# Experimental and numerical investigation of a vehicle fire with fixed-firefighting system

Stephan Klüh[1], Marie Kutschreuter[1], Frank Leismann[2], Max Lakkonen[3]

[1]Fogtec Brandschutz GmbH, Cologne, Germany
[2]STUVA e.V., Cologne Germany
[3]IFAB Institute for Applied Fire Safety Research, Berlin Germany
e-mail: stephan.klueh@fogtec.com

## ABSTRACT

Vehicle fires in underground car parks represent a big challenge for the fire protection systems of the facility, especially concerning modern vehicles that are getting larger and contain a higher amount of combustible materials. Adding the evolution of new energy carriers (NEC), like Li-Ion batteries, the challenge further increases. By prevention or slowing down the fire spread, fixed-firefighting systems can control a fire until emergency responders arrive. The current work was part of the research project “Safety of Urban Underground Transportation Areas considering New Energy Carriers” (SUVEREN) that aims among others to produce reliable data in order to support a performance-based design of such system. The use of both experimental and modelling tools is utilized in the analysis.

Major parts of this work have been fire tests including two of "vehicle mock-ups” in interaction with a water mist system. All fire tests have been performed at IFAB’s facilities in Northern Germany. Based on these, the vehicle fires were modelled including the suppression system. The experimental fire load consisted of wood pallets, which were placed inside the vehicle mock-up, thus being mostly covered by it. Gas temperatures and concentrations have been measured near the fire and inside the exhaust duct. The water mist system was activated manually and the heat release for the simulation was gained from a scale below the wood pallets.

Common water mist is on a micrometre scale, which makes it challenging to resolve in CFD modelling, thus FDS contains module for fire suppression using a Lagrangian particle approach to deal with this. Modelling the complete interaction of water mist with fire on a micro-scale remains impossible while keeping the scope of the approach of a performance based design analysis to be used for an entire car park. The results presented focus on the comparison and validation of the numerical model of the water mist system and using the experimental data to identify the current capabilities and limitations of mpodelling water mist in FDS from an industry application point of view.

## INTRODUCTION

The mobility sector is facing big challenges in both individual and public transportation, as the reduction of carbon dioxide and other greenhouse gases is becoming a political and social need. This enforces both new propulsion technologies and vehicle designs, leading to changes in the field of fire protection as well. In order to reduce a vehicle’s weight, combustible materials like plastics and composites often replace metal components. Therefore, the overall fire load of passenger vehicles has increased due to increased.

### Consequences for fire protection due to changes in the mobility sector

These trends described above have been analyzed during the SUVEREN project and lead to a design fire proposal for modern passenger cars that cover all common propulsion technologies [Kutschreuter2020].

Another result from the project is the introduction of performance-based design for assessing the fire risks and adapting the fire protection design in underground or enclosed car parks.. This suggestion shall complement current prescriptive standards like the German 'Muster-Garagenverordnung' [M-GarVO] or the internationally accepted NFPA 88A meeting the increased risks from larger fire loads and e.g. battery fires.

In Germany, fixed fire-fighting systems are mandatory in closed car parks, regardless if located on the ground or underground, only if there are buildings on top. Based on the results from the SUVEREN project, the installation of water-based fire-fighting systems is highly recommend for closed car parks in any case.

Fixed fire-fighting systems should be customized for the specific facility. Therefore, fire tests need to be conducted. As those tests are rather expensive, there might be the requirement and the intention to model the influence of water-based suppression systems in fire simulations. The current capabilities and limits of fire simulations including high-pressure water mist were investigated within the project based on two vehicle mock-up fire tests.

These fire tests that are described more in detail below were part of the first fire test series that was performed during the SUVEREN project. The focus of this research project has been on the burning characteristics of new energy carriers, mainly Lithium-Ion batteries but were accompanied by vehicle mock-up tests in order to close the gap from the propulsion system to the whole vehicle.

### Performance based design as a tool to deal with new energy carries

The SUVEREN project deals with several aspects of fire safety and offers solutions for a better understanding of risks caused by NECs and appropriate measures. The results related to car parks include the following:

- Performance-based design methods should be used for assessing the fire risks in car parks as modern vehicles are not covered by current prescriptive standards [Klüh2019].
- Vehicle fires can easily reach a peak heat release rate of around 7 MW while a fast fire growth rate has to be considered as well. The investigation of vehicle fires lead to the proposal of a new design fire curve, describing the heat release rate (HRR) of passenger vehicles, thus supporting a fire safety analysis with a conservative approach. The details of the time-dependent HRR are described in [Kutschreuter2020] and can be used for all types of vehicles, including electric vehicles driven by Li-Ion batteries.
- Preventing the fire spread from one vehicle to another is crucial in terms of fire safety in car parks, regarding both the structural safety and the safety of rescue services entering the building. Fixed firefighting systems, like high-pressure water mist, are a proven technology and are able to control a fire.

Moreover, this work describes the approach to the following question: *Can the modelling of water mist system in large models be used during performance design analysis and if yes, how?*

## FIRE TEST SET-UP

The fire tests of the two vehicle mock-ups included a fixed fire-fighting system based on high-pressure water mist. The behavior of the fire and especially the interaction with water mist is recorded  temperature and gas measurement inside the calorimeter and the exhaust duct.

The calorimeter that was developed for the battery fire testing during the SUVEREN project (s. Kutschenreuter2019) was adapted for the mock-up fire test presented here. The calorimeter was equipped with mechanical ventilation and various measurement systems. It was developed by IFAB (Institute for Applied Fire Safety Research) and set up in their fire test facilities in Northern Germany. The key data of the calorimeter is summarized in Table 1.

*Table 1 Dimension and materials of calorimeter*

| Property of calorimeter | Specification |
|---|---|
| Ground area | 4 m x 4 m |
| Height of walls | 2 m |
| Total height including roof | 4.6 m |
| Diameter exhaust duct | 0.5 m |
| Leakage area underneath side walls | 0.2 m |
| Material (sidewalls & roof) | gypsum-based fireboard |
| Material (exhaust duct) | Stainless steel |

For the mock-up fire tests, the calorimeter described above was slightly modified as two side walls were removed leaving the two others in place (rear wall and right side wall). The chosen half-open set-up enabled a sufficient supply of air and kept the fire fuel-controlled until the suppression systems was activated. This was further ensured by a forced mechanical induced by a fan that was connected to the exhaust . Gas measurements were installed downstream of the exhaust duct.
A drawing and a photo of the calorimeter are displayed in **Fehler! Verweisquelle konnte nicht gefunden werden.** and Figure 2.

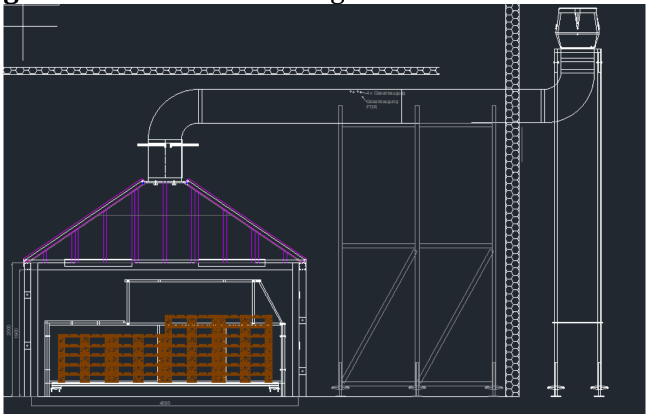

*Figure 1 Drawing of calorimeter including fan. ©IFAB*

*Figure 2 Photo of the calorimeter and the mock-up equipped with the fire load used during fire test. ©FOGTEC*

The results gained from the fire test series are part of the SUVEREN aim to improve the fire safety of modern vehicles. However, real vehicles especially current models are hard to get for fire testing and the development of a vehicle fire strongly depends on its ignition [Klüh2019, Lam2016]. Because of this, a design fire load replaced the actual vehicle. Doing so, the fire load can be created from experimentally well-known materials that are well reproducible thus allowing comparison for different firefighting strategies. The fuel used were wood pallets, which were ignited with heptane.

During a real fire, the car body or at least parts of it can block suppression agents from reaching the inside of the car and all combustibles located there. A mock-up of a vehicle simulates this behavior. The mock-up used during the fire tests consisted of two sidewalls, a front and a rear wall as well as a roof and an “engine cover”. Its geometry is based on a fire test protocol from the International Maritime Organization (IMO) [IMO2008]. While this document addresses the fire protection onboard of ships, in particular on RORO vessels[1], the fire test set-up had to be slightly modified to match the given scenario. However, the situation on the cargo deck of a RORO vessel and the one inside a closed car park are similar regarding main aspects of fire risk and scenario. Assuming a passenger car only ferry, the main fire load is the same, so is the potential risk of fire spread to nearby vehicles.

The mock-up itself represents a passenger vehicle and serves as cover and protection against the direct impact of water towards the fire. The mock-up is made of steel and has a ground area of 1.8 m x 3.8 m. It also includes a roof and an engine cover. The latter was not part of the IMO set-up but was added for a more realistic model. The increased coverage of the fire lead to a smaller cooling effect of the fire load itself as this fire phenomenon is not resolved in the simulations.

The results of the following measurement equipment was evaluated:

- Type K thermocouples
  - Positions: exhaust duct (both vertical and horizontal part), multiple positions near and around the mock-up
- Oxygen gas sensor
  - Position vertical part of the exhaust duct
- FTIR measurement: CO (among other species)
  - Position vertical part of the exhaust duct

Within the SUVEREN fire test series, both mock-up fire tests (SU08 and SU09) have been performed using the design fire load made from wood pallets. In both tests the same fire load was used, causing an identical situation during the first 3 minutes. At this time, the water mist system was activated in SU08 while the second test was continued under free burning conditions for another 2 minutes. Therefore, SU09 can be used as a reference case for SU08 regarding the influence of water mist. Table 2 summarizes fire load and suppression of both tests.

*Table 2 Fire load and water mist activation of SUVEREN fire tests*

| | SU08 | SU09 |
|---|---|---|
| Fire load | 24 EUR wood pallets (dimensions each: 1.2 m x 0.8 m 0.14 m) | |
| Source of ignition | 2 l Heptane on two pans, located at the bottom of the stacks | |
| Type of nozzle | FOGTEC High-pressure water mist nozzle[2] | |
| Layout of nozzles | 4 nozzles with a 3.5m spacing | |
| Height of nozzles | 1.85 m | |
| Activation of water mist | 3 minutes after ignition | 5 minutes after ignition |

## SUPPRESSION MODELLING

The simulation model of the calorimeter was created based on the technical documentation of the SUVEREN fire tests that included construction drawings, information about the materials and equipment used as well as photos and notes taken during the fire tests. The resulting geometry of both the calorimeter and the mock-up was modelled as realistic as possible given the restriction of the numerical grid. Figure 3 shows a perspective view of the model from a left-front position. The

---

[1] Roll-on/roll-off (RORO) vessels are cargo ships designed to carry wheeled cargo, such as cars, trucks. The vehicles are driven on and off the ship using their own power and wheels.

[2] The nozzles were modified during and for the research project and are similar to those used in OH2 applications, like car parks or related type of fire risks.

mock-up is displayed in lighter gray and positioned above the replacement of the scale. The red surface inside represents the fire area.

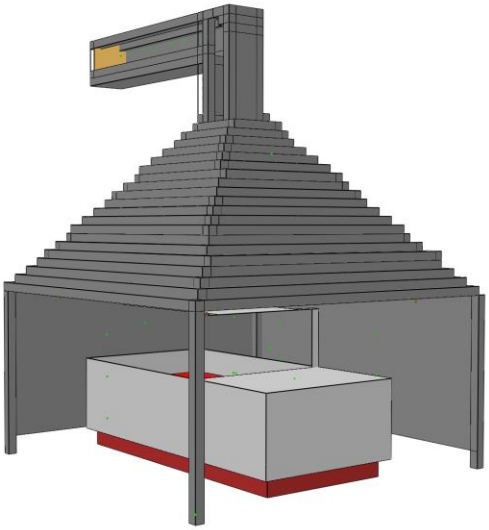

*Figure 3 FDS model of the calorimeter and the mock-up used for the FDS simulations of the  fire tests*

The duct is connected on top of the roof and of rectangular shape due to the fact that FDS only allows rectangular cells. It is cut off at 3 m length and blocked via the yellow part at the end, which connects the 3D CFD domain and the 1D HVAC model. The latter was used to implement the ventilator described in **Fehler! Verweisquelle konnte nicht gefunden werden.** in the simulations.

The simulations described in this paper were performed using a uniform 10 cm grid. The grid size represents a medium resolution due to the suggestion based on the characteristic fire diameter $D^*$ [McGrattan2020a]:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)$$

The selection of a medium resolution was based on the aim of evaluating the efficiency of including water mist in simulations as part of fire protection analysis using performance-based design. Thus, one aim was to identify which phenomena of a water mist simulation can be calculated accurately, knowing water mist droplets are far beyond common grid sizes in fire simulation. In addition, the influence of the grid size to the simulation results was investigated and further justified the chosen grid size.

## Water mist modelling

A modeling approach for the suppression of a fire with water from sprinklers and nozzles is part of FDS since recent years. Water mist droplets are far below common grid sizes, as droplets from high-pressure water mist can easily be in 100 μm range. In FDS, this is addressed by representing water or other suppression agents by Lagrangian particles [McGrattan2020a], thus allowing the induction of sub-grid size particles and solving an obvious need of modeling water droplets far below common grid sizes. The water particles interact with the flow field and are induced from nozzles inside the domain. A detailed description of the theoretical approach is given in the FDS User and Technical Reference Guide [McGrattan2020a, McGrattan2020b].

The nozzles used were modelled based on the information about the nozzles used during the fire tests as nozzle layout, height, operation pressure and k-factor can be applied to the FDS code. In addition, some more uncommon parameters are needed to set-up the numerical model of the nozzle. The droplet median size and the droplet size distribution have to be determined as well as spray angles in both latitude and longitude directions are required. All parameters were taken from

FOGTEC technical documentations and complemented with extra measurements and observations from fire test where needed.

## Fire modeling & heat release determination

As displayed in Figure 3, the mock-up is included in the FDS model and the fire area is located inside of it. Rather than calculating a real fire spread, the fire load in FDS was a prescribed based on mass loss from the fire tests. The time-dependent total weight is displayed in Figure 4 along with the mass loss rates (MLR), which were calculated from the total weights.

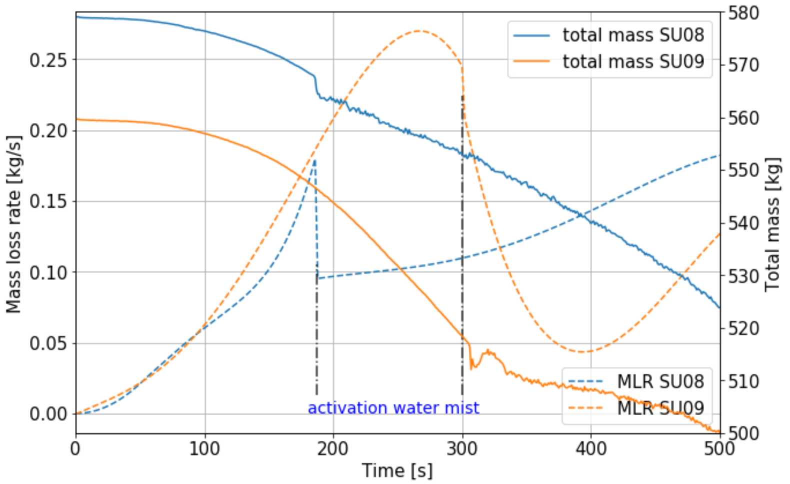

*Figure 4 MLR and total mass loss (right side) from fire tests SU08 and SU09. The former have been calculated based on the experimental data of the latter and has been used as boundary condition in FDS*

These mass loss rates have been used as input values in FDS to describe the development of the fire. Table 3 lists the combinations of HRR and water mist system that were used in simulations.

*Table 3 HRR and suppression configuration of FDS simulations*

| No. of fire test / simulation | HRR | Water mist |
|---|---|---|
| Su08 | Experimental fire test | activated 180 s |
| V1 | Reduced (fire test SU08) | activated 180 s |
| V2 | Continues fire growth (SU09) | activated 180 s |
| V6 | Reduced (fire test SU08) | No activation |

## RESULTS FROM FIRE TESTS AND FIRE SIMULATIONS

As described above, the two fire tests share the same set-up until the activation of water mist after 3 minutes in test SU08. The development of temperature over time from the fire tests can be taken from Figure 5 being comparable in general, with differences from approximately 100 s after ignition. The thermocouple positions O1 and O5 are located inside the exhaust duct right before the elbow. The differences in the developing can be explained as fires do not tend to be the same. However, the calculation of the mean absolute error over all 19 thermocouples between the two fire tests gave a value of around 10 K.

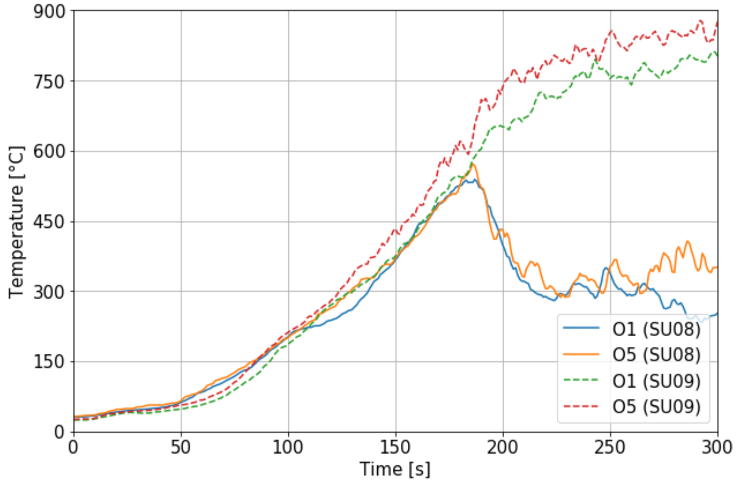

*Figure 5 Temperature over time in exhaust duct before the activation of water mist for fire test SU08 and SU09. The temperature of SU08 have been affected by suppression after 180 s*

Figure 6 displays the time dependent species concentrations measured during the fire tests and calculated with FDS. The oxygen concentration predicted by the simulation follows the one measured in the tests. The largest differences occur shortly after the activation of water mist. In terms of this issue, the modelling of the fuel and its combustion reaction is modelled tolerably accurate. The same comparison was made for CO measurements. In this case, the CO values in FDS are significant low, whereas the experimental data shows a sudden rise of the CO concentration shortly after the activation of water mist. The CO values remain at a high level throughout the fire tests. Both gauges were located in the horizontal part of the exhaust duct.

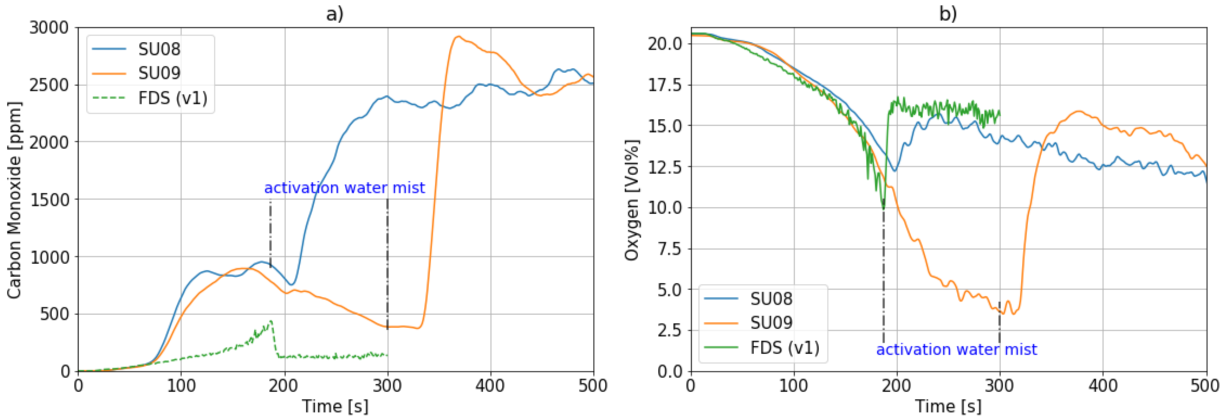

*Figure 6 Species concentration in exhaust duct measured in fire tests and calculated with FDS. CO (a) and Oxygen (b)*

The impact of the suppression system on the gas temperature is the focus of this investigation as the gas temperature plays an important role when assessing the structural safety in a car park. Heat transfer from the gas phase to the ceiling or other components can lead to a loss of stability and in the end to a collapse of the building. Controlling the gas temperature is one of the key elements a water mist system provides, thus being able to simulate this effect is important in terms of a performance-based design analysis.

The developing of temperature over the first two minutes after the start of suppression is displayed in Figure 7 for the simulation configurations documented in Table 3.

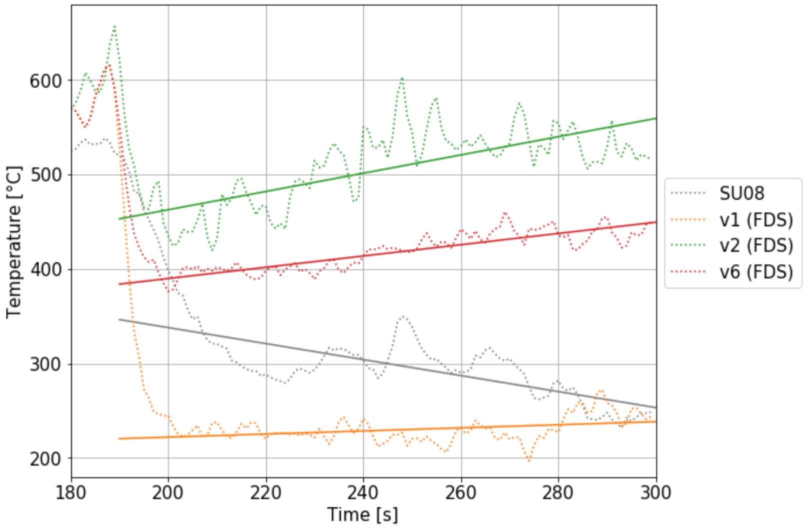

*Figure 7 Calculated Temperature right after activation of water mist and added linear trend lines for each simulation result (in same color as the dotted FDS results)*

As expected, the combination of a reduced HRR and an activated suppression system causes the largest temperature drop of the three simulation variations. In all cases, the drop in temperature happens rapidly. In simulation v2, the temperatures start rising quickly after the activation and with operating water mist system, as shown by the trend line (solid) of the temperature.

V1 underestimates the temperatures in the fire test, possibly due to an underestimated HRR. The HRR was calculated based on the scale used in the fire tests and water mist droplets have influenced the mass measurements by hitting the mock-up. Even though the water mist nozzles were installed for room protection, water mist hitting the mock-up and the fire load could only be minimized and not prevented.

## CONCLUSIONS

This work summarizes the comparison of fire tests and fire simulations under the influence of water mist. As the fire tests were performed within a research project, multiple quantities at different locations had been measured and were used both for setting up and validating (parts of) the model. The following conclusions have been drawn:

- The FDS sub-module "suppression with water" allows the description of high-pressure water mist nozzles using various experimental parameters.
- The overall computation time of water mist in FDS is strongly influenced by a couple of numeric parameters. While some can be easily turned off depending on the objective of the simulations others can cause non-physical behavior, like water droplets travelling through walls. These parameters have to be handled carefully in order to get reliable results within an acceptable matter of time.
- In comparison with the fire tests, the temperature drop caused by the activation of the water mist system is more rapid. Investigations by the authors show, that this specific behavior of the water mist in FDS does not depend on the droplet size or the modelling of the measured pressure rise in the fire test.
- The water mist system caused an abrupt temperature drop in the exhaust duct, which was identified to be caused by two larger influences: The calculation of the cooling of the gas by vaporization of water mist droplets and the reduction of mass loss rate at that time.
- The reduction of the mass loss rate and corresponding heat release rate has to be modelled in order to keep temperatures in the range of those from real fires. When using a fire load e.g. for passenger vehicles that was determined based on experimental data under free burn

conditions in a performance-based design analysis and predict the influence of a fixed water mist firefighting system, the temperature distribution calculated will be unrealistic high if no reduction in the fire's burning rate is considered. The results might be conservative when only looking at the temperatures. But regarding fire protection design, the calculations might be too conservative and lead to very strict measures.

- The reduction of the mass loss rate due to the influence of water mist can and should be estimated based on fire test results, especially considering the cover of the vehicle to influence the interaction with water mist. This is true both for providing a MLR for the complete fire simulations and the dynamic calculation of the reduction, that can be performed using the E_COEFFICIENT in FDS.
- It can be stated that after and while the water mist system was operating, the CO production was increasing in the fire tests. This can and should be regarded e.g. by modelling the fuel and switch between two reaction schemes. In a performance-based design analysis, CO is mainly used in terms of life safety, an objective that is less important for planning the fire protection in a car park / garage due to the statistically low number of people being hurt from fires inside those facilities.
- The CO production rate might become more important when another water mist effect is modelled: the depletion of oxygen. When considering this in terms of calculating the heat release, the CO yield in the reaction equation needs to be set along with the amount of oxygen needed for the calculated combustion. This was not implemented in this work, as more adaptions would be needed on how to use certain parameters in the FDS code.

## OUTLOOK

Multiple fire tests and various fire simulations proofed that the application of fire simulations is still limited and that the support of fire testing is needed in order to accomplish good and conservative results. The main focus of further development in water mist simulations should be the improvement of the estimation and calculation of reduced burning rates during a suppressed fire. Since stand-alone calculation does not seem to be available in short-term, the following questions have been left for deeper research:

a) FDS offers the E_COEFFICIENT to reduce the burning rate dynamically and correlated to the amount of water hitting the surface. Values for the E_COEFFICIENT are determined experimentally. The shape and position (height) of the surface modelling the fire in FDS has an influence on this.
b) The heat release for the entire simulation is given from the start. This has to be justified by experiments. While using weight measurements is a proven method, it is affected by water mist. In addition, the use of another proven method, oxygen consumption calorimetry (OCC), should be taken into account. In a suppressed fire, the OCC will be affected by water vapor and the influence has to be quantified in future investigations. A combination of both techniques seems to be a promising way to determine HRR data appropriate for the use in FDS simulations with water mist.
c) There are some numerical parameters left to be investigated as they influence the calculation time, which is already rather long. The performance of water mist simulations should be improved by performing sensitivity studies for those parameters.

The evaluations presented in the given paper are based on the current status of data analysis. Work on this is still proceeding and CFD in general is considered to gain better accuracy. Therefore, it can be expected that fire safety design supported by CFD simulations is further improving.

## Acknowledgements

The research presented here is part of the research project SUVEREN that is funded by the German Federal Ministry of Education and Research (BMBF) under contract No. 13N14391. The authors appreciate the possibility given by the funding and the work done by several of our colleagues in support of the fire test program.

## **REFERENCES**

Fachkommission Bauaufsicht (2008), „Muster einer Verordnung über den Bau und Betrieb von Garagen (Muster-Garagenverordnung M-GarVO).

International Maritime Organization (2008) "IMO MSC.1/Circ.1272: Guidelines for the approval of fixed water-based fire-fighting systems for ro-ro spaces and special category spaces equivalent to that referred to in resolution a.123(V)".

Klüh, S., Kutschenreuter, M., Leismann, F. Lakkonen, M. (2019) "Fire safety in car parks using Performance based design", In *Book of Abstracts NFSD Nordic Fire Safety Days*, August 20-21, Copenhagen, Denmark, 6.

Kutschenreuter, M. Feltmann, An., Usner, T., Leismann, F. (2019) "Experimental and numerical investigation of a car fire with fixed-firefighting system", *Proceedings of the STUVA Conference – International Forum for Tunnels and Infrastructure, Frankfurt, Germany*. November 26-28, 392-397.

Kutschenreuter, M. Klüh, S., Leismann, F. Lakkonen, M., (2020) "How electric vehicles change the fire safety design in underground structures", *ISTSS 2020 (postponed)*.

Lam C. et al, "Full-scale fire testing of electric and internal combustion engine and vehicles", *Proceedings of the Fourth International Conference on Fire in Vehicles*, October 5-6, 2016, Baltimore, USA, 95-106.

McGrattan, K., Hostikka, S., Floyd, J., McDermott, R., Vanella, M. (2019), "Technical Reference Guide Volume 1: Mathematical Model", October 31, http://dx.doi.org/10.6028/NIST.SP.1018

McGrattan, K., Hostikka, S., Floyd, J., McDermott, R., Vanella, M. (2020), "Fire Dynamics Simulator User's Guide", March 9, http://dx.doi.org/10.6028/NIST.SP.1019.

NFPA 88A, (2019), "Standard for Parking Structures".

Tewarson, A. (2002), Generation of Heat and Chemical Compounds in Fires ", In *SFPE Handbook of Fire Protection Engineering (P. J. DiNenno et al.)*, 3-82 – 3-161.