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A Study on Gas Explosions in Garages: LPG as Fuel or for Air-Conditioner?

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Abstract

A gas explosion occurred while liquefied petroleum gas (LPG) taxis were being repaired in a garage situated on ground floor of a multi-storey building in Hong Kong. The explosion brought severe damage to the building structure with the cause unknown. The explosion pressure had to be over 21 kPa or about 0.21 bar. This alerted the public on the potential explosion hazards in using clean fuel vehicles. Explosion caused by the leakage of LPG will be studied in this paper by Computational Fluid Dynamics through the software Flame Acceleration Simulator (FLACS). Dispersion of leaking LPG will be simulated first. Afterwards, explosion due to ignition of LPG will be simulated. The transient gas explosion pressure will be better understood for protecting firemen during operation.

Keywords - liquefied petroleum gas leakage; gas explosions; garage

1. Introduction

A very big gas explosion [1] occurred in a garage of about 200 m^2 for repairing taxis using clean fuel liquefied petroleum gas (LPG) in Hong Kong in April 2015. This gas explosion not only damaged the building structure, but also killed the owners staying inside. However, the cause of explosion is unknown and might involve the flammable clean refrigerant [2,3] composed of LPG.

The transient gas explosion pressure has to be better understood in order to provide better protection for firemen during operation. The explosion pressure should not exceed 21 kPa or about 0.21 bar to avoid serious damage to the building as suggested [4]. Approximate amount of LPG involved in that explosion in a garage is estimated [3,5] using empirical equations reported in the literature. The amount of LPG required to generate 21 kPa in that 200 m^3 garage is about 3 kg.

LPG vapour is highly flammable and will easily ignite and explode when its concentration with air ranges from 2% to 10% when an ignition source is present in the vicinity. As LPG is stored in the fuel tank at elevated pressure, any leakage will immediately vapourise and disperse. In Hong Kong, the supply of LPG contains butane and propane [6]. Its specific gravity is greater than 1, indicating a higher density than air. Thus, LPG could accumulate in the basement, below the ground plane cabin and low-level places. It is not only used in heating, drying and other processes in many industries, but also used as cooking fuel and in transportation.

Based on the information regarding the explosion in that garage found in the internet [5], the explosion incident is simulated by Computational Fluid Dynamics [7-9] and reported in this paper. The numerical simulation software used is Flame Acceleration Simulator (FLACS) [10].

2. Numerical Simulations

The interior dimension of the garage [3,5] is 8.1 m in length (x), 7.2 m in width (y) and 3.9 m in height (z), as shown in Fig. 1. The leakage source of LPG from a car, whether due to LPG fuel tank or clean refrigerant from the air-conditioner, is assumed to be located in the centre of the garage. The LPG enters the garage through the nozzle of rectangular sectional dimensions 0.25 m × 0.25 m, and the leakage source is projected upwards in the z direction.

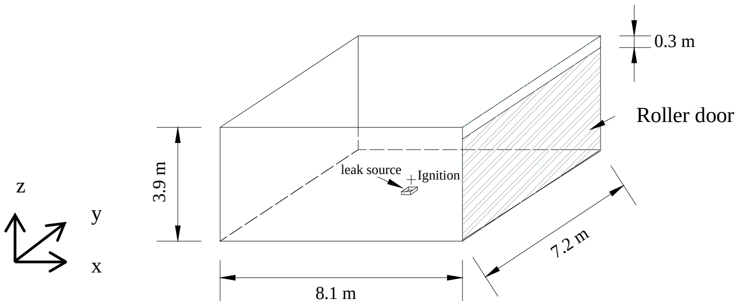


Fig. 1 The garage

The garage is positioned at where x = 8.1 m. The roller shutters are less than 0.3 m from the wall. Due to the effect of excessive pressure, the roller shutter is pushed out from the garage, causing the roller shutter to be in direct contact with the area outside the garage. In order to accurately capture the change of airflow, a sophisticated grid is used to segment the container space. However, considering the capacity of the computer used in this experiment, as well as the accuracy of the result, the size of the grid is designed to be 0.3 m x 0.3m x 0.3 m. To minimize the effect on the airflow field caused by the computational domain boundaries located at the leakage source of the roller shutter and to facilitate the observation of the results of the explosion caused by abrupt increase in pressure of the roller shutter, the area subject to calculation is extended laterally from the opening of the garage by 1.5 m.

LPG is consisted of 60% propane and 40% butane. The amount of LPG required to generate 21 kPa in that 200 m^3 garage is predicted [3] to be about

3.9 kg involved in the explosion to give such adequate high pressure rise. Therefore, the scenario of releasing a constant leak rate sufficient to release 5 kg in 15 minutes (900 s) is assumed. The mass flow rate is 5.55 g/s under standard condition of 1 atm and 293K. The ignition point of the garage is located at a position 0.5 m above the ground.

Dispersion of the leaked LPG from the car source in the garage is predicted first. Distribution of different combustible gas caused by three different leakage times is used to study explosion at the ignition position. The three different times of ignition are 300 s, 600 s and 900 s after leakage. The rolling door is taken to be initially closed in this presentation. When the roller shutter is closed, the garage becomes an enclosed space. Two cases where the rolling door is kept closed after explosion and kept open when pressure reaches 0.2 bar will be considered in the following sections.

3. Concentration of LPG Leaking Out

The distributions of the LPG concentration at height after leaking out at 300 s, 600 s and 900 s are shown in Fig. 2.

As observed, LPG is mainly deposited in the garage below 1.5 m because it is heavier than air. Moreover, the concentration of LPG at the bottom of the garage increases with the diffusion time.

When the leakage time of LPG reaches 300 s, 600 s and 900 s, the highest concentration of LPG near the ground can reach a maximum of 2.5%, 4.5% and more than 6.5% respectively, and the LPG concentration with a distance of 0.5 m from the ignition point on the ground can reach 2%, 3.7% and 5.5% respectively. These concentrations are sufficient to trigger LPG explosions.

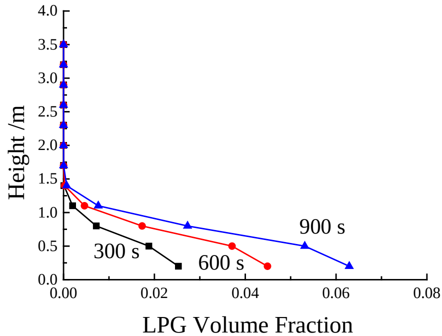


Fig. 2 Vertical variation of LPG concentration at different leaking times

4. Rolling Door is Not Opened Due to High Pressure

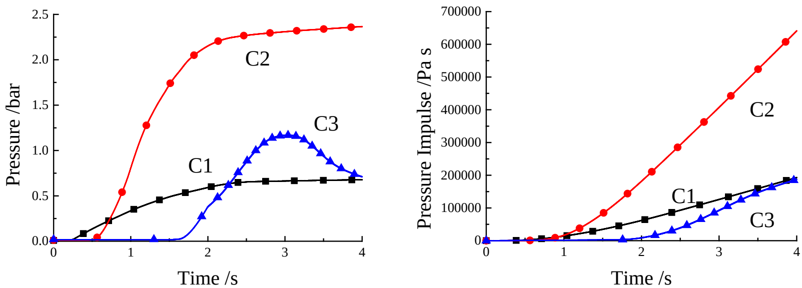
In order to investigate the proliferation of explosion of LPG triggered by the ignition in 300 s, 600 s and 900 s respectively, the rolling door of the garage is not opened due to overpressure. The diffusion of LPG and the explosion are assumed to occur in an entirely enclosed garage.

Three different explosion scenarios at different time of diffusion are simulated:

- Scenario C1:
  When the diffusion of LPG is at 300 s, the ignition process starts. This causes the pressure of the garage to increase gradually after 0.3 s.
- Scenario C2:
  When the diffusion of LPG is at 600 s, the pressure of the garage increases at about 0.5 s.
- Scenario C3:
  When the diffusion of LPG is at 900 s, the pressure of the garage increases only after 1.6 s.

In an enclosed garage where the door will not be pushed open due to overpressure, the pressure of the garage and the pressure impulse caused by the ignition of LPG at 300 s, 600 s and 900 s for the three scenarios are shown in Fig. 3. The ignition time is at 300.01 s, 600.01 s and 900.01 s respectively. In order to analyze the results of three different explosions which occur at three different absolute times on the same chart, the horizontal axis in Fig. 3 is a relative time period, and 0 refers to 0.01 s before ignition. Pressure impulse I_p is calculated by the following formula to characterize the effect of pressure over time:

$$I_P = \int_{t1}^{t2} P dt \tag{1}$$



(a) Pressure

(b) Pressure impulse

Fig. 3 Transient pressures and pressure impulses for rolling door kept closed

According to Fig. 3, since the garage is in an entirely enclosed state, when LPG diffuses to the internal area of the garage, LPG causes the internal pressure of the garage to increase. However, since the volume of the LPG is relatively small compared to the volume of the garage, only a small increase in the internal pressure is observed before ignition.

The increase in pressure in the garages rises the quickest for scenario C2 when LPG diffuses at 600 s. The pressure can reach as high as 2.3 bar within 4 s after ignition, and the high pressure sustains for a relatively long time.

Although the pressure of the garage for scenario C1 after ignition at 300 s can increase to about 0.6 bar for a certain period of time, the rate of increase in pressure and magnitude of the increase are the smallest among the three scenarios. Although the rate of increase in pressure and the magnitude of increase for scenario C3 is faster than those for scenario C1, the pressure only increases up till 1.2 bar after 3 s before declining gradually, and after 4 s, the pressure declines to a value that occurs at 300 s after ignition.

The pressure impulse I_p is the highest when the LPG is ignited at 600 s after diffusion. The increase in I_p starts earlier when LPG is ignited at 300 s than that at 900 s, but the values of I_p of these two scenarios are similar after being ignited for 4 s.

The reason for this phenomenon is due to the difference in concentrations of LPG in the garage. As the concentration of LPG is close to the optimum concentration equivalent ratio of LPG explosion when it is ignited at 600 s, explosion occurs followed by an increase in pressure. Scenario C1 with ignition at 300 s after leakage will give the condition without adequate fuel. Only a weak explosion results upon ignition. Scenario C2 with ignition at 600 s is rich in ignition fuel. However, there is a lack of oxygen needed for combustion, thus the development of a relatively powerful combustion is more time-consuming. Although some areas of the concentration of LPG have high explosion pressure within a short period of time, the fuel in the garage tends to burn with a slow combustion rate. A high pressure cannot be kept in the garage.

When explosion occurs for scenarios C1, C2 and C3 after the ignition of the leaked LPG at 300 s, 600 s and 900 s, the typical time temperature on the garage is shown in Figs. 4 to 6. The figures represent the high temperature region where the flames from the explosion cover. As seen from the figure, since there is a small amount of fuel when LPG diffusion is at 300 s, the flame stretches horizontally at the bottom of the garage while most of the flames are formed at the upper part of the garage, reaching the upper part of the garage until its movement is limited by the vertical wall. Then, the flame starts to move along the wall horizontally, during which the high-temperature region moves downward due to convection of air current and the limitation of the sides of the garage.

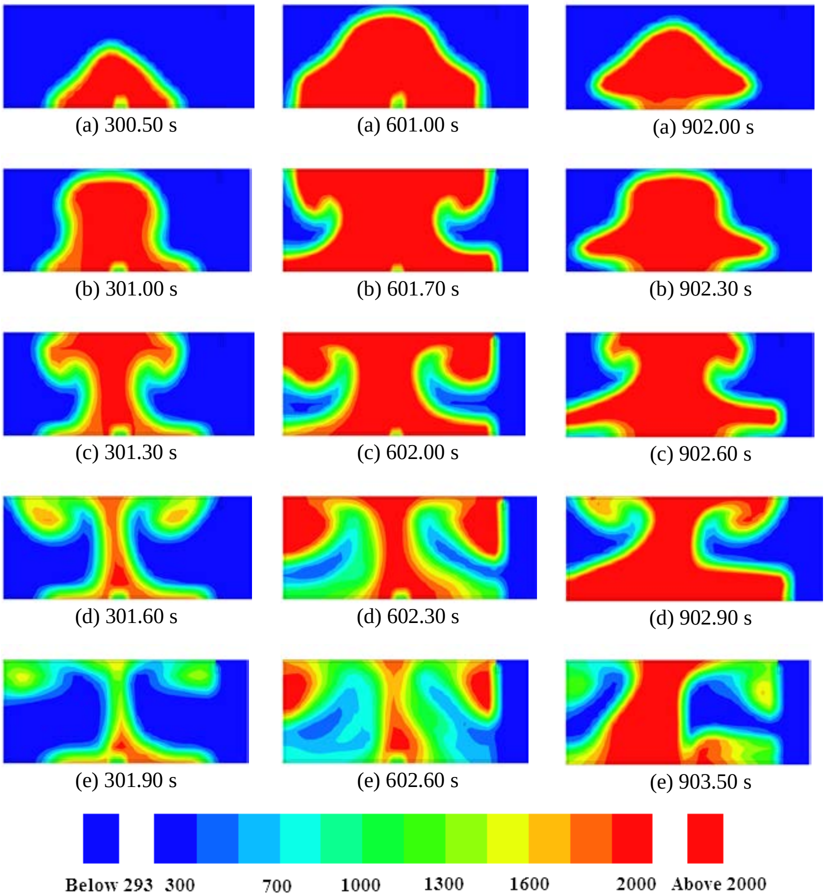


Fig. 4 Transient temperature for scenario C1

Fig. 5 Transient temperature for scenario C2

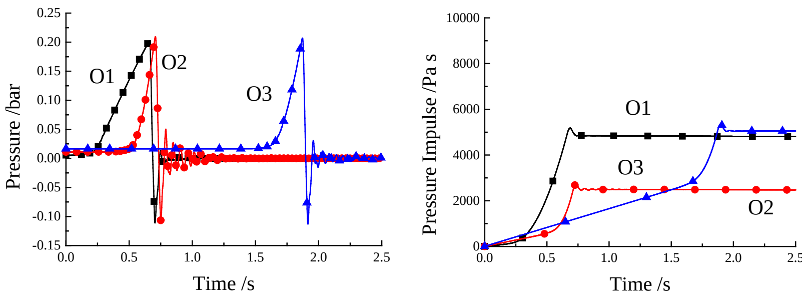
Fig. 6 Transient temperature for scenario C3

The movement of flames caused by ignition at 600 s for scenario C2 is similar to the above situation. However, since the amount of fuel is higher than the above situation and the fuel and air equivalence ratio is relatively higher, the area covered by the flames is larger. When LPG is ignited at 900 s for scenario C3, the flames from the ignition point moves horizontally from the ground at a certain height and are moving vertically upward. At this time, the temperature of the area near the ground of the garage is relatively low. As the explosion continues, the high-temperature area of the flames gradually expands to the ground area of the garage. This is due to the fact that the composition of LPG and air is relatively better at a certain height. In the area between this particular area and the ground of the garage, there is relatively less oxygen required for combustion, so the early stage of the explosion cannot form explosion flames with high temperatures. As the explosion flames expand to the area near to the ground of the garage at 902.9 s, the bottom area full of fuel starts to burn slowly. As the fuel near the bottom of the garage lacks oxygen, the fuel moves to the middle of the garage in the vertical area of the burning zone, forming a high-temperature region in the middle part of the garage.

5. Rolling Door Forced to Open

Again, three scenarios O1, O2 and O3 are considered for the ignition of the leaked LPG at 300 s, 600 s and 900 s. As shown from the results of the overpressure of the explosion caused by the ignition of the LPG in the three scenarios, the pressure of the explosion can be over 0.2 bar. Under such pressure, there is sufficient energy to push open the door. The rolling door is forced to open in these three scenarios.

When the door of the garage opens, the change in pressure of the garage with time is shown in Fig. 7. As shown from the figure, the pressure in the garage rapidly declines when the pressure is over 0.2 bar after the door is pushed open. The biggest drop in pressure reaches -0.1 bar. Afterwards, the pressure quickly rises back to about 0 bar, and the pressure in the garage becomes stable after several fluctuations around 0 bar.



(a) Pressure (b) Pressure impulse

Figure 7 Transient pressures and pressure impulses when rolling door was forced to open

In the three scenarios, the pressure rises the earliest for scenario O1 when LPG diffusion is at 300 s, but the rate of increase is the slowest, causing the pressure impulse to reach the largest value. For scenario O2 where LPG is ignited at 600 s, the rate of increase in pressure is the quickest, and the pressure curve reaches 0.2 bar before the volume reduces. As the pressure of the transient curve is the lowest for scenario O2, the value of the pressure impulse is the smallest. For scenario O3 where LPG is ignited at 900 s, the change in pressure starts the latest among the three scenarios despite the rate of increase in pressure is faster than scenario O1. However, the pressure stays at that high value for a relatively long time. Consequently, the rate of increase in pressure impulse is relatively slow. When ignition starts after 1.6 s, the pressure increases rapidly and the rate of increase in pressure impulse is faster than that in the previous scenario. Although the rise in pressure impulse is relatively slow, the value is the highest in this scenario.

Transient temperatures for these scenarios are shown in Figs. 8 to 10. As seen from the figure for scenario O1, the door of the garage is pushed open although the high temperature zone has not yet extended to the area near the bottom of the garage. After the door of the garage is pushed open, the flames near the bottom of the garage move from the opening to the exterior. At the same time, the flames in the high temperature zone of the garage simultaneously move towards the door and develop upwards.

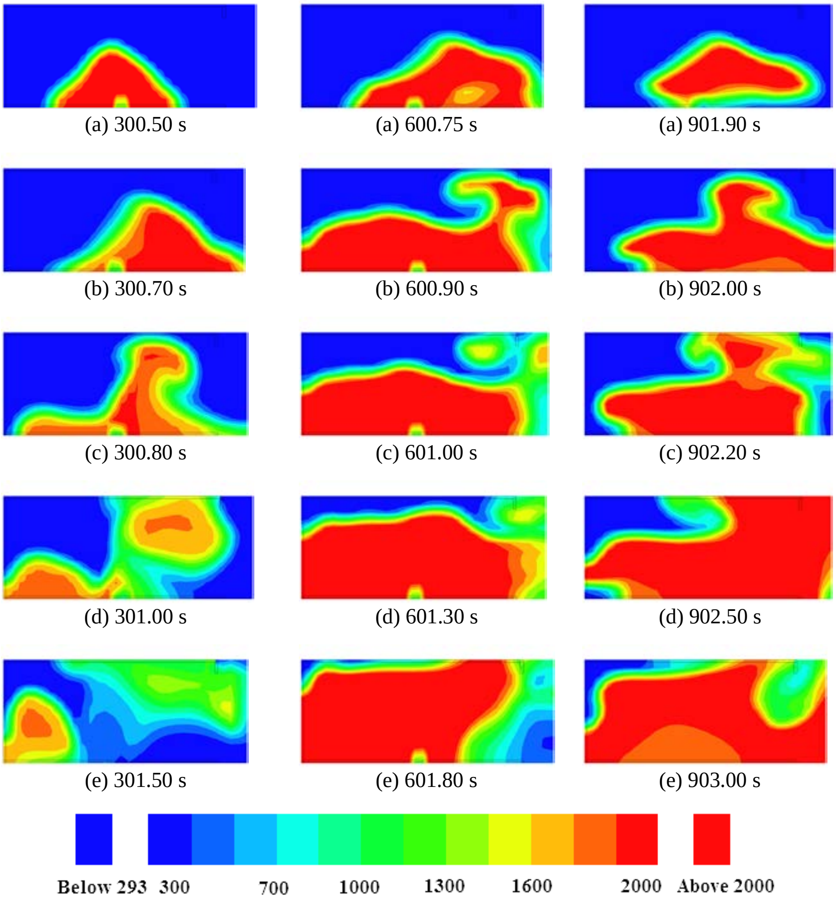


Fig. 8 Transient temperature for scenario O1

Fig. 9 Transient temperature for scenario O2

Fig. 10 Transient temperature for scenario O3

Also, there is still unburned combustible gas remaining in the area far from the door, which causes part of the flames near the bottom of the garage to move towards the area far from the door, forming two different high temperature zones at the corner of the garage and at the area near the upper part of the door.

In scenario O2 where the LPG is ignited at 600 s after diffusion, the movement of the high temperature zone is similar to that of scenario O1, but the high temperature zone covers a significantly larger area in the garage. At 601.8 s, the high temperature zone covers almost the entire space in the garage.

The concentration of LPG is higher at the bottom of the garage for scenario O3. The high temperature area expands horizontally at a certain height from the bottom of the garage before expanding to the entire space of the garage.

6. Conclusion

The big gas explosion in a garage with an area around 200 m^2 for repairing LPG taxis was studied by CFD using FLACS. The transient gas explosion pressure was better understood in order to offer better protection for firemen during operation. Another possibility of having explosion due to flammable clean refrigerants [11] including LPG will be studied. A taxi might have 0.5 kg of refrigerant HFC134a (R134a) stored in the air-conditioning unit. Although the amount of flammable gas is relatively small, an explosion could occur as a result. There were 47 leakage incidents over the past five years in which fire and explosion caused 45 casualties, which included 9 firefighters [12]. Causes of the incidents are mainly attributed to the lack of awareness of the leakage of LPG by the occupants, carelessness of workers when carrying works and possible suicide attempts by occupants. As firefighters are always exposed to the risk of explosion when carrying out rescue operation in the gas-filled environment, the explosion pressure has to be better understood for protecting firefighters during their operation. The CFD studies [7-9] in this paper will provide useful information on pressure and temperature rise due to explosion of LPG. With reference to such, firefighters can then work out appropriate fire action plans.

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