Design fire heat release rate of flammable liquid fires under water mist suppression in a tunnel

Yunlong Liu, Sean Cassady, Petr Pospisil, Eric Jones
HNTB Corporation, USA
E-mail: yuliu@hntb.com

ABSTRACT

Tunnel fire which involves flammable liquid cargo (FLC) fuel can resulted a heat release rate (HRR) as high as 200 to 300 MW, and its growth rate can be faster than that of a heavy goods vehicle (HGV) or other type of vehicles. Fire suppression is one of the approaches to control the fire spread, however, sprinkler system is not effective for FLC fire because the water density of higher than the flammable liquid and the liquid fuel tend to float on top of the water. Foam is a better solution since it can generate a bubble blanket on top of the fuel isolating the oxygen from the fuel, however this would result in environmental issues. This paper discussed a water mist suppression approach which would be an alternative for controlling the FLC fires in tunnels, and eliminate the environmental concerns caused by foam discharge in the local area. With the aid of computational fluid dynamics (CFD) modelling, the fire HRR growth curve has been developed based on the experiment recorded temperature and the portal oxygen concentration, and it has been confirmed that water mist if effective for controlling FLC fires in a tunnel environment, where ventilation airflow exists.

KEYWORDS: Water mist, fire suppression, flammable liquid cargo (FLC), fire heat release rate, tunnels, design fire

INTRODUCTION

Water mist fire suppression systems have been successfully applied in industrial application and several European road tunnels, but until recently not in US tunnels. This paper will discuss and review the effectiveness of water mist fire suppression systems to control flammable liquid cargo (FLC) fires in a tunnel environment.

In regions throughout the United States, some road tunnels which accommodate FLC's rely on foam suppression systems for fire events, which generate a foam 'blanket' on a fuel spill surface. The foam agent's lower density allows the foam to cover the fuel surface and isolate the fuel from the oxygen; hindering the combustion process. However, environmental and personal health concerns are becoming more prevalent for tunnel owners, operators, and first responders using traditional foam suppression systems.

The application of water mist systems should be explored for its ability to alleviate environmental concerns associated with traditionally used roadway tunnel foam suppression systems. When water mist reaches the surface of a FLC fuel fire, it can easily evaporate and the latent heat from its phase change absorbs a substantial portion of energy and decreases the temperature of the fuel surface. The gas phase water, i.e., water vapor, will also reduce oxygen concentration, further slowing fire growth. Because gas phase water has lower density than the air (as the density of water vapor is 0.804g/litre, which is significantly less than that of dry air at 1.27g/litre at STP), it tends to flow upward; displacing and diluting the oxygen concentration in the tunnel feeding the combustion process.

Computational Fluid Dynamics (CFD) modeling with the software Fire Dynamics Simulator (FDS) has been performed for FLC pool fire under water mist application in a tunnel environment. Gas temperature and oxygen concentration has been recorded to understand the mechanism of the water mist fire suppression on flammable liquid fuel fires. Heat release rate (HRR) growth curve for pool fire with applied water mist suppression has been developed with the computer modelling approach.

This paper will also review the existing tests that have been conducted to understand the efficiency of water mist to extinguish FLC pool fires. The existing tunnels that have been designed with water mist system and these under design and construction are also presented as secondary reference.

EXISTING FIRE TESTS

Though fire tests comprising small droplets nozzles were carried out at factory Mutual since 1940s, it was not until 1990s that this technology started to draw attention [1]. NFPA 502 – 2020 Appendix E compiled some existing tests with fixed water-based systems in road tunnels [2]. There are seven reported water mist tests on class B (flammable liquid) fires referenced in NFPA 502.

Car fire tests in a tunnel mockup with mist suppression were completed in Switzerland in 2003, and full-scale HGV fire tests at San Pedro de Anes (Spain)[3] and the Runehamar tunnels (Norway)[4-7] are among the most widely referenced ones.

According to Fernandez [3], the tests at the Center of Experimentation "San Pedro of Anes" which is a 600 m tunnel with a removable false ceiling for reproducing different ceiling heights and ventilation conditions, has recorded a ceiling gas temperature decrease from 720 °C to 70 °C in test #2. Analysis has shown that the fire HRR can be controlled to no more than 30 MW.

Cesmat et al [8] reported in a paper at the ISTSS conference 2008 that the model tests have shown the water mist can effectively control the class A and class B fire, with the peak HRR decreased by 70% within 30 seconds upon activation of the water mist Fixed Fire Fighting Systems (FFFS).

In 2008 Kristen Opstad and Thai Trung Mai of SINTEF reported water mist tests in Runehamar Tunnel in Norway [9], where heavy goods vehicle and 100 m^2 pool fires filled with diesel oil on top of water were used as fuel for a potential fire HRR of 200 - 250MW. These tests have shown that water mist can control class A and class B fires effectively.

Lakkonen M, Feltmann A and Sprakel D [10-11] reported water mist fire suppression on pool fire and compared the performance of low-pressure deluge system and the high-pressure water mist system.

This paper will reference SINTEF test report, to back calculate the pool fire heat release (HRR) development curve based on its test case#6, to confirm the effectiveness of the pure water mist system[12] for controlling the FLC pool fires, so that the fire suppression system can eliminate the Aqueous Film Forming Foam (AFFF) additives and avoid the environmental concerns.

FDS FIRE MODEL

CFD simulation has been performed to understand the gas temperature with water mist suppression for the other project, where the highway is trenched and covered with a lid which results in a short tunnel. CFD model was setup using the Fire Dynamics Simulator[13]. The prevailing wind and traffic developed airflow, which is represented by a 4 m/s velocity, was considered at the portal.

As shown in Figure 1, the tunnel has a cross section area 8.5m wide x 5.4m high and 245m long. For the portion of the tunnel considered for the CFD model, total number of mesh is 570 x 34 x 27 along the length, width, and height direction, respectively. Total required CPU time is approximately 72 hours with 4 processors running in parallel to complete 300 seconds fire time.

Water mist fire suppression employed a high-pressure system, detailed mist parameters of Test #6 detail in SINTEF report[5] are shown below in Figure 1.

To modelling the test #6 and back calculate the HRR growth, the pool fire was simulated with a 25m long and 4m wide uniform heat source, which generate of maximum heat release rate of 2500 kW/m^2, which represent a FLC pool fire of 100 m^2 with a bi-linear growth rate of 5 MW/minute during the first 30 seconds, then grows at 165 MW/min to 250 MW for unsuppressed free burning condition. When water mist is applied at 166 seconds as shown in Figure 2, the pool fire can be effectively controlled and its HRR will decrease to approximately 25 MW within 20 seconds. The fire HRR will further decrease to 0 at 240 seconds, and the fire has completely extinguished.

Water application rate: 4.0 mm/min.
liquid pool area: 100 m²
pure water mist, 0 AFFF
spacing of nozzles: 3.0m x 3.5m
Rows of nozzle: 3 rows along the tunnel
flowrate per nozzle: 42 L/min
pressure at the nozzle: 30 bar = 435 psi
droplet size: Dv0,9= 200 microns
mist droplet discharge velocity: 60 m/s

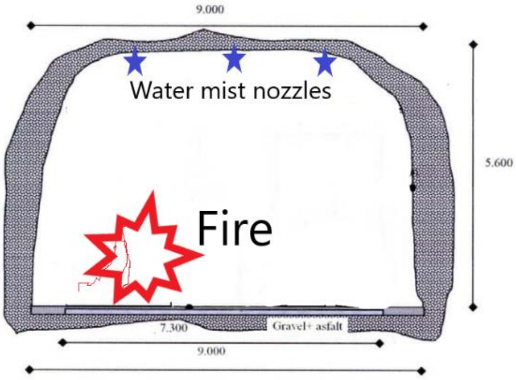

Figure 1: Cross section of the Runehamar Tunnel

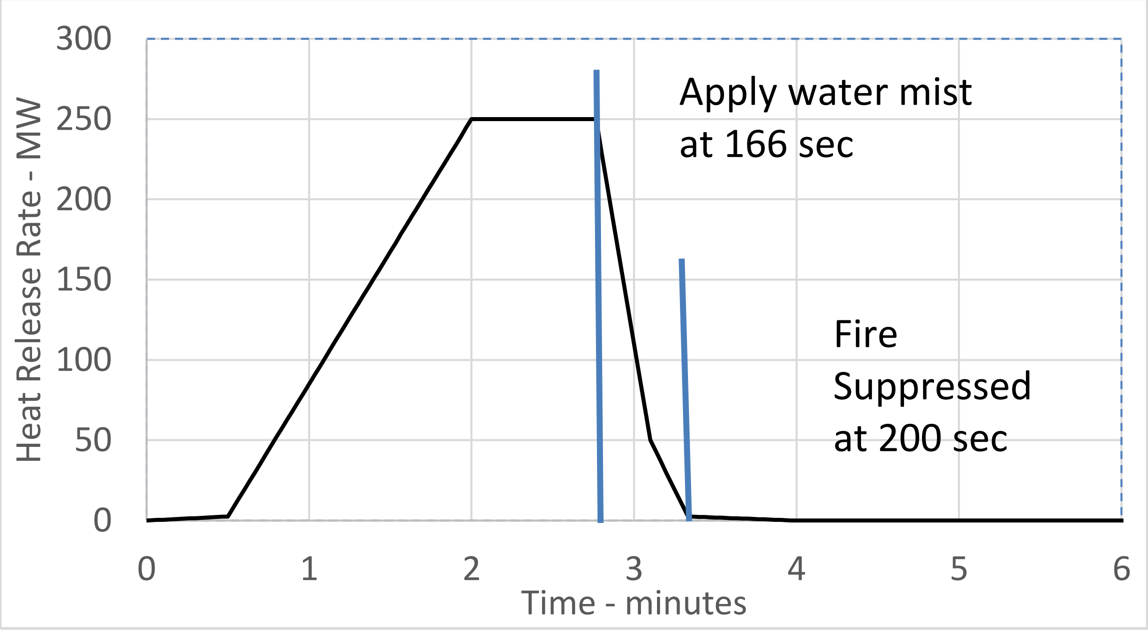

Figure 2: FLC Fire HRR curves with water mist suppression of Test #6 of SINTEF report[5]

Transient gas temperatures recorded at CFD model test locations are shown in Figure 3A and compared to the experiment tested temperature curves in Figure 3B (only curve 18 which recorded the highest temperature in Figure 3B, has been used here for comparison). The CFD model obtained gas temperature agrees well with the tested temperature of 1100 °C which is recorded at 4.5m above the fire. This has not only validated the CFD model, but also back calculated the HRR growth curve, which can be used as a reference design fire HRR curve for the FLC pool fire with water mist fire suppression. The CFD model has demonstrated that high pressure water mist can serve as an effective tool to control the FLC fire and without the need of any addition of AFFF.

Figure 4A and 4B compare the FDS modelling Oxygen concentration at 142m downstream of the fire and 0.4m below the tunnel ceiling with measurements from the SINEFF test. The oxygen concentration decreased to approximately 10% when peak HRR is reached during 120 sec – 180 sec. The CFD model agrees with Runehamar test result well. Red curve in Figure 4A for O_2 represents the Oxygen concentration measured in the tunnel test at 142m downstream of the fire, which agrees well with the modelling results as shown in Figure 4B. The oxygen concentration is reduced to 10% at the time of the peak hear release rate.

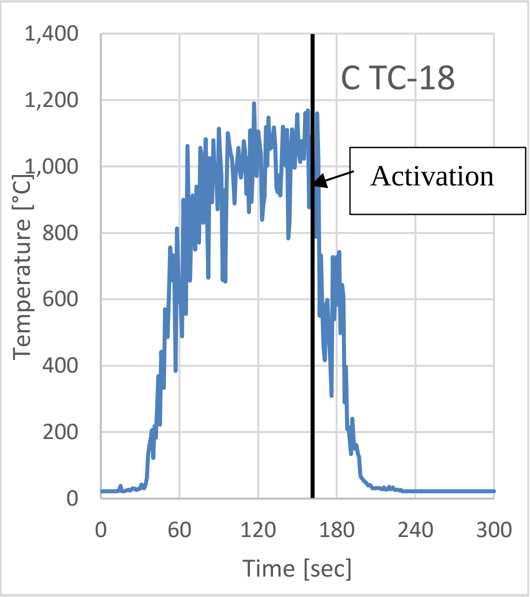

Figure 3A: CFD record gas temperature at 18

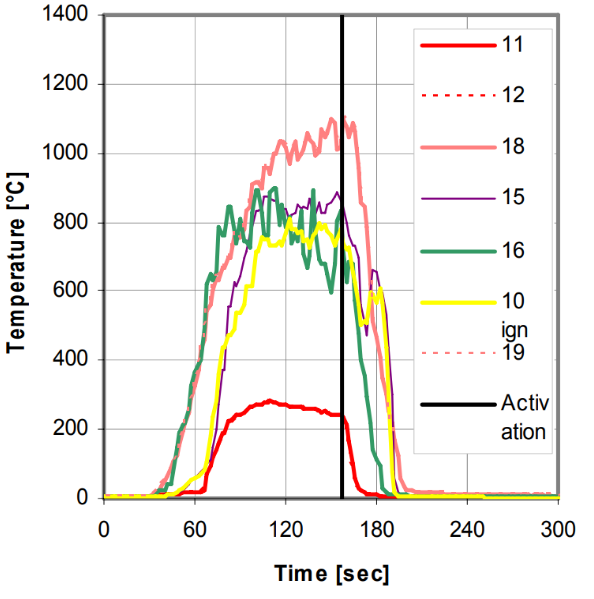

Figure 3B: SINTEF tested gas temperature

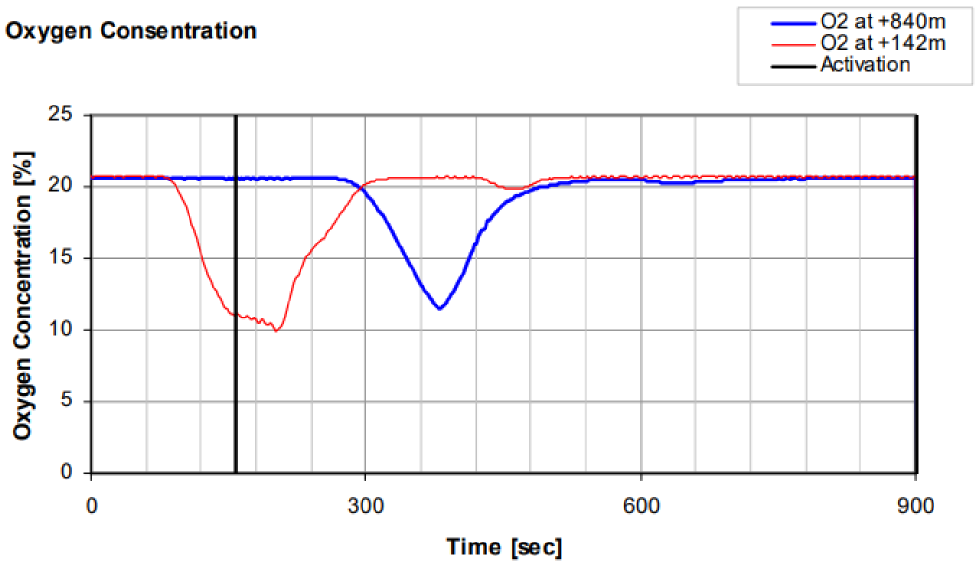

Figure A1, 84 *Test No. 6, Liquid pool, 100m2. Pure Water Mist (Date 20080109).*

Figure 4A: SINTEF tested oxygen concentration +142m downstream of the fire

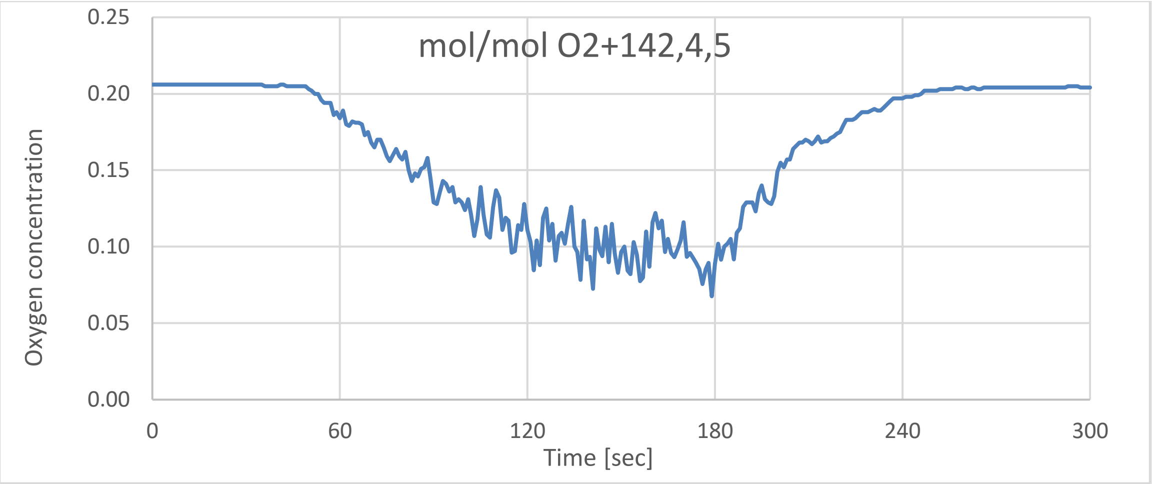

Figure 4B: CFD modelling oxygen (O2) concentration +142m downstream of the fire

FIRE HRR AND TUNNEL GAS TEMPERATURE

It is apparent that FLC pool fire growth rate is extremely fast in the Runehamar test. After the initial incipient stage, fire HRR grows at 165 MW/min since the flammable liquid pool has already spread out in the test case#6. The flammable liquid pool should be spread out gradually if there is a leakage from FLC vehicle. However, this test has established the worst fire growth rate and should be referenced when nominating a design fire for FLC fire case. The FLC fire peak HRR will heavily rely on the surface area of the flammable liquid pool and the tunnel fire/smoke detector's settings and performance, and these parameters will determine the activation time of high-pressure water mist system.

In order to understand the influence of specific tunnel on the fire detection time and its HRR, additional CFD modelling have been performed for Runehamar tunnel and an example tunnel project named NHHIP, to understand the influence of tunnel geometry on peak heat release rate and the maximum gas temperature under an ideally developed 100 m^2 pool fire. Table 1 shows the cases and parameters that have been used in the two example tunnels, the resulting peak HRR is also given in the table. The difference between these two CFD cases and the test case #6 is that detection time is based on the heat detector's triggering time in these two CFD cases listed in Table-1. Both CFD case #1 and #2 consider a 4m/s longitudinal ventilation and with water mist suppression activated with a 60 sec delay after the fire is detected.

Table-1: HRR and tunnel geometries

Case ID	Tunnel Name	Tunnel Width	Tunnel Height	Detector height	Detection time	Water mist discharge	Peak HRR
Case #1	Runehamar	8.5m	5.4m	5.2m	30 sec	90 sec	190 MW
Case #2	NHHIP	25.0m	6.8m	6.6m	32 sec	92 sec	200 MW

Figure 5 shows the HRR curve of a 100m^2 pool fire for Runehamar and NHHIP tunnel under water mist suppression which is activated with heat detectors. Since the tunnel width and ceiling height of the two tunnels are different, the fire detection time for NHHIP tunnel is longer, resulting in a higher peak HRR since the water mist application is a few seconds later than for Runehamar tunnel.

Figure 6 shows the recorded gas temperature at location #18 as indicated in the SINTEF test [5], which is 4.3m above the tunnel base, Runehamar recoded a maximum gas temperature of around 1000 °C and the NHHIP recorded 600-700 °C for the same pool size, though the peak HRR of the NHHIP tunnel is higher than that for Runehamar tunnel. This can be explained by the fact the NHHIP tunnel cross section area is approximately 4 times that of the Runehamar tunnel, especially NHHIP tunnel height differs by 1.4 m, which also can reduce the ceiling temperature, as it needs more energy to heat up the air-smoke mixture in the tunnel. This also explains why each tunnel would require performance-based design for fire and life safety and structural fire durability solutions.

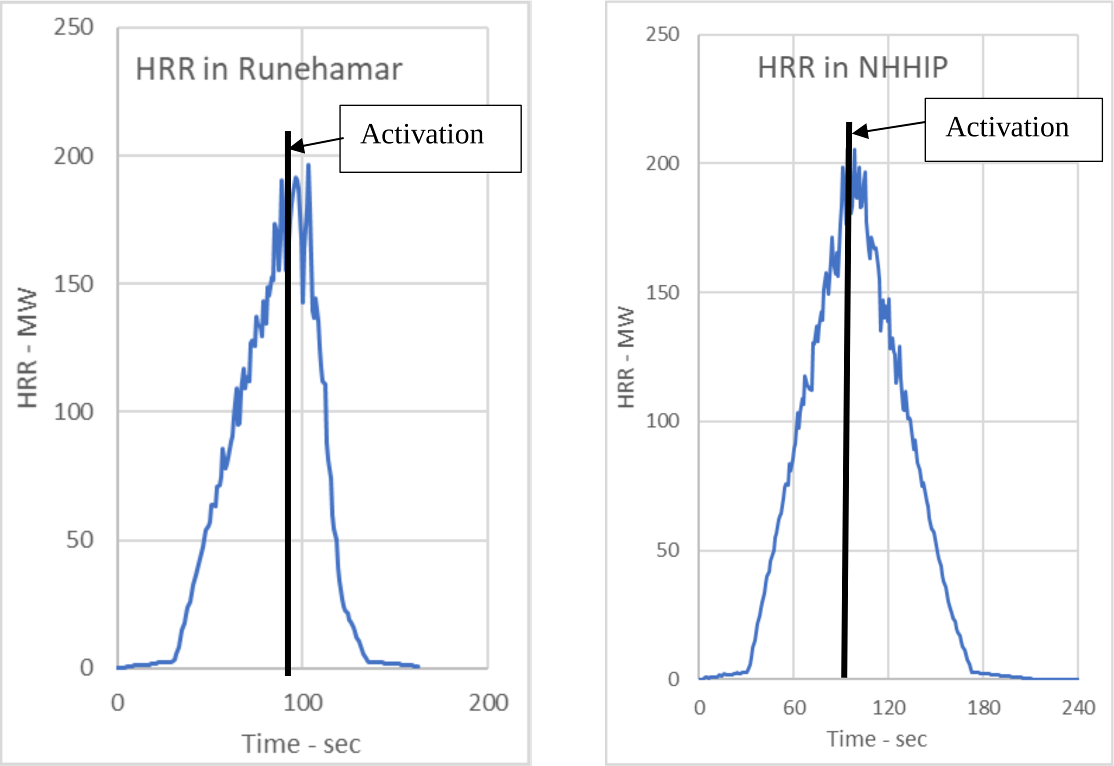

Figure 5: HRR curve of pool fire with water mist suppression in Runehamar and NHHIP

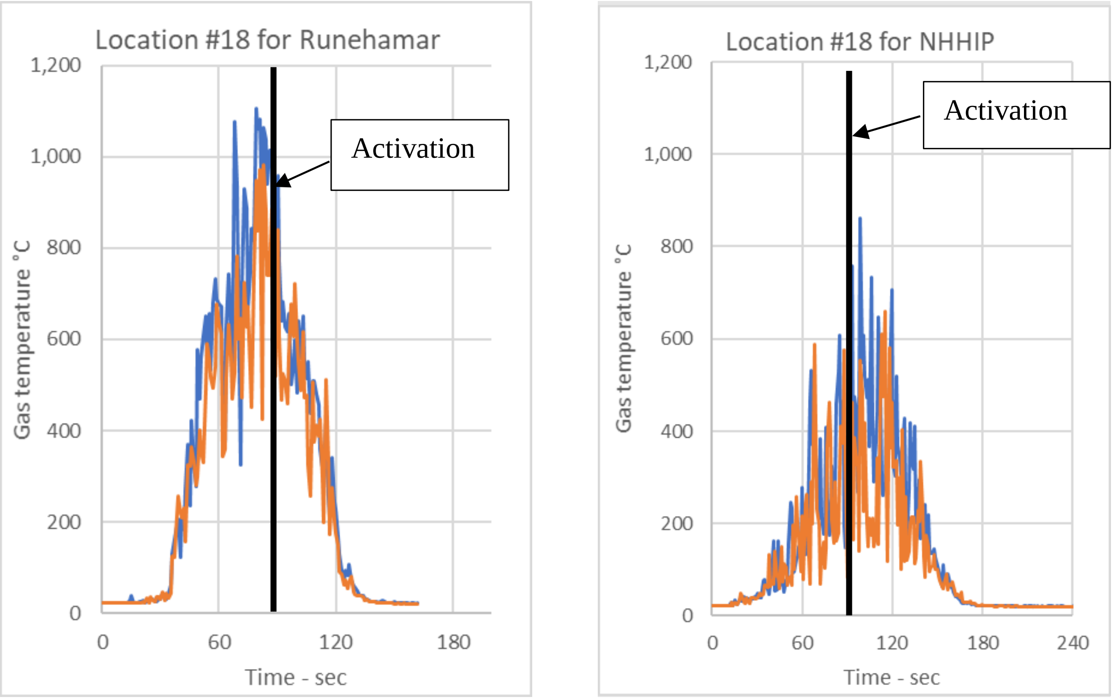

Figure 6: Gas temperature curve of pool fire with water mist suppression in Runehamar and NHHIP

DISCUSSION

With a heat detector setting of 68°C, a FLC fire should be detected at 40 seconds after fire starts (assuming a linear fire growth rate 20 MW/Min.), if a delayed operation of water mist by 60 seconds is assumed, the FLC fire can develop a 250 MW fire at 120 seconds for a well-established flammable liquid pool. However, a more realistic condition is a case that its growth rate would be slower because the fully developed liquid pool in the mockup test is ideally setup which resulted in a maximum growth rate. In an actual situation, if the road surface is sloped or the drainage are available, some of the liquid may have been drained away leaving a limited size of the liquid pool. However, in the test situation the pan filled with flammable liquid itself make it easier to extinguish the fire, and in real cases it may worsen it due to interaction of the unforeseen boundary conditions, and its initial HRR development is slower as discussed in the FDS fire model section of this paper. A fire growth rate of 20MW/minute has been proposed for the NHHIP project. Figure 5 shows a design fire growth curve used in NHHIP project, if assuming the water mist can start operation 60 seconds after fire detection which happens at 15 seconds of the FLC pool fire starts, the water mist discharge can operate at full capacity at 105 seconds, and its peak HRR is capped at 35 MW at 105 seconds after fire starts.

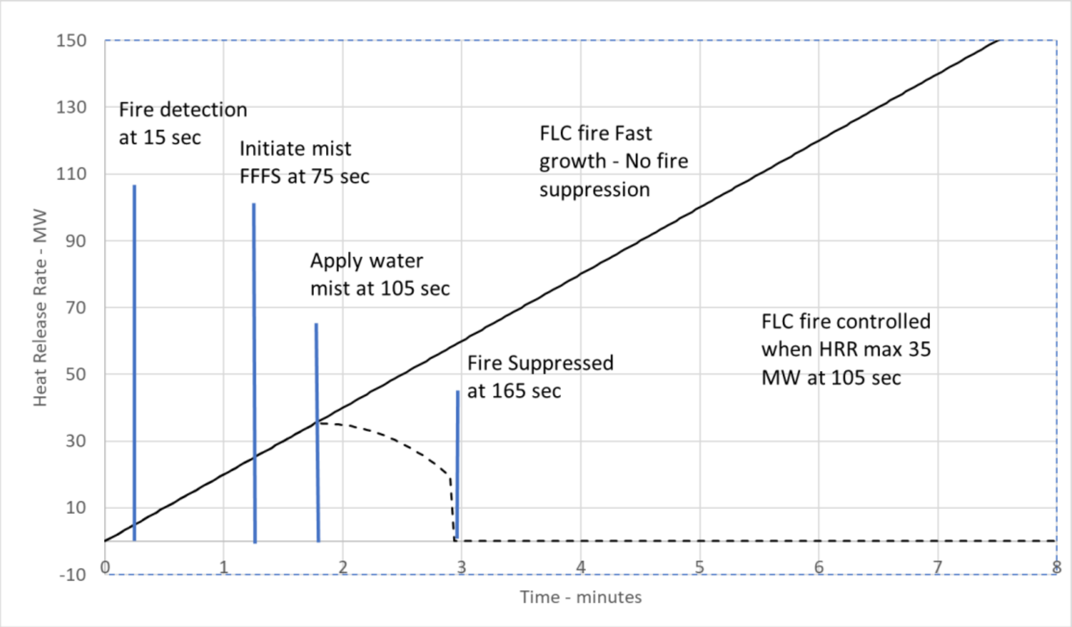

Figure 5: Design fire used in NHHIP Project

Water mist systems which utilize pure water can eliminate environmental issues associated with foam suppression systems. Furthermore, it has been shown to be as effective as deluge systems where large water droplets are involved [5]. However, for shielded HGV fires, e.g. under a tarpaulin if it not burned away, its fire cannot always be effectively controlled by deluge systems. Water has a high density forcing the water to penetrate through the flammable liquid fuel, allowing the fuel to layer on top of the deluge water where it can remain as part of the combustion process. Deluge water droplets also have larger diameters, taking longer to evaporate, making them not as effective as water mist to cool the tunnel structure and airborne combustibles.

On the other hand, water mist can be a promising solution for controlling FLC fires in roadway tunnels if properly designed. Most importantly, the amount of water required for fire suppression can significantly be reduced.

Water mist is effective in interrupting the oxygen supply, resulting in a reduced combustion process, and therefore reducing the convective heat transfer and decreasing the associated temperatures of adjacent fuel materials with reduction in pyrolysis. The mist can also absorb or block radiative heat transfer to adjacent fuel materials therefore resulting in reduction in pyrolysis, slowing down the combustion. Mist is also effective at reducing fire hazards in the vicinity, and the temperature reductions improving tenability and may coalescing smoke particles out of the air.

Based on the existing tests and CFD results shown in Figures 2, 3A, 4B, the heat release rate has been back-calculated based on the test measured temperature curve in test case#6, CFD modeling of the test results have demonstrated that water mist exhibits satisfactory performance on FLC fires in the test environment. The design fire peak HRR of FLC relies on detection which determines the time when water mist is to be applied on the fire. Furthermore, development and formation of flammable liquid pool needs time when a FLC leakage happens, and the road slope as well as the availability of drainage system will also significantly impact the size of the flammable liquid pool, compared to an ideally developed pool fire, which may have a decisive impact on peak HRR. Therefore, in a field scenario, FLC fire may not always be able to develop into a 100 m^2 liquid pool and result in a fire as high as 250 MW.

CONCLUSION

Water mist is effective in controlling FLC pool fires, its HRR growth rate can be as fast as 165 MW/min after the incipient stage. However, peak HRR of FLC fire with water mist operation is highly dependent on the fire detection time, size of the existing flammable liquid pool when the fire started. Currently, application of water has been proposed for some new projects, such as Hugh L. Carey Tunnel Manhattan in New York, and Houston Highway lid project in Texas. An incomplete list of the tunnels in the world has been listed below for reference.

EXISTING WATER MIST APPLICATION IN TUNNELS

As of 2022, The following tunnels uses the water mist system:

- Mona Lisa tunnel (775 m, Austria, installed in 2004)
- Felbertauern tunnel (at an altitude of 1632-1650m, exposed to temperatures of -30°C at cold winter in Austria, 5034m long, high wind speeds up to 1968 fpm, i.e. 10m/s, system installed in 2006)
  (Note: the Felbertauern tunnel and the Mona Lisa Tunnel have both been existing tunnels which have been retrofitted with water mist systems.)
- Roermond tunnel, NL, and Tunnel Swalmen, NL (A73, Roermond tunnel is 2.45 km long, longest road tunnel in Netherlands; a sister tunnel, Tunnel Swat men, 400 m long; both are new tunnels and installed mist system in 2008)
  (Note: both tunnels are equipped with mist systems to allow dangerous goods passing through)
- Tunnel A73 Swalmen, Netherlands, 0.4km, new twin bore tunnel, 3-lane each bore
- Öresund Tunnel DK-SE (service gallery only)
- Virgolo tunnel (887m, dual lane, main link through the Alps from Italy through Austria to Germany, especially for cargo transport, 30% traffic is Heavy Vehicles, Italy)
- Critical sections of M30 Tunnels, Madrid (2006, Spain)
- Silver Forest Tunnel (Moscow, Russia, 2.1km, 2006)
  (The tunnel design comprises two parallel tubes, each measuring 2.1km long with a diameter of 14.2m and double-deck construction)
- New Tyne Crossing (Newcastle, UK, 2009)
  (Two under-river tunnels are the vital part of the Tyne and Wear Road network)
- Dartford crossing (M25, London K, 2 tunnels, 1.43 km, 2010)
- Train tunnel projects (metro Budapest, Hungary)
- Eurotunnel (channel tunnel), France/UK
- Cable tunnels in various countries
- A86 Duplex Tunnel in Paris (road tunnels) 2005-2009
- 2 x NDIA Taxiway tunnels (road tunnels, 2x340m), 2009-2010, Qatar

- Helsinki Service Tunnel (road tunnels, 850m; 2000m) 2009-2010 Finland
- City Tunnel A14 Bregenz, Austria, 1.4km, refurbished in 2014
- Arlberg tunnel, St. Jakob, Austria, 14km, refurbished in 2017
- Tunnel A1 Liefering, Salzburg, Austria, 0.55km, refurbished in 2017
- Main Tunnel Heathrow Airport, UK, 0.65km, refurbished in 2021
- Thu Thiem Tunnel, Hoo Chi Minh City, Vietnam, refurbished in 2022
- Koralm Tunnel, Austria, 0.9km, new tunnel under construction (expected to complete soon).
- Hugh L. Carey Tunnel Manhattan, NY, USA (expected to complete soon)

ACKNOWLEDGEMENT

The authors would like to acknowledge that the paper has included the input from the conversation with Helmut Kern of Aquasys. Discussion with HNTB colleague Ralph Trapani on reference projects and a final review of the paper by Dave Parker of HNTB are kindly acknowledged.

REFERENCES

1. Ragnar Wilghus, Bettina McDowell, Water mist technology – history, effectiveness and efficiency, Asis Pacific Fire, page 27-28, Issue 45, wwww.iwma.net.
2. NFPA 502 - 2020, Standard fot Road Tunnels, Bridges, and other limited access highways.
3. Fernández, S.; Del Rey, I.; Grande, A.; Espinosa, I.; Alarcón, E, Large Scale Fire Tests for the "Calle 30 Project", Fifth International Symposium on Tunnel Safety and Security, New York, USA, March 14-16, 2012, page 429 -438.
4. Ingason Hakur and A. Lönnermark, "Heat Release in Tunnel Fires: A Summary," Handbook of Tunnel Fire Safety, 2nd edition, 2012
5. Ingason, H., Y. Z. Li, and A. Lönnermark, Tunnel Fire Dynamics, Springer, 2015.
6. Ingason H, Li Y.Z, Bobert M., "Large scale fire tests with different types of fixed firefighting system in the Runehammer tunnel", SP Report 1026:76, SP Technical Research Institute of Sweden: Boras, Sweden
7. Yingzhen Li, Haukur Ingason, "Use of water-based Fixed Fire Fighting Systems in Tunnels", Fire protection engineering, magazine.sfpe.org, Q2 2019, Page 18 -22
8.Cesmat, E., et al., Assessment of Fixed Fire-Fighting Systems for Road Tunnels by Experiments at Intermediate Scale, 3rd International Symposium on Tunnel Safety and Security, Stockholm, Sweden, 2008.
9. Kristen Opstad, Thai Trung Mai, Real-scale tests of Aquasys Water Mist Fire Suppression System in Runehamar Test Tunnel, Norway 2008. SINTEF NBL Report No. NBL F08113
10. Lakkonen M, Feltmann A and Sprakel D, "Impact of AFFF to the Performance of Fixed Fire Fighting Systems in Tunnels", Seventh International Symposium on Tunnel Safety and Security, Montréal, Canada, March 16-18, 2016. Page 271
11. Lakkonen, M., A. Feltmann, and D. Sprakel, "Comparison of Deluge and Water Mist Systems from a Performance and Practical Point of View," Graz, Austria, 2014
12. NFPA 750, Standard on Water Mist Fire Protection Systems.
13. FDS Users Guide, National Institute of Standards and Technology, NIST.