Interaction of blast waves with helium-filled rubber balloons

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Abstract. Gas-filled elastic bags are a convenient means for storing blast mitigation materials, such as inert gases and two-phase media, and delivering them to protected objects. If the blast wave resulting from an accident propagates through air, it can undergo significant transformations when interacting with various inhomogeneities. This study explores the possibility of blast-wave attenuation by interaction with a thin enclosure (shell) filled with helium, which has a low specific acoustic impedance compared to air. High-speed shadow photography was used to investigate the wave patterns and dynamics of helium compression in the balloons under blast loads resulting from explosions of hydrogen–air mixtures. Blast loads transformations were analyzed. A comparison with three-dimensional numerical simulations showed that the motion of a thin shell can be computed by solving fluid dynamics equations without specifying boundary conditions across the shell.

1. Introduction

In a case of emergency arising from accidental releases of flammable gases, such as hydrogen, spontaneous or forced ignition can lead to a fire or an explosion producing a thermal or shock-wave (blast) impact on nearby objects. Experimental and theoretical studies of the dynamic loading by premixed hydrogen–air combustion are required to develop well-substantiated recommendations for the design and safe operation of nuclear power plants and hydrogen energy facilities. Experiments conducted under conditions simulating potential emergencies, combined with verified numerical models, provide a scientific basis for mitigating the hazards of premixed hydrogen–air explosions.

To present day, a vast amount of data has been collected concerning combustion, transition to detonation, and detonation in hydrogen–air mixtures [1–3]. Numerical simulation packages have been developed for predicting various aspects of hydrogen combustion [4–6].

Current research is generally characterized by a lack of focus on measures designed to mitigate the hazard of a hydrogen explosion, which is determined in particular by the magnitude of blast load. Studies of combustion characteristics and explosive mixture formation are still being proposed as research areas of primary importance [7]. In other words, there is a gap between basic research and practical solution of hydrogen safety problems. Overcoming this drawback
requires a shift of emphasis in fundamental (laboratory) studies. The end result of such studies should be technological solutions that reduce blast loads to a safe level.

It was shown in [8] that the load from a premixed hydrogen–air explosion on an enclosing surface can be reduced by using a particulate material (e.g., Aerosil) or an aqueous foam as a blast protection barrier. Creating two-phase layers of this kind and placing them on the surfaces to be protected typically involves the use of gravity. This imposes certain technological requirements on the use of such systems to protect structural parts.

One alternative to two-phase bulk materials are nonflammable gases. However, their load-reducing ability is severely hindered by diffusion, as well as natural and forced convection, which leads to degradation of protective layers. A localized barrier capable of reducing the load from an accidental explosion of a hydrogen–air mixture on structural and equipment parts can be created by using a thin enclosure (shell). In such a system, the shell prevents the barrier from degradation through mixing with air or a hydrogen–air mixture. Furthermore, its use makes it easier to transport a load-reducing material to an appropriate place.

This study explores the possibility of blast wave attenuation by interaction with a thin shell filled with helium, which has a low specific acoustic impedance compared to air.

2. Experimental method

A technique using a vertical shock tube has been developed to simulate interactions of shock and detonation waves with shells containing a barrier material (shell barriers). Figure 1 shows a schematic of the experimental setup, whose key components include an ignition section, an explosion chamber, and a test plate.

The ignition section, 54 mm in diameter and 70 mm long, is equipped with an ignition source (automotive spark plug). The ignition system is powered by a remote-controlled high-voltage...
Figure 2. Schlieren images of the flow in the absence of a shell barrier. Explosive mixture: 35 vol % H\textsubscript{2} + 65 vol % Air, \(P_0 = 0.1\) MPa. Interval between frames is 52.4 \(\mu\)s. ISW—incident shock wave; RSW—reflected shock wave; PF—detonation product front.

pulse generator. The explosion chamber is a tube of 54 mm in diameter and 1.5 m in length with regularly spaced ring obstacles. To reduce the wave attenuation due to transverse expansion, the open bottom of the tube is fitted with a 0.2 m long flared section with a flare angle of 36°.

Burst diaphragms are not used to avoid impact by high-speed particles on the objects under study. The tube is filled by blowing hydrogen premixed with air. The amount of premixed gas blown through the setup is at least 5 times the volume of the setup. Thus, the initial gas pressure is 0.1 MPa. The spark is fired 3 to 4 s after the blowing is complete. Since the mixture used in the experiments is highly reactive, 35 vol % H\textsubscript{2} + 65 vol % Air (concentration is given in volume percentage), the length of the section with obstacles is sufficient for a deflagration-to-detonation transition to occur. The pressure in the explosion chamber is monitored by pressure sensors PS1 and PS2. As the detonation wave exits the flared section into open space, the reaction zone decouples from the leading shock.

The setup is designed to generate a blast load, which is recorded by pressure sensors PS3 and PS4 mounted flush with the surface of the test plate. Sensor PS3 is on the tube axis, while sensor PS4 is at a radial distance of 150 mm from the axis. Sensor outputs are recorded with a high-speed multichannel data acquisition system based on a T512 ADC module installed in a personal computer. Gasdynamic discontinuities and behavior of the shell barrier under blast loading are visualized by means of high-speed schlieren photography (up to 20 000 fps). Figure 1 shows the optical system configuration. In several experiments, a Nikon 1 J1 camera has been used to perform color imaging at a frame rate of 1200 fps.

For reference, an experiment has been conducted in the absence of a shell barrier. Figure 2 shows a sequence of schlieren images of the flow, with shock waves and detonation product fronts indicated.

Images 1–4 illustrate the propagation of an incident shock wave. The product front follows the ISW at a lower velocity. The surface of the test plate is at 15 mm below the frame. This explains the observed time interval between the passage of the ISW in image 4 and the appearance of a reflected shock wave in image 6. The reflected wave moves opposite to the product front and
Table 1. Balloon parameters and experimental outcome.

| Balloon | Shell thickness, $\mu$m | $H$, mm | $D$, mm | Shape              | Outcome     |
|---------|-------------------------|---------|---------|--------------------|-------------|
| No. 1   | 5                       | 50      | 100     | oblate spheroid    | rupture     |
| No. 2   | 15                      | 100     | 150     | oblate spheroid    | rupture     |
| No. 3   | 160                     | 100     | 150     | oblate spheroid    | no rupture  |
| No. 4   | 260                     | 100     | 150     | semi-oblate spheroid| no rupture  |

interacts with the products in image 8. As a result, the wave dissipates (smears out) because of a difference in acoustic impedance, and subsequent images do not show any discontinuities. The product front halts (images 9 and 10) and then proceeds in the same direction.

3. Numerical simulation

The influence of an elastic shell on the dynamics of blast loading is investigated by comparing experimental results with numerical simulations. Fluid dynamics computations (unlike experiments) can be performed for a localized barrier material without a shell, such as a spatial region occupied by helium.

Comparing a computed trajectory of the free air–helium boundary with visualized motion of a shell provides information about the effect of shell parameters (shell thickness, density, etc) on the wave pattern associated with blast loading. In this approach, the first step is a numerical simulation of the reference experiment conducted in the absence of a shell. The goal is to achieve the best possible agreement between numerical results and experimental data. The numerical simulation is performed for a reactive, viscous, heat-conducting, multi-component, compressible gas by using three-dimensional (3D) modeling and taking account of the actual geometry of the shock tube employed. The program code was developed at the Laboratory of Mathematical Modeling of IJHT RAS and successfully tested by solving a number of problems of ignition, combustion, and detonation.

To improve agreement with experiment, simulations are performed for several degrees of filling of the tube with the flammable mixture at ignition time, because the use of blowing makes it difficult to determine this parameter. It is found that the reference experiment is adequately matched by a simulation with mixture–air boundary set at a distance of 100 mm upstream of the nozzle exit.

In figure 3, 3D simulation results are compared with the reference experiment. The computed temperature fields in figure 3 are used to determine the trajectories of the shock wave and the product front. It is clear that good agreement is obtained in both the trajectories of gasdynamic and contact discontinuities, figure 3(b), and the pressure behind the reflected shock, figure 3(c). Here, $H$ is the distance from the test plate surface. The initial conditions thus determined (most consistent with the experimental flow pattern) are used to simulate the behavior of the air–helium boundary in the “ideal” case of the absence of a shell. Figure 4 presents the numerical results obtained for a helium-filled oblate spheroid with a polar diameter (height) $H$ of 100 mm and an equatorial diameter $D$ of 150 mm. The expanding product front is shown in blue; the boundary of the helium layer, in yellow. Note that the helium layer is compressed most in the axial direction; i.e., the spheroid transforms into a toroid-like shape. This behavior cannot be visualized by schlieren photography, which can only be used to measure the instantaneous height of a helium-filled balloon.
Figure 3. Comparison of 3D simulation with reference experiment. (a) Computed temperature fields; the time step between images is 100 µs. (b) Distance–time diagrams of shock and product-front propagation: ISW and RSW: 1—observed, 2—computed; PF: 3—observed, 4—computed. (c) Pressure profiles on the test plate: 1—measured with PS3; 2—computed for PS3.

4. Experimental results and discussion
Experiments on blast loading with the use of helium-filled latex balloons, whose parameters are listed in table 1. The shell thicknesses are given for inflated balloons.

Figure 5 shows the experimental results obtained for balloon No. 2. To prevent it from rising, a net is used as shown in figure 5(a). High-speed schlieren photography, figure 5(b), provides a sufficiently accurate method for determining the trajectories of the upper shell surface, the net,
Figure 4. Simulated density profiles at compression of a helium layer in a balloon impacted by a blast wave. Time after starting of interaction between the blast wave and the balloon is given in microseconds in top left corner of each frame.

Figure 5. (a) Full density distributions for the helium layer in the balloon. (b) Pressure trace in the presence of a barrier (curve 1) and without a barrier (curve 2). (c) x–t diagrams for the gasdynamic discontinuities. The shell starts moving in image 2, reaching a velocity of 300 m/s. It stops after 150 µs (image 5) and then moves back upwards (images 9–12). Starting from image 13, the net can be seen against light, which may be a sign of shell rupture. The pressure trace in figure 5(d) (curve 1) provides insight into blast load transfer across shell barriers. The pressure upon reflection is half that in the absence of a barrier, in agreement with the computed result (curve 2). The pressure bursts recorded at later times can be attributed to the impacts of shell fragments accelerated by the post-shock flow on the test-plate surface.

When analyzing the contribution of the impact described above to the total blast load, one should bear in mind that the pressure-sensitive area of the sensor is 5 mm in diameter; therefore, the sensor output cannot be interpreted as characterizing the average load on an object having a large area. Furthermore, it is well known that a piezoelectric sensor can generate spurious output signals when the surface on which it is mounted is exposed to mechanical disturbances. Therefore, correct evaluation of blast load mitigation requires the use of additional instrumentation for measuring the total load. One relatively simple and reliable device serving this purpose is the crusher-type diaphragm pressure gauge (crusher gauge) [9]. The pressure-sensitive part of the device can be a thin lead plate, an aluminum foil, or an annealed copper foil. When the crusher gauge is mounted in the blast impact zone, the foil deforms under overpressure, and the amount of its deflection can be used to estimate the peak overpressure.

Diaphragm gauges of this type have been successfully used to measure the attenuation of blast waves from high explosives [10].

The present experiments are conducted by using a 50-mm diameter crusher gauge analogous to that used in [11], with a sensitive element made of a 0.1-mm thick double-layer aluminum foil. Figure 6 shows an overall view and position of the crusher gauge in experiments with and without a shell barrier. The maximum diaphragm deflection is $h_0 = 10.5$ mm for an unprotected crusher.
Figure 5. Experiment on blast loading of a helium-filled balloon. (a) An overall view of the experimental setup and an enlarged view of the balloon. (b) Schlieren visualization of a flow pattern; the time step between images is 52.4 µs. (c) x–t diagram: 1—ISW; 2—shell; 3—net. (d) Traces of pressure on the test plate: 1—experiment; 2—simulation.

gauge and $h_1 = 4$ mm in the absence of a barrier. Thus, it holds that $h_0/h_1 \equiv \Delta p_0/\Delta p_1 = 2.5$, where $\Delta p_0$ and $\Delta p_1$ denote overpressures in the absence and presence of a barrier, respectively. Therefore, the secondary pressure bursts due to local impacts of shell fragments on the plate have negligible effect on blast load mitigation.
Figure 6. Outcomes of experiments using a diaphragm crusher gauge without a barrier (left) and with a barrier (right).

Figure 7. Compression of shells under blast loading of balloons: 1—No. 1; 2, 3—No. 2 (two balloons with identical parameters); 4—No. 3; 5—No. 4; 6—computed trajectory of free air–helium boundary under blast loading.

Comparative analysis of behavior of different shells is facilitated by representing experimental and numerical results in dimensionless form. High-speed schlieren images can be used to determine the time variation of the shell compression parameter $\delta = x/x_0$, where $x$ and $x_0$
are current and initial shell thicknesses, respectively. Figure 7 shows a selection of experimental data obtained for different shells. In cases 1–3, the shell ruptures between 600 and 800 µs after impact. Curves 4 and 5 are obtained in experiments with non-ruptured shells. In these cases, a weak pressure (quasi-acoustic) wave forms initially, followed by a pressure burst corresponding to maximum compression after 1 ms. A comparison with numerical results (curve 6) shows that that the motion of a thin shell can be computed by solving fluid dynamics equations without specifying boundary conditions across the shell.

5. Conclusion
An experimental technique is developed and a setup is constructed for examining interactions of shock and detonation waves with helium-filled enclosures (shells). High-speed schlieren photography is used to analyze the behavior of the shell material under blast loads generated by premixed hydrogen–air combustion. Characteristics of blast load transfer associated with dynamics of shell compression and rupture are demonstrated.

A comparison with results of multi-dimensional numerical simulations shows that the motion of a thin shell can be computed by solving fluid dynamics equations without specifying boundary conditions across the shell.

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