FIRE SPREAD SCENARIOS INVOLVING HYDROGEN VEHICLES

Liu, W.[1]; Riba Clascà, F. G. [4]; Markert, F.[2]*; Giuliani, L.[3]

[1]Department of Civil Engineering, Technical University of Denmark, Brovej 118, Kongens Lyngby, 2800, Denmark, weliu@byg.dtu.dk

[2]Department of Civil Engineering, Technical University of Denmark, Brovej 118, Kongens Lyngby, 2800, Denmark, fram@byg.dtu.dk

[3]Department of Civil Engineering, Technical University of Denmark, Brovej 118, Kongens Lyngby, 2800, Denmark, lugi@byg.dtu.dk

[4]Chemical Engineering, IQS, Brovej 118, Barcelona, Spain, francescribac@iqs.edu

ABSTRACT

Fire spread between vehicles provides a potential risk in parking areas with many vehicles. Several reported very large fires caused the loss of a great number of vehicles. These fires seem to be in contradiction to the European design rules for car parks assuming only a very limited number of vehicles may be on fire at the same time. The fire spread in a car park environment is dependent on many factors of both the vehicles and the structure, e.g. the latter has an impact on the rate of fire spread due to re-radiation of the vehicles heat release. Therefore, a CFD model is established to develop a tool to assess vehicles and better understand fire scenarios in different structures. Further, the model enables testing of building design to prevent and mitigate such fires scenarios involving hydrogen vehicles. In this study, a real layout of a car park is modelled to investigate the effects of hydrogen emergency releases that have used different TPRD diameters. The results provide insight into the behaviour of hydrogen cars and the release pattern of the TPRD's as well as the temperature development of the concrete ceiling and concrete beams above the cars. It shows that the TPRD diameter has a little effect on the TPRD activation time of the no.1 vehicle when the amount of H2 in the tank is the same. For the surface temperature of the ceiling and beam, the peak temperature for a 1mm diameter TPRD release is found highest.

Keywords: Hydrogen vehicle; TPRD nozzle diameter; surface temperature; heat release

1.0 INTRODUCTION

In car parks, vehicle fires damage the nearby vehicles and damage the structure of the car park. In 2020, a fire started in a parking house at Stavanger airport Sola [1]. After 20 min the fire started, ten vehicles were reported being on fire on the fire brigades arrival, and after 25min the fire had spread to another storey. The fire resulted in a collapse of the steel structure after 2 hours, and some hundred cars had been damaged [1]. In 2017, an accidental fire occurred in a 7-storey car park in Liverpool. This fire is reported to reach temperatures between 800 and 1000 ^{o}C. In this fire, around 1400 cars were destroyed, and it caused major structural damages [2,3]. In 2002, the Schiphol airport parking garage fire destroyed about 50 cars [4]. In 2004, 10 cars were burned out completely, and the steel structure collapsed in the Odense car park fire [5]. According to these events' results, to ensure vehicle safety and car park structure, it is necessary to understand and model possible vehicle fires in car parks.

To assess vehicle fires, some tests with burning cars have been carried out concerning the fire safety of car parks. Mangs et al. [6] designed three full-scale fire experiments with passenger cars. The cars were tested, including oil, petrol, and ordinary passenger cabin materials. The experiment obtains the heat release rate (HRR) curve for a car fire. Dayan et al. [7] used two 4-door sedan passenger cars to design the full-scale vehicle fire tests, which can obtain the burning behaviour and describe the spread of fire to the adjacent car by the measured temperatures, radiant heat flux and photo images. In this test, the flame spread from the engine compartment to the car cab through the air-conditioning vents. Katsuhiro et al. [8] carried out four full-scale car fire tests to establish the burning behaviour of minivan passenger cars under different conditions, such as door window opening and ignition point. The results indicated that the breaking of the windows could affect the fire behaviour directly.

Tamura et al. [9] investigated the fire spread between the hydrogen-fueled vehicles by two-vehicle fire tests. The test results indicated that the flames spreading from the interior and exterior materials of the fire origin vehicle is the direct reason for the ignition of the adjacent vehicles.

From the existing vehicles fire tests, it is obvious that researches are mainly focused on traditional fuel vehicles. However, hydrogen-fueled vehicles are on the market worldwide, fewer investigations on hydrogen-fueled vehicles fires. At present, many researchers studied the hydrogen-fueled vehicles fires by the CFD simulation.

To predict the fire spread of cars in car parks, Leander [10] developed a vehicle fire model based on the effects of the governing radiative heat transfer. But the model was in the development phase and needed further validation and improvement. Therefore, Sommer and Lauridsen [11] developed a new numerical CFD car model, which can simulate fire spread between vehicles and include gasoline and hydrogen fuels. The simulation results indicated that fire spread from one car to another after about 9 minutes, earlier than the assumption in the CTICM guideline [12].

In addition, Márton et al. [13] used FDS to study the fire spread between cars in an open steel car park. According to the simulation results, the fire spread between cars is strongly influenced by the geometrical layout of the car park. Markert et al. [14] studied the impact of the parking distance on the adjacent vehicles' fire spread, confirming the importance of the parking distance between cars on the fire spread rate and ignition of adjacent cars.

Thus, in case of vehicles fires occur in a semi-open car park, the fire performance is affected by the ignition location, parking distance, ventilation rate, etc. An important ongoing discussion is the best TPRD diameters in hydrogen vehicles. The larger sizes may release the tanks stored hydrogen quickly but increases the risk of explosive vapour clouds. The actual view is to minimize the diameters up to very small diameters below 1mm on the cost of longer releases or in case of ignition jet fire durations. The effect of hydrogen emergency mass release rates through activated TPRD's with different diameters on vehicle fire in car park is weak from the existing research. Therefore, this paper will focus on the hydrogen vehicles fire in a semi-open car park considering the TPRD diameter.

2.0 VEHICLE MODEL

In this article, the vehicle model will be based on the car model established by Nielsen and Lauridsen [11], see fig.1. This model comprises different submodels, such as tires, seats, interior material and fuel. The material parameters can be seen in table 1.

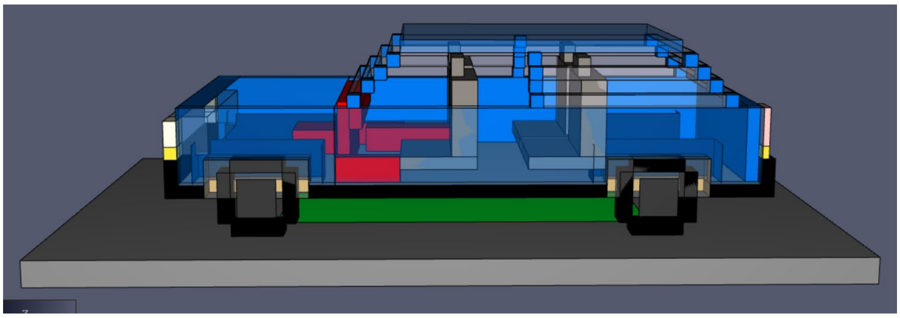


Figure 1. Hydrogen vehicle model [11, 15]

Table 1 Material Parameters

Submodel	**Material**	**Specific Heat Capacity [KJ/kg · K]**	**Thermal Conductivity $[10^3 KW/m \cdot K]$**	**Density $[10^{-3} kg/m^3]$**
Tire[16]	Rubber	2.01	0.13	650
Seat[17]	Foam, PUR	1	0.05	65
	Fabric	1	0.1	100
Interior material[17]	Polypropylene, PP	2.16	0.2	960

The fuel is hydrogen, and the amount the hydrogen tank contains is 5 kg. The TPRD nozzle diameter applied in this study are 0.5mm, 1mm, 2mm, 3mm, 4mm and 5mm. A sensitivity analysis has been done for a 4 mm diameter. The release profiles can be seen in fig.2. The assumption for the hydrogen model is a vertical downwards jet that impinges the floor after a short distance. Therefore, the release of the hydrogen is modelled as a burner, as FDS can't simulate gas flows which speed is higher than 0.3 Mach number. The hydrogen gas is released from the burner surface (3 m^2 area) with a variable mass flow rate placed underneath the car. When the temperature near the gas cylinder reaches 110°C, the TPRD in the hydrogen vehicle will be activated, and the hydrogen will be released. Therefore, the DEVC parameter will be used to trigger this in the FDS simulation. The hydrogen module is tested in a domain of 560 m^3, and the mesh size has been varied with $0.2m \times 0.2m \times 0.2m$, $0.1m \times 0.1m \times 0.1m$ and $0.05m \times 0.1m \times 0.2m$. The total energy released is shown in table2.

Table 2 Mesh size and the total energy released

Mesh Size [m]	**No. of cells**	**Total Energy Release [MJ]**	**LHV reference calculation [MJ]**	**Deviation from LHV calculation [%]**
0.20×0.20×0.20	70000	612.445	600	2.07
0.10×0.10×0.10	560000	608.897	600	1.48
0.05×0.10×0.20	4480000	615.116	600	2.52

In the table 2, the LHV reference calculation is obtained by multiplying the material mass and heat of combustion [16]. The total energy release is obtained from the FDS simulation results. It can be seen from this table that $0.1m \times 0.1m \times 0.1m$ mesh size is more close to the theoretical calculation. The deviation from LHV is minimal among the three mesh sizes, and it is just 1.48%. Therefore, in the subsequent hydrogen model, the mesh size will adopt $0.1m \times 0.1m \times 0.1m$. When the mesh size is $0.1m \times 0.1m \times 0.1m$, the result of the HRR and the hydrogen releases can be seen in fig.3 and fig.4, respectively. In fig.3, the maximum HRR is about 54000KW. After ignition, the HRR value reaches the highest value very soon.

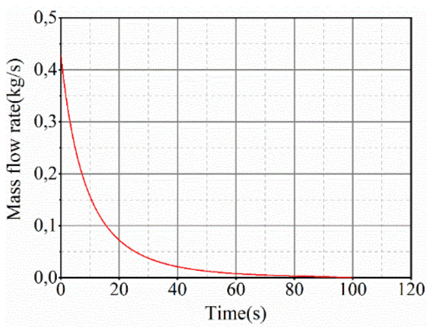


Figure 2. Hydrogen release profile

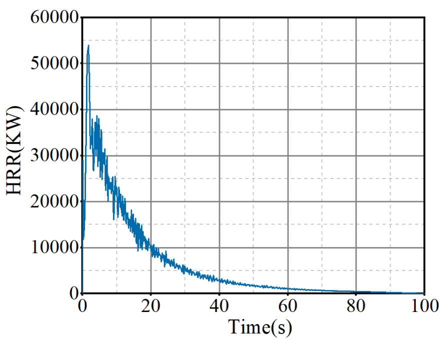
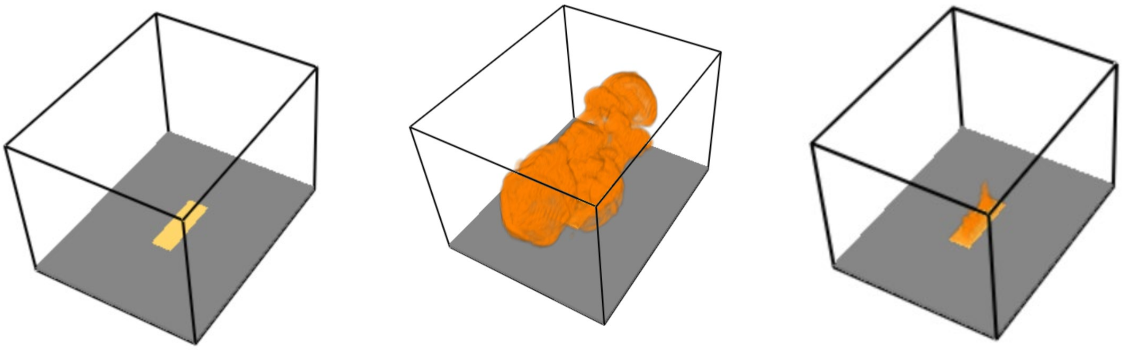


Figure 3. HRR of hydrogen



(a)T=0s (b)T=1.5s (c)T=50s

Figure 4. Development of the hydrogen fire after during a release

3.0 DESCRIPTION OF THE SCENARIOS

3.1 Vehicle fire spread model

When study the hydrogen vehicle fire spread in a car park, the car park will adopt a real car park design in Copenhagen. Fig.5 shows the described dimensions of the concrete structure of the car park. And in the model, it will consider three hydrogen vehicles in the car park. The fire spread involving hydrogen vehicles is investigated for identical layouts, only variating the respective TPRD nozzle diameters for all vehicles (0.5mm, 1mm, 2mm, 3mm, 4mm, 5mm), see in table 3.

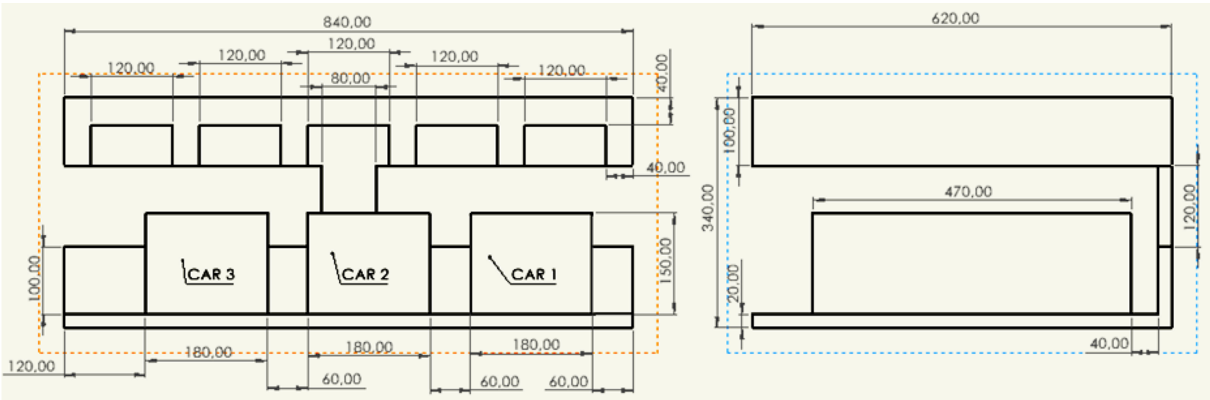
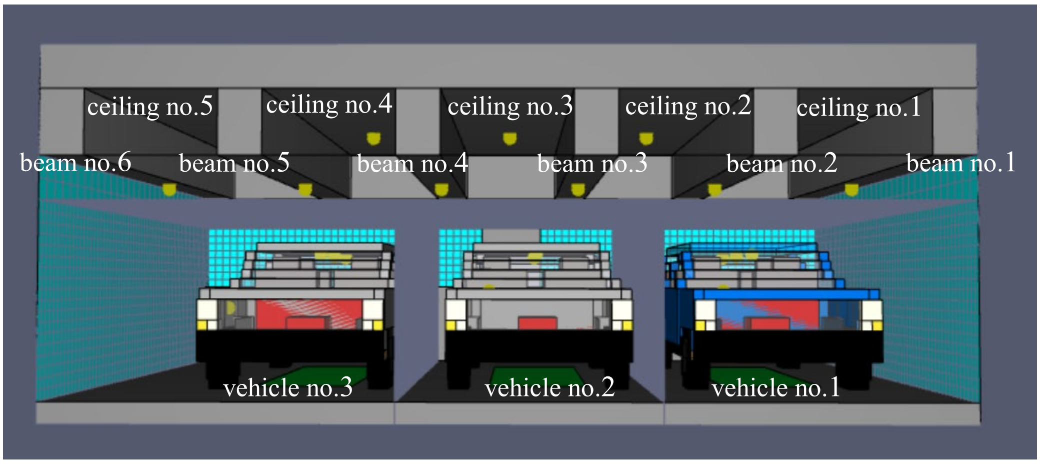
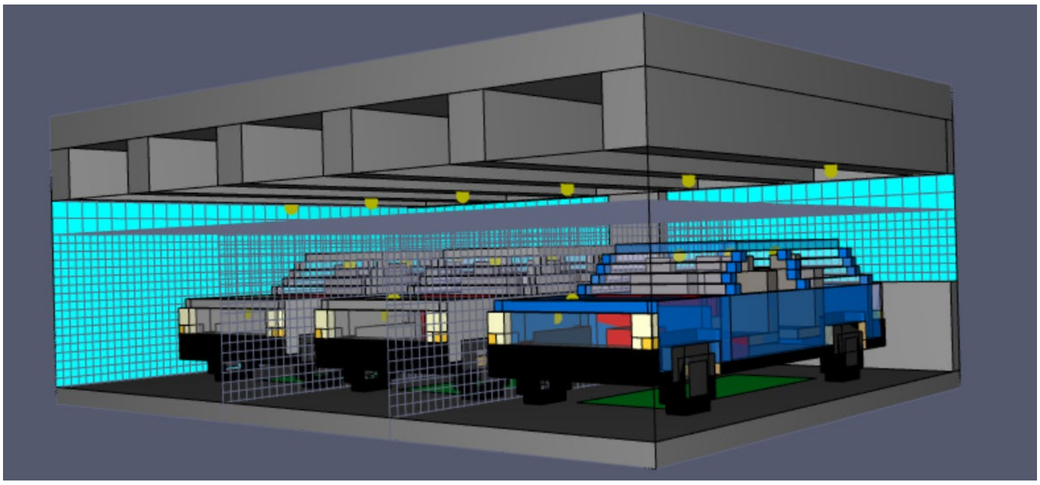


Figure 5. Sketch of the dimensions of the car park

The model mesh is divided into four sub meshes, see in fig 6, which are the top one grid division of 0.2m × 0.2m × 0.2m and three vehicles grid division of 0.1m × 0.1m × 0.1m. To ensure proper ventilation, the VENTS are used in the mesh boundaries that are not obstructed by the concrete structure. And solid-phase devices are placed on the concrete structure to measure the temperatures during the fires. The amount of H2 the tanks contain is 5 kg, and the "FC H2 e-laboratory obtains the mass flow rate released by the VENT in the model". The fire is designed to start in the right front seat of the no.1 vehicle, and the default REAC propane has been used in the final model.



(a)Front view



(b)Lateral view

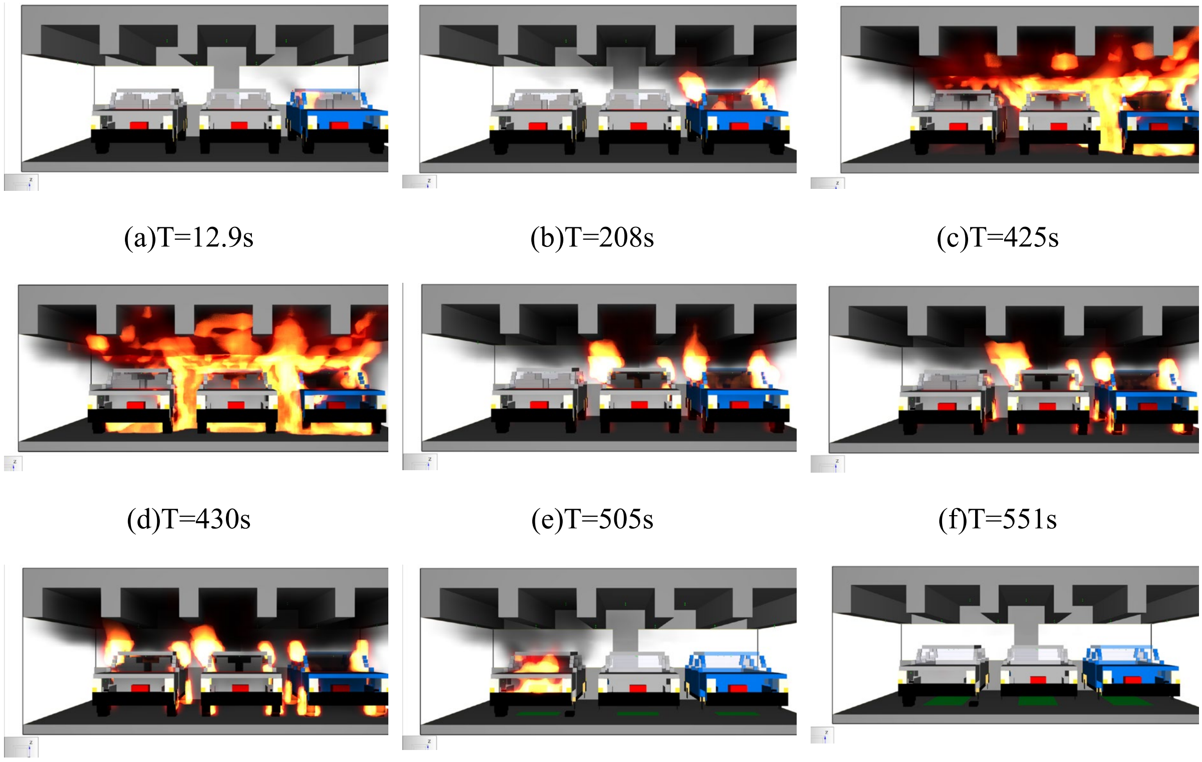
Figure 6. Hydrogen-vehicles fire spread model [15]

Table 3 Scenarios Parameters

Scenarios	TPRD diameter/mm	Ignition location	Vehicle number	Vehicle distance /cm	Fuel
0.5	0.5	Vehicle no.1	3	60	hydrogen
1	1	Vehicle no.1	3	60	hydrogen
2	2	Vehicle no.1	3	60	hydrogen
3	3	Vehicle no.1	3	60	hydrogen
4	4	Vehicle no.1	3	60	hydrogen
5	5	Vehicle no.1	3	60	hydrogen

4.0 RESULTS

In fig.7, the hydrogen vehicle fire spread simulation results using the 5mm TPRD nozzle diameter. It can be seen from fig.7 that the ignition location is in vehicle no.1 and the fire spread between the adjacent vehicles is very quick. Fig.7(c) is the biggest possible flame of H_2 blowdown captured escaping the bottom of the first car right after TPRD activation at 425s, and fig.7(d) is the biggest possible flame of H_2 blowdown captured escaping the bottom of the three cars right after the TPRD activations at 430s. From the first vehicle's TPRD activation to the third vehicle's, it only takes about 5s. Fig.7(e) shows the time when vehicles no.1 and no.2 completely are on fire and the third vehicle showing only a little fire spread after H_2 runs out. From fig.7(f), it is seen that for the third vehicle, the fire starts spreading through the car's back left wheel; at 609s, the fire fully developed through the third vehicle. Finally, fire self-extinguished in the car park when the time is about 3680s.



(a)T=12.9s (b)T=208s (c)T=425s

(d)T=430s (e)T=505s (f)T=551s

(g)T=609s (h)T=2799s (i)T=3680s

Figure 7. Burning history for the 5mm TPRD nozzle diameter

According to the scenario's parameters in table 3, the vehicles TPRD activation times are obtained after calculation. In table 4, it is seen that the TPRD diameter has a little effect on the TPRD activation time of the no.1 vehicle when the amount of H2 in the tank is the same. And three vehicles' TPRD are activated almost simultaneously when the TPRD nozzle diameter is 5mm. However, when the vehicle's TPRD nozzle diameters are 0.5mm, 2mm and 3mm, the remaining vehicle's TPRD is not activated. In the 4 mm and the 1 mm simulation, fire takes time to propagate from car nº2 to car nº3. In the 4mm, 960 seconds pass between their TPRD activations, and in the 1 mm, 1260 seconds pass. This behaviour could indicate that a steady heat outcome is more likely to propagate the fire slower between HFCVs rather than a shorter but higher heat release.

Table 4 Vehicles TPRD activation

TPRD diameter [mm]	**TPRD activation vehicle no.1 [s]**	**TPRD activation vehicle no.2 [s]**	**TPRD activation vehicle no.3 [s]**
0.5	490	None	None
1	430	600	1690
2	427	None	None
3	426	None	None
4	425	430	1385
5	425	430	430

Fig.8 shows the heat release rate (HRR) of the hydrogen-fueled vehicle fire in a car park, and the HRR curves of 6 kinds of TPRD diameters are shown in it. On the 5mm diameter scenario curve, there are four rising stages. Stage a indicates that HRR starts to rise once the fire spreads through all the car cabins. Stage b indicates that a huge HRR peak occurred when all the TPRDs activate together in a very short time. In stage c, after the H_2 runs out, HRR raises again once the second car is fully in flames. And in stage d, HRR enters an increasing tendency again once the third car is fully on flames.

In addition, observed from fig.8, slow phases of HRR curve raising are produced when fire spread happens through the whole car and slowly decrease until the fire self-extinguishes or another car sets on flames. When vehicle TPRD nozzle diameter is 5mm, the HRR value is about 29000KW, which is the maximum HRR value in the six scenarios. For 0.5mm, 2mm and 3mm diameter scenarios, there is only one rising stage in these HRR curves because the TPRD of vehicles no.2 and no.3 are not activated in the simulation.

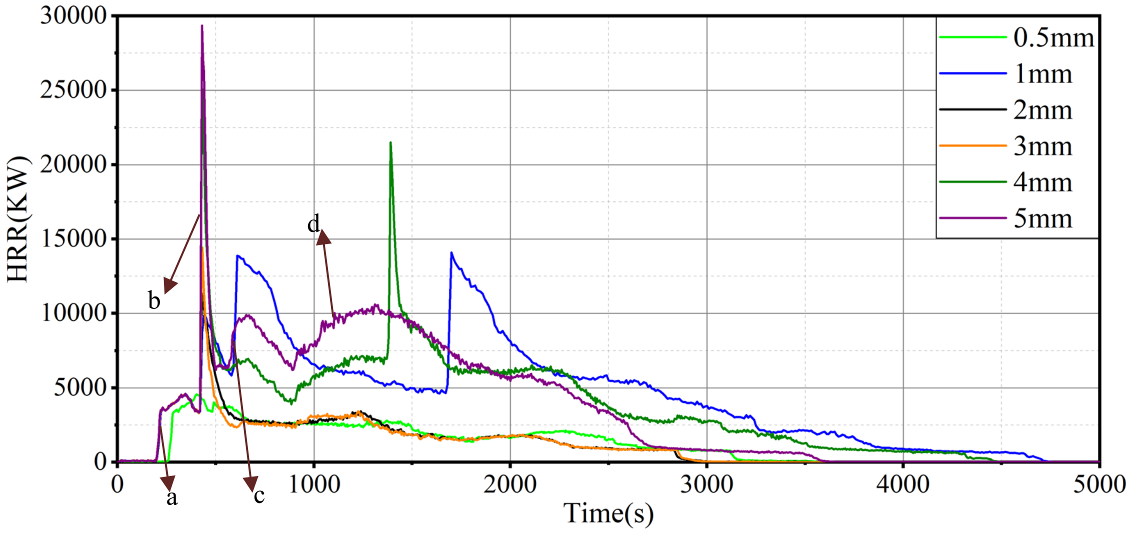


Figure 8. HRR of the vehicle fire in different TPRD diameter

Assing a worst-case scenario for the structure of the car park, it is necessary to study the beam which has the maxim surface temperature. In the simulation scenarios, the surface temperature of beam no.4 arrives at the maxim temperature value between other beams. Therefore, it is the surface temperature of beam no.4 in fig.9 having the highest surface temperature. In the 5 mm diameter scenario, the highest temperature reaches almost 950ºC. This beam reaches a higher temperature because it is right in the middle of vehicles no.2 and no.3. The flames escaping the vehicle cabin through the windows hit the concrete beam directly when they are burning. In this curve, there are two rising stages. Stage a indicates that the temperature raises super-fast when all the TPRDs activate in a very short time. In stage b, once vehicles no.2 and no.3 are completely on fire temperature starts rising again, almost reaching a peak of 800ºC. There are only one rising stage in these temperature curves for 0.5mm, 2mm and 3mm diameter scenarios. The temperature is much lower than that of other scenarios because vehicles no.2 and no.3 are not completely on fire in the simulation.

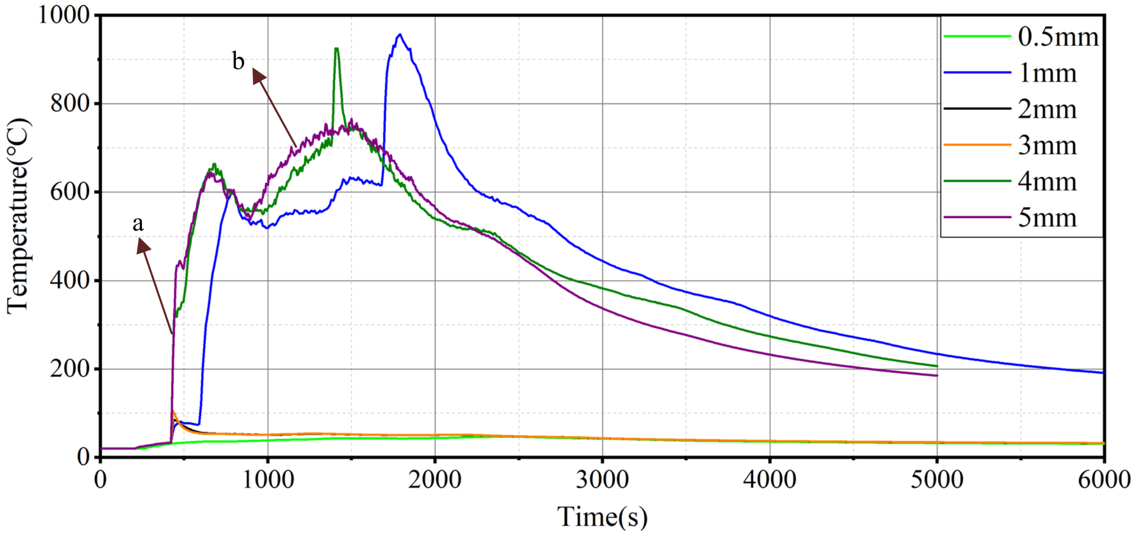


Figure 9. Beam no.4 surface temperature in different TPRD diameter

According to table 4, some scenarios in which the TPRDs of vehicles no.2 and no.3 are not activated. Thus, compared to other ceiling temperatures, the surface temperature of ceiling no.2 is studied in this paper. Fig.10 shows the surface temperature of ceiling no.2, which is the one being hit by the flames exiting the right windows of vehicle no.1. It can be seen in fig.10 that the maximum temperature is achieved in a 1mm diameter scenario, which is about 900℃. The temperature curves of the 4mm and 5mm diameter scenarios are very similar. This is because vehicles' TPRD activation time of vehicles no.2 and no.1 is very close. Apart from this, the temperature curves of 0.5mm, 2mm and 3mm diameter scenarios are also very similar because the TPRDs of vehicles no.2 and no.3 are not activated in the two scenarios.

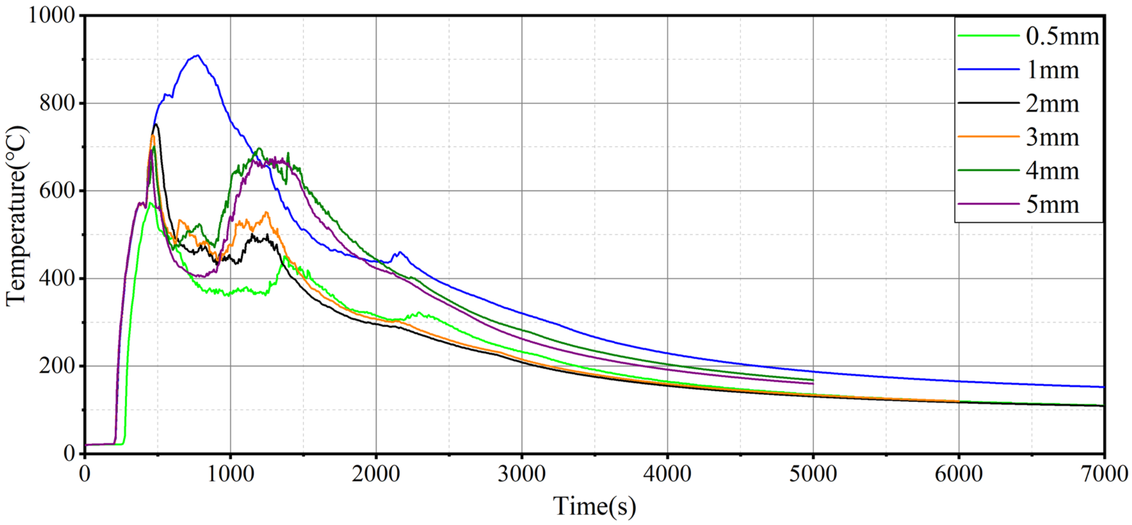


Figure 10. Ceiling no.2 surface temperature in different TPRD diameter

5.0 DISCUSSION AND CONCLUSION

In this paper, six different scenarios have been studied. The results show the influence of TPRD nozzle diameter on hydrogen vehicle fire in a semi-open car park. 1) The TPRD diameter has a little effect on the TPRD activation time of the no.1 vehicle when the amount of H_2 in the tank is the same. 2) When the TPRD nozzle diameter is greater than 3mm, the peak HRR value increases rapidly. 3) For the surface temperature of ceiling and beam, the peak temperature value of 1mm diameter TPRD nozzle is larger than others.

According to the simulation results, the variation of the TPRD exit nozzle diameter has resulted in the variation of the HRR peaks produced during the burning of the vehicles. It has been concluded that if the nozzle diameter is too big, the high HRR peak can start a very dangerous chain reaction that can almost instantly trigger all the TPRDs of the adjacent vehicles. This would increase the burning of all vehicles and with the potential to create very dangerous and uncontrollable scenarios. Like the 1 mm diameter studied, a small exit nozzle may result in a long, steady heat source. This may slow down the fire spread compared to bigger diameters. However, the longer duration of the heat released by such a small TPRD may make the adjacent car reach a self-ignition temperature that would not have been reached with a little faster or slower blowdown.

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