

CAPTURE OF PARTICLES DISPERSED BY DETONATION USING AN AQUEOUS FOAM CONFINEMENT

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ABSTRACT

Over the past decades, the need to mitigate detonation effects have significantly increased. To deal with these issues, the French Nuclear Energy Agency has studied aqueous foam confinement. This solution has two advantages. Firstly, the presence of this two-phase medium leads to drastically attenuate the blast wave generated by the detonation of an explosive device. Secondly, the presence of the liquid phase slows down and ultimately captures the micrometric and potentially harmful particles dispersed by the explosion. This specific topic will be discussed in this paper. Over the last year, we have conducted an experimental campaign which dealt with the potential of an aqueous foam confinement to capture micrometric particles. For this purpose, two configurations were tested: 88 g of micrometric tungsten powder for a 44 g explosive charge and 300 g of micrometric tungsten powder for a 150 g explosive charge. In the two cases, the tungsten powder has been dispersed in the air by the explosive charge. Two tungsten powder mean diameters were used, 1 and 4 μm , and confinements of various sizes were placed over the particles in order to quantify the ability of the foam to capture them. After the charge detonation, the airborne particles were sampled and both the concentration of this airborne aerosol and the particles size were monitored. The results obtained from the different configurations were compared in order to quantify the capture ratio depending on the size of the confinements, the particle size and the mass of explosive charge. They confirm the foam's efficiency in capturing particles. However, an observation of the particles velocity and dispersion reveals that this efficiency is not linearly dependent on the foam's length.

Keywords: capture, confinement, detonation, foam, particle.

1 INTRODUCTION

Aqueous foams have been known, since the 1970s, to be an effective way to mitigate explosion repercussions. Their ability to attenuate the effects of a blast wave has been widely studied over the past decades. Many shock tube and detonation experiments have been performed on these biphasic media [1], [2].

Another interesting aspect of foam is its propensity to slow down or capture solid fragments that could be propelled by a detonation. This characteristic offers a solution for two problems: projectiles and shrapnel generated by the detonating object or toxic particles released by an explosion.

Few studies have been conducted about the fragment decrease in speed brought on by aqueous foam. Le Goff studied the trajectory, the impact and the deceleration of a polypropylene sphere in several media [3]. Amongst them, she studied shaving foams and certain liquid film structures. The sphere, 5 mm in diameter, was propelled at 50 m/s into the foam. It was stopped by the foam after 20 milliseconds. De Krasinski [4] studied the decrease in velocity of a small caliber projectile propelled by a gas gun into a tube filled with shaving foam. The projectile was a 0.345 g sphere, 4.34 mm in diameter with initial velocities ranging from 30 to 150 m/s as well as for a 260 and 450 mm long foam tube. Recently, Breda, during her PhD thesis [5], conducted a rich experimental campaign to characterize the slowing down offered by aqueous foam on a spherical steel projectile of 6 mm in diameter. She explored expansion ratios between 20 and 66 for initial velocities around 1500 m/s.



We conducted ourselves a series of experiments with the same ranges of particles velocity and dimensions [6]. It appears that the particles velocity reduction increases with the square of the length of foam gone through.

We propose, in this paper, to study foam propensity to slow down or capture micrometric particles. More precisely, we will focus on metallic particles, 4 μm or 1 μm in diameter. This means that the particles we are interested in are much smaller than the bubbles constituting the foam. We can then understand that their behavior may be different from the objects mentioned above. Except works we did have yet done [7], no information or work have been found on the subject in the open literature.

In this article, the results from an experimental campaign are used in order to understand the behavior of a particle cloud dispersed through foam by a detonation. After quickly describing the aqueous foam used for that experiment, the behavior of a particle cloud propagating through the foam will be observed and discussed. Then, the dispersion of a particle cloud outside a foam confinement will be studied and analyzed. A conclusion will be made about the whole study and its perspectives.

2 THE DRY AQUEOUS FOAM

In this part, the complex nature of foam is presented. Composition and structure of the foam are described, in order to better understand this biphasic medium. Then, the generator used to produce foam is described. Its design and its technology ensure the production of a very stable foam.

Aqueous foam is classified as a biphasic medium because it is composed of two mixed phases. Dusty gases, droplet clouds or granular media are other examples of biphasic media. In the case of aqueous foam, the dispersed phase is the gaseous one and the continuous phase is the liquid one. They are classified in this way because the liquid is organized into films that form bubbles enclosing the gas.

Aqueous foams are mainly characterized by their expansion ratio F , defined as:

$$F = \frac{V_{\text{foam}}}{V_{\text{liquid}}} = \frac{1}{\alpha_{\text{liquid}}}, \quad (1)$$

where V is the volume of the subscript phase and α is its volume fraction.

Foams are considered to be dry if their expansion ratio is above 20 and wet if it is below. If the expansion ratio is lower than 3, the medium is not considered as foam anymore but as a bubbly liquid. In our case, we will only study dry aqueous foams with an expansion ratio of 60.

Chemically, the foam can exist and remain stable because of the presence of surfactant in the liquid phase. These long molecules, with a hydrophilic head and a hydrophobic tail lead to a drastic reduction of the surface tension and therefore enhance the resistance of the liquid films. A thickener agent is also added in order to limit the migration of the liquid through the films because of gravity.

3 ATTENUATION OF AEROSOL DISPERSION

The objective of this campaign is to quantify the dispersion of micrometric particles by a detonating charge confined with aqueous foam. The principle is to use an explosive charge to disperse metallic powder and to sample the ambient air after the charge detonation. By placing, or not, an aqueous foam confinement over the charge and the particles, we can compare the different results and assess to the efficiency of foam in capturing particles.



3.1 The experimental set-up

The experimental campaign, whose set-up is schematized in Fig. 1, is conducted in a closed vessel. A cylindrical explosive charge is centered on a metallic table. The explosive mass is changed from one experiment to another. This charge is used to disperse a mass of tungsten trioxide particles (WO_3), as big as the explosive mass, contained in a cardboard cartridge. The median diameter of the particles is 1 or 4 μm , with a standard deviation of 1.7. The particles and their dispersive charge are eventually covered by an aqueous foam confinement.

Six High Volume Sampler (HVS) are set around the table (Fig. 2), separated by 60° . Their role, once the charge has detonated and the particles have been dispersed, is to pump the air in the vessel through fiberglass filters in order to capture the aerosol in suspension. All of them have a pumping rate of $100 \text{ m}^3/\text{h}$ and ran during 90 minutes after the detonation occurred.

A nephelometer, device used to measure the aerosol concentration versus time, as well as an impactor, instrument used to analyze the concentration and the grain size of the aerosol (Fig. 2), have been implemented. The nephelometer has a flow rate set at $0.1 \text{ m}^3/\text{h}$ and a concentration measurement ranging from $0.1 \mu\text{g}/\text{m}^3$ to $400 \text{ mg}/\text{m}^3$.

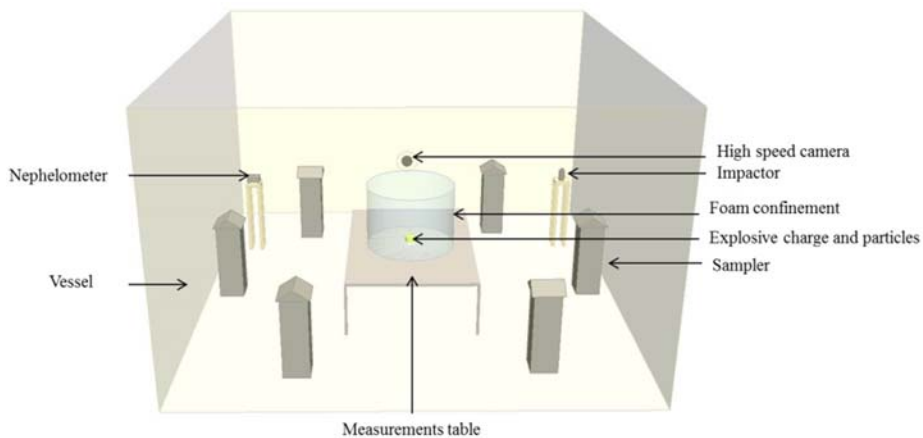


Figure 1: Set-up diagram.

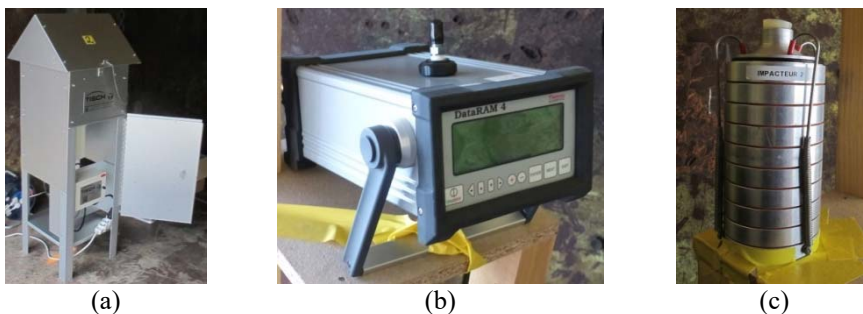


Figure 2: (a) High volume sampler; (b) Nephelometer; and (c) Impactor.

The impactor has a sampling rate of $1.7 \text{ m}^3/\text{h}$ and uses circular fiberglass, filters with a diameter of 81 mm. Each filter is placed on one of the impactor stages and the deposits on each stage correspond to a given particle size class. These classes are determined by a number and a diameter of orifices, at each stage, through which the air flow carrying the particles circulates. The deposit is then carried out by inertial impaction.

Three cylindrical confinement sizes were tested, and their characteristics are detailed in Table 1. A high-speed camera (HSC) captured the detonation of the charge and the dispersion of the particles.

Throughout this part, a code will be used to identify the experiments. This code consists of three character strings separated by dashes. The first chain designates the mass of the explosive charge used, the second correspond to the nature of the particles used and the third is related to the height of the confinement implemented. The letter S represents the absence of particles or confinement, depending on its position. P1 will be used for particles of $1 \text{ }\mu\text{m}$ and P2 for those of $4 \text{ }\mu\text{m}$. Thus, the test 44-P1-150 will designate a test carried out with an explosive charge of 44 g, with particles of $1 \text{ }\mu\text{m}$ in average diameter and with a confinement height of 150 cm. The experiments which have been performed are listed in Table 2.

3.2 The experimental results

In this part, we will introduce and analyze the different results obtained during this campaign. At first, we will analyze pictures acquired by HSC. Then, we will examine results coming from the weighing and analysis of filters, as well as from the samplers. We will discuss then the results of measures coming from the impactor. In last time, we will couple the different sources of results to deduct from it the effectiveness of the aqueous foam in the capture of micrometric particles.

Table 1: Size of the confinements.

| Confinement size | Radius (cm) | Height (cm) |
|------------------|-------------|-------------|
| Small | 50 | 100 |
| Medium | 50 | 150 |
| High | 100 | 150 |

Table 2: Experiments.

| No. | Explosive (g) | Particles (g) | Confinement (cm) | Particles diameter (μm) |
|-----|---------------|---------------|------------------|--------------------------------------|
| 1 | 44 | Without | Without | Without |
| 2 | 44 | 88 | Without | 1 |
| 3 | 44 | 88 | r=50 h=100 | 1 |
| 4 | 44 | 88 | r=50 h=150 | 1 |
| 5 | 44 | 88 | Without | 4 |
| 6 | 44 | Without | r=50 h=150 | Without |
| 7 | 44 | 88 | r=50 h=150 | 4 |
| 8 | 150 | Without | Without | Without |
| 9 | 150 | 300 | Without | 4 |
| 10 | 150 | 300 | r=100 h=150 | 4 |



3.2.1 Images description

The analysis of the videos acquired during the trials will be made using a frame of 12 images representative of the phenomenon observed. The reading direction is from left to right and from top to bottom.

The 44-S-S experiment (Fig. 3) shows the unfolding of the detonation of a 44 g V401 explosive charge in the air. We notice a propagation of the detonation products in two privileged directions, axially and radially.

Thus, particles loading on the V401 cylinder will benefit from the energy and axial acceleration of the detonation products to disperse in the chamber.

The presence of particles for an air experiment (44-P1-S), as shown in Fig. 3, changes the shape of the blast wave and the expansion of the detonation products that follow it. The blast wave is flattened axially, and the particles slow down the dispersion of the detonation products, which are confined by them. The expansion of detonation products, accompanied by particles, forms a central dome surrounded by a crown of dendrites. The particles thus advance the fireball but are synchronous with the blast wave. As previously assumed, their expansion is mainly vertically. However, it will be necessary to ensure, thereafter, that this expansion allows a homogeneous dispersion in the vessel. It is also assumed that particles close to the explosive charge agglomerate to form particles of larger diameter.

Fig. 3 shows also the images of the first 57 milliseconds, after detonation, of the 44-P1-100 experiment. The particles emerge from the free surface of the foam into dendrites, all directed upwards. They are covered with foam, which supposes that out of the confinement, they tear and take with them packages of foam integrity. The dispersion of particles and detonation products here seems already much weaker than that in the air. Their flight speed, in the air, seems weaker than before.

In the same figure, the course of the similar experiment to the previous ones with a confinement of 150 cm in height is depicted. The first observation is that the phenomenon here is even slower than before. Indeed, one puts 66 ms against 57 ms, to obtain a state roughly similar. This is simply explained by the greater length of foam to cross. The same dendrites are observable, although in less quantity. Except from the behavior of the different



Figure 3: Left to right, HSC images of the 44-S-S, 44-P1-S, 44-P1-100, 44-P1-150 experiments.

structures already studied previously and which does not differ here, we can note two points for the experiments done with 4 μm diameter particles.

They disperse much faster than those of 1 μm in air. We also note that the confinement seems to be more efficient for particles of 4 microns. For the explosive charge of 150 g experiments, the foam also seems to significantly reduce the dispersion of the particles.

3.2.2 Estimated speed of flight

From visualization of video recordings, the speed of flight of the particles is estimated, whether in the air or on the free surface of the foam. This speed is calculated by averaging the speed calculation over a distance of 30 cm from the appearance of the upper particle front to its exit from the optical field. It should be noted that this speed is taken as constant. The set of flight rate measurements are detailed in Fig. 4. The speed of these is plotted as a function of a homogeneous quantity at a linear density μ_m , which is defined by the following relation:

$$\mu_m = \sqrt{\frac{h \cdot \rho_l \cdot m}{F}}, \quad (2)$$

where h is the height of the confinement, ρ_l the density of the emulsifier, m the mass of the explosive charge and F the expansion ratio. This quantity transcribes well the axial trajectory of the particles as well as the fact that they pass through a quantity of liquid with an initial energy depending on the mass of explosive used.

For tests carried out in air, particles of 4 μm have a upper velocity than 1 μm . The larger particles have a greater contact area with the airflow and therefore are better accelerated by the moving gases. Now, if we compare the two trials including 4 microns particles in average diameter, we note that the speed is higher for 88 g of particles. This could be due to a greater confinement of the charge and its detonation, inducing a greater radial expansion due to the mass of the particles. Axial axis is less privileged and speeds are lower. Whatever the configuration, the presence of foam drastically decreases the speed of the particles.

Regarding the test with particles of 1 micron diameter, one realizes that this slowdown depends directly on the quantity of water crossed. Although the confinement seems to be more efficient on the particles of 4 μm in diameter, we obtain a confinement exit velocity close enough for two loadings which, in the air, had 200 m/s difference. Still with particles

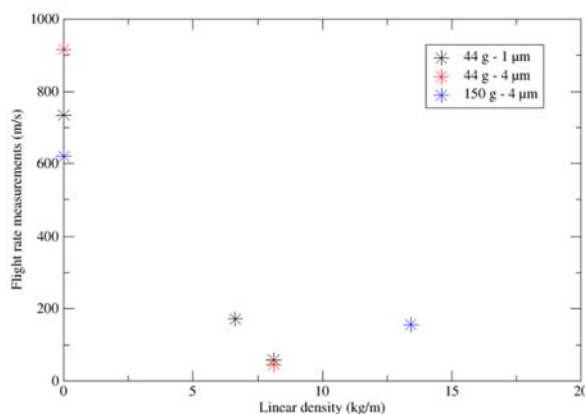


Figure 4: Flight rate measurements of WO_3 .

of 4 microns in average diameter, but this time with a load of 150 g, we have no concordance nor can we highlight a scale effect. Nevertheless, the same conclusions are observed and one reaches, for all the studied tests, a rate of slowing going from 92–95%.

3.2.3 Filters analysis

As explained above, the ambient aerosol was taken 90 minutes, after the detonation. This sampling was carried out by samplers who saved, every minute during their operation, data on the sampling rate and the local environment. These data will then be used to analyze the results. Each filter, whatever it is, is weighed before the test, put under transparency and weighed again after the test, taking care to let it dry for 4 hours. It is then returned under transparency. Thanks to the different tests carried out, we can go back to the source term and thus deduce the quantity of tungsten trioxide by weighing. All the filters resulting from the tests were then analyzed by Inductively Coupled Plasma Mass Spectroscopy (ICP-MS). It is a method for quantifying the mass of metal particles given in a sample. The results from the filters of the samplers allow us to go back to the mass of WO_3 collected by them and those from the impactor, information on the size of these particles. The different results are presented below.

Fig. 5 shows the histogram of the total mass collected on the filters for each trial. P1 and P2 respectively denote particles of 1 and 4 microns in average diameter. The light grey shades concern the trials made without particles, and the dark grey shades with particles. Similarly, the gray bars correspond to trials made without containment and blue with containment. For trials carried out without confinement, masses ranging from 3–23 g of aerosol composed of WO_3 particles and detonation products are collected.

It should be noted that all the filters, during these experiments, have been clogged. A certain amount of the aerosol has therefore not been filtered and collected and is not represented here. Nevertheless, the collection performed here is fairly representative of the scattered mass to draw certain conclusions. Firstly, by comparing the tests with and without particles of WO_3 without confinement, whatever the explosive charge used, we obtain a percentage of detonation products between 20 and 30% compared to the particles of. We also note that we collect 32% in addition to particles P2 than P1. This can be explained by the fact that the P2 particles having a larger particle size, the clogging effect is slower. In general, confinement is as effective on the detonation products as on the particles of WO_3 . In fact, an

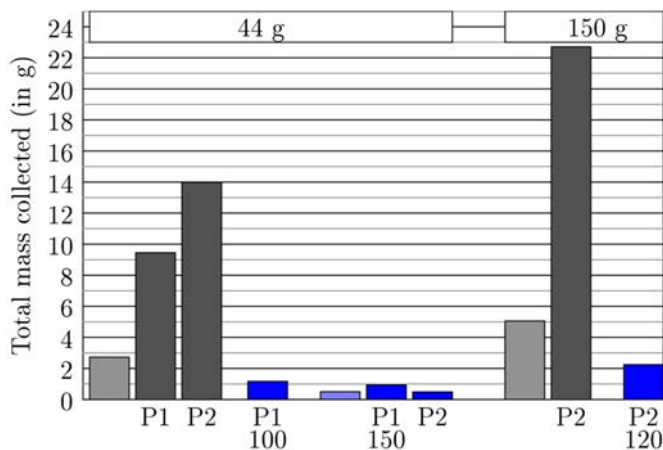


Figure 5: Total mass collected measures by weighing.

efficiency of 83% is obtained for detonation products alone, 90% when P1 is added and 96.5% when P2 is added, for tests carried out with an explosive charge of 44 g. and 89% for an explosive charge of 150 g.

By performing the mass difference obtained for a trial with and without particles, in the same configuration, the mass collected is determined.

The sampling filters have also undergone chemical analysis by ICP-MS, allowing the exact quantification of the particles from which they are collected. Standard filters, sent for the same quantifications allowed us to establish the error related to this method of quantification, which is of the order of 1.7%.

A comparison between the two methods was made on all the filters and allowed us to update the uncertainty related to the weighing method which is 18.9%. Therefore, the analysis of the results will be entered on the data resulting from the ICP-MS analysis.

Fig. 6 shows the histogram of the mass of collected particles given by the ICP-MS analysis. Bulks ranging from 7–12 g are collected, without confinement, on a dispersed mass initially of 88 and 300 g. We find the same trends already highlighted from Fig. 5. P2 particles are well collected in greater numbers. On the other hand, they are better captured by containment.

In general, confinement is extremely effective in capturing particles, regardless of its volume. By increasing this, the amount of dispersed and collected particles on the filters is reduced, thereby increasing the number of particles retained by the foam. By doubling the mass of the charge/particle pair, a scale effect in capture by particle confinement is not trivial here. Indeed, without confinement, clogging filters does not allow us, at this stage, to know the amount dispersed and therefore theoretically collectable, and to go back to a ratio between the two tests. With confinement, when tested with an explosive charge of 150 g, a technical problem did not allow us to have a confinement of 1.5 m high. Tests 44-P2-150 and 150-P2-120 are therefore not directly comparable. It is interesting to watch the dispersion of detonation products. Comparing the results of Figs 5 and 6, it is noted that these represent only between 20 and 30% of the aerosol for the tests without confinement, 20% corresponding to the particles P1 and 30% to the P2. With confinement, this percentage reaches values of more than 70%. This assumes that the percentage of detonation products collected depends not only on the placement of a containment or not, but also on the particle size used.

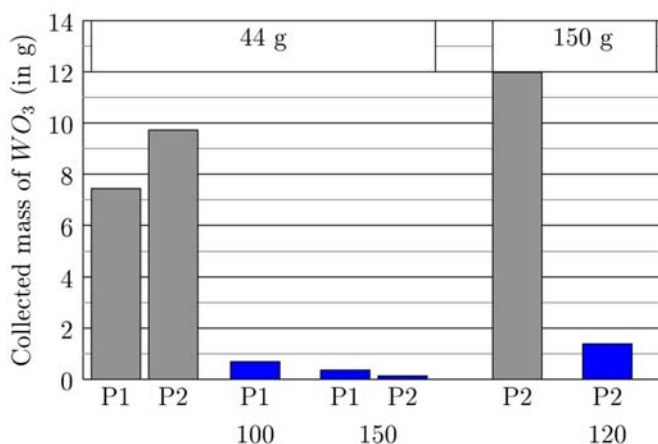


Figure 6: Particles collected mass measures by ICP-MS.

Fig. 7 gives us the histogram of the effectiveness of the aqueous containment used. It is given by the following formula:

$$\eta_c = 1 - \frac{\text{collected mass}_{\text{with confinement}}}{\text{collected mass}_{\text{without confinement}}} \quad (3)$$

Whatever the confinement used, the quantity of particles, or the mass of filler used for the dispersion, the dispersion of the particles is drastically reduced by this one.

Thus, for a charge of 44 g, more than 90% of the particles are captured for average confinement and P1 particles, more than 95% for the same particles with a large confinement and more than 98% for P2 particles and a large confinement. With a dispersion generated by a load of 150 g, more than 88% of the particles are captured. We find the fact that at identical confinement P2 particles are better captured than P1. It is crucial to keep in mind that the data here are derived from collected mass data and not from scattered masses. The biggest error being made on the tests without confinement, where the filters were plugged, it can be supposed that the values given here are values lowering the real efficiency of the confinement, in terms of particle dispersion.

The particle collection being very reduced on the different stages of the impactor, only the results obtained by ICP-MS analysis will be presented.

It is important, in order to have a good analysis of the granulometric data after the tests, to analyze them before these. Fig. 8 therefore shows the particle size distribution of the two batches of particles used. We will use the particle size classes of the impactor, which are listed in Table 3. The particle size distribution of particles of 4 microns in average diameter is faithful to this one. Smaller particles are present, but in smaller quantities. Regarding the particles of 1 micron average diameter, we are left with a lot with almost as many particles as 6 microns than 1 micron particles or less.

The spread of particle size of 1 μm should be taken into account for the study of the particle size after the experiments.

The analysis of particle size after the test is carried out separately according to the median diameter thereof and the mass of the explosive charge. The graph, Fig. 9, presents the results of the tests carried out with an explosive charge of 44 g and particles of 1 μm in average diameter.

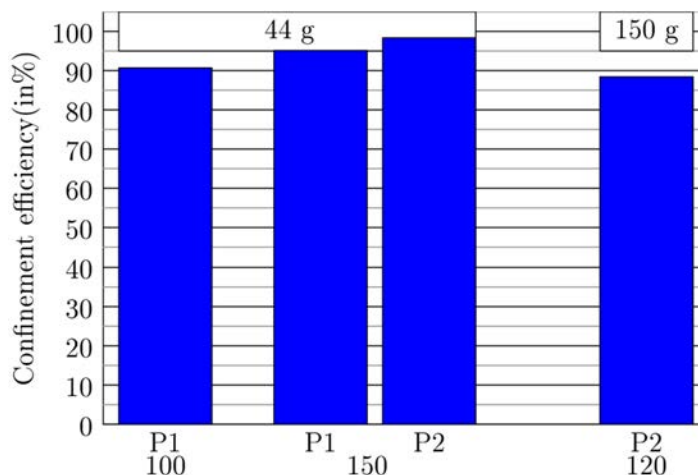


Figure 7: Confinement efficiency.

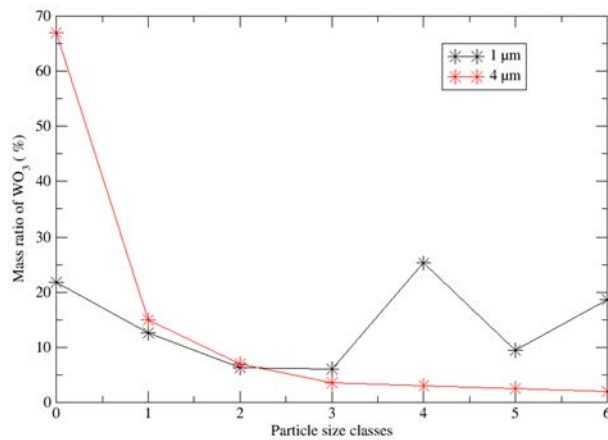


Figure 8: Particle size of WO₃ repartition before experiments.

Table 3: Particle size classes.

| Classes | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---------------|----------|----------|----------|------------|------------|------------|------------|
| Diameter (μm) | [6, 3.9] | [3.9, 3] | [3, 2.2] | [2.2, 1.4] | [1.4, 0.7] | [0.7, 0.5] | [0.5, 0.1] |

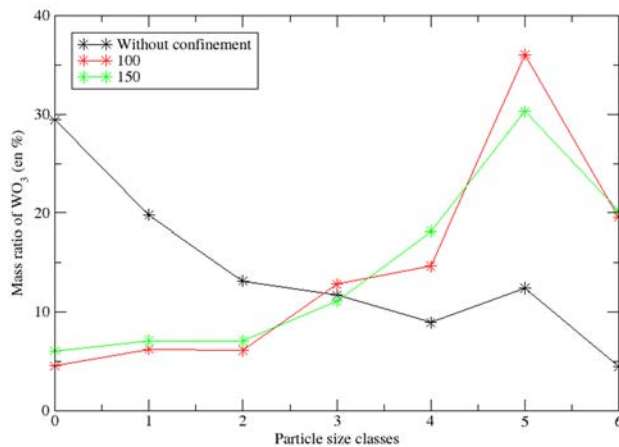


Figure 9: Particle size repartition for 44 g explosive charge experiments.

First, for the non-containment test, there is a general increase in particle size, relative to the particles before testing. This is due to the phenomenon of agglomeration of the particles being close to the fireball, under the effect of the increase of the temperature. Containment, as seen with the red and green curves, has a higher capture power for large particles than for smaller ones. In fact, we find ourselves, in the two cases that interest us, with a tightening of the grain size curve around the median diameters of 0.7 and 0.5 μm. The particles whose

diameter is between 6 and 3.9 microns are captured in their quasi-totality. Concerning particles of 4 μm , same conclusions are observed.

4 CONCLUSION

In accordance with our expectations, aqueous foam globally slows down and captures micrometric solid particles.

The campaign confirms the foam's efficiency in capturing particles. Even for small quantities of foam, the capture ratio is far more than 90%. By increasing foam quantities, more than 95% of the normally dispersed particles were captured. The best capacity of the foam to capture small particle size was also demonstrated.

More experiments of this nature will be needed in order to better understand and precisely quantify the influence and the ability of the foam to capture micrometric particles.

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