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Impact Assessment of Thermal Radiation Hazard from LPG Fireball

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Abstract

The failure of the pressure vessel containing pressure liquefied petroleum gas leads to Boiling Liquid Expanding Vapour Explosion (BLEVE). Further, ignition of released gas results in the formation of fireballs. In the present paper the semi-empirical equations are presented that represent the impact assessment of thermal radiation hazards from the liquefied petroleum gas fireball. Also an attempt has been made to determine the safe separation distance.

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Keywords: Thermal radiation hazards, fireball, safe separation distance

1. Introduction

Liquefied petroleum gas (LPG) is among the fuel which is the most widely used energy sources. Huge amounts of flammable materials (chemicals, hydrocarbons) are being transported regularly by various means of transportation (rail, road, ship, etc.). Often, these flammable materials are transported through inhabited areas with a variety of population densities; therefore there is potential risk of causalities if any accident takes places. In fact, there are several such examples of accidents involving flammable and hazardous materials that occur during transportation. Nevertheless, accidents in transportation continue to happen since avoiding them completely is practically impossible. Table 1 provides a list of fireball incidents. It is very important to assess the possible consequences and gain proper understanding about the accidental scenario. In the present paper, an attempt has been made to analyse the consequences of release of liquefied petroleum gas (LPG) from a transportation tanker. The sudden release of liquefied gas from a pressure vessel to the ambient is the beginning of a complex event which often leads to Boiling Liquid Expanding Vapour Explosion (BLEVE). Further, if the released material gets ignited it ends up with formation of large fireball. Fireballs can emit huge amount of energy causing property damages, injuries or deaths.
Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{\text{max}}$</td>
<td>maximum diameter of fireball, m</td>
</tr>
<tr>
<td>$H$</td>
<td>height of fireball center from ground, m</td>
</tr>
<tr>
<td>$R$</td>
<td>radius of fireball, m</td>
</tr>
<tr>
<td>$t_{\text{max}}$</td>
<td>maximum duration of fireball, s</td>
</tr>
<tr>
<td>$m'$</td>
<td>burning rate, kg/m²s</td>
</tr>
<tr>
<td>$q'$</td>
<td>heat flux, kW/m²</td>
</tr>
<tr>
<td>$X$</td>
<td>distance from fireball to object, m</td>
</tr>
<tr>
<td>$\tau_a$</td>
<td>atmospheric transmissivity, -</td>
</tr>
<tr>
<td>$F_{\text{view}}$</td>
<td>view factor, -</td>
</tr>
<tr>
<td>$P_r$</td>
<td>probit function, -</td>
</tr>
<tr>
<td>$P$</td>
<td>probability, %</td>
</tr>
<tr>
<td>$F_k$</td>
<td>correction factor, -</td>
</tr>
</tbody>
</table>

Table 1. Fireball incidents

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Material</th>
<th>Transport involved</th>
<th>Death/Injuries</th>
<th>Fireball radius (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>Amarillo, TX</td>
<td>Oil</td>
<td>Strong tank</td>
<td>20d, 32i</td>
<td>-</td>
</tr>
<tr>
<td>1974</td>
<td>Aberdeen, UK</td>
<td>Butane</td>
<td>Road tanker</td>
<td>-</td>
<td>35</td>
</tr>
<tr>
<td>1975</td>
<td>Eagle Pass, TX</td>
<td>LPG</td>
<td>Road Tanker</td>
<td>17d, 34i</td>
<td>-</td>
</tr>
<tr>
<td>1976</td>
<td>Gadsden, AL</td>
<td>Petrol</td>
<td>Tank farm</td>
<td>4d, 28i</td>
<td>-</td>
</tr>
<tr>
<td>1977</td>
<td>Goldona, VA</td>
<td>LPG</td>
<td>Rail tank car</td>
<td>2d, 9i</td>
<td>160</td>
</tr>
<tr>
<td>1978</td>
<td>Donnellson, IA</td>
<td>LPG</td>
<td>Pipeline</td>
<td>2d, 2i</td>
<td>305</td>
</tr>
<tr>
<td>1978</td>
<td>Lewisville, AR</td>
<td>VCM</td>
<td>Rail tank car</td>
<td>2i</td>
<td>155</td>
</tr>
</tbody>
</table>

2. Modeling of fireball

The modeling of fireball covers the following aspects: (1) the amount of fuel in fireball, (2) the fireball diameter and duration, (3) the amount of energy radiated and (4) the view factor and atmospheric transmissivity.

2.1. Dimension and duration of fireball

Many researchers and investigators have proposed several correlations for determining the diameter and the duration of fireball. Some correlations are listed in table 2. The correlation proposed by Robert is commonly used for determining the diameter as well as duration of fireball is given as follows:

$$D_{\text{max}} = aM^b$$

$$t_{\text{max}} = cM^d$$

Where $D_{\text{max}}$ is the maximum diameter of fireball (m), $t_{\text{max}}$ is the maximum duration of fireball and $M$ is the mass of fuel (kg). The constant $a$ ranges from 5.25 to 6.48. The most common value for exponent $b$ is 0.333, although some models are slightly on lower side.

Table 2. Empirical correlations of fireball diameter and durations time for hydrocarbons
### 2.2. Mass burning rate

The mass burning rate, \( m' \) (kg/m\(^2\) s), is defined as the rate with which the fuel forms the fireball burns. The burning rate can be calculated as a function of the mass of the fuel and the total fire ball duration and is expressed as:

\[
m' = \frac{M}{(0.888\pi D_{\text{max}}^2)T_{\text{max}}} \tag{3}
\]

Where, \( (0.888\pi D_{\text{max}}^2) \) is the time–average surface of the fireball sphere.

### 2.3. Surface emissive power

The surface emissive power is the power emitted from the surface of the fireball. The maximum surface emissive power can be calculated as a function of the mass burning rate and the heat of combustion and is expressed as:

\[
SEP_{\text{max}} = F_s m' \Delta H_c \tag{4}
\]

Where \( \Delta H_c \) is the heat of combustion, (kJ/kg) and \( F_s \) is the fraction of energy which is radiated from the surface of fireball. The fireball is considered as sphere. However, no surface correction proportional is required for the above expression as the mass burning rate already refers to the surface of the perfect sphere. The radiation fraction can be calculated by following expression\(^2\).\(^3\).

\[
F_s = 0.00325P_{\text{sv}}^{0.32} \tag{5}
\]

Where \( P_{\text{sv}} \) is the vapor pressure inside the tanker, (Pa). The actual surface emissive power is almost equal to the maximum surface emissive power in case of fireball which is due to the fact that the duration of fireball is very small and it is considered that less amount of soot is formed to be able to affect the heat flux emitted from surface of fireball.

### 2.4. View factor

The view factor quantifies the geometric relationship between the emitting and receiving surfaces. The fraction of the emitted radiation that strikes the receiving surface per unit area. For calculating the view factor for fireball the shape of the fire is assumed to be a perfect sphere as shown in figure 1.

\[
F_{\text{view}} = \left(\frac{R}{X}\right)^2 \tag{6}
\]

Where \( X = \sqrt{H^2 + x^2} \)
2.5. Atmospheric transmissivity

The atmospheric transmissivity is defined as the fraction of thermal radiation exposure received at a certain distance after passage through the atmosphere, relative to that which would have been received at the same distance if no atmosphere were present. Transmissivity depends on several factors; water vapour and carbon dioxide absorption of infrared radiation, ozone absorption of ultraviolet radiation and multiple scattering of all radiation. The atmospheric transmissivity can be determined by following correlation 4.

\[
\tau_a = 2.02[P_w(X - R)]^{-0.09}
\]  

(7)

Where \(P_w\) is the partial water vapor pressure in air, \(X(m)\) is the distance of the receptor from the center of the fire of radius \(R(m)\) whereas the partial vapor pressure in air is equal to the product of relative humidity and saturation water vapor pressure, \(P_w = RH \times P_w^0\).

2.6. Heat flux

The heat flux \(q'(kW/m^2)\), in a certain distance from the centre of the fireball is determined by given correlation.

\[
q' = SEP_{act}F_{view}\tau_a
\]  

(8)

3. Effect of thermal radiation on people

The effect of thermal radiation emitting from fireball can cause burns or deaths. In order to estimate the number of burns and deaths, the term "thermal radiation dose," \((w^{4/3}s,m^{−8/3})\), is employed and is expressed as follows:

\[
D = t_{eff}(q')^{4/3}
\]  

(9)

Where \(t_{eff}\) is the persons exposure time to heat flux, (s).

For determining the probit values and probability of injury (1st or 2nd degree burns) or death as a consequence of a specified dose, the following correlations are employed 1. The coefficients for determining probit values for deaths and injuries are listed in table 3.

\[
P_r = a + b\ln D
\]  

(10)

Table 3. Coefficients a and b

<table>
<thead>
<tr>
<th>Effect</th>
<th>(a)</th>
<th>(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st degree burn</td>
<td>-39.83</td>
<td>3.0186</td>
</tr>
<tr>
<td>2nd degree burn</td>
<td>-43.14</td>
<td>3.0186</td>
</tr>
<tr>
<td>Deaths</td>
<td>-36.38</td>
<td>2.56</td>
</tr>
</tbody>
</table>
\[ P = F_k \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{P_r - 5}{\sqrt{2}} \right) \right] \]  

(11)

Where, \( F_k \) is the correction factor which refers to clothing. The value of \( F_k \) is taken as unity, i.e., which means clothes have no effect.

4. Safe separation distance

The maximum allowable limit of thermal radiation for people (without protection) and houses are considered to be 4.7 kW/m² and 10 kW/m² respectively\(^5\). It was considered that the houses were commonly built using plastic materials. By considering these values and the calculated values of thermal radiation, the safe separation distance was determined for the scenario discussed in section 5.

5. Example

A tanker carrying liquefied petroleum gas (LPG) met an accident which increases the pressure inside the tanker resulting BLEVE. The capacity of the tanker was 65 m³ but only 75 \% was full with LPG. After the accident all the LPG gets spilled and gets ignited immediately forming a fireball. Calculate the following:

- The intensity of heat flux 200 m away from the tanker and also the safe separation distance.
- The probability of death and injury due to 1\(^{st}\) and 2\(^{nd}\) degree burn in a distance of 50 m from the accidental area.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of LPG, ( \rho_{LPG} )</td>
<td>517 kg/m³</td>
</tr>
<tr>
<td>Ambient temperature, ( T_a )</td>
<td>293 K</td>
</tr>
<tr>
<td>Relative humidity, ( RH )</td>
<td>0.5</td>
</tr>
<tr>
<td>Saturation water vapor pressure, ( P_{sw} )</td>
<td>2320 Pa</td>
</tr>
<tr>
<td>Pressure inside the tank, ( P_{in} )</td>
<td>1.6 MPa</td>
</tr>
<tr>
<td>Heat of combustion, ( \Delta H_c )</td>
<td>46000 kJ/kg</td>
</tr>
</tbody>
</table>

The amount of liquid propane gas release in case of complete failure of tanker and it can be calculated as:

\[ M = 0.75 \times \rho_{LPG} \times V = 25203.75 \text{ kg} \]

The diameter of the fireball and the duration is calculated from employing the correlation of Roberts ()

\[ D_{max} = 5.8M^{0.\overline{3}33} = 169.47 \text{ m} \]

\[ t_{max} = 0.45M^{0.\overline{3}330} = 13.15 \text{ s} \]

While the height of the fireball is \( H = D_{max} = 169.47 \text{ m} \).

Using eq. (3) the mass burning rate is obtained as

\[ m' = \frac{M}{(0.888\pi D_{max}^{2})t_{max}} \]

\[ = 0.0239 \text{ (kg/m}^2\text{s)} \]

In order to calculate the actual surface emissive power firstly the radiation fraction has to be calculated

\[ F_s = 0.00325P_{sw}^{0.32} = 0.314 \]

and thus from equation (4) the maximum surface emissive power is calculated as
\[ SEP_{\text{max}} = F_p m' \Delta H_c = 345.21 \text{ kW/m}^2 \]

Since it was considered that the soot formation was negligible.

\[ SEP_{\text{max}} = SEP_{\text{act}} = 345.21 \text{ kW/m}^2 \]

By substituting the values one can obtain the view factor for specified distance

\[ X = \sqrt{H^2 + x^2} = \sqrt{169.47^2 + 200^2} = 262.14 \text{ m} \]

\[ F_{\text{view}} = \left( \frac{R}{X} \right)^2 = 0.104 \]

The atmospheric transmissivity is obtained from equation (7) and then by direct substitution in equation (8) the heat flux can be calculated. Where the partial vapor pressure in air is \( P_v = 0.5 \times 2320 = 1160 \text{ Pa} \)

\[ \tau_a = 2.02 [P_v(X - R)]^{-0.09} = 0.671 \]

thus

\[ q' = SEP_{\text{act}} F_{\text{view}} \tau_a = 24.09 \text{ kW/m}^2 \]

The amount of heat flux received at the distance of 200 m is about 24.09 kW/m². Also the fig. 2 represents the relation between amount of heat flux reaching at various distances. Fig. 3 shows the safe separation distance versus tank volume for present accident scenario.

The probability of deaths and injuries in a distance of 50 m from the accidental area can be calculated by following steps. Firstly the heat flux received at 50 m away from the accidental is calculated from equation (8) which is \( q' = 56.68 \text{ kW/m}^2 \). In case of fireball and flash fires the exposure time of a person is considered equal to the duration of fireball. The thermal radiation dose is calculated from equation (9) which is equal to \( D = 28.6 \times 10^6 \text{ (w}^{4/3} \text{. m}^{-8/3}) \). Then using the thermal radiation dose, probability of deaths and injuries can be calculated from equation (11). Table 4 shows the probability of injuries and death for various distances.
Fig. 2. Variation of heat flux as a function of distance

Fig. 3. Safe separation distance vs. tank volume

Table 4. Probability of injuries and death

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>1st degree burn, (%)</th>
<th>2nd degree burn, (%)</th>
<th>Death, (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>100</td>
<td>99.9</td>
<td>99.4</td>
</tr>
<tr>
<td>75</td>
<td>100</td>
<td>99.9</td>
<td>98.6</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>99.7</td>
<td>96.2</td>
</tr>
<tr>
<td>125</td>
<td>100</td>
<td>98.4</td>
<td>89.2</td>
</tr>
<tr>
<td>150</td>
<td>99.9</td>
<td>93.8</td>
<td>77.4</td>
</tr>
<tr>
<td>175</td>
<td>99.9</td>
<td>81.7</td>
<td>58.5</td>
</tr>
<tr>
<td>200</td>
<td>99.9</td>
<td>60.8</td>
<td>37.4</td>
</tr>
<tr>
<td>225</td>
<td>99.8</td>
<td>36.6</td>
<td>19.9</td>
</tr>
<tr>
<td>250</td>
<td>99.1</td>
<td>17.4</td>
<td>8.87</td>
</tr>
</tbody>
</table>

6. Conclusions

The following conclusions were drawn:
- The diameter, duration and height of the fireball is directly proportional to the amount of flammable material present in the tanker at the time of accident/failure.
- The heat flux received by the object depends on the distance between the center of fireball and the object. As the distance was increased the heat flux tends to decrease.
- Safe separation distance and the probability of injuries and death varies depending on the amount of fuel carried by the tanker.

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