

Effect of water mist on the dispersion of a flammable gas inside traffic tunnels – an LPG experimental study

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The release of flammable gases inside a traffic tunnel can result in a hazardous atmosphere, potentially leading to explosions. The use of mechanized ventilation and water mist systems for fire protection, could improve the safety of road tunnels in case of accidents or fires by mitigating the explosive area of the released gas. The effects of water mist on the dispersion of flammable Liquified Propane Gas (LPG) inside a 1:15 scaled road tunnel is investigated to assess if specific operating conditions with ventilation and water mist could be effective in reducing the explosive area and related risk of casualties or damage. 15 different experiment scenarios were investigated which showed that steady state LPG concentration profiles could be measured at multiple longitudinal locations. This data can be used in further statistical and numerical models to evaluate the effect of ventilation speed and water mist types on the dispersion of LPG inside road tunnels. In addition the improved models can be used to further refine risk analyses required for full-ADR road tunnels.

Keywords LPG, Risks, Tunnel Design, Scaled tunnel, Transport dangerous goods, Experiment, Water mist

Introduction

The transportation of dangerous goods, such as flammable gases or liquids, through tunnels caries inherent risks as accidents may lead to spillage and possibly explosions. When assessing the risk of such accidents different scenarios need to be considered such as Boiling Liquid Expanding Vapour Explosion (BLEVE), Gas Expansion Explosion (GEE) caused by the rapid expansion of an inert gas, or a gas explosion caused by a deflagration or detonation of gas-air mixtures. The scenarios that need to be considered depend on the properties of the transported substance, the spill scenario and tunnel parameters such as the tunnel geometry and ventilation speed.

Witteveen+Bos (W&B) is, together with SWECO, tasked by LANTIS to design the so-called Oosterweel Link project in Antwerp Belgium, where in total five tunnels will be constructed to improve traffic mobility in Antwerp. Several of these tunnels will be a so-called "full-ADR" tunnels, meaning that it will be designed for the transport of all dangerous goods. These TERN-tunnels will be equipped with several fire prevention systems, including a water mist fire suppression system. In this article the focus is on the OKA-tunnel which crosses underneath the Albert canal in Antwerp.

A study by Weerheim (J. Weerheijm, 2018) showed that the quantitative risk assessments of gas explosions inside road tunnels requires models for both the probability of occurrence, the gas dispersion and gas explosion overpressure. Analysis of the structural loads on the OKA tunnel indicated that worst case deflagrating explosions or gas detonations could well exceed the structural limits of the tunnel (M.G.M. van der Heijden, 2018). Following further analysis it was shown that significant gains might be achieved if these gas explosion scenarios could at least be partially mitigated using active suppression techniques such as the use of ventilation or water mist systems.

Water mist systems (WMS) have been studied extensively in the suppression of fires in tunnels. The primary role for water mist systems is to reduce the size of the fire and to prevent the fire from spreading between vehicles. However, it was also demonstrated that a water mist can prevent a BLEVE in a LPG truck when activation of the mist is sufficiently fast in order to reduce fire development and cool the tank (Lemaire, 2008), (Van den Berg A.C., 2006). There are further indications that the dispersion and the subsequent development of an explosive air/gas mixture inside the traffic tunnel might be influenced. (Van Doorn, 1981) (Hald, 2005)

Based amongst others on these findings an experimental study was therefore designed and executed to determine if a water mist might be used to reduce the risks associated with the accidental release of explosive gasses inside the "full-ADR" tunnels of the Oosterweel Link project.

Methodology

1. Context

The risk of a gas explosion is only present for air/gas mixtures between specific lower and upper explosive limits (LEL and UEL). A release of a flammable gas such as LPG will thus primarily pose a risk when it is diluted sufficiently to fall within these limits and an ignition source is present.

Figure 1 shows a simplified representation of the expected dispersion of a continuous flow of flammable gas that is released in an air ventilated traffic tunnel with height *H*. At the point of release, which is located at height *h* above the tunnel floor, the gas concentration varies strongly across the height of the tunnel (y-direction), with the highest concentration at *Y=h*. Further downstream (in positive x-direction), the concentration field becomes more homogeneous, as the gas is distributed more evenly. At a sufficiently large distance from the point of release, the gas is homogeneously distributed and the concentration field becomes more or less constant across the height of the tunnel.

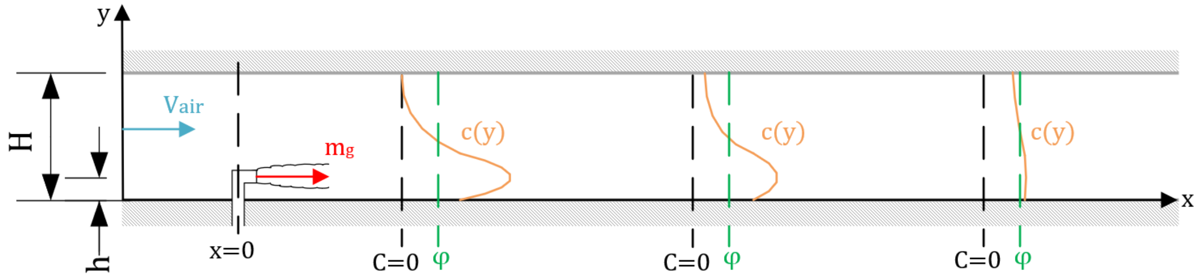

Figure 1 Conceptual view of propane release in a road tunnel.

In case the equilibrium mixture is obtained before the end of the tunnel, an area is formed where a mass explosion is possible. Close to the spill source, the explosive area is limited as the mixture is significantly above the UEL and only limited mixing between the gas and airflow occurs. Downstream in the tunnel the gas volume is more homogeneously mixed and a larger volume of gas falls within the explosive limits. Depending on the ventilation speed v_{air} [m/s], spill rate, m_g [kg/s], the tunnel cross-section A [m^2] and the gas properties (ρ_g = density), an homogeneous mixture ratio φ_g can be derived from first principles (equation 1). When considering risk for an explosion, the evolution of such a gas plume is very dependent on whether the end state will be below, between or above the explosive limits. The distance in the tunnel where the mixture falls between the explosive limits *Lexp* can then be evaluated as function of the spill scenario and any mitigating measures such as activation of ventilation and water mist.

$$\varphi_g = \frac{1}{1+\left(\frac{\rho_g A v_{air}}{m_g}\right)} \times 100\% \qquad \text{(eq 1.)}$$

The goal of the water mist experiments is to: evaluate whether the use of water mist and ventilation settings can be used to influence the dispersion of gas in the OKA road tunnel. This has the ultimate goal to evaluate and reduce the risk of gas explosions inside a traffic tunnel.

2. Mechanisms

Several mechanisms have been identified that might reduce the risk of a gas explosion inside traffic tunnels. These involve factors that can alter either the probability of the occurrence of a gas explosion such as the reduction in ignition sources, reduction of the length of the explosive area and ignitability of the explosive mixture, or factors that mitigate the severity of a gas explosion such as the length of the explosive area, and the energy release of the explosion per unit volume.

In order to understand *how* a water mist around a continuous gas spill could potentially reduce the risk of a gas explosion in a tunnel, the effects of a water mist on the individual 'risk factors' were evaluated. A water mist could have the following effect on the explosion risk factors:

- A water mist could result in a smaller 'explosive area' (smaller L_{exp}) inside the tunnel reducing the chance of ignition and reducing the volume of gas achieving mass explosion.
- A water mist could make the mixture harder to ignite reducing the probability of an explosion.
- A water mist could decrease the energy release of the explosion per unit of volume reducing the severity of the explosive area.

The evaluation of these factors require different experimental approaches. Acting both on the probability and effect of the explosion risk, it was chosen to focus primarily on the dispersion of gas within the tunnel. Three ways in which a water mist is expected to influence the evolution of gas within a tunnel have been identified. Depending on the homogenous mixture ratio for a given spill scenario these effects can be both positive and negative, effectively decreasing or increasing the explosive area and associated risk.

First; if the gas is soluble in water, fine water mist droplets with a very high surface area, are expected to remove some of the gas from the tunnel reducing the average concentration.

Secondly: the water droplets can induce turbulence and therefore might improve mixing inside the tunnel. More rapid mixing however might also move the boundaries of the explosive area towards the spill point. For the tunnels in the Oosterweel Link project both high and medium pressure water mist systems are considered with fine and coarse droplet distributions respectively. Other spray parameters to consider are the spray flux density [L/min m^2] and geometry of the water mist zones around the point of the accidental release.

Thirdly: the water mist might affect the overall flow field inside the tunnel. It can be expected that the addition of a water mist induces a form of downward convection inside the tunnel. Similarly the water mist is likely to affect the gas jet directly around the spill point.

Depending on the spill scenario and associated homogeneous mixture ratio these three mechanisms might reduce the explosive area. As the end goal of these experiments is to search for ways to reduce or mitigate the risks of gas explosions inside traffic tunnels, the operating conditions will be chosen in such a way to pursue the most promising results.

Experiment Design

A 1:15 scaled traffic tunnel was designed and is shown in figures 2-3. Based on literature the appropriate scaling relationships were identified to not only determine the tunnel geometry but also to obtain representative water mist behaviour and spill scenarios. As the experiment generated potentially explosive gas/ air mixtures the experiments were conducted inside TNO's rocket propulsion test facility. In addition special care was taken to assess the required safety measures to prevent inadvertent ignition of the gases.

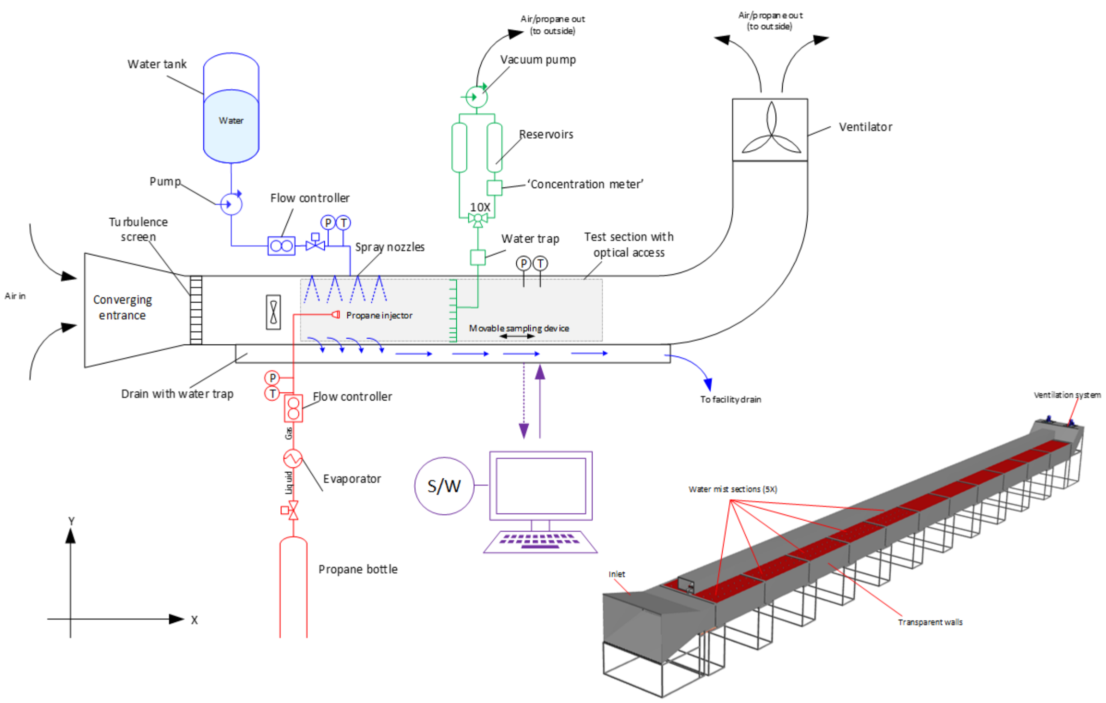

Figure 2 Overview of the scaled model tunnel.

Figure 3 Scaled model tunnel as constructed.

The set-up included a scaled water mist and ventilation system, a gas injection system capable of creating a range of spill scenarios and a flow characterization system capable of measuring the gas concentration field in the vertical and longitudinal directions.

1. Scaling Relationships

For the water mist test setup a suitable scaling factor S is defined as the ratio between full scale dimensions and model dimension.

$$S = \frac{Full\ Scale\ Dimensions}{Model\ Dimensions} \quad \text{(eq 2.)}$$

Based on literature the governing forces that drive the gas dispersion inside a tunnel are inertia, gravity and viscosity (Zavila, 2017). The relationship between these relations are given by the Reynolds and Froude dimensionless numbers. For flow in a closed conduit ("pipe flow"), the Reynolds number at which the flow becomes fully turbulent lies around 1.0×10^4. At larger Reynolds numbers, the flow can be considered to be governed primarily by inertial forces (Incropera, 2007). The ratio between the inertial and viscous forces (i.e. the Reynolds number) is therefore not critical in achieving similarity for the tunnel model, as long as the Reynolds number in the scaled situation is larger than the transition point around $Re=1.0 \times 10^4$.

The Froude number is constructed such that if it is equal to one, gravity and inertial forces are assumed to have an equal effect on the movement of the gases. For the reference tunnel, the Froude number lies between 0.2 and 1.2, depending on the exact operating conditions that are considered. This indicates that both inertial and gravity forces play an important role in the movement of gases in the tunnel. Based on these considerations it is imperative that the Froude number is conserved during the design of the setup.

For the expected range in dimensions the scale of 1:15 is found to be the lowest at which turbulent flow can be assured. This is in agreement with literature as a widely used scale in modelling of tunnel fires (Li, 2011).

2. Model Tunnel

The reference and scaled model tunnel dimensions are provided in table 1.

Table 1: Scaling relationship based on conservation of Froude number.

Parameter	Scaling relationship
Length (m)	$L_F/L_M=S^1$
Gas concentrations (%)	$C_F/C_M=S^0=1$
Ventilation rate (m^3/s)	$V_F/V_M=S^{5/2}$
Ventilation speed (m/s)	$V_F/V_M=S^{1/2}$
Time (s)	$t_F/t_M=S^{1/2}$
Pressure difference (Pa)	$\Delta P_F/\Delta P_M=S^1$

The reference OKA-tunnel consists of a six-lane, 22 meter wide, 6 meter high cross-section. The ventilation speed to be achieved in this tunnel can be between 0.5-6 [m/s]. The dimensions of the reference and model tunnel scaled with the provided scaling functions is provided in table 2. It is noted that the length of the test tunnel was chosen based on the available space in the test facility and was deemed sufficiently long for the purpose of these experiments.

Table 2: Scaling relationship based on conservation of Froude number.

Parameter	Unit	Full scale value	Subscale value
Geometry			
Tunnel height	m	6.0	0.40
Tunnel width	m	22.0	1.47

Tunnel length	m	300	20
Ventilation system			
Ventilation speed	m/s	0.5 – 6	0.13 – 1.55

An overview of the model tunnel is shown in figure 1. The design was constructed from 10 identical sections with either closed or water mist roof sections. A moveable cart was able to translate along a guide rail and allowed remote positioning of the flow measurement boom between 2.5 [m] upstream of the injection point to 15 [m] downstream of the injection point. To allow efficient removal of the water without compromising the leak tightness of the tunnel two gutters were included along the length of the tunnel with syphoned drains at regular intervals.

3. Water mist

As mentioned previously, for the Oosterweel Link project, two types of water mist systems are considered: a high and medium pressure system which result in greatly differing droplet dimensions and spray flux densities. The goal of the scaled subsystem was to reproduce the mixing and flow characteristics of both type of water mist systems. To limit the complexity and costs of the setup it was decided to use a single nozzle type to approximate both water mist systems.

When water mist is applied, the flow of water droplets will transfer momentum to the gas mixture, affecting the convective flow of the gases. The pressure gradients caused by the water droplets should scale in the same way as the pressure gradients in the dry flow in order to preserve the mist's effect on gas dispersion in the model tunnel. In addition, the trajectories of the water drops should scale geometrically with the tunnel to ensure the same extent of the water mist within the tunnel volume. Using the equations of motion of a water droplet (including the aerodynamic forces acting on it) results in the required scaling laws (Heskestad, 2002). Based on these considerations and the resulting scaling laws pressure is a derivative parameter for the scaled water mist system.

Table 3: Scaling laws for water mist based on preservation of droplet trajectories and correct scaling of pressure gradients.

Water flow rate (m^3/s)	$Q_F/Q_M = S^{5/2}$
Drop diameter (m)	$d_F/d_M = S^{1/2}$
Initial drop velocity (m/s)	$u_F/u_M = S^{1/2}$
Water flux (m/s)	$F_F/F_M = S^{1/2}$

The full size, scaled ideal and realized water mist characteristics are shown in table 4. One of the nozzles, as shown in figure 4, was characterized using laser diffraction to find the atomization characteristics 20 cm from the nozzles at different operating pressures. Based on these measurements operating conditions were defined that provided representative water mists by changing the water mass flow, and with that, the nozzle inlet pressures. As a single nozzle was selected for both types of water mist, not all spray characteristics could be perfectly reproduced. Specifically the spray flux density of the medium pressure water mist exceeded the scaled ideal values.

Figure 4 Water mist nozzle.

Table 4: Water mist properties of the scaled model tunnel.

Parameter	Unit	Full scale	Scaled ideal	Realized
Ideal water mist properties of a scaled high pressure system				
Spray angle	degrees	90 – 100	90 – 100	80
Nozzle Pressure Differential	barG	40 – 60	2.7 – 4.0	7
Spray flux density	L/min m^3	0.7 – 0.9	2.7 – 3.5	3.4
Vol. median diameter (DV50)	µm	75 – 150	19 – 38	26.9 ± 0.9
Vol. 10% diameter (DV10)	µm	35 – 50	9-13	14.2 ± 0.5
Vol. 90% diameter (DV90)	µm	150 – 250	38 – 65	48.1 ± 1.9
Ideal water mist properties of a scaled medium pressure system				
Spray angle	degrees	90 – 100	90 – 100	80
Nozzle Pressure Differential	barG	10 – 15	0.7 – 1.0	2.5
Spray flux density	L/min m^3	0.3 – 0.45	1.16 – 1.74	2.2
Vol. median diameter (DV50)	µm	125 – 250	32 – 65	60.9 ± 1.4
Vol. 10% diameter (DV10)	µm	75 – 125	19 – 32	30.1 ± 0.6
Vol. 90% diameter (DV90)	µm	200 – 400	51 – 103	114.6 ± 7.2

In case of an incident three mist sections around the accident will in general be activated as a fire prevention/ suppression measure, regardless of an actual fire outbreak. Hence, there will always be a *nominal* water mist zone with a length of typically 75 meter, around the location of accident. It also has been studied to activate additional sections around the nominal water mist zone, which leads to multiple possible water mist geometries with 3, 4 or 5 scaled 25 meter water mist sections.

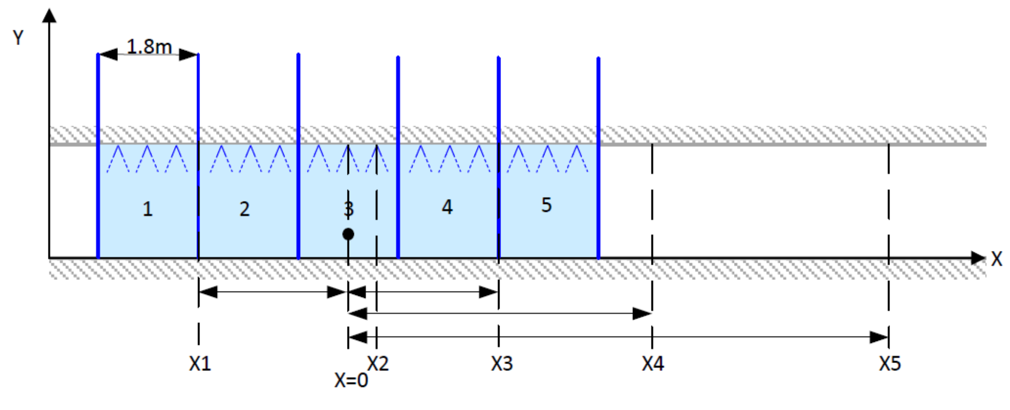

Figure 5 Water mist geometry around the propane release point at x=0.

In the scaled model tunnel these water mist sections, 1.8 [m] tunnel segments with a total of 8x9=72 nozzles installed were independently activated. Water mist pressure and mass flow was set using a mass flow controller allowing fine control of the spray characteristics.

4. Spill Scenario

The transport of LPG is most relevant for tunnel safety and was chosen as representative for the tunnel study discussed in this paper. Liquefied Petroleum Gas (LPG) is a highly flammable liquid. Its explosive limits (LEL and UEL) are 2.1 and 9.5%

(%vol of gas in air). Its auto-ignition temperature is ~410–580 °C and the specific calorific value is ~50 MJ/kg. The density of pure propane at ambient temperatures is 1.865 kg/m^3, so heavier than air.

A 'spill scenario' is defined by the combination of propane mass flow rate (ma), propane injection velocity (Vg) and propane injection angle (θ). Based on a previous TNO study the following full-scale ranges for these parameters were identified as most relevant, when considering an accidental release of gaseous LPG inside a traffic tunnel (J. Weerheijm, 2018):

• Propane mass flow rate : 15-30 kg/s

• Propane injection velocity : 246.5 m/s (sonic velocity, choked flow)

• Propane injection angle : 0-360 degrees

Table 5: Scaling laws for spill scenario

Parameter	Unit	Full scale	Scaled
Propane mass flow rate	kg/s	15 – 30	0.017 – 0.034
Injection velocity (aonic)	m/s	246.5	246.5
Injection angle	deg	0 – 360	0 – 360

Critical in attaining a steady state spill scenario is the capacity of the propane injection system to provide a controlled and continuous stream of propane at a fixed (room) temperature. To limit the complexity of the setup the propane is stored as a saturated liquid in standard storage tanks. During the experiments, liquid propane flowed first through an evaporator, a heated water tank, which supplied the required thermal capacity to evaporate the flow. The propane mass flow rate was controlled by a mass flow controller. Depending on the spill scenario four 12.9 kg industrial propane tanks could allow between 30-40 minutes of steady state tunnel operation.

5. Propane Concentration Measurements

In situ propane concentration measurements were achieved by sampling the propane concentration field in the XY plane of the model tunnel. The system consists of a moving 'sampling boom' connected to a nearby Flame Ionization Detector (FID). The sampling boom consisted of a pillar with a fixed vertical arrangement of sampling tubes, mounted on a translating cart that moved along the length of the tunnel as shown in Figure 6. The flow field in the tunnel was sampled by sequentially directing the flow from each sampling tube towards the FID using a periodically actuated selection valve.

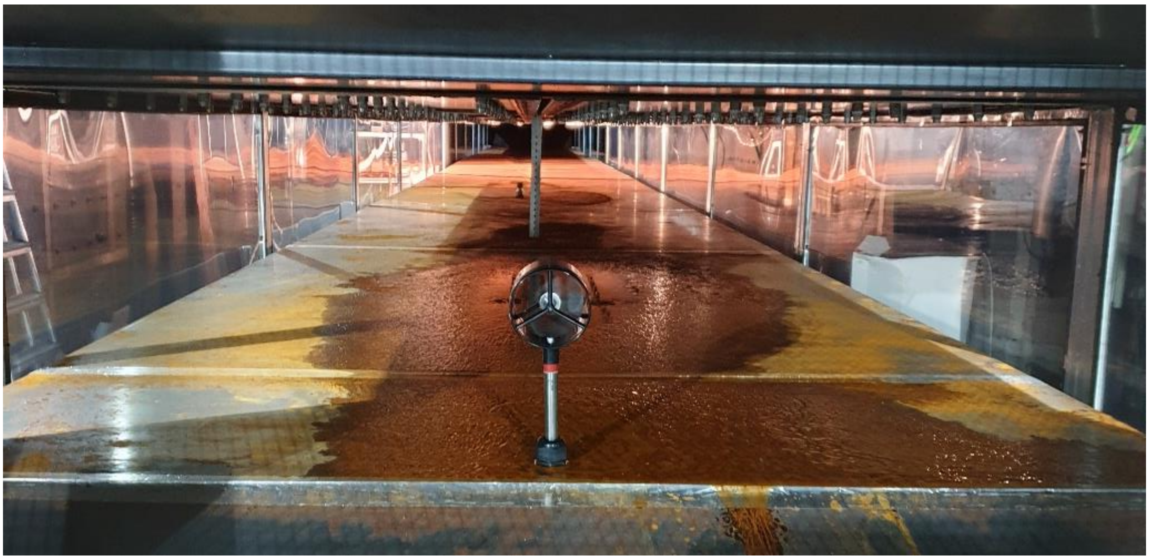

Figure 6 View down the tunnel with anemometer, sampling boom and propane inlet slightly offset from the center axis.

To evaluate steady state concentrations the concentrations were measured at 10 Hz for 12.5 seconds per (XY) location resulting in approximately 125 measurement samples at every location. This was a trade-off between measuring sufficiently long to eliminate most of the high frequency variations in the flow caused by turbulence and covering sufficient locations in the model tunnel.

To assure steady state conditions two downstream measurement locations X3, X4 were measured twice during every experimental run.

6. Safety Considerations

As the experiment involves a risk of explosive deflagration within the model tunnel, a critical part of the design consisted of the prevention of unwanted ignition and in part on the mitigation of the effects of such an explosion to within the test facility should this occur. The model tunnel was placed inside TNO's rocket test facility in Rijswijk, the Netherlands. Calculations showed that worst case explosive deflagration of a tunnel at scale 1:10 could be contained within the complex. The final model scale, 1:15, therefore has a considerable additional safety margin.

Prevention of explosive deflagration inside the setup is achieved by using ATEX systems inside the model tunnel, furthermore all wall and tunnel sections are grounded to prevent build-up of static electricity. Mitigation of the effects is achieved by assuring sufficient pressure release via model tunnel walls in case of ignition of the gas. The experimental setup is furthermore remotely operated.

To prevent any chance of explosive deflagration outside the model tunnel the entire setup was thoroughly leak tested before the experiments. Furthermore, the model tunnel is operated at a slightly negative pressure to prevent the release of gas from the setup. It is important to note that propane is heavier than air at standard temperature and pressure and will accumulate on the ground. As such the propane detectors were placed close to the facility floor. The propane concentration at which the detectors will trigger and the experiment would be halted was 0.2 %vol or 10% LEL, well below the critical concentration.

Results

A total of fifteen tests were conducted at two different spill scenarios of 17 and 26 g/s and at approximately three different ventilation speeds between 0.7 and 1.5 m/s. The tests were performed in pairs, with repetitions of the spill scenario with and without water mist. Higher propane mass flows and lower air speeds proved challenging as the propane tended to trigger the propane detectors at the front of the tunnel. The different scenarios tested are provided in table 6.

A representative time trace of one such experiment and the resulting XY concentration profiles are shown in figure 7. The error bars indicate the standard deviation per XY measurement. As the measured signals are strongly correlated in time the reproducibility per test could not be ascertained with a standard t-test. However, statistical analysis of all tests indicated that the difference between repeated measurements was normally distributed with μ=−0.062 [$\%vol$], σ=0.16 [$\%vol$] proving that steady state concentration measurements were sufficiently achieved.

Observations of the various water mist systems without propane gave insight into the interaction of the mist with the flow of air in the tunnel. This showed that the droplets created turbulence mainly around the point of injection at the top of the tunnel cross-section. They were subsequently transported downstream with the air in the model tunnel.

The theoretical far field concentration (equation 1, with measured values for windspeed, propane mass flow) as compared to the measured mean concentration at X5=10 [m], indicated that not all tests converged to the theoretical value. These differences were sometimes as large as 0.5 [%vol].

Table 6: Overview of the tested experimental scenarios.

testID	**Type**	**Settings**					**Far Field**	
		Mprop [g/s]	Vventilation [m/s]	WMS [-]	Qwms [l/min]	Pwms [barG]	$\varphi_{g,th}$ [%vol]	$\varphi_{g,x}$ [%vol]
test 1	benchmark	17	0.8			0.00	1.6	1.13
test 2	benchmark	17	0.7			0.00	1.99	0.69
test 4	benchmark	17	1.5			0.00	0.92	0.17
test 7	benchmark	26	1.15			2.50	1.95	2.01
test 10	benchmark	26	1.5			0.00	1.45	1.12
test 6	benchmark	17	1.15			0.00	1.46	1.06

test 2	HP watermist	17	0.8	2,3,4	11	7.00	1.85	0.71
test 4	HP watermist	17	1.5	2,3,4	11	7.00	0.95	0.41
test 8	HP watermist	26	1.15	2,3,4	11	7.00	2.02	2.09
test 10	HP Watermist	26	1.5	2,3,4	10.8	7.00	1.98	2.1
test 1	MP watermist	17	0.8	2,3,4	7.1	3.50	1.81	2.12
test 3	MP watermist	17	1.5	2,3,4	7.1	3.50	0.95	0.37
test 5	MP watermist	17	0.8	1,2,3,4,5	11.8	3.50	1.84	1.7
test 6	MP watermist	17	1.15	2,3,4	7.1	3.50	1.31	0.76
test 7	MP watermist	26	1.15	2,3,4	7.1	3.50	1.98	1.97
test 9	MP Watermist	26	1.15	1,2,3,4,5	11.5	3.50	1.92	1.89

Discussion

Sixteen datasets were collected that give confidence that the continuous release of LPG in traffic tunnels can be safely simulated inside a scaled model tunnel. This allows the comparison of the dispersion and effective mixing length as a function of water mist, ventilation speed and spill scenarios.

Following a further statistical analysis of the test data and a modelling effort, the measured concentration profiles can be used to refine the risk assessment for the accidental release of explosive gases inside a traffic tunnels and to assess the independent effects of water mist and ventilation. A modelling effort is needed both to confirm that scaling is done properly and to allow extrapolation of the cases where the gas cloud also extends forward in the tunnel and to evaluate scenarios that were not possible with the current setup due to safety constraints.

Steady state operation was shown to be achieved reliably, although deviations in the far field propane concentration showed significant differences from the theoretically expected values. This might be explained by horizontal gradients along the width of the model tunnel. Although these might be further investigated experimentally by modifying the sampling boom this can also be investigated using numerical methods allowing for a higher resolution cross-section of the concentration field.

Further improvements could be achieved by including scaled obstructions such as stationary traffic in the model tunnel which are expected to have a large influence on the turbulence and mixing characteristics of the propane plume and are a key aspect of the risk analyses such as discussed by Weerheijm (J. Weerheijm, 2018). Lastly the transparent walls allow direct observations of the plume and could be used to even further improve the understanding of the flow field using more advanced optical methods such as particle image velocimetry (PIV). The confidence that these experiments can be conducted safely inside TNO’s facility is key in expanding to more complex and expensive measurement techniques.

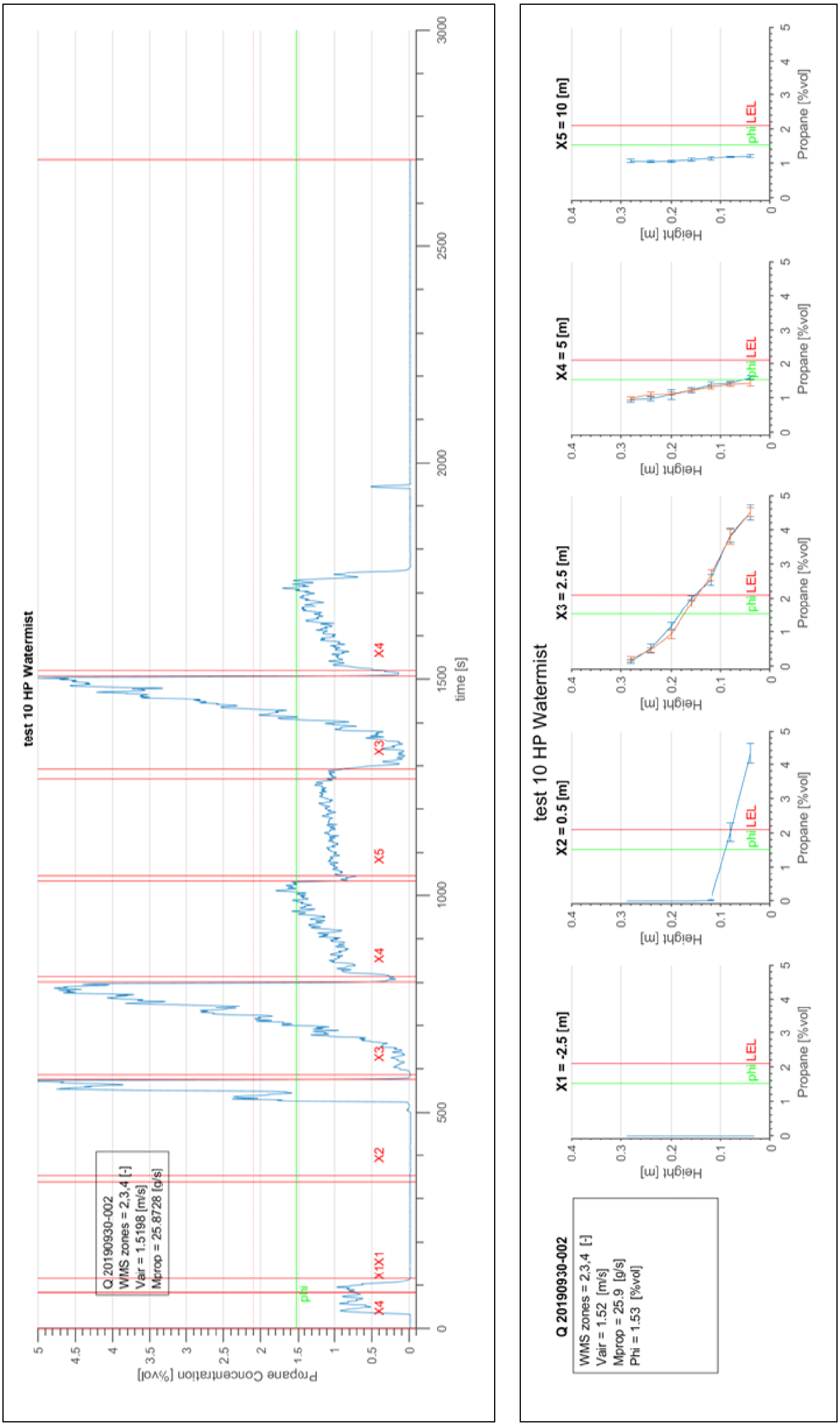

Figure 7 Representative concentration measurements with 3 water mist sections.

Conclusion

As part of the design for the Oosterweel Link project in Antwerp, Belgium a scaled traffic tunnel reflecting the OKA-tunnel crossing underneath the Albert Canal was build which allowed the investigation of continuous LPG spill scenarios and subsequent gas dispersion. These spill scenarios are considered critical when evaluating the risks of full ADR tunnels as explosive deflagrations or detonations of gas-air mixtures can easily exceed the structural limits of road tunnels leading to damage beyond economic repair. The designed setup allows the simulation of various spill scenarios and operating conditions with scaled ventilation and water mist systems.

15 tests were conducted with LPG showing that steady state behaviour was achieved inside the model tunnel. With the measured concentration profiles and a statistical analysis of the various test scenarios allow the investigation of the effect of water mist and ventilation speed on the dispersion of LPG inside road tunnels. However occasional deviations of the measured average concentration in the far field shows that 1D sampling is insufficient to fully resolve the dispersion of propane throughout the traffic tunnel. Recommendations are made to investigate this further by altering the sampling arm or using different measurement techniques such as PIV methods.

Alternatively the experimental data could be used to validate numerical simulations of these LPG incident scenarios. The modelling effort combined with the experiment data could provide the insight into the underlying mechanisms. In addition the results could be expanded to different tunnel geometries, allow the inclusion of stationary traffic such as might be encountered in a traffic jam and investigate spill scenarios that are currently not possible to recreate experimentally due to safety constraints.

This experimental study provides valuable insight into the dispersion of propane gas downstream of an accidental spill as can be used for the engineering practise and in particular for design of the Oosterweel Link project. The experimental results indicate amongst others the length of the tunnel along which the main part of the dilution of the propane gas occurs given the various scenarios tested. This could provide for the means to refine the risk assessment in particular for spill scenarios in which ultimately a non-flammable propane concentration is reached but potential explosion risks in the area surrounding the accident location need to be considered.

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