Numerical Simulation and Experimental Investigation of Blast Wave Mitigation in Dry Aqueous Foams

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1 Introduction

Blast waves resulting from explosions in air can cause serious damages to structures and human being located at many charge radii from the explosion point of origin. When the detonation wave propagating through the condensed explosive reaches the air interface, an intense shock wave with order of hundred atmospheres pressure is propagated radially outwards through the air. It has been shown that the strength of the blast wave can be greatly attenuated by surrounding the explosive charge with aqueous foam [1]. In the last half century, several laboratories in the world have been conducting experimental campaigns to characterise the efficiency of aqueous foam to mitigate blast waves. The goal of this presentation is to understand the underlying physics and to model the multiphase flow resulting from the blast wave/foam interaction.
Aqueous foam is a two-phase system in which gas cells are enclosed by thin liquid films [2]. The gaseous phase is dispersed in bubbles, whereas the liquid phase is the continuous one. The bubbles take the form of polyhedral cells (Figure 1), with liquid surfaces meeting in lines and lines merging at vertices. The lines are called Plateau borders, which are channels of finite width and where the liquid is mainly to be found. This topological description corresponds to dry foam. As liquid volume fraction increases, Plateau borders swell and bubbles progressively recover their spherical shapes. This corresponds to wet foam. Any further increase of liquid will allow them to come apart and the foam becomes a bubbly liquid. Aqueous foams are natural but in metastable states. Under high pressure ratio shock wave impingement, the liquid matrix is likely to be shattered into more stable droplets [3].

2 Numerical Modeling

In this study, a two-fluid model is developed assuming a disequilibrium between pressure, velocity and temperature. Indeed, the passage of shock wave over a two-phase system will bring the two phases in different mechanical and thermodynamic states because of their impedance contrast. Relaxation processes will attempt to edge the phases towards equilibrium. The post-shock states of liquid and gas will then relax to a same thermo-mechanical state at the end of the relaxation zone. The model is derived based on the eulerian balances for the volume fraction, mass, momentum and energy of each phase [4]. Under a compact form, the two-fluid model in spherical coordinates r can be written.

$$\frac{\partial}{\partial t}(\alpha W)_k + \frac{\partial}{\partial r}(\alpha F)_k = F_k^{lag} \cdot \frac{\partial \alpha_k}{\partial r} + S_{geom,k} + S_{d,k}$$

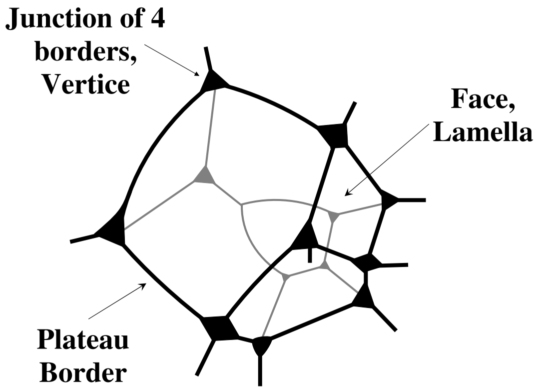

Figure 1: Structure of a dry foam [2]

Where α_k, ρ_k, u_k, 3_k, P_k are respectively the volume fraction, the density, the velocity, the total energy and the pressure of each phase. $W = (1,\ \rho,\ \rho u,\ \rho E)$ is the fluid conservative variable, $F = \left(0,\ \rho u,\ \rho u^2 + P,\ \rho E u + P\right)$ the fluid eulerian flux and $F^{lag} = (u_i,\ 0,\ P_i,\ P_i u_i)$ the fluid lagrangian flux. Each phase is governed by its own equation of state: perfect gas law for the gas and stiffened gas for the liquid phase. The interfacial variables of the problem are issued from the homogenization method Discrete Equation Method (DEM) [4]. S_{geom} stands for the spherical divergence and S_d accounts for the momentum and energy exchanges between phases. The model is unconditionally hyperbolic. An asymptotic derivation towards a one velocity one pressure hyperbolic model can be achieved. Its analysis shows that the sound speed of the two-phase medium is the non-monotonic sound speed of Wood/Wallis.

3 Experimental Setup

The Figure 2 depicts the experimental configuration which has been designed with a particular attention paid to the sphericity of the air incident blast wave.

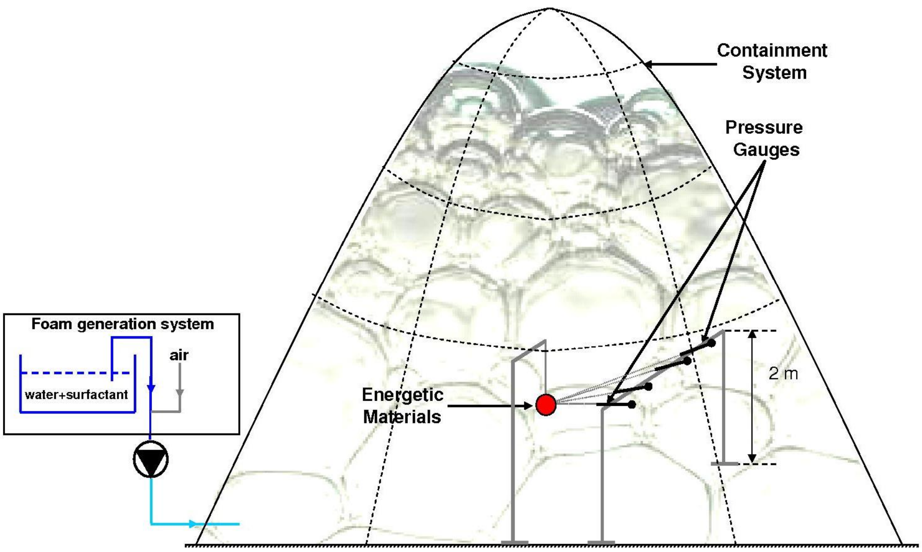

Figure 2: Experimental configuration of CEA campaign [5]

The High Explosive (HE) is packed in a spherical envelope to insure a spherical detonation wave. Its ignition is done at its center. The device is placed at a height of 2 meters from the ground to insure the sphericity of the incident blast wave. The pressure gauges are placed at the same height as the HE, so that the reflected Mach waves from the ground do not alter the duration of the positive impulse. The pressure sensors are PCB blast pressure pencil sensors. They are placed on a gantry. The pencils point towards the center of the charge. The measurements are done in the direction of the outflow. They are placed between 2 and 5 meters from the detonator. Several sets of experiments were made: important weights of energetic material as well as tiny devices were tested. In this paper, we only describe the case of the detonation of a charge of 6.6 kg of Plastrite - a pentrite based explosive. A first experiment was conducted in air. The results validate the choice of the configuration made earlier. The TNT effectiveness factor was found to be 1.27. Then, a second experiment was done with the same mass of HE but the energetic material was confined with an aqueous foam of expansion ratio of around 1:125.

4 Numerical Results and Discussion

The mesh contains 1500 cells for a computational domain of 3.5 $m.kg^{-1/3}$. The droplet size of the fragmented aqueous foam is chosen to be 50 m and is about the same order of magnitude as the Plateau border radius. The aqueous foam is considered to be in atmospherical conditions at sea level. The volume fraction is the inverse of the expansion ratio. As for the initial conditions for detonation products, the constant volume approach has been used. The initial density of the HE is 1654 $kg.m^{-3}$ and the detonation energy is 4.18 $MJ.kg^{-1}$. The other thermodynamic variables are deduced from the equations of state.

4.1 Overpressure Results

At first, the experimental overpressures have been compared with the tables given in [6] and reported on Figure 3.

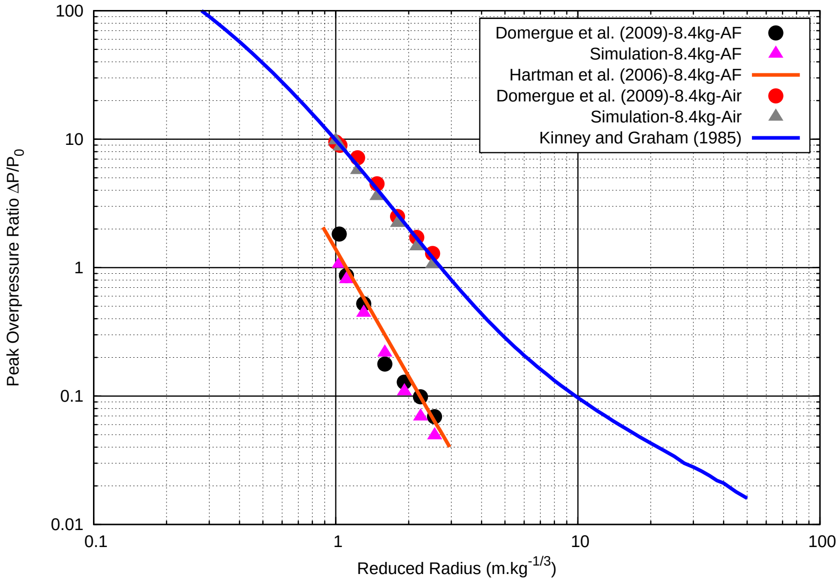

Figure 3: Overpressure ratio comparison between an air explosion and an aqueous foam confined explosion

There is a good agreement between the two sets of data, with a relative effectiveness factor of 1.27 for the Plastrite energetic material. It can be seen that for mean field, there is also a good agreement between the numerical results and the experimental data. In the studied range, the blast wave overpressure decreases with the reduced radius at approximately a power of two. Not shown here, the positive impulse as well as the time of arrival and the shock velocity are also compared favourably with experiments. Regarding the overpressures when the HE is confined by the aqueous foam, the experimental results are fitted by the empirical relations derived from [1]. The numerical results show also a good agreement. The ratio of overpressures in the air over those in foams increases from approximately 1 decade to 1.5 decade in the range of reduced radius of 1 to 3 $m.kg^{-1/3}$. This clearly demonstrates the blast mitigation capabilities of aqueous foams.
Indeed, the post-shock total energy can be estimated via linearized Riemann invariants and can be shown to decrease with an increase of the acoustic impedance of the confining medium. This energy radiates spherically, and will result in a lower overpressure. Moreover, a two-phase shock is a composite shock, which consists of a shock wave followed by a relaxation zone. The spherical rarefaction will tend to smooth the peak overpressure. In addition, the compressibility of the two-phase confinement is mainly driven by the gaseous phase. The liquid phase tends to store the kinetic energy given by the spherical shock wave. Decreasing the temperature of the gas will also decrease the level of overpressure.

4.2 Wave diagram

The fireball position, the main shock as well as the subsequent ones are shown in Figure 4 in the case where the detonation takes place in air.

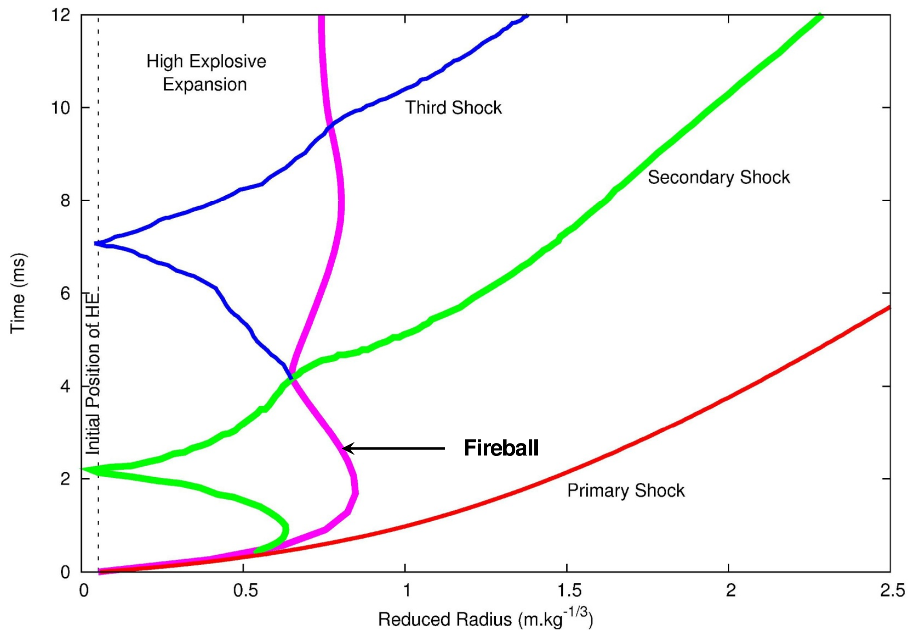

Figure 4: Wave diagram of shocks and fireball interface in air

As the acoustic impedance of air is very low compared to that of the detonation products, the shock wave in air starts with an initial strength well below that of the high pressure volume and very shortly decays with the spherical divergence. This shock is mainly responsible for the maximum overpressure seen by the pressure gauges. Between the outward moving shock and the inward rarefaction wave, a second shock develops and begins to grow inward from the fireball interface while the latter moves out in general expansion. This inward secondary shock then implodes and reflects on the origin. At that time, the fireball is ending its expansion and is beginning to shrink. The detonation products are still cooler than the air immediately outside. Thus the reflection from the secondary shock gives rise to rarefaction waves. Like in the initial rarefaction waves, they are followed by a third shock. Then this complex shock inverts the fireball velocity abruptly. The succession of shocks continues in this fashion until the energy of the detonation products is dissipated. The origin of these inward shocks lies in the necessity of a compression wave at the junction between a spherical rarefaction wave moving away from a spherical shock wave [7].

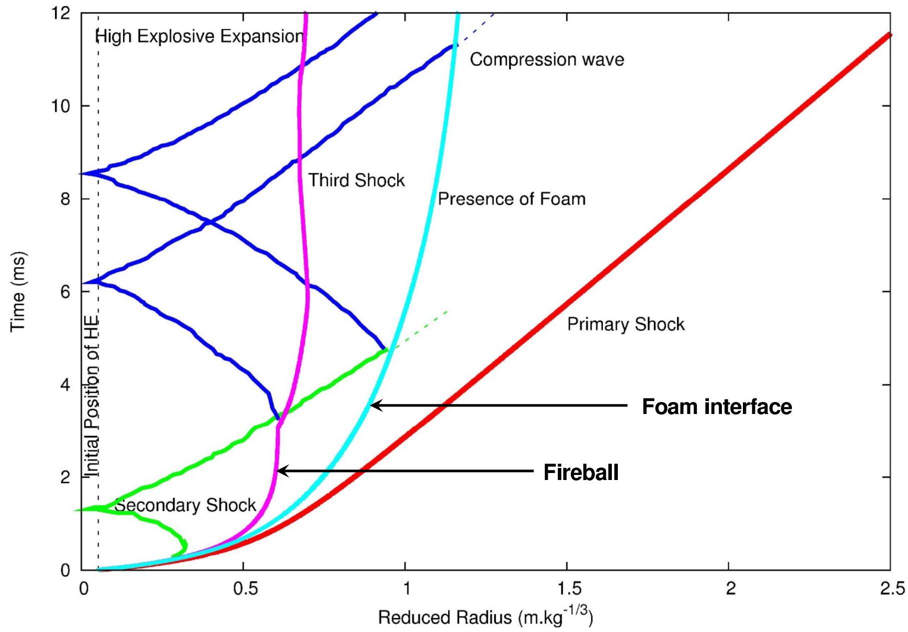

Figure 5: Wave diagrams of shocks, fireball and liquid/gas interfaces in aqueous foam

In the same way as previously, the wave diagram presented in Figure 5 is in the case of aqueous foam confinement; it shows the different shocks as well as the liquid and gaseous interfaces. Indeed, the liquid phase has its own dynamics and own velocity. The same global features of inward and outward shocks are found as compared to the air configuration. However, there is another interface. During the first phase of expansion, the liquid and gas fluids of the aqueous foam have approximately the same velocity. Then the gas slows down with spherical divergence. But as the liquid inertia is greater than the gas one, its final abscissa is greater. The liquid is then projected at a greater distance than the gas. The aqueous foam and the fireball are thus separated. The secondary shock reflects on this liquid interface. A weak compression wave is transmitted to the foam and a shock gets reflected in the gaseous phase which lies between the aqueous foam and the fireball. More complex dynamics of reflected and transmitted shocks will ensue with the presence of this gap. The final position of the fireball in the air configuration is slightly greater than in the foam configuration, as the foam density is greater. Moreover, the dynamics are also different. In air, after an initial phase of expansion, the fireball shrinks before being impacted by the secondary shock, which inverts its velocity. In the second case, as the acoustic impedance of the foam is greater, the initial velocity of the fireball is less important. The secondary shock impacts the interface at the same time as the contracting phase begins to occur. In addition, the time at which the secondary shock implodes on the origin is shorter because the rarefaction waves are weaker in the first instants. As a consequence, the oscillating character of the fireball in the air will be more marked than in the confinement case in the first period of expansion shrinking. Then the internal wave pattern into the gap, that is the multiple goings and comings of the different compression/expansion waves into the gap will smoothen the evolution of the position of the fireball towards its end position. The dynamics of the liquid and gaseous phase are also different in the far field. After the passage of the primary shock wave, the gas is put in motion. The liquid will then be put into motion by the gas phase. So after an initial expansion phase, the gas velocity will fall during the shrinking phase. However, due to the greater liquid inertia, the distance travelled by droplets will be in the end greater than the gas particle. The trajectories of the liquid and gas can clearly be seen to be intertwined. The velocity of the fireball in the first stage of expansion is lowered with the aqueous foam confinement. It acts as a piston on its environnment. The time during which this piston is maintained is less. This will result in a lower overpressure field. In addition, the gap between the aqueous foam and the fireball acts as a buffer.

5 Conclusion

A multifluid formalism is used to describe an aqueous foam as a dense two-phase medium. After shock impingement, the initially encapsulated gas pores and liquid ligaments become respectively the carrier phase and the dispersed phase composed of liquid droplets. Conventional constitutive relations for gas-droplets have been used to describe the inter-phase exchanges within a multifluid approach. A good agreement between the numerical results and the experimental data is obtained.
Moreover, the particularities of the two-phase wave diagram in comparison to the air configuration have been discussed. A gap is created between the fireball and the two-phase media. Liquid and gas trajectory paths are intertwined. This emphasizes the non-equilibrium effect of the aqueous foam under shock impingement and its blast mitigation capabilities.

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