International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 04, April-2015

Modeling of Fire and Explosion at Bulk Storage of Hazardous Flammable Substances

Anas Haque[1], Abhaynath Kumar[2], Praveen Patel[3]
[1,2]M. Tech Student, [3]Professor,
Department of Fire technology and Safety Engineering,
IES-IPS Academy, Indore (M.P), India

***Abstract*— In the modern world fire and explosion modeling is one of the most important tool to control and detect the intensity of any fire and the explosion and also the intensity of accidents can be predict by the fire modeling. The fire modeling which is used in the analysis of fire behavior like heat release rate, flame height, plume etc similarly explosion modeling which is used to evaluate the pressure wave, fire ball including vapor cloud explosions, boiling liquid expansion vapor explosions, the storage tank explosions. This paper gives an overview to the fire and explosion modeling on a storage tanks, as the storage tanks contain bulk amount of flammable substances (both liquids and gases). Such modeling can be used in minimize the impacts of fire and explosion and can also be used as an important tool to develop emergency preparedness plan.**

Keywords— Heat Release Rate; Flame Height; Fire Ball; Pressure Wave; Thermal Radiation;Duration of Boiling liquid Expansion Vapor Explosion.

I. INTRODUCTION

Modeling is an inherent part of research in science and its application to fire is as older as scientific research into fire behavior itself. Modern fire research was published in power of computers, has given rise to highly complex models that can only be implemented as computer fire models. While computer fire model have popularized fire modeling, these computer based models do not suffer substantially from earlier fire models, they just are more complex and possess greater capabilities. The importance of modeling, in its application to fire safety design, has grown in past decade, with this widespread application comes a critical need for detailed understanding and appropriate use of models related to the problem in concern.

Fire has many highly complex phenomena and no single fire model describes all these phenomena at the same level of detail. The fire models predict the environmental condition with one or more physical bounded spaces. It predicts heat release rate, flame height, plume, smoke, radiant heat flux to the target, mass loss rate are produced by fire and how each of these variables is distributed over the time. Similar the explosion models predict the fire ball, height of the fire ball, intensity of radiation from the fire ball to the target, blast wave and over pressure. The most important points about the model which are currently exits must be their capabilities and application. In many situations the results are in good agreement with the experiments, but it is important to keep in mind that the models have their limitations so the choice of model depends upon the level of accuracy, details required and time available for the calculations.

II. OVER VIEW OF CHARACTER, STORAGE AND HAZARDOUS SUBSTANCES

A. Character

First In The collection of data is basically concerns to those areas where there are the storage of the flammable substances are done. Many industries used the flammable substances either in liquids forms like oils, petrol, diesel, paints etc or in gas like propane, butane, compressed gases etc. Some industries process these flammable substances from crude oil and separate them into various intermediate products. Some of them only stored them for supplying purposes like depots some of them has house hold installations. Ware house is also one of them where the bulk storage of flammable substances has been stored. A very special precaution has to be taken at a place or area where the flammable substances are stored because any leak or mistake or equipment malfunction leads to the deteriorate result.

B. Storage

The storage tanks are defined as “Atmospheric Pressure Storage Tank” and “Low Pressure Storage Tank” The tanks which are designed as per API STD-650 or equivalent are called “Atmospheric Storage Tanks” These tanks are designed to operate at internal pressure equal to the atmospheric pressure. Those tanks which are designed as per the API STD-620 or equivalent called “Low pressure Storage Tank” These tanks are designed to operate at a pressure at a pressure exceeding those permissible in API STD-650. So in the construction of the tanks the main features which keep in mind are Dimensional Accuracy, Robust Construction, Abrasion resistance and High Tensile Strength. All these properties make the tanks self sufficient and strong enough to take all kinds of loads and resist the conditions like environmental conditions, over pressure, over filling, temperature difference. In study the structure of the tank the following dimensions have to determine like material, weight, thickness, designed pressure, designed temperature, maximum diameter, maximum length, design code, type of substances, capacity of substances, maximum filling ratio.

C. Hazardous Substance

The product which is used in the modeling is propane gas which is a petroleum gas found mixed with the natural gas and petroleum deposits deep underground. Propane is from liquefied petroleum (LP) family so it is also known as LP-gas. Its chemical formula is C3H8. Under the normal conditions means at atmospheric pressure and temperature it is a gas while under the moderate pressure and/or low temperature it changes into a liquid. Propane takes up much less space in its liquid form, 27 times more compact in its liquid state than it is as a gas. Propane has been nicked name as a portable gas because it is easy to store and transport than the natural gas. The more data can be easily found in the MSDS of the propane. Since propane is denser than air if leaks in a propane tank occur, the gas will have a tendency to sink into any enclosed area and thus poses a risk of fire and explosion. As the propane is stored in different storage tanks ranging from Horizontal Tank, Vertical Tank, Spheres, Bullets to house hold storage. So all the propane cylinders must have pressure relief valve, service valve, bleeder valve (fixed liquid level gauge), protective collars, foot rings.

Properties and character tics of propane

- Propane burns cleanly and has high heat value.
- In its normal state, propane is neutral, and non-poisonous.
- Propane is heavy than air and can collect in low lying area.
- Propane presents a freeze burn hazard if it's cold liquid contact unprotected skin.
- Escaping of propane can create a fire and explosion hazard.
- Put on safety spectacles and complete face guard when working with propane tanks and cylinders.
- Consult MSDS of propane for more information about its physical, chemical and thermal properties.

TABLE I. PROPERTIES OF PROPANE

Property	Value
Boiling point	-42°C @ 1 atm
Freezing point	-188°C
Vapor pressure	1435 K pa at 37.8°C
Vapor density	1.52(Air=1)
Solubility in water	Slight, 6.1% by volume
Specific gravity	0.51(water= 1)
Heat of combustion	46,000 kJ/kg
Flammable	Yes
Flash point	-104°C

D. Available Model for fire and explosion

A model is a set of equations which mathematically represents some physical process. In fire and explosion there are numbers of factors which contribute to fire and explosion. So a model should ideally take all these variables into the account. In additional to this, the model should also contain appropriate physics which be able to deal with different fuels and ambient conditions and easy to use. In many situations the results of the simulation are in good agreement with the experiment but it is important to remember that the models have their limitations and the choice of the model depends on the level of detail, accuracy required and time available for calculations. The model which is used can be apply to any storage tanks, transportation trucks or Lorries, Rail wagons, are house storage.

The main component of any fire or a pool fire is:

1. Heat Release Rate
2. Flame Height
3. Radiant heat Flux to the Target

Similar to this the components of the explosion are:

1. Duration of fire ball
2. Height of fire ball
3. Fire ball diameter
4. Thermal radiation from fire ball

As there is a large amount of storage of flammable substances in the storage areas depend on the need like bulk storage, intermediate storage (Depots) and house hold storage. If there is any leaks or malfunction of the devices leads to the fire and explosion which results in release of large amount of heat also called heat release rate. It is denoted by Q and measured in kW/m². A simple equation of this as given in Fire protection Handbook. [1]

$$Q=\Delta H_c \times m$$

Q= Heat release rate
ΔH_c= Heat of combustion of fuel (kJ/kg)
m= mass loss rate (kg /s)

Radiant heat flux to the target is defines as the amount of the heat radiation received by a target located at distance from the fire. The point source model of intensity of Radiant Heat Flux to the Target as given by Drysdale is expressed as: [1]

$$q'' = \chi_r Q/4\pi R^2$$

Q= Estimated heat release rate (kW)

R= Distance from centre line of the radiation source to the target (m)
q″=Radiative Heat Flux by target (kW/m²)
χ_r = Radiative Fraction of total heat released whose value lies between 0.2 to 0.4 depend on fuel type and pool diameter.

Also, as given by Vytenis Babrauskas [2]

$$Q=\Delta H_c \times A \times m''$$

Where A is the Burning Area (m²)

Also the general equation for the pool fire as given by Burgess and Zabetakis is [2]

$m\cdot'' = m_\infty (1-e^{-k\beta D})$

Where, $m\cdot''$ = mass liquid burning rate
This requires the determination two factors: m and kβ.

The flame geometry is characterized by the flame base diameter, visible flame height and the flame tilt. The flame height is depending on the pool diameter and the rate of burning of fuel.

Heskestad gives the flame height model for zero wind condition is expressed as: [3]

$H=0.23Q^{2/5}-1.02D$

Q= energy release rate

In the presence of wind, the expression for estimating flame height is expressed by the following correlation, based on experimental data given by Thomas: [3]

$H/D= 55(fr^{0.67}) \times (u^{-0.21})$

$fr=m\cdot''/\rho_a\sqrt{g\times D}$ and $u=(u_w^3\times\rho_a/g\times D\times m\cdot'')$

Fr is the Non dimensional Froude's number and u is non dimensional Wind velocity.

ρ_a = Ambient air density
g=Acceleration due to gravity

Also due to the wind the flame get a tilt by an angle from the vertical. So, the expressions for estimating the tilt angle from the Vertical flame. [4]

$\cos\theta_v = \{1$ for $u_w/u_c < 1$
$\{(u_w/u_c)^{-0.5}$ for $u_w/u_c \geq 1$
Where, u_w is the wind speed and u_c is given as:

$u_c= (\sqrt{g\times m\cdot''\times D/\rho_a})^{1/3}$

ρ_a is density of air
D is diameter of pool
g is acceleration due to gravity

III. SAMPLE CALCULATION OF FIRE AND EXPLOSION AT PROPANE YARD FACALITY

A) *Calculation of fire modeling at propane gas:*

The calculation of fire at a bullet storage tank capacity of 3000 kg propane which is liquefied under the pressure at ambient temperature. Some data as per need are assumed.

A situation comes when the bullet is subjected to fire and the following calculations have done.
Heat Release Rate: The heat release rate is given as:

$Q=\Delta H_c \times m\cdot''\times A$

ΔH_c=46,000kj/kg, A=7.49 m², D=3.08 m, m_∞=0.099, kβ=1.4

$m\cdot''=m_\infty (1-e^{-k\beta D})$

$D=\sqrt{4A}/\sqrt{\pi}$ for (for non circular pool)

$m\cdot''=0.099(1-e^{-1.4\times3.08})$
= 0.0976

Q= 46000×0.0976×7.49

= 33627.10 kW

So the Heat Release Rate is 33,627.10 kW.

Height of Flame:

CASE I: When there is No Wind
The height of the flame is given by the following expression:

$H=0.23Q^{2/5}-1.02D$

= 0.23×64.6659-1.02×3.08
= 11.73 m
The height of the flame is 11.73 m

CASE II: When there is a wind.

The following equation is used for the height of the flame:

$H/D=55(fr^{0.67}) \times (u^{-0.21})$
Where,
$u=(u_w^3\times\rho a/g\times D\times m\cdot'')$

$fr=m\cdot''/\rho a\sqrt{g\times D}$

u_w= Wind velocity (2 m/s assumed)
ρ_a= ambient air density (1.275 kg/cm³)
g = acceleration due to gravity

$H/D=55(0.0139)^{0.67}\times (1.5176)^{-0.21}$

= 3.138×.917×3.08

H= 9.24 m

CASE III: Tilt angle of the flame

Because of the wind the flame get a tilt due to which its height is decrease and the tilt angle from the vertical is given by the following expression:

$\cos\theta_v= \{ 1$ for $u_w/u_c < 1$
$\{(u_w/u_c)^{-0.5}$ for $u_w/u_c \geq 1$

$u_c = (g \times m'' \times D/\rho a)^{1/3}$

$= (9.81 \times 0.0976 \times 3.08/1.275)^{1/3}$

$= 1.31$

$(u_w/u_c) = (2/1.31) = 1.51 > 1$

So, $\cos\theta_v = (u_w/u_c)^{-0.5} = (1.51)^{-0.5}$

$\cos\theta_v = 0.812$ or $\theta_v = 35.70°$

So in the speed of 2 m/s the flame get a tilt of 35.70° from the vertical.

Radiant Heat Flux to the Target: The intensity of the heat radiation at a target is given by the following expression:

$q'' = \chi_r Q/4\pi R^2$

$\chi_r = 0.3$ and R=10 m (assumed)

$= 0.3 \times 33658.53/4 \times \pi \times 100$

= 8.03 kW/m² (Incident thermal flux)

A target located at a distance of 10 m will receive a radiation of 8.03 kW/m² similar at 20 m it receives 2.007 kW/m², at 30 m it receives 0.894 kW/m², at 40 m it receives 0.502 kW/m² and at 50 m it receives 0.321 kW/m².

Thermal radiation (kW/m²)	Distance(m)
8.03	10
2.007	20
0.894	30
0.502	40
0.321	50

Since at 30 m it receives minimum radiation so the safe zone lies after at a distance of 30 m from the tank.

B) Calculation of explosion modeling at propane gas:

As similar the calculation of explosion modeling for bulk storage of propane;

Duration of fire ball: The duration of fire ball is expressed as: [5]

$t_d = 0.41\ M^{0.340}$

Where, M= mass in kg

So, t_d= 6.23 seconds

Maximum Diameter of Fire ball: The maximum diameter is given as: [5]

$D_{max} = 6.14\ M^{0.325}$

$= 82.8$ m

The maximum diameter of fire ball is 82.8 m.

Height of the Fire Ball: The Height of the Fire Ball is given as: [5]

$H_{fb} = 0.75x\ D_{max}$

$= 0.75x82.8 = 62.12$ m

The height of the fire ball is 62.12 m.

Radiation Received by Surface or Target: The radiation received by a target is given by: [5]

$I = \tau\ x\ f\ x\ E_p$

Where: $\tau = 2.02x\ (P_w\ x)^{-0.09}$ (Atmospheric transmisivity)
$= 2.02\ x\ (4035.7\ x\ 21.51)^{-0.09}$
$= 0.726$

F= view factor= $D^2/4(R+x)^2$

$= (82.8)^2/15835.57$
$= 0.432$

$E_p = \eta\ M\ Hc / \pi\ D^2\ t$ (Emissive power)

$= 257.11$ kW/m^2

I= 0.726 x 0.432 x 257.11
=80.63 kW/m^2

So the radiation received by a target at a distance of 10 m is 80.63 kW/m^2. As similar the following table is:

Thermal radiation (kW/m²)	Distance(m)
80.63	10
73.94	20
65.62	30
55.71	40
46.05	50

IV. VULNERABILITY TO HUMANS

The vulnerability to humans can be determined by the probit model which is a function that relates lethality to the intensity or concentration of a hazardous effect and the duration of exposure. Lethality refers to the quantitative effect, namely fraction or percentage of the exposed population who would suffer fatality on exposure to a given consequence level. It typically takes the form: [6]

$Pr = k_1 + k_2 \ln V$

Where k_1 and k_2 are constants
For thermal radiation ($V= I^{4/3}. t$) called the thermal dose with units $(kW/m^2)^{4/3}$
I= Incident thermal flux
T= exposure time

Depending on the duration, intensity and area of exposure. The effect of fire range from pain through first, second and third degree burns to fatality. Humans are vulnerable to the fire in the followings ways:

- Engulfment by fire
- Thermal radiation from fire
- Within a construction that is exposed to fire

The explosion results in the blast wave. The person who comes into the effect of the explosion over pressure results in the injuries like lung damage, gastrointestinal and ear drum damage. So the humans are vulnerable to the blast effect of the explosion in the following:

- Burn by the radiation
- Flying Fragments
- Person hit by the solid objects

The effects of the thermal radiation depend on the thermal radiation flux, duration of exposure, type of clothing worn and the individual exposed. The pathological effect of the thermal radiation on humans is the most appropriate in the direct area of an incident. When a person is exposed to the thermal radiation either from a fire or a fire ball results in the injury or fatality which categorized as:

- Pain
- First degree of burn
- Second degree of burn
- Third degree of burn
- Fatality

The thermal radiation exposure effects information table provides the relationships between thermal radiation and effects valid in all circumstances.

TABLE II. THERMAL RADIATION EXPOSURE EFFECTS [6]

Thermal radiation (kW/m^2)	Effect
1.2	Received from the sun at noon summer
2	Minimum to cause pain after 1minute
Less than 5	Will cause pain in 15 to 20 seconds and injury after 30 seconds exposure
Greater than 6	Pain within approximately 10 seconds; rapid escape only is possible
12.5	• Significant chance of fatality for medium duration exposure • Thin steel with insulation on the side away from the fire may reach the thermal stress level high enough to cause structural failure • Wood ignites after prolonged exposure
25	• Likely fatality for extended exposure • Spontaneous ignition of wood after long exposure • Unprotected steel will reach thermal stress temperature that can causes failure
35	• Significant chance of fatality for people exposed instantaneously • Cellulosic material will pilot ignite within one minute's exposure

The probit model for the thermal radiation dose is expressed as:[6]

$Pr= -14.9+2.56 \ln V$
Where $V=I^{4/3}. t$

Here I= 8.03kW/m² or 8030 W/m² and is 60 seconds (assumed)

$= -14.9+2.56 \ln 60\times (8030)^{4/3}$

= 3.73 probit

Hence for the probit of 3.73 from probit table [6] exposure of 60 seconds the population affected is 10-11 %.

The thermal dose is expressed as: [6]

$$V= t.q^{4/3} \quad (kW/m^2)^{4/3}$$

$$= 60 \times 15.96 = 958.12 \ (kW/ m^2)^{4/3}$$

So the thermal dose for the radiation flux of 8.03 kW/m² for the 60 seconds results in 2nd degree burn similar for 50, 40 and30 seconds results in 1st degree burn for 20 and 10 seconds results in pain.

Time(s)	Degree of Burn
60	2^{nd}
50	1^{st}
40	1^{st}
30	1^{st}
20	Normal Pain
10	Normal Pain

The probit model for the peak over pressure is expressed as:[6]

$$Y=5.13 + 1.37 \ln P$$

Where p is peak over pressure

$$=5.13+1.37 \ln (0.89)$$
$$= 6.38 \text{ probit}$$

Hence for the probit of 6.38 from probit table [6] for the 0.89 over pressure the fatality is 91%

TABLE III. RANGES OF THERMAL DOSE REQUIRED CAUSING PAIN, BURNS AND FATAL OUTCOME [6]

Effect	Thermal Dose	Comments
Pain	108-127	Bare skin
	85-129	Bare skin
Significant injury level/ First degree burns	600-800	Bare skin
	250-350	Bare skin
	210-700	Bare skin
Second degree burns/ 1% lethality for average clothing	900-1300	Bare skin
	500-3000	Bare skin
Third degree burns/ 50% lethality level for average clothing	2000-3000	Bare skin

V. CONCLUSION

Fire protection is always important for the industries and the domestic users. Modeling in this paper gives a snapshot of the outside exposure of heat liberation, flame height, fire ball height, fire ball diameter and thermal radiation from a bullet structure of bulk storage of a hydrocarbon. Careful planning and careful analysis was needed to determine the impact of an accident of fire before any accident occurs. The vulnerability of the hydrocarbon fire and explosion can be determined by a systematic analytical procedure from the different kinds of modeling. This will help to determine the intensity of an accident in a right way and the percentage of the population affected is evaluated with the degree of burns and the safe distance/ safe zone from the storage of bullet has been determined.

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