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Experimental Evaluation of LPG Release and Dispersion in the Enclosed Car Parks

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Despite the fact that LPG is used in a large number of cars, tests have not yet been carried out on whether parked cars in enclosed garages are a greater threat than petrol cars. The problem of LPG-powered vehicles in enclosed car parks applies to both public and industrial areas.
This paper describes real scale tests, which demonstrate conditions that can occur in a garage in the event of LPG release from a car installation. The validation of FDS code (NIST) for using in the case of modelling LPG release and dispersion in different situations is also described. Over the course of the tests, a series of six real scale LPG spillage experiments were performed to study emission time and cloud formation according to the leak size in the car installation. As a tested scenario, the release of 0.17 L of LPG in liquid phase, from the pipe connecting the tank and the engine, was used. On the basis of these measurements results, the distribution of LPG in the garage was obtained. The test results were used to create the optimal CFD model of LPG outflow and validation of FDS code against simulations of LPG gas release and dispersion.

1. Introduction

LPG (liquefied petroleum gas) is a mixture of hydrocarbon gases, mostly consisting of propane (C3H8) and butane (C4H10). In winter, LPG contains more propane, while in summer, it contains more butane, but its average composition is about 35 % of propane and 65 % of butane. LPG exists as a gas at normal atmospheric pressure and temperature, but for minimalizing its volume, it is liquefied by the application of high pressure. Vapours of LPF gas can travel considerable distances from the source of release to a source of ignition, where they can ignite, flash back, or explode. This can create vapour/air explosion hazards in confined spaces. In addition, car tanks may rupture if subjected to high temperatures.
There are some publications on the technical problems with LPG powered vehicles, for example, methods for the determination of the required safety control levels for this process (Akyuz, Celikb, 2015), hazards analysis in the LPG refuelling stations (Rajakarunakaran et al., 2015), or huge tankers (Kumar, 2013), but there are no publications about the problem with relatively small LPG tanks and installations, which exist in cars, which are very often situated in relatively small enclosures, like enclosed (very often underground) car parks.
A study in Canada have shown that human error was the major cause of accidents involving LPG vehicles. The information on 80 accidents was gathered by Transport Canada’s Investigation Office and the Ontario Ministry of Consumer and Commercial Relations from August 1981 to May 1986. Among them, 47 cases were caused by human error, which accounts for 58 % of accidents (Liu et al., 1997). Further current statistics are unavailable.
It is well known, that probability of LPG release from car installation always exists, and this fact promotes the necessity of equipping underground car parks with LPG detection systems along with automatically activated ventilation. In a situation where there is no ventilation, LPG vapour being heavier than air, would settle down at car park’s ground level, in low lying places, and would accumulate in any pockets or water outflows.
Jet fans are often applied to support ventilation process in car parks (Viegas, 2010). The jet fans are mounted under the ceiling of the enclosure to generate momentum. This causes induction of air and promotes mixing and transport of the polluted air. The Jet fan system is a stream ventilation system, ductless, based on

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simultaneous action of a group of fans to transport the air from supply point(s) to exhaust point(s). Working in first gear, fans ventilate the enclosure in the quantities necessary to discharge pollutants from exhaust gases of cars circulating in the garage (daily ventilation). Second gear is used for smoke exhaust during a fire, and often in the case of LPG detection. Jet fans are often used in situations where large amounts of air need to be transported with a relative high velocity (Betta et al., 2010). However jet fan systems were previously used only for tunnels, and premature use in garages, prior to thorough testing and adaptation to the new destination of car parks. The design of this type of ventilation is based mostly on the CFD simulations, because it is the best tool for showing the conditions which may occur in a garage or tunnel in the case of fire or pollutant propagation (Loomans et al., 2009).

Compared with traditional (duct) ventilation systems, CFD modelling of jet fans is much more difficult. This is due to the high dynamics of air flow in the vicinity of the jet fan outlet stream (Brzezinska, 2013). In addition, their outlets are usually equipped with guide vanes, giving the opportunity to shape the direction of the air stream. In result, CFD modelling of jet fan systems requires the use of special turbulent coefficients for resolving the Navier - Stokes equations. Because of the large gas flow rates in the case of unsealing the installation CFD, modelling of this phenomenon it is also very difficult and requires the execution of many tests in order to obtain satisfactory results, as shown in the following article.

Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) model originally created for fire-driven fluid flow. The software solves numerically a large eddy simulation form of the Navier–Stokes equations appropriate for the thermally-driven flows, with an emphasis on smoke and heat transport from fires, but it is also used for mechanical ventilation systems analyses, sprinklers, nozzles flows etc. FDS is developed by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce. Smokeview is the companion visualization program that can be used to display the output of FDS. Throughout its development, FDS has been aimed at solving practical fire problems in fire protection engineering, while at the same time providing a tool to study fundamental fire dynamics and combustion and fire protection systems like sprinklers, smoke detection or smoke ventilation efficacy. It was also tested as a tool for gas dispersion modelling.

The problem of LPG-powered vehicles in the enclosed car parks applies to both public and industrial areas and there are no specific tools to analyze the emergency situations of gas release from the car installation in any enclosures. Because of this, real scale tests of fluid phase LPG release from the car installation were conducted and described in this article. On the basis of these measurement results, the distribution of LPG in the garage was obtained. The test results were used for creation the optimal CFD model of LPG outflow and for validation of FDS code against simulations of LPG gas emission and dispersion.

2. LPG release time and dispersion measurements

After loss of containment from the tank or other part of LPG car installation gas immediately releases and disperses in the atmosphere. During this process it cools, drops down and evaporates.

LPG at atmospheric pressure and temperature is present as a gas which varies between 1.5 to 2.0 times heavier than air. LPG has an explosive range of 2 % to 10 % volume of gas in air. This gives an indication of hazard of LPG vapour accumulated in underground car parks in the eventuality of a leakage or spillage from a car installation. The auto-ignition temperature of LPG is around 410 °C to 580 °C and hence it will not ignite on its own at normal temperature, however, it is possible to ignite the cloud of gas phase LPG, through contact of hot car elements, which can reach even 1,000 °C. LPG gas is not poisonous in vapour phase, but can cause suffocation when found in large concentrations, due to the fact that it displaces oxygen. In addition to this, the vapour possess mild anaesthetic properties.

2.1 LPG car installation and the worst case scenario of gas spillage

An LPG car installation consists of two main parts. The first is the installation of fluid phase LPG, the second consists of gas vapour. In the fluid phase part, there is the tank and the pipe connecting it with the vaporizer. In the vaporizer, LPG is decompressed to gas and goes to the engine.

Depending on the size of the vehicle, gas tanks can be sized from 35 L to 70 L. According to Polish regulations, LPG tanks with their multi-valves need to have legislative approval through an mandatory annual test. As stated by the author, fatigue failure of the tank wall, caused by corrosion, is a negligible hazard.

The tank is connecting with other parts of installation with the pipe placed under the car. Standard pipes are most often of 6 mm diameter and up to 6 m long. Its volume is about 0.17 L (Figure 1).

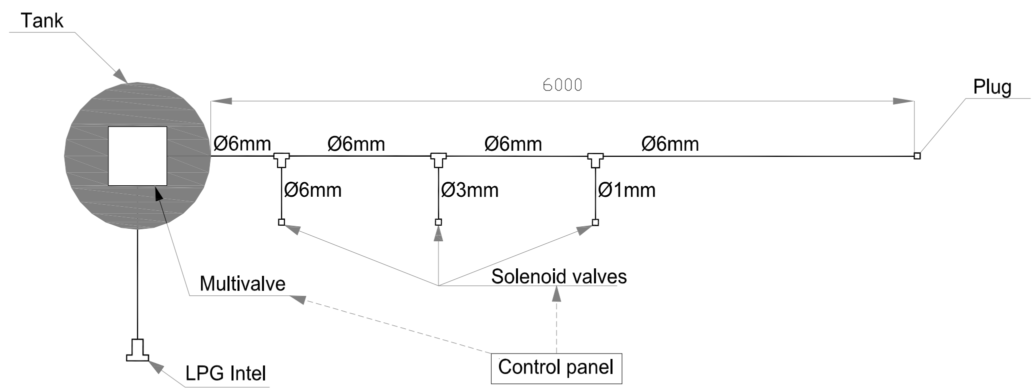


Figure 1. The scheme of the tested LPG installation.

There are no statistics on the failure of LPG automotive systems. Based on surveys carried out in the vehicle control stations it was found that unsealed tanks are practically unheard of and, if a gas leak occurs, it occurs due to a leak from the installation, especially at the connecting points of its parts. This means that, if the flow of the whole tank is excluded, the worst case scenario, is the discharge of the gas from the rest of installation. This scenario was examined in the tests. In this case the full volume of fluid phase LPG which could be released is equal to volume of the described above pipe and equals 0.17 L. Taking into account that 1 L of liquid LPG creates 250 L of gas phase LPG, from 0.17 L liquid LPG we have 42.5 L of pure gas. This dilutes in air to 425 L of 10 % gas (Upper Explosion Limit) and later into 2,125 L of 2 % gas (Lower Explosion Limit).

2.2 Measurement layout

Measurements have been carried out in an enclosure of plan dimensions 23.7 m x 4.2 m and height of 6 m (Figure 2). The LPG installation was mounted in the passenger car body.

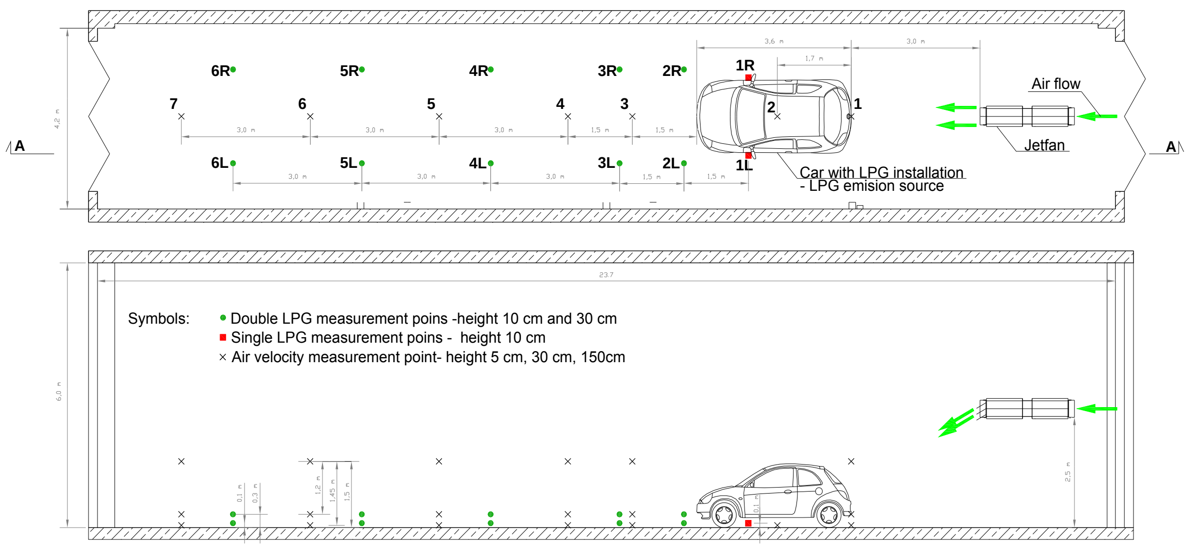


Figure 2. Scheme of the measurement layout for the LPG dispersion.

The LPG installation was consist with a standard LPG tank with multivalve and pipe of liquid phase LPG, mounted under the car body. In the pipe three solenoid valves were mounted, controlled from a control panel. Each solenoid valve was equipped with an orifice of a diameter of 1 mm, 3 mm and 6 mm respectively, imitating various sizes of holes in the pipe. The layout of the installation is shown in Figure1.

The stream ventilation system was provided in the enclosure by the jet fan with a diameter of 315 mm. This type of fan is most commonly used in garages. During the tests with working of ventilation, the ventilator worked in the first gear and had a flow rate of 0.61 m^3/s. The jet fan's guide vanes were sloped towards the floor, at an angle of 30° in relation to the longitudinal axis of the fan. LPG concentration was measured in the measurement points shown in the Figure 2.

2.3 Measurement results

To investigate the phenomenon of gas flow from the car installation and its dispersion in the garage six tests were conducted. The first 3 tests were without ventilation. For each leak size (1 mm, 3 mm, 6 mm) gas release time was estimated. Then all the tests were repeated with the jet fan switched on. The ventilation was switched on at the moment the detector placed at a distance of 9 m from the gas source found the LPG concentration at the level of 10% of lower explosion limit. Maximum fan rotation was achieved 20 s after switching on the fan. The tests results are shown in the table 1.

Table 1. Gas outflow time and rate and ventilation activation time during the tests.

Test series	Gas volume	Diameter of the hole	Gas outflow time	Gas outflow rate	Ventilation switch on time	Ventilation full efficiency time
1	0,17 l	1 mm	20,75 s	0,008 l/s	Not active	-
2	0,17 l	3 mm	5,30 s	0,032 l/s	Not active	-
3	0,17 l	6 mm	3,95 s	0,043 l/s	Not active	-
4	0,17 l	1 mm	20,75 s	0,008 l/s	150 s	170 s
5	0,17 l	3 mm	5,30 s	0,032 l/s	25 s	55 s
6	0,17 l	6 mm	3,95 s	0,043 l/s	27 s	57 s

The highest concentration of LPG was detected close to the source of release, during the test with the biggest hole diameter – 6 mm, and reached 350 % of the lower explosive limit, but this was a relatively short-lived phenomenon. The possibilities of explosion (concentration between lower explosion limit and upper explosion limit) were found for about 10 seconds and later the concentration of LPG decreased on its own. It was seen, that a ventilation system could be activated when the LPG concentration was already very low.

At a greater distance from the LPG source, the concentration of gas reached much lower levels and huge differences of gas concentration between detectors localized at 10 cm and 30 were observed. At a distance of 3 m from LPG outflow the concentration was still high at height of 10 cm (up to about 180 % of lower explosion limit), but at 30 cm it reached only 23 % of lower explosion limit (Figure 3). At a distance of 9 m from LPG outflow, the differences between concentrations at 10 cm and 30 cm were smaller and concentrations only reached 10-20% of lower explosion limit.

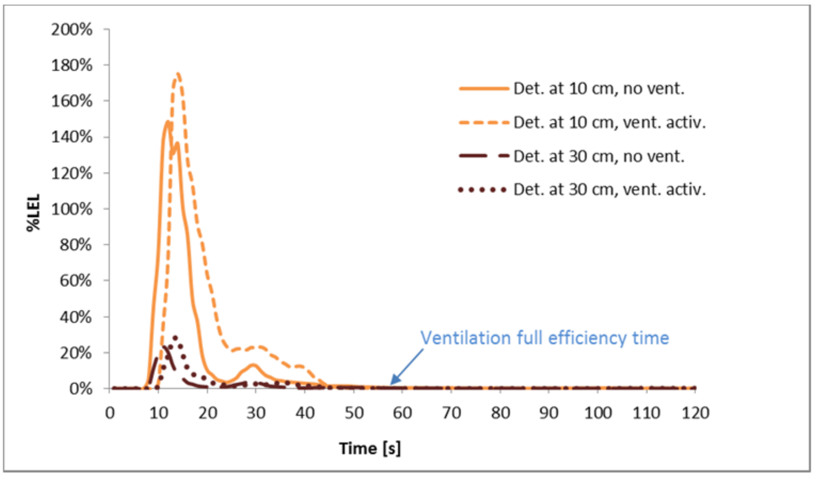
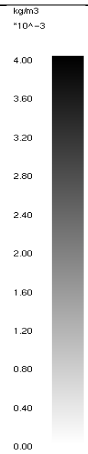


Figure 3. LPG concentration 3 m from emission source with 6 mm gap (measurement point No. 3L).

3. CFD simulations

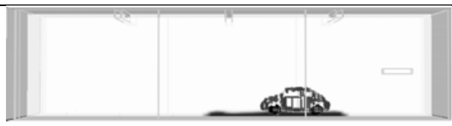
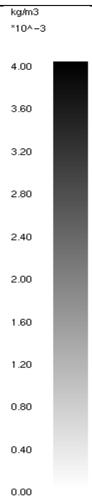
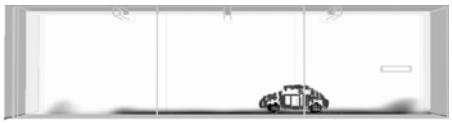
On the basis on the measurements prescribed above, CFD simulations with the FDS 6 code were prepared. Their goal was to check, if there is possible to use FDS code for risk assessment of explosion of LPG in the car parks, and for the evaluation of detection and ventilation systems. All simulations were prepared in 3D model of the enclosure, with LPG emission source and jet fan localisation, which were identical as during the tests. All measurement points in the CFD model were in the same positions as during the tests.
For grid sensitivity analysis three densities of meshes were used: 5 cm, 10 cm and 30 cm with 10 cm in the „z” direction. It was found that grid of 5 cm gives the best results and the LPG concentration received was very similar to the concentration reached in real scale tests. In the FDS simulation results, differences between LPG concentration at 10 cm and 30 cm, observed earlier during the tests, were mapped very well. It is shown in Table 2, where the concentration of LPG (represented by propane) at a height of 30 cm is presented graphically as being several times lower than at the level of 10 cm.

*Table 2. CFD results - LPG concentration at the height of 10 cm and 30 cm respectively (4*10-3 kg/m3 at the scale equals 10 % of lower explosion limit).*

LPG concentration at the height of 10 cm	LPG concentration at the height of 30 cm	Scale
		

Simulations results confirmed also that the jet fan ventilation has a major impact on the reduction of LPG concentration (Table 3). “Time” column in Table 3 means the “Time from the beginning of LPG emission”, which was used in the simulations.

*Table 3. CFD results - LPG concentration in two cases: with ventilation active and with ventilation not active (4*10-3 kg/m3 at the scale equals 10 % lower explosion limit).*

Time	Ventilation active	Ventilation not active	Scale
20s			
50s			
70s			
110s			

4. Conclusions

The paper describes real scale tests and concentration measurements of the LPG release from the typical car installation. The data received from tests was used for CFD simulations in FDS 6 code and gave successful validation results. FDS 6 code was also used for the LPG dispersion analyses, especially for evaluating the ventilation systems influence on LPG dispersion in air.
On the basis the tests and simulations it was found that:
1. in conditions of poor ventilation released LPG accumulates on the floor of the enclosure;
2. the LPG detectors must be located as close as possible to the floor;
3. good ventilation (especially jet fan systems) can remove released LPG very quickly;
4. FDS 6 code is a good CFD tool for simulation of LPG release and dispersion, and it can be used for analysis of:
 - the LPG explosion hazards (evaluated on the base of predicted gas concentrations),
 - the effectiveness of the ventilation systems for the LPG discharge,
 - the effectiveness of LPG detection systems.

For further studies in this field, it is planned to make the tests and simulations of other dangerous gases release from different internal industrial installations.

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