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EMERGENCY SCENARIOS DURING ACCIDENTS INVOLVING LPG. BLEVE EXPLOSION MECHANISM

Scenariusze awaryjne podczas zdarzeń z LPG. Mechanizm wybuchu BLEVE

Streszczenie
W artykule przedstawiono możliwe scenariusze awaryjne podczas zdarzeń z LPG. Należy tu wymienić zjawiska tj.: emisja gazu bez zapłonu z rozprzestrzenianiem w powietrzu, pożar chmury palnej mieszaniny – Flash Fire – po opóźnionym zapłonie, wybuch chmury par w przestrzeni ograniczonej – Vapour Cloud Explosion – i nieograniczonej Unconfined VCE, pożar strumieniowy – Jet Fire, wybuch rozprężających się par wrzącej cieczy – Boiling Liquid Expanding Vapour Explosion, pożar kulisty – Fire Ball oraz odłamkowanie. Następnie opisano kilka wybranych awarii z udziałem LPG w Polsce i w świecie oraz zestawiono w tabeli zawierającej opis, przyczyny, skutki i zauważone zjawiska podczas przedmiotowych awarii. W artykule omówiono teorie wybuchu fizycznego BLEVE szczegółowo opisując mechanizm prowadzący do wybuchu i jego efektów fizycznych. W podsumowaniu zawarto wskazówki dla Kierującego Działaniem Ratowniczym podczas zdarzeń z LPG oraz oznaki zbliżającego się wybuchu BLEVE.

Summary
This article presents potential emergency scenarios during accidents involving Liquefied Petroleum Gas (LPG). In this context it is appropriate to mention incidents such as: gas emissions without ignition, which disperse in the atmosphere, fire of a combustible cloud after delayed ignition, Flash Fire (FF), Vapour Cloud Explosion (VCE) within a confined space, unconfined VCE, Jet Fire (JF), Boiling Liquid Expanding Vapour Explosion (BLEVE), Fireball (FB) and fragmentation. Furthermore, the article describes a number of industrial accidents in Poland and across the world, involving LPG. These are summarised in a table describing the cause, effect and phenomena observed during such incidents. The article discusses the theories of a BLEVE explosion, describing the mechanism which leads to an explosion and its physical outcome. The summary contains guidelines for the Rescue Operations Commander, when dealing with LPG incidents and provides recognition signs of an approaching BLEVE explosion.

Słowa kluczowe: LPG, scenariusze awaryjne, wybuch BLEVE;
Keywords: LPG, emergency scenarios, BLEVE explosion;

Introduction

First information about untypical phenomenon occurring during incidents involving liquid gases dates back to the 1940's. At the end of 1950's the concept of Boiling Liquid Expanding Vapour Explosion (BLEVE) was introduced. Since then several studies were conducted on the phenomenon, its course, structure and prevention methods.

Rescue Operations Commanders may face hazards, which are strongly linked to physical and chemical properties and storage parameters of a propane-butane mixture. Failures during transportation, distribution and storage of LPG poses a serious threat to both humans and environment. Road cisterns containing liquefied hydrocarbon gases present the main hazard, since they run a risk of collision and accidents, resulting in the release of dangerous gasses, fire or in the most unfavourable conditions – explosion. The cause of LPG release from a pressurised container can be a combination of fire and mechanical damage e.g. effect of an impact, corrosion etc.

1. LPG properties

Main components of liquefied petroleum gas (LPG) are C3 propane, C4 butane and non-saturated hydrocarbons. Propane and butane belong to a group of light saturated hydrocarbons. Small quantities of gas are obtained from oil drilling. The largest LPG gas volumes are obtained during the treatment of crude oil. The main suppliers of liquefied petroleum gas are refineries. Gas is produced during a process of cracking and hydrogenation of crude

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oil. The amount of gas obtained from the complex processes cannot be estimated with precision. Gas capacities can vary with type of raw material and method of treatment, which is mainly oriented to petrol and diesel oil production.

Liquefied petroleum gas vapour is colourless, 1.9 times heavier than air, and odourless, which makes it difficult to detect. Propane and mixture of propane and butane are odorized using an agent with a detection threshold lower than the lower explosion limit (LEL). The liquefied petroleum gas is non-toxic. In high concentrations and at longer exposure time it can act as a narcotic and suffocate, as well as cause fainting due to displacement of oxygen from the area where the emission occurs. Dangerous combustion products in the air can contain: carbon dioxide, nitrogen oxides, and non-combusted hydrocarbons. In the initial phase, LPG dispersion from a tank or pipeline leak occurs close to the ground. All obstacles such as technological infrastructure, buildings or vegetation cause an increasing turbulence causing LPG to mix with air and in case of ignition provide a path for flame acceleration. Such processes decrease resultant air density, causing the emergence of vertical cloud propagation. The LPG emission rate from a leakage depends mainly on the pressure and breach opening. Fig. 1 presents the relationship between pressure and temperature of propane, butane and pressure of a 50-50 mixture. This relationship is the result of the Peng-Robinson Equation of State simulation prepared in MATLAB.

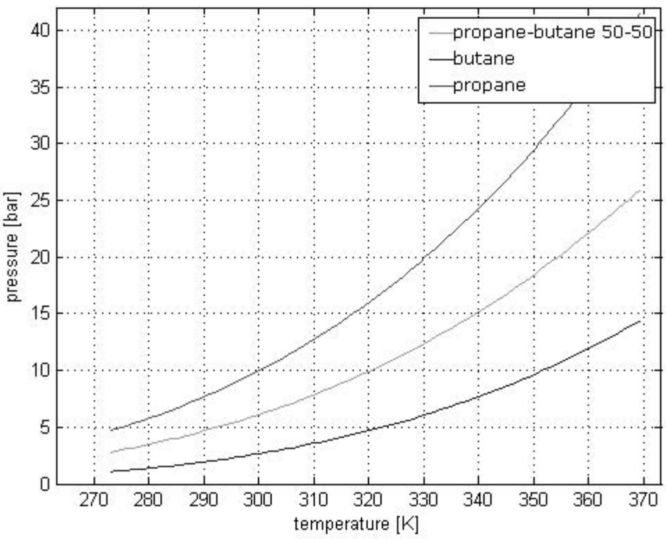

Fig. 1. Vapour pressure of propane, butane and 50-50 propane-butane mixture [Peng-Robinson Equation of State simulation]
Ryc. 1. Ciśnienie w zbiorniku z propanem, butanem i mieszanina 50-50 propan-butan [symulacja Równaniem Stanu Penga-Robinsona]

2. Failures and accidents with LPG

There have been many tragic failures and accidents involving LPG in Poland and across the world. On many occasions such incidents culminated in significant material losses and consumed many lives. Ensuing paragraphs describe and briefly analysed a range of selected accidents, which attracted much attention in Poland and across the world.

2.1. Mexico City, Mexico

On 19th of November 1984 the greatest and the most tragic gas explosion in the world took place in Mexico. Mexico City with 16 million of inhabitants consumes considerable amounts of gas. There are several large gas warehouses around the city. One of them in St. Juanico – Ixhuatepec, was located in the suburbs of the Mexico City. It was a large plant, where a vast amount of gas stored. The storage area consisted of four spherical LPG tanks with a capacity of 1600 m^3 each, two spherical tanks of 2400 m^3 each, and 48 cylindrical tanks of different diameters stored horizontally. At the moment of explosion the total amount of LPG in the refinery was within the range of 11000 and 12000 m^3. As a consequence of the explosion about 5000 people were killed, and 7000 were injured.

On the day, early in the morning, a large amount of LPG leaked, most probably from a storage tank or pipeline. The gas, which is heavier than air propagated in the valley forming a 1 m high wall. At the moment of ignition the cloud reached a height of 2 meters. At 5:45 ignition of vapours occurred. Propagating gas penetrated houses and these were totally destroyed by internal explosions after ignition of the vapour cloud. A minute after the explosion, there was a second violent explosion coupled with series of fireballs. A large amount of heat associated with the explosions produced a series of successive BLEVE explosions in remaining tanks.

The explosions completely destroyed four smaller spherical tanks, while in the larger ones the pillars were buckled. Only 4 out of 48 tanks remained at their original locations.

Twelve of them were thrown at a distance of 100 m, and one even as far as 1200 m. The diameter of the fireball was 200-300 m and its duration was approx. 20 seconds. This was accompanied by high thermal radiation, violent blast and fragmentation, as well as burning gas droplets, which travelled a large distance [4].

2.2. Feyzin, France

On 4th of January 1966, at Feyzin Refinery in France, a leakage occurred from the storage tank containing LPG. The gas ignited and the fire around the tank caused a BLEVE explosion. Consequently 18 people died and 81 were injured.

The LPG storage system in the Feyzin refinery consisted of eight spherical tanks, four with propane of 1200 m^3, four with butane of 2000 m^3, and two pressure tanks for LPG storage. The tanks were located at the distance of 450 m from refinery and 300 m from the houses of neighbouring village. The shortest distance between the tanks and road was 42 m. The distances between the tanks ranged between 11,3 to 17,2 m.

Periodically, gas samples were taken for analysis. An operator's action, contrary to procedures in the operation manual, contributed to the freezing of the valve and its blockage in an open position, resulting in the release of a large amount of propane. Most probably, a passing car was the source of ignition. The flame travelled back to the source of the gas leak.

The storage tank, which was the source of leakage, was not cooled down. At 8:40 the tank broke up into five large pieces. A large fireball was formed, which killed and injured 100 people. Five minutes later a second tank exploded, and the third was completely emptied by damaged pipelines. Three remaining tanks exploded without fragmentation. Feyzin village, at a distance of 400 m from the place of explosion, suffered extensive losses.. The fire caused the death of 18 people and 81 suffered injuries. Five spherical tanks were destroyed [2].

2.3. Naftobaza, Poland

On 15th of March 2007 about 4:30 pm, a State Fire Service station in Hajnowka received information about a gas fire of rail cistern at NO 15 Fuel Depot, NAFTOBAZA" in Narewka.

A bottom valve split in one of the rail cisterns containing about 40 tons of liquefied propane-butane gas. Gas leakage and vaporization occurred forming a gas cloud, which was propagated in the direction of the wind. The gas ignited, most probably as a result of un-extinguished fire. Based on recordings from the monitoring cameras it was determined that a tank ruptured at 4:22 pm, and at 4:26 pm a flash fire occurred, which later converted into a jet fire. Undergrowth in the forest located near the plant also ignited. Fire brigades concentrated their efforts on extinguishing the fire in the tank, to prevent its overheating. The undergrowth fire was also extinguished and the remaining rail cisterns, close to the fire were towed away to a safe distance. After the suppression of the fire and primary cooling down of the cistern, firefighters secured the leaking valve to prevent a further escape of gas. Direct fire-fighting operations lasted about 2 hours, in which 11 fire-fighting vehicles with crew took part (including a plant rescue team from NAFTOBAZA).

During a fire suppression test one of the employees of the plant sustained burn injuries. He was evacuated by fellow workers to the medical centre in Hajnowka. The tank insulation and 1 hectare of forest undergrowth was burnt [8].

2.4. Warsaw, Poland

During 1997 there was an explosion of liquefied petroleum gas at the „Autogas" filling station in Warsaw. The accident was caused by a drunken driver who collided with one of 4 storage tanks containing LPG. A gas leak and fire occurred. The explosion and rupture of the tank was caused by a fire. Storage tank fragments were scattered at a distance of several meters, causing the rupture of successive tanks. A fire embraced two further tanks, each with a capacity of 3 m^3 of gas, a building containing 11 kg cylinders, two containers belonging to a meat warehouse, car wash, and two cars parked nearby.

An officer who coordinated the operation conducted a reconnaissance, which revealed that the fire embraced 3 tanks located in the neighbourhood of the destroyed one. Practically all were located within an area of 1000 m^2. Additional forces and resources were declined.

A further explosion occurred and the fire at the filling station intensified. It was probably caused by a leak from a broken installation. Rescue operations were conducted a few meters from the tank.

During the accident two people were killed, and dozens were injured [7].

3. Hazards during emergency incidents involving LPG

Rescue operations during incidents involving LPG storage tanks are associated with the existence of many hazards, depending on how the situation develops at the scene of the incident. Depending on the shape, magnitude and type of failure, the Rescue Operations Commander should consider the following during operations:

- Uncontrolled gas escape into the atmosphere, the formation of flammable gas-air mixture and possibility of its ignition;
- Rapidly moving flame caused by ignition of a mixture of air and flammable substance (Flash Fire (FF));
- Vapour explosion in a confined or unconfined space (Vapour Cloud Explosion – (VCE) and Unconfined VCE (UVCE));
- Jet Fire (JF);
- Boiling Liquid Expanding Vapour E xplosion (BLEVE);
- Fire Ball – (FB);

and secondary phenomena associated with fires and explosions, such as:

- Heat radiation;
- Overpressure wave;
- Fragmentation.

Propagation of gas in the air depends on the physical properties of the substance, meteorological conditions and topography of the terrain. The main meteorological factors influencing propagation

Table. 1.

Comparison of causes and effects of selected failures and accidents [2]

Tabela. 1.

Zestawienie przyczyn i skutków wybranych awarii i katastrof [2]

Lp	Location	Flammable material	Cause	Failure effect	Phenomena associated with explosion
1.	San Juan Ixhuatepec, Mexico	propane-butane	Leakage of large amount of LPG.	650 died, 6400 were killed, complete damage within 400 m. Main cause of such high number of deaths was: thermal radiation generated by firewall, overpressure and fragmentation.	BLEVE
2.	Nijmegen, Holland	propane-butane	Leakage during refuelling.	Fireball of 40 m diameter at height of 25 m, radiant power of 180 kW/m^2. Cause: radiation and overpressure wave.	BLEVE FIREBALL
3.	Feyzin, France	propane-butane	Disregard of operation manual.	18 people dead, 81 injured, extensive damages within 400 m. Cause: heat radiation from generated cloud, fragmentation.	BLEVE
4.	Albert City, USA	propane-butane	Driver carelessness, who run into the ground pipelines from the tank to two vaporizers.	2 people died, 7 were injured, a few buildings destroyed. Cause: overpressure wave, radiation due to BLEVE.	UVCE BLEVE
5.	Mill Woods Area, Canada	propane-butane	Excessive pressure increase in pipeline, and ignition by a passing vehicle	Evacuation of 19 000 people. Cause: heat radiation from the ignited gas cloud.	UVCE
6.	Lynchburg, Virginia, USA	propane	Gas leakage after disturbance to the tank.	2 people died, 5 injured, fireball diameter of 120 m. Cause: burns due to gas cloud ignition.	FIREBALL
7.	BP Oil West Glamorgan	propane – butane	Damage of a recirculation pump seal.	Area around the tanks was seriously damaged.	JET FIRE
8.	Belt Montana	propane	Train derailment and cascading down the embankment.	2 people died, 11 injured, 40 houses destroyed, 19 cars destroyed. Cause: heat radiation.	BLEVE FIREBALL
9.	Donnellson Iowa,	propane	Pipeline unsealing, unknown cause.	2 people died, 3 injured. Cause: heat radiation.	FLASH FIRE
10.	Crescent City	propane	Train derailment, puncture of cistern and gas leakage.	No victims, dozens people injured, fireball diameter of 270 m. Cause: fragmentation, heat radiation	BLEVE FIREBALL
11.	Kingman, Arizona	propane	Propane leakage caused by a leaking tank.	Fire destroyed everything within 120 m, pieces scattered within 360 m, 12 people died. Cause: burn due to explosion	BLEVE FIREBALL
12.	Port Hudson, Missouri, USA	propane	Pipeline breakage, unknown cause.	Explosion of 50 000 TNT, explosion in form of detonation. Cause: high pressure increase and radiation.	FF
13.	Oneonta, New York	propane	Train derailment.	One part of 12 tons thrown out in the air at the distance of 400 m, 50 people injured (mainly firemen). Cause: unknown.	BLEVE FIREBALL
14.	Enschede, Holland	propane	Container toppled during its relocation.	Destroyed building structure and part of the building facade, no accident victims.	FF
15.	Naftobaza, Poland	propane – butane	Unsealing of the bottom valve, ignitron by un-extinguished fire.	1 person injured, storage tank installation and forest undergrowth burnt. Cause: burn due to radiation.	PF, JF
16.	Uroczysko – Cygan, Poland	propane – butane	During reloading of gas from cisterns to storage tanks.	Window glass fragments flying to a distance of 3 km. Cause: overpressure wave due to BLEVE.	BLEVE
17.	Prażmów, Poland	propane – butane	Unknown.	Slight.	JF
18.	Station „Autogaz" Warsaw, Poland	propane – butane	Out of control gas release, disregard of fire safety regulations and technical conditions.	2 people died, dozens injured, extensive damages around the filling station. Cause: heat radiation and overpressure wave.	BLEVE, FIREBALL

of the substance in the air is wind velocity, time of the day, temperature and temperature gradient with height. Topographical factors include shape of the terrain, coverage, land development and other obstacles. The physical property, which significantly impacts on gas behaviour in the air is density. Gases and vapours with density higher than the density of air have a natural tendency to settle at a faster rate where the density difference between the two is greater. Propane and butane is 1.5 and 2 times heavier than the air and will gravitate downwards, and at the same time mix with air. Heavy gases or vapours will deposit themselves in hollows and propagate close to the ground. After a release of LPG, all ditches, culverts and other spaces at ground level or below, will be quickly filled with the heavier LPG substance. During an LPG storage tank failure, without a fire in the vicinity, the liquefied substance will evaporate or cause a gas leak. A propane-butane mixture is non-toxic, thus it poses no threat to people and environment. The threat is fire or explosion. The most dangerous circumstances, especially for firefighters, are situations where a cloud is formed by the initial mixture of gas and air, in which the concentration of a flammable mixture will be between low and high explosion limit. Even the smallest ignition agent can initiate the fire or explosion of such a flammable cloud. A retarded ignition of the flammable cloud more often will cause burning back to the source of emission. Such a phenomenon is called Flash Fire, which means a fire of the cloud made up from a mixture of flammable substance and air.

The explosion of a gas cloud rarely happens during accidents with LPG. In order for the explosion to occur in an unconfined space or transition made from a cloud fire of the flammable mixture into an explosion a number of conditions should be present. The appropriate shape, minimum mass (so called critical mass), the presence of obstacles, such as buildings causing enhanced combustion velocity, as well as large turbulence inside the cloud are necessary. The wave created as a result of the explosion in the unconfined space is characterized by relatively slow pressure rise to a maximum value and relatively long time lag of overpressure (a few tenths of second). The explosion of gas or vapour cloud in an unconfined space gives overpressure of about 1 bar [2] and in a confined space overpressure is up to 10 bar (fig. 2.).

In the event of an explosion or fire of a cloud of gas-air mixture, where there is a continuous release of flammable substances e.g. caused by a broken LPG cistern valve, the flames will travel back to the emission source thus causing a jet fire (fig. 3). A jet fire can also occur during initial ignition of flammable gas leaking through an opening in the tank or pipeline. The average radiation intensity during LPG jet fires is about 350 kW/m^2, while the temperature of the flame is 1200°C [1]. Heat radiation from the flame causes high heat loads on the structural elements and equipment, reducing their strength, thus exposing them to destruction.

Fig. 2. Vapour explosion in a confined space – VCE [11]
Ryc. 2. Wybuch par w przestrzeni ograniczonej – VCE [11]

Fig. 3. Jet Fire [6]
Ryc. 3. Pożar strumieniowy – Jet Fire [6]

Continuous and long term heating of the tank's casing results in an internal increase in temperature and rapid pressure growth. It causes weakening of the storage tank structure, plasticisation of steel, and consequential rupture of the tank with a catastrophic leakage into the environment. Such a phenomenon is called Boiling Liquid Expanding Vapour Explosion (BLEVE). The term was defined and introduced by the National Fire Protection Association (NFPA) in USA. It stands for the explosion of the boiling liquids expanding vapours. A BLEVE explosion is the sudden physical process related to a rapid phase in the transition of the liquid. At once, an enormous amount of substance changes from a liquid state to the gas state, significantly and rapidly increasing its volume.

Fire located under a storage tank, contributes to an increase in temperature of the tank's wall. Heat accumulation in the tank is slow and mainly depends on the tank's volume. Large volumes cause the temperature and pressure increase inside the tank to develop slowly. It gives time for appropriate action to prevent the approaching danger of BLEVE. After

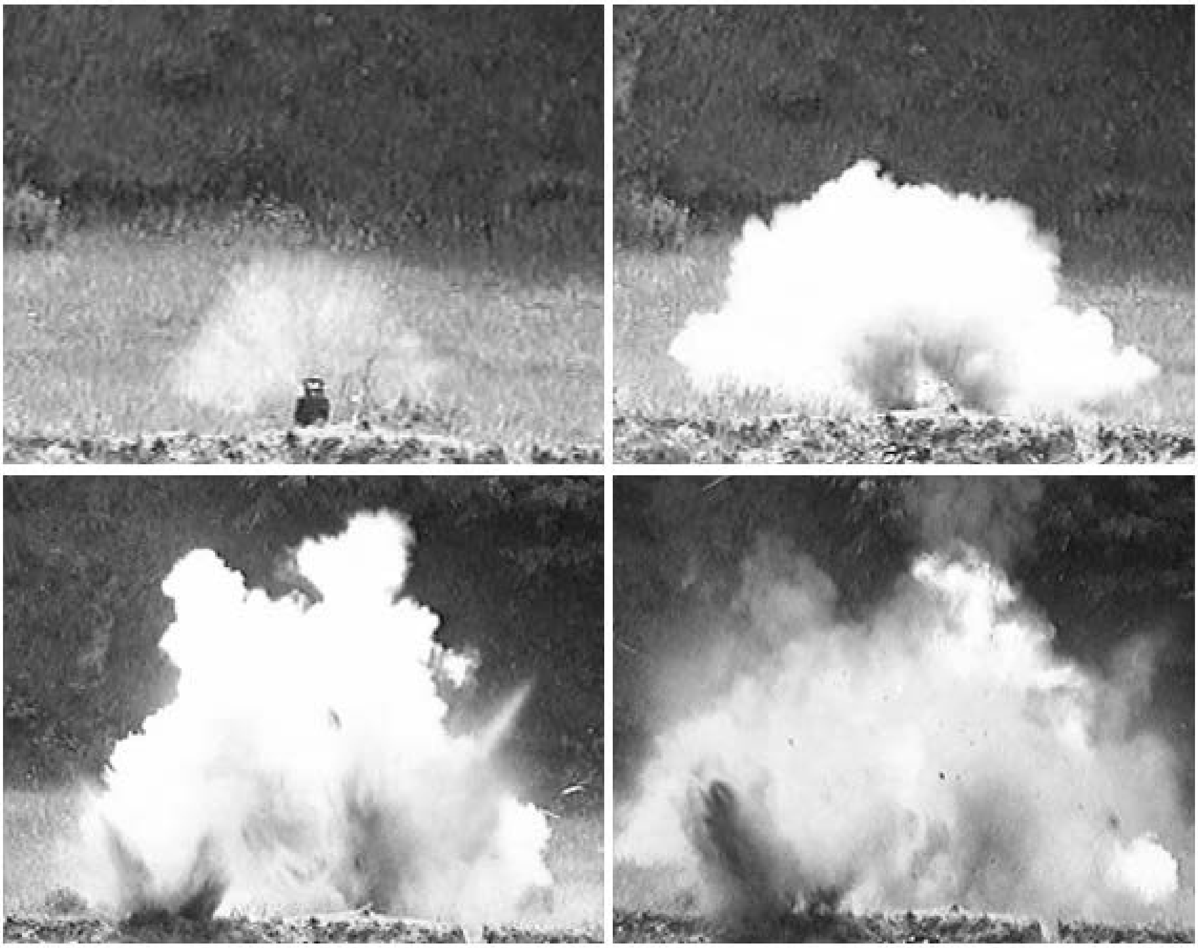

Fig. 4. BLEVE explosion [9]
Ryc. 4. Wybuch BLEVE [9]

the safety valve pressure limit is exceeded the valve opens and gas is released into the atmosphere. This in turn results in the lowering of the liquid level inside the tank. If the storage tank is surrounded by burning gas the temperature increase to the wall of the container is significantly faster, as well as the increase in temperature and pressure inside the tank, which accelerates the BLEVE occurrence. Figure 4 shows a BLEVE explosion.

When the temperature and pressure increases inside the tank there is an accompanying increase to the internal energy of the system. After exceeding strength parameters of the tank, there is a release of the accumulated energy in the form of physical explosion and creation as well as dispersion of fragments. In the case of a physical explosion we are dealing with the phenomena of rapid compensation of pressure difference between the tank interior and its external environment. Additionally, during a BLEVE incident the transition from liquid state to gas state is made, accompanied by an the increase in the volume occupied by the stored substance. It produces overpressure, which propagates in the atmosphere with destructive potential.

Part of the internal energy is transferred to the tank's walls, which causes their disintegration and fragmentation into different shapes and sizes. Consequently, fragments are scattered around the tank area at high speed. In open spaces the dispersion zone can be up to a 1 km diameter around the storage tank. The number of fragments generated during a BLEVE explosion, as well as during other explosions is unpredictable.

In the case of a gas cloud ignition, a BLEVE explosion is accompanied by a *fireball*. A fireball can occur when there is a release of flammable substances. Characteristics of a fireball are heat flux versus distance from the centre of the fire and duration of the phenomenon. Figure 5 illustrates a fireball.

Fig. 5. Fireball [10]
Ryc. 5. Pożar kulisty – fireball [10]

4. BLEVE explosion mechanism

The explosion defined as BLEVE in the literature, is a sudden physical process related to the tank disintegration and a rapid transition in the state of the substance present in the tank. A wave of overpressure is produced, which propagates in the atmosphere, and due to its power can cause significant damage. However, it should be noted that the disintegration of the tank is not always the result of a high power explosion. It will occur only in specific conditions exist. Such conditions mainly refer to the state of the substance present in the tank at the moment of the tank's break-up.

If the internal pressure of a container is increased as a result of heating, then the boiling temperature of the contents will increase correspondingly. Therefore, the liquid in the tank can have a temperature significantly higher the one at which it would boil in the environment. Temperature, which is higher than the boiling temperature at normal conditions, is defined in literature as superheat limit temperature. For the majority of substances used in industry, it is (p_{atm}) at the atmospheric pressure and takes the value T_{lim} = 0,89 – 0,90 of the critical temperature T_c [3]. In standard applications substances have a temperature of T_1 and pressure of p_1. If there is an impact of heat flux from the fire surrounding the tank, the temperature of the substance present inside the tank will increase. The temperature increase will be accompanied by a pressure increase, according to the saturated vapours pressure curve vs. temperature. The curve indicating phases of the liquid state is moving upward, through points 2, 3, 4 (fig. 6). Despite the fact that each pressurised container used for storage or transportation of liquefied gases is designed to withstand high pressures, much higher than operational ones, it is impossible to predict the pressure, which will cause the break-up of a container during accidents. It is worth observing that the impact of a fire weakens the shell of the container. The cause of failure can also have an impact on strength reduction, e.g. creation of a mechanical damage (indentation, scratches, etc.). Thus, there is a real possibility of a tank break-up at each moment of the pressure increase process.

Let us consider a situation, where a container bursts at the moment when the liquid has not reached the superheat temperature limit. For such a situation, with reference to the curve, the liquid state will be determined by any point along the curve between points 1 and 3. The fracture of the tank's walls will cause a rapid pressure drop up to p_{atm}, at which the boiling temperature for liquefied gases is significantly lower than the ambient temperature. The released liquid will partly evaporate and rapidly create a boiling pool, and if ignition occurs, its vapours will burn. The rate of state transition will depend on the heat transfer from the environment, and it will not be high enough to create a destructive pressure wave. From the curve, it can be seen when the liquid temperature will exceed superheat limit temperature. It will be any point located at the curve between point 3 and 5. After a fracture of the tank's shell the pressure will decrease down to the level of atmospheric pressure. At some point of the pressure decrease liquid temperature will equal superheat limit temperature, corresponding to instantaneous pressure. A further pressure decrease will cause the liquid temperature to exceed superheat limit temperature and the substance will rapidly change its state from that of liquid to gas. This is attributable to the fact that the evaporation heat needed for the transition was accumulated in the liquid. The transition from liquid state to gas will cause a significant increase in volume taken up by the substance. After exceeding critical parameters a change from liquid state to one defined as 'overcritical liquid' will occur. A fracture of the tank, after exceeding critical parameters will result in an explosion of the 'overcritical liquid' [1, 2].

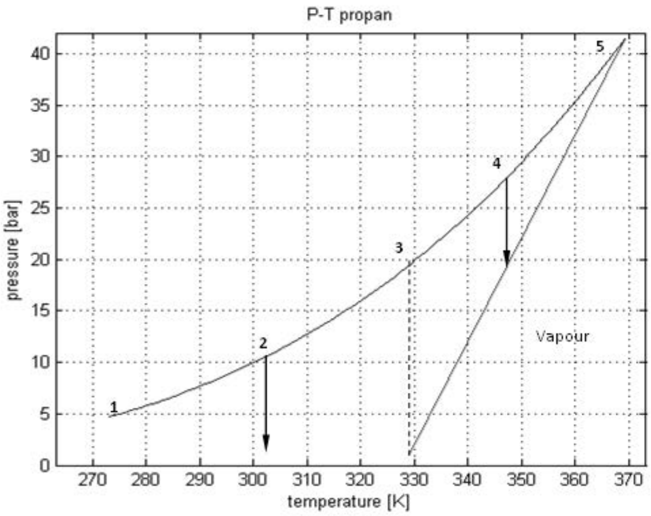

Fig. 6. Pressure vs. temperature of liquefied propane in a container – heating stages
Ryc. 6. Ciśnienie vs. temperatura skroplonego propanu w zbiorniku – etapy ogrzewania

5. Summary

From the point of view of safety during firefighting and rescue operations, the least hazardous situation occurs, when a leakage and gas ignition occurs without the heating of the container's shell. The most unfavourable situation is a leakage without ignition and leakage with ignition accompanied by heating of the container shell by flames.

In order to eliminate hazards during out-of-control LPG gas leaks from pressurised tanks, officers co-ordinating operations should take into account many influencing factors associated with the release of propane-butane gas. The first, which may give rise to further action, is to identify whether ignition has occurred. If ignition has occurred, it should be determined how the tank is affected by the flame.

If the flame is vertical and does not surround the tank, different steps should be taken compared with the situation where the tank is surrounded and heated by flames.

During situations where flames do not surround the container, pouring water on the shell of the container should be avoided. Otherwise, the expanding gas and liquid state evaporation will cause frosting and cooling of the container down to temperatures below zero. Sprinkling the container with water from fire appliances, hydrants and watercourses, which have temperature higher than 0°C, will result in heating of the container shell and supply of higher temperatures required for the evaporation process. Avoiding such action is very beneficial because the evaporation process of the liquid involves absorbing heat from the environment. Sprinkling of the tank with water results in increased evaporation, increased amount of leaking gas, and increased flame height. Additionally, such action will cause a slower pressure decrease inside the tank. In case of a real fire it will be difficult to determine the temperature of liquid and gas state, as well as obtain precise pressure readings inside the container because of e.g. broken manometer. The feature of a jet fire is the shape of the flame, which indicates that in an out-of-control leakage of LPG, gas temperature at the liquid state has reached a limit value and stabilized, while the pressure in the container has dropped to the lower value. When the flame is high, vertical, without any deflections, it means that liquid state temperature is high and pressure inside the tank is high. When the flame is shrinking, and is no longer stable, it means that the liquid state temperature and pressure in the tank will soon reach the lowest possible value. Such a flame display indicates the time for action to seal the leak and transfer remaining gas into a replacement container.

Where flames surround the container, the shell should be totally cooled with water, since the temperature of flames can reach up to 1200°C, which can result in an explosion of the container. Flames engulfing a container heat it thus posing a danger to life and health of firefighters, as well as people in the surrounding area. In such a situation, cooling of the container will prevent a rapid liquid and gas state temperature increase, minimise danger for humans, reduce the risk of rising temperature to the container shell and culminate in a quicker drop in pressure.

Estimation of the time lag from the start of a gas leak until the container is empty is very difficult. During a jet fire it is not possible to check the diameter of the outflow, which is one of the parameters necessary to determine the predicted duration of a fire. Apart from the outflow diameter, a knowledge of the evaporating liquid volume is also required, to correctly estimate the duration of discharge. Dynamically changing fire-thermal conditions and heat transfer to the container structure preclude precise calculation of discharge duration or time lag to a BLEVE explosion.

Emergency Rescue Operation Commanders should establish a hazard zone during accidents involving LPG, where there is a high probability of an explosion, which is not less than 250 m distance from 11 kg containers, 350 m – for road cisterns and LPG storage tanks at filling stations, and even 1000 m for rail cisterns [5].

If the temperature of the liquid in an LPG container exceeds approximately 60ºC, there is a high probability of a BLEVE explosion. Additional signs indicating an approaching BLEVE explosion are:

- Safety valve indications of a pressure increase inside the tank. A tank shell should be intensively cooled down. In case of water vapour occurrence and/or dry spots on the container's shell surface, the cooling intensity should be increased.
- Frequency level of the tone associated with a gas escape depends on the velocity of the gas leak. A higher frequency equates to higher gas velocity and higher pressure inside the container.
- The height of flame depends on the velocity of a gas leakage. A higher flame means higher pressure inside the container.
- Buzzing noises and other disturbing sounds indicate increasing steel loads and strength reduction.
- Change to the shell colour, visible fragments of metal coating, peeling paint indicate high temperature of the container shell.
- Deformations, swelling, blisters indicate rapid pressure increase and melting steel.

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