Study of small scale experiments of detonations in an aqueous foam confinement

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1 Introduction

In the last decades, aqueous foams have been studied for their ability to mitigate blast effects (see [1] for a general review). Moreover, its use is desirable as a mean to capture the inhalable particles released by an explosion. Aqueous foam is a cellular two phase medium made of a liquid phase which is a mixture of water and surfactant and a gaseous phase which is air in most cases. Foam is described mainly by its expansion ratio (ER) which is the ratio between the volume of the foam and the volume of liquid within it. If ER is less than 20, foam is qualified as wet; if ER is greater than 20 it is dry. Another important property of foam is the size of the liquid cells enclosing the gas: their diameter range from 0.1 to 1 mm. To understand and to predict the process of blast mitigation, we have recently carried out experiments of blast wave propagation generated by high explosive (HE) detonation in aqueous foams.
Section 2 describes the experimental campaign and its set-up. Section 3 presents the experimental results where the comparison with tests in air will enable to draw conclusions in Section 4.

2 Experimental campaign description

2.1 Objectives

The main objective of this campaign was to complete our experimental database about HE detonation confinement by aqueous foams. Indeed, earlier experiments have been led in order to quantify the influence of the foam characteristics on the blast mitigation, such as its expansion ratio or its generation method [2]. Therefore, this new campaign has been designed to study the influence of the HE detonation source characteristics. For that end, several masses of high explosive have been used: 3 g, 14 g, 70 g and 120 g. An air exclusion volume has also been placed over the charge in some cases to study the influence of post-combustion. The use of the different masses allows us to obtain results on a wide range of scaled distances. We recall the definition of scaled distance R in the Eq. (1).

$$R = \frac{d}{W^{\frac{1}{3}}} \tag{1}$$

with d the distance from the center of the charge and W the TNT equivalent weight of the charge.

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2.2 Description of the experimental set-up

The experimental set-up, illustrated in Figure 1, consists of a metallic plate facing an instrumented concrete block sided by two Plexiglas panels. A 4 m^3 rectangular tank is thus formed that we can fill with foam. These experiments have been led with hemispherical charges of FORMEX®, a high explosive composed of 89 % of PETN and 11 % of inert rubber. The charge is glued on the metallic plate. This plate is also instrumented with three rows of pressure gauges. In the whole set-up, a total of 23 pressures gauges are placed: 20 are measuring incident overpressures and 3 reflected overpressures. The incident pressure gauges are disposed as follows. On the plate, 7 are on each side of the charge (Pi1 to Pi7 and Pi8 to Pi14) and 4 under the charge (Pi15 to Pi18). The Pi19 is within the tank between the plate and the instrumented block and the Pi20 is outside the foam, over the tank. The 3 reflected pressures gauges are placed in the concrete block in front of the charge. This experimental configuration allows us to obtain 2 or 3 measurements at the same distance from the charge. This gives us some insight about the dispersion of our experimental set of data. The Pi19 gauge lies within the foam and can be compared to the Pi6 and the Pi13 which are at the same distance. This guarantees that there is no boundary effect coming from the vertical plate. The Pi20 gauge is outside the foam and helps to understand and verify the transmission of the blast at the foam/air interface. The results of this gauge will not be presented in this paper but seem to support our conclusions. A high-speed camera is also placed on the side of the enclosure to record the propagation of the blast wave in the foam along the Plexiglas panel.

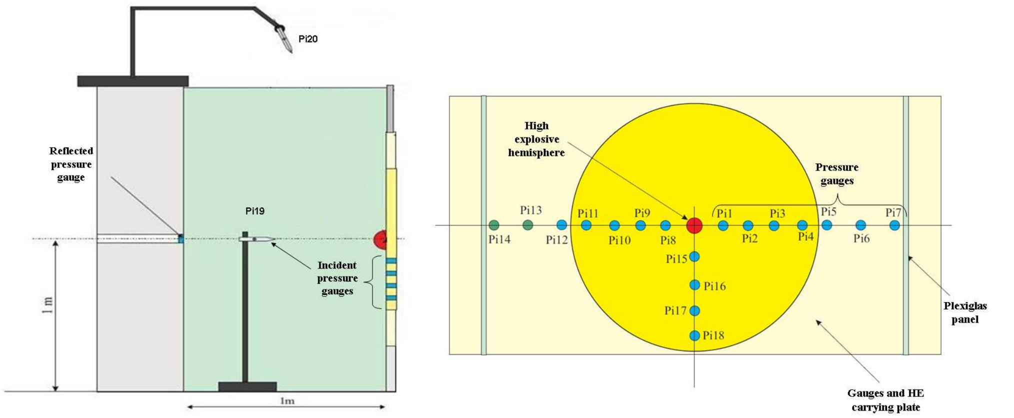

Figure 1: Experimental set-up. Side view of the rectangular tank on the left and frontal view of the carrying plate equipped of the pressure gauges on the right.

The tank is filled with foam of ER 60 or 120. A controlled air flow along with a mixture of 92 % in mass of water and 8 % of surfactant are blown through a strainer in order to generate the desired foam. the comercial surfactant used is Retofoam R2, which is provided by the *Eau et Feu* company [10]. Its use offers a very good stability of the ER between the generation time and the shot execution time. For each HE mass, a shot in air has been carried out as a reference. In some cases, the charges were covered with a thin metallic structure wrapped with plastic film in order to create an exclusion volume of air around the charge. Two structures of 300 mm and 500 mm in diameter have been tested for two masses of 14 g and 70 g.

It has been proved in [4] that, in air and in this configuration, a hemispherical charge of FORMEX® is considered to be equivalent in pressure effects to a TNT spherical charge of 2 times its weight. We will see that this is also true in the foam.

3 Results and discussion

The Figures 2 and 3 represent the peak overpressure and the scaled arrival time, respectively, as a function of scaled distance for detonations in air and in foam. The scaled arrival time is defined as follows:

$$t_a^r = \frac{t_a}{W^{\frac{1}{3}}} \tag{2}$$

with t_a the arrival time of the blast wave and W the TNT equivalent weight of the explosive charge. Our experiments with 4 HE masses have been compared for air to the UFC 3-340-02 predictions [5] and for foam to the Sandia Laboratories data [6].

3.1 Scaling laws validity

The first point we were able to verify in this campaign is the validity of the Hopkinson-Cranz scaling laws for detonations in foam [7] [8]. Indeed, this notion has been developed in air but may be unverified in other media. Indeed, this can be a reliable tool in order to compare experiments between them.
The displayed results allow us to validate the use of scaled parameters for foam. The use of the scaled distance is relevant as far as we are concerned with scaled arrival time and peak overpressure. Indeed, the overall overpressures for each mass produce a remarkable continuous line as a function of scaled distance (see Figure 2). The analysis is the same for the scaled arrival time (see Figure 3). The same study has been conducted for the positive phase duration and the positive impulse. However, even if the positive phase duration is also scalable, the positive impulse does not seem to comply with the same scaling laws.

3.2 Comparison of blast wave in air and in foam

We will focus now on the direct observation of the foam effects on the blast wave. The peak overpressure is the major criteria to evaluate the blast mitigation. It is considered predominant in term of personal and light material protection. We can easily notice on Figure 2 the clear difference between the results obtained in air and those obtained in foam. At first, close to the charge, the peak overpressure in aqueous foam is similar to the one in air. Considering that foam is a medium with a higher acoustic impedance than air, therefore that better couples with the high impedance detonation products, we could even expect the peak overpressure to be higher. Nonetheless, farther away from the charge, the two-phase medium enhances the peak overpressure decrease. The overpressure decrease rate is higher in the aqueous foam than in air. By that phenomenon, we obtain a mitigation of the maximum overpressure, which reaches a factor of 10 at a scaled distance of 1 m.kg$^{-1/3}$ and which increases further away from the charge. This is explained by the fact that the shock front of the blast wave is slowed down in the foam and that the rarefaction waves following the shock attenuate it faster in foam than in air. Indeed, the main difference between the air and the foam is their sound speed.
For a two-phase medium, the sound speed c_W is calculated by the Wood formula, [9] which is defined as follows:

$$\frac{1}{\rho_f c_W^2} = \frac{\alpha_L}{\rho_L c_L^2} + \frac{\alpha_G}{\rho_G c_G^2} \tag{3}$$

with ρ, c and α the density, the sound speed and the volume fraction, respectively and the subscripts L, G and f for the liquid phase, the gaseous phase and the foam, respectively.
Therefore, the sound speed of foam is much lower than the one of air. This assertion is verified on the Figure 3, where we can see that the arrival times of the blast wave in the air are sensibly lower than those in foam. Indeed, the difference of sound speeds induces that the blast wave is slowing down faster in the

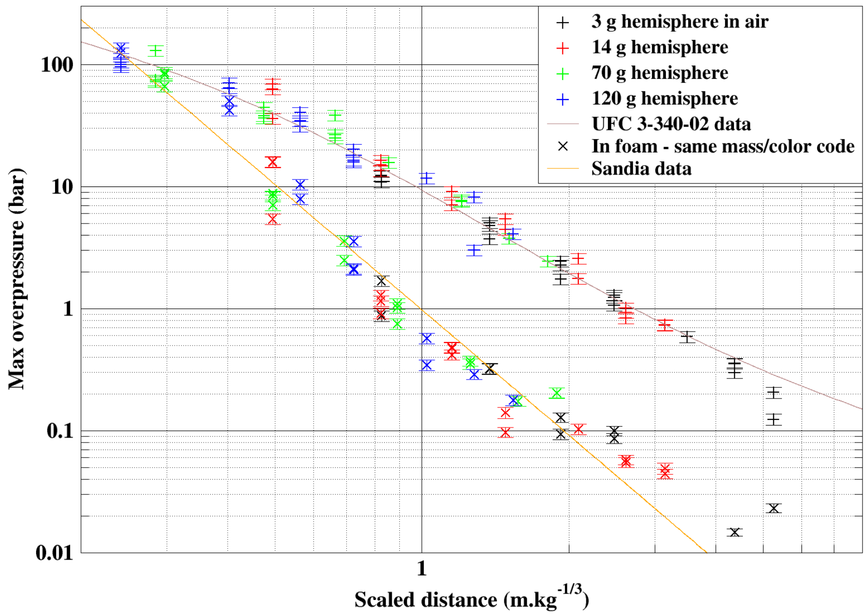

Figure 2: Peak overpressure in air (+) and in foam (x) for the 4 HE masses compared to the UFC 3-340-02 [5] and the Sandia curves [6]

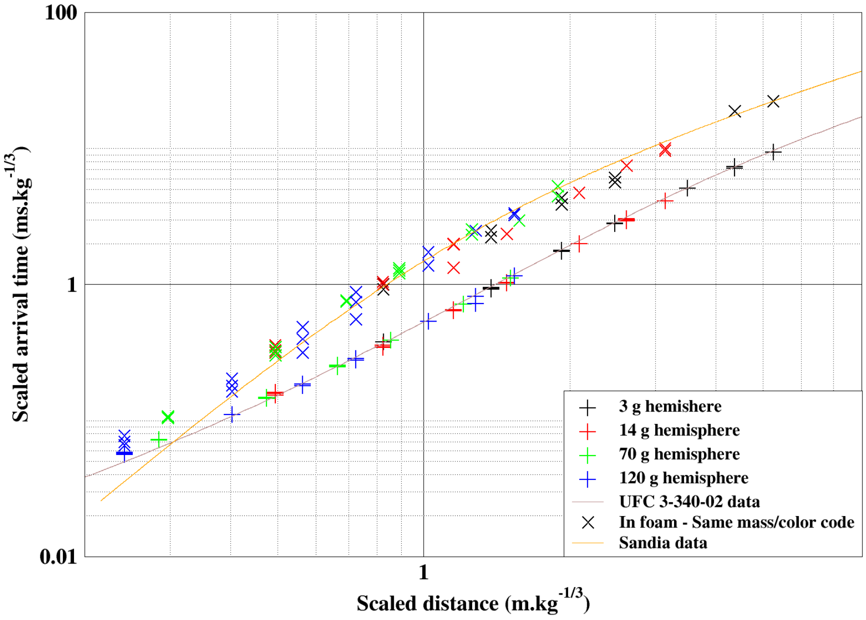

Figure 3: Scaled arrival time in air (+) and in foam (x) for the 4 HE masses compared to the UFC 3-340-02 [5] and the Sandia curves [6]

foam compared to what takes place in air.

Positive impulse is also a decisive criterion to evaluate the effects of a blast wave. It is particularly representative of the damages inflicted upon solid structures. The scaling of positive impulse does not seem relevant.Even if Larsen propose a scaling law for positive impulse [10], Hartman et al. clearly indicates that some care should be taken, based on one experiment [6]. This is confirmed by our own conclusions on a larger set of experimental data. Nonetheless, the influence of the foam on this parameter can be evaluated by comparing the results of the detonations in air with those in foam for a given HE mass. We present on Figure 4 the comparison of the positive impulse for the 14 g hemisphere detonated in the air and in the foam.

The comparisons for each mass underline a common pattern: close to the charge, the positive impulse is higher in the foam than in the air but away from the charge the trend becomes the opposite. This change occurs around 0.7∼0.8 m.kg$^{-1/3}$. The positive impulse at 1 m.kg$^{-1/3}$ is then approximately reduced by a factor of 2.

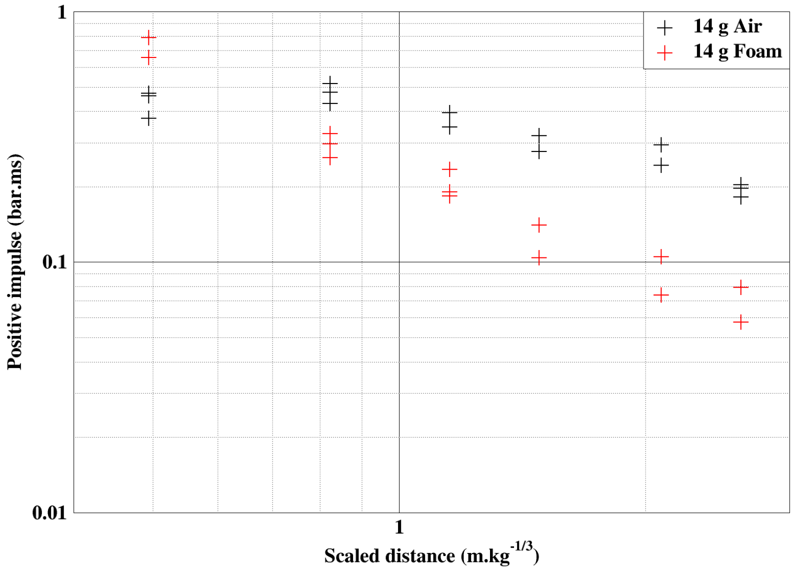

Figure 4: Positive impulse in air (black) and in foam (red) for the 14 g HE hemisphere

3.3 Complementary results

The campaign has also brought some complementary results. Firstly, we studied the influence of the expansion ratio. Many results from past experiments, which are reinforced by this campaign, confirm that the lower is the ER, the better is the peak overpressure mitigation. However, the difference between ER 60 and ER 120 is not negligible (+70%) but small compared to that with air (+1000%). An opposite conclusion with regards to the positive impulse, is brought about by this campaign: the higher is the ER, the better is the impulsion mitigation. Moreover the difference between the two ER is of the same order than the difference with air. Finding the best compromises between overpressure and impulse mitigation remains an issue.

Secondly, the use of an exclusion volume over the charge allowed us to observe that its influence over the peak overpressure and on the positive impulse is minor as long as the exclusion is under 0.5 m.kg$^{-1/3}$ and there is the same length of foam behind it. We can deduce from this observation that the post-combustion has little impact on the pressure response of the foam under blast.

The multiphase formalism [2] is used through a numerical code to model the interactions of the liquid phase with the gaseous phase, as well as the interaction of the detonation products with the two-phase medium. We will also try to reproduce the general trends shown by the experiments and predict the response of the foam under blast loading.

4 Conclusion

This experimental campaign has enabled us to complete our database about detonation confinement by dry aqueous foams. Generally, we can affirm that the mitigation by dry aqueous foams is highly efficient since it mitigates the shock front, the maximal overpressure and the positive impulse of a blast wave. Scaling laws can be used for overpressure and arrival time, but are no more pertinent with regard to the impulse. It is then proved that the detrimental effects to goods and people are drastically reduced for foams of expansion ratio between 30 and 150.

References

[1] Britan A.B., Shapiro H., Liverts M., Ben-Dor G., Chinnayya A., and Hadjadj A. (2013). Macro-mechanical modelling of blast wave mitigation in foams. Part I : Review of available experiments and models, *Shock Waves*, 23(1), 5-23.

[2] Del Prete E. (2012). Choc et onde de souffle dans les mousses aqueuses - Etude expérimentale et modélisation numérique. PhD Thesis. University of Rouen, France.

[3] Eau et Feu. http:\\www.eauetfeu.fr. April 2015 connexion.

[4] Lefrancois A., Chapelle S., Pauly S., Donadieu F., and Mespoulet J. (2008). Tremendous increase of the blast effect above HE plates characterised by small scale experiments, *MABS 20 Proceedings*, Oslo, Norway.

[5] United State of America Department of Defense (2008). Unified Facilities Criteria 3-340-02: Structures to resist the effects of accidental explosions.

[6] Hartman W., Boughton B., and Larsen M. (2006). Blast Mitigation Capabilities of Aqueous Foam. Technical Report SAND2006-0533, Sandia National Laboratories.

[7] Hopkinson B (1915). British Ordnance Board Minutes, 13565.

[8] Cranz C. (1926). Lehrbuch der Ballistik, *Springer-Verlag*.

[9] Gardiner B.S., Dlugogorski B.Z., Jameson G.J., and Chhabra R.P. (1998). Yield stress measurements of aqueous foams in the dry limit, *Journal of Rheology*, 42(6), 1437-1450.

[10] Larsen M. (1994). NEST containment calculator, Technical Report SAND94-2030, Sandia National Laboratories.