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Prediction Method for Damages Resulting from BallisticImpact on Chemical Plants

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Abstract: This paper reviews a typical accident (emergency) on chemically hazardous objects (facilities) (CHO) resulting from the explosive damage effects, as well as possible accident (emergency) development scenarios. Explosion related accidents and accidents that result in chemically hazardous gases as a result of emergency (CHGE) discharge without a major explosion are essentially different in terms of destructive and damage effects characteristics. Four major types of emergency situation that result from the accidents at CHO and differ by the resulting damage effects are considered. 1st CHO emergency type is related to momentary depressurizing (explosion) of the vessels and plant equipment containing gaseous (pressurized) and superheated liquefied CHGE. 2nd CHO emergency type is connected with the accidental releases and spills of utilized, stored, or transported liquefied gaseous or superheated liquid CHGE. As a result, both primary and secondary cloud is created. 3rd CHO emergency type corresponds to the spill of ample quantity of liquefied gaseous or superheated liquid CHGE with evaporation temperature close to the environment temperature. 4th CHO emergency type corresponds to the accidental release (spill) of ample quantity of semi-volatile CHGE. The method suggested by the authors allows for predicting possible damage ensuing from fuel spillage over underlying surface and possible explosion and fire.

Key words: Emergency · Damage prediction · Fire · Explosion · Deflagration

INTRODUCTION

Today, the hazard level of the accidents that cause environmental damage and pollution remains to be high. For accident prediction and impact assessment purposes on chemical sites or during the transport of chemical liquids, the hazard level is determined on the basis of the toxicity (combustibleness) of the substance and the amount of exposed area. The latter depends on the physical and chemical properties of the liquid, size of the spill, amount of damage suffered by the vessel, weather conditions and the land environment. Exposure of chemically hazardous objects to unauthorized activity of third parties may result in different types of emergency situations beginning with deliberate and malicious damage to plant equipment that results in discharge of chemically hazardous gases as a result of emergency (CHGE) into the atmosphere and ending with earthquakes, flooding, etc.

MATERIALS AND METHODS

The main research methodology was represented by system analysis and mathematical and physical simulation of the formation and development of the combustion / exposure area.

The main research methods included: probability method (defining stochastic characteristics of the incendiary agents), group parameter accounting (processing of experimental and analytical data on

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dispersion of incendiary agents) and efficiency theory methods (calculation of individual and generalized characteristics of the damage effects of incendiary agents).

Information base of this research is formed by scientific papers from around the world.

RESULTS AND DISCUSSION

Potential terrorist attacks on chemical facilities using conventional weapon result in a local emergency situation that may transform into a regional or global emergency situation. In such cases, accident management may require considerable human resources and technical capacities, involvement of high number of health professionals and will inevitably result in enormous material costs. Today, the object level methods of facilities with fire, explosion and chemically hazardous facilities demonstrate the highest level of development [1].

Explosion related accidents and accidents that result in CHGE discharge without a major explosion are essentially different in terms of destructive and damage effects characteristics. Accordingly, the accident scenarios will differ [2].

The main parameter of the chemically hazardous object (CHO) is the total number of CHGE observed onsite. CHO have many other parameters with values that are sometimes not included in the model simulation of the test object due to practicability reasons. Such test object simulations, therefore, only retain the main characteristics of the real world scenarios [3].

In order to use test CHO as an effective model of formation and development of the emergency situation, it is necessary that its parameters are realistic enough and correspond to objective parameters of existing group of CHO. In other words, its characteristics should correspond with the characteristic of the CHO for which the simulation was built [4]. In order to achieve this, we must determine the general parameters of such object as a part of the group of similar objects and then select one object from this group as the test CHO (one with actual parameters as close as possible to general parameters). We've selected a typical emergency situation at CHO: an emergency situation with damage of basic plant equipment as a result of terrorist attack with conventional weapons, with a corresponding CHGE discharge into the surface layer of the atmosphere in form of primary and secondary contaminated air clouds [5].

There are four main types of emergency situations that result from the accidents at CHO and differ by the physical and chemical properties, storage and transport conditions of CHGE, as well as the resulting damage effects.

1st CHO emergency type is related to momentary depressurizing (explosion) of the vessels and plant equipment containing gaseous (pressurized) and superheated liquefied CHGE. During the emergencies of this type mainly the primary vapour and aerosol CHGE cloud (parts of the aerosol quickly vaporise) is created. The main damage factor is related to the inhalation effects of the highly concentrated CHGE in the primary cloud [6].

2nd CHO emergency type is connected with the accidental releases and spills of utilized, stored, or transported liquefied gaseous or superheated liquid CHGE. The first part of CHGE is vaporised instantaneously creating a primary cloud, while another part is spilled onto the pallet or underlying surface where it starts to vaporize slowly - thus creating a secondary cloud [7]. The main damage factors are inhalation effects of the highly concentrated CHGE in the primary cloud, as well as continuous exposure (hours, days) to the secondary cloud. The spill may also result in soil and water contamination.

3rd CHO emergency type corresponds to the spill of ample quantity of liquefied gaseous (isothermal storage) or superheated liquid CHGE with evaporation temperature close to the environment temperature, including fire events. Mainly the secondary cloud is created [8].

4th CHO emergency type corresponds to the accidental release (spill) of ample quantity of semi-volatile CHGE (i.e. liquids with evaporation temperature much higher than the environment temperature, solid toxic materials). This type of emergency results in the area, soil and water contamination, typically with high concentration of contaminants.

Let us consider the consequences of ballistic attacks on CHGE storage vessel. Our test objects are fuel storage tanks. We will only consider ballistic attacks that result from the explosion damage effects (explosion products, blast wave, fragmentary and high-temperature shells), as well as the effect of secondary shells [9].

The fuel tanks containing inflammable liquids and liquefied gases are ruptured as a result of explosion.

The main parameters of the liquid spill area include spill area and fluid transfer speed with variable ground filtration parameters in course of time.

Preliminary analysis of the physical phenomena related to the liquid spillage through the vessel openings and ground filtration parameters for different liquids demonstrates that in general spillage area may be represented as:

$$S_{pacm} = f\left(Q_p, Q_\phi, k, \tau\right), \quad Q_p = f\left(n, S_o, V_u\right) \tag{1}$$

Where Q_ϕ- rate of liquid flow (ground filtration) in m^3/sec;

k - dimensionless ratio obtained experimentally;
τ - spillage shaping time, sec.

Rate of liquid flow Q_p varies depending on the number of openings (punctures) n, the area of openings S_o and the fuel efflux rate V_u.

Two different groups of test vessels are distinguished as a result of analysis of their characteristics. 1st group: single vessels (fuel tanks, cisterns, etc.) and 2nd group: low capacity modules and vessels.

It should be noted that while performing the calculations for the 2nd group of test vessels, it is important to take into account the change of the rate of liquid flow due to the fall of middle pressure H_{cp}.

In order to determine $Q_p(\tau)$ for different kinds of liquids one should take into account such parameters absolute viscosity coefficient η and mass density ρ, or kinematic viscosity coefficient v that combines these two parameters as $\frac{\eta}{\rho}$. Flow rate Q_p in its turn depends on the efflux rate V_u. Consequently, in order to determine the liquid efflux rate v_u one should take into account middle pressure H and acceleration of gravity g and kinematic viscosity coefficient v. In this case, the function takes the following form: $V_u = f\left(H, g, v\right)$. By employing physical simulation methods, the following analytical dependence may be obtained:

$$V_u = I\sqrt{2gH}\left(\frac{v_e}{v_\varsigma}\right)^{\frac{1}{3}}, \tag{2}$$

Where v_e, v_ς - kinematic viscosity coefficient of water and fuel m/sec.

After considering different characteristics of natural and artificial underlying surfaces for test vessels, we have selected two main surface types: artificial underlying surface with filtration coefficient k_ϕ = 0 (reinforced concrete, asphalt, steel) and natural underlying surface with k_ϕ >0 (hard soil, sandy soil). By applying the similarity law methods, the following function of liquid spillage area S_{pacm} over underlying surface with $k\phi = 0, K_{0cp} = const$. has been obtained. [10]

$$S_{pacm} = V\tau d_{np} f\left(\frac{V\tau}{d_{np}}\right), \tag{3}$$

Where d_{np} - opening diameter, m.

The results of experimental analysis have shown that with $K_{0cp} = const$

$$f\left(\frac{V\tau}{d_{np}}\right) = 2$$

Considering the functions given above, liquid spillage area over underlying surface function takes the following form with $k_\phi = 0$:

$$S_{pacm} = 2\frac{k}{\sqrt{\pi}}\mu\sqrt{2gH_{0cp}}\left(\frac{v_e}{v_\partial}\right)^{\frac{1}{3}} S_{np}\frac{1}{\sqrt{S_{np}}}\tau, \tag{4}$$

Where H_{0cp} - middle pressure, m;

S_{np} - total area of openings on the lateral face, m;
τ- fuel effusion time, sec.

In case with small vessels the fluid level should also be taken into account, as H_{0cp} and n will change in course of time. The change of these parameters cause the change of rate of fluid flow and overall liquid volume v_B that ran out through the openings in T seconds.

Based on spillage area S_{pacm}, liquid level decrease in section ΔH and decrease of H_{0cp} at the end of each following section, the time τ is then determined as follows:

$$S_{pacm}=\int_0^{\tau}K_1K_2\left\{\left[S_{np}-S_0\frac{H_{0cp}-\left(\sqrt{H_{0cp}}-\frac{K_2S_{np}\tau}{4S_c}+\frac{K_2S_0\tau}{2S_c}\right)^2}{\Delta H}\right]\left[\sqrt{H_{0cp}}-\frac{K_2S_{np}\tau}{4S_c}+\frac{K_2S_0\tau}{2S_c}\right]\right\}d\tau, \quad (5)$$

Where $K_1=2\frac{K}{\sqrt{\pi}};K_2=\mu\left(\frac{\nu_e}{\nu_\partial}\right)^{\frac{1}{3}}\sqrt{2g};S_{np}=nS_0;$

S_o - cross sectional tank area, m^2;

ΔH - interval between openings (the distance between top liquid level and the height of the highest opening), m.

After simple mathematical manipulations, the formula (5) takes the following form:

$$S_{[pacm}=\int_0^{\tau}K_1K_2S_0^{\frac{1}{2}}\left(n-\frac{H_{0cp}}{\Delta H}+\frac{\left(\sqrt{H_{0cp}}-K_3\tau\right)^2}{\Delta H}\right)^{\frac{1}{2}} \quad (6)$$

$$\left(\sqrt{H_{0??}}-K_5\tau\right)d\tau,$$

Where $K_5=K_2K_3K_4;K_3=\mu\frac{S_0}{4S_c};K_4=n-2.$

Upon integration, the following analytical dependency for spillage area has been obtained:

$$S_{pacm}=\frac{gKS_c\Delta H}{3\sqrt{\pi}\sqrt{S_c}(n-2)}\left[n^{\frac{3}{2}}\left(n-\frac{H_{0cp}-\left(\sqrt{H_{0cp}}-K_3\tau\right)^2}{\Delta H}\right)^{\frac{3}{2}}\right]. \quad (7)$$

We can give the following arguments for determination of spillage area over underlying filter surface.

In general case, the volume of liquid flow through element of area per time unit is determined as $dQ = VdS$, where V- mean fictitious fluid velocity in accordance with Darcy law:

$$V=k_\phi I, \quad (8)$$

where $k_ф$- filtration coefficient, m/sec;

I- hydraulic grade.

Parameters $k_ф$ and I are determined based on the following laws [11]

$$k_?=\frac{cg}{\nu},I=\left(\frac{\rho_3}{\rho_?}-1\right)(1-m)\frac{1}{m}, \quad (9)$$

where C - permeability of soil, m^2;

ρ_3,ρ_∂ - density of soil and liquid particles, kg/m^3;

m - porosity factor.

We can determine total liquid flow per filtration based on filtration coefficient V, filtration area $S^?$ and filtration time филтРадии $\tau_ф$.

Therefore, liquid spillage area over underlying filter surface is a difference between spillage area over underlying filter surface with filtration coefficient $k_\phi = 0$ and fictitious area S_{MHUM}:

$$S'_{pacm}=S_{pacm}-S_{MHUM}. \quad (10)$$

In accordance with Darsy law, liquid filtration rate of flow equals to:

$$Q_\phi=k_\phi SI,$$

where S- filtration area or fictitious spillage area, m^2.

Spillage area over underlying filter surface with $H_{0cp}=const$ is determined as:

$$S_{pacm}^{\phi n}=K_1K_6\int_0^{\tau}\left(K_7K_8\sqrt{H_{0cp}}-Q_\phi\right)d\tau=K_1K_6K_7K_8 \quad (11)$$

$$\sqrt{H_{0cp}}\tau-\int_p^{\tau}K_1K_6Q_\phi d\tau,$$

The first term is area of liquid spillage over underlying surface with $k_\phi \approx 0$ and the second term is fictitious spillage area.

In case of infinitely small period of time $\tau_0 = \Delta\tau_j$, parameter S_{MHUM}=0. Therefore, spillage area over underlying filter surface after a period of time $\tau = 2\Delta\tau_j$ equals to:

$$S_{pacm}^{\phi n} = K_0 K_1 K_2 K_3 = \sqrt{H_{0cp}}\tau - K_0 K_2 V_\phi \Delta S_0(\tau - \Delta\tau_j), \quad (12)$$

and after $\tau_0 = \Delta\tau_j$

$$S_{MHUM} = K_0 K_2 V_\phi \Delta S_j \left[(\tau - \Delta\tau_j) + (\tau - 2\Delta\tau_2) + \ldots + \tau(e-1)\Delta\tau_j\right]. \quad (13)$$

The expression in square brackets is a sum of arithmetical progression $\Delta\tau_1 = \Delta\tau_2 = \ldots = \Delta\tau_j$, therefore the analytical dependence for determining liquid spillage area over underlying filter surface takes the following form:

$$S_{pacm}^{\phi n} = K_0 K_2 = \left[K_1 K_3 \sqrt{H_{0cp}}\tau - V_\phi S_0^\phi \frac{\tau(l-1)}{2}\right], \quad (14)$$

Where V_ϕ - actual filtration rate, m/sec;
$S_0{}^\phi$ - initial filtration area, M^2.

Let us take a look at the most complex case when liquid spillage over filter surface with $k_\phi > 0$ is observed together with decrease of liquid level inside of a test vessel. In this case, an increase of spillage area ΔS per equal time intervals Δt will itself decrease. The following formula for S_{pacm} has been obtained based on expressions [7,9,11]:

$$S_{pacm} = \frac{8KS_c\Delta H}{3\sqrt{\pi}\sqrt{S_c}(n-2)}\left[n^{\frac{3}{2}}\left(n - \frac{H_{0cp} - \left(\sqrt{H_{0cp}} - K_5\tau\right)^2}{\Delta?}\right)^{\frac{3}{2}}\right] - K_1 K_6 \frac{cv}{g}\left(\frac{\rho_3}{\rho_?} - 1\right)(1-m)\sum_{j=1}^{l-1}\Delta S_j \frac{\tau(l-j)}{l}. \quad (15)$$

The formulae above have been obtained by employing both experimental and analytical methods and enable for determination of liquid spillage area, volume of vaporized liquid, depth of liquid absorption of the soil and, consequently, the volume of soil absorbing liquid at any given moment of time. Liquid type and vessel dimensions are also taken into account. Flammable liquids may ignite as a result of contact with incendiary fragments, which may in turn establish the point of steady source of fire. Observed dependence of the fuel inflammation probability with an incendiary fragment (IF), "acorn" type, consisting of «*Ti+C*» from time τ from the moment of IF arming to the moment of impact.

In the range of displacement speed V_Π = 0...1,0 m/sec and with $T_{\min}^{v=o} = 500^0C$ and $T_{\max}^{v=0} = 800^0C$ probability of fuel ignition $P_ç$ is determined by the following formula obtained by group argument accounting method:

$$P_3 = \frac{K_0 T_{a\sigma} e^{-(K_1\tau + K_2\sqrt{\tau})} - 500V_\Pi}{300} \quad (16)$$

Where $T_{a\sigma}$ - adiabatic temperature of chemical reaction, °C;

$K_O = \frac{e^{a_o}}{T a\sigma}$ - preheating coefficient;
$K_1 = a_1, K_2 = a_2$ - heat transfer coefficient;
τ - time, sec.

The formula (16) with $K_0 T_{a\sigma} e^{-(K_1\tau + K_2\sqrt{\tau})} - 500V \geq 300$ gives probability of fuel ignition P_3=1. The universal formula (16) is used for any incendiary fragments with a different incendiary composition. It is important to discern a special combustion mode known as deflagration. Deflagration is a mode of chemical transformation of fuel-air mixture cloud with the blast wave speed less than the speed of sound i.e. deflagration does not create the blast wave. The combustion of condensed charges is in any case associated deflagration or explosive transformation. The combustion processes in the fuel-air mixture cloud is more complex. Inflammation of a cloud with different air oxygen stoichiometric ratio will lead to different speed and size of reaction. Such artificial clouds typically exist from several fraction of a second to 1.5 - 2 seconds and can, accordingly, demonstrate different emission temperatures and blast wave effect. A weak blast wave does not necessary imply that a full-scale explosive reaction has taken place in the whole volume of the fuel-air mixture cloud. An explosion of a fuel-air mixture cloud over a fuel spill is also possible. In this case, the cloud will have a semi-sphere shape with volume υ_{TBC} and radius r_i:

$$v_{\text{TBC}} = \frac{2240\chi M_T T}{\mu C_{CTX} T_o}, r_o = 0{,}78\sqrt[3]{v_{\text{TBC}}}$$

Where M_T- initial fuel mass, kg; χ- initial fuel mass fraction transferred to fuel-air mixture cloud; T- environment temperature, $^0K, T_0 = 273\,^0K, \mu$ - fuel molecular weight.

The pressure on the brim of detonation wave within fuel-air mixture cloud:

$$P_{дET} = 2{,}586(\eta\text{-}1)q_m$$

Where η- Adiabatic index of initial mixture; q_o- gravimetric energy density of explosion, kJ/kg.

Surplus pressure on the brim of detonation wave:

$$\Delta p_{дET} = P_{дET} - P_0,$$

Where P_0- atmospheric pressure.

As a result of fuel-air mixture detonation outside, an air blast wave spreads outside of the cloud (ABW). Explosive energy transferred to the ABS E_{YB}:

$$E_{yB} = 2\left[1 - \left(\frac{2P_0}{P_{\Pi ET}}\right)^{\frac{\gamma_1 - 1}{\gamma_1}}\right] q_v V_{TBC} \quad (17)$$

Where γ_1- Adiabatic index of gas;
q_v- Explosive energy to volume ratio of stoichiometric mixture, kJ/m^3.

As function of reduced distance limits:

$$\bar{R} = R\left(E_{yB}\right)^{\frac{-1}{3}},$$

Where $\bar{R}$ - reduced distance, m/kJ; R- distance, m; Pressure surplus is calculated as follows [12]:

$$\Delta P_\Phi = 1{,}227 \cdot 10^{-6} / \overline{R}^{4{,}68} + 0{,}49, \text{ with } 0{,}05 < \overline{R} \le 0{,}068$$

$$\Delta P_\Phi = 4{,}156 / \overline{R}^{1{,}7}, \text{ with } 0{,}068 < \overline{R} \le 0{,}31$$

$$\Delta P_\Phi = 4{,}96 / \overline{R} + 0{,}974 / \overline{R}^2 + 0{,}146 / \overline{R}^3 \text{ with } \overline{R} > 0{,}31$$

Where ΔP_Φ - surplus pressure on the brim of ABW, kPa

The fuel-air mixture ignition may result from the contact with high temperature burning fragments (incendiary fragments, secondary shells, sparks). Incendiary fragments (secondary shells) moving with low speeds and immobilized fragments (e.g. after an impact with the fuel tank wall) have the highest ignition ratio.

Critical incendiary conditions are observed with v = 0.

Theory of ignition, combustion and detonation developed by Yakov Zel'dovich then assumes the following form:

$$r = \sqrt{\frac{\lambda}{2q} \frac{(T_s - T_0)^2}{W(T_s)} \frac{E}{RT_s^2}}, \quad (18)$$

Where r - reduced radius of incendiary fragment

CONCLUSIONS

This formula allows for determining critical size of incendiary fragment with temperature T_s which would cause the explosion of vapour/gas mixture with fuel thermal effect q and reaction speed W. All parameters with an exception of reaction speed are table values.

The suggested mathematical model allows for estimating possible damage ensuing from different ballistic attacks scenarios on chemically hazardous objects and facilities.

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