Prediction of Temperatures under a Ceiling for Momentum Controlled Hydrogen Jet Fires

Dr. Harem Hussein

ID: 9596

Year: 2025

**Corresponding author email: haremhussein88@gmail.com*

ABSTRACT

A momentum controlled, impinging hydrogen jet fire has been considered for two scenarios; impingement on an unconfined ceiling and on the ceiling of a naturally ventilated covered car park. The two scenarios have been numerically simulated and compared with Alpert's correlations to predict the maximum temperature and velocity in the ceiling jet. The Alpert correlations were developed nearly four decades ago and have been used since to predict maximum temperature and velocity under a flat and unobstructed ceiling for buoyancy dominated fire. However, to date, there has not been a form of this correlation which is directly applicable to momentum driven jet fires. The increased use of hydrogen and fuel cell applications indoors necessitates better understanding and prediction of temperatures under a ceiling in an impinging jet, specifically to calculate and predict heat detector and sprinkler activation in a confined space. Five cases of momentum driven, impinging hydrogen fires, were simulated and the results were compared with the original Alpert correlations to investigate their prediction capability. It was found that the original correlation for temperature provided a reasonable agreement with numerical predictions. However, the simulated velocity in the high momentum jets was 3 to 4 times greater than that predicted by the original correlations in all cases. The value of the constant in the original correlations was modified to achieve good agreement for both temperature and velocity. It is shown that if the constant is modified from 5.38 to 6, good agreement for temperature can be obtained for all cases. In addition, a velocity constant in the range of 0.5 to 1 instead of the original 0.197 provided good agreement with numerical results depending on the mass flow rate of the release. It is concluded that maximum temperature and velocity of a ceiling jet for a momentum driven hydrogen jet fire can be predicted using modified constants in the Alpert correlations

KEYWORDS: Hydrogen jet fire, enclosure fire, ceiling jet, unconfined ceiling, hydrogen safety, ceiling temperatures, ceiling velocities.

INTRODUCTION

Hydrogen as a high-pressure compressed gas (35 and 70 MPa) is used for onboard vehicle storage tanks. which must be fitted with a Thermally activated Pressure Relief Device (TPRD) to allow hydrogen to be released once the temperature outside the tank reaches 110^{o} C or higher to prevent tank rupture. By necessity, these vehicles will be parked indoors for example in a garage, car park, maintenance shop etc. In the event of a TPRD release, the hydrogen jet is likely to ignite [1]. An upward orientated ignited release through a TPRD, creates a momentum-controlled jet fire with combustion products propagating beneath the ceiling of an enclosure. It is important to understand and predict the maximum temperature and velocity of this initially momentum dominated flow for public and structural safety, enabling engineers to design and estimate sprinkler or heat detector activation for indoor hydrogen jet fire scenarios. A ceiling jet is often referred to as radially spreading gas produced by an impinged fire plume to a flat and unobstructed ceiling [2]. The Alpert correlations have been widely used for the last four decades to predict temperatures and velocities of hot gases beneath a ceiling from a fire in an enclosure [3,4] as a function of heat release rate, radial position and ceiling height. These correlations allow safety engineers to calculate heat detector and sprinkler activation in a confined space as well as damage which might occur to the ceiling. In order for these correlations to be applicable, the ceiling should be flat and without any obstructions. This enables the plume to move radially beneath the ceiling, eventually cooling down as it spreads owing to both heat loss to the ceiling and air entrainment. The Alpert correlations are applicable for steady-state conditions and unconfined ceiling jets. For an unconfined ceiling the ceiling jet will have a maximum thickness of about 5 to 13% of the total height of the enclosure, and the maximum temperature and maximum velocity can be measured in a distance of about 1% of H, which is the height from the fuel source to the ceiling [5]. This unconfined ceiling exists only in the earliest stages of fire development before gas accumulation and creation of a hot layer in the confined space [6]. To date, these correlations have been considered for buoyancy-driven flows only. To the authors' knowledge, there is no existing form to account for momentum driven jet fires and hence this is the subject of this work.

PROBLEM DESCRIPTION

This work focuses on the prediction of maximum temperature and velocity under an impinged ceiling for a momentum drove hydrogen jet fire. Two geometries were considered: an unconfined ceiling and a naturally ventilated covered car park. Five scenarios were simulated to account for different hydrogen release rates and hence heat release rates, as shown in Table 1. The validated numerical model described in previous work by the authors [7] was used and results were compared with the Alpert correlation for maximum temperature and velocity beneath a flat and unobstructed ceiling. **Table 1. Scenarios considered for ceiling jet temperature and velocity prediction**

Case number	Enclosure type	Real release diameter (Notional nozzle diameter) (mm)	Car geometry	Blowdown model	Hydrogen mass flow rate (kg/s)	Total heat release rate (kJ/s)
1	Unconfined ceiling	3.34 (56.4)	No	No	0.2993	35895
2	Car park	3.34 (56.4)	No	No	0.2993	35895
3	Car park	0.5 (8.44)	No	No	0.0067	803
4	Car park	2 (33.8)	Yes	Yes	0.1072	12852*

5	Car Park	0.5 (8.44)	Yes	Yes	0.0067	803*

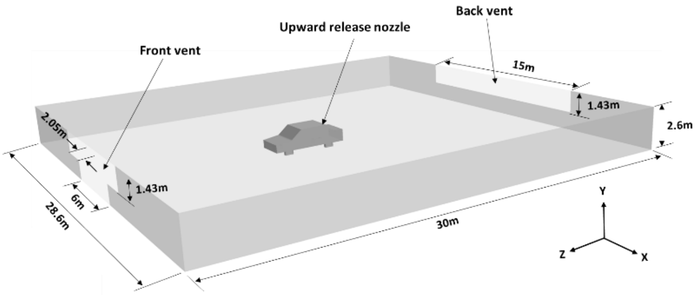
* The total heat release rate ($\dot{Q}$) was assumed based on a constant release to apply correlations.

Unconfined ceiling

A large unconfined ceiling (100 m x 100 m) was considered with a constant 0.299 kg/s ignited hydrogen release from a 3.34 mm TPRD diameter, (case 1 in Table 1). The release was assumed to occur 0.5 m above the ground, directed upward and situated at the centre of the domain. The car park height was 2.6 m, hence the distance from the nozzle to the ceiling was 2.1 m. All sides of the ceiling were open in order to directly compare to the Alpert correlations for maximum temperature and velocity, by avoiding accumulation of hot gas. The high momentum cased= was chosen to ascertain the applicability of the analytical model. The notional nozzle approach developed at Ulster University [8,9] was used to calculate the equivalent diameter for the leak inlet.

Car park

The unconfined ceiling geometry described previously is an ideal case, thus the study was extended to a real car park geometry with dimensions L x W x H = 30 x 28.4 x 2.6 m as shown in Fig. 1. The car park has two ventilation openings: back and front, of equal area (21.45 m^2). The front vent consists of a top to bottom opening and two small side vents flush with the ceiling. The back vent is located on the top centre of the wall directly opposite to the front vent. The ventilation requirements were based on British Standard (BS 7346-7:2013) [8]. It is recommended that a covered car park with natural ventilation should have an opening area equivalent to 5% of the floor area for each floor in a level. Similarly, the standards in the Netherlands (NEN 2443) [9], require vents equivalent to 2.5% (5% in total) of floor area on each opposite wall. The car geometry, shown in Fig. 1 was replaced with a simple pipe in 3 of the cases. Four car park scenarios were considered to investigate ceiling jet maximum temperature and velocity prediction for momentum dominated hydrogen jet fire. As in the unconfined case, the Ulster notional nozzle [10,11] was used to calculate the equivalent diameter for the leak inlet. The car geometry was included in 2 of the 5 cases, in 3 scenarios, to eliminate the effects of the car body geometry on the flow behaviour, the upward release was modelled as a short pipe, located at the centre of the car park 0.5 m above the floor. Two constant release rates, 0.299 and 0.0067 kg/s, were considered for the scenario with no car, which are equivalent to a hydrogen fire with a constant total heat release rate of 35895 and 803 kJ/s respectively. This allows for direct comparison between simulation and correlation. However, it should be noted that in reality the mass flow rate from a release through a TPRD from onboard storage is not constant, and will blowdown with time.



(b)

Fig. 1. Sketch of the naturally ventilated covered carpark

The car geometry was considered for two scenarios, 4 and 5 in Table 1. In these cases, the blowdown model was used to account for decreasing the mass flow rate of the release. It was assumed that the release nozzle is directed vertically upward on the car roof thus the distance between the leak and with the car park ceiling is 1.13 m. A typical saloon car with dimensions of 4.9 m length, 1.88 m width and 1.47 m height was chosen, as shown in Fig. 1. It was assumed that the car was stationary at the time of the leak and the onboard hydrogen tank was filled to capacity, representing a worst case scenario. The hydrogen tank was assumed to have a volume of 117 litres and storage pressure of 70 MPa, with a capacity of approximately 5 kg. The centre of the leak was situated in the centre of the car park, meaning the car body was positioned slightly left of centre. The ambient temperature and pressure were taken as 293 K and 101325 Pa respectively, and fully quiescent conditions were considered, i.e. no wind effects, replicating a car park in an urban setting.

METHODOLOGY Analytical calculation

A ceiling jet can be described as hot gases rise from a fire plume spreading out radially under an impinged ceiling. Since fire detection and its suppression devices are mostly located close to the ceiling surface, in order to evaluate their response time temperature and velocities beneath the ceiling should be determined. The Alpert correlations are widely used to predict temperatures and velocities of hot gases beneath a ceiling from a fire in an enclosure [3,4]. These correlations allow safety engineers to calculate heat detector and sprinkler activation in a confined space as well as damage which might occur to the ceiling. In order for these correlations to be applicable, the ceiling should be flat and without any obstructions. This enables the plume to move radially beneath the ceiling, eventually cooling down as it spreads owing to both heat loss to the ceiling and air entrainment.

CFD approach

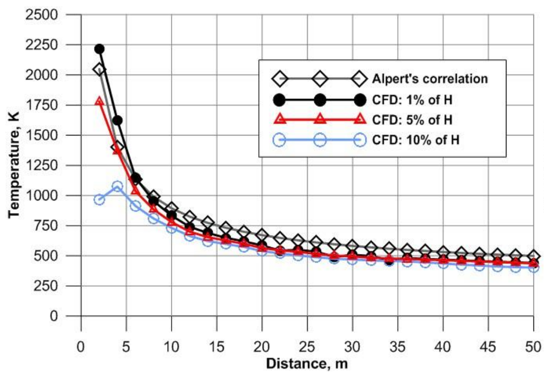
CFD simulations were performed to model an ignited hydrogen release and the impingement and spread of the resultant hot jet under the ceiling, providing insight into the entire combustion and flow process, including the prediction of flammable zone formation, combustion, temperature gradient, and flow patterns inside an enclosure. The CFD package FLUENT [12] was the base software tool used to simulate the high-pressure hydrogen release scenarios. The numerical approach was validated by the authors [7] for overpressure prediction in an enclosure due to an ignited release, and a similar model was applied, and results compared to the validated analytical model for pressure peaking prediction inside a residential garage [13]. Currently, no experimental data is available for momentum driven hydrogen jet fires impinging on a ceiling, Hence, the analytical models developed by Alpert were used for comparison. ICEM CFD was used to generate the geometries and hexahedral meshes, with ANSYS Fluent to solve the governing equations. A pressure-based solver has been used and PISO (Pressure implicit with the splitting of operators) was applied due to the transient flow. The compressible flow was considered with an ideal gas law. Second-order upwind schemes were used for all spatial discretisation, with the exception of the pressure gradient where the PRESTO! interpolation method was applied. A least-squares cell-based approach was used for interpolation methods (gradients). The absorption coefficient described by Yan et al. [14] was implemented, where the air is considered to be 100% dry. In addition, the realisable k-epsilon turbulent model has been used to model turbulence flow [7]. The Eddy Dissipation Concept model (EDC) was used to capture hydrogen combustion in the air. Ignition was modelled as a spark by patching a temperature until it could be confirmed the flame had begun to propagate. This combustion modelling approach has been successfully applied and described by the authors in previous work [13], in the work presented here the modelling approach is extended to compressible flow. Further details and governing equation can be found in the author's previous publication [7].

The outer domain for the unconfined ceiling geometry was 180 x 180 x 40 m (L x W x H) while the car park outer dimensions were 170 x 128.6 x 92.6 m (L x W x H). Both geometries were axissymmetric lengthwise. A hexahedral mesh was generated throughout the domains. Whilst the walls were not meshed, conduction heat transfer through them was accounted for. The floor, walls (only for the car park), and the roof had a thickness of 0.15 m and were assumed to be constructed of concrete. The material properties chosen are similar to brick and concrete typically used for car parks in the UK. Two materials were used in this study: aluminium and concrete, further details on materials properties can be found in previous work by the authors [7]. A box mesh technique with mesh interfaces was implemented to provide a refined mesh around the nozzle making it possible to have improved resolution in the required areas without a significant increase in total control volumes. A no-slip condition was applied at the solid surfaces. The domains were assumed to be initially 100% air at STP at normal ambient pressure and temperature i.e. 101325 Pa and

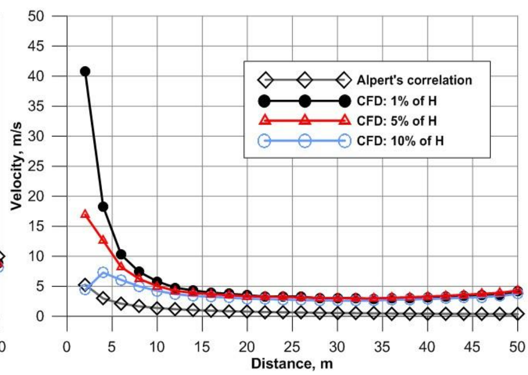
293K respectively. A hydrogen release from a 70 MPa tank is an under-expanded jet and will lead to the creation of a complex shock structure at the nozzle exit, which is computationally intensive to resolve. Resolution of this shock structure is beyond the scope of this study. Therefore, the under-expanded jet was replaced with an expanded jet, applying the notional nozzle theory developed by Molkov et al. [9]. For realistic scenarios blowdown from 70 MPa should be considered. The blowdown process and volumetric source model used by the authors is described in a parallel publication [15].

RESULTS Assessing the distance to compare maximum temperature and velocity

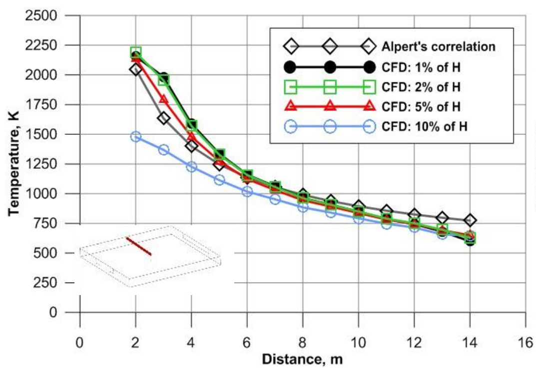
Alpert [6] cited that maximum temperatures and velocities underneath an impinged ceiling for buoyancy dominated fire occurs at a height of 1 to 2 % of the distance from the top of the enclosure to the fuel source [5,6]. In order to find the maximum values for a momentum dominated jet, four different locations were compared: 1, 2, 5 and 10% of the height (H) from the leak nozzle to the ceiling. Fig. 2 shows a comparison of temperature and velocity at varying positions for a 0.2993 kg/s release through a 3.34 mm TPRD in an unconfined and confined car park



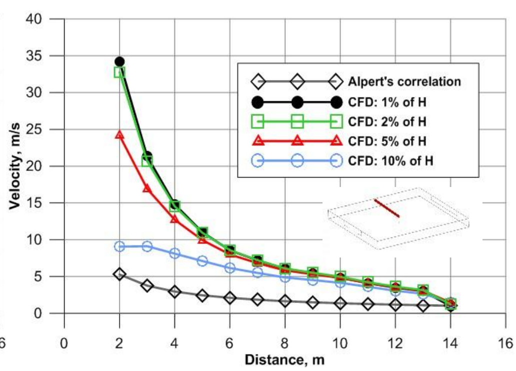
(a)



(b)



(c)



(d)

Fig. 2. A comparison of the Alpert correlation and CFD predictions of radial temperature and velocity beneath the ceiling at a range of heights for a 0.2993 kg/s hydrogen release through a 3.34 mm TPRD in a unconfined car park at 30 s (case 1) and a confined covered car park at 8 s (case 2) (a) case1 temperature, (b) case 1 velocity, (c) case 2 temperature, and (d) case 2 velocity.

It was found that for momentum dominated jets 1 and 2 % of H is the position at which the maximum temperature and velocity can be observed with slightly higher values at 1% H i.e a difference of 10

to 15 K with 2% H, and 1 to 2 m/s in the case of velocity. It can be concluded that the maximum radial temperature and velocity of an impinging momentum dominated jet can be measured at 1% of H.

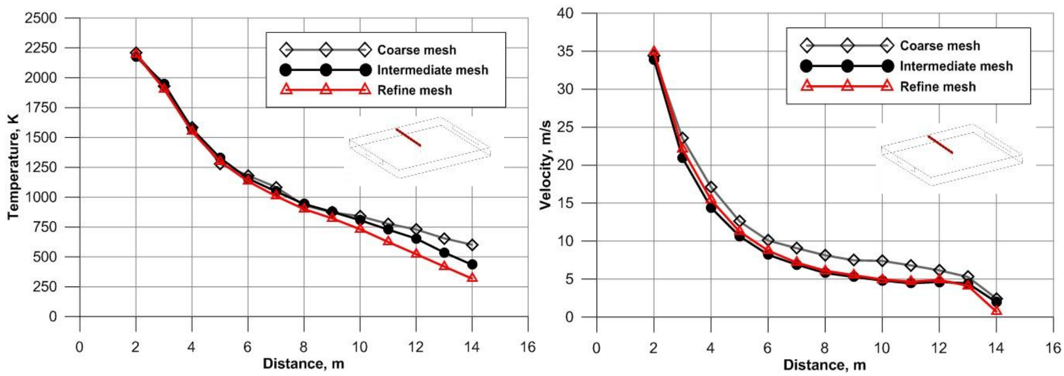
Grid independence study

In order to comply with the CFD model evaluation protocol [16], three different grids were simulated (coarse, intermediate, and refined). In each grid refinement, the average length of the computational cells was halved inside the car park, particularly in areas where high gradients and complex phenomena were expected. Specifically, localised refinement was provided around the hydrogen inlet, the ceiling and regions of the enclosure volume for all grids as recommended by Baraldi et al. [16]. The study was conducted for case 2 and the mesh details are summarised in Table 2.

Table 2: Mesh details for grid independence study

Mesh size	No. of cells	No. of faces	No. of nodes	Cells at leak
1. Coarse	691,759	2,297390	745,416	one
2. Intermediate	1,013,449	3,293,809	1,072,606	one
3. Refine	2,656,244	8,402,247	2,758,610	four

The temperature and velocity were measured at points under the car park ceiling at 1% of H, at an increasing radius from the jet axis at a flow time of 5.5s. Maximum temperature and velocity results are shown in Fig. 3. It can be seen that mesh resolution does not affect the results at the points close to the jet axis for temperature although a difference is evident for points, further from the axis, closer to the car park walls, in this region the gird is coarser with cells in the region of 20 to 30 cm lengthwise. However, the height of the cells is constant with distance from the jet axis to ensure the points at a distance of 1% H are captured. In the vicinity of the car park walls, the temperature differs by a factor of 2 between meshes, with the temperature predicted using a coarse grid twice that twice predicted by the refined mesh. The difference was most pronounced at this position. In terms of velocity prediction, higher values were predicted by the coarser mesh with little difference observed for the two more refined meshes. Both coarse and intermediate meshes were used in this study due to the computational expense of the refined mesh. The differences in temperature and velocity prediction in the regions of most interest were deemed minor compared to the difference in computational time (1 week versus 7 weeks for 5 s on a 64 core machine).



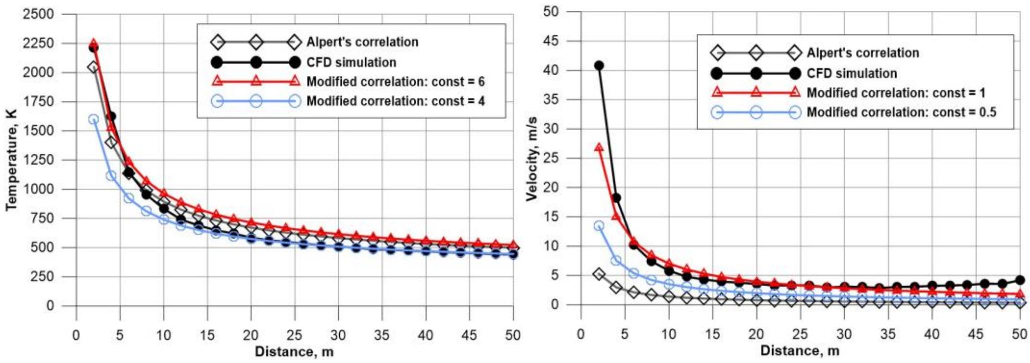
(a) (b)

Fig. 3. Temperature (a) and velocity (b) along the ceiling, for varying mesh resolutions in the covered car park, with a 0.2993 kg/s hydrogen release through a 3.34 mm TPRD (case 2) at flow time 5.5s

Unconfined ceiling with a constant release

Temperature predictions beneath the ceiling for a constant release through a 3.34 mm TPRD diameter into the unconfined ceiling geometry are shown in Fig. 4. The maximum temperature was calculated using the Alpert correlation and compared with CFD predictions at a height of 1% of H when the flow release time was 30 s and the hot gas had reached the edge of the unconfined ceiling 50 m from the jet axis. It was observed that there was good agreement between the numerical predictions and Alpert's correlation for a momentum dominated hydrogen jet fire, despite Alpert's correlation being developed for buoyancy dominated fire. The difference in temperature values close to the jet axis may be attributed to combustion occurring at this position, as opposed to hot gasses for which Alpert's correlation is appropriate. The correlation predicted larger temperatures by 9 to 15% for points further than 10 m from the jet axis. This may be attributed to the momentum dominated jet resulting in increased airflow and hence entrainment and cooling of the hot combustion products. In order to obtain better agreement between the temperature predicted by the numerical simulations, and Alpert's correlation, the constant (α) in equation 1 was modified from the original value of 5.38. Temperature predictions for modified α values of 6 and 4 are shown for the unconfined ceiling scenario in Fig. 4. When an value of 6 was used there was good agreement with CFD predictions of temperature in the region where combustion is occuring and close to the jet axis, with the modified correlation predicting tempartures 1 to 2 % higher than the CFD value at distances 10 m or greater from from the jet axis. When an value of 4 was used good agreement was seen in regions further from the jet axis, but temperature predictions using the modified correlation were lower than those simulated closer to the jet axis. However, the temperature predictions by both the modified and original correlations followed a similar trend to the simulation results, despite these correlations has been previously used only for bouyancy dominated fire only.

The Alpert correlation for velocity [6] predicted values 90% lower under the ceiling than those simulated. The original correlations were developed for buoyancy driven flows whereas the scenarios considered here are momentum dominated. Using the simulation values as a basis, the constant γ was modified, from the original value of 0.197. Fig. 4 compares the velocity predicted by the simulations to both the original and modified correlations, with a γ equal to 0.5 and 1 for a 0.2993 kg/s hydrogen release through a 3.34 mm TPRD in a unconfined car park at 30 s (case 1).



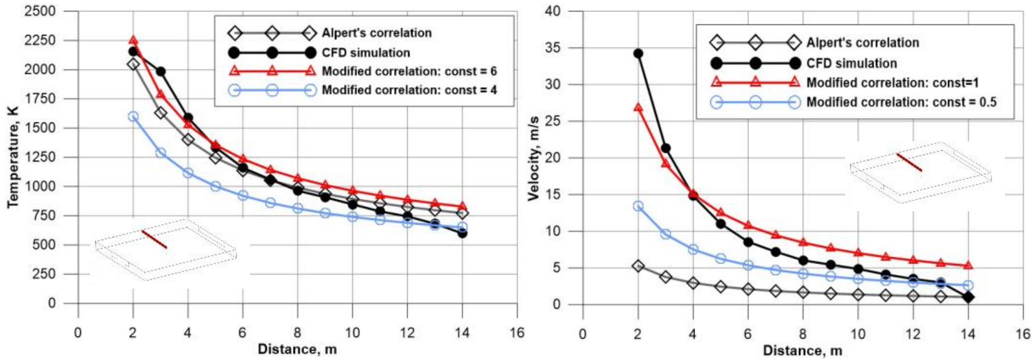
(a) (b)

Fig. 4. Comparison between simulation and correlation predictions for a 0.2993 kg/s hydrogen release through a 3.34 mm TPRD in an unconfined ceiling (case 1) at 30 s. The value was taken at radial positions (a) temperature and (b) velocity.

It was noticed that γ =1 provided the best match to numerical results at all positions except those closest to the jet axis, where the jet still had a very high momentum. In this near region γ, = 1.5 gave better agreement rather than 1.

Car park scenarios with a constant release

A 0.2993 kg/s constant release through a 3.34 mm TPRD in a naturally ventilated confined covered car park was simulated (case 2), the difference between this case and that discussed in the previous section is the enclosure geometry, particularly the inclusion of walls. Temperature and velocity measurements predictions under the ceiling for both simulations and correlations are shown in Fig. 5. In order to be comparable to the correlations, the numerical results were taken at a time where that jet had spread along the ceiling but before the hot gas had started to accumulate in the enclosure. Temperature contours with time are shown for the central plane of the car park in Fig. 7. The temperature and velocity measurements are based on a flow time of 8 s. It can be seen how, similar to the unconfined ceiling case, the modified Alpert correlation with a constant of 6 provided good agreement with the numerical results in the region closer to the jet axis. Differences are observed nearer to the car park walls which may be attributed to a number of factors including the flow dynamics and heat transfer to the surrounding surfaces. A modified constant of 4 in the Alpert correlation resulted in temperature predictions lower than the simulated results in the region of the jet axis. Velocity predictions followed a similar trend to that observed for the unconfined ceiling with an exception of the point closest to the wall. The modified Alpert correlation with constant of 1 showed good agreement with the numerical results, with differences observed in the immediate vicinity of the jet where to the highest momentum flow can be found. A slight overprediction by the modified correlation at distances further from the jet axis may be considered as a potential conservative approach.

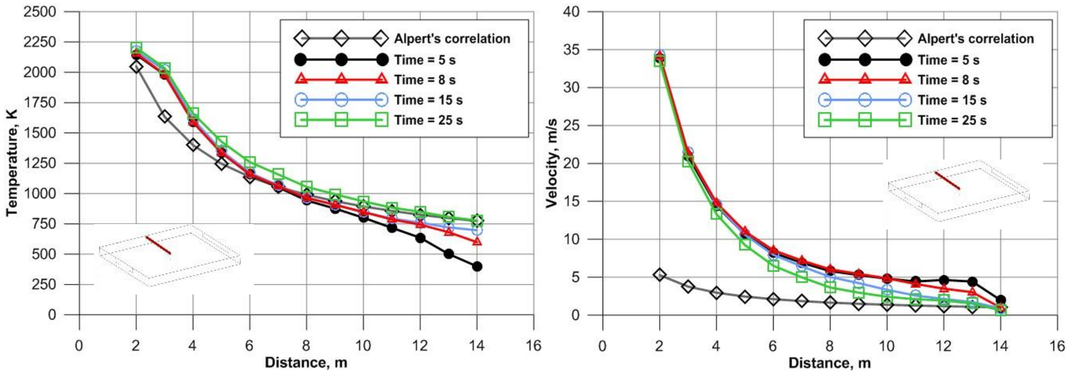


(a) (b)

Fig. 5. Comparison between simulation and correlation predictions for a 0.2993 kg/s hydrogen release through a 3.34 mm TPRD in a covered car park (case 2) at 8 s. The value was taken at radial positions : (a) maximum temperature and (b) maximum velocity.

Maximum temperatures and velocities under the ceiling for a 0.2993 kg/s hydrogen release through a 3.34 mm TPRD in a covered car park (case 2). were considered at different flow times in order to understand the effects of hot product accumulation and momentum dominated flow dynamics under the ceiling. Temperature and velocity values for four flow times (5, 8 15 and 25 s) are shown in Fig. 6. It was found that for the short period of 25 s there were no significant differences in terms of maximum temperature and velocity predictions at positions close to the jet axis. The temperature at the positions closer to the walls increased with time and reached a value near that predicted by the original Alpert correlation. Velocity decreased with increasing time in the regions further from the jet axis only Temperature contours in the central plane of the car park are flame shown in Fig. 7. Within 15 s accumulation is observed with hot gasses reaching the carpark walls within 8 s. Within 25 s, the car park is fully occupied by a hot gasses at 390 K or above, which is higher than the recommended no harm temperatures 343 K and harm and injury temperature of 388 K [10]. It was observed how the temperature of the car park walls and floor temperature started to rise to 390 K after just 2 s as a result of radiative heat transfer.

This work indicated that safety issues for an ignited hydrogen release in a car park should be further investigated beyond this study.



(a) (b)

Fig. 6. Radial results for a 0.2993 kg/s hydrogen release through a 3.34 mm TPRD in a covered car park (case 2) for a range of flow times: (a) maximum temperature and (b) maximum velocity.

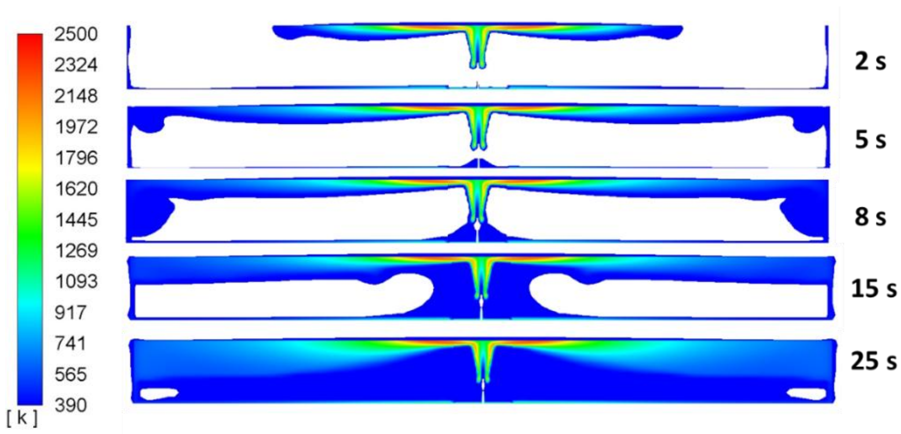
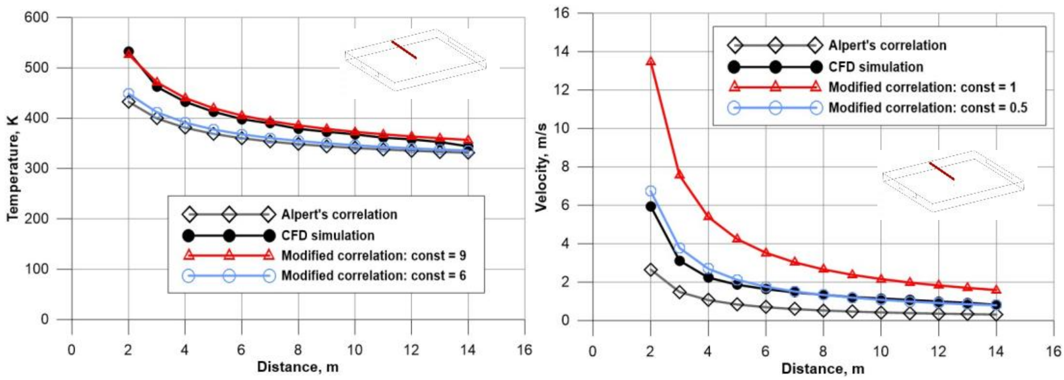


Fig. 7. Temperature contours along the central plane of the covered car park, for a constant 0.2993 kg/s hydrogen release through a 3.34 mm TPRD.

The previous sections have focused on releases through a 3.34 mm TPRD and it has been clearly shown how for such a release, hot gasses fill the car park enclosure in 25s. Thus a smaller release diameter of 0.5 mm was considered (case 3) in the same car park geometry. The mass flow rate of the release was 0.0067 kg/s, yielding a heat release rate of 803 kJ/s. As with the previous scenarios, maximum temperature and velocity under the car park ceiling were compared with both the original and modified Alpert correlations. Predicted temperatures and velocities are shown in Fig. 8. Temperatures predicted by the simulations were approximately 8% greater than those predicted by the Alpert correlation. Unlike the previous, higher release rates considered, a modified correlation with a constant of 6 did not provide the best agreement with simulations, particularly in the region close to the jet axis. Instead, for the smaller release rate, a constant of 9 was found to show closer agreement. This case represents a lower momentum release closer to the ceiling and unlike the higher release rates, the combustion process is not observed close to the ceiling. The best agreement between simulation and correlation for velocity predictions was observed for a modified correlation with a constant of 0.5, compared to 1 for the higher release rates. This is to be expected, given the difference in the momentum of the jets closer to the ceiling.

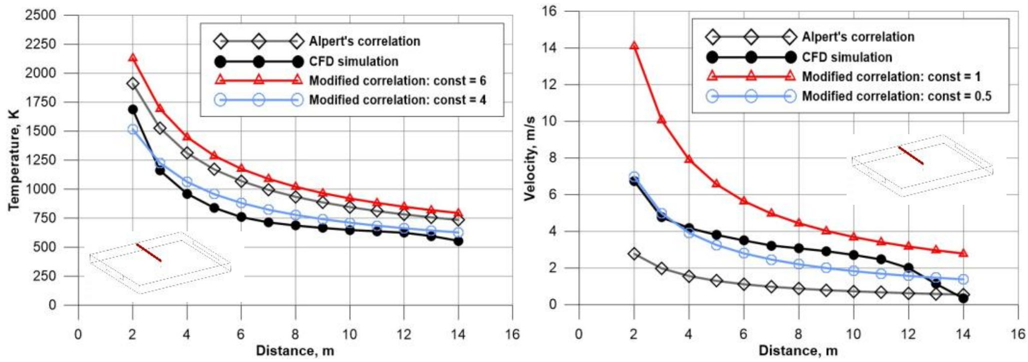


(a) (b)

Fig. 8. Radial results for a 0.0067 kg/s hydrogen release through a 0.5 mm TPRD in a covered car park (case 2) for a range of flow times Points from the jet axis to the edge of the covered car park (case 3) at flow time 20s: (a) maximum temperature and (b) maximum velocity.

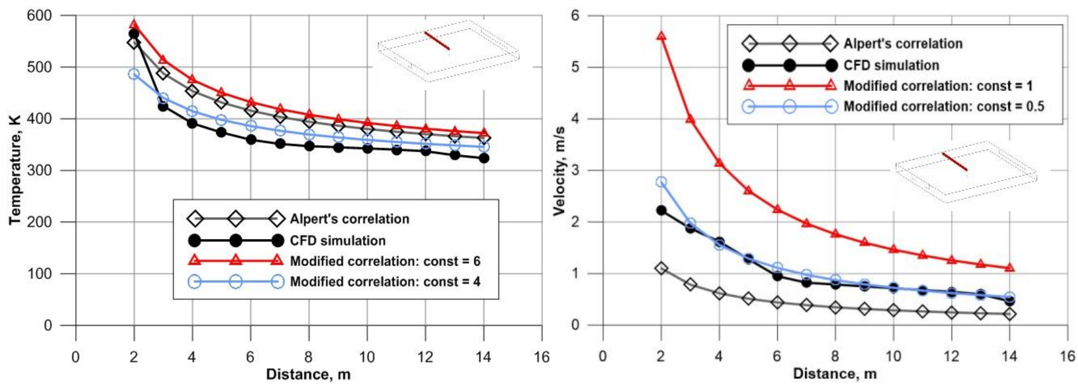
Release in a car park with blow-down

The releases considered in the previous sections were the constant rate, facilitating more direct comparison with the Alpert correlations. It should be noted that a constant hydrogen release is an ideal case, and in reality, there will be blown down from hydrogen onboard storage, resulting in mass flow rate decay. Two real case scenarios were considered, representing a TPRD release from onboard storage in a covered car park, in both cases blow down and the car geometry were accounted for. Blowdown from 700 bar storage was simulated through a TPRD diameter of 2 (case 4) and 0.5 mm (case 5). It was expected that the decay of mass flow rate would directly affect the maximum temperature and velocity under the ceiling and thus a comparison was made to understand the applicability of the modified Alpert correlations. Predicted temperature and velocity for blow down through a 2 mm TPRD are shown in Fig. 9. The original Alpert correlation and modified versions predict higher temperatures than those simulated, this is not unexpected as the correlations were developed based on a constant total heat release rate. However, as previously mentioned the correlations could be used to provide conservative estimates. As with the previous scenarios, the Alpert correlation for velocity predicted values lower than those simulated. However, a modified correlation with a constant of 0.5 for case 3 shows good agreement in this scenario. Predicted temperature and velocity values for blowdown from 700 bar through a 0.5 mm diameter TPRD are shown in Fig. 10.



(a) (b)

Fig. 9. Radial results for blowdown through a 2 mm TPRD diameter in a covered car park (case 4) at flow time 10s: (a) maximum temperature and (b) maximum velocity.



(a) (b)

Fig. 10. Radial results for blowdown through a 0.5 mm TPRD diameter in a covered car park (case 5) at flow time 22s: (a) maximum temperature and (b) maximum velocity.

From Fig. 10 it can be seen how temperatures predicted using the correlations are greater than those simulated by approximately 13% in the case of the original correlation an from 7 to 19% for the modified correlation. As with the previous case, the best agreement for velocity predictions was found between simulation and a modified correlation with a constant was 0.5

CONCLUSION

Five cases were numerically simulated and compared with the original Alpert correlations [6] for maximum temperature and velocity under a ceiling in order to understand the applicability of these correlations to a momentum controlled hydrogen jet fire. An unconfined large ceiling with dimensions (100 m x 100 m) was used to directly compare the correlation with the numerical model, The applicability to “real scenarios” was also considered by investigating two constant hydrogen release cases in a naturally ventilated covered car park, and two blow down scenarios. It has been demonstrated that, as with buoyancy dominated fires, maximum temperature and velocities occur for momentum dominated jets at an height of approximately 1 % of H. It can be concluded that the original Alpert correlations can provide an estimate of the maximum temperatures under the ceiling for a momentum driven jet, with values estimated as 10% greater than those observed in simulations. However, a modified correlation with a constant of 6 shows good agreement with simulations for temperature predictions, particularly closer to the jet axis in cases of higher release rate, momentum dominated jets. A modified correlation with a constant of 4 showed good agreement with simulations at positions outside the combustion zone for a constant hydrogen release. This modified correlation also showed better agreement with simulation results for blowdown scenarios. Simulations predicted velocities 90% greater than those predicted by the original Alpert correlation, which may be attributed to the high momentum of the jet high. A modified correlation for velocity, with a constant of 1 provided good agreement with simulations for the highest momentum jets, and a modified correlation with a constant of 0.5 showed better agreement in the case of lower momentum jets and blowdown scenarios.

REFERENCES

[1] B.P. Xu, J.X. Wen, Numerical study of spontaneous ignition in pressurized hydrogen release through a length of tube with local contraction, Int. J. Hydrogen Energy. 37 (2012) 17571–17579. doi:10.1016/j.ijhydene.2012.04.150.

[2] R.L. Alpert, The Fire-Induced Ceiling-Jet Revisited, Fireseat. (2011).

[3] R.L. Alpert, Calculation of response time of ceiling-mounted fire detectors, Fire Technol. 8 (1972) 181– 195. doi:10.1007/BF02590543.

[4] R.L. Alpert, Turbulent ceiling-jet induced by large-scale fires, Combust. Sci. Technol. 11 (1975) 197–213. doi:10.1080/00102207508946699.

[5] B. Karlsson, J. Quintiere, Enclosure fire dynamics, CRC press, 1999.

[6] R.L. Alpert, Ceiling jet flows, in: SFPE Handb. Fire Prot. Eng. Fifth Ed., 2016. doi:10.1007/978-1-49392565-0_14.

[7] H. G. Hussein, S. Brennan, D. Makarov, V. Shentsov, V. Molkov, Numerical validation of pressure peaking from an ignited hydrogen release in a laboratory-scale enclosure and application to a garage, Int. J. Hydrogen Energy. (2018). https://doi.org/10.1016/j.ijhydene.2018.07.154.

[8] British Standard institution BS 7346-7:2013, Components for smoke and heat control systems – Part 7: Code of practice on functional recommendations and calculation methods for smoke and heat control systems for covered car parks, 2013.

[9] Nederlands Normalisatie-Instituut NEN 2443. parkeren en stallen van personenauto's op terreinen en garages, ICS 91.040.99, 2000.

[10] V. Molkov, Fundamentals of Hydrogen Safety Engineering I, eBooks and textbooks from bookboon. com., 2012.

[11] V. Molkov, D. Makarov, and M. Bragin, Physics and modelling of underexpanded jets and hydrogen dispersion in atmosphere, in: 2009.

[12] ANSYS Fluent R16.2 User Guide, (2016).

[13] S. Brennan, H. G. Hussein, D. Makarov, V. Shentsov, V. Molkov, Pressure effects of an ignited release from onboard storage in a garage with a single vent, Int. J. Hydrogen Energy. (2018). https://doi.org/10.1016/j.ijhydene.2018.07.130.

[14] L. Yan, G. Yue, B. He, Development of an absorption coefficient calculation method potential for combustion and gasification simulations, Int. J. Heat Mass Transf. 91 (2015) 1069–1077. doi:10.1016/j.ijheatmasstransfer.2015.08.047.