Dynamic Response Characteristics of a Sealing Airbag under Different Impact Types and Impact Pressures

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ABSTRACT: The rapid isolation of the disaster area underground coal mine can effectively prevent the spread of disaster accidents. Rapid sealing of the disaster area can be realized through sealing in the form of an inflatable capsule. The cushioning performance of the inflatable capsule to an explosion shock wave is an important factor affecting sealing reliability. The response process of a small inflatable capsule under an explosion shock wave was studied using the pipeline explosion experimental system to examine the dynamic response characteristics of the coal mine airbag under the impact load. The deformation buffering process of the inflatable and hydrogel capsules was tested by a drop hammer impact test. Results showed that under the action of three explosion impact pressures (0.3, 0.4, and 0.5 MPa), the inflatable capsule could absorb 22% of the impact energy through its deformation and reduce the maximum explosion impact pressure. Moreover, under the impact of falling weight at different heights (20, 30, 40, and 50 cm), the cushioning process of the inflatable and hydrogel capsules absorbed the impact energy through the compression deformation of the capsule, which is the loading stage. When the hammer speed decreased to zero, the deformation and absorbed energy of the capsule were at maximum. The capsule recovered its deformation and converted the absorbed energy into kinetic energy to make the hammer rebound, which is the unloading stage of the capsule. The capsule body realized the absorption and transfer of impact energy through its deformation and completed the energy buffer through the dynamic response process of multiple loading and unloading.

1. INTRODUCTION

With the utilization of coal resources, the mining intensity increases year by year, and the underground mining conditions become more complex, resulting in an increase in disasters and accidents, such as fires, explosions, and outbursts. After a coal mine disaster, the rapid sealing and isolation control of the disaster area can effectively prevent further accidents. To improve the mine emergency response ability to deal with disasters and accidents, scholars conducted relevant research on the technology and equipment for rapid closed isolation of disaster areas after disasters. Chang proposed a solidified door structure for a mine rescue cabin, established a three-dimensional model of a mine mobile protective closed door, and analyzed the strength of an arc door with ANSYS software. The results showed that the strength and stiffness of the arc door are better than those of the ordinary flat door. Ying-hua studied a new type of airbag-type rapid air tightness device; calculated the stress and strain of the airbag in x, y, and z directions under certain pressure and temperature conditions; and carried out a field test. Sosa and Cheng studied the stability and air tightness of rapid sealing airbags in a simulated tunnel by combining theoretical analyses and experiments. The results showed that the air leakage rate and air pressure change rate of fluororubber material are 4.25 and 4.66%, respectively. The ability of fast sealing and isolation equipment in disaster areas to resist the shock wave of explosion in closed areas is an important factor affecting the safety of closed areas, which is of great significance for restraining the impact range of disasters. In-depth research on its impact resistance under service conditions should be conducted.

An impact dynamics experiment is the most effective means to test the cushioning performance of the coal mine closed capsule. Through testing, the dynamic response characteristics of the coal mine closed capsule in an actual working environment can be truly reflected. Based on the developed rapidly sealed capsule, through the gas pipeline explosion and drop hammer impact test, this study examines the cushioning characteristics of a sealed capsule under the action of high-temperature explosion shock wave and drop hammer impact and the transmission and release process of explosion impact energy. This study also analyzes the dynamic response characteristics of the sealed capsule under impact.

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2. EXPERIMENTAL SAMPLE

Glass fiber cloth, coated with a modified nanocalcium carbonate toughened coating material and ZnSn(OH)$_6$/Sb$_2$O$_3$ flame-retardant coating material, is selected as the bearing layer. The cloth is also pressed into the capsule wall material through heat sealing. The average tensile strength of the modified lightweight high-strength capsule wall material is 104.81 ± 7.25 MPa. Moreover, the average elastic modulus is 1038.41 ± 66.26 MPa, the average toughness is 13.05 ± 0.48 J/mm$^3$, and the maximum deformation is 29 mm.

The sample of the experimental specimen is made according to the drop hammer test-bed and gas pipeline explosion test-bed. The drop hammer impact experimental capsule is 60 × 60 × 60 cm$^3$, and the size of the capsule in the gas pipeline explosion experiment is 13 × 13 × 20 cm$^3$. The capsule is designed with an inflation port, a fixed pull ring, a pressure monitoring port, and a safety pressure relief port (Figure 1).

3. EXPERIMENTAL INSTALLATION

3.1. Pipeline Explosion Impact Experiment. The pipeline gas explosion suppression comprehensive experiment system mainly includes a multichannel dynamic gas distribution system, a high-speed camera, a pressure monitoring system, a system control cabinet, and others. The experimental device can realize automatic gas injection, ignition, data acquisition, data transmission, data storage, and data analysis. This device can also automatically draw a time pressure curve. Figure 2a shows the experimental system. We place the experimental capsule on the upper part of the pipe, inflate it to fit closely with the inner wall of the pipe, and then close the pipe with a cover plate. Figure 2b depicts the sample layout.

3.2. Drop Hammer Impact Experiment. The drop hammer impact experiment system (DHR-1205) is mainly composed of a counterweight, hammerhead, fixed fixture, an experimental airbag, a force sensor, and a pressure sensor. Figure 3 presents the experimental system.

3.3. Experimental Parameters. 3.3.1. Pipeline Explosion Impact Experiment. The experimental explosion gas is CH$_4$. The multichannel dynamic gas distribution system is equipped with explosion premixed gas of different concentrations. The experimental materials are shown in Table 1.

3.3.2. Drop Hammer Impact Experiment. According to the design of the drop hammer impact test, the weight of the hammerhead is 37.4 kg, the counterweight is 100.39 kg, and the total weight is 137.79 kg. The static loading test and drop hammer impact test of inflatable and hydrogel capsules were carried out, respectively. The experimental heights were 20, 30, 40, and 50 cm.

4. RESULTS AND DISCUSSION

4.1. Response of the Inflatable Capsule under Explosion Shock. Three explosion experiments with different gas concentrations and three inflatable capsule antexplosion impact experiments were carried out in a closed pipeline. Figure 4 shows the explosion process.

Figure 5 depicts the change curve of explosion pressure according to the monitoring data of the pressure sensor in the explosion pipeline. Figure 5a depicts the change in pipeline explosion pressure when the CH$_4$ gas concentration is 7%. When the pipeline has no experimental capsule, the maximum explosion pressure is 0.36 MPa and the time to reach the maximum explosion pressure is 676 ms. The explosion pressure generated after putting the experimental capsule in the pipeline is 0.28 MPa. Moreover, the time to reach the maximum explosion pressure
is 785 ms, which is 109 ms later than when there is no explosion in the experimental cabin in the pipeline. At a concentration of 9.5% CH$_4$, the maximum explosion pressure reached in the antiexplosion experiment of the experimental capsule is 0.38 MPa. Moreover, the time to reach the maximum explosion pressure is 50 ms later than that in the gas explosion experiment. When the concentration of CH$_4$ is 10.5%, the time for the two experiments to reach the maximum is the same. In the explosion experiment with the same gas concentration, the maximum pressure produced by a gas explosion is greater than that of the inflatable capsule antiexplosion experiment. Moreover, the time required to reach the maximum pressure is shorter. CH$_4$ gas is premixed in the explosion pipeline, the bottom of the pipeline is ignited, and the explosion shock wave gradually propagates from the bottom to the top. In the process of explosion shock wave propagation, the pressure is gradually superimposed and finally reaches the maximum at the top of the pipeline. In the antiexplosion experiment of the inflatable capsule, the explosion shock wave acts on the capsule after superposition and transmission. After the inflatable capsule is subjected to the impact pressure, the capsule will deform, squeezing the internal gas. The inflatable capsule then converts the energy of the explosion shock wave into the elastic potential energy of the inflatable capsule and compresses and does work on the internal gas of the inflatable capsule to realize the absorption of explosion energy. After the explosion impact, the elastic potential energy stored in the capsule wall material will be released. Furthermore, the gas expansion inside the capsule will release the internal energy to realize the transfer of explosion impact energy.

4.2. Pressure Change of Capsule under Static Pressure. We slowly lower the drop hammer and counterweight through the tractor to contact the capsule and start the static loading experiment. After the hammerhead contacts the

Table 1. Experimental Materials

| number | $\phi$ (stoichiometric ratio) | CH$_4$ vol % | O$_2$ vol % |
|--------|-----------------------------|--------------|-------------|
| no. 1  | 0.72                        | 7            | 19.53       |
| no. 2  | 1                           | 9.5          | 19.01       |
| no. 3  | 1.12                        | 10.5         | 18.80       |

Figure 3. (a) Drop weight experimental system. (b) Experimental equipment layout.

Figure 4. Pipeline explosion process.
capsule, the pressure increases gradually. Figures 6 and 7 show the pressure changes of the hammerhead and the bottom of the capsule. When the hammerhead gradually drops to fully compress the capsule, the contact pressure between the hammerhead and the capsule reaches the maximum value of 0.58 kN. In addition, the average pressure monitored by the four pressure sensors in the loading stability stage is 16 N. The maximum force exerted by the hydrogel capsule is 0.19 kN, and the average force acting on the bottom of the capsule is 12.4 kN after decompression. After the top of the capsule is subjected to pressure, the outer tissue structure is deformed through tension. Moreover, the internal flexible medium
absorbs the top pressure through compression, and only a small part of the pressure is transmitted to the bottom of the capsule.

4.3. Drop Hammer Impact Response Characteristics of the Capsule. 4.3.1. Response Characteristics of the Inflatable Capsule under Impact. According to the experimental design of the drop hammer impact test, we inflate the capsule to a pressure of 0.6 kPa and then lift the hammerhead and counterweight it to a predetermined height. Figures 8 and 9 depict the changes in the hammerhead pressure and the pressure at the bottom of the capsule. The drop hammer is released from a height of 20 cm, which acts on the capsule through free-fall movement. During the impact process, the shape variable of the capsule increases, the drop speed decreases, and the hammer force increases accordingly. When the capsule shape variable is the largest, the hammer speed decreases to zero and the hammer force increases to the maximum value, which is 28 kN. The gravitational potential energy of the falling hammerhead is converted into the elastic potential energy of the capsule material and the internal energy formed by the compression of the gas in the capsule. The residual energy is transmitted to the base of the test bench through the capsule. When the shape variable of the capsule reaches the maximum, the elastic potential energy of the outer material reaches the maximum and then enters the release stage. Moreover, the elastic force of the material reacts to the hammerhead. The elastic potential energy is transformed into the gravitational potential energy of the hammerhead, the hammerhead rebounds upward, and the force decreases gradually. According to the change curve of impact force, when the force of the hammerhead is zero, the hammerhead is out of contact with the capsule and continues to move upward. In addition, the force increases in reverse. When the hammerhead moves to the highest position, the force reaches the extreme value, and the maximum force is 13 kN. The hammerhead falls down again from the rebound height, impacts the capsule twice to the maximum deformation position, and then rebounds again. In multiple reciprocating actions, the maximum impact force of the hammerhead on the capsule each time decreases gradually.

When the impact height is 30 cm, the change trend of the impact force is consistent with that when the impact height is 20 cm. Multiple reciprocating actions also exist, and the maximum force of the first impact is 36.8 kN. The pressure at

Figure 8. Pressure change of the hammerhead during falling hammer impact. (a) Drop hammer height of 20 cm. (b) Drop hammer height of 30 cm. (c) Drop hammer height of 40 cm. (d) Drop hammer height of 50 cm.
the bottom of the capsule increases gradually with the action process and rises to the maximum when the impact force of the hammer is the maximum. When the drop hammer rebounds and impacts the capsule again, the secondary impact pressure decreases and the pressure at the bottom of the capsule decreases slowly. When the lifting heights of the drop hammer are 40 and 50 cm, the maximum impact pressures of the hammerhead are 42.4 and 58 kN, respectively. Moreover, the corresponding maximum pressure at the bottom of the capsule is 35 N. After the drop hammer release height increases, the impact force strengthens and the pressure response strength at the bottom of the capsule increases. After the initial pressure peak, the secondary impact pressure decreases, but the reduction range is small. The pressure at the bottom of the capsule is always large in the process of multiple reciprocating impacts, and the pressure tends to be stable after the hammerhead stops the repeated impacts.

4.3.2. Response Characteristics of the Hydrogel Capsule under Impact. Figure 10 shows the pressure change of the hydrogel capsule at different heights under the drop hammer impact. When the hammer first acts on the capsule, the maximum impact force is 33.8 kN and the rebound height of the hammer after impacting the capsule is lower than that of the inflatable capsule. After the hammerhead rebounds to the highest position after the shape change of the capsule, it has a secondary impact on the capsule. The impact force is reduced by 50%, and the shape variable of the capsule is also reduced by 60%. The maximum pressure value monitored at the bottom of the capsule is the same as that during static loading. The results show that when the elastic deformation of the hydrogel capsule is absorbed by the elastic material of the outer layer of the capsule, most of the impact energy can be absorbed through the deformation of the hydrogel in the capsule as internal energy and elastic potential energy. After the shape change of the hydrogel capsule reaches the maximum, the outer material and internal colloid of the capsule release elastic potential energy to realize the secondary release of absorbed energy. Through the deformation recovery process of the capsule, the effective buffer of the impact process is realized.
When the drop weight height is 30 cm, the initial maximum impact pressure is 52 kN, which is 18.2 kN higher than that of the 20 cm height experiment. The reaction force of the hammerhead after the first impact is enhanced, the rising speed of the hammerhead is accelerated, and the time interval between the first and second impacts is shortened. When the drop heights are 40 and 50 cm, the maximum impact pressures are 59.6 and 65.6 kN, respectively. As the self-stiffness of the hydrogel capsule is greater than that of the inflatable capsule, the force of the hammerhead and hydrogel capsule is greater than the impact force of the inflatable capsule at the same drop weight release height.

4.4. Capsule Deformation under Drop Hammer Impact. Figure 11 presents the deformation of the inflatable capsule after being impacted by the drop hammer at different heights. The shape variable generated by the hammer acting on the capsule for the first time is the largest. When the drop weight heights are 20 and 30 cm, the shape variable of the capsule filled with hydrogel is greater than that of the inflatable capsule at the same drop weight release height.
capsule is 10 cm. When the drop weight impact height is 50 cm, the maximum shape variable of the inflatable capsule center is 20 cm and the deformation rate is 33.3%. After being impacted by the drop hammer, the central position of the inflatable capsule is deformed, the air in the capsule is compressed, and the external tissue is laterally deformed. When the impact force of the drop hammer increases, the vertical deformation at the center of the inflatable capsule and the lateral deformation around it gradually increase. The elastic mechanical properties of capsule wall materials and internal inflation pressure are the main factors affecting its cushioning performance.

Figure 12 shows the shape variable of the hydrogel capsule under the impact of the drop hammer at different heights. Under the maximum impact height, the shape of the hydrogel capsule is 10 cm, and the maximum shape variable of the inflatable capsule center is 20 cm and the deformation rate is 33.3%. After being impacted by the drop hammer, the central position of the inflatable capsule is deformed, the air in the capsule is compressed, and the external tissue is laterally deformed. When the impact force of the drop hammer increases, the vertical deformation at the center of the inflatable capsule and the lateral deformation around it gradually increase. The elastic mechanical properties of capsule wall materials and internal inflation pressure are the main factors affecting its cushioning performance.

Table 2. Pressure at Different Impact Heights of the Inflatable Capsule and Hydrogel Capsule

| experiment number | impact height (m) | inflatable capsule | hydrogel capsule |
|-------------------|------------------|-------------------|------------------|
|                   |                  | hammerhead pressure (KN) | pressure (MPa) | hammerhead pressure (KN) | pressure (MPa) |
| 1                 | 20               | 28                | 0.89            | 33.8             | 1.08           |
| 2                 | 30               | 36.8              | 1.17            | 52               | 1.66           |
| 3                 | 40               | 42.4              | 1.35            | 59.6             | 1.90           |
| 4                 | 50               | 58                | 1.85            | 65.6             | 2.09           |

The hammerhead is made of steel, and its strength and elastic modulus are much greater than those of a capsule material. During the impact process, the hammerhead always maintains elasticity.25 Taking the hammerhead as the research object, according to the momentum theorem, the change of the momentum of the hammerhead is equal to the impulse under the combined external force.26 According to the maximum impact pressure measured in the experiment and the action area between the hammer and the capsule (0.0314 m²), the maximum pressure under different impact heights is obtained according to the pressure calculation formula, as shown in Table 2.

When an external force strikes, the capsule begins to load and the air (hydrogel) in the capsule is compressed. The capsule then absorbs some energy and converts it into elastic potential energy.27,28 During the unloading stage, the elastic potential energy of gas and gel stored in the capsule plays a role. The energy first transforms from friction into a part of thermal energy, and the rest is released in the form of kinetic energy.29,30 Starting from the moment of impact between the drop hammer and the capsule, the drop hammer impacts the capsule at a certain initial speed of \( v_1 \). After the impact, the drop hammer bounces back at a speed of \( v_2 \). After the drop hammer contacts the capsule, the impact speed of the drop hammer gradually decreases from \( v_1 \) to 0. The capsule has the maximum elastic deformation, and the force between the drop

Figure 13. Stress process of the airbag.
hammer and the capsule reaches the maximum, which is the loading process. The elastic potential energy of the capsule is released, and the elastic force acts on the hammerhead in the opposite direction. Moreover, the speed increases in the opposite direction until the hammerhead is separated from the object and the speed reaches \( v_o \), which is the so-called unloading process.

The hammerhead is made of rigid material and will not deform after being impacted. When the hammerhead with a certain initial speed collides with a stationary capsule, the maximum impact force generated by the impact is directly proportional to the stiffness of the impacted object. With an increase of the stiffness of the capsule, the impact force in the impact process will also increase and vice versa.

When the velocity of the hammerhead decays to zero during the impact process, the deformation should be restored to the initial position. After a part of energy \( E_0 \) is lost in the impact process, the remaining elastic potential energy is released and converted into the rebound kinetic energy of the hammerhead to push the hammerhead away from the capsule and accelerate from 0 to \( v_o \). The collision between the capsule and the hammer is elastic. In the process of impact, considering the energy loss caused by friction and other factors, the elastic potential energy stored in the capsule will be released into kinetic energy in the next stage. The energy absorption rate of the object is directly proportional to \( E_0 \) which means that the lower the rebound speed, the better the cushioning performance.

4.5.2. Dynamic Response Equation of the Inflatable Capsule under Impact. The impact dynamics analysis is carried out by taking the inflatable capsule as an example. Considering the inflatable capsule with \( m \) mole gas, its volume is \( V \), its bottom area is \( S \), its internal air pressure is \( P \), and its temperature is \( T \). Moreover, its internal air pressure, volume, and temperature meet the ideal gas equation.

\[
P V = nRT
\]  
(1)

where \( R \) is the gas constant.

The mass of the hammerhead impacting the inflatable capsule is \( m \), and the upward direction is defined as the positive displacement direction of the hammerhead. Moreover, the external ambient pressure is \( P_o \), and the stiffness of the capsule itself is \( k \).

Taking the rigid contact between the hammerhead and the airbag as the initial position and assuming that the mass displacement at any time is \( u \), the motion equation of the contact between the hammerhead and the airbag is established according to Newton’s second law.

\[
ma + (P - P_o)S + ku - f_0 = mg
\]  
(2)

where \( S \) is the action area between the hammerhead and the airbag, \( f_0 \) is the support force provided by the airbag to the hammerhead when the hammerhead just contacts, and \( a \) is the drop weight acceleration. The hammerhead is in a free-falling state, and the initial deformation of the capsule is taken as the origin for analysis.

\[
(P - P_o)S = f_0
\]  
(3)

Assuming that the initial volume of the airbag is \( V_o \), the initial air pressure is \( P_o \) and the initial temperature is \( T_o \). Equation 1 can be rewritten from \( V \) and \( T \) into the following form

\[
P = \frac{nRT}{V}
\]  
(4)

When the hammerhead impacts the airbag, the initial distance from the hammerhead to the bottom of the airbag is \( L_o \). Moreover, the gas volume in the capsule at any time can be expressed as follows

\[
V = V_o + uS = (L_o + u)S
\]  
(5)

We bring eq 5 into eq 4 to obtain the air pressure in the capsule at any time.

\[
P = \frac{nRT_o}{(L_o + u)S}
\]  
(6)

As can be seen from eq 6, air pressure \( P \) in the inflatable capsule is only a function of compression displacement \( u \). At the initial position \(( u = 0) \), Taylor expansion is made for eq 6.

\[
P = \frac{nRT_o}{V_o} \left( 1 - \frac{S}{V_o} u \right)
\]  
(7)

The inflatable capsule mainly relies on the internal gas to provide the support force for the hammerhead. The additional stiffness is related to the tendency to expand during the compression of the inflatable capsule, which is generally as follows

\[
k = \frac{P_o S^2}{V_o}
\]  
(8)

We replace eq 7 with eq 2 and simplify it according to the initial pressure.

\[
ma + P_o S^2 u = mg
\]  
(9)

We can solve from eq 9 the natural frequency of inflatable capsule vibration as follows

\[
\omega = \sqrt{\frac{P_o S^2}{V_o m}}
\]  
(10)

We assume that the initial condition of falling weight is \( u(0) = 0 \) and \( u(0) = v_o \). Combined with eq 10, the displacement response of the inflatable capsule is as follows

\[
u = \frac{v_o}{\omega} \sin \omega t + \frac{g}{\omega^2} (1 - \cos \omega t)
\]  
(11)

5. CONCLUSIONS

(1) The compression and buffer response process of the inflatable capsule under three explosion impact intensities of 0.3, 0.4, and 0.5 MPa was tested by a pipeline explosion experiment. Under the three explosion shock pressures, the capsule has evident deformation, energy storage, and recovery release energy response. In the process of explosion impact, the inflatable capsule absorbs 22% of the impact energy and reduces the maximum explosion impact pressure.

(2) The maximum impact pressures of the inflatable and hydrogel capsules under a 50 cm drop hammer impact are 1.85 and 2.09 MPa, respectively. The cushioning variables of the inflatable and hydrogel capsules are 33.3 and 16.7%, respectively. Moreover, the absorption of the
impact energy is achieved through the stretching of the wall material, the compression of the inner medium, and the increase of internal energy.

(3) The hammerhead impacts the capsule through free-fall acceleration. The impact of the capsule is divided into two stages: energy loading and energy unloading. In the loading stage, the hammerhead impacts the capsule at a certain speed to cause compression deformation until the speed of the hammerhead decreases to 0. The capsule recovers its deformation for energy release, converts the elastic potential energy into kinetic energy of the hammerhead, and rebounds in the opposite direction, that is, the unloading stage of the capsule. The capsule completes the buffer consumption of energy after multiple loading and unloading stages.

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