Article

Simulation of Possible Fire and Explosion Hazards of Clean Fuel Vehicles in Garages

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Abstract: Clean fuel is advocated to be used for sustainability. The number of liquefied petroleum gas (LPG) and hydrogen vehicles is increasing globally. Explosion hazard is a threat. On the other hand, the use of hydrogen is under consideration in Hong Kong. Explosion hazards of these clean fuel (LPG and hydrogen) vehicles were studied and are compared in this paper. The computational fluid dynamics (CFD) software Flame Acceleration Simulator (FLACS) was used. A car garage with a rolling shutter as its entrance was selected for study. Dispersion of LPG from the leakage source with ignition at a higher position was studied. The same garage was used with a typical hydrogen vehicle leaking 3.4 pounds (1.5 kg) of hydrogen in 100 s, the mass flow rate being equal to 0.015 kgs^{-1}. The hydrogen vehicle used in the simulation has two hydrogen tanks with a combined capacity of 5 kg. The entire tank would be completely vented out in about 333 s. Two scenarios of CFD simulation were carried out. In the first scenario, the rolling shutter was completely closed and the leaked LPG or hydrogen was ignited at 300 s after leakage. The second scenario was conducted with a gap height of 0.3 m under the rolling shutter. Predicted results of explosion pressure and temperature show that appropriate active fire engineering systems are required when servicing these clean fuel vehicles in garages. An appropriate vent in an enclosed space such as the garage is important in reducing explosion hazards.

Keywords: explosion hazard; clean fuel; LPG vehicles; hydrogen vehicles; garages

1. Introduction

Clean fuel [1–3] is expected to be widely used for vehicles in advocating for sustainability. Liquefied petroleum gas (LPG) has been used as fuel for vehicles on a limited scale as early as 1912 [1,4]. The desire to reduce the dependence on crude oil boosted the popularity of LPG fueled vehicles in 1970s and 1980s. With growing environmental concerns, the demand for alternative fuels is also increasing.

Although LPG is suitable for different types of vehicles, e.g., vans, truck and buses, this fuel is mainly used in passenger cars including taxis in many dense urban Asia-Oceania areas, such as Hong Kong. In order to reduce emissions from vehicles, the LPG Vehicle Scheme was introduced in 1999 [4,5].

- An incentive scheme in 2000 for replacing diesel taxis with LPG taxis.
- An incentive scheme in 2002 for the replacement of diesel light buses with LPG or electric light buses.

The LPG taxi incentive scheme and the diesel light buses replacement scheme were completed at the end of 2003 and 2005, respectively. About 99.9% taxis and over 3100 light buses were switched to LPG through these schemes.

In April 2017, there were 18,152 LPG taxis and 4031 LPG mini buses registered in Hong Kong [6]. With the government's strong incentive for phasing out diesel commercial vehicles, the number of LPG taxis and mini buses is expected to surge continuously.

On 30 April 2017, a compressed natural gas (CNG) fuelled taxi caught fire and exploded in Buona Vista, Singapore [7]. Four people, including an SCDF officer, were injured. The incident once again alerted the public to the fire and explosion hazards of clean fuel vehicles.

The LPG filling station in Hong Kong is classified as a "notifiable gas installation" under the Gas Safety Ordinance Cap. 51 [8]. As part of the approval requirement, a quantitative risk assessment is required to demonstrate that the risk levels associated with stations are acceptable. Moreover, all operators of the stations shall receive proper training on filling operation and emergency response. Specially designed safety features are also required for LPG stations.

The safety of filling facilities has drawn a wide range of public concerns and detailed construction requirements have been formulated [9]. Yet, few people were aware that LPG vehicle maintenance may possibly be ticking time bombs until a deadly explosion occurred at a garage in Hong Kong in April 2015 [10] (Figure 1).

Figure 1. Garage explosion in Wong Tai Sin, Hong Kong.

Although the use of hydrogen vehicles is not yet popular in Hong Kong, the number of hydrogen vehicles is surging all over the world; still, explosion hazards are not properly discussed. There have been many reported fires and explosions caused by fuel.

In this study, the explosion hazards of LPG and hydrogen vehicles in a garage were numerically studied by computational fluid dynamics (CFD) simulations [1–3,11–22]. The software Flame Acceleration Simulator (FLACS) [23] was used to simulate explosions in different scenarios.

2. An Example Garage

An example garage of size 8.1 m (x-direction) × 3.6 m (y-direction) × 3.9 m (z-direction) as shown in Figure 2a is used in the simulation. A roller shutter is provided at x = 8.1 m with a height of 3.6 m from ground level. The rolling shutter is assumed to be able to withstand a pressure of 0.2 bar.

The horizontal direction of the computational domain, i.e., x-direction, is extended to 1.5 m outside the roller shutter.

A typical amount of 95.5 L (48.705 kg) LPG, which is a full tank for a typical five-seater taxi, would be released [24]. According to Van den Schoor et al. [25], the vapour mass rates for the most probable release scenarios of LPG are shown in Table 1. LPG is assumed to be composed of 40% propane and 60% butane.
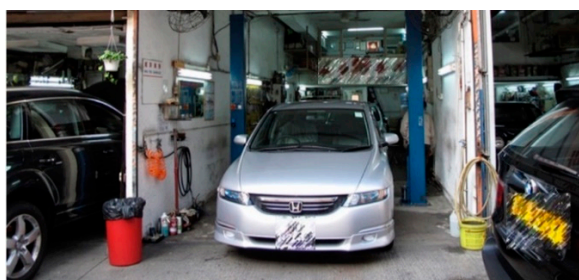
(**a**)
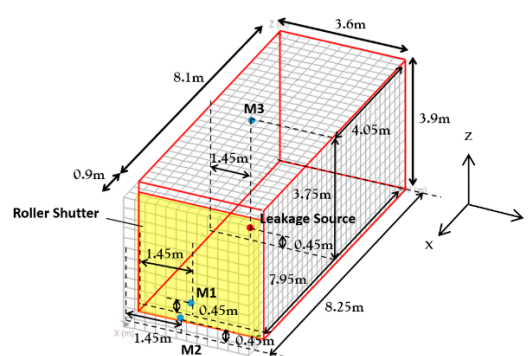
(**b**)

Figure 2. The simulation garage used in the present study. (**a**) Outlook; (**b**) Monitoring points in 3D views.

Table 1. Vapour mass flow rate.

Release Scenario	Initial Pressure (Barg)	Initial Temperature (°C)	Mass Flow Rate (kgs^{-1})
Overfilling and subsequent opening of pressure relief valve (PRV).	27	27	0.59
PRV opens spuriously.	9	27	0.21
Leakage from a hole in the fuel tank.	9	27	0.21
Vehicle fire and subsequent opening of PRV.	27	74	0.55

Considering the scenario of leakage from a hole in the fuel tank, the mass flow rate would be 0.21 kgs^{-1}. A fully filled LPG tank would be completely released in about 231 s. The leakage source is located at the centre of the garage with a height of 0.45 m above floor level, i.e., x = 4.05 m, y = 1.45 m and z = 0.45 m. LPG is discharged through a rectangular nozzle of dimensions 0.3 m by 0.3 m with a downward ($-$z) leakage direction. For simplicity, the vehicle is not modelled in the simulation.

3. Numerical Simulation

The grid system with mesh size used in software FLACS is 0.3 m $\times$ 0.3 m $\times$ 0.3 m as shown in Figure 2b.

According to a previous study by Hansen et al. [26], the FLACs simulation results were reasonably close to experimental data for different experimental configurations with a maximum grid size Δx, Δy and Δz given in terms of the cloud volume V as:

Max (Δx, Δy, Δz) = 0.1 $\times$ V$^{1/3}$.

For a cloud volume V of about 58.32 m^3 (8.1 m $\times$ 3.6 m $\times$ 2 m), the maximum allowable grid size would be 0.39 m.

Through assigning the boundary conditions of the computation domain, possible effects of surface compression at the roller shutter to the convective flow field are considered.

In the preliminary study of the explosion behaviour of an LPG taxi in a garage, three scenarios at different operation times judging from the fire investigation report are considered:

● Simulation C1:

The ignition process starts at 50 s after the start of the leakage. The ignition point is assumed to be x = 4.05 m, y = 1.45 m and z = 0.15 m with x, y, z directions shown in the figure.

- Simulation C2:

  The ignition process starts at 100 s after the start of the leakage.

- Simulation C3:

  The ignition process starts at 150 s after the start of the leakage.
  The monitoring points M1 and M3 are inside the garage, M2 is outside as in Table 2 to present CFD simulation results.

Table 2. Monitoring points inside and outside the garage.

Monitoring Point	x/m	y/m	z/m	Remarks
M1	7.95	1.45	0.45	Near the roller shutter in the garage
M2	8.25	1.45	0.45	Near the roller shutter out of garage
M3	4.05	1.45	3.75	Near the ceiling above the point of ignition

4. Pressure Explosion

Pressure explosion comes from the building up of pressure during combustion. For monitoring point M1, i.e., near the roller shutter in the garage, the variations of pressure in the above three scenarios are as shown in Figure 3a–c.
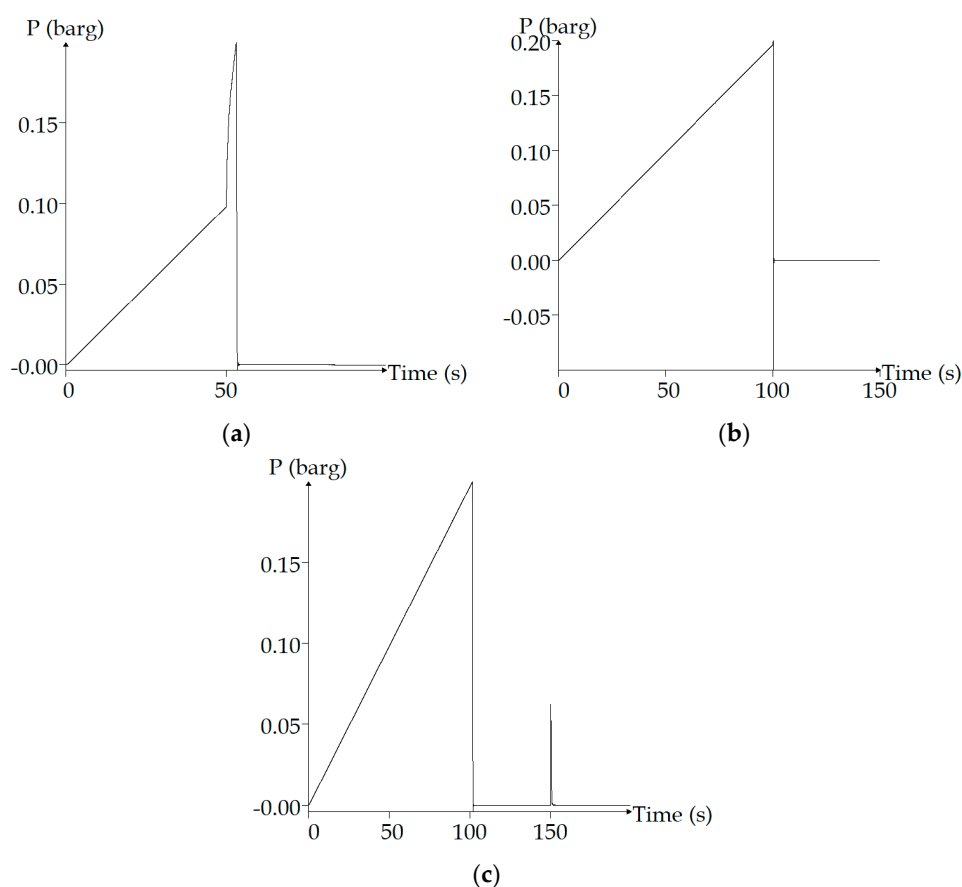
Figure 3. Pressure variations at monitoring point M1. (**a**) Simulation C1; (**b**) simulation C2; (**c**) simulation C3.

In simulation C1, before the ignition at t = 50 s, pressure is built up inside of the garage due to the leakage of LPG. However, the pressure is below 0.2 barg and the roller shutter

is kept in the closed position. At t = 50 s, the ignition process starts and a rapid surge in pressure is observed. At about t = 53 s, the pressure reaches 0.2 barg and a drop in pressure is noted due to the opening of the roller shutter for controlling pressure rise.

In simulation C2, alike to Simulation C1, pressure is built up constantly inside of the garage due to the leakage of LPG before the ignition. A jump of pressure is observed during the ignition at t = 100 s, followed by a drop in pressure due to the opening of the roller shutter at 0.2 barg.

In simulation C3, pressure is built up constantly inside of the garage due to the leakage of LPG. At t = 102 s, the pressure is over 0.2 barg and the roller shutter is opened due to the over pressure. A drop in pressure due to the opening of the roller shutter at 0.2 barg and a surge in pressure is observed during the ignition at t = 150 s.

For monitoring point M2, i.e., near the roller shutter out of the garage, as shown in Figure 4a, surges are noted at the time of ignition in all three scenarios. The maximum surge in pressure is noted in Simulation C2.
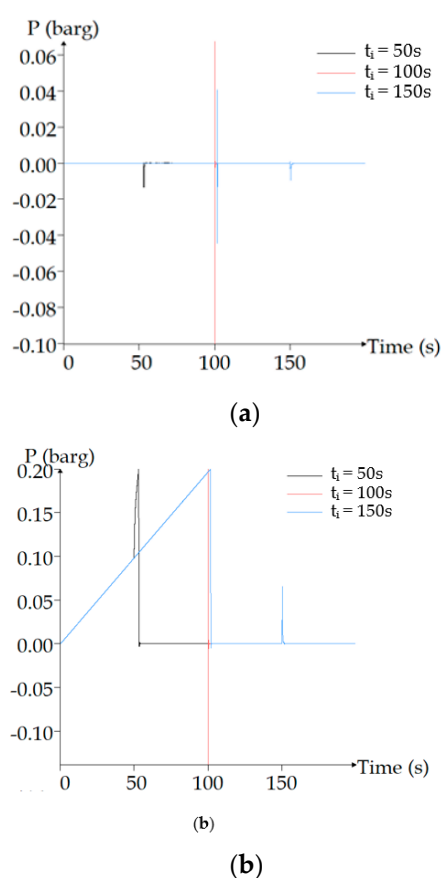
(a)

(b)

Figure 4. Pressure variations. (**a**) At monitoring point M2; (**b**) at monitoring point M3.

For monitoring point M3, i.e., near the ceiling above the point of ignition in Figure 4b, the maximum pressures recorded in all three scenarios are 0.2 barg. For simulations C1 and C2, the pressures are built after the ignition of leaked LPG. However, the pressure in simulation C3 is built up to 0.2 barg due to the accumulation of LPG in the garage.

5. Temperature

The transient temperature distributions for the three scenarios are compared in Figure 5.
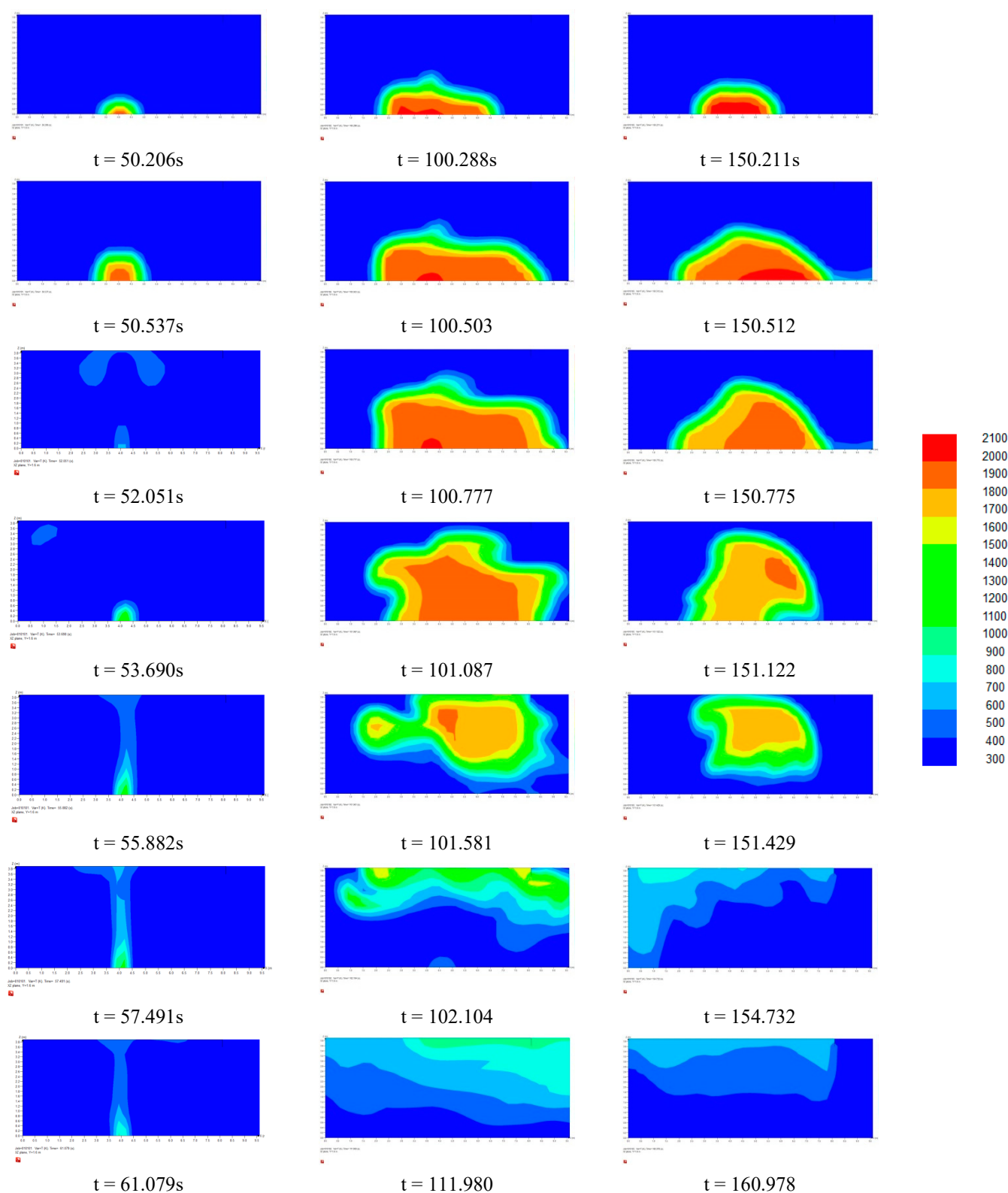
Figure 5. Transient temperature distributions.

In simulation C1, the surge in temperature is localized near the point of leakage and ignition. However, the extent of temperature increase in simulations C2 and C3 is much greater than that of C1. Similar post-explosion transient temperature profiles are noted in both simulations C2 and C3.

The area of high temperature then propagates in the upward direction which is a natural phenomenon due to the hot gas movement.

It is also noted that the transient temperature profiles in simulation C2 are extended towards positive x-direction when compared with that of C3. In simulation C2, higher explosion pressure is generated by the explosion which would push the hot gas and cause the elongation of transient temperature profile.

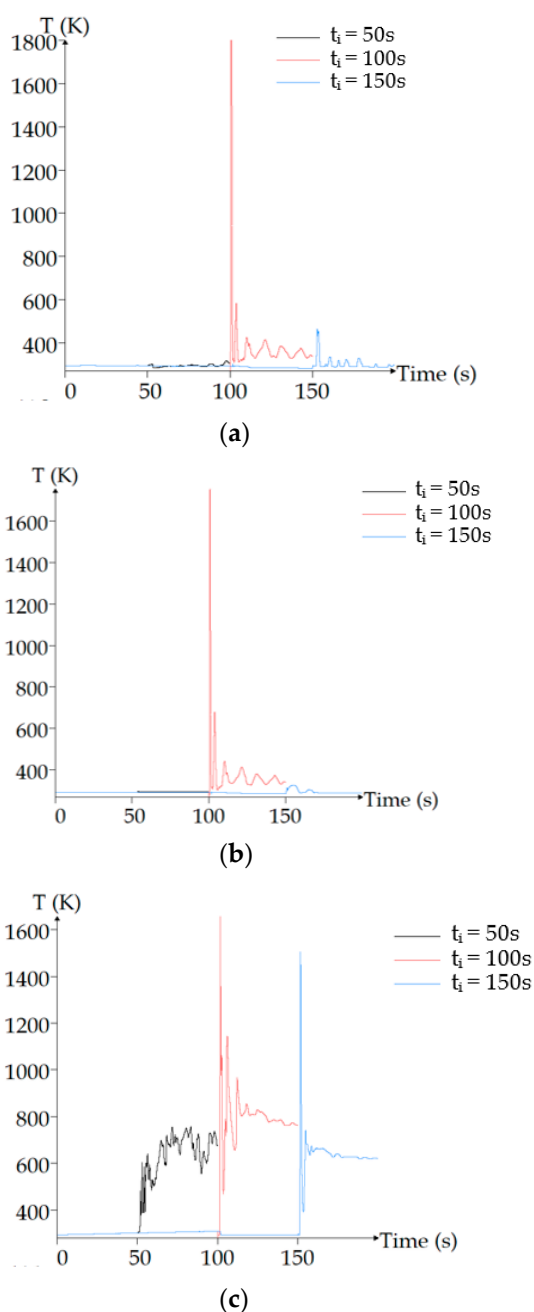The temperature profiles measured at monitoring point 1 are shown in Figure 6a.

(a)

(b)

(c)

Figure 6. Temperature profiles. (**a**) At monitoring point M1; (**b**) at monitoring point M2; (**c**) at monitoring point M3.

For C1, the maximum temperature at the monitoring point 1 is observed at t = 53.2 with T = 302.362 K.

For C2, the maximum temperature at the monitoring point 1 is observed at t = 101.0 with T = 1791.02 K.

For C3, the maximum temperature at the monitoring point 1 is observed at t = 152.8 with T = 462.04 K.

The temperature profiles measured at monitoring point 2 are shown in Figure 6b. The temperature profiles measured at monitoring point 3 are shown in Figure 6c. Among the three monitoring points, the maximum surge in temperature is noted in Simulation C2.
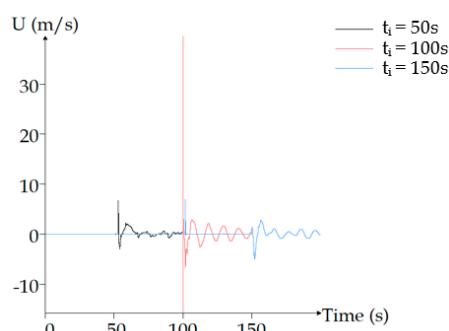
6. Horizontal Component of Velocity

The horizontal component of fluid velocity U at the three monitoring points M1 to M3 are shown in Figure 7. Positive U refers to out-flowing of fluid from the garage while negative U means the flowing of fluid into the garage.
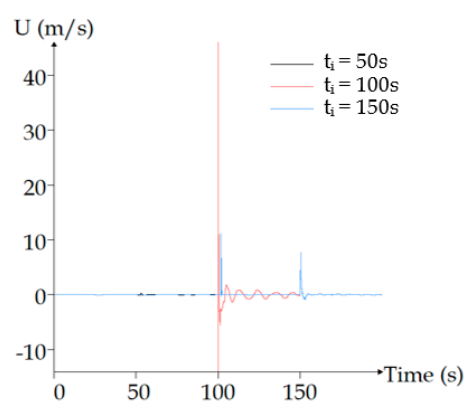
(a)
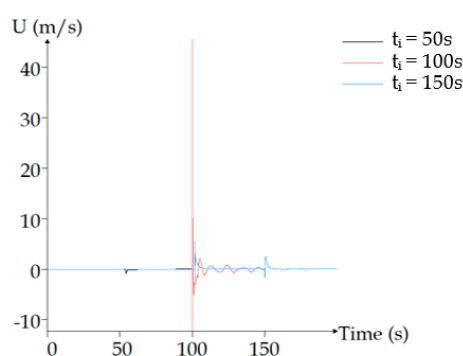
(b)

(c)

Figure 7. Transient horizontal velocity. (**a**) At monitoring point M1; (**b**) at monitoring point M2; (**c**) at monitoring point M3.

Among the three monitoring points, the maximum change in velocity is also noted in Simulation C2.

7. Discussion

Among the three monitoring points, the maximum surge in velocity is also noted in Simulation C2.

In the above simulation scenarios, it is noted that scenario C2 would result in a greater increase in pressure, temperature and velocity than that of C3.

In C3, the pressure is built up constantly inside of the garage due to the leakage of LPG until the pressure is over 0.2 barg. Then the roller shutter is opened due to the over pressure and LPG is allowed to diffuse out of the garage. The tragic consequences of the explosion are lessened in Simulation C3.

To further study the effect of ventilation on explosion [27–31], the following simulations are conducted:

- Simulation C2-1:

Simulation configuration is exactly the same as for C2, with the ignition process started at 100 s after the start of leakage. (d = 0 m, where *d* is the distance from the floor)

- Simulation C2-2:

Simulation configuration is exactly the same as for C2, with the ignition process started at 100 s after the start of leakage, except with a gap of 0.3 m located at the bottom of the roller shutter. (d = 0.3 m)

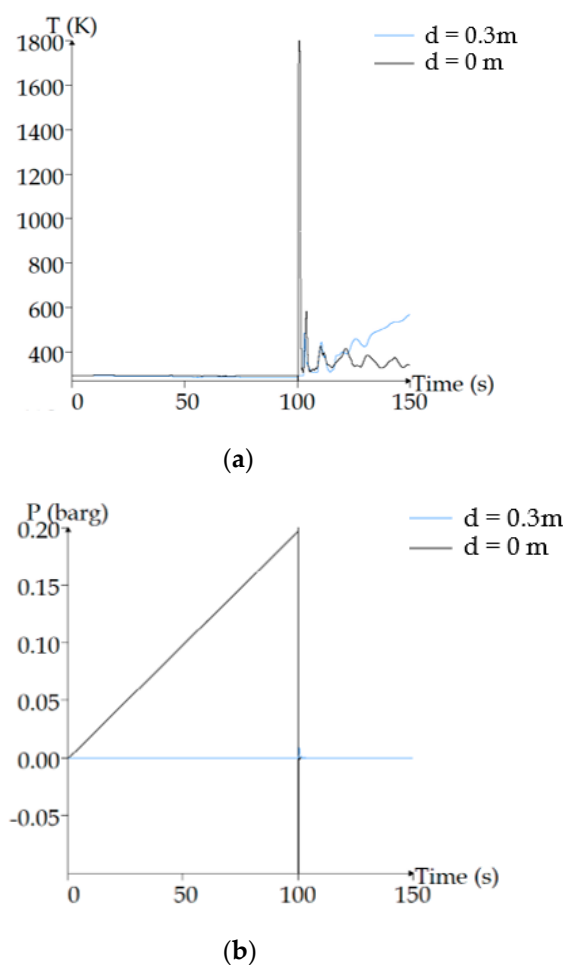The temperature, velocity and pressure profile at monitoring point M1 are shown in Figure 8a–c.
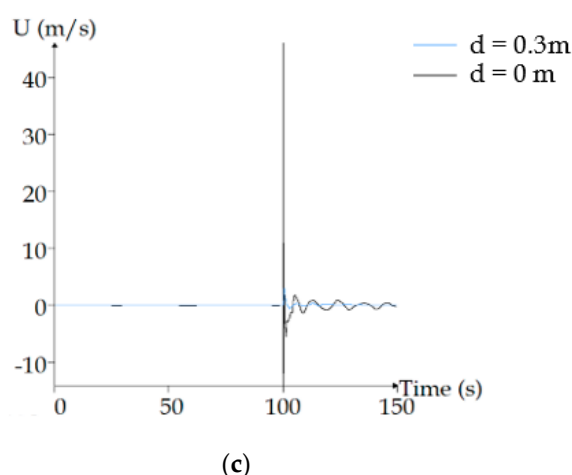
(a)

(b)

Figure 8. *Cont.*

(c)

Figure 8. At monitoring point M1. (**a**) Temperature; (**b**) pressure; (**c**) horizontal velocity.

With the presence of a gap of 0.3 m at the bottom of the roller shutter, a smaller increase in temperature, velocity and pressure induced by the ignition at t = 100 s is observed.

The results highlighted the importance of low-level ventilation in a garage, which might effectively lessen the tragic consequences of an explosion.

8. Thermal Hazard of Hydrogen Vehicles in Enclosed Spaces

The explosion hazards of hydrogen vehicles [32–37] were also studied using the CFD-FLACS.

The same simulated garage was used. According to the fuel leak simulation by Swain [38], a hydrogen vehicle leaked 3.4 pounds (1.5 kg) of hydrogen in 100 s. The mass flow rate is then assumed to be 0.015 kgs^{-1}. Taking the Toyota Mirai as a reference hydrogen vehicle in the simulation, the Mirai has two hydrogen tanks with a three-layer structure made of carbon fibre-reinforced polymer and the tanks have a combined capacity of 5 kg. The whole tank would be completely vented out in about 333 s.

Two more simulations were carried out on hydrogen vehicles:

● Simulation H1

The ignition process of hydrogen starts at 333 s after the start of leakage.

For M1 near the roller shutter inside the garage, the pressure is built up constantly inside of the garage due to the leakage of hydrogen before the ignition as shown in Figure 9. A jump in the pressure is observed at ignition at t = 333 s. However, the small increase in pressure is still far from being sufficient to open roller shutter, although the full tank of hydrogen has leaked out.
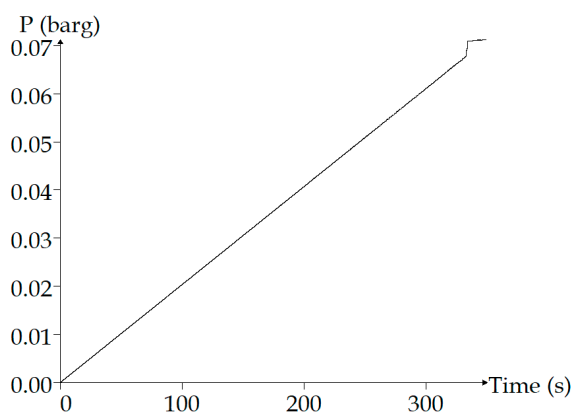

Figure 9. Simulation H1.

● Simulation H2

The ignition process of hydrogen starts at 100 s after the start of leakage.

The temperature measured at M3 near the ceiling above the point of ignition is provided in Figure 10.
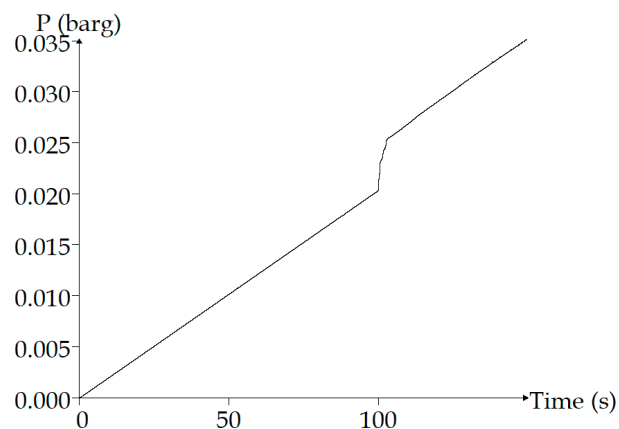

Figure 10. Simulation H2.

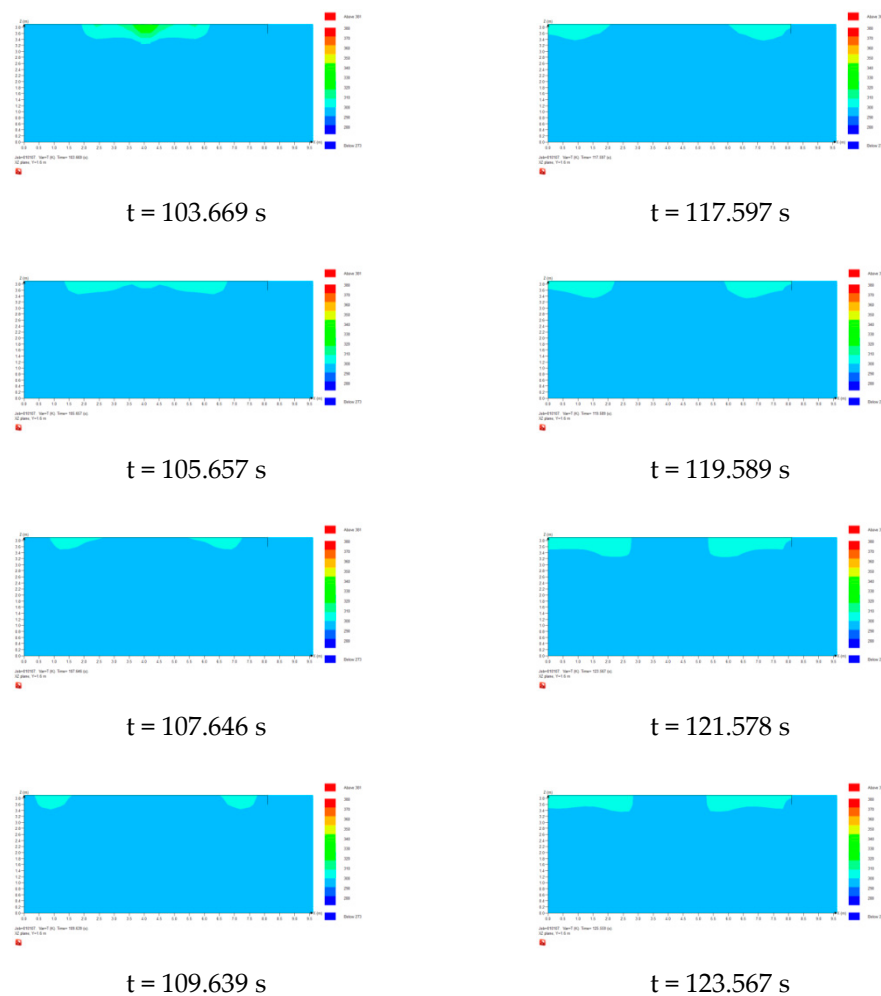The transient temperature distributions for scenario H2 are shown in Figure 11.

t = 103.669 s

t = 117.597 s

t = 105.657 s

t = 119.589 s

t = 107.646 s

t = 121.578 s

t = 109.639 s

t = 123.567 s

Figure 11. *Cont.*

t = 111.627 s

t = 125.559 s

t = 113.616 s
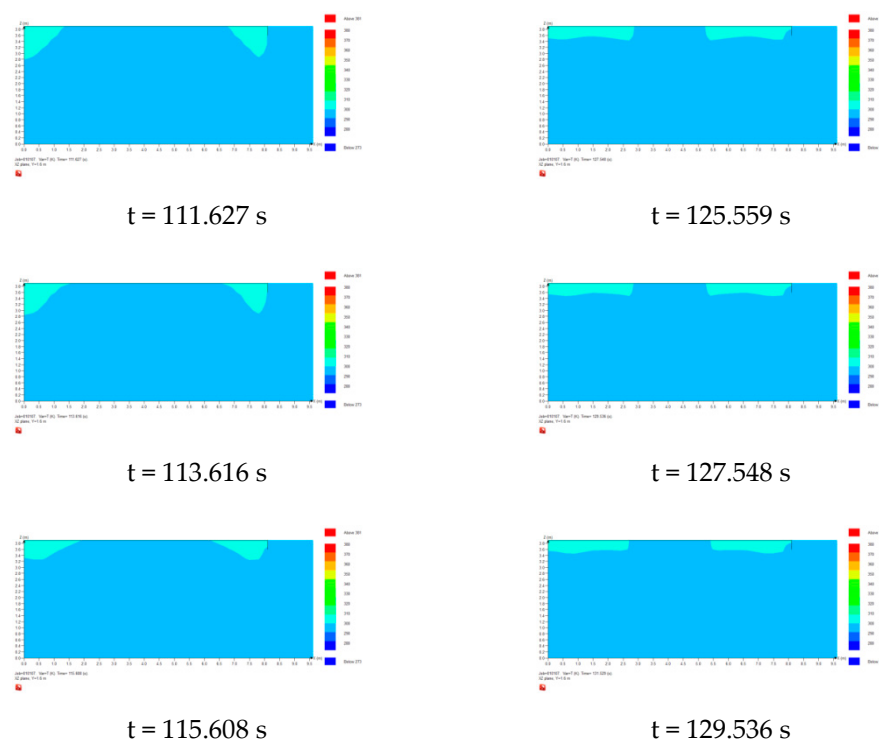

t = 127.548 s

t = 115.608 s

t = 129.536 s

Figure 11. Transient temperature distributions of simulation H2.

The temperature of hot gas is found much lower than the case of LPG vehicle explosion. Unlike the transient temperature profile in Figure 5, the hot gas region is located at the upper part of the garage and pushed toward the ends of the garage.

Although the ignition time is at t = 100 s for simulation C2 for LPG taxis and H2 for hydrogen taxis, the surge in temperature at M3 near the ceiling above the point of ignition is found to be much greater in case of LPG leak in C2 (Figure 12).
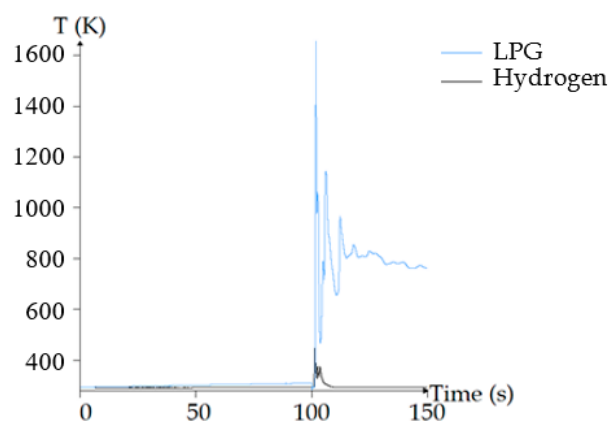

Figure 12. Comparing LPG and hydrogen at monitoring point M3.

Two more simulations on lower-level ventilation for H2 are carried out:

- Simulation H2a

Simulation configuration is exactly the same as H2, with the ignition process started at 100 s after the start of leakage (d = 0 m).

- Simulation H2b

Simulation configuration is exactly the same as H2, with the ignition process started at 100 s after the start of leakage, except with a gap of 0.3 m located at the bottom of the roller shutter (d = 0.3 m).

The pressure variations measured at M3 in Simulation H2a and H2b are shown in Figure 13a. Due to the 0.3 m opening at the bottom of the roller shutter, the pressure fails to build up in Simulation H2b.
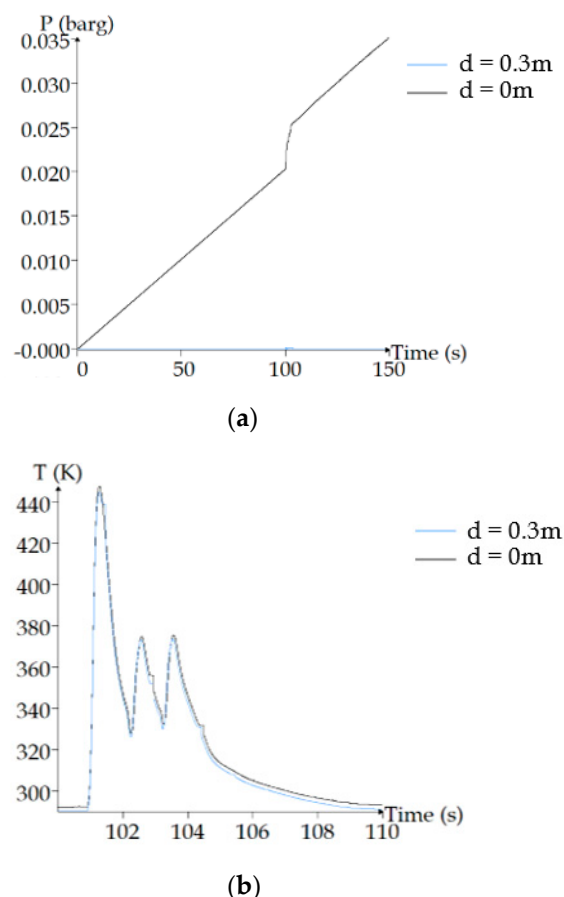

(a)

(b)

Figure 13. Results at monitoring point M3 of simulations H2a and H2b. (**a**) Pressure variations; (**b**) temperature variations.

The temperature variations measured at M3 in Simulation H2a and H2b are shown in Figure 13b. Similar temperature profiles are noted in both cases. The peak temperature measured in Simulation H2b is slightly lower than that in H2a. Since hydrogen is lighter than the air, the leaked hydrogen would accumulate in the upper part of the garage. Low-level ventilation could not improve the situation in this case. The slight drop is attributed to the heat exchange with the atmosphere through the 0.3 m opening.

9. Conclusions

The explosion hazards of LPG and hydrogen vehicles are outlined in this paper.

The technology of LPG fuelled vehicles has been well established for a long time. The major hazard of LPG fuelled vehicle is the gross leakage under failure condition of the fuel tanks and associated piping [39].

Our simulation results highlighted the importance of low-level ventilation in lessening the hazardous consequences of an LPG vehicle explosion.

Comparing the simulation results of C2 and H2, it is noted that the resulted surge in temperature and pressure by the explosion at t = 100 s are smaller in the case of hydrogen. However, the explosion risk of hydrogen should not be overlooked.

Hydrogen could leak out of a system which is considered as gas-tight for other gases. Hydrogen also has a wide range of flammable limit (4–75%) while the flammability limit of LPG only ranges from 2.1–9.5%. Besides, the gross calorific value of hydrogen is 158.9 MJkg^{-1} which is much higher than 50.49 MJkg^{-1} of LPG [24].

Although the surge in temperature at M3 near the ceiling above the point of ignition for simulation H2 is much smaller than that in the case of an LPG leak in C2, this is due to the large difference in the flow rates adopted in the simulations. Given a large enough flow rate of hydrogen, the consequences of an hydrogen explosion would also be devastating.

References

1. Huo, Y.; Ng, Y.W.; Chow, W.K. A Study on Gas Explosions in Buildings: Lpg as Fuel or for Air-Conditioner? In *CLIMA 2016—Proceedings of the 12th REHVA World Congress*; Heiselberg, P.K., Ed.; Aalborg University, Department of Civil Engineering: Aalborg, Denmark, 2016; Volume 5.
2. Huo, Y.; Chow, W.K. Flame propagation of premixed liquefied petroleum gas explosion in a tube. *Appl. Therm. Eng.* **2017**, *113*, 891–901. [CrossRef]
3. Ng, Y.W.; Huo, Y.; Chow, W.K.; Chow, C.L.; Cheng, F.M. Numerical simulations on explosion of leaked liquefied petroleum gas in a garage. *Build. Simul.* **2017**, *10*, 755–768. [CrossRef]
4. Lau, E.; Yue, S.Y.; Lee, J. *A Study on LPG as a Fuel for Vehicles. Legislative Council Secretariat*; Research and Library Services Division, Legislative Council Secretariat: Hong Kong, China, 1997.
5. Electrical and Mechanical Services Department. LPG Vehicle Scheme 2017. Available online: http://www.emsd.gov.hk/en/gas_safety/lpg_vehicle_scheme/index.html (accessed on 1 November 2018).
6. Transport Department. Transport in Hong Kong 2017. Available online: http://www.td.gov.hk/filemanager/en/content_4855/table44.pdf (accessed on 2 August 2018).
7. The Straits Times. Blasts Rare, but Vehicle Fires on the Rise: Experts. 2017. Available online: https://www.straitstimes.com/singapore/transport/blasts-rare-but-vehicle-fires-on-the-rise-experts (accessed on 22 July 2018).
8. Laws of Hong Kong. Cap. 51 Gas Safety Ordinance. 2014. Available online: https://www.elegislation.gov.hk/hk/cap51!en-zh-Hant-HK (accessed on 10 November 2018).
9. Electrical and Mechanical Services Department. LPG Vehicle Initiatives 2003. Hong Kong. Available online: https://www.devb.gov.hk/filemanager/tc/content_437/article.pdf (accessed on 10 May 2019).
10. South China Morning Post. Wong Tai Sin Garage Blast 'Started when Passer-by Stopped to Light Cigarette'. 2015. Available online: http://www.scmp.com/news/hong-kong/education-community/article/1777550/hong-kong-blast-neighbours-want-mechanics-garages (accessed on 1 May 2019).
11. Chow, W.K. Ventilation of enclosed train compartments in Hong Kong. *Appl. Energy* **2002**, *71*, 161–170. [CrossRef]
12. Chow, W.K. Fire and Explosion Hazards of Green Architecture in the Asia-Oceania Regions. In Proceedings of the 8th Conference on Fire Science and Fire Protection Engineering (on the Development of Performance-based Fire Code), Nanjing, China, 27–29 October 2017.
13. Chow, W.K. About Hidden Fire and Explosion Hazards Associated with Modern Life in Dense Urban Areas. In Proceedings of the HKIE Safety Specialist Committee—Annual Symposium 2018, Safety Engineering: High Risk Activities, Hong Kong, China, 22 June 2018.
14. Chow, W.K. Fire and Explosion Hazards of Color Powder Sprayed. In Proceedings of the 3rd International Symposium on Urban and Industrial Safety, Nanjing, China, 15–17 November 2019.
15. Chow, W.K.; Chan, M.Y. Field measurement on transient carbon monoxide levels in vehicular tunnels. *Build. Environ.* **2003**, *38*, 227–236. [CrossRef]

16. Chow, W.K.; Chow, C.L. Fire and explosion hazards to watch in developing big dense areas such as the Guangdong-Hong Kong-Macao Greater Bay Area. *J. Chang. Univ.* **2020**, *32*, 1–12.
17. Chow, W.K.; Wong, L.T. Field measurement of the air flow characteristics of big mechanically ventilated spaces. *Build. Environ.* **1996**, *31*, 541–550. [CrossRef]
18. Chow, W.K.; Yin, R. A new model on simulating smoke transport with computational fluid dynamics. *Build. Environ.* **2004**, *39*, 611–620. [CrossRef]
19. Chow, W.K.; Lau, K.W.; Gao, Y.; Dong, H.; Lau, S.L.; Poon, M.W.; Wu, Y.C. Theoretical consideration in developing rigs for studying explosion control in residential flats. *Int. J. Eng. Perform Based Fire Codes* **2006**, *8*, 43–49.
20. Gao, Z.M.; Gao, Y.; Chow, W.K.; Wan, Y.; Chow, C.L. Experimental scale model study on explosion of clean refrigerant leaked in an underground plant room. *Tunn. Undergr. Space Technol.* **2018**, *78*, 35–46. [CrossRef]
21. Ip, W.T.; Chow, W.K. Preliminary Study on Explosion Control for Gas Leakage in Residential Buildings. In Proceedings of the First International Conference on Building Energy and Environment (COBEE), Dalian, China, 13–16 July 2008; Volume 1–3, pp. 1179–1186.
22. Półka, M. An analysis of flammability and explosion parameters of coke dust and use of preliminary hazard analysis for qualitative risk assessment. *Sustainability* **2020**, *12*, 4130. [CrossRef]
23. GexCon, A.S. *FLACS v9.0 User's Manual*; GexCon AS: Bergen, Norway, 2009.
24. Electrical and Mechanical Services Department. Guideline for Revalidation of LPG Fuel Tanks for LPG Vehicles. 2015. Available online: http://www.emsd.gov.hk/filemanager/en/content_394/gs4_revalidation_guideline_en.pdf (accessed on 6 July 2017).
25. Van den Schoor, F.; Middha, P.; Van Den Bulck, E. Risk analysis of LPG vehicles in enclosed car parks. *Fire Saf. J.* **2013**, *57*, 58–68. [CrossRef]
26. Hansen, O.R.; Hinze, P.; Engel, D.; Davis, S. Using computational fluid dynamics for blast wave predictions. *J. Loss Prev. Process Ind.* **2010**, *23*, 885–906. [CrossRef]
27. Jo, Y.D.; Kim, J.Y. Explosion hazard analysis in partially confined area. *Korean J. Chem. Eng.* **2001**, *18*, 292–296. [CrossRef]
28. Jo, Y.D.; Park, K.S. Minimum amount of flammable gas for explosion within a confined space. *Process Saf. Prog.* **2004**, *23*, 321–329. [CrossRef]
29. Bauwens, C.R.; Chaffee, J.; Dorofeev, S.B. Vented explosion overpressures from combustion of hydrogen and hydrocarbon mixtures. *Int. J. Hydrog. Energy* **2011**, *36*, 2329–2336. [CrossRef]
30. Huo, Y.; Zuo, H.; Chen, C.H.; Chow, W.K. Numerical Study on Hydrogen Explosion due to Leakage from a Car Inside a Garage. In Proceedings of the 2016 International Symposium on Safety Science and Technology, Kunming, Yunnan Province, China, 17–19 October 2016.
31. Huo, Y.; To, C.W.; Cheng, C.H.; Chow, W.K. Numerical Study on Explosion Hazards of Hydrogen Cars in a Garage. In Proceedings of the 4th Thermal and Fluids Engineering Conference (TFEC), Las Vegas, NV, USA, 14–17 April 2019. Paper no. TFEC-2019-27142.
32. Crowl, D.A.; Jo, Y.D. The hazards and risks of hydrogen. *J. Loss Prev. Process Ind.* **2007**, *20*, 158–164. [CrossRef]
33. Venetsanos, A.G.; Baraldi, D.; Adams, P.; Heggem, P.S.; Wilkening, H. CFD modeling of hydrogen release, dispersion and combustion for automotive scenarios. *J. Loss Prev. Process Ind.* **2008**, *21*, 162–184. [CrossRef]
34. Haugom, G.P.; Friis-Hansen, P. Risk modelling of a hydrogen refuelling station using Bayesian network. *Int. J. Hydrog. Energy* **2011**, *36*, 2389–2397. [CrossRef]
35. Prasad, K.; Yang, J. Vertical release of hydrogen in a partially enclosed compartment: Role of wind and buoyancy. *Int. J. Hydrog. Energy* **2011**, *36*, 1094–1106. [CrossRef]
36. Rodionov, A.; Wilkening, H.; Moretto, P. Risk assessment of hydrogen explosion for private car with hydrogen-driven engine. *Int. J. Hydrog. Energy* **2011**, *36*, 2398–2406. [CrossRef]
37. Shirvill, L.C.; Roberts, T.A.; Royle, M.; Willoughby, D.B.; Gautier, T. Safety studies on high-pressure hydrogen vehicle refuelling stations: Releases into a simulated high-pressure dispensing area. *Int. J. Hydrog. Energy* **2012**, *37*, 6949–6964. [CrossRef]
38. Swain, M.R. Fuel Leak Simulation. In *Proceedings of the 2001 DOE Hydrogen Program Review*; University of Miami: Miami, FL, USA, 2001.
39. Astbury, G.R. A review of the properties and hazards of some alternative fuels. *Process Saf. Environ. Protect.* **2008**, *86*, 397–414. [CrossRef]