SIMPLIFIED EULERIAN SIMULATION OF BLAST WAVE PROPAGATION

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ABSTRACT

The computational analysis of blast waves involves various techniques and models to simulate the complex phenomena of blast wave generation, propagation and interaction with obstacles. In this study, a numerical simulation using the Eulerian model in ABAQUS is applied to analyse the blast wave generated from an unconfined explosion of 2.3 kg TNT charge. The study offers an efficient approach to simulate blast wave propagation in free air which can provide an accurate prediction to blast wave parameters and reduce time of analysis. Three-dimensional non-linear finite element analysis is performed to predict blast peak-overpressure, time of arrival and blast shock wave velocity. The results of Eulerian model are compared and validated with empirical model. The findings of this study clarified an excellent match with empirical model by Kingery–Bulmash. The advanced numerical simulation models can precisely capture complex phenomena of explosions in different burst events without necessity to conduct costly and unsafe blast field tests.

Keywords: Euler's model, blast, shockwave, ABAQUS, Kingery–Bulmash, empirical model.

1 INTRODUCTION

Simulating blast wave propagation in different media such as air, water, and soil is a challenge and complicated task. This complexity involves non-linear nature of blast shock wave which mean the characteristics changing rapidly at a very short period [1]. Hence, a small change in initial conditions can make a tremendous difference in blast wave intensity and make capturing shock wave propagation difficult [1], [2]. Rapid energy release from the source of the explosion generating shock waves in air travels away from the explosion location. Engineers have considered empirical equations to estimate blast shock wave intensity and blast response due to accuracy and ease of computations [3]–[5]. Blast wave parameters have been published in blast standards and graphically simulated with respect to scaled distance (Z) [6]–[8]. The empirical blast models had not taken in account flow environment conditions like temperature and assumed idealized tests environment [9]. Moreover, empirical blast models' accuracy is questionable for the near-field explosion [9]. The limitations of empirical models have been considered in the advanced hydrocodes models to accurately simulate blast and predict blast wave characteristics in different ambient conditions [10]–[12]. Various hydrocodes software blast models have been developed to overcome this issue with specified capability and range of applicability of presenting materials flow at high pressure and temperature [2]. Conventional Eulerian models can give a precise prediction of blast wave characteristics for the near-field burst but require small-mesh size and processing time is costly [1], [2]. Moreover, three-dimensional Euler model equations are complex to solve, and simulation of non-linear blast shock wave propagate requires high computation cost. The current study offers an efficient approach to simulate blast wave propagation in free air which can provide an accurate prediction to blast wave parameters and reduce time of analysis. In this study, a proposed explosion scenario resulted from an unconfined explosion of in free air is considered. Conventional coupled simulation methods of blast shock wave propagation have been considering 3D models for complex multi-phase flow problems. These approaches measure blast wave propagation environment precisely with high computation cost. For far-field burst, blast shock wave propagation and

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pressure within the Euler domain is uniform [13]. This study suggests a simple approach to model explosive as built-in instance within the Eulerian domain. The proposed Eulerian analysis is primarily focused on capturing the in-plane dynamic blast shock wave characteristics without adding complexity of modelling the out-of-plane parameters. This method can significantly reduce the computational time and maintain the accuracy of results. The blast peak-overpressure (P_{so}), time of arrival (t_a) and blast shock wave velocity (U) are predicted. The results of Eulerian model in ABAQUS are compared and validated with empirical model by Kingery–Bulmash [6].

2 EULER MODEL EQUATIONS OF BLAST SHOCK WAVE

This study adopted Euler's model equations to simulate blast wave phenomena in free air. The governing equations of this model include conservation form of mass, momentum, and energy [9]. The general mathematical expressions of these partial differential equations (PDEs) are:

Mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho v) = 0. \tag{1}$$

Here, ρ is the air density, v is velocity vector of air, and t is the time.

Momentum equation:

$$\frac{\partial (pv)}{\partial t} + \nabla.(\rho v \otimes v) + \nabla p = 0. \tag{2}$$

Here, p is the air pressure, v is velocity vector of air, and t is the time.

Conservation of energy:

$$\frac{\partial (pe)}{\partial t} + \nabla.(\rho v e + pv) = 0. \tag{3}$$

Here, p is the air pressure, v is velocity vector of air, e is internal energy per unit mass of air, and t is the time.

Moreover, the ideal gas law correlates the relation among pressure, density, and temperature od air as in the following mathematical expression.

$$p = \rho R T. \tag{4}$$

Here, p is the air pressure, R is the specific gas constant, and T is the temperature.

3 KINGERY–BULAMSH EMPERCAL BLAST MODEL

Kingery and Bulmash introduced the most admitted empirical blast model equations to estimate blast wave parameters of spherical and hemispherical bursts [6]. The developed equations provide data of incident peak-overpressure (P_{so}), reflected peak-overpressure (P_r), incident impulse (i_s), reflected impulse (i_r), duration of positive pressure phase (t^+_o), time of arrival of the shock wave (t_a) and shock front velocity (U) [5], [7]. The data were presented graphically in design graphs in terms of scaled distance (Z) [7], [8]. Thereafter, the negative phase blast wave parameters were included [7]. The only limitation of Kingery–Bulmash model is the accuracy of the data in close-field burst due to high generated temperature at the early time of explosion [14]. The estimated blast wave parameters and blast response are accurate and valid for freely blast wave propagation without interrupt by obstacles [15]. In this case, blast load-structure interaction is negligible.

The mathematical expression of Kingery–Bulmash model equations applicable ranges of scaled distance, 0.053 m/kg$^{1/3}$ ≤ Z ≤ 40 m/kg$^{1/3}$, and from 0.067 m/kg$^{1/3}$ ≤ Z ≤ 40 m/kg$^{1/3}$ for spherical and hemispherical TNT, respectively [14], [16], [17]. Eqn (5) shows the Kingery–Bulmash equation

$$Y = C_o + C_1 U + C_2^2 + \cdots + C_N^N, \tag{5}$$

where $U = K_0 + K_1 T$, Y, is the measured blast parameter, T is the base 10 logarithms of (Z), and N is the order of fit. These equation parameters are only open for the U.S. military and contractors [18].

4 NUMERICAL ANALYSIS RESULTS

4.1 Finite element model: Summary

Three-dimensional (3D) non-linear dynamic finite element model using Eulerian model in ABAQUS/Explicit [19]. The dimensions of the Eulerian domain are 10 m × 5 m × 1 cm. The Eulerian domain boundaries were considered based on studied standoff distances to ensure that shock wave does not leave the domain and becomes undetectable to the solver. Moreover, the Eulerian element in ABAQUS can only be applied for 3D models, therefore, the third dimension is given only small value to reduce computations cost. The TNT equivalent mass of the explosive charge is 2.3 kg, the height of the explosive is 2.5 m. The explosive charge is modeled within Eulerian domain and Eulerian–Eulerian contact is performed without need to define contact interaction [19]. Fig. 1 shows the model geometry description and Finite element meshed parts and explosive charge setup of the Eulerian model considered in this study. The air part is modeled inside Eulerian domain which is meshed as a volume element using 8-node linear Eulerian brick, reduced integration, hourglass control (EC3DR) element. This approach has a perfect capability to support multi-materials flow and good for large deformation. The Eulerian domain size has been selected based on considered scaled distances and guarantee blasts wave is not extended out of the domain boundaries.

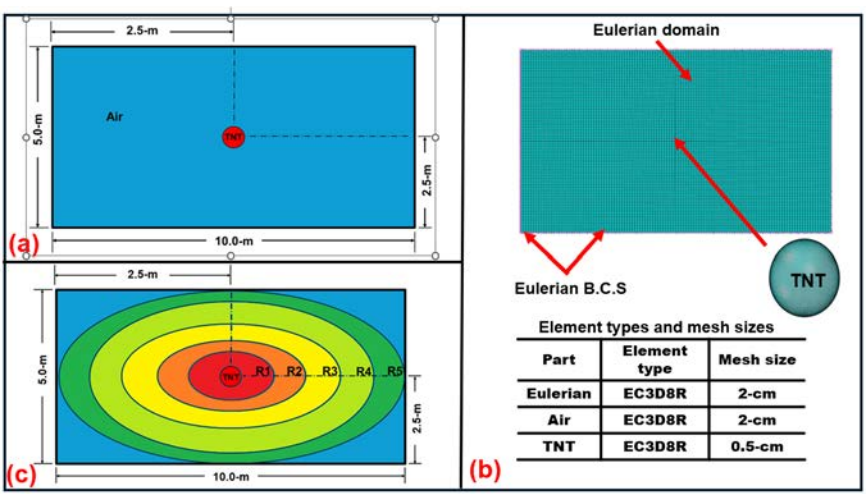

Figure 1: (a) Eulerian model geometry details; (b) Meshed parts and mesh sizes; and (c) Standoff distances where blast wave parameters measured.

4.2 Material models

The TNT explosive charge is modeled using the Jones–Wilkins–Lee (JWL) equation of state (EOS) [20]. The JWL model is a reliable method to simulate blast pressure generated from explosives burst [20], [21]. The generated blast pressure can be calculated using the equation-of-state-JWL as shown in eqn (6)

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + \left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V}. \tag{6}$$

Here, P is the pressure, A and B, are pressure parameters, ω, R_1 and R_2 are dimensionless nonlinear pressure parameters, V is the relative volume, E is the internal energy/unit volume [22]. The JWL TNT material parameters are listed in Table 1 [23].

Table 1: JWL model parameters of TNT [23].

Parameters	**Value**
P (kg/m^3)	1630
velocity (m/sec)	6930
A (GPa)	3.738
B (GPa)	3.747
R_1	4.15
ω	0.35
V_o	1.0
E (MPa)	6.0

The air domain is simulated suing ideal gas equation of state. This model can capture the air behaviour at low pressure level utilizing the proportional of air volume to temperature [19]. The ideal gas model equation of state cab be expressed as in eqn (7). Table 2 lists the material properties and EOS model parameters of air [24]

$$p + p_A = \rho R(\theta - \theta^Z). \tag{7}$$

Here p is the generated pressure, p_A, is the ambient pressure, R is a gas constant, θ is the current initial temperature, and θ^Z *is* absolute zero on the temperature scale [19].

Table 2: EOS model parameters of air [24].

Parameters	**Value**
P (kg/m^3)	1.297
p_A (kPa)	101.325
R (J/kg-k)	287
C_p	717.6
θ^Z (k)	0

4.3 Blast wave parameters

The Eulerian model analysis results of blast wave parameters are validated with empirical model of Kingery–Bulmash [7]. The Eulerian volume fraction (EVF) is an efficient method often used in fluid dynamics, specifically for multi-phase flow simulations. It describes the portion of the element volume filled with material. The value of EVF is equal to zero when the domain is empty and equal to one when it is filled with material [25]. The volume fraction of each particle, expressed as a Eulerian value, and associated with the mesh cell [26]. For elements partially filled with material, the EVF value is interpolating between adjacent elements [19]. The simulation is performed using grid-based technique which is often apply for classical multi-phase flow. While the simulation provides highly accurate results of blast shock wave propagation in open air, the accuracy for other blast scenarios such as confined explosions, non-ideal explosives, material behaviours, and multi-phase interactions requires further validation and examination [19]. Fig. 2(a) and (b) shows two-dimensional simulation of the EVF contour plot of air and TNT propagation within Eulerian domain, respectively.

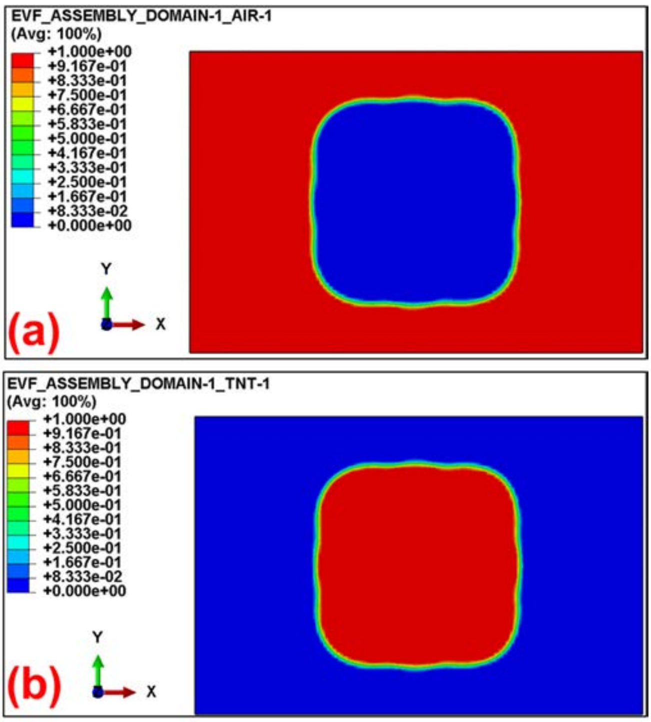

Figure 2: 2D Eulerian volume fraction contour. (a) Air; and (b) TNT.

4.3.1 Incident blast peak-overpressure

The considered Eulerian analysis model is applied to simulate blast wave extending in free air. Table 3 lists the measurement variables, standoff distance, *R* (m), explosive charge mass, *W* (kg), and scaled distance, *Z* (m/kg$^{1/3}$) of the current study (see Fig. 1(c)). Peak incident peak-overpressure is computed and validated with Kingery–Bulmash model data [7]. The results of the Eulerian model of incident peak-overpressure showed a good convergence with empirical data with maximum difference of 27.78 as shown in Fig. 3.

4.3.2 Time of arrival

The Empirical models of blast wave have measured time of arrival of blast shock wave considering optical-photo techniques [5], [7]. Fig. 4 shows the prediction of the time of

Table 3: Measurement variables.

P_t #	R (m)	W (kg)	Z (m/kg$^{1/3}$)
R_1	1.0	2.3	0.76
R_2	2.0		1.52
R_3	3.0		2.3
R_4	4.0		3.0
R_5	5.0		3.8

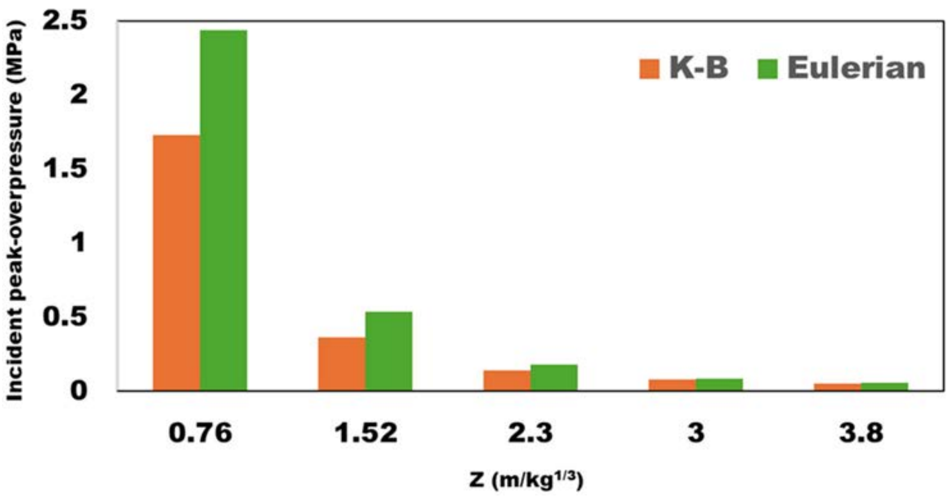

Figure 3: Incident peak-overpressure of Eulerian model and Kingery–Bulmash data.

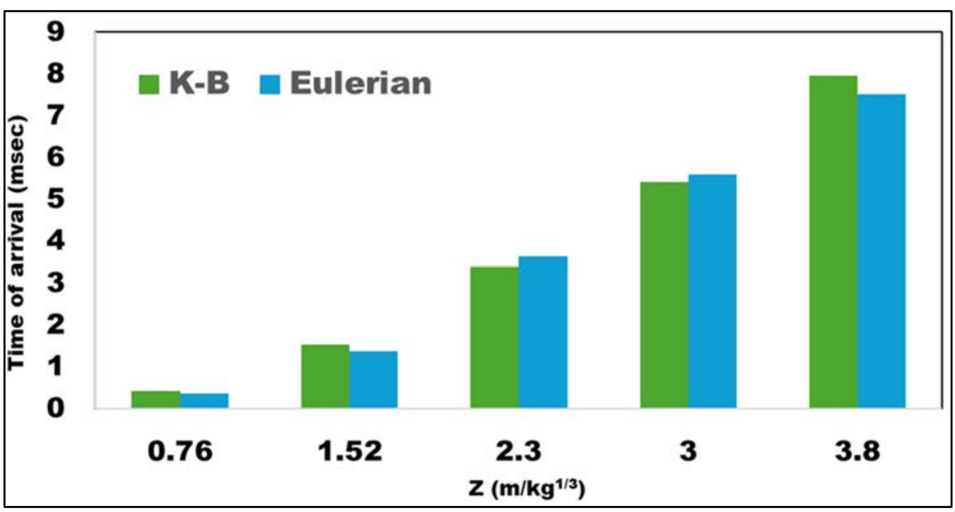

Figure 4: Time of arrival of Eulerian model compared to Kingery–Bulmash data.

arrival of blast wave (t_a) of the proposed Eulerian model with respect to Kingery–Bulmash data. The results of Eulerian demonstrated a good match with empirical model with maximum difference of 7.52%.

4.3.3 Blast shock wave velocity

The blast shock wave travels through the domain at a higher speed of sound. The amplitude of the shock wave velocity depends on different factors like density of the medium, ambient temperature, released energy and distance from source of explosion [27]. Fig. 5 shows the comparison of the current Eulerian model prediction and Prediction of the empirical model by Kingery–Bulmash. The results of the proposed model showed a good agreement with empirical model data with maximum difference of 20.13%.

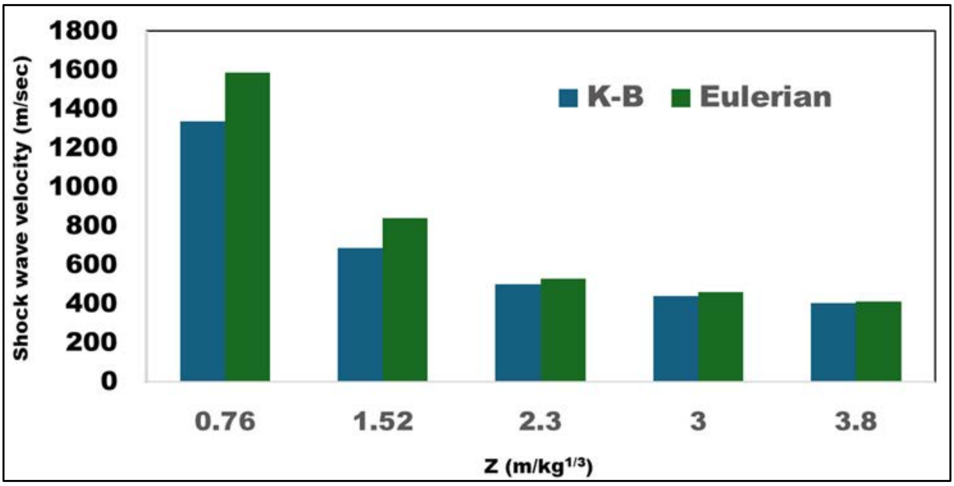

Figure 5: Comparison of Eulerian model Peak blast shock wave velocity with Kingery–Bulmash data.

5 CONCLUSIONS

In summary, the proposed Eulerian model indicates that analyzing blast shock wave propagation in open air using a Eulerian approach can be effectively represented by a simplified model that accurately predicts the characteristics of the blast wave with minimal computational effort. The results of the study highlighted the effectiveness of this approach in capturing the blast wave phenomena, eliminating the need for unsafe blast field tests or costly computational models. However, the accuracy of other blast scenarios such as confined explosions, non-ideal explosives, material behaviours, and multi-phase interactions requires further validation and examination. Future research should focus on developing simplified approaches that can be used by engineers to predict blast load parameters and blast response of structural systems.

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