Optimisation of ventilation systems costs by using fixed fire fighting systems (FFFS) in tunnels

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ABSTRACT

This paper discusses the efficiency of fixed fire fighting systems (FFFS) in conjunction with ventilation systems in road tunnels in case of fire. The paper presents shortly two most used FFFS types, water mist and deluge systems. The interface between FFFS and ventilation systems is discussed in theory and demonstrated also with a full scale fire test results. The experimental results were collected in the SOLIT² research project that was carried out 2009-2012. This research program was so far the largest focusing on using FFFS in combination together with other safety measures.

KEYWORDS: tunnel, fixed firefighting system, ventilation, compensation

1 FIXED FIRE FIGHTING SYSTEMS (FFFS)

Fixed fire fighting systems (FFFS) mean active way to fight fires in tunnels. There has been already number of high-profile tunnels in Europe where FFFS is the key part for fire and life safety systems. There are two main streams in terms of used technologies in tunnels; A. Low-pressure deluge systems (often called as "sprinkler systems") and water mist systems (normally applying high-pressure). So far 17 tunnels are equipped or under installation with FFFS in Europe. 13 of them are with water mist system and rest mainly with deluge systems.

Deluge systems

Low-pressure deluge systems have been applied longer time e.g. in Japan, USA and Australia having a very wide range of design basis (6-21mm/min). This is mainly due to missing fire tests, typically system designs have been done decades ago with design fire sizes of 25-30MW maximum. The application rates have stayed same although modern design fires are multiple times higher. This has been also on reason why deluge systems have been tested in order to see the performance in full scale tests. The following is the list of known fire tests with modern HGV design fires:

Figure 1 FOGTEC Deluge System

- FOGTEC Fire Protection 2011, comparison tests of deluge and water mist systems
- Land Transport Authority (LTA) 2013, deluge system fire tests
- Tunnel Mont Blanc 2012, comparison fire tests high-pressure water mist, low-pressure water mist and deluge systems
- FOGTEC Fire Protection 2012, fine spray deluge system fire tests with/without AFFF
- SP 2013, deluge system tests

The results from the deluge tests have been very limited reported to public so far. But it has been noted that deluge systems can provide also a good performance especially in terms of prevention of fire spread, life safety and safety of fire services. The data for tunnel structure protection is still very limited. Also dangerous goods, as Class B fires, have been tested very limited. The fire tests also suggest that performance of deluge systems is strongly dependent on application rates, droplet distribution and nozzle lay-out. The common misconception is that deluge systems are alike but they also vary depending on the used nozzle head and its characteristics. Deluge systems have been noticed to have a positive impact to the ventilation design parameters as this paper presents the theory.

Water mist systems

Water mist systems are another main FFFS type especially researched and applied in Europe. The background of water mist is related to scientific research projects as the consequence of catastrophic fires more than a decade ago. Water mist was tested and developed first as part of European research projects UPTUN. Later on there have been other research projects like SOLIT and SOLIT[2]. Water mist has been also tested by number of other organisations or national institutes.

Figure 2 FOGTEC Water Mist System

- UPTUN water mist tests, 2005
- Paris A86 tunnel fire tests, water mist system
- M30 tunnel fire tests, water mist system
- Madrid Fire Service fire tests 2006, water mist system
- Marioff 2006. water mist fire system
- SOLIT research project, 2006 water mist systm
- Rikswaterstaat A73 tests, water mist system
- Private tests by LPWM manufacturer 2009, water mist system
- Eurotunnel fire tests, water mist system
- Dartford tunnel tests, water mist system
- FOGTEC 2011, water mist system
- SOLIT2 research project, water mist system
- Tunnel MontBlanc 2012, comparison fire tests high-pressure water mist, low-pressure water mist and deluge systems
- FOGTEC 2012, water mist system

Water mist systems, similar to deluge systems, have different fire fighting performance depending on the application rates, nozzle characteristics and lay-outs. This make comparison of the difficult as different nozzles / manufacturers can have different results.

INTERFACE BETWEEN FFFS AND VENTILATION

The interface between FFFS and ventilation is relatively well studied with experimental tests. The positive impacts have been presented for example by Leucker & Kratzmeir („Brandversuche zu Wassernebel-Brandbekämpfungsanlagen“, Tunnel 8/2011). The possibility to downsize ventilation system design in new build tunnels or upsize the capacity of existing ventilation in refurbishment project when FFFS is applied. This is also accepted by most of standards, also by NFPA502 2014 edition. When the interface between ventilation system and FFFS is discussed it can be divided to two aspects, FFFS impact to design fire size and FFFS impact to convective heat transfer. These are shortly explained in following.

FFFS and the ventilation design fire size

Previous research projects have shown that FFFS are very effective to fight and suppress fires to portion of size compared to being unsuppressed. This is the most important impact for the ventilation system as the initial design parameter in terms of HRR can be significantly reduced. For example SOLIT2 research project results suggest that heavy goods vehicle (HGV) fire loads with over 150MW potential HRR were suppressed with FFFS to maximum 20-40MW HRR. Such results have been achieved with both water mist and deluge systems. If design fire is suppressed to a smaller value, this can be utilised when dimensioning the ventilation. The design HRR can therefore be significantly reduced compared to fires without FFFS. Very important aspect is that typically design HRR for ventilation systems is given assuming that only one vehicle is involved to fire. There is very likely possibility that fire will spread to other vehicles during the self-rescue phase in tunnels. Applying FFFS is noticed to limit fire spread to other vehicles when dimensioned correctly. There are number of ways FFFS fight and suppress fires. The most important ones are cooling the pyrolysis and fuel itself by wetting. Additionally FFFS, especially water mist, can apply localised oxygen displacement.

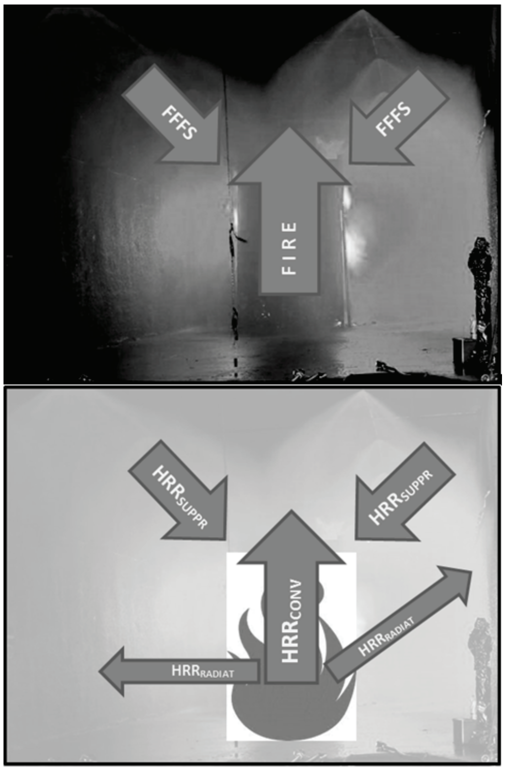

Figure 3 Heat release rate

FFFS and impacts to convective heat transfer

The total heat release rate, $HRR_{TOTAL,}$ can be divided to sub parts which define the effect HRR that ventilation system needs to be able to cope with. The total HRR is often called also a chemical $HRR_{CHEMICAL}$ that is created in the combustion of fuel. A part of total heat release rate will be absorbed by the tunnel structure or other equipment due to heat radiation HRR_{RADIAT}. The second part, much more significant, will be absorbed energy by the FFFS. This HRR_{FFFS} can absorb a significant part of the energy depending on the flow rates used and portion of evaporation. The remaining energy of combustion will be transferred to combustion gases and further to surrounding air. This convective HRR_{CONV} is the effective HRR that has the ventilation system needs to operate with.

$$HRR_{TOTAL}\ (HRR_{CHEMICAL}) = HRR_{RADIAT} + HRR_{FFFS} + HHR_{CONV} \quad (1)$$

The impact of FFFS in terms of cooling and absorbing the energy depends on the FFFS type and flow rates. The most important is the evaporation rate of the system as it defines the cooling energy. The total heat absorption effect can be calculated with following equation.

$$\dot{Q_{water}} = \dot{m} \cdot (c_p + H_r) \quad (2)$$

$\dot{m}$ = Water mass rate for evaporation (kg/s)
c_p = Specific heat for water (4.1831kJ/kgK @ 25°C)
H_r = Heat of water vaporisation (2260kJ/kg)

As equation (2) shows the evaporation of water absorbs the most; therefore water evaporation mass rate is in the decisive factor when the effect of FFFS is calculated for the total HRR. When different FFFS are compared, smaller droplet sizes provide much larger reaction surface and therefore provide more effective evaporation. This suggests water mist systems are more effective in cooling because of higher evaporation rate. This can be partly compensated with much higher flow rates of deluge systems.

FFFS and ventilation design process

There are number documents like German RABT, North American NFPA502 and British BD 78/99 that define tunnel ventilation design process. However it is important to understand the difference between the design processes applying the effects described above. A simplified (fire) ventilation design process with main pros and cons are described below.

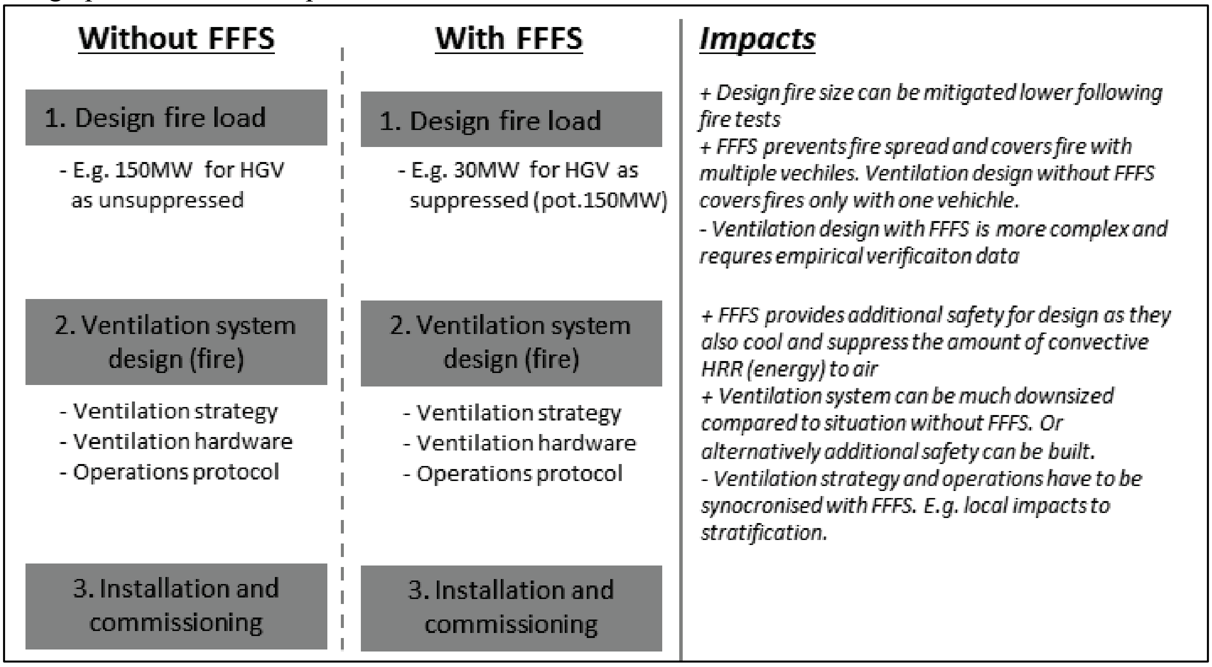

Figure 4 Simplified ventilation design process

FFFS enhanced ventilation because design fire can be sized completely different. It is important to assess the experimental data achieved from the full scale verification fire tests. FFFS can provide also additional safety as the fire will be limited to only one vehicle, which is just the expectation with normal ventilation design. Additionally FFFS can give additional safety as it is known that convective HRR will not be as high as used for the ventilation dimensioning process. This is due to the energy absorption effect of FFFS.

EXPERIMENTAL RESULTS TESTING VENTILATION SYSTEM WITH FFFS

SOLIT² Research Project

The experimental results shown in this chapter have been measured as part of the SOLIT2 research project. The full scale fire tests were carried out in the San Pedro des Anes test gallery in Asturias, Spain. Test program included over 30 full scale fire tests in order to test the efficacy of FFFS in conjunction with the fire ventilation system in road tunnels. Half of the test fires were executed as class A (solid) fires involving complete lorry-loads (fire load consisting of wooden pallets with a potential heat release rate (HRR) of over 100 MW) the other half as class B pool fires (fire load consisting of diesel fuel with HHR ranging from 30 to over 100 MW).

The research project “Safety of Life in Tunnels 2” (SOLIT²) started in 2009 with the aim of investigating the interaction between FFFS water mist fire suppression systems and other road tunnel safety equipment as e.g. the fire ventilation. It had to be examined how safety measures like the fire ventilation could be compensated by the use of a FFFS. Beside the improvement of the technical safety installations the project also focused on the development and validation of simulation tools for the mathematical-numerical appraisal of the interaction between water mist, fire and ventilation.

The project ended in 2012 and was partly funded by the federal Ministry for Economics and Technology as a result of a decision by the German Bundestag. The results and reports are publically available from www.solit.info.

Fire tests arrangements

Fire test tunnel

The SOLIT² fire test series was carried out in the test facility TST (Tunnel Safety Testing) located in San Pedro des Anes, Asturias, Spain. The available tunnel, only build for test purposes, has a total length of 600 m and a longitudinal slope of 1 %. The shell construction has a horseshoe cross-section typical for road tunnels (9,55m wide and 8,10 m high). But for most of the length the tunnel is equipped with an intermediate ceiling which limits the height to 5,2 m in the tunnel. This ceiling is protected by a structural fire protection and serves to build up an exhaust duct for the semi-transversal ventilation system.

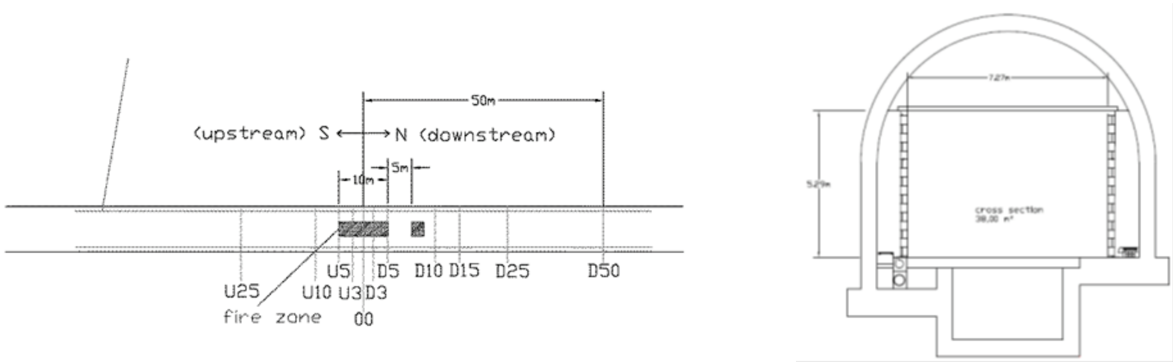

Figure 5 Top view on the test tunnel with measurements positions, Cross-section drawing of the test tunnel

In addition to the intermediate ceiling the tunnel is equipped with additional side walls in order to protect the tunnel from excessively high temperatures within the fire zone, these walls are indicated in the drawing above and limit the cross-section to a width of 7,25 m. Behind of one of this walls there was space to install all the measurement equipment.
In order to unify the naming of different measurement areas, the middle of the fire load was defined as 0 for all distances along the tunnel axis. In the direction of the prevailing longitudinal ventilation direction all positions were called “D” for downstream + the corresponding distance in m. Against the direction of the air flow all positions were called “U” for upstream + the corresponding distance in m.

Ventilation system

The test tunnel is equipped with systems for longitudinal and semi-transversal ventilation. The longitudinal one is powered by 6 jet-fans attached to the tunnel ceiling within the horseshoe section in the beginning of the tunnel, velocities between 1 to 6 m/s can be achieved. The semi-transversal ventilation system is build up in a ventilation station with 2 axial fans which can extract 120 m³/s. This air flow will be extracted through 14 dampers which are installed in the intermediate ceiling between the tunnel and the exhaust duct above, each damper has a cross-sectional area of 1,5 m². This set up of the semi-transversal ventilation is designed to exhaust the smoke volume of a fire with a Heat Release Rate of 30 MW.

FFFS

For the tests a fixed firefighting system, type high-pressure water mist, was installed in the test zone over a length of 60 m covering the tunnel from D30 to U30. The 2 branch lines of the system were fixed to intermediate tunnel ceiling and were fed via a main supply line located in the exhaust duct above. The water supply was achieved by diesel driven pumps set up in a container beside the tunnel fed by 500 m³ water storage. The pressure and the flow rate of the pump were adjustable by controlling the revolutions per minute (rpm) of the engine. However, all major layout parameters of the water mist system were corresponding to the real installation in the tunnel, as e.g.:

- Type of the nozzle (Shape, K-factor, etc.)
- Nozzle lay-outs
- Angle of the nozzles regarding the vertical axis
- Distance of the nozzle to the fire load/carrier
- Pressure at the most remote nozzle

Measurement system

In order to measure and register all relevant parameters during a fire test, a measurement system with a total of 152 sensors was set up. Every 2 seconds measurement values from following type were recorded:

- Air humidity
- Air speed
- Air temperatures
- Gas concentrations (CO, CO_2, O_2)
- Heat Radiation
- Material temperatures
- Flow rate of the water mist system
- Pressure of the water mist system

Furthermore the tests were documented by photos and video recording (including Infrared cameras) in order to know the visibility conditions during the test. Before each fire test the weather conditions outside the tunnel were documented as well.
Some of the air measurement points were set very close to surfaces of the tunnel wall or ceiling that the obtained values could be also interpreted as surface temperatures even though the real surface temperatures were lower than the measured values.

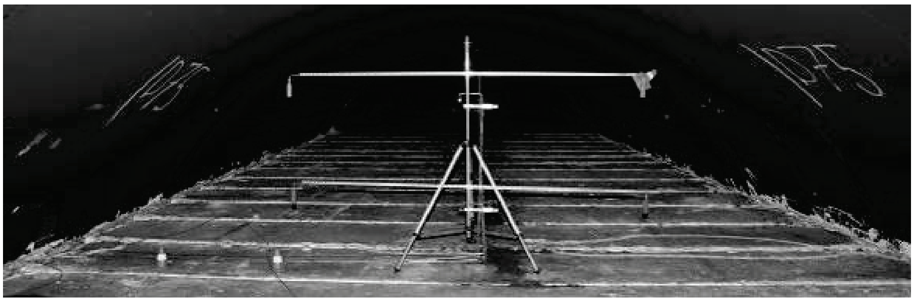

Figure 7 Gas, temperature and air velocity measurements in the intermediate ceiling

Class B / pool fire load

In order to obtain a uniform class B fire with a predictable Heat Release Rate multiple steel trays were arranged together to form one continuous surface. Depending on the desired HRR (e.g. 30, 60 or 100 MW) the according number of 40 cm high pools were arranged together and pre-filled with a 30 cm layer of water in order to protect the steel trays. The desired amount of diesel oil was put on top of the water and 1 litre of petrol was used to facilitate the ignition procedure.

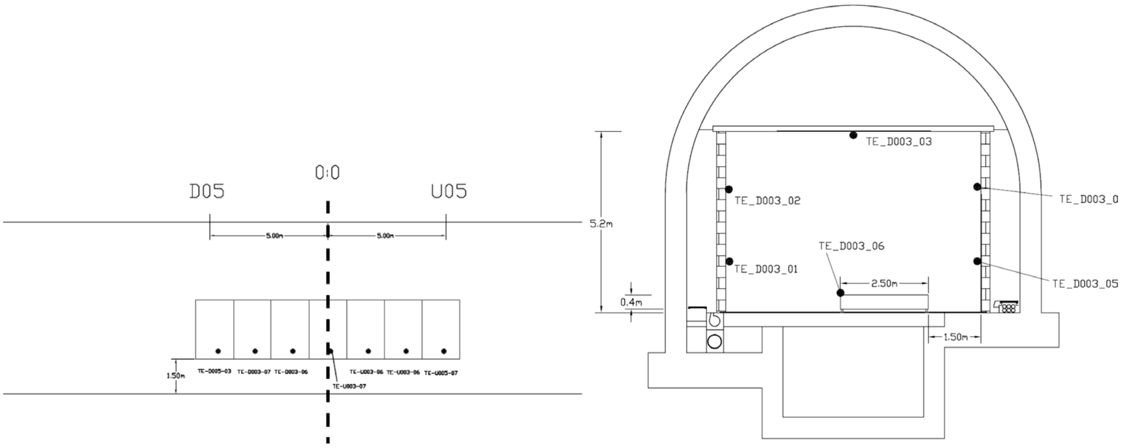

Figure 8 Pool arrangements for exemplary 60 MW fire test

Class B / pool fire load / Test Result

In the following the effectiveness of a water mist FFFS in conjunction with emergency ventilation is demonstrated with test results of a class B fire which had an actual HRR of 100 MW. The dimensioning of the ventilation system was configured to cope with a 30MW fire.

After the ignition of all the 17 pools; which were standing side-by-side and built together one surface to generate a minimum 100 MW pool fire; the fire growth was really fast as known for pool fires. The HRR reached the 100 MW after 90 seconds, the delay occurred because of traveling time of gases from the fire location to the gas concentration measurement in D45. The temperatures underneath the ceiling rose up to 1000°C in the fire zone within 60 seconds after ignition.

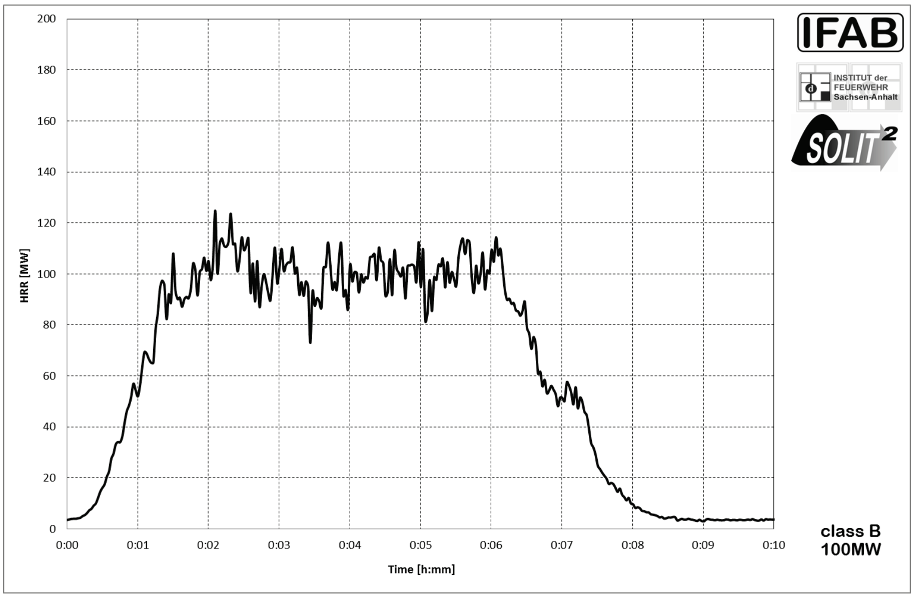

Figure 9 Heat release rate for a 100MW class B fire test

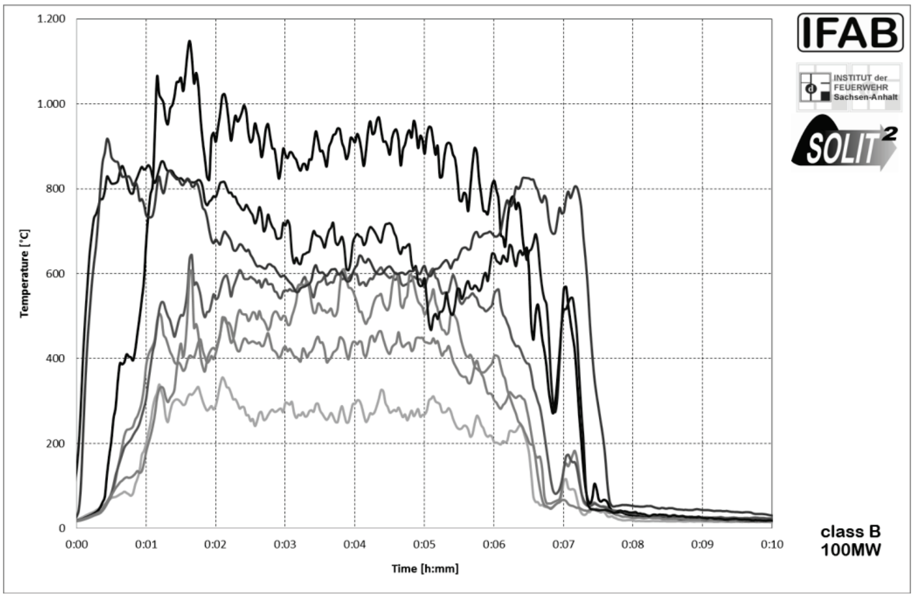

Figure 10 Temperatures near the fire zone at different heights during a 100MW class B fire test

In that time, the smoke volume produced by the fire was higher than the volume which could be managed by the combined ventilation system, although the extraction via the semi-transverse ventilation was already running as the fire was ignited. The longitudinal ventilation velocity was slower than the critical velocity which resulted in the observed “back-layering” phenomenon. This means that hot fire gases moved against the longitudinal flow of 3 m/s and caused a thick layer of black smoke in the upper sector of the tunnel on the upstream side of the fire. This observation could be proven by the increased temperatures in the upper section (in 5 m height, just underneath the tunnel ceiling in 5.2 m) of the tunnel cross section in 15 m distance (upstream) of the fire load centre.

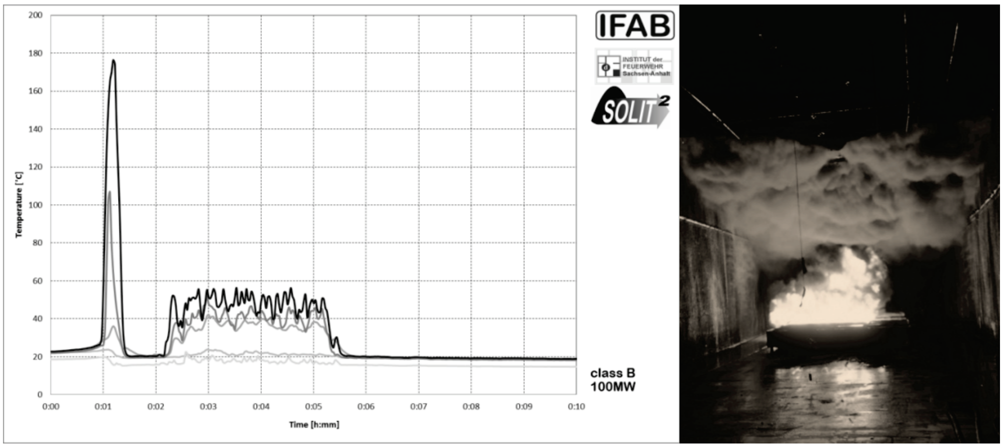

Figure 11 Temperatures 15m upstream due to “Back layering” during a 100MW class B fire test

Furthermore most of the smoke was led throughout the whole tunnel which could be proven by the measurement in D215, the air flow direction is positive and downstream with the longitudinal ventilation, the temperatures are higher than the ambient temperatures. Which means that hot smoke was led till the end of the test tunnel and out through the portal.

The Activation of the water mist FFFS was 60 seconds after ignition of the first pools and reached his full flow rate and system pressure after 100 seconds. After activation of the FFFS; the 100 MW Pool fire was supressed and furthermore manageable with the combined ventilation system designed for 30 MW fires.

The smoke output of the supressed fire was now lower than the extraction flow rate of the fire ventilation system (120 m³/s), which could be proven by the fact that back-layering disappeared and negative/upstream air flow occurred on the downstream side of the fire at D215 near to the end of the tunnel. This means that the exhaust volume was adequate to soak out the produced smoke volume and even more fresh air.

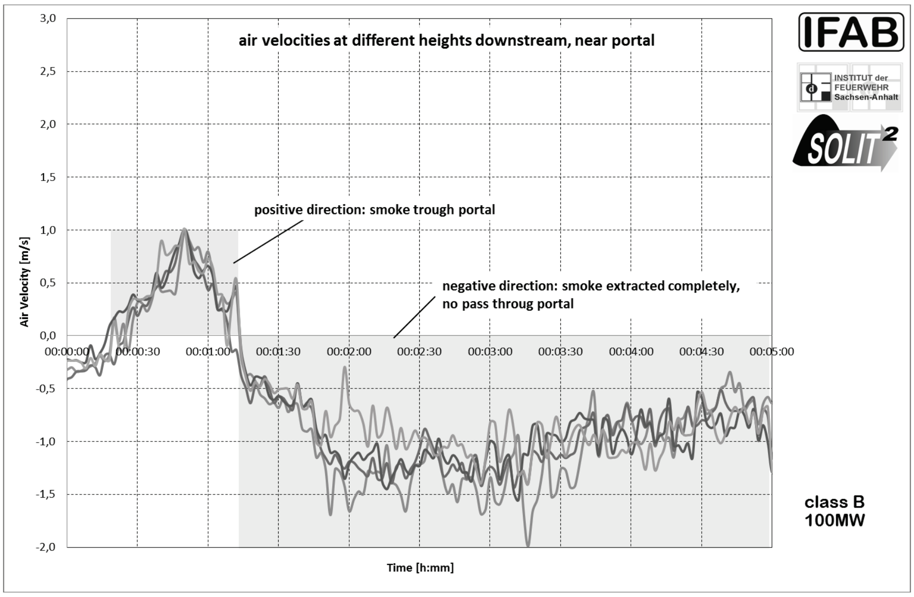

Figure 12 Air velocities near the downstream tunnel portal during a 100MW class B fire test

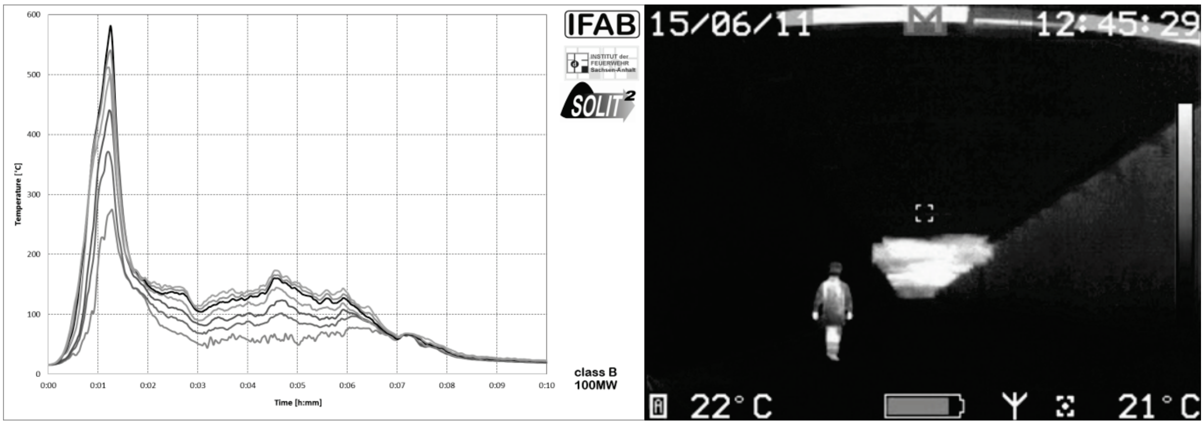

Figure 13 Temperatures 35m downstream the fire load during a during a 100MW class B fire and activated water mist system, Thermal image from downstream portal, shows a person entering the tunnel without any protective equipment and the hot gas layer during a 100MW class B fire and activated water mist system

Conclusion from fire tests
Fire tests showed in very practical way that:

1. Ventilation system capacity can be greatly enhanced by using FFFS as a mitigation method. Ventilation system design for 30MW fire without FFFS can control smoke of 100MW fire with FFFS.
2. Water as fire fighting agent is affecting by many means in fire zone resulting prevention of back-layering that had started before activation of FFFS.
3. Water mist is cooling very efficiently with high evaporation rate that is one of the main effects limiting convective heat transfer to air. For example air of 900 °C has a specific volume of 3.37 m^3/kg whereas air with 60 °C has 0.96 m^3/kg. The effects can be seen in measured air temperatures.

SUMMARY

Fixed fire fighting systems (FFFS) mean in practice deluge and water mist systems being applied to enhance tunnel fire safety. Both systems apply water and their performance is strongly related to used application rates, nozzle characteristics (droplets sizes) and lay-out. Water mist system generally use far less water and work more in gaseous level whereas deluge system apply more water and work on surface basis. Both systems have been used in real tunnels for longer times.

FFFS can impact positively to ventilation system design. The fact is that FFFS can reduce potential HRR by suppressing and controlling fire size to a portion compared to a free burning fire. Secondly FFFS fights against the output of fire, especially convective heat transfer, which is the primary design aspect for ventilation systems. FFFS, especially water mist systems, have been tested also experimentally in full scale fire tests for demonstrating the theory in practice. Presented results from SOLIT research projects showed that ventilation system design for a 30MW design fire was able to cope with 100MW pool fire when FFFS was applied. FFFS will be seen more in future as the mitigation method to assist ventilation designs.

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