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Simplified method for estimating the effect of a hydrogen explosion on a nearby pipeline

Boohyoung Bang [a, b], Hyun-Su Park [b], Jong-Hun Kim [c], Salem S. Al-Deyab [d], Alexander L. Yarin [a, e, **], Sam S. Yoon [a, *]

[a] School of Mechanical Engineering, Korea University, Seoul 136-713, South Korea
[b] Plant & Environmental Research Team, Daewoo Institute of Construction Technology, Suwon, Kyungki-do, 440-210, South Korea
[c] Process Engineering Team, Daewoo Engineering and Construction, Seoul, 110-713, South Korea
[d] Department of Chemistry, College of Science, King Saud University, Riyadh 11451, Saudi Arabia
[e] Department of Mechanical & Industrial Engineering, University of Illinois at Chicago, 842 W. Taylor St., Chicago 60607, USA

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ABSTRACT

To predict the effect of hydrogen gas tank explosions on nearby pipelines, we first evaluate the increase in air pressure and velocity on a pipeline after a strong explosion. Then, we calculate the bending of an initially straight pipe. We investigate the bending amplitude for various exploded masses of hydrogen, distances measured from the explosion center to the pipeline, and thicknesses of steel pipeline walls. The proposed analytic approach provides a conservative estimate of the worst-case accident scenario involving an instantaneous explosion of a large hydrogen mass leading to the formation of a shock wave. The results may be useful for plant engineers to evaluate the risks associated with pipelines under the presumed explosion scenario of not only hydrogen, but also any other fuel types.

1. Introduction

Offshore and onshore petrochemical plants and refineries incorporate pipelines that are located near tanks containing flammable liquids or gases. Although these structures are regularly monitored and undergo safety maintenance, there is the potential for leakage of flammable substances because the plant structures are typically subjected to corrosive environments that can cause structural damage and potential equipment malfunction over time. Potential leakages can result in explosions, which would jeopardize lives and inflict large economic losses. Therefore, it is important to have an estimate of the potential damage that would be caused by such an explosion. (Jo and Ahn, 2002; Sklavounos and Rigas, 2006; J. R. Taylor, 2003) In the case of explosions accompanying the leakage of explosive substances from tanks located close to pipelines, the question to be addressed is whether these pipelines can survive the impact of shock waves generated by such explosions.

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

In addition, the increased pressure resulting from explosions of different masses of fuel can also be predicted by computational codes, such as EXSIM (EXplosion SIMulator) and FLACS (FLame ACceleration Simulation) (Lea and Ledin, 2002; Kestenboim et al., 1974). However, FLACS is limited only to deflagration cases, and cannot be extended to model detonation or fast-deflagration scenarios. For this reason, in this paper, we discuss an analytical method that predicts the increase in pressure that results from strong instantaneous explosions, shock wave formation, and propagation in unconfined environments. The theory is not applicable to highly congested environments.

* Corresponding author.
** Corresponding author.
E-mail addresses: ayarin@uic.edu (A.L. Yarin), skyoon@korea.ac.kr (S.S. Yoon).

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2. Strong-explosion theory

The proposed analytic approach described in this section considers the worst-case accident scenario for the instantaneous explosion of a large hydrogen mass leading to the 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 shockwave front, as in Refs. (Landau and Lifshitz, 1987; Sedov, 1946, 1993; Taylor, 1950a, 1950b; von Neumann, 1963; Yarin, 2007):

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

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

and

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

where E_0 denotes the total energy released during the explosion, ρ_a is the air density before the shockwave, γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume (of air), and t is the time from the moment of explosion, which is considered to occur instantaneously and pointwise at $t = 0$. This theory implies an instantaneous pointwise explosion having such strength that the pressure created behind the shock wave that propagates from the explosion center is so high that the atmospheric pressure in front of the shock wave can be neglected. This theory was independently developed by J. von Neumann (von Neumann, 1963), L.I. Sedov (Sedov, 1946, 1993), and G. 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 and 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 the shock wave and the accompanying gas motion. These assumptions tend to overestimate the strength of the shock wave. As an example, in reality, liquid hydrogen spillage and evaporation will take some time and space, and can be accompanied by liquid atomization (losses). In addition, 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 the real shock wave compared to the idealized predictions of the theory of strong explosions. The strong-explosion theory is purely gas-dynamical, and does not consider the turbulent eddy viscosity or the effect of turbulence on the energy-release rate or gas motion. With all the simplifying assumptions listed above, the first estimates of the effects of a strong explosion 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 the 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), the pressure and velocity at the shock wave front as it contacts the pipe are

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

and

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

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

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

3. Calculation of pipe bending

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

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

Here, the pipe is assumed to have a circular cross-section, ρ_1 and ρ_2 are the respective densities of the pipe wall and a gas (or liquid) that may be inside, f_1 and f_2 are the cross-sectional areas occupied by the pipe material and the gas (or liquid) inside, respectively, and H is the bending displacement. In addition, t is the time (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 determined along the axis of the unperturbed pipe, and Δp_{dyn} is the dynamic pressure difference across the pipe.

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

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

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

We find 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 ($k = 2\pi/\lambda$, with $l = \lambda/2$ being the pipe length between two fixed sections).

Then, Eq. (9) yields

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

where