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Numerical method and simplified analytical model for predicting the blast load in a partially confined chamber

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ABSTRACT

The paper presents a study aimed at understanding the characteristics of an internal explosion within a chamber with limited venting. The study includes numerical simulations and analytical derivations. An in-house 3D code employing an improved weighted essentially non-oscillatory (WENO) conservative finite difference scheme was used to carry out the simulations. It is indicated that the proposed improved WENO scheme can resolve the shock waves with higher accuracy and resolution. Further, a simplified analytical model to predict the quasi-static overpressure was developed based on the conservation law of total energy and dimensional analysis theory. It is demonstrated that the proposed simplified approach for prediction of the quasi-static overpressure agrees well with simulation results for a wide range of explosive weights and venting hole sizes. The studies in this paper provide an efficient method to predict the blast load inside a partially confined chamber for the analysis of the consequences of explosion.

1. Introduction

Partially confined explosions may occur for various reasons. The explosion may occur in an ammunition depot or result from a terrorist action or from a warhead that had penetrated into a confined space. A confined explosion [1] can cause more damage than an external explosion [2,3] under similar conditions due to its more significant overpressure time history acting on the interior boundaries of the confined space. The effects may be extremely severe, leading to serious damage to structures and even to structural collapse [4].

The time history of the blast pressure inside a partially confined space is significantly more complex than that of an external explosion. This complexity is due to the multiple shock wave reflections from the interior boundaries. Even for the one-dimensional problem (a spherical charge exploding in a spherical vessel), the history of internal contact pressure is characterized by a number of peaks [5,6]. Typical time histories of overpressures acting on the wall of a vented confined structure can be seen in [7]. Loading from an explosive charge detonated within a vented structure consists of two almost distinct phases. The first phase is reflected blast loading. It consists of the initial high pressure, short duration reflected wave, with the addition of several following reflected shocks, which are usually attenuated in amplitude because of an irreversible thermodynamic process with very complex waveforms. The second phase is characterized by a slowly decaying pressure, which is a function of the volume and the venting area of the structure, and the nature and energy release of the explosion.

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The analysis of an internal explosion in a confined space is aimed at both evaluating the overpressures acting on the interior space boundary and predicting the structural response and its induced damage and consequences. The damage analysis may be carried out as a coupled analysis, in which the shock wave propagation and reflection within the confined space are analyzed together with the resulting structural response [8,9] or as an uncoupled analysis in which the pressures are analyzed independently of the structural response and a separate analysis of the structural response may follow later, where the pressures are given at this stage [10–14]. The latter is obviously simpler and consumes less calculation time, and may perform well in cases where the boundary of the confined space is quite rigid, which is a common case for many explosion confining structures.

Vented high explosive (HE) explosions have been studied theoretically and experimentally in earlier works. Baker and Westine [15] had presented methods for estimating long term (quasi-static) pressures generated by internal explosions within vented suppressive structures, and attenuated blast pressures escaping from suppressive structures with various vent panel designs. Analytical and experimental studies in explosion venting are described in [16]. Charges of cast cylinders of composition B explosive were detonated inside several small scale three- and four-wall cubicles of different shape and size to establish methods and criteria for predicting the blast environment (positive and negative pressures, durations, and impulses) in and around cubicles containing fully and partially vented explosions in [17]. In [7], similarity analysis has been used to obtain dimensionless parameters for peak quasi-static pressures, blow-down duration, and specific impulse for blast loading within enclosures. Data from various sources have been collected and analyzed, and then displayed graphically according to relationships derived from similarity analysis. Although several empirical formulas for predicting the quasi-static pressure in the literature discussed above were proposed based on the experimental results, these formulas still have some disadvantages. In recent papers [11–13], a full scale experimental study was presented, in which charges were detonated at the center of a cubicle room with rigid boundaries that had limited venting in its roof. Further, an effective simplified model with lumped parameters based on the Bernoulli equation has been developed for the quasi-stationary phase of the outflow of detonation products from the room through the venting openings.

Based on the status of research presented above, this paper is devoted to study and enhance the understanding of some characteristics of an interior explosion within a chamber with limited venting, including numerical simulations and analytical derivations. An in-house 3D code employing the proposed improved WENO scheme was developed, and a simplified analytical model to predict the quasi-static overpressure was proposed in the present work.

2. Numerical methods

2.1. Governing equations

The conservative Euler equations for compressible fluid in Cartesian coordinates read:

$$\frac{\partial U}{\partial t}+\frac{\partial E\left(U\right)}{\partial x}+\frac{\partial F\left(U\right)}{\partial y}+\frac{\partial G\left(U\right)}{\partial z}=0 \tag{1}$$

where U is the variables vector, and $E(U)$, $F(U)$, and $G(U)$ are the fluxes in x, y, and z directions, respectively. They are defined by:

$$U=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ E\end{pmatrix},\ E(U)=\begin{pmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ u\left(E+p\right)\end{pmatrix},\ F(U)=\begin{pmatrix}\rho v\\ \rho vu\\ \rho v^2+p\\ \rho vw\\ v\left(E+p\right)\end{pmatrix},\ G(U)=\begin{pmatrix}\rho w\\ \rho wu\\ \rho wv\\ \rho w^2+p\\ w\left(E+p\right)\end{pmatrix} \tag{2}$$

$$E=\rho e+\frac{1}{2}\rho u^2+\frac{1}{2}\rho v^2+\frac{1}{2}\rho w^2 \tag{3}$$

where ρ and p are the density and pressure, and u, v, and w are the velocities of each direction. E is total energy per unit volume, and e is internal energy per unit mass.

In the literature [18], two typical equations of states are suggested to describe the detonation products. One is the ideal gas state equation and another one is the Jones–Wilkins–Lee (JWL) state equation. The simplest equation of state proposed is the perfect gas law. For calorically perfect gases, it reads:

$$p=\left(\gamma-1\right)\rho e \tag{4}$$

where γ is the ratio of specific heats, and a constant value of 1.4 is used in the present calculation.

2.2. Third-order WENO scheme

In order to simplify the description, only the construction process of the positive flux is given. The second-order fluxes are defined on the two stencils $\{x_{i-1}, x_i\}$, $\{x_i, x_{i+1}\}$ as follows:

$$\bar{f}^{+}_{0,i+1/2}=-\frac{1}{2}f^{+}_{i-1}+\frac{3}{2}f^{+}_{i},\bar{f}^{+}_{1,i+1/2}=\frac{1}{2}f^{+}_{i}+\frac{1}{2}f^{+}_{i+1}. \tag{5}$$

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