

Detonation Characteristics of Emulsion Explosives Sensitized by Hydrogen-Storage Glass Microballoons

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Abstract: In order to improve the detonation performances of emulsion explosives, a new type of emulsion explosives sensitized by hydrogen-storage glass microballoons is proposed. The influences of hydrogen in glass microballoons on explosion characteristics of emulsion explosives were studied. Brisance testing and underwater explosion experiments showed that, compared with traditional emulsion explosives, the shock impulse and specific total energy of hy-

drogen-storage glass microballoons sensitized emulsion explosives are improved significantly. The brisance (compression of lead block) of hydrogen-storage emulsion explosives is 23.0 mm, 3.2 mm more than that of traditional emulsion explosives. Therefore, the hydrogen-storage glass microballoons could be a promising energetic additive for developing high-power emulsion explosives.

Keywords: Emulsion explosives • Underwater explosion • Glass microballoons • Explosion energy

1 Introduction

Emulsion explosive is a kind of anti-water industrial explosive which developed in 1969 by Bluhm [1]. Because of its excellent explosion performance, water resistance, wide material source, simple production process, good security, low cost, no TNT, small pollution and low concentration of blasting guns, emulsion explosives are widely used in engineering blasting [2,3]. Emulsion explosives consist of emulsion matrix which is of no detonation sensitivity, and sensitizer which is added to emulsion matrix to convert it into an emulsion explosive by a physical or chemical method [4]. The emulsion matrix is a kind of water-in-oil (W/O) structure of explosives, which consists of ammonium nitrate, water, sodium nitrate and mineral oil. Glass microballoons (GMs) are the most common physical sensitizer used in emulsion explosives. The effect of GMs is to introduce uniformly distributed bubbles in the emulsion matrix. When shock wave propagates into the emulsion explosives, hot spots are created as the shock wave compresses air bubbles and the reaction initiates in the explosive around the hot spots and accelerated to detonation [5–8].

Although the work capability of traditional emulsion explosives is pretty well and their brisance even exceeds that of TNT, we find through underwater explosion experiments that the peak pressure, impulse, shock wave energy and other parameters of traditional emulsion explosives are relatively lower [9], which illustrates that the traditional emulsion explosives ensure a weak energy output and need to be improved.

Hydrogen has a high energy density, which is three times that of liquid hydrocarbon raw materials, and it can increase the explosion power of explosives if added into ex-

plosives [10]. GMs can be used as hydrogen storage container in industry and the diameter of which ranges from 15 μm to 135 μm . GMs are non-permeable at room temperature or lower, but have good permeability from 570 K to 670 K so that hydrogen can penetrate into the GMs under pressures of several megapascals [11,12]. Hydrogen will be stored in the GMs when lower the temperature and will be released when increase the temperature [13]. The mass fraction of hydrogen stored can theoretically reach 15 % to 25 % [14].

In this study, hydrogen-storage GMs were put into the traditional emulsion explosives in order to improve the detonation characteristics of them. The detonation characteristics of emulsion explosives sensitized by hydrogen-storage GMs were studied through underwater explosions.

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2 Experimental Section

2.1 Explosives Preparation

There were two kinds of GMs used in this experiment, which were purchased from Minnesota Mining and Manufacturing Company (St. Paul, MN, USA) and Bengbu Glass Industry Design & Research Institute (Bengbu, Anhui, China), respectively. The average particle size of the former (defined as GM-A) was 55 μm , the effective density is 0.25 g/cm^3 and the compressive strength is 5.2 MPa. For the later (defined as GM-B), The effective density is also 0.25 g/cm^3 but it has a higher compressive strength which is 10 MPa.

Some raw GMs would be broken due to the hollow internal structure, which can be seen in Figure 1. The purification of the GMs could be achieved by density separation method, i.e., alcohol was used to separated broken GMs and complete GMs. The former would sink to the bottom, while the later would float on the alcohol surface. Then take out the complete GMs and dry using a drying cabinet. We finally got the complete GMs which could be used in the following experiments.

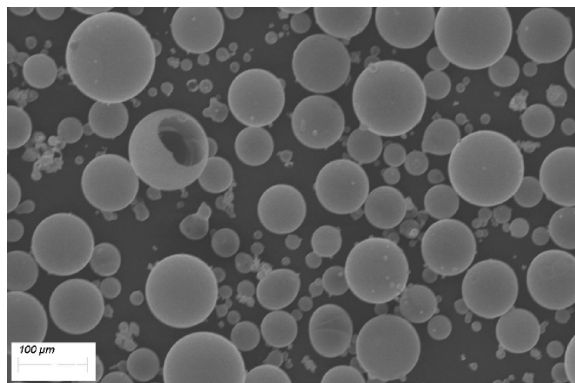


Figure 1. SEM image of glass microballoons.

Subsequently, the GMs were filled with hydrogen. Because gas permeability in glass is significantly affected by temperature, a reaction kettle which can provide high temperature and pressure conditions was used (Figure 2). It was purchased from Anhui Kemi Machinery Technology Co., Ltd. (Hefei, Anhui, China). The higher the temperature, the higher the gas permeability in glass. So heating GMs to allow high pressure hydrogen to penetrate into them and hydrogen would not come out when GMs reached room temper-



Figure 2. Reaction kettle.

ature. This was a simple and effective way to store hydrogen. Hydrogen was stored into GMs in the reaction kettle at a temperature of 300 $^{\circ}\text{C}$ and pressure of 5.0 MPa for about 3 hours.

As reported by Cheng [10], the emulsion explosives energy is the maximum when the mass ratio of GMs and emulsion matrix is 4:100. So emulsion matrix and GMs were mixed in a mass ratio of 100:4. Finally we got four kinds of emulsion explosives. The composition of the emulsion matrix is tabulated in Table 1. The density of the emulsion matrix was 1.31 g/cm^3 and it was purchased from Huainan Shun Tai Chemical Co., Ltd. (Huainan, Anhui, China). Four kinds of emulsion explosives were listed in Table 2.

Table 2. Four kinds of emulsion explosives.

Sample	GM type	initial pressure of the reaction kettle
EE-A	GM-A	No hydrogen
HEE-A	GM-A	5 MPa
EE-B	GM-B	No hydrogen
HEE-B	GM-B	5 MPa

Table 1. Composition of emulsion matrix.

Component	ammonium nitrate	sodium nitrate	wax	mineral oil	span-80	water
Formula	NH_4NO_3	NaNO_3	$\text{C}_{18}\text{H}_{38}$	$\text{C}_{12}\text{H}_{26}$	$\text{C}_{24}\text{H}_{44}\text{O}_6$	H_2O
Mass ratio (%)	75	10	4	1	2	8

2.2 Underwater Explosion Experiment System

Because water has lower wave impedance than air, the underwater explosion was designed to obtain better signal of shock wave. Experiments were conducted in a steel water tank with 4.9 m in diameter (D) and 5 m in depth (H). The charge placed in the center of tank in order to reduce wall boundary effect on the signal of shock wave. Explosion signal was detected by a PCB-W ICP138A25 type pressure sensor and a 482A22 constant current source (PCB Piezotronics, Inc. USA). Meanwhile, the data was collected and stored by a Tektronix 4104 digital oscilloscope (Tektronix, Inc. USA). Charge and sensor position (h) were both 3 m deep below water surface, and the test distance (d) from charge center to sensor center was 1.0 m and 1.2 m, as shown in Figure 3.

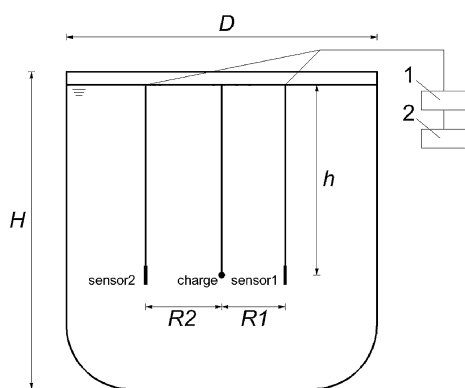


Figure 3. Scheme of the underwater explosion experiment system (1 – signal conditioner, 2 – digital oscilloscope).

3 Results and Discussion

3.1 Brisance Testing Experiments

Brisance is a key issue of interest for emulsion explosives and is represented by compression value of lead columns. In these experiments, a Q235 steel column is used between emulsion explosives and lead column in order to compress lead column. Diameters of the lead and steel columns are 40 mm and 41 mm respectively, and height were 60 mm and 10 mm respectively. Emulsion explosives used in the experiments was 50 g in each case.

Figure 4 shows the lead column and steel column from the experiment of four kinds of sample. From left to right, they are uncompressed lead column, lead from sample EE-A (emulsion explosive with GMs-A), sample HEE-A (hydrogen-stored emulsion explosive with GMs-A), sample EE-B (emulsion explosive with GMs-B) and sample HEE-B (hydrogen-stored emulsion explosive with GMs-B) respectively. The compression values of lead columns h_b were list in Table 3. Sample HEE-B not only has the biggest compression value of lead column, but also destroys steel column and lead column, which means the brisance of sample HEE-B is big enough to exceed the compression limit of lead column. Brisance of the sample HEE-A also was increased related to sample EE-A.

Brisance of emulsion explosives was improved by replacing GMs with hydrogen-storage GMs, which means hydrogen can provide energy for explosive explosions.

3.2 Detonation Velocity

Detonation velocity is a widely recognized parameter of characterizing explosives and is important in analyzing results of underwater explosion experiments.

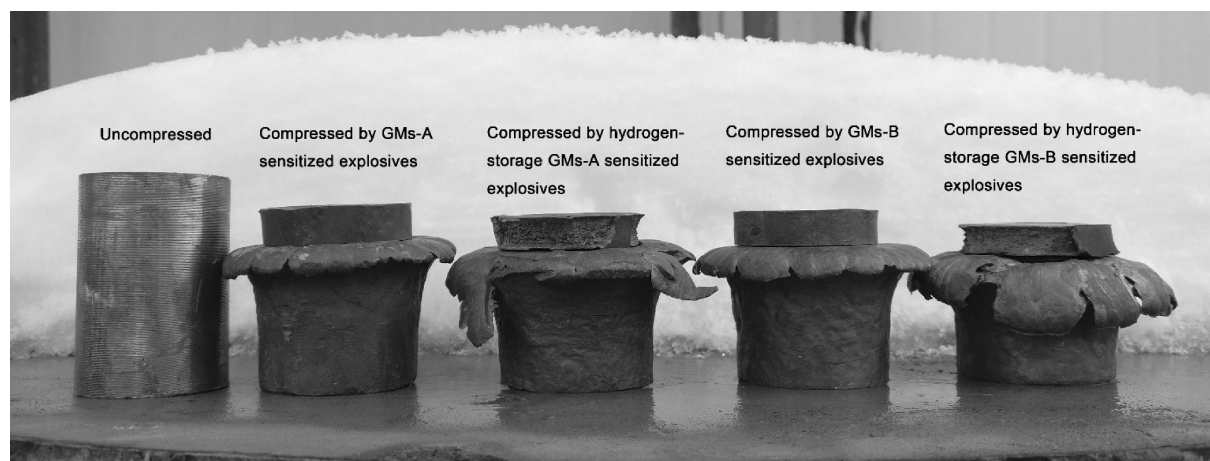
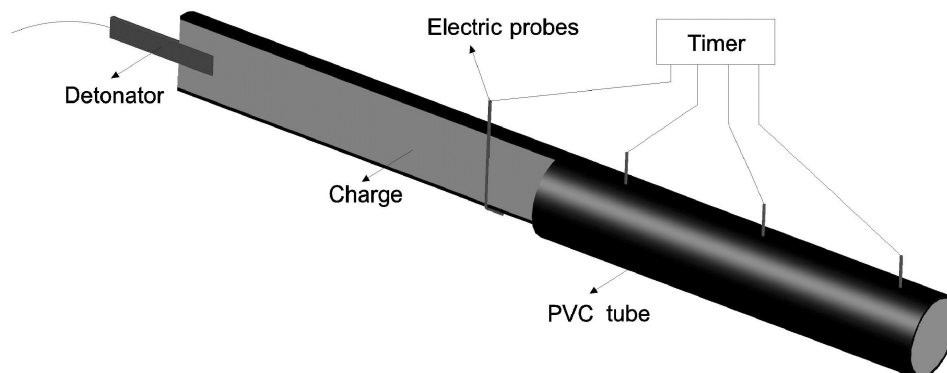


Figure 4. Brisance of different emulsion characterized by compression of a lead column.

Table 3. Data of experiments of four samples.

sample	h_b/cm	$V_w/(\text{m/s})$	R/m	P_m/MPa	$I/(\text{Pa}\cdot\text{s})$	$E_s/(\text{MJ/kg})$	$E_b/(\text{MJ/kg})$	$E_v/(\text{MJ/kg})$
EE-A	18.9 ± 0.7	4840 ± 9.8	1.0	11.621 ± 0.330	554.08 ± 5.41	0.691 ± 0.025	1.915 ± 0.029	3.030 ± 0.073
			1.2	8.360 ± 0.111	380.74 ± 17.85	0.478 ± 0.016	1.910 ± 0.029	2.682 ± 0.058
HEE-A	20.6 ± 0.8	4950 ± 10.2	1.0	12.699 ± 0.749	553.17 ± 20.64	0.742 ± 0.031	1.979 ± 0.028	3.200 ± 0.084
			1.2	8.908 ± 0.223	390.24 ± 21.45	0.529 ± 0.010	1.982 ± 0.032	2.853 ± 0.051
EE-B	19.8 ± 0.3	4784 ± 9.7	1.0	10.054 ± 0.614	482.75 ± 6.01	0.497 ± 0.029	1.844 ± 0.035	2.647 ± 0.086
			1.2	8.252 ± 0.445	426.28 ± 18.88	0.383 ± 0.002	1.905 ± 0.013	2.524 ± 0.019
HEE-B	23.0 ± 0.4	5036 ± 10.7	1.0	10.013 ± 0.156	526.79 ± 11.99	0.531 ± 0.025	1.867 ± 0.018	2.741 ± 0.062
			1.2	8.052 ± 0.255	453.89 ± 7.12	0.397 ± 0.006	1.973 ± 0.023	2.625 ± 0.035

**Figure 5.** A PVC pipe filled with emulsion explosives for measuring detonation velocity.

The detonation velocity of emulsion explosives was measured by discrete points electric method (Figure 5) [15]. The emulsion explosives filled into the PVC pipe. One end of the electric probe was inserted into the charges, and the other end was connected to a high-resolution electric timer to record time gap (Δt) between adjacent probes. The distant between each two adjacent probes was close to 40 mm (L) measured before detonation. There were four probes in total. Δt was divided by L to obtain detonation velocity. The average detonation velocities are shown in Table 3.

It can be seen that detonation velocity of the hydrogen-storage GMs sensitized explosives is significantly higher than that of conventional GMs sensitized explosives. According to Chapman-Jouguet (C–J) theory, prediction of chemical energy released during detonation reaction can be formulated as Equation (1) [16]:

$$D_v^2 = 2(\gamma^2 - 1)Q \quad (1)$$

where D_v is detonation velocity (m/s), γ is heat capacity ratio of gas product, and Q is energy released during detonation (J/kg). Because hydrogen provided energy for detonation to improved Q , D_v increased accordingly.

3.3 Peak Overpressure

The detonation parameters and their standard deviations from underwater explosion experiments are all presented in Table 3. Peak overpressure (P_m in MPa) could be read directly from pressure history curve (P – t , t is the time), which represents the strength of shock wave and is related to energy of the explosive.

Comparison of P_m of different sample is shown in Figure 6. The peak overpressure of HEE-A was significantly higher than that of EE-A and increased about 7.9%, whereas that of HEE-B did not increase compared to EE-B, with a slightly decrease even at 1.2 m. The reason of this phenomenon will be discuss in the next section.

3.4 Shock Impulse

The shock impulse I of the explosives in underwater explosion is the integral of the shock wave pressure with respect to time and is calculated from Equation (2) [17]:

$$I = \int_0^{6.7\theta} p(t)dt \quad (2)$$

Here $p(t)$ is the shock wave pressure (Pa), and θ is the shock wave attenuation time (s), which is the time for shock

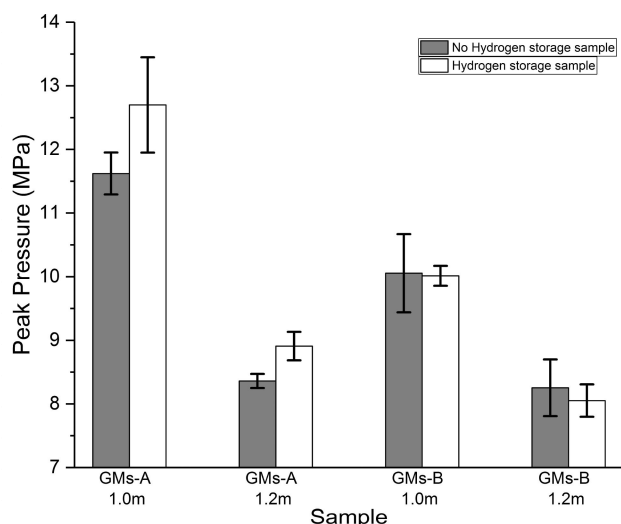


Figure 6. The peak overpressure of emulsion explosives sensitized by different GMs at different distances.

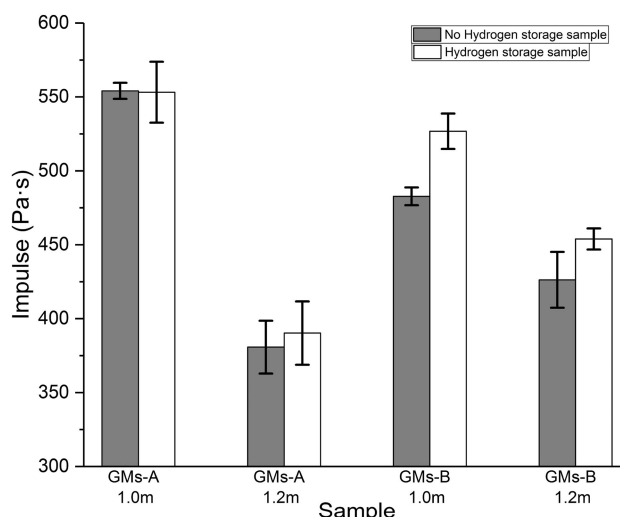


Figure 7. The shock impulse of emulsion explosives sensitized by different GMs at different distances.

wave pressure to decrease from P_m to P_m/e and e is the mathematical constant.

Different from the peak overpressure, no obvious can be observed. While GMs-B sensitized emulsion explosives had obvious improvement in impulse which was 9.1% at 1.0 m and 6.5% at 1.2 m.

The reasons can be listed as follows. First, the main reason may be that the strength of the two GMs is different. For the GMs-A which are lower-strength, we could hear cracking sound after taking out the hydrogen-storage GMs from reactor, which means there was hydrogen breaking the GMs out. So we can figure that some GMs would burst and hydrogen would release into emulsion matrix to form bubbles from the time of mixing into the emulsion matrix until detonation. These hydrogen bubbles would react first as hot spots in emulsion explosives before react of matrix. Because hydrogen is an energetic gas, combustion of hydrogen would release energy to improve peak overpressure. While for the GMs-B which are higher-strength, they would not be broken until shock wave or detonation wave passed through them in emulsion explosive. It took time to break GMs before the hydrogen inside GMs was burned which resulted in the energy of hydrogen combustion used to slow down the attenuation of shock wave, so the impulse of shock wave would be enhanced rather than the peak overpressure.

3.5 Specific Shock Energy

Specific shock energy (E_s in MJ/kg) is one part of the explosion energy and calculated from Equation (3) [18]:

$$E_s = \frac{4\pi R^2}{W\rho_w C_w} \int_0^{6.7\theta} p^2(t) dt \quad (3)$$

Here R is the distance from sensor to charge (m), W is the mass of charge (kg), ρ_w is the density of water (kg/m^3), and C_w is the wave speed of water (m/s).

Figure 8 illustrates that the two GMs sensitized emulsion explosives were all improved in specific shock energy with hydrogen addition. Specific shock energy of emulsion explosives sensitized by GMs-A increased 7.3% at 1.0 m and 10.6% at 1.2 m respectively, and those of GMs-B increased 7.0% at 1.0 m and 3.6% at 1.2 m respectively. It is corresponding to our expectation that the energy of the shock wave is increased as a result of storing hydrogen in GMs.

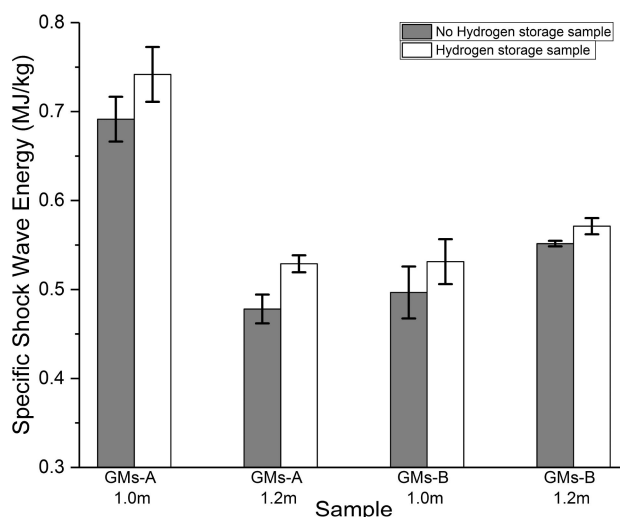


Figure 8. The specific shock energy of emulsion explosives sensitized by different GMs at different distances.

3.6 Specific Bubble Energy

Bubble energy reflects the pulsation characteristics of explosion gas product and is other part of the explosion energy. Because the underwater experiment was carried out in a tank, specific bubble energy (E_b in MJ/kg) cannot be calculated from Willis formula directly. An improved Equation [19], which considers the effects of surface and bottom, is used to calculate specific bubble energy:

$$E_b = \frac{1}{8WC^3K_1^3} (\sqrt{1 + 4Ct_b} - 1)^3 \quad (4)$$

where C and K_1 are experimental constants which calculated from Equation (5) and Equation (6) respectively, t_b is the first bubble period (s)

$$C = b/a^2 \quad (5)$$

$$K_1 = 1.135\rho_w^{1/2}P_h^{5/6} \quad (6)$$

where a and b are constants fitted from Equation (7), which describes the relation of bubble period with charge weight, and P_h is the total hydrostatic pressure at charge depth (Pa).

$$t_b = aW^{1/3} + bW^{2/3} \quad (7)$$

Constants a and b have been determined experimentally in previous research, where $a = 0.28489$ and $b = -0.07463$, resulting in $C = -0.9195 \text{ s}^{-1}$ [20].

A similar trend of specific shock energy was achieved that the two GMs sensitized emulsion explosives were all improved in the specific bubble energy after storing hydrogen. The specific bubble energy of emulsion explosives sensitized by GMs-A increased 3.3% at 1.0 m and 3.7% at 1.2 m respectively, and those of GMs-B increased 1.3% at 1.0 m and 3.6% at 1.2 m respectively.

3.7 Specific Total Energy

Specific total energy (E_t in MJ/kg) is combination of the specific shock energy and specific bubble energy. It can be obtained by the following Equation [19]:

$$E_t = K_s(\mu E_s + E_b) \quad (8)$$

Here K_s is shape parameter of explosive, which equals to 1.00 for spherical explosives and 0.02–1.10 for nonspherical charges. In our experiments, we made the emulsion explosives spherical so K_s equals to 1.00. μ is attenuation coefficient of shock wave. Because energy dissipation due to non-isentropic propagation process is diverse in different ambient mediums, we replaced the specific shock energy with initial specific shock energy which is the product of

shock loss factor (μ) and specific shock energy at test point. μ is calculated from Equation (9):

$$\mu = 1 + 1.3328 \times 10^{-1} p_{C-J} - 6.5775 \times 10^{-3} p_{C-J}^2 + 1.2594 \times 10^{-4} p_{C-J}^3 \quad (9)$$

where p_{C-J} is the value of detonation pressure (GPa).

Detonation pressure of high explosive is usually at the magnitude of 10 GPa, in addition, the magnitude of detonation wave duration is 0.1 μs and the temperature is as high as thousands of degrees. Such extreme conditions make it difficult to conduct an accurate detonation pressure measurement, hence, Equation (10) is employed for an approximate prediction:

$$p_{C-J} = 1/(1+\gamma)\rho D_v^2 \quad (10)$$

where ρ is density of the charge (kg/m^3). Heat capacity ratio γ is reckoned to be a constant of 3 for detonation pressure calculation, unit of p_{C-J} is Pa. The specific total energy E_t we calculated is listed in Table 3.

The specific total energy of emulsion explosives was increased 5.61%, 6.38, 3.57% and 3.99% for the two types emulsion explosives sensitized by different GMs at different distances. In other words, emulsion explosives sensitized by hydrogen-storage GMs can release more energy than that sensitized by conventional GMs.

3.8 Experiments of Storing Helium in GMs

In order to explore the mechanism of improvement of detonation characteristics of emulsion explosives sensitized by hydrogen-storage GMs, the experiments of storing helium in GMs were carried out. We chose helium to compare with hydrogen, because helium has similar physical properties with hydrogen and helium will not burn to release energy.

The underwater explosion of emulsion explosives sensitized by helium-storage GMs and conventional GMs was accomplished. Because the properties of emulsion matrix would change over time, we also did the experiments of conventional emulsion explosives for comparison at the same time. The experimental parameters of helium were the same as those of hydrogen. The pressure was 5 MPa before heating and the time for maintaining 300 °C was 3 hours. The peak pressure, impulse, specific shock wave energy, specific bubble energy and specific total energy were showed in Figure 11.

As shown in Figure 11, the peak pressure, impulse and specific shock wave energy were not increased after storing helium while specific bubble energy and specific total energy had risen a little, about 6.2% and 4.2% respectively. The improvement of specific total energy is due to the improvement of specific bubble energy. Why did specific bub-

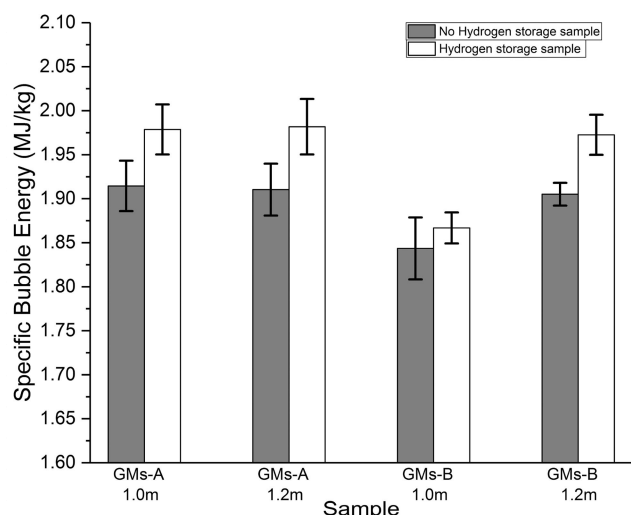


Figure 9. The specific bubble energy of emulsion explosives sensitized by different GMs at different distances.

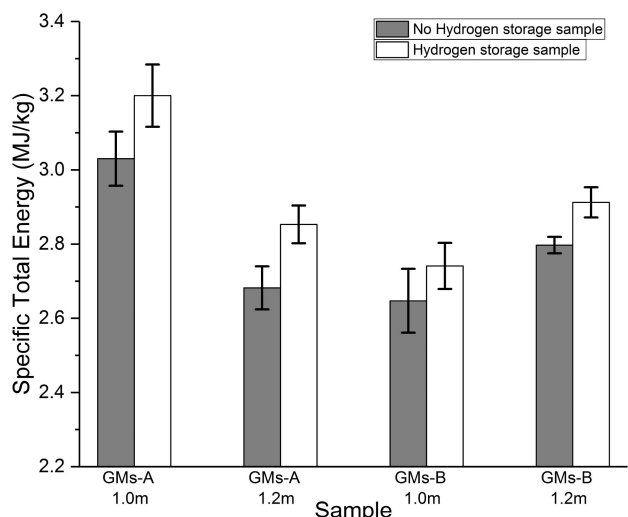


Figure 10. The specific total energy of emulsion explosives sensitized by different GMs at different distances.

ble energy increase and specific shock wave energy have nothing changed? We considered the reasons as follow.

On one hand, shock wave is produced by explosion and its intensity is determined by explosion heat. Adding helium to explosives did not increase explosion heat because helium is noble gas and was not involved in reaction. Shock wave did not change after storing helium, therefore the parameters related to shock wave, such as peak pressure, impulse and specific shock wave energy, had not been upgraded. On the other hand, the bubble in water consists of explosion product gas. Though the reaction product did not increase, the total gas after explosion was increased because of the addition of helium. The specific bubble energy is mainly determined by the amount of total gas after ex-

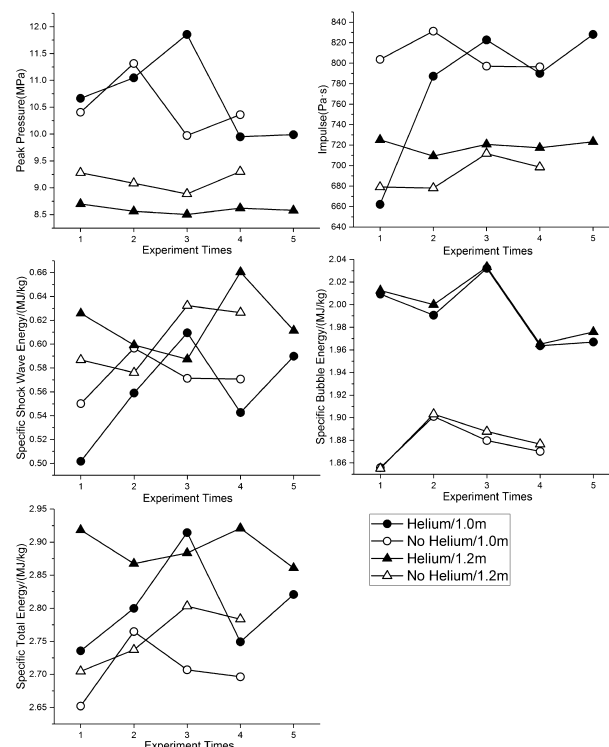


Figure 11. The comparison of detonation parameters of emulsion explosives sensitized by helium-storage GMs and ordinary GMs.

plosion, so specific bubble energy would be increased with adding helium.

3.9 The Amount of Hydrogen Storing in GMs

In order to obtain the mechanism of energy improvement of the hydrogen-storage explosives, we calculate the amount of hydrogen in explosives.

First, the related parameters of GMs were calculated. We chose GMS-B to study. The composition of GMs spheres is borosilicate and its density is 2.52 g/cm³. Inside of the spheres is nitrogen of which pressure is 1 atm and density is 1.25 g/L. The apparent density of GMS-B is 0.25 g/cm³. We calculated the ratio (λ) of volume of the cavity inside GMs and the shell of GMs.

$$\lambda = \frac{2.52 - 0.25}{0.25 - 0.00125} = 9.1 \quad (11)$$

Second, the experimental steps were as follows. 10 g of GMs was placed into a 300 cubic centimeter reaction kettle. The kettle was sealed and evacuated. Then 5 MPa of hydrogen was filled into the reaction kettle. The kettle was heated to 300 °C, kept for 3 hours and then lowered to room temperature (28 °C). The internal pressure of kettle changed to 4.5 MPa which was read from pressure gauge.

Third, calculate the amount of hydrogen in GMs. Volume of 10 g of GMs is 40 cm^3 ($= 10\text{ g} : 0.25\text{ g/cm}^3$). Volume of the cavity inside GMs (V_1) and the shell of GMs (V_2) were calculated.

$$V_1 = 40\text{ cm}^3 \times \frac{\lambda}{\lambda + 1} = 36.04\text{ cm}^3, V_2 = 40\text{ cm}^3 - V_1 = 3.96\text{ cm}^3 \quad (12)$$

The container for containing GMs was 40.3 cm^3 , so the volume of cavity outside GMs was 219.7 cm^3 ($= 300\text{ cm}^3 - 40.3\text{ cm}^3 - 40\text{ cm}^3$). Before and after heating the kettle, the total amount of the gas inside and outside the GMs remained unchanged. According to the ideal gas law $pV = nRT$, we can get the follow equation:

$$5\text{ MPa} \times 219.7\text{ cm}^3 + 0.101\text{ MPa} \times 36.04\text{ cm}^3 = 4.5\text{ MPa} \times 219.7\text{ cm}^3 + P \times 36.04\text{ cm}^3 \quad (13)$$

where P is the pressure inside GMs after the temperature of kettle dropped to room temperature. The left of the equation (13) was pV before heating and the right was after. We can get $P = 3.15\text{ MPa}$. Finally, the hydrogen storing in GMs was the hydrogen from 5 MPa to 4.5 MPa outside GMs. The amount of substance of storing hydrogen (n_{hy}) was calculated from the ideal gas law.

$$n_{\text{hy}} = \frac{pV}{RT} = \frac{(5 - 4.5) \times 10^6 \times 219.7 \times 10^{-6}}{8.314 \times (28 + 273.15)} \text{ mol} = 0.044\text{ mol} \quad (14)$$

That is, 10 g of GMs-B can store 0.044 mol of hydrogen which is 0.088 g of hydrogen. Then 10.088 g of hydrogen-storage GMs could make 262.288 g of emulsion explosives. The total storing hydrogen would release 0.0124 MJ ($= 282\text{ kJ/mol} \times 0.044\text{ mol}$) of energy during combustion, so the energy release of emulsion explosives sensitized by hydrogen-storage GMs would be increased by 0.047 MJ/kg ($= 0.0124\text{ MJ} / 262.288\text{ g}$).

Next we did hydrogen storage shelf life experiment. Hydrogen-storage GMs (0.3 g) were placed into a small sealed vessel (12.7 cm^3) and the pressure in vessel can be read from electronic pressure gauge of which resolution is 1 kPa. The number of gauge showed no change for a week, indicating that hydrogen leakage did not exceed 1 kPa. In industrial applications, emulsion explosives are generally produced on site, so the storage time of hydrogen-storage GMs can meet the requirements.

3.10 Influence of Storing Hydrogen in GMs

We considered the reasons for improvement of detonation characteristics of emulsion explosives sensitized by hydrogen-storage GMs as follow.

On one hand, for conventional GMs, they fill with nitrogen inside and the pressure is 1 atm. They work as hot spots to burn emulsion explosives when added into emulsion matrix. When the gas in the GMs is replaced to hydrogen, the hydrogen not only acts as hot spots, but also burns to release energy to boost emulsion explosives energy output. From front section, we know the energy of hydrogen-storage emulsion explosives would be increased by 0.047 MJ/kg if hydrogen in GMs is completely burned. According to Table 3, the specific shock wave energy of HEE-B was increased by 0.034 MJ/kg in 1.0 m and 0.014 MJ/kg in 1.2 m. This is because the hydrogen wasn't burned completely within a few micrometers of detonation time in the actual situation. Theoretical and experimental results are of the same magnitude. Future research will continue to refine the theory and experiment to reduce errors.

On the other hand, the specific bubble energy was increased after storing hydrogen. This was because the total gas after explosion was increased the same as storing helium. Difference was that hydrogen combustion generated water vapor while helium did not participate in the reaction. Bubble is more significant in underwater explosion while negligible in the air explosion.

As for elastic energy storing in the GMs shell upon pressurization. We thought that glass is a brittle material and deforms very little under high pressure. The elastic energy can be negligible.

Conclusions

The hydrogen-storage GMs significantly improve the explosion performance of emulsion explosives. Through the brisance experiments, detonation velocity experiments and underwater explosion experiments, effects of the hydrogen-storage GMs in emulsion explosives are studied. The brisance and detonation velocity of hydrogen-storage emulsion explosives are improved significantly compared with conventional emulsion explosives, which are increased by an average of 2.5 mm (compression value of lead column) and 181 m/s, respectively. The underwater explosion experiments also gave evidence that the energy improvement with hydrogen addition.

The amount of hydrogen storing in emulsion explosives was calculated. The increased energy was computed theoretically and experimentally. There was some difference between the two data but the same in magnitude which illustrated that the storing hydrogen method is correct but need to be precise in the future.

It is noteworthy that the difference between the data of emulsion explosives sensitized by two types of GMs, such as specific total energy, is caused not only by the difference of strength of the two types GMs, but also by the difference between experimental conditions. Temperature has a great impact on the performance of emulsion explosives. The effects of temperature and pressure of storing hydrogen on

the properties of emulsion explosives will be studied more deeply further.

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