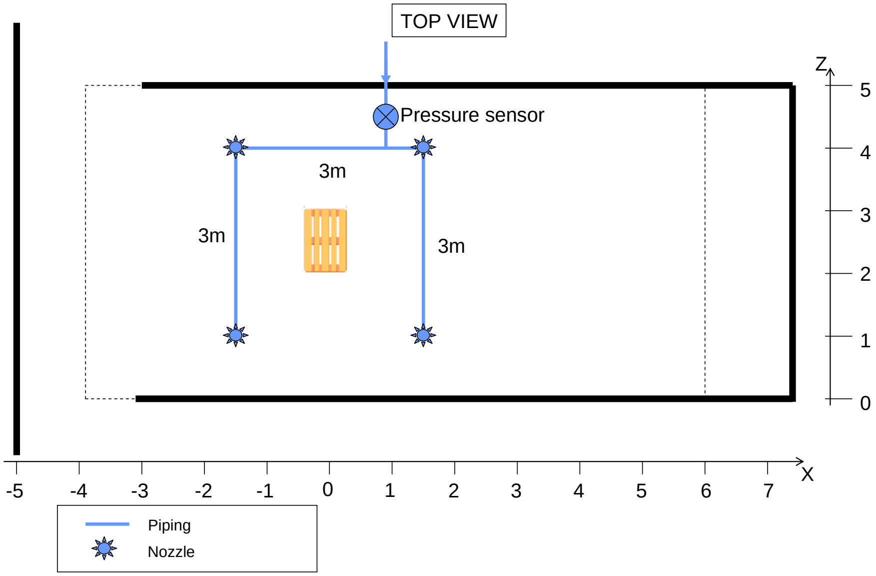


Figure 6: Installed suppression system during the laboratory fire tests

3.4 Fire tests and fire test schedule

The first fire test #1 was carried out on 14th November 2011 (after a pretest, test #0). However, the heat release rate and accompanying temperatures as measured during test 1 were much higher than expected. In subsequent tests the total fire load was reduced in order to be able to carry out the remaining part of the test program without destroying the test setup.

The number of pallets was therefore reduced from 19 to 15 and the size of the pallets was reduced from full 1.20m x 0.80m pallets, to about 0.70m x 0.80m ("semi-pallets"). The number of plastic pallets was also reduced (in line with the total pallet number) from 4 to 3. Finally, the thermal mirror was removed. The test schedule is given in Table 1.

Table 1: Schedule of fire tests carried out

Test no.	Nozzle type	Discharge density (mm/min)	Activation at	# Pallets	Fire load shielding
0 (pre)	Standard	7	13 min	10 full width	Uncovered
1	Standard	11.2	Max HRR (6 min, 45 min)	19 full width	Uncovered
2	-	-	-	15 partial width	Covered
3	-	-	-	15 partial width	Uncovered
4	Dir. 180°	12.2	Max HRR (6 min)	15 partial width	Covered

5	Dir. 180°	12.2	Max HRR (6 min)	15 partial width	Uncovered
6	Dir. 180°	7.9	Max HRR (9 min 18 min)	15 partial width	Covered
7	Dir. 180°	7.9	4 min	15 partial width	Covered
8	Standard	7.9	4 min	15 partial width	Covered
9	Standard	7.9	Max HRR (8min 32s)	15 partial width	Covered
10	Dir. 110°	7.9	4 min	15 partial width	Covered
11	Dir. 180°	12.0	4 min	15 partial width	Covered

3.5 Measurement setup

Heat release rate

To determine the heat release rate via oxygen calorimetry, the following parameters were measured: oxygen concentration in the exhaust gases; carbon dioxide concentration in the exhaust gases, pressure difference over the bi-directional probe to determine volume flow in the exhaust channel and the temperature of exhaust gases in exhaust channel.

Based on this data, the volumetric flow of exhaust gases can be calculated, taking into account the exhaust channel dimensions. Additionally, the oxygen depletion factor was calculated as per the following equation:

$$\phi = \frac{X_{O_2}^{A^0}(1 - X_{CO_2}^{A}) - X_{O_2}^{A}(1 - X_{CO_2}^{A^0})}{X_{O_2}^{A^0}(1 - X_{O_2}^{A} - X_{CO_2}^{A})}$$

(Equation 2)

and the fire heat release rate was calculated using

$$\dot{q} = \frac{\Delta H_C}{r_0} 1.1C \sqrt{\frac{\Delta p}{T_e}} \left(\frac{\phi}{1 - 1.105\phi}\right) X_{O_2}^{0}$$

(Equation 3)

The terms within the oxygen depletion factor ϕ and the fire heat release rate $\dot{q}$ are defined by Parker (1984).

The whole pallet stack is placed on a balance to determine the mass loss and the absorbed water from the fire suppression system. This is shown in detail in Figure 7.

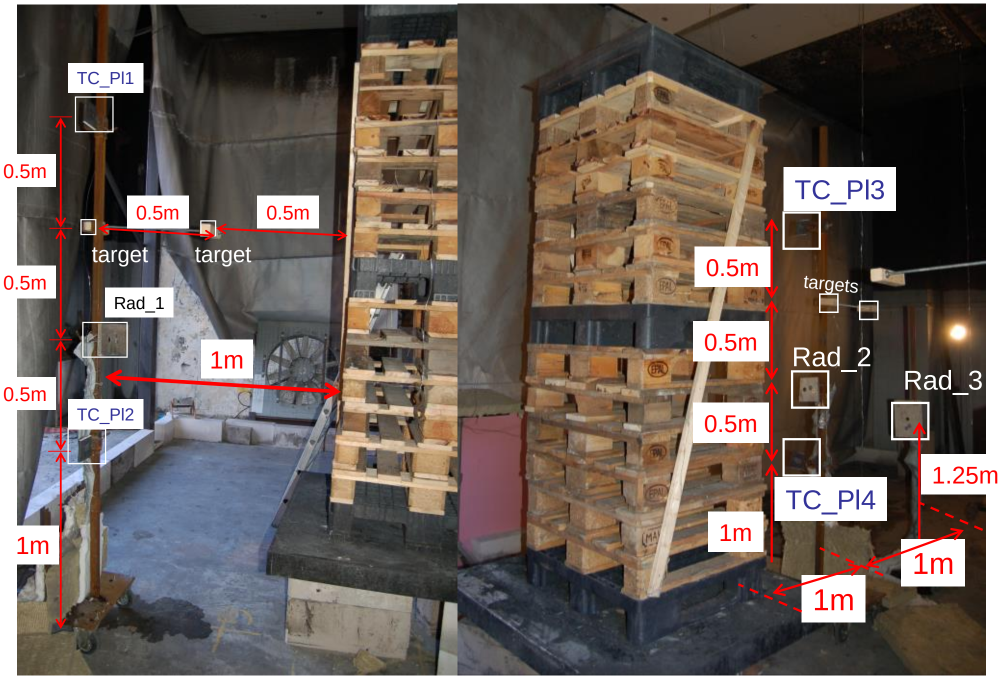


Figure 7: Measurement setup and naming around the fire source

Suppression system and water
The flow rate and pressure of the suppression system are measured in the piping towards the nozzles. The water temperature of the inflowing suppression system water is also measured in the piping towards the nozzle. Additionally the water temperatures in the basin are measured at two locations, about 1m and 2m downstream of the fire.

4 WATER BALANCE

4.1 General Water Balance

The water balance for the laboratory fire tests is shown in Figure 8 below.

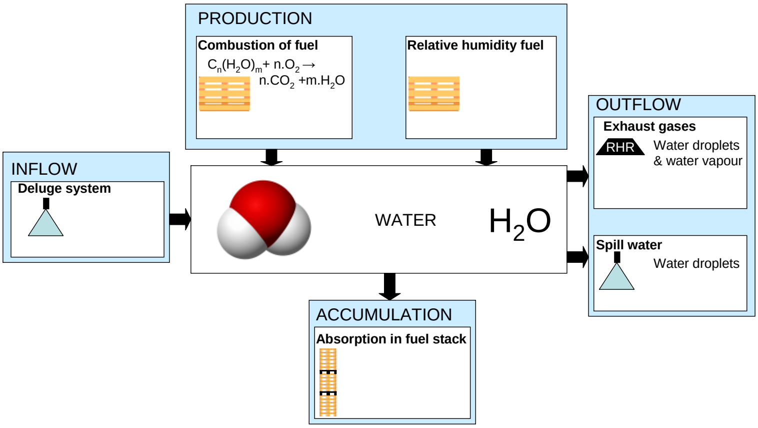


Figure 8: Water balance for the laboratory fire tests

The moisture content of the fuel has been determined by analysing different samples of the fuel stack. This is done by taking a sample, determining the mass and volume and drying it to evaporate all water from the sample. The result showed a moisture content of the fuel samples (roughly) between 12 and 17%.

4.2 Water Inflow

The inaccuracy of the inflow is estimated to be less than 1% due to the high accuracy of the measurement device.

Note that the inflow of water as vapour in the inflowing air can be determined from the water vapour contents of the exhaust gases (at the start of the test, the ambient air is measured). This is not explicitly shown in Figure 8, but all balances are corrected for the initial water vapour contents, as well as the energy balance in the next section.

4.3 Water Production

The production of water in the control volume can be deduced from the heat release rate and moisture content of the fuel, because the water production is related to the consumed oxygen. Assuming a chemical formula of $C_n(H_2O)_n$ for wood and (CH_3)n for plastic and a plastic mass ratio of about 30%, the produced water mass is calculated as 0.52 times (molecular mass ratio) the consumed oxygen mass (which can be deduced by dividing the released heat by 13.1 MJ/kg).

The contribution of the moisture content of the fuel to the water production is first related to the initial moisture content of the burnt fuel (10-15% of the fuel mass). However, additional water is evaporated from the preheated fire load, making this first estimate too low. The magnitude of the required correction should be dependent of the value of the heat release rate and temperatures inside the fire source, however for simplicity the correction is linked to the moisture content for the free burning tests until the moment of suppression activation to 'calibrate' the contribution. The moisture content of the burnt fuel is increased by 20% to account more or less for this contribution.

The inaccuracy of this contribution is estimated to be about 20% of the value, because of the use of deduced quantities.

4.4 Water Accumulation

The accumulation is estimated from the theoretical mass burnt (integrated heat release rate divided by heat of combustion, assuming 30% mass percent plastic pallets) and the mass loss measurements. In case of collapse, the water accumulation is considered at the moment of collapse or a correction is applied due to the collapse.

The inaccuracy of this contribution is estimated to be 10-20% of the total measured value (due to the use of deduced quantities).

4.5 Water Outflow

The contribution of the water in the exhaust gases to the outflow of water is measured by measuring the moisture content, temperature and the volume flow rate of the exhaust gases. A correction is made for the humidity of the inflowing air (the humidity at the start of the test is subtracted from all values measured later), so only the increase in humidity is taken into account.

The inaccuracy of this contribution is estimated to be 5-10% of the total measured value (accurate measurement equipment, possibly missing a part of the exhaust gases or some (limited) condensation before measurement).

The contribution of the spill water is determined by collecting the spill water in a basin and measuring the level increase after the fire test. Because of the measurement principle, the expected inaccuracy is estimated to be at least 50 litres (1mm level difference over 50m^2), added to the effects of possible leakage of water etc.

4.6 Water balance

The resulting water balance is shown in Table 2. The mismatch of the balance is calculated as (+) inflow + production – accumulation – outflow.

Table 2: Water mass balance

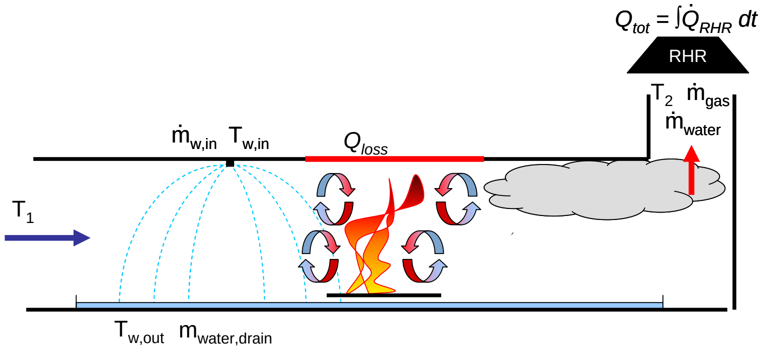
Test	Inflow (l)	Production (fuel) (kg)	Production (RH+Evap) (kg)	Accumulation (kg)	Outflow (exhaust) (kg)	Outflow (spill) (l)	Balance missmatch (kg)(%)
1	2875	102	41	ND	331	ND	-
2	225	67	27	***	117	ND	-
3	45	90	36	***	138	ND	-
4	4116	37	15	41	81	4150	-104 (2.5%)
5	4052	39	15	29	88	4000	-13 (0.3%)
6	3668	57	23	33	130	3700	-115 (3.0%)
7	7448	66	26	39	211	7400	-110 (1.4%)
8	6086	65	26	31	207	6000	-61 (1.0%)
9	1895	45	18	23	106	1850	-21 (1.1%)
10	6589	41	16	52	134	6450	+10 (0.2%)
11	10283	55	22	70	178	ND	-

*** Collapse before suppression (free burning test)
ND = not determined

5 ENERGY BALANCE

5.1 Overview

The energy balance for the suppressed laboratory fires is shown in Figure 9 below.



$$Q_{tot} = Q_{conv} + Q_{water} + Q_{loss} \quad \rightarrow Q_{loss} = Q_{tot} - Q_{conv} - Q_{water}$$

$$Q_{tot} = \int \dot{Q}_{RHR}\, dt$$

$$Q_{conv} = Q_{conv,gas} + Q_{conv,water} = \int \dot{m}_{gas}\, C_{p,g}\, \Delta T\, dt + \int m_{water}\, C_{p,w}(T)\, \Delta T^{\cdot} dt + \int m_{water}\, H_v\, dt$$

$$Q_{water} = m_{water,drain}\, C_{p,w}\, (T_{w,out} - T_{w,in}) \qquad \Delta T = T_2 - T_1 \text{ or } \Delta T = T_2 - T_{w,in}$$

Figure 9: Energy balance for the laboratory fire test

The different contributions are explained below:

Q_{tot} - total energy
The total chemical energy released by the fire due to the combustion, which is the integrated heat release rate. Q_{tot} is the heat release rate measured by the oxygen depletion calorimetry.

Q_{conv} – convective heat transfer
Energy transferred away from the fire source by convection. This means the energy transferred by heating the combustion gases and energy transferred to heat the water contents of the combustion gases. This also includes the energy absorbed by the phase transition from liquid to vapour.

Q_{water} – Energy absorbed by liquid suppression system water
The energy absorbed by the liquid suppression system water in the liquid phase (when falling from the nozzle) is determined by the temperature rise of the collected water in the basin relative to the inflow temperature.

In this stage it is assumed that the temperature measured inside the basin is from the start of the suppression system representative for the temperature rise of the suppression system water. The temperature rise of the basin itself ('water floor') before system activation is assumed to be part of the heat losses to the surroundings (see below).

Q_{loss} – heat losses
The heat losses are mainly the radiative heat transfer from the fire source and result in temperature rises of the floor, walls and ceiling. This is used as closure term (when negative it indicates cooling of the walls).

Integrated analysis (energy)
The energy contributions and energy balance are shown in Table 3 for the time the suppression system is activated.

Table 3: Energy balance (in MJ and in % of the HRR) ($Q_{ConvLiquid}$ and $Q_{ConvVapour}$ omitted) during the activation time of the suppression system

Test	Q_{RHR}	$Q_{ConvGas}$	$Q_{ConvEvap}$	$Q_{WaterBasin}$	Q_{Loss}
4	256	115 (45%)	119 (46%)	75 (29%)	-61 (-24%)
5	313	129 (41%)	141 (45%)	165 (53%)	-133 (-43%)
6	411	190 (46%)	165 (40%)	188 (46%)	-145 (-35%)
7	1423	632 (44%)	460 (32%)	362 (25%)	-79 (-6%)
8	1441	621 (43%)	454 (31%)	340 (24%)	-22 (-2%)
9	269	136 (51%)	133 (49%)	108 (40%)	-118 (-44%)
10	772	377 (49%)	267 (35%)	245 (32%)	-140 (-18%)
11	1080	274 (25%)	372 (34%)	594 (55%)	-180 (-17%)
Average		43%	39%	38%	-23%

5.2 Observations from Measurements

The most important contributions in the convective heat transfer are the convective heat transfer to the gas phase and the evaporation of water.

After activation, 31-49% (average 39%) of the released energy is absorbed by the evaporation of water (Table 3, $Q_{ConvEvap}$). About half of this is assumed to be absorbed by the water vapour generated in the combustion products; hence 15-25% of the released energy is absorbed by evaporation of suppression system water.

After activation, 25-55% (average 38%) of the released energy is absorbed by heating of the (liquid) water (Table 3, $Q_{WaterBasin}$). The energy absorbed by heating of the (liquid) water is assumed to be partly due to energy absorption from the hot structure (walls/ceiling). As the balance should add up to 100%, and it adds on average to 120%, about half of the heating (20%) is assumed to be caused by absorption of heat from the walls and the ceiling (due to heat released earlier by the fire); hence about 20% of the heat generated is removed from the setup due to heating of suppression system water.

After activation of the fire suppression system the walls are cooled by water, and this increases the rate of heat removal from the fire source. An average of 23% to the total (chemical) fire heat release rate is gained from the floor, walls and ceiling of the enclosure (Table 3).

It is estimated that the convective heat transfer represents 25-51% (average 43%) of the released fire heat release rate (Table 3).

5.3 Results from Full-Scale Fire Tests

A number of full-scale fire suppression tests on mock HGVs were undertaken by the LTA, with detailed results described in a companion paper to this Symposium. Table 4 summarises the tests carried out, while Figure 10 shows the ratio of the convective heat flow to the total measured heat release rate.

Table 4: Description of full-scale fire tests

Test	Description	Discharge Density (mm/min)	Nozzle Type	Activation time (min)	Suppression system length (m)
1	Base case	12	Dir. 180°	4	50
2	Low suppression	8	Dir. 180°	4	50
3	Nozzle	12	Standard	4	50
4	Nozzle (repeated)	12	Standard	4	50
5	Reduced cooling length	12	Standard	4	40
6	Late activation	12	Standard	8	50
7	Unsuppressed	-	-	-	-

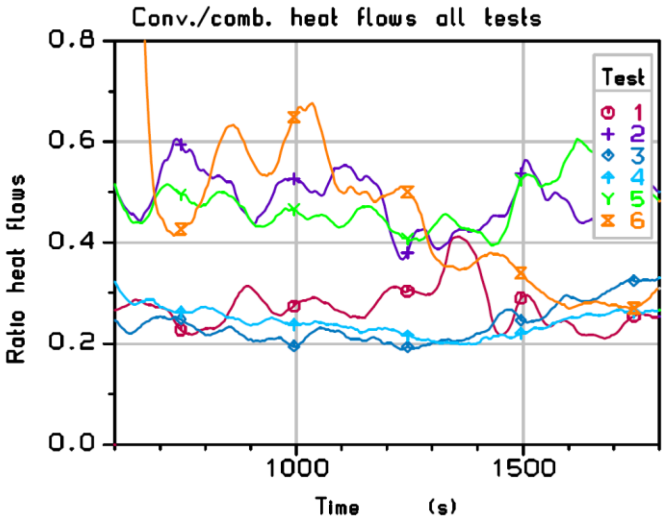


Figure 10: Ratio of convective to total heat flows for full-scale fire suppression tests

From the results of the full-scale fire suppression tests, it is apparent that the ratio of convective heat transfer to total fire heat release rate is generally below 50%, with the exception of the late activation test (number 6) and the reduced density case (number 2).

6 IMPLICATIONS FOR TUNNEL VENTILATION DESIGN

Only the convective component of heat transfer, $Q_{ConvGas}$, is relevant in terms of the dimensioning of a tunnel ventilation system. This is because the thermal buoyancy of the hot gases issuing from a fire is controlled by convective heat transfer, i.e. hot air rising. The critical velocity for smoke control is dependent on buoyancy effects, as described by the ratio between the inertial and buoyancy forces. Since only a fraction of the heat transfer in suppressed fires flows out via convection, it follows that appropriate allowances may be made in the relevant calculations, including estimates of critical velocity and the setting of boundary conditions for 1D to 3D CFD codes.

For unsuppressed fires, it is common practice to assume that 70% of the fire heat release rate is convectively transported, with the balance being lost due to radiation to the surrounding environment and to the fuel source (Heselden, 1976). Calculations of the critical velocity for smoke control are typically based on the convective component of fire heat release rate only (Kennedy, 1996).

It was observed that the convective heat transfer was generally less than 50% of the suppressed fire heat release rate. Depending upon the risk assessment process undertaken, and the degree of confidence attached to the performance of the fire suppression system, a significantly lower value for the fire heat release rate may be assumed for suppressed fires. For example:

- A typical unsuppressed HGV fire heat release rate may be set at 100 MW (BD78/99, 1999) with a convective component of typically 70 MW.
- If a deluge-type fire suppression system is properly designed, installed and maintained, and is activated shortly after fire detection, it may be possible to limit the fire heat release rate to 30 MW (Tarada and Bertwistle, 2010; Connell Wagner, 2007).
- If the assumption is made that only 50% of the fire heat release rate is convectively transported, with the balance being lost due to radiation, latent heat of evaporation and heating up of suppression water, it follows that 15 MW should be considered in the estimation of the critical velocity.

The application of deluge-type suppression therefore produces multiple benefits from a fire safety perspective: not only can the fire heat release rate be reduced, but in addition, a smaller proportion of the residual heat release rate is transported convectively (through the movement of hot gases).

It should be noted that fires introduce an aerodynamic pressure drop in tunnels. Dutrieue and Jacques (2006) have suggested that this pressure drop is related to the convective portion of the fire heat release rate - hence a reduction in the aerodynamic pressure drop can be expected for suppressed fires. On the other hand, the presence of water droplets will increase the pressure drop within a tunnel due to aerodynamic friction between the droplets and the airflow. The latter issue in particular requires additional research work to allow quantification of its effect.

The present measurements considered specific geometric and fire suppression arrangements, and hence general recommendations cannot be made regarding the appropriate proportion of convective heat transfer as a percentage of the total fire heat release rate.

Based on the findings of Wighus (1995), it appears that mist systems produce a greater proportion of evaporative heat transfer (60%) than low-pressure deluge systems (39% as measured by the current tests). It would therefore be reasonable to conclude that the proportion of convective heat transfer would be lower for mist systems compared to low-pressure deluge systems, although more research work would be required to provide reliable estimates.

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