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Modelling Flow Past Obstacles in Vented Explosions

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Abstract
The present study deals with the mathematical modelling of vented explosions of hydrogen. The main focus is on the realistic scenarios of flow past an obstacle which increase the observed peak pressure significantly. The framework of a basic model is described first. Then formulation to account this obstacle is given in detail and validations from recent experiments on a 20-foot ISO container are shown. The model predictions match well with the experimental results for various model obstacles in different configurations.

Keywords: *flow past bluff bodies, vented explosions, hydrogen combustion, spherical flame propagation, obstacles.*

I.INTRODUCTION

Various industrial processes require storage or generation of flammable gases. Compressed LPG or CNG are also used in household applications like cooking or heating. The amount of gas produced or stored is often much more than what is required to cause an explosion. Hence it becomes necessary to assess plant and building safety adequately. Explosion venting is a very common technique used for building safety. It requires mounting vent panels on building walls, which will open at the time of explosion and reduce pressure. Moreover, hydrogen has been identified as a potential "green" fuel which has potential to replace the more commonly used hydrocarbons. Hydrogen is also generated in a nuclear reactor as the cooling water reacts with the Zirconium claddings, and the accumulated hydrogen needs to be removed periodically. Fukushima nuclear accident was a result from explosion of this accumulated hydrogen (Yanez et al. [1]). Hydrogen, having very different properties from hydrocarbons, particularly its higher flame speed, appears to be more hazardous and needs to be investigated in detail characterizing its explosion behaviour. HySEA project aims to study this aspect and provide safety guidelines in using hydrogen for industrial applications. Previous studies on vented explosions of hydrogen focus mainly on "idealized" empty container with uniformly mixed fuels and no obstacles (Kumar [2, 3], Daubech et al. [4]). The configurations proved to be useful for fundamental studies, but a practical industrial installation will have equipment, pipes, and other objects in flame path which will act as obstacle. Recent experiments (Bauwens et al. [5], Skjold et al. [6, 7]) have demonstrated that the presence of obstacles will increase the peak pressure significantly. Hence, this configuration needs to be studied in more details and focussed modelling efforts are required.

It is important to understand that experiments are costly, dangerous, and require significant infrastructure and safety installations to conduct experiments on a real scale enclosure or building. On the other hand, computational models are found to give errors of an order of magnitude higher than the measured pressure, as observed in a recent blind prediction studies (Skjold et al. [8, 9]). This could be attributed to the challenge in accurately modelling the large range of length and time scales involved. Additionally, computational modelling involves significant computational costs and run-time owing to the large and complex geometries involved. Engineering models appear to be a preferred method for overpressure predictions and give reasonably accurate results [9].

In recent reviews on engineering models (Sinha et al. [10-12]), it has been pointed out that currently existing models are not equipped to handle realistic accidental scenarios and focussed modelling efforts are required for practical configuration like presence of obstacles. The present study aims to address this objective. A basic model has been proposed in a previous study (Sinha et al. [12]), which deals with empty containers. The present paper will extend this model for cases with obstacles.

II. METHODOLOGY

The present model is based on external cloud formation and explosion. During an accidental explosion, vent opens and relieves pressure by releasing unburnt gases. These gases form an external cloud (Sinha and Wen [13]), which gets ignited as the flame reaches the vent. The combustion of this external cloud results in external explosion, which hinders further venting from the enclosure. Also, as the flame reaches the vent, it attains maximum surface area, which results in peak pressure. The phenomenon of pressure generation in vented explosion can be explained using the following analysis.

The enclosure initially is filled with fresh, unburnt gases and burnt gases are formed by combustion. So the total gas volume (V) inside an enclosure can be expressed in terms of burnt and unburnt gases [5]:

$$pV = p\left(\frac{m_u}{\rho_u} + \frac{m_b}{\rho_b}\right) \quad (1)$$

where p is the internal pressure, m denotes mass, ρ is density, subscripts u and b denote unburnt and burnt gases respectively. Assuming the gases to be compressed adiabatically and differentiating pressure with time, for maximum pressure:

$$\frac{1}{\rho_u}\frac{dm_u}{dt} + \frac{1}{\rho_b}\frac{dm_b}{dt} = 0 \quad (2)$$

Also, change in mass of burnt and unburnt gases is caused by combustion. Rate of combustion can be estimated using the flame-speed and flame surface area. At the instant of peak pressure, the rate of gas venting will be equal to the volumetric rate of production of the burnt gases minus volumetric rate of consumption of unburnt gases. Hence,

$$A_f U_{rel}(\sigma - 1) = \frac{\dot{m_v}}{\rho_v} \quad (3)$$

where A_f is the flame surface area, U_{rel} is the flame speed relative to unburnt gases, σ is the expansion ratio, and m_v and ρ_v denote the equivalent mass and density of unburnt gases, respectively. The internal peak pressure can thus be obtained using Tamanini's equation for venting [14]:

$$\frac{\dot{m_v}}{\rho_v} = u_{cd}\, A_v \sqrt{\frac{p - p_{ex}}{p_{cr} - p_{ex}}} \quad (4)$$

where p is the internal pressure, A_v is the vent area, p_{cr} is critical pressure, p_{ex} is external pressure caused by external explosion, and u_{cd} is the parameter used in Taminini's orifice equation [14]. Various steps involved in vented explosion and approximations used to model them are explained in the following discussion.

A. Modelling of Vented Explosion

(i) Flame propagation- After ignition, the flame grows into a flame-ball, and reaches the vent opening. The flame speed can be approximated by spherical flame propagation velocity, which can be expressed as (Bauwens et al. [15]):

$$\frac{U}{U_0} = \left(\frac{R}{R_0}\right)^{\beta} \quad (5)$$

where U is the flame speed at radius R, and U_0 is the critical flame speed at critical radius R_0, and β is the fractal excess, experimentally found to be 0.243 for hydrogen. The flame speed will be used to calculate time the flame requires reaching the vent. Assuming that there is negligible time lost between ignition and vent opening, this computed time gives the cloud formation time.

(ii) External cloud formation and External explosion – The unburnt gases start venting out as soon as the vent opens. The vented gases form an external cloud whose radius can be calculated [12] using the vortex roll up equations from Sullivan et al. [16]:

$$R_c = \sqrt[3]{\frac{9\,\pi\, R_0^2\, L_P}{4\alpha^2 \Lambda\,(1 + k)}} \quad (6)$$

where R_c is the cloud radius, R_0 and L_P are the equivalent piston radius and stroke length respectively, k=0.65, and α is Saffman vortex core size [16]. This unburnt cloud will be ignited by the flame reaching the vent. The pressure generated by external explosion (p_{ex}) can be computed using Taylor's spherical piston analogy (Strehlow et al. [17])

$$p_{ex} = 2\,\gamma_u \left(1 - \frac{1}{\sigma}\right) \sigma^2\, M_P^2 \quad (7)$$

where γ_u is specific heat ratio for unburnt gases, and M_P is the Mach number of the equivalent spherical piston, obtained using flame speed from Eq. 5.

(iii) Internal overpressure – As explained in previous section, the internal pressure generation depends on two factors- rate of burnt gases produced, and rate of venting. External explosion constraints venting. The peak internal pressure can be calculated by combining Eqs. (3) and (4):

$$p = \left[\left(\frac{A_f U}{u_{cd}\, A_v}\right)^2 (p_{cr} - p_{ex})\right] + p_{ex} \quad (4)$$

Also, the maximum flame surface area can be computed assuming that the flame-ball is formed in the shape of a semi-ellipsoid in case of back-wall ignition [12].

(iv) Accounting for obstacles - Obstacle can be treated as a bluff body in flame path. Flow past an obstacle creates a recirculation wake region in downstream direction. This recirculation region has high shear at its boundary and it impedes flame moving towards the obstacle in downstream direction. Bluff-body stabilized combustors utilize this recirculation region to stabilize or hold the flame. Similar strategy is also utilized in swirl-stabilized flames, where a recirculation zone is produced to anchor flame. In case of vented explosion, the additional flame wrapped around the obstacle provides increased flame-surface area and hence results in rise in overpressure. The surface area of the flame around an obstacle can be equated to the recirculation region formed by the obstacle. This recirculation length (L_{rec}) can be approximated as (Minguez et al. [18]):

$$L_{rec} = 0.6\ L_{obs} \qquad (9)$$

where is L_{obs} the characteristic length of the obstacle. It is assumed that the recirculation region is not affected by the enclosure geometry or fuel concentration.

III. RESULTS AND DISCUSSION

Experiments are carried out on a 20-foot ISO container using hydrogen as fuel and model obstacles of bottle basked and pipe rack. More details about the experimental study can be found elsewhere [6-9]. The container during an explosion test and model obstacles are shown in Fig. 1. Modelling details are explained in the previous section. The comparison of model predictions from the present model and experimental results for peak pressure are shown in Table 1. As observed, the overpressure rises significantly with the addition of obstacle as compared to empty enclosure. This observation further emphasizes the significance of present modelling effort. It is evident that the model predictions are in reasonably good agreement with the measured values.

Table 1: Comparison of measured and predicted overpressures for 20-foot ISO container tests

H2 %	Config.	p-exp (bar)	p-mod (bar)
15	Empty	0.040	0.031
15		0.047	0.031
15		0.039	0.031
15	Bottle Basket	0.077	0.041
15		0.064	0.041
15		0.045	0.041
18		0.130	0.147
21		0.190	0.428
24		0.390	1.068
15	Pipe Rack	0.050	0.044
18		0.120	0.155
21		0.279	0.449

IV. CONCLUSIONS

The paper presents a study focussed on modelling efforts on vented explosion of hydrogen. Particular attention has been paid to the modelling of case with obstacles which represent a more realistic accidental scenario. Modelling assumptions and procedure has been listed and briefly explained. An obstacle in vented explosion is understood to behave similar to a bluff body placed in a uniform flow and form a recirculation zone. Flame stabilizes around this recirculation zone and produces additional burning at the time of peak pressure. Model predictions are compared with experimentally measured pressure peaks and found to be in good agreement.

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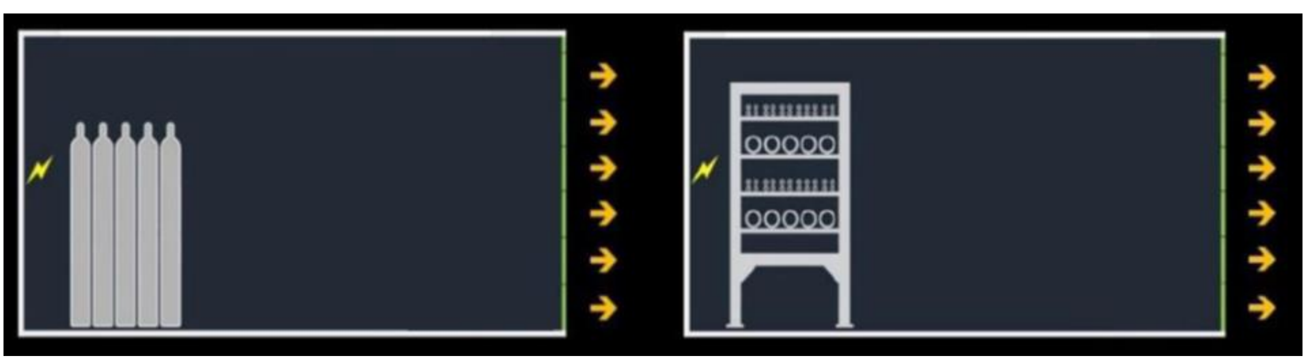
(a) 20-foot ISO enclosure used in the present study

(b) Model obstacles used (i) Bottle basket, (ii) Pipe rack



(c) Experimental configuration used and positioning of model obstacles

Figure 1. Container and obstacles used in the present study along with model obstacles [7]