(R1) A simplified method for estimation of the effect of hydrogen explosion on a nearby pipeline

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Abstract

To predict the effect of hydrogen gas tank explosion on a nearby pipeline, air pressure rise and velocity on a pipeline after a strong explosion is evaluated first. Then, bending of an initially straight pipe is calculated. This bending amplitude was further scrutinized at various exploded masses of hydrogen, distances measured from the explosion center to the pipeline, and thicknesses of steel pipeline walls. (R2) The proposed analytic approach provides a conservative estimate of the worst-case accident scenario of an instantaneous explosion of a large hydrogen mass leading to formation of a shock wave. It can be useful for plant engineers to evaluate risks associated with pipelines under the presumed explosion scenario of not only hydrogen, but also any other fuel types.

Keywords: Explosion; Overpressure; Shock wave; Pipeline

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1. Introduction

Any off- or on-shore plant of petrochemical and refinery type incorporates pipelines located in the vicinity of tanks containing flammable liquids or gases. Though these structures are regularly monitored and undergo safety maintenance, potential leakage of flammable substances is always possible because the plant structures are typically subjected to corrosive environment which causes structural damages and potential malfunction in equipment over time. A potential leakage can result in explosion which would jeopardize lives and inflict large economic losses. Therefore, an estimate of potential damage caused by such explosions is important.(Jo & Ahn, 2002; Sklavounos & Rigas, 2006; J. R. Taylor, 2003) In the case of explosions accompanying leakage of explosive substances from tanks located close to pipelines, the question to be addressed is whether these pipelines can survive an impact of shock wave generated by such explosions.

The classical self-similar theory of the strong explosion can estimate the pressure, gas velocity, and density at the shock wave front for a given large mass of fuel which exploded (von Neumann, 1963; Sedov, 1946, 1993; Taylor, 1950a, 1950b) ; see also the general fluid mechanical texts (Landau&Lifshitz 1987; Yarin 2007). These information can be used to evaluate loads applied on the surrounding pipelines and, in particular, predict their bending expected at the distances corresponding to their location from the explosion center (Rigas & Sebos, 1998). The outcome of such evaluations should affect design of petrochemical and refinery plants to avoid the worst-case scenarios.

In addition, to the analytic tools, pressure rise resulting from explosions of different massed of fuel can also be predicted by computational codes, e.g. such as EXSIM(Explosion

SIMulator) and FLACS (Flame ACceleration Simulation) (Lea & Ledin, 2002). However, FLACS is limited only to deflagration cases and cannot be extended to model detonation or fast deflagration scenarios. **(R2, R6)** For this reason, here we discuss an analytical method which predicts the pressure rise as a result of strong instantaneous explosion and shock wave formation and propagation for an unconfined environment. The theory is inapplicable to highly-congested environments.

2. The strong explosion theory

(R2) The proposed analytic approach describes in this section considers the worst-case accident scenario of an instantaneous explosion of a large hydrogen mass leading to formation and propagation of a strong shock wave. The classical theory of strong explosions specifies, among other parameters, the pressure, P_{sh}, gas velocity, V_{sh}, and density, ρ_{sh}, at the shock wave front as in Refs. (Landau &Lifshitz, 1987; von Neumann, 1963; Sedov, 1946; Sedov, 1993; Taylor, 1950a, 1950b; Yarin, 2007):

$$P_{sh} = \frac{8\rho_a}{25(\gamma+1)}\left(\frac{E_0}{\rho_a}\right)^{2/5}\frac{1}{t^{6/5}}, \tag{1}$$

$$V_{sh} = \frac{4}{5(\gamma+1)}\left(\frac{E_0}{\rho_a}\right)^{1/5}\frac{1}{t^{3/5}}, \tag{2}$$

and

$$\rho_{sh} = \frac{(\gamma+1)}{(\gamma-1)}\rho_a. \tag{3}$$

where E_0 denotes the total energy released in the explosion, ρ_a is the air density before the shock wave, γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume (of air), and t is time from the moment of explosion, which is considered to happen instantaneously and pointwise at $t=0$. **(R5)** This theory implies an instantaneous pointwise explosion of such strength that the pressure created behind the shock wave propagating from the explosion center is so high, that the atmospheric pressure before the shock wave can be neglected. This theory was independently developed by J. von Neumann (von Neumann, 1963), L.I. Sedov (L. I. Sedov, 1946; 1993) and G.I. Taylor (Taylor, 1950a, 1950b) (the work of von Neumann was published long after his original result), and is discussed in brief in general books on fluid and gas dynamics (Landau&Lifshitz, 1987; Yarin, 2007).

Accordingly, the front of the shock wave, which is spherical when unaffected by obstacles, r_{sh}, is

$$r_{sh} = \frac{2}{(\gamma+1)}\left(\frac{E_0}{\rho_a}\right)^{1/5} t^{2/5}. \tag{4}$$

The strong-explosion theory is based on the assumption that the explosion energy, E_0, is released instantaneously at a point, and is much higher than the atmospheric pressure. This implies that fuel is instantaneously evaporated and mixed with the oxidizer, and the reacting mixture is stoichiometric. The theory also neglects energy losses due to thermal radiation- the entire released energy is converted into the energy of shock wave and the accompanying gas motion. These assumptions tend to overestimate the strength of the shock wave. In reality, liquid hydrogen spillage and evaporation, for example, will take some time and space, and are accompanied by liquid atomization (losses). Also, mixing with the oxidizer (oxygen in air) can be far from complete when the explosion occurs, and nitrogen in air will act as a thermal ballast. Typically, a fuel-oxidizer mixture will be lean (not pre-mixed). These factors diminish the strength of a real shock wave compared to the idealized predictions of the theory of strong explosion. The strong-explosion theory is purely gasdynamical and does not consider turbulent eddy viscosity and the effect of turbulence on the energy-release rate or gas motion. With all the simplifying assumptions listed above, the first estimates of the strong explosion effects should be based on the strong-explosion theory outlined above.

Based on Eq. (4), the time required for the shock wave to reach a pipe located a distance *L* from the center of explosion is:

$$t = L^{5/2}\left(\frac{\gamma+1}{2}\right)^{5/2}\frac{1}{(E_0/\rho_a)^{1/2}}. \tag{5}$$

Then, according to Eqs. (1), (2) and (5), pressure and velocity at the shock-wave front as it contacts the pipe are

$$P_{sh,L} = \frac{64}{25}\frac{1}{\left(\gamma+1\right)^4}\frac{E_0}{L^3}, \tag{6}$$

and

$$V_{sh,L} = \frac{4\sqrt{8}}{5}\frac{1}{\left(\gamma+1\right)^{5/2}}\frac{1}{L^{3/2}}\left(\frac{E_0}{\rho_a}\right)^{1/2} \tag{7}$$

Denoting the pipe diameter as 2a, with a being the cross-sectional radius, and using Eq. (2), we find the time ΔT required for the shock wave front to cross the pipe as

$$\Delta T = 5a\left(\frac{\gamma+1}{2}\right)^{5/2}\frac{L^{3/2}}{\left(E_0/\rho_a\right)^{1/2}} \tag{8}$$

3. Calculation of pipe bending

Equations of the pipeline dynamics are well-known (Svetlitskii, 1982; V.M. Entov, 1987), and in the simplest case of planar bending of an initially straight pipe, they can be reduced in the first approximation to the following bar-bending-like equation

$$\left(\rho_1 f_1 + \rho_2 f_2\right)\frac{\partial^2 H}{\partial t^2} + EI_1 \frac{\partial^4 H}{\partial x^4} = 2a\Delta p_{dyn} \tag{9}$$

Here the pipe is assumed to be circular in cross-section; ρ_1 and ρ_2 are densities of the pipe wall and a gas or a liquid which can be inside; f_1 and f_2 are the cross-sectional areas occupied by the pipe material and the gas (or liquid) inside, respectively; H is the bending displacement, t is time (obviously different from t of section 2), E is Young's modulus of the pipe wall; I_1 is the moment of inertia of the pipe wall cross-section; x is the Cartesian coordinate reckoned along the axis of the unperturbed pipe; Δp_{dyn} is the dynamic pressure difference across the pipe.

The geometric parameters involved in Eq. (9) are found as

$$f_1 = 2\pi a h, \quad f_2 = \pi a^2, \quad I_1 = \pi a^3 h \tag{10}$$

where a is the pipe radius (not including the wall), and h is the wall thickness.

We search the solution of Eq. (9) in the following form

$$H = A(t)\sin kx \tag{11}$$

where $A(t)$ is the bending amplitude and k is the wavenumber (k=2π/λ, with ℓ=λ/2 being the pipe length between two fixed sections).

Then, Eq. (9) yields

$$\left(\frac{d^2 A}{dt^2} + \omega^2 A\right)\sin kx = \frac{2a\Delta p_{dyn}}{\left(\rho_1 f_1 + \rho_2 f_2\right)} \tag{12}$$

where

$$\omega^2 = \frac{EI_1(2\pi/\lambda)^4}{\rho_1 f_1 + \rho_2 f_2} \tag{13}$$

The dynamic pressure drop acting on the pipe is associated with the shock wave front, as found in Eq. (6). It fades in time, as the shock wave passes the pipe cross-section, and has its maximum in the middle of the pipe length. Therefore, it is possible, in the first approximation to take

$$\Delta p_{dyn} = \left(p_{sh,L} + \frac{\rho_{sh} V_{sh,L}^2}{2} \right) \cos\omega t \sin kx \tag{14}$$

which is considered during the time period when $0 \le \omega t \le \pi/2$.

Then, Eq. (12) is reduced to

$$\frac{d^2 A}{dt^2} + \omega^2 A = F\cos\omega t \tag{15}$$

with F being given by the following expression

$$F = \frac{2a\left(P_{sh,L} + \rho_{sh} V_{sh,L}^2 / 2\right)}{\rho_1 f_1 + \rho_2 f_2} \tag{16}$$

The solution of Eq. (15) subjected by the initial conditions

$$t = 0 : A = \frac{dA}{dt} = 0 \tag{17}$$

yields the following result for the bending amplitude

$$A = \frac{F}{2\omega} t \sin\omega t \tag{18}$$

At short times, when ωt<<1, the asymptotical behavior following from Eq. (18) is

$$A = \frac{F}{2} t^2 \tag{19}$$

(R8) The critical bending amplitude (or displacement) is normally determined by the design engineers who would consider different safety factors affecting the design. The engineers can utilize the model/theory provided herein to yield the most conservative estimate which would prevent the collapse of their pipe system in case of explosion.

4. Calculation of pipe squeezing

According to (Timoshenko, 1961), a pipeline will be squeezed by the outside pressure $P_{\mathrm{sh,L}}$ if

$$P_{sh,L} > P_{crit} = \frac{Eh^3}{4a^3(1-\nu^2)} \tag{20}$$

where ν is Poisson's ratio of pipe wall.

(R7) The inequality Eq. (20) implies an empty pipeline, or the one with pressure inside being relatively low compared to $P_{\mathrm{sh,L}}$. It should be emphasized that a high internal pressure would just diminish the effect of $P_{\mathrm{sh,L}}$, and the inequality Eq. (20) would be re-written for the pressure difference.

5. Results and discussion

Heat release in hydrogen explosion is associated with the reaction of hydrogen oxidation in air. The hydrogen specific heat release is Q = 120 MJ/kg at the LHV (Lower Heating Value) (Baker, Cox, Kulesz, Strehlow, & Westine, 2012). Then, the total energy released in hydrogen explosion is $E_0 = Q\ m$, where m is the hydrogen mass which has exploded. The other parameters of interest have the following values: the adiabatic index γ = 1.4, the air density $\rho_a = 1.21\times10^{-3}$ g/cm^3, the density of the pipe material ρ_1 = 7.8 g/cm^3 (steel), its Young's modulus E = 200 GPa (steel) and Poisson's ratio v = 0.303 (steel). We assume that the pipeline is empty, and thus take $\rho_2 = 0$.

First, the effect of hydrogen mass (m) on the bending amplitude (A) was studied, for which the distance between the point source and the pipe was L = 10 m; the pipe wall thickness was h = 1 cm; the pipe length was l = 10 m; and pipe cross-sectional radius was a = 0.24 m. Second, the effect of L on A was also studied under the fixed values of m = 1000 kg, h = 1 cm, l = 10 m, and a = 0.24 m. Last, the effect of wall thickness (h) was studied while using L = 10 m, m = 1000 kg, l = 10 m, and a = 0.24 m. **(R3)** Note, that it is assumed that while traveling the distance L, the shock wave have not impinges on any other obstacles, and the first such encounter is with the pipe under consideration. In a highly-congested environment this assumption might be inapplicable and the shock wave could lose its strength on the wave to a pipe.

Notably, it should be emphasized that the pipe length was taken as a half of the wavelength ($\ell = \lambda/2$). Because the wavenumber is $k=2\pi/\lambda$, the effect of the pipe length is incorporated in the argument of sine in Eq. (11). However, the sine function is at the end cancelled and does not appear in the F expression in Eq. (16) and thus l will not affect the bending amplitude, A. The bending amplitude is finally expressed in terms of F, as in Eq. (19), which is a function of the shock pressure ($P_{sh,L}$) and velocity ($V_{sh,L}$) from Eq. (16). One may also see that F depends on pipe geometry, namely, on a and h.

Figure 1 shows how the shock wave pressure depends on the distance (L) between the explosion center and the pipe location. When the shock wave propagates away from the explosion center (and L is increasing), pressure at the shock wave front reduces dramatically. Larger exploded mass of hydrogen, result in much larger pressures at the shock wave front as is seen in **Figure 1**. For example, if a pipeline is located beyond the distance of L = 60 m from the explosion center, the shock wave weakens and the pressure at its front is below $P_{sh,L}$ ~ 0.1 bar for exploded masses less than m = 200 kg.

Figure 2 shows how the bending amplitude increases in time when a pipeline is affected by the compressed gas in the wake of the shock wave resulting from explosions of different masses of hydrogen at a distance of L = 10 m from the pipeline.

Table 1 illustrates how the shock wave enhances as the exploded mass of hydrogen increases. In Case 7 in the table, the shock wave pressure increased up to 92.6 bar when the mass of hydrogen of 1000 kg exploded at the distance of L = 10 m. Then, the ratio of the squeezing gas pressure to the critical pressure for a pipeline with h=1 cm, a = 0.24 m, L=10 m, and l = 10 m is $P_{sh,L}/P_{crit}$ = 2.325. This ratio is well over unity, and thus an absolute destruction of the steel pipelines is guaranteed within 0.19 ms. In Case 5 in **Table 1**, the ration $P_{sh,L}/P_{crit} < 1$, which means that the steel pipelines would not fail. However, the shock wave pressure would increase up to 18.52 bar, which is high enough to destroy any concrete structure.

Figure 3 shows how the bending amplitude increases in time at various pipeline locations (L) after explosion of m = 1000 kg. As evident, the pipelines would definitely be bent and squeezed when they are close the explosion center. On the other hand, in cases of L > 100 m, the pipelines would not undergo severe bending. In petrochemical plants, the range of L of structures from potential explosion centers is within a few to tens of meters. Thus, according to **Figure 3**, pipelines in such plants will be endangered, i.e. severely bent and squeezed, in the case of explosion of m = 1000 kg. The present analysis allows an estimate of a safe interspace distance between structures when designing a petrochemical plant.

Figure 4 illustrates the effect of the wall thickness of a pipeline on its bending amplitude following an explosion of m = 1000 kg at a distance of L=10 m. It is seen that bending of about 40 cm is possible even for pipes with the wall thickness of 5 cm under such conditions.

6. Conclusion

(R6) The most conservative estimate for pipe bending is established by employing the strong explosion theory. This conservative estimate is important for petrochemical plant engineers who need to provide the design parameters for their pipe location and characteristics for cases of unexpected explosion. These analytical equations are simple to use, unlike fully 3D direct numerical simulations, and therefore quick parametric studies can be conducted to yield design parameters with intended safety factors.

The explosion of m = 1000 kg of hydrogen resulting from a leakage from a tank, will be absolutely catastrophic for a pipeline located at a distance of L = 10 m from the explosion center: it will be bent and squeezed, and most probably completely destroyed. The pipeline will be also significantly bent due to the explosion of m = 100 kg of hydrogen. These results probably overestimate the explosion strength, since the explosion was considered to be instantaneous and pointwise, and all the factors leading to losses (atomization, radiation, turbulence, etc.) were neglected. Still, they provide a pretty realistic pattern of the effect of hydrogen explosion on a pipeline located L = 10 m apart. An increase in the distance between the hydrogen tank and the pipeline will diminish dramatically the effect of the explosion, since, the latter decreases as L^{-3}, i.e. doubling the distance diminishes the explosion effect 8 times.

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