Proof of suitability of a water mist fire protection system in a hotel atrium as compensatory measure combining different engineering methods

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In general, appropriate functionality of fixed firefighting systems using water mist has to be proven by fire tests. However, fire tests are expensive and sometimes not feasible due to general simplifications and geometrical limitations. Using a hotel atrium as case study, an alternative approach to fire testing using different engineering methods has been investigated. The results shall suffice requirements regarding fire safety given by German building authority. A combination of previously conducted fire tests, simulations with CFD-software FDS and extensive spray tests were used. The fire tests used the same water mist nozzles as shall be used in the application, but mounted in different height and installed vertically instead of horizontally. Spray tests with a single nozzle have been conducted to validate the nozzles modelled with FDS by comparing the water distribution on the floor. FDS was then used to simulate the previously conducted fire tests for validation purposes. Additionally, the water distribution with a set of 16 nozzles as planed in the hotel atrium was simulated and compared to the fire and spray tests. The validated model was then used to simulate temperature distribution in the atrium and its glass façade when in interaction with a given design fire. The simulations demonstrated sufficient agreement with experiments. It could be proved that the water mist system is appropriate to protect the atrium against a conservative fire scenario and to function as compensatory measure for structural fire protection. It is possible to prove effectiveness of water mist protection systems with engineering methods instead of fire tests under specific circumstances. However, comparable experimental data is required for validation.

I. Introduction

The verification of fire protection in a hotel atrium was used as an example for application of compensatory measures implementing different engineering methods. The atrium, which contains a bar with a typical OH1 fire load on the ground level, has a height of 27.5m. A floor plan of the ground level is shown in Figure 1. Its floor plan is uniform up to 22m and rejuvenates above. Between the heights of 5m and 22m the atrium consists of a glass façade. Due to German high-rise building guideline, the whole atrium has to be covered by a conventional sprinkler system [1]. Due to the height, an appropriate installation of a sprinkler system is not feasible. Nevertheless, the façade needs to meet fire safety standards in order to prevent a fire to spread from the atrium to the floors. Due to commercial reasons it was not considered appropriate to use fire safety glass. Instead, thermal protection of the façade by a different fire-suppressing system should be used as compensatory measure and to comply with a similar safety level. In general, appropriate functionality of water based fixed firefighting systems using water mist has to be demonstrated by fire tests. As fire testing is very expensive, a different approach using engineering methods was conducted. This approach will be described in section II.

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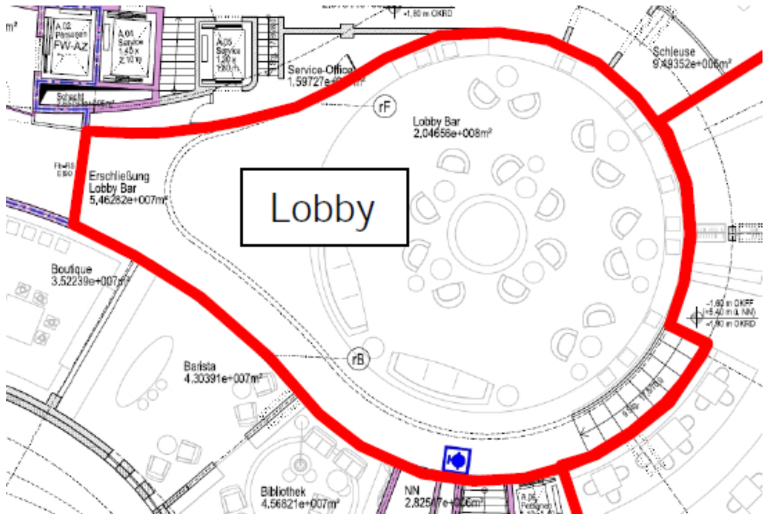

Figure 1: Floor plan of the hotel atrium

II. Description of Methodology

A. Design of HPWM

The high pressure water mist (HPWM) system was designed following the design of a comparable scenario referred to as "Water-Mist fire tests on a public open-space scenario based on IMO RES A.800" based on [2]. Fire tests with this comparable geometry and similar fire load have been successful regarding the performance criteria [3]. An IMO open-space fire load was used as fire scenario. It consists of 4 frames with 2 foam mattresses on each of them. With a maximum heat release rate of 4MW (see [4]), this is considered a conservative approach, taken into account the possible furnishing in the hotel atrium. It was considered important to use a HPWM design that has already proven sufficient performance in fire tests. This is because:

1. similar fire-fighting performance is expected with a system that has comparable design parameters
2. results of fire tests allow validation and calibration of CFD model used for evaluation of HPWM design

There are, however, three major differences of the reference HPWM design and the one chosen for the hotel atrium:

1. the height of the room to protect
2. due to architectural specification, the nozzles need to be installed horizontally instead of vertically at a given level above ground at the boundary of the atrium
3. nozzle grid is different due to geometrical limitations mentioned in 2.

The first difference is not considered a substantial influence on the firefighting performance, because the nozzles are not installed at the ceiling as in the fire tests. The void space above the nozzles will not have a significant influence on the firefighting performance. However, the second difference requires thorough assessment, because the momentum and its direction of the water mist spray has an influence of how deep the fire is penetrated by water mist. Furthermore, the grid of nozzles requires the water mist to have a high momentum to cover the center of the atrium. The momentum of the spray was not examined in the reference fire tests as the spray direction was consistent with gravity. The impact of differences in the nozzle grid and spray directions will be discussed in detail in chapters II C and II D.

The average amount of water applied per area of the reference fire tests is approximately 2 l/min/m². With respect to the more challenging nozzle grid, a safety factor of 10% has been applied for the hotel atrium. It is important to note that not only the amount of water per area is a relevant property of a HPWM system, but also spray dynamics and the droplet size of the water have a significant impact on the performance. The latter is of special interest particularly for firefighting systems involving water mist, whose cooling performance is directly dependent on the integral surface of water. This is referred to as quality of water mist.

B. Results of Reference Fire Tests

The following criteria were considered for evaluating the performance of the HPWM system for the reference fire tests:

- A set of sofas with the same furnishing as the fire load was used as target. This should mimic the possible spread of a fire and was chosen the main criteria. In order to have a worst-case approach, spacing between fire source group and target was as low as 1m.
- Reduction of radiative heat
- Reduction of the temperature at the ceiling level and the vicinity of the fire
- Control/Suppression of the fire

Although the performance criteria were different for the reference fire tests, it is important to use a system that has proven the capability of protecting a room with comparable properties. The main aim for designing the HPWM system for the hotel atrium is protecting the glass façade. Thus, the further analysis focuses on the temperatures. Also not explicitly required, it is, however, also essential to prevent the fire from spreading, reduce the radiative heat and suppress the fire.

Temperature graphs at the ceiling of a representative fire test are shown in Figure 2. The performance of the test is as follows:

- source group of sofas is completely damaged
- no propagation of fire to the target group
- moderate surface damages on the most exposed edges of the target mattresses
- performance level of HPWM system is considered fire control

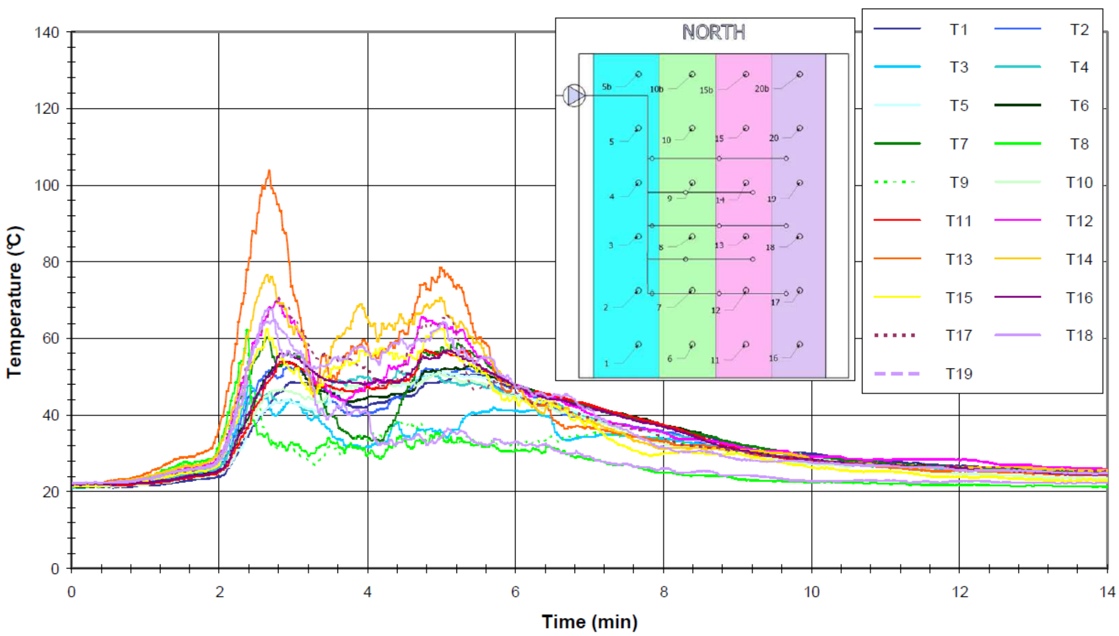

Figure 2: Temperature graphs at the ceiling for reference fire tests

C. Spray Tests

The atrium has a diameter of approximately 16m. Since the nozzles can only be installed at the walls bounding the atrium, it needs to be assured, that the water mist reaches the center of the atrium with high momentum. Furthermore, a uniform spray pattern across the floor is desired. Thus, spray tests have been conducted with one nozzle, which should clarify the best nozzle parameters. The water distribution on the floor was measured with small containers placed evenly across the floor. During the spray tests, parameters as the spray angle and the operating pressure have been varied. The results of the spray tests are shown in Figure 3. With regard to spray distance and uniformity of the water distribution, it was decided to install nozzles with a spray angle of 0° to the horizontal and use a design pressure of 100bar.

The spray tests were also used for calibration of the CFD model used later for assessment of the performance of the HPWM system. The open source software Fire Dynamics Simulator (FDS) was used for the subsequent simulations [5] [6]. As the spray pattern of a water mist nozzle is very complex, it is not possible to simulate the nozzle directly, especially as the nozzle used consists of several micro-nozzles, whose water sprays interact with each other. Therefore, properties of the water spray some distance from the nozzle need to be defined by the user. Some of them are unknown (velocity, spray angle) and need to be calibrated with the results of the spray tests.

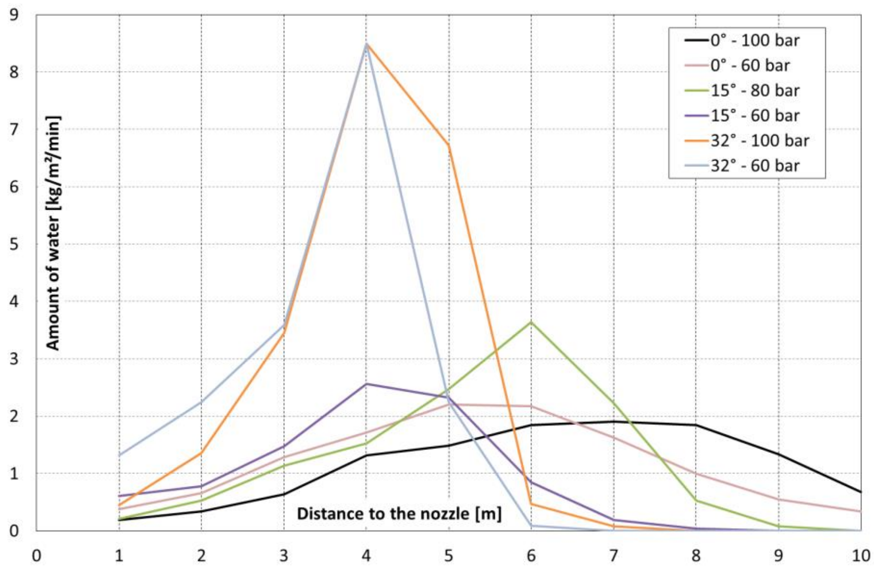

Figure 3: Results of spray tests

D. Simulation of Water Distribution on the Floor in Example Case

Although the amount of water of the HPWM system in the hotel atrium is higher than in the reference fire tests, it needs to be assured, that the water distribution on the floor is uniform. This is considered a basic prerequisite for transferability of the performance of the open-space scenario fire tests.

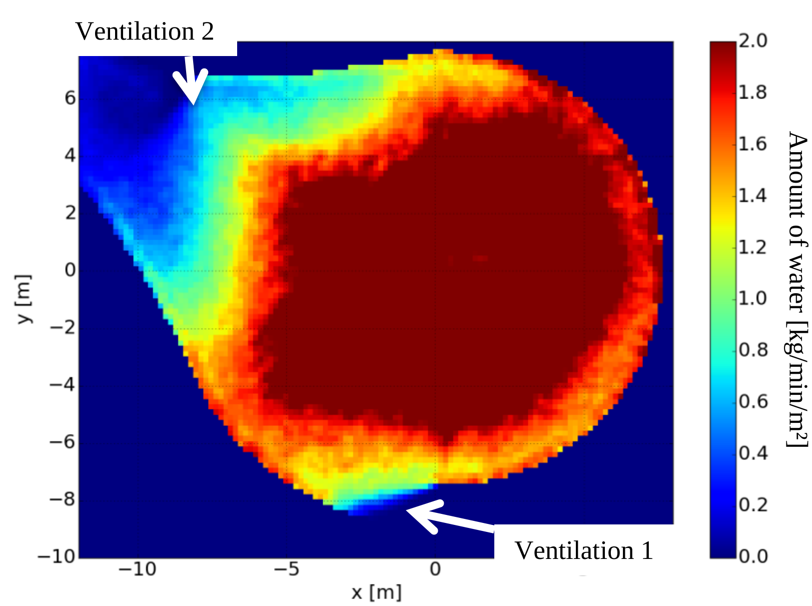

Figure 4: Simulation of water distribution in hotel atrium with design HPWM system

The calibrated nozzle was implemented in the CFD model of the hotel atrium and arranged as defined in the HPWM system design and the spray tests. With a total of 16 nozzles arranged evenly around the atrium, the amount of water mist on the floor was simulated (Figure 4). Most parts of the atrium are covered well with a sufficient amount of water (>2 kg/min/m²). The areas with less water are influenced by the forced ventilation which is activated in case of fire. If a fire starts in such an area, it will be deflected towards the center of the atrium by the ventilation as well, which is covered with a sufficient amount of water. Thus, the water distribution is considered appropriate.

E. Development of a Simulation Model

In order to simulate the thermal stress of the glass façade, a CFD model with all boundary conditions was built. The discretized geometry is shown in Figure 5. Furthermore, the following features were included in the model:

- A smoke evacuator with openings distributed equally at the top of the atrium will activate in case of fire. The volume flow rate of smoke evacuator is 68000 m³/h. Doors will open in case of fire, which allow air to move inside the atrium to balance the air sucked by the smoke evacuator. See Figure 4 and Figure 5 for their location in the model.
- The heat release rate of IMO open-space fire load was used [4]. See Figure 6 for the discretization of the heat release rate which was used in the simulations. The fire load was positioned in two different locations which were considered most conservative with regard to thermal stress of the glass façade.
- The HPWM nozzles were positioned evenly around the atrium in a height of 4.2m. See section II D for further information.
- Several output quantities monitoring temperatures, air velocities, pressure and smoke distribution were monitored throughout the whole domain with point measurements and planar slices (scalars and vectors).

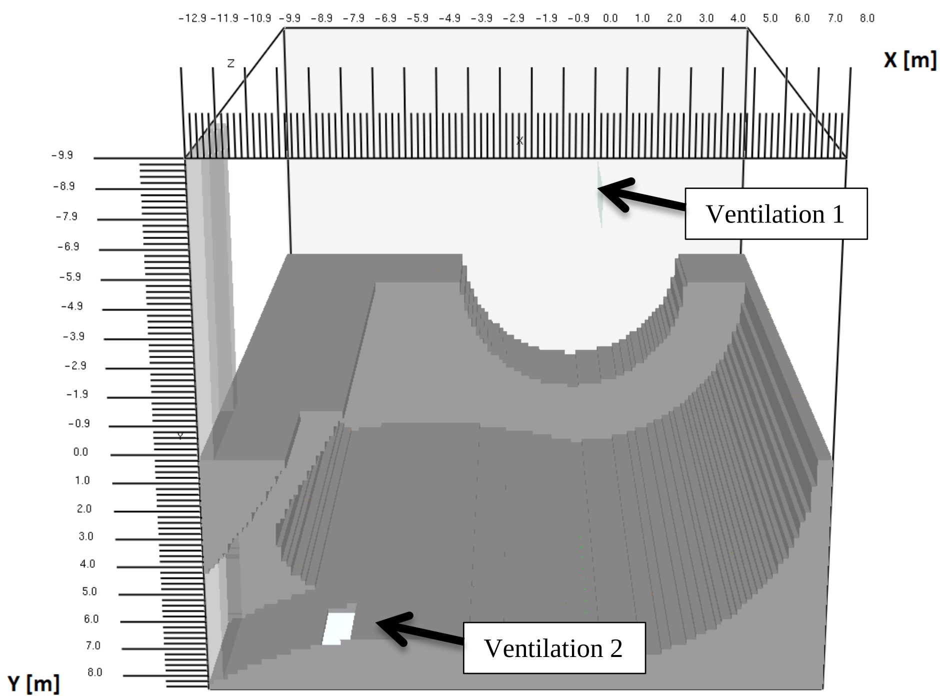

Figure 5: Sectional view of the simulation domain (from below)

In order to validate the model with a focus on the discretized HPWM system, the reference fire tests were simulated. Although all used features of FDS, especially temperature suppression with water, were validated by others (see [7] [8] [9] [10] [11] [12] [13] [14]), this is necessary in a complex case as described here. Validation in general focuses on isolated elements of the software. As a model becomes more complex, the interaction of the individually validated features can lead to disambiguation. Also, this is a good practice to check for mistakes made by the user.

However, several simulations using FDS 6.1.2 resulted in an unphysical behavior in the temperature distributions when very fine droplets were simulated. It was found later that this behavior is a bug in the software, which allows the temperature of the droplets to overshoot the ambient air temperature. Thus, the former version FDS 5.5 has been used, which has proven to simulate the fire protection performance of very fine water droplets sufficiently. Results of the simulation are shown and compared with the results of the reference fire tests in Figure 7. Although the temperatures are slightly lower in the simulation, the agreement of the results is considered sufficient. The differences are addressed to uncertainty of the heat release rate used for the reference simulation. The heat release rate for the reference fire test has been decreased compared to the curve shown in Figure 6 due to suppression of the fire which has been observed in these tests.

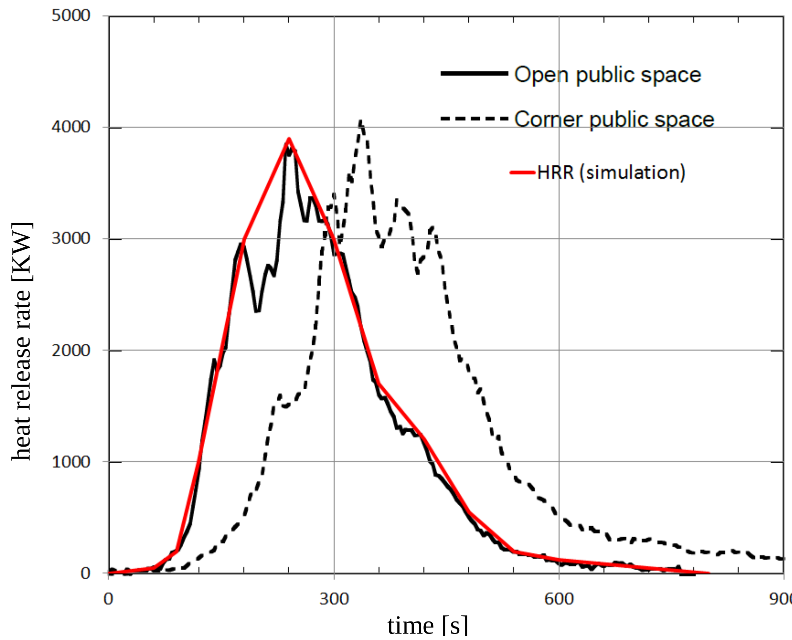

Figure 6: Discretization of heat release rate for simulation [4]

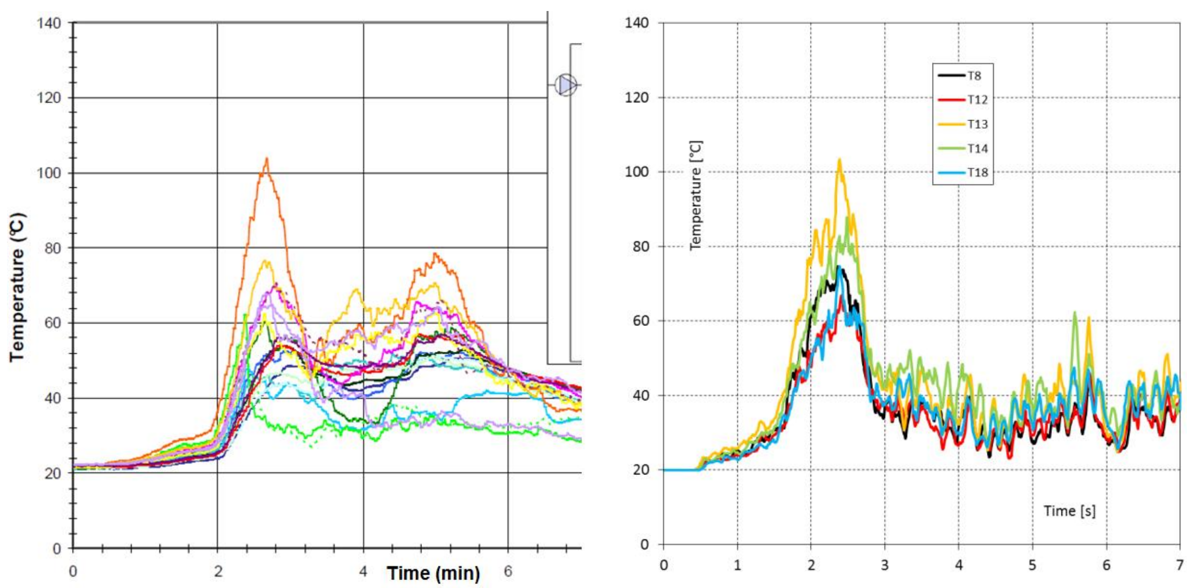

Figure 7: Ceiling temperatures of reference fire tests (left) and simulation (right)

F. Results of Simulation of Hotel Atrium with Fire Load

The validated model was used for simulation of the hotel atrium. The focus was set on surface temperatures of the glass façade. See Figure 8 for results. The surface temperature remains below 60°C before and throughout activation of HPWM system. The performance of the designed HPWM can thus be considered sufficient with regard to protection of the glass façade.

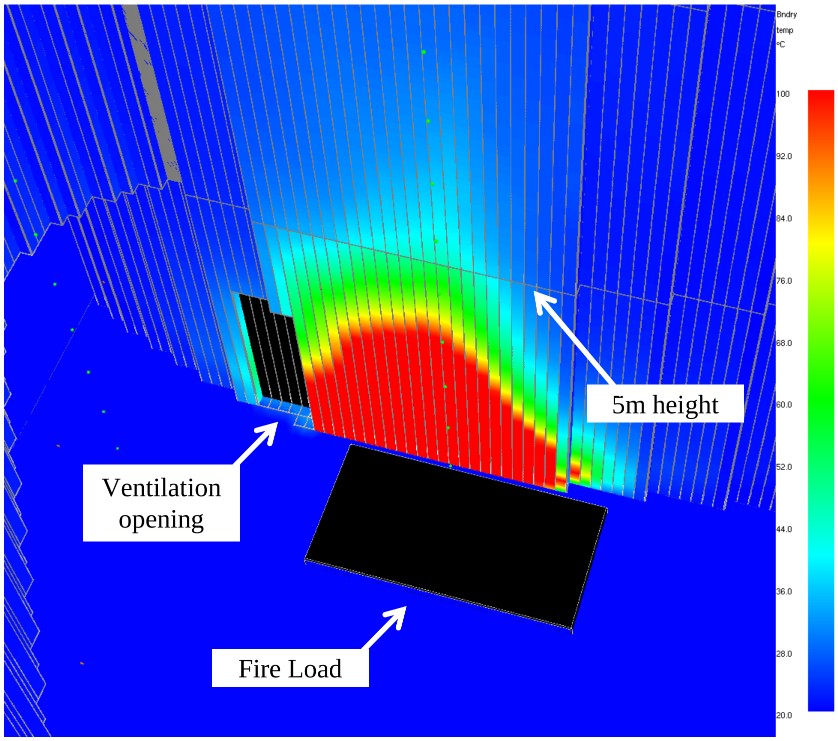

Figure 8: Maximum temperatures on the surface of the glass façade at 275s

III. Discussion and Conclusion

This paper demonstrates an approach of proving the performance of a HPWM system using engineering methods with focus on CFD simulation. The results were accepted by the German building authority. In general, it is not possible to prove performance involving water mist with simulations only. The approach in the example shown is appropriate as it involves results from spray tests and is validated with a large-scale fire test with comparable characteristics. However, the shown approach using engineering methods is only one possibility of proving performance.

Often, CFD simulations are performed by unexperienced users without questioning the results or investing effort in plausibility/validation studies. Although the tools are validated with real test data very often, it is not possible to completely rely on these results. This has been demonstrated in the example case, which revealed a bug in FDS 6.1.2 when very small water droplets are involved. It is important that not only the user of CFD software is aware that results have to be put on a sound basis. Also the person who further processes the results of a CFD simulation should be aware that results of complex cases without validation/plausibility analysis may be questionable. To prevent wrong conclusions, CFD simulations should be waived when there are doubts about their ability to appropriately comprehend the problem.

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