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A Consequence Analysis of the Explosion of Spherical Tanks Containing Liquefied Petroleum Gas (LPG)

Hadi Zareei[1], Mohammadreza Khosravi Nikou[2*], and Ahmad Shariati[3]

[1] M.S. Student, Department of Gas Engineering, Petroleum University of Technology, Ahwaz, Iran
[2] Assistant Professor, Department of Gas Engineering, Petroleum University of Technology, Ahwaz, Iran
[3] Associate Professor, Department of Gas Engineering, Petroleum University of Technology, Ahwaz, Iran

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Abstract

A consequence analysis was performed in one of the gas refineries in Iran to investigate the risks and potential losses resulted from accidents. Specifically, the consequences of an explosion in LPG spherical tanks were modeled using PHAST and MATLAB software. In this paper, three methods of calculation of PHAST software TNT, multi-energy, and BST were used. The results showed that multi energy method is the best method to evaluate overpressure. It was 0.150 bar and 0.159 bar in a distance of 1000 m far from the blast using PHAST and MATLAB respectively. This overpressure can damage a wall with 30 cm thickness. It also affects the human threshold (1%) ruptured eardrum. Finally, it was found that 100% lethality in a minute happened at 285.5 m and 37.5 kW/m^2 when the explosion happened.

Keywords: Consequence Modeling, Overpressure, LPG, Explosion

1. Introduction

The explosion, leakage, and catastrophic dispersion of liquefied petroleum gas from storage tank are the most important events in gas treating plants (AIChE/CCPS, 1987). In order to keep safe from the damaging effects of these events, consequences should be properly investigated and understood. One of the methods to reduce the effects of accidents is modeling shock waves, radiation effects, and toxic effects. An explosion is defined as a sudden and violent release of energy that causes a blast with a high potential of damage. The energy released can be physical, chemical, or nuclear. A variety of explosions are classified depending on the type of energy and the environment of the release. Explosions are very significant in terms of their damage potential, often leading to fatalities and damage to property (Khan and Abbasi, 1999). Explosions must be modeled to predict the potential destructive power of the blast that can be produced in a given installation. In the process industry, the substances which can cause an explosion are essentially hydrocarbons such as LPG, gasoline, or cyclohexane. LPG explosion in Mexico City resulted in hundreds of deaths and several thousands of injuries (Lees, 1996). A massive explosion in Pasadena, Texas in 1989 resulted in 23 fatalities and 314 injuries (Lees, 1996). A number of such disastrous industrial events have occurred in the past and are still occurring in the world. Thousands of people are killed and injured during these disasters. For vapor cloud explosions, the multi-energy model is often used to determine overpressure and positive

Corresponding Author:
Email: mr.khosravi@put.ac.ir

phase duration time as a function of distance (Mercx et al., 1997). Lees gives reference to this method in his textbook (Khan and Abbasi, 1999). Henk W. M. Witlox presents the prototype of the computer code, Atlantide, developed to assess the consequences associated with accidental events which can occur in an LPG storage plant (Witlox et al., 2010). The models and correlations implemented in the code are relevant to flashing liquid releases, heavy gas dispersion, and other typical phenomena such as BLEVE/Fireball. An industrial LPG storage accident due to the release of propane from a tanker is described by Demichela et al., and the sequence of events, which led to the collapse of a storage tank, is examined using simulation software (Demichela et al., 2004). An integrated computer code, named Atlantide, has been developed to perform the consequence analysis in LPG installation; it allows analyzing the main accidental scenarios originated from typical accidental events occurring in such plants, according to the Italian regulation (Roberts 1982). Using characteristic curves simplifies the approach since both overpressure and impulse can be determined in one step, avoiding any calculations of scaled magnitudes. This model, based on characteristic curves, allows an overview of the evolution and relationship of all variables involved in the detonation of explosives, pyrotechnics, or unstable substances (Alonso et al., 2006). In literature, an accident occurred in liquefied petroleum gas (LPG) tank filling and LPG transferring installations with EFFECTS (TNO 2007), ALOHA, or integrated computer code (Atlantide) is simulated. This paper contains an investigation of the consequence analysis of LPG vessels in a gas refinery using PHAST and MATLAB software.

2. Theory and modeling

In order to start the analysis, a specified scenario is defined. A tank contains the liquefied petroleum gas at a pressure of 4.2 bar and a temperature of 20 $^{\circ}$C. Tank is made of carbon steel with a diameter of 10 meters. The *catastrophic rupture* scenario is designed to model an incident in which the vessel is destroyed by an impact, a crack, or some other failure, which propagates very quickly. Due to the large amount of force produced in a short time of the event, environmental parameters such as spreading of substance to atmospheric are not important. Meteorological conditions of the site are presented in Table 1. The atmospheric conditions are classified according to six different stability classes (A-F), shown in Table 1. The stability classes include A (extremely unstable), B (moderately unstable), C (slightly stable), D (neutrally stable), E (slightly stable), and F (moderately stable). The stability classes depend on wind speed and quantity of sunlight.

Table 1
Meteorological conditions of the site (plant) (AIChE/CCPS, 1989).

Climatic conditions	Temperature(°C)	Moisture content (%)	Wind(m/s)	Atmospheric stability
Hot	32.2	79.3	2	A/B
Neutral	26.9	66.3	5	D
Cold	21.6	56	2	F
Windy	18.2	80.3	12.4	D

The physical-chemical properties of the liquefied petroleum gas which is stored in storage tanks are listed in Table 2. The LPG compositions are necessary for the simulation. Moreover, from the satellite image of the plant, the surface roughness of site considered to be 1 m.

Table 2
Gases flammable in winter.

Material	Molecular weight	Mass percent (%)	Lower Flammability Level %	Upper Flammability Level %	Flash point(K)
Propane	44.1	30.27	2.2	9.5	168.7
iso butane	58.12	22.18	1.8	8.4	-
Butane	58.12	44.55	1.9	8.5	213.1
iso pentane	72.15	2.77	1.4	7.6	<222
Pentane	72.15	0.21	1.5	7.8	<233.1

3. Explosion consequence modeling

Explosions in the storage or process units can be categorized in four main groups, according to their mode of occurrence and damage potential:

1) Confined vapor cloud explosion CVCE);
2) Unconfined vapor cloud explosion (UVCE);
3) Boiling liquid expanding vapor explosion (BLEVE);
4) Vented explosion (VE).

Confined explosions, or confined vapor cloud explosions, usually occur inside a largely confined space such as enclosed modules or oil tanks, or on a leg of a concrete platform. Liquids of low boiling points, flammable gases, or highly reactive chemicals processed under extreme conditions are most likely to generate CVCE (AIChE / CCPS, 1984). A CVCE occurs when the pressure in a confinement reaches certain critical limits beyond safety levels. Partially confined and highly congested conditions are typical of the process area of floating production storage and offloading (FPSO) vessel and some offshore modules. The ignition of any vapor cloud in such conditions will lead to an explosion referred to as a partially confined explosion. In this case, overpressure generation is mainly due to turbulence generated by the obstacles such as process equipment in the path of the expanding gas. BLEVE is caused by a sudden release from the confinement of a liquid at a temperature above its boiling point. The sudden decrease in pressure results in an explosive vaporization of a fraction of the liquid and a cloud of vapor and mist, with accompanying blast effects. If the material is flammable and an ignition source is present, a fire ball may be formed. Generally, BLEVE occurs when a pressurized vessel containing a flammable liquid is exposed to fire, which may weaken the vessel walls and lead to ruptures. Vented explosion is a phenomenon observed because of the formation of fire torch in a vessel due to the ignition of a flammable chemical (gas or liquid) at release point. In this situation, the flame front may move backwards in the vessel at a high speed and ignite the contents of the vessel resulting in excessive pressure development and leading to an explosion. In vented explosion flame front speed may reach over 50 m/s. It is differentiated from CVCE by its mode of initiation and its damaging effects.

In general, there are three methods to calculate the energy of explosion:

1- TNT-equivalent method;
2- Multi-energy method:
3- Baker-Strehlow-Tang method

3.1. Equivalent TNT mass method

According to this method, the power of the vapor cloud explosion equates to an equivalent mass of TNT (tri-nitro toluene) that would produce the same explosive power. First, the mass of the flammable gas in the cloud at concentrations between the lower and the upper flammability limits (LFL and UFL) is estimated. This mass is consequently multiplied by the heat of combustion to obtain the total available energy of the combustion. In general, the TNT method is employed today only as a first estimate in the determination of the effects of an explosion. The method is based on the empirical diagram of Brasie and Simpson and produces the overpressure, P_S (kPa), as a function of a scaled distance, Z (m/kg$^{1/3}$), defined by the below equation (Brasie et al., 1977):

$$Z = \frac{x}{M_{TNT}^{1/3}} \tag{1}$$

where, x(m) is the distance from the center of the explosion and M_{TNT} (kg) denotes the equivalent TNT mass, obtained from the below expression:

$$M_{TNT} = \frac{f_E \Delta H_C M_G}{\Delta H_{TNT}} \tag{2}$$

In the above expression, M_G (kg) denotes the mass of the flammable gas that takes part in the explosion; ΔH_c (kJ/kg) and ΔH_{TNT} (kJ/kg) are the heat of combustion of the flammable gas and the heat of combustion of TNT (= 4,760 kJ/kg) respectively. The dimensionless coefficient, f_E, denotes the fraction of the energy released as shock wave, the value of which is usually between 0.01 and 0.1. Alternatively, one can use the following more recent analytical expression for the overpressure, P_S (kPa), of the shock wave:

$$P_s = \frac{80800(1 + [\frac{Z}{4.5}]^2)}{\sqrt[2]{1 + [\frac{Z}{0.048}]^2}\sqrt{1 + [\frac{Z}{0.32}]^2}\sqrt{1 + [\frac{Z}{1.35}]^2}} \tag{3}$$

The most important disadvantages of this method are as follows:

a) The TNT method calculates the overpressure of an explosion without taking the space configuration where the explosion takes place into consideration;
b) Parameter f_{E} in most cases is unknown, and it greatly influences the prediction;
c) The method does not calculate the time evolution of the explosion.

3.2. Multi-energy method

The most important assumption of this method is that the strength of the explosion blast, and thus the overpressure developed, depends upon the layout of the space where the cloud is spreading. More precisely, only the obstructed or partially obstructed regions (regions with a high equipment density) will contribute to a high strength explosion blast. The remaining parts of the cloud will slowly burn, without a serious contribution to the strength of the blast (Berg, 1985; Berg and Lannoy, 1993; Mercx et al., 2000). This is achieved by the following steps.

-Cloud dimensions

The volume, V (m^3), of the resulting vapor cloud (composed of flammable gas and air) is calculated from the reaction stoichiometry, from which the volume of the oxygen required, and thereby the volume of the required air, is obtained. The radius of the resulting cloud, R (m), is derived from the volume, V (m^3) of the cloud, being considered as a hemisphere, as follows:

$$R = (\frac{3V}{2\pi})^{1/3} \tag{4}$$

-Obstructed regions

A non-obstructed region is a region that does not include any kind of obstacles, and therefore the cloud can be evenly distributed; i.e., the strength of the explosion blast is very low. On the contrary, an obstructed region is a region of high density of obstacles (equipment, walls, buildings, etc.) resulting in the increase of the spreading velocity of the cloud as flow changes from laminar to turbulent, and thus the strength of the explosion blast becomes very high. Hence the area surrounding the explosion center must be separated into obstructed and non-obstructed regions (Berg, 1985; Berg and Lannoy, 1993).

-Strength of explosion blast and overpressure

The scaled dimensionless overpressure, P_S', is given as a function of the scaled dimensionless distance, r'. Both these quantities are defined (Berg, 1985) as given by:

$$P_S' = \frac{P_S}{P_a} \tag{5}$$

$$r' = \mathrm{x}(\frac{\mathrm{E}}{\mathrm{P_a}})^{-1/3} \tag{6}$$

The parameter of these curves is the coefficient of the strength of the explosion blast as mentioned above. A coefficient of 10 refers to a high strength explosion with a very high overpressure. P_s (MPa) denotes the overpressure caused by the explosion, P_a (MPa), the ambient pressure (= 0.1 MPa), x (m), the distance from the center of the explosion, and E (MJ), the total energy released by the explosion. In the multi-energy method the unknown parameter is the coefficient of the strength of the explosion blast. This must be estimated according to the equipment density in the surrounding area. If the equipment density is high in the area, the value of the coefficient of strength will then have a large value. For the two cases of blast strength 10 and 3, the following equation can be used:

$$P_s = 10^{-\mathrm{b}\log \mathrm{r}' - \mathrm{c}} \tag{7}$$

Table 3

Coefficients *b* and *c* (AIChE / CCPS, 1994).

Coefficient of strength of Explosion	Range of r'	*b*	*c*
10	$0.15<r'<1.0$	2.3721	0.3372
	$1.0<r'<2.5$	1.5236	0.3372
	$r'>2.5$	1.1188	0.5120
3	$r' \leq 0.6$	0	1.3010
	$r' > 0.6$	0.9621	1.5145

One of the advantages of the multi-energy method is that it predicts the duration of the positive phase of the explosion, t_p (s). It can be calculated using the following equation.

$$t_P = \frac{t_p'}{C_s}\left(\frac{E}{P_a}\right)^{1/3} \tag{8}$$

where, P_a (MPa) denotes the ambient pressure (= 0.1 MPa); E (MJ) is the total energy released, and C_s (m/s) represents the velocity of sound (= 340 m/s).

3.3. Baker-Strehlow-Tang method

The Baker-Strehlow method (Baker et al., 1996; Baker et al., 1998) was first published in 1996 and is based upon the same idea of obstructed regions that were initially put forward by the multi-energy method (Baker et al., 1998). In both methods, the presence of obstacles in the expansion of the flame causes vapor cloud explosions of a higher intensity. In the multi-energy method, obstructed regions are determined. In these regions, the explosive blast is of a higher intensity, and is characterized by the explosion blast coefficient. Baker et al. suggested considering three different categories for the reactivity of fuels:

- High reactivity fuels: hydrogen, acetylene, ethylene oxide, and propylene oxide;
- Low reactivity fuels: methane and carbon monoxide;
- Medium reactivity fuels: all other gases and vapors.

4. Results and discussion

Figure 1 shows the overpressure calculated by TNT method. It is clear that maximum overpressure is 1 bar at 200 m, and it is declined to 0.08 barg at 1000 m from the center of explosion rapidly. The calculations showed that the breakage of small windows happened under strain. The pressure waves on the plot plan of the site are shown in Figure 2. It was shown that the radius of blast waves reached 200 m from the center of explosion.

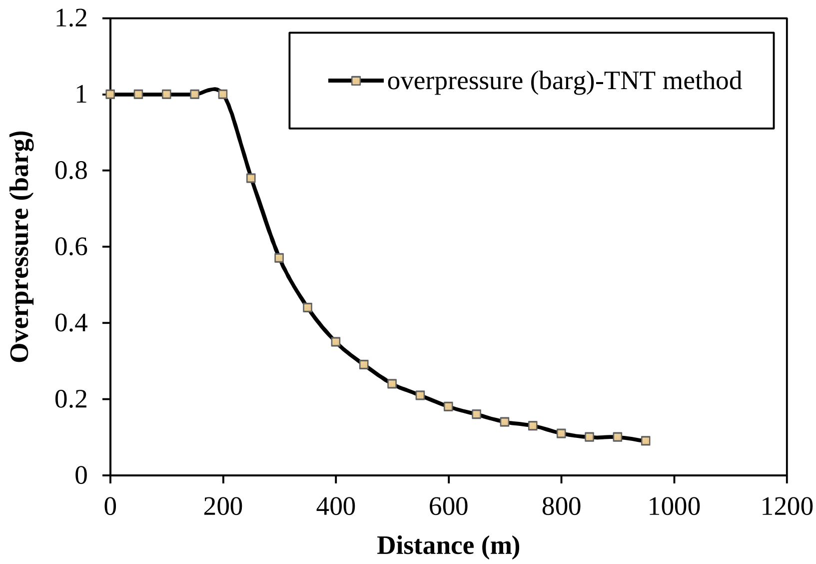

Figure 1
Early explosion overpressure versus distance.

Figure 2
Early explosion on site plan.

Figure 3 shows the overpressure calculated by the multi-energy method. It is shown that an overpressure of 2.03 barg is obtained at 195 m. It decreases with increasing the distance from the center of pressure, and an overpressure of 0.15 barg is obtained at 1000 m. This pressure can damage a 30 cm thick concrete wall. Figure 4 shows the pressure waves counters on the plot plan of the site. It is shown that the radius of blast waves reached 400 m from the center of pressure waves.

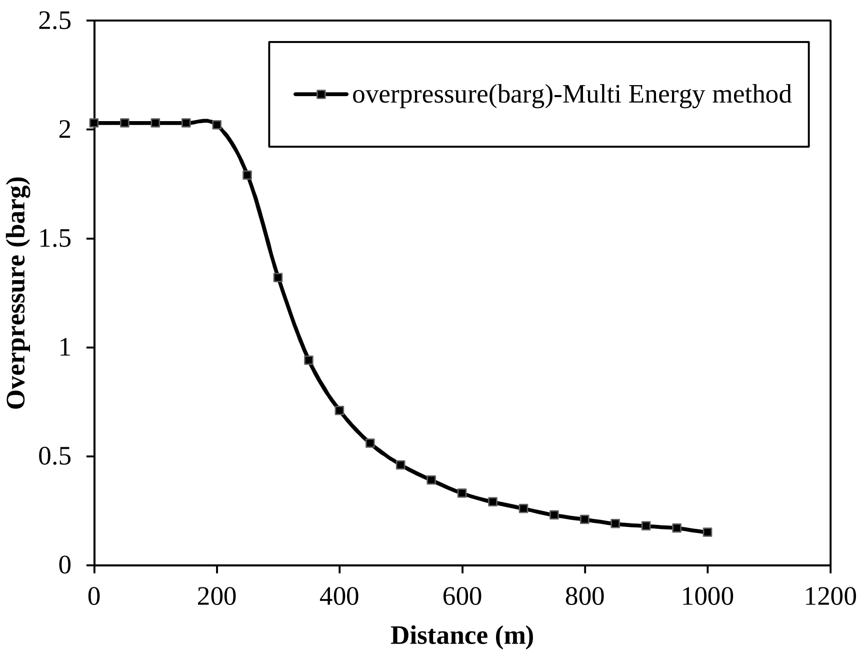

Figure 3
Early explosion overpressure versus distance.

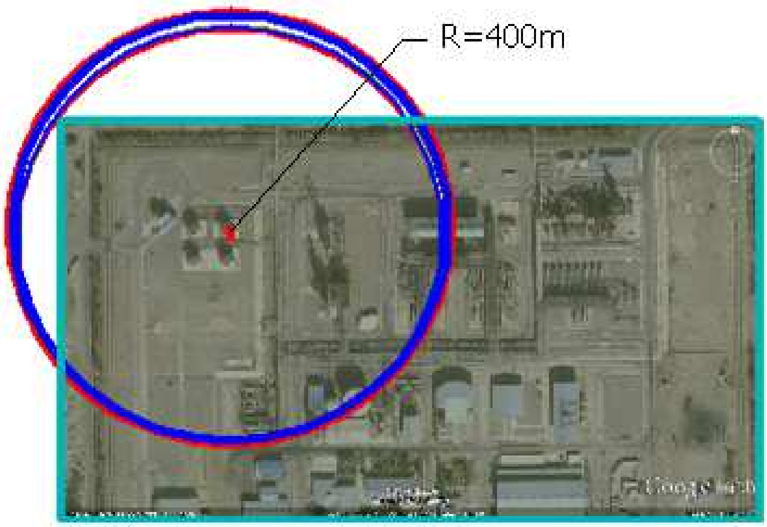

Figure 4
Early explosion on site plan.

Figure 5 shows the overpressure calculated by the BST method. The overpressure of 3.51 barg is obtained at 65 m from the center of pressure. It decreases with increasing distance from the center of pressure to the extent that an overpressure of 0.19 barg is obtained at 1000 m. Figure 6 shows the pressure waves counters on the plot plan of the site. It is shown that the radius of blast waves reached 700 m from the center of pressure waves. For the sake of comparison, the results of overpressure for the TNT method and multi-energy method by coding with MATLAB are reported at different distances. These results can be compared with PHAST software results. For a fraction of the energy released by TNT method (f_E), three values, namely 0.05, 0.1, and 1 were selected. The results of the simulation are given below.

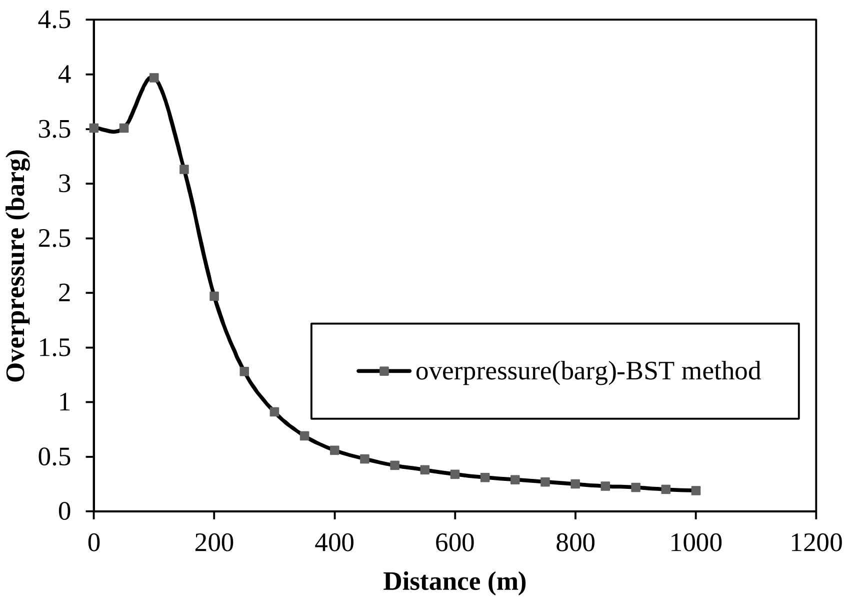

Figure 5
Early explosion overpressure versus distance.

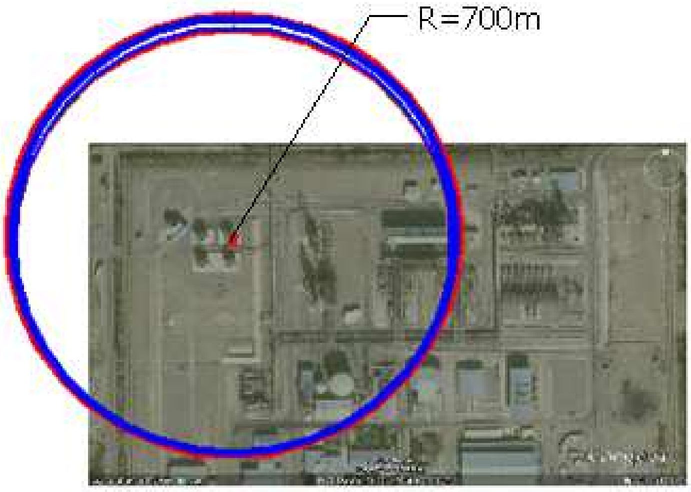

Figure 6
Early explosion on site plan.

Figure 7 shows the overpressure calculated for the distances between 25 to 100 m with TNT and multi-energy methods. As it can be seen, the overpressure decreases with increasing the distance.

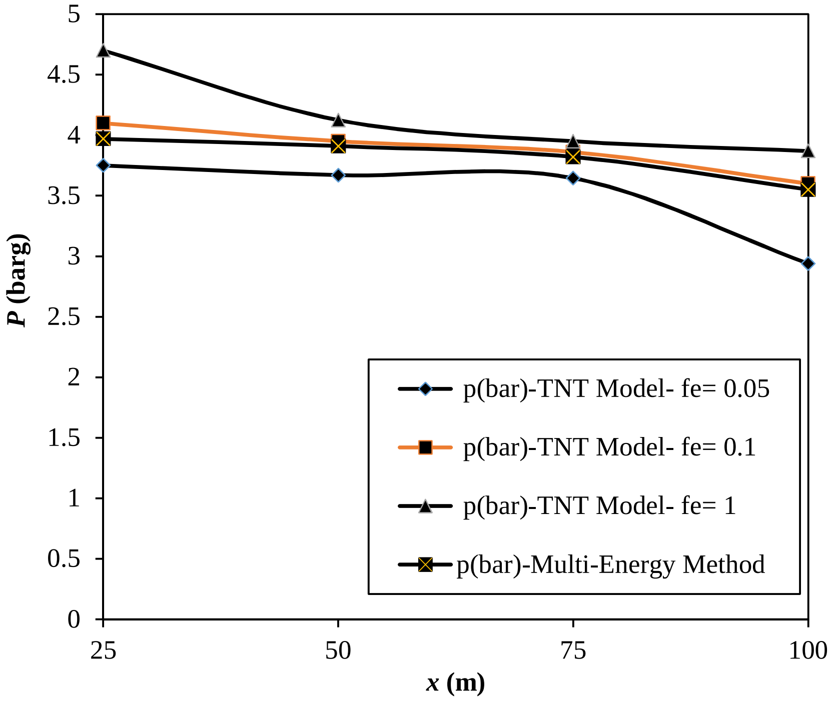

Figure 7
Calculated overpressure for the distances between 25 to 100 m with TNT and multi-energy methods.

Figures 8 and 9 show the overpressure calculated for the distances between 100 to 1000 m with TNT and multi-energy methods. According to the results of the above tables and the figures given below, it can be observed that TNT method with an f_E=0.1 is close to multi-energy method within a distance of 600 m and gives reasonable results; however, beyond 600 m, TNT method with an f_E=1 can be used and this is the optimum distance, in which the values of overpressure for TNT and multi-energy methods are the same, i.e. 0.33 barg.

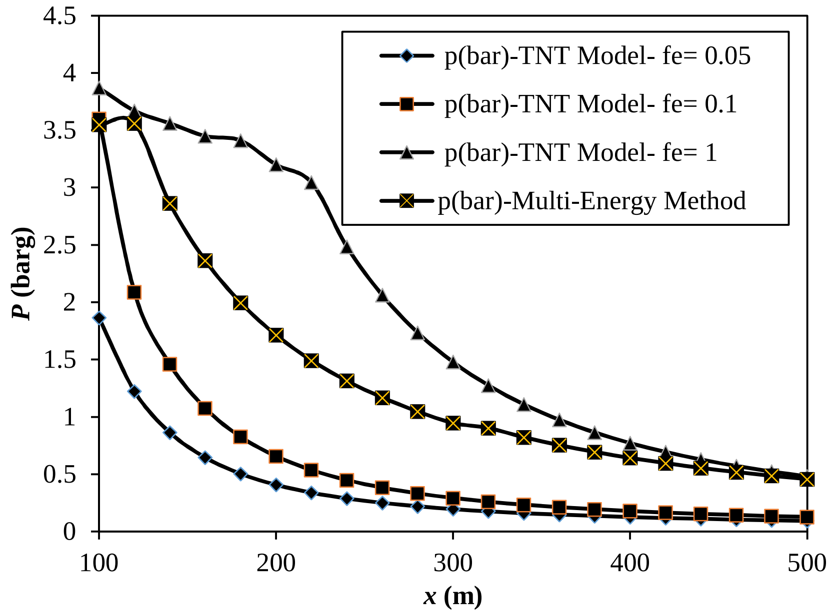

Figure 8
Calculated overpressure for the distance between 100 to 500 m with TNT and multi-energy methods.

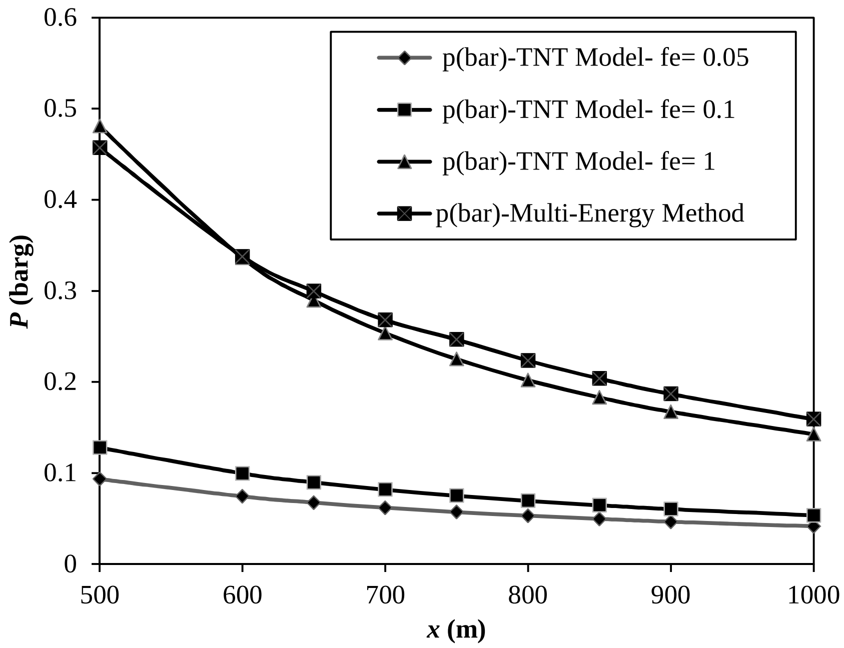

Figure 9
Calculated overpressure for the distances between 500 to 1000 m with TNT and multi-energy methods.

Figure 10 shows the calculated overpressure versus distance using software PHAST and MATLAB. The results from the codes compared with PHAST software. It is found that multi-energy method has the best results due to the small error. At a distance of 1000 m, PHAST software calculates an overpressure of 0.15 barg using multi-energy method and the MATLAB code gives a value of 0.1590 barg. From figure 10, it is clear that multi-energy and BST methods give the same results over a broad range of overpressures and distances.

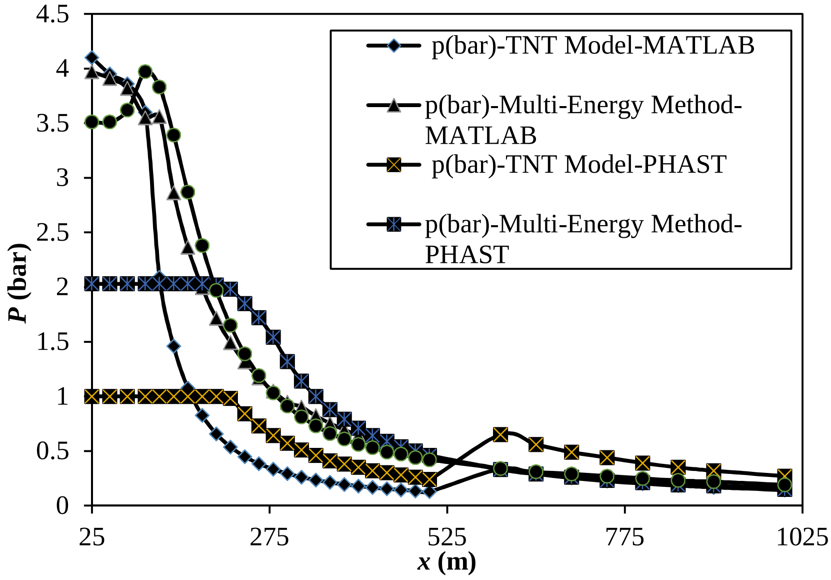

Figure 10
Calculated overpressure versus distance using software PHAST and MATLAB.

These limits are directly related to specific radiation effects to people and materials, and they are in full agreement with those proposed by the American Petroleum Institute (API) (Bubbico et al., 2008). The effects of heat on personnel are evaluated using simple rule sets based on human response to 5, 12.5, and 37.5 kW/m^2. Figure 11 shows the amount of radiation and death percentage in terms of distance. At the distance of 285.52 m, heat radiation is 37.5 kW/m^2 and the death percentage is 100% in about 1 minute, while at a distance of 647.98 m, the death probability is 6.53%. By examining the events and occurrences, it can be observed that primary effects can have secondary consequences. As an example, we can refer to PEMEX, in which the proximity of tanks to each other intensified the effects of the event. This phenomenon even damages the surrounding of refinery, primary gas separation unit (UNIT 200), and gas liquid stabilization unit (UNIT 700).

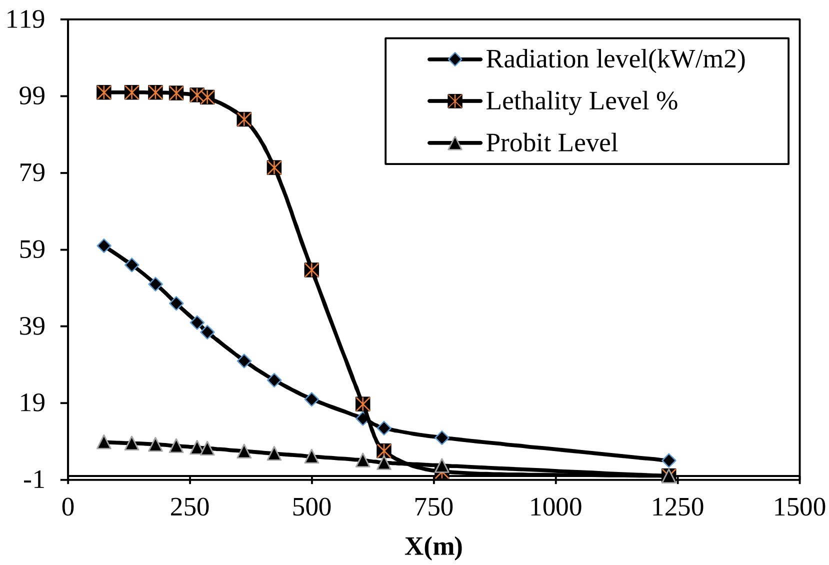

Figure 11
Effect of explosion on personnel and equipment.

5. Conclusions

Explosions are very significant in terms of their damage potential, often leading to fatalities and damages to properties. The consequences of an explosion in LPG spherical tanks were modeled using PHAST software and the results were compared with the results obtained from the model coding in MATLAB software. In this paper, three methods for the calculation of PHAST software, TNT, multi-energy, and BST were used. The overpressure at the distance of 1000 m is 0.19, 15, 0.08 barg in BST method, multi-energy method, and TNT method respectively. According to these results, on a broad range of overpressure and distance, BST method and multi-energy method are in good agreement. It is also concluded that, within 600 m, TNT method with an f_E=0.1 is close to multi-energy method and gives reasonable results, but beyond 600 m, TNT method with an f_E=1 can be used and this is the optimum distance in which the values of overpressure for TNT method and multi-energy method are the same, i.e. 0.33 barg. The results showed that multi-energy method is the best method to evaluate overpressure; values of 0.150 and 0.159 barg were obtained at a distance of 1000 m from the blast using PHAST and MATLAB respectively. This overpressure can damage a wall with a thickness of 30 cm and affect the human threshold (1%) ruptured eardrum. Finally, it was found that 100% lethality in a minute happened at a distance of 285.5 m and a heat radiation of 37.5 kW/m^2. For the future works, computational fluid dynamics can be used to improve explosion models.

Nomenclature

E	: Total energy released by the explosion (MJ)
f_E	: Fraction of the energy released as shock wave
ΔH_c	: heat of combustion (kJ/kg)
ΔH_{TNT}	: Heat of combustion of the flammable gas (kJ/kg)
M_{TNT}	: Equivalent TNT mass (kg)
M_G	: Mass of the flammable gas (kg)
P_a	: Ambient pressure (Pa)
P_S	: Overpressure (kPa)
P'_S	: Scaled overpressure
R	: Radius (m)
r'	: Scaled distance
X	: Distance (m)
Z	: Scaled distance (m/kg$^{1/3}$)

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