Mitigation of explosions of hydrogen–air mixtures using bulk materials and aqueous foam

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Abstract. The objective of this work is to determine experimentally the effectiveness of protective barriers under conditions when blast waves are generated during premixed hydrogen–air combustion in various regimes. Experiments are conducted in a vertical tube having a diameter of 54 mm and a length of up to 2 m. Blast loads are produced by acceleration of premixed hydrogen–air flames in the tube with ring obstacles. Comparative tests are performed between protection barriers made of bulk materials with different densities and aqueous foams with different expansion ratios. It is demonstrated that the degree of blast load attenuation by an aqueous foam barrier increases with decreasing molecular weight of the filling gas and increasing density (decreasing expansion ratio) of the foam. An Aerosil barrier three times thicker than a titanium-dioxide one is found to have a similar attenuating effect on blast action. However, the mass per unit area of an Aerosil barrier is lower than titanium dioxide by a factor of 6 and is comparable to foam. The observed dependence of blast load attenuation on parameters of bulk materials and aqueous foams must be taken into account in systems designed to mitigate the consequences of accidental hydrogen release and combustion.

1. Introduction
In loss prevention engineering, considerable attention is devoted to blast protection barriers of various types. The use of such barriers in hydrogen safety engineering requires an understanding of emergencies resulting from an accidental hydrogen release. Unlike heavy hydrocarbons, hydrogen tends to accumulate in near-ceiling spaces. In a large-scale enclosure, such as the containment building of a nuclear power plant, a protective barrier must be installed in the potential damage area of a hydrogen explosion. Static gas-permeable barriers are usually pre-installed structures (mazes, perforated plates, blast dampers, flame arresters) and have a limited capacity to protect lateral surfaces (enclosure walls). Such devices are not suitable for reducing the blast load on an inner dome because of a high barrier mass per unit area of the protected surface. Furthermore, many barriers of this type provide ineffective protection from reactive gas flows. In summary, a hydrogen safety barrier intended for use in nuclear power plants should meet the following requirements:

- relatively low mass of the barrier material per unit area of the protected surface;
- high flame-extinguishing effect over a wide range of hydrogen burning rates;
- high degree of attenuation of blast loads resulting from explosions of hydrogen–air mixtures;
• technological ease of installation, including in near-ceiling spaces.

The first requirement is satisfied when the barrier contains gas-filled voids and has a high void fraction \( \varphi \). In the limit case of \( \varphi = 1 \), an inert gas layer can be created to serve as a barrier. The void fraction of gas–dust systems varies from \( \varphi = 0.2–0.3 \) for densely packed bulk materials to \( \varphi = 0.9997 \) for dilute aerosols such as tobacco smoke. High void fractions, \( \varphi = 0.9–0.99 \), are characteristic of the aqueous foams widely used in firefighting systems.

Barriers made of densely packed granular materials effectively reduce blast load [1]. However, their bulk density \( \rho_n \) can be as high as 60–70\% of particle density. In a densely packed state, bulk density varies from \( \rho_n \approx 6000 \text{ kg/m}^3 \) for steel to \( \rho_n \approx 600 \text{ kg/m}^3 \) for plastics (e.g., polystyrene). Dust–gas suspensions with densities between 1 and 5 kg/m\(^3\) can also attenuate shock waves [2, 3], but achieving this effect requires either a thick barrier or an increase in particle concentration. These requirements are difficult to meet in practice when changing from channel or pipe geometry to semi-infinite space. Apart from the cases of high and low particle concentration mentioned above, of special interest is the class of loosely packed bulk materials. They usually consist of nanosized particles that cannot be compacted because of their intricate shape. One example of this class is fumed silica, commercially available as Aerosil, with a bulk density of \( \rho_n \approx 40–50 \text{ kg/m}^3 \). Another material of similar density is high-expansion aqueous foam.

Aerosil has been used in firefighting powders [4]. It is also interesting to investigate the direct effect of Aerosil on flames in hydrogen-containing mixtures. Flame extinction by Aerosil via heat loss from the reaction zone is controlled by the specific surface area of the powder, which amounts to hundreds of square meters per kilogram. It should be noted that an increase in detonation run-up distance was observed for hydrogen–air mixtures containing Aerosil in the form of a dust layer or dust–air suspension [5].

In this work, we focus on the reduction of dynamic (shock) loads from hydrogen–air mixture explosions, using bulk materials and aqueous foams as barriers.

2. Experimental setups

The attenuating effect of barriers on blast action is examined in experimental setups where the main sections are vertical cylindrical explosion chambers equipped with devices simulating basic types of blast loads from accidental explosions. The choice of an experimental technique is based on the type of protective barrier and the simulated blast load from a hydrogen–air mixture. The nature of the latter is determined by the assumed scenario of an accident resulting from ignition of a hydrogen–air mixture.

The first scenario starts with ignition of a pocket of flammable hydrogen–air mixture. As the mixture burns at a certain rate, a transient shock wave (a blast wave with pressure decreasing downstream of the front), accompanied by a combustion wave, develops and propagates into a nonflammable (not necessarily inert) ambient gas. Interaction of a shock with structural or equipment parts may cause unanticipated loads leading to their structural failure. In this scenario, the barrier is located outside the flammable gas cloud, near the protected surface.

In the second scenario, where the entire enclosure containing a source of hydrogen is filled with a flammable hydrogen–air mixture, both premixed combustion and shock propagation can occur in the region where the protective barrier is located.

Accordingly, blast loads are simulated by using two types of setups. In one, load is created as a result of an explosion of hydrogen–air mixture in a channel with obstacles, followed by shock-wave formation and release of combustion products into an air-containing volume. In the other, after flame acceleration in a section with obstacles filled with hydrogen–air mixture, the explosion process continues in a smooth section filled with a similar mixture.

To explain the difference between the setups, we describe their operation in more detail. Figure 1 shows the schematic layout and exterior view of the setup of the first type. A key part
Figure 1. Experimental setup of the first type: 1—ignition section; 2—explosion chamber; 3—test section; 4—spark plug; 5—high-voltage pulse generator; 6—burst diaphragm; 7—pressure-monitoring sensor; 8—test-section pressure transducers.

here is the burst diaphragm 6 separating the explosion chamber from the test section. After mixture ignition in the ignition section 1, the flame propagates along the explosion chamber with ring obstacles 2 and pressure increases until it exceeds the failure limit of the diaphragm. Once the diaphragm ruptures, a shock wave with a “triangular” blast pressure profile forms in the test section 2, followed by a flame front. The resulting load is measured with a piezoelectric transducer mounted on the end plate of the test section. The protective effect of a barrier located in the test section is evaluated by comparing the transducer output with that obtained without the barrier. This technique has the advantage that evacuating the test section is not required. This is particularly important for experiments with aqueous foam barriers.

The second type of setup differs from the first type in two main aspects: no diaphragm is used, and the test section is a transparent acrylic glass tube of the same diameter as the explosion chamber (54 mm). The schematic layout and exterior view of the setup are shown in figure 2. All sections of the setup (including test section) are evacuated before each experiment and then filled with hydrogen–air mixture. When a fine powder is deposited in the test section, both evacuation and gas-filling are performed slowly under visual control to prevent removal of particles. As a result, the space between barrier particles is filled with a flammable gas, and the flame-extinguishing action of the barrier can be tested. This technique cannot be used in experiments with aqueous foams.

The bulk materials used in gas–solid particle barriers are Aerosil and titanium dioxide. Aerosil is pure amorphous silicon dioxide ($\text{SiO}_2$). It is an extremely light powder that looks semi-transparent and bluish when poured in a thin layer. Since Aerosil particles are flaky aggregates, the powder consists of 90% air. While the $\text{SiO}_2$ particle density is 2200 $\text{kg/m}^3$, the bulk density of Aerosil varies between 40 and 60 $\text{kg/m}^3$, depending on particle size. We have used Aerosil 200 produced by Degussa, with a particle size of 12 nm and a bulk density of 42 ± 2 $\text{kg/m}^3$. According to [6], the thermal conductivity of Aerosil produced by Degussa is $(3.25\pm0.07)\times10^{-3} \text{ W m}^{-1}\text{K}^{-1}$. The TiO$_2$ grade used is DuPont R-105 (92 wt% TiO$_2$ min., 3.2% Al$_2$O$_3$ max., 3.5% SiO$_2$ max.), with a particle size of 310 nm, a particle density of 4.0 g/cm$^3$. 

and a bulk density of $760 \pm 10 \text{ kg/m}^3$. According to [7], the thermal conductivity of the TiO$_2$ powder is $0.118 \text{ W m}^{-1}\text{K}^{-1}$; i.e., the difference in thermal conductivity between the two kinds of powder is more than 30 times.

In the experiments with aqueous foams, different filling gases are used and foam expansion ratio is varied. Foam is prepared by using an impeller mixer or the foam generator shown schematically in figure 3. The foaming solution consists of 6 vol% PO-6TsT foaming agent
and 94% water at room temperature. The solution is introduced under pressure into a foam nozzle simultaneously with a filling gas (argon, nitrogen, or helium). The expansion ratio varies between 20 and 30 for foams produced by this technique and is approximately 10 for those produced using the impeller.

3. Results and discussion

The degree of blast load attenuation by a barrier is evaluated by comparing loading dynamics on the bottom end plate of the test section between experiments performed with and without the barrier. Consider the experimental results obtained in the setup of the first type. Figure 4 compares overpressure profiles measured with the end-plate transducer in experiments with Aerosil barrier thicknesses $L = 0$, 0.15 and 0.43 m. When the barrier has an intermediate thickness, $L = 0.15$ m, only a minor decrease in peak load is observed, whereas secondary waves are effectively attenuated. With dust-barrier thickness increased to $L = 0.43$ m, the peak pressure is reduced by a factor of 4, a gradual pressure rise is observed instead of a shock profile during the initial loading stage, and the load duration increases significantly. The load redistribution over time indicates that the loading regime changes from dynamic to quasi-static. This effect should be taken into account in analysis and design of structures exposed to blast loads.

Figure 5 shows overpressure profiles measured with the end-plate transducer for barriers of thicknesses $L = 0$, 0.12 and 0.21 m in experiments using aqueous foam with an expansion ratio of 10. It is clear that the peak load is reduced by half even for $L = 0.12$ m. The use of a thicker aqueous foam barrier, with $L = 0.21$ m, reduces the peak pressure by a factor of more than 6. It should be noted that, unlike in the case of a dust barrier, the load duration does not increase; i.e., such a foam barrier can effectively reduce both peak load and overpressure impulse.

The foam-generating technique used for creating closed-cell foams with an expansion ratio of 30 makes it possible to examine the dependence of blast protection capability on the kind of
Figure 5. Blast pressure–time profiles obtained with and without aqueous foam barrier with expansion ratio 10. Explosive mixture: 15% H$_2$ + 85% air, $P_0 = 0.1$ MPa. Foam barrier thickness $L = 0$ (1), 0.12 (2) and 0.21 m (3).

Figure 6. Blast pressure–time profiles obtained in the experimental setup of the first type with and without an aqueous foam barrier with expansion ratio 30. Explosive mixture: 10% H$_2$ + 90% air, $P_0 = 0.1$ MPa. Foam barrier thickness: 1—$L = 0$; 2—$L = 0.31$ m, argon; 3—$L = 0.31$ m, nitrogen; 4—$L = 0.26$ m, helium.
Figure 7. Attenuation factor versus molecular weight of the filling gas for aqueous foam barriers. Explosive mixture 10% H\textsubscript{2} + 85% air, \( P_0 = 0.1 \text{ MPa}. \) Data: 1—foam expansion ratio about 30 (density \( \approx 33 \text{ kg/m}^3 \)), helium, nitrogen, argon; 2—foam expansion ratio about 10 (density \( \approx 100 \text{ kg/m}^3 \)), air.

filling gas. Figure 6 compares overpressure profiles measured with the end-plate transducer in experiments with foam barriers of thickness \( L = 0.26 - 0.31 \text{ m} \) filled with different gases. Whereas only a minor decrease in peak load is observed in the case of argon or nitrogen, the use of helium as a filling gas significantly reduces the blast load.

Following [8], we characterize the protective effect of a barrier in terms of the blast-load attenuation factor defined as \( \eta = \Delta P / \Delta P_0 \), where \( \Delta P \) is the peak overpressure on the surface behind the barrier and \( \Delta P_0 \) is the peak overpressure in the absence of a barrier. Its dependence on the filling gas is illustrated by figure 7, where the attenuation factor is plotted against the molecular weight of the cell-filling gas. It is clear that a significant protective effect of foam with an expansion ratio of approximately 30 is achieved only with the use of helium. However, expansion ratio is itself a determining parameter. When the expansion ratio is 10 and the filling gas is air, the attenuation factor is close to 0.1. Thus, the protection effectiveness of an aqueous foam barrier against blast load increases with decreasing molecular weight of the filling gas and increasing foam density (decreasing expansion ratio). However, the design and use of foam protection systems must take into account foam stability, which is better for high-expansion foams.

In the setup of the second type, a flammable mixture fills both the explosion chamber and the test section where an inert barrier is located. Since aqueous foam barriers are difficult to test in this experimental scheme, only experiments with dust barriers are performed in the setup of the second type. Figure 8 compares overpressure profiles measured with the end-plate transducer in experiments with Aerosil and titanium dioxide barriers of thicknesses \( L = 0 \) and 0.15 m. In the absence of a barrier, the blast loading histories are similar to those measured in the setup of the first type. An important difference is that the arrival of a shock wave is preceded by a
Figure 8. Blast pressure–time profiles obtained in the experimental setup of the second type with and without a dust barrier. Mixture in explosion chamber and test section 12% H₂ + 88% air, \( P_0 = 0.1 \) MPa. Curves: 1—\( L = 0 \); 2—\( L = 0.15 \) m, Aerosil 200, particle size 12 nm; 3—\( L = 0.15 \) m, titanium dioxide, particle size 310 nm.

Figure 9. Blast pressure–time profiles obtained in the experimental setup of the second type with an extended test section. Mixture in explosion chamber and test section 17% H₂ + 83% air, \( P_0 = 0.1 \) MPa. Curves: 1—\( L = 0 \); 2—\( L = 0.45 \) m, Aerosil 200, particle size 12 nm.
gradual pressure rise due to acceleration of flame propagation along the explosion chamber with obstacles. In the presence of an Aerosil layer of thickness 0.15 m, the peak pressure slightly increases rather than decreasing. However, replacing Aerosil with titanium dioxide reduces the peak pressure by a factor of 4. The revealed different effects of the tested materials are explained by difference in bulk density, which plays an important role in load transfer across barriers of this kind [8].

The use of Aerosil generally requires a significant increase in barrier thickness. In such experiments, the cylindrical section made of acrylic glass is replaced with a steel section of length 0.85 m. Figure 9 compares overpressure profiles measured with the end-plate transducer for Aerosil barriers of thicknesses $L = 0$ and 0.45 m.

All results obtained in setups of different types using bulk materials and aqueous foam as blast protection barriers are represented by the parameter $\eta$ plotted against barrier thickness in figure 10. It is clear that an Aerosil barrier three times thicker than a titanium-dioxide or higher density aqueous-foam barrier has a similar attenuating effect on the peak load behind the barrier. However, the mass per unit area of an Aerosil barrier is lower than titanium dioxide by a factor of 6 and is comparable to foam.

4. Conclusions
Setups of different types designed to simulate dynamic loads created by accelerating premixed hydrogen–air flames propagating through obstacles have been used to perform comparative tests
of blast protection barriers made of bulk materials with different densities and aqueous foams with different expansion ratios. It is demonstrated that the attenuating effect of an aqueous foam barrier on blast load increases with decreasing molecular weight of the filling gas and increasing foam density (decreasing expansion ratio). It is found that the mass of an Aerosil barrier is much lower than that of titanium dioxide required to achieve similar protection effectiveness. The results of this experimental study provide a scientific basis for systems designed to mitigate the consequences of accidental hydrogen release and combustion.

Acknowledgments
This work was supported by the ROSATOM State Atomic Energy Corporation under contract No. N.4h.241.9B.17.1015.

References
[1] Medvedev S P, Frolov S M and Gelfand B E 1990 Inzh.-Fiz. Zh. 58 924–8
[2] Igra O, Ben-Dor G, Aizik F and Gelfand B 1995 Experimental and numerical investigation of shock wave attenuation in dust-gas suspensions Shock Waves @ Marseille III, Proc. 19th Int. Symp. Shock Waves ed Brun R and Dumitrescu L Z (Berlin, Heidelberg: Springer) pp 49–54
[3] Igra O, Falcovitz J, Houas L and Jourdan G 2013 Prog. Aeronaut. Sci. 58 1–35
[4] Bobkov S A, Baburin A V and Komrakov P V 2014 Fiziko-khimcheskie Osnovy Razvitiia i Tusheniia Pozharov (Moscow: Akademiya GPS MChS Rossii)
[5] Khomik S V, Medvedev S P, Olivier H, Polenov A N and Gelfand B E 2007 The influence of inert nanoparticles on DDT in hydro–air mixtures Proc. 21st ICDERS 0132
[6] Bardakhanov S, Zav’yalov A, Zobov K, Lysenko V, Nomoev A, Obanin V and Trufanov D 2008 Nanoindustriya 5 24–9
[7] Kuz’min A P, Lyashkov V I and Kuz’min A A 2007 Vestn. Tamb. Gos. Tekhn. Univ. 13 101–5
[8] Gelfand B E, Medvedev S P, Borisov A A, Polenov A N, Frolov S M and Tsyganov S A 1989 Arch. Combust 9 153–65