Effectiveness of Protective Covers in Case of a Detonation Wave Reflection

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Introduction

The accidental explosions in industrial plants can occur in the complex environment that in part consists of rigid surfaces covered by layers of porous materials, dust, foams etc. The knowledge of the parameters determining the shock loading transmitted through such deposits is both of practical and fundamental importance. First evidence for the unusual trends of the pressure behavior caused by a shock-loaded deposit of polyurethane foam was reported in Gelfand et al. (1975). It was experimentally verified by Gelfand et al. (1975) and Skews (1995) that the presence of polyurethane foam at a rigid surface amplifies the reflected pressure. The experiments on weak shock wave loading in thin layers of granular or dust materials revealed the same effects (Adachi et al. (1984), Gelfand et al. (1989)).

In most previous works the laboratory experiments were performed using conventional shock tubes producing planar stepwise shock waves. However, real explosions or blast waves, arising in the environment as a result of an accident, are characterized by triangular (blastwise) pressure profiles. It was found in Medvedev et al. (1995) that the loading transmitted through a compressible deposit of a fixed thickness is strongly influenced by the duration and shape of the pressure profile of the shock wave. It has been shown that for sufficiently short shock pulse the loading of the rigid wall covered with porous material is lower than in the case of an uncovered wall. Thus, the compressible layers can be protective or destructive.

Detonation waves in gaseous mixtures belong to the category of explosion (blastwise) waves since the pressure behind the front is not constant. So far there is no any data on the dynamic response measured at rigid surfaces covered by a porous layer upon loading by a detonation wave.

Experimental

The experiments were performed in the TH-1 shock/detonation tube of the Shock Wave Laboratory of Aachen University. The inner diameter of the tube amounts to D_0 = 141 mm and the overall length of the tube is 7.3 m. The protective layers were placed immediately adjacent to the endwall of the tube and were fixed by a flange with 110 mm inner diameter at the front side facing to the incident detonation wave. The arrangement allows to record the parameters of the incident and reflected detonation wave as well as to measure the parameters of the pressure loading onto the endwall. The mixture considered was 30% H_2 in air mixture at the initial pressure of p_0 = 1 bar. The protective porous layers consist of metal rubber and compressed steel wool The metal rubber presents a specially designed material consisting of closely spaced spirals from stainless steel wires with a diameter of 0.2 mm. The overall bulk density of this material amounts to 2 g/cm^3. The commercially available steel wool was compressed up to a bulk density of 0.3 g/cm^3. The experimental procedure is similar to the one described in Medvedev et al. (2003).

Results and Discussion

The main attention of the present study is focused on the parameters of loading at the rigid wall (endwall) covered by layers of different thickness and material. The overpressure at the endwall is measured by Kistler 603B pressure transducer. During preliminary tests the reflection of the detonation at the uncovered endwall was investigated to provide reference data for the successive experiments with porous covers. The experiments revealed excellent reproducibility of the pressure history of a detonation wave interacting with the uncovered endwall.

The evolution of the pressure-time histories at the endwall covered by different layers of steel wool is shown in Fig. 1*a*. As it is seen the value of the maximum (peak) overpressure Δp_{max} depends on the thickness (depth) h of a layer (marked near each pressure profile in Fig. 1*a*). The value of Δp_{max} increases in the range of $0 < h < 50$ mm. The absolute maximum of the overpressure ($\Delta p_{max} \approx 130$ bar) is achieved at $h = 50$ mm. A further increase of the layer thickness results in a decrease of the peak overpressure. However at $h = 60$ and 100 mm the value Δp_{max} is still higher than the value of Δp_0. For the most thick layer of $h = 156$ mm the value of maximum overpressure becomes slightly smaller than that in the case of an uncovered surface ($h = 0$). The revealed behavior of the maximum overpressure values has much in common with the observations of Gelfand et al. (1989) for the case of shock loading of dust layers. This suggests that a common mechanism underlies the dynamics of shock compression of strictly different porous materials.

The performed experiments revealed that, at least for $h < 150$ mm the steel wool covers do not reduce the overpressure for a detonation wave reflection. On the contrary, the overpressure is enhanced significantly. Nevertheless for a more complete understanding, along with the maximum value of the overpressure, it is necessary to take into consideration the applied impulse of the static pressure since it represents a second important parameter for the response of a construction due to shock loading. The measured pressure-time history $\Delta p(t)$ yields the time dependence of the specific impulse $I(t)$:

$$I(t) = \int_0^t \Delta p(t) dt \,,$$

where time zero corresponds to the beginning of the loading.

Figure 1*b* represents evolution of the impulse-time histories at the endwall covered by different layers of steel wool. The thickness (depth) of a layer is marked for each impulse profile. The values of the impulse I_4 taken at $t = 4$ ms could be adopted as ultimate reference values. As it is easy to see contrary to the overpressure values the parameter of I_4 is almost independent on the layer thickness. All values of I_4 are within a range of ±10% around of the value of $I_{4(h=0)}$ for the uncovered surface. Thus, at least for the investigated range of layers thicknesses ($0 < h < 156$ mm) no mitigation of the detonation wave loading was found. Moreover, there is evidence that the presence of the porous layer of steel wool leads to an enhanced loading. The substitution of steel wool by metal rubber changes the observed dynamics of the pressure loading. However general features are the same.

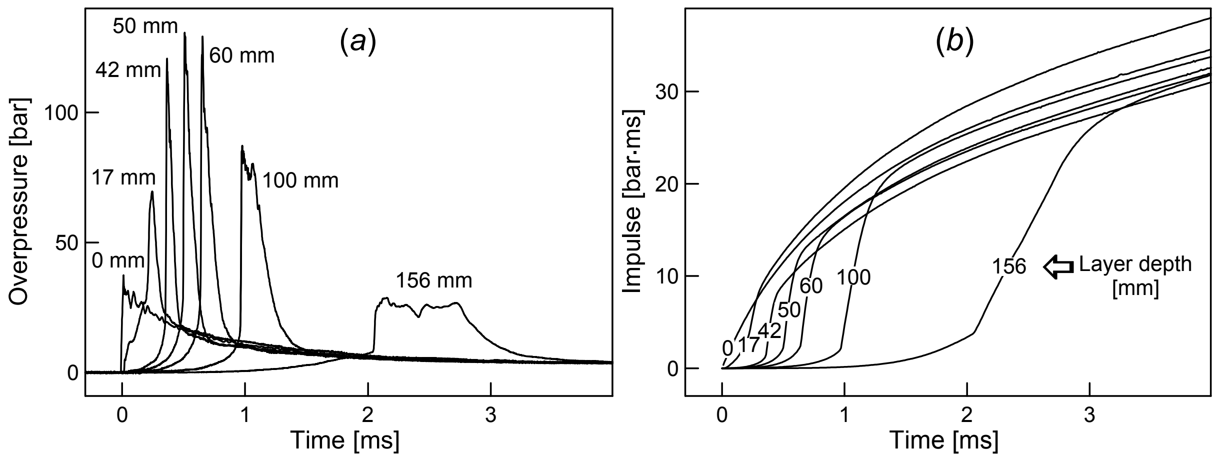

Figure 1. Evolution of the pressure-time (*a*) and impulse-time (*b*) histories at the endwall covered by different layers of the steel wool

The revealed dependencies of the maximum overpressure on the layer thickness are presented in Fig. 2 in terms of the ratio $\Delta p_{max}/\Delta p_0$, where Δp_0 is the maximum loading with layer thickness zero. According to the analogy by Gelfand et al. (1989) the ratio $\Delta p_{max}/\Delta p_0$ represents the maximal relative loading coefficient. Beside of this for the sake of comparison the data of Gelfand et al. (1989) for layers of sand are added. As it is seen from Fig. 2 the presence of the layers of steel wool approximately leads to the same values of $\Delta p_{max}/\Delta p_0$ as in the case of a sand deposit. However it appears for a larger layer thickness. On the other side the bulk density of sand is 1.8 g/cm^3 i.e. comparable with the value for metal rubber (2 g/cm^3). The metal rubber features much better mitigation properties than the sand. This can be explained by the difference in material densities of metal rubber and sand. The metal rubber material is steel with the density nearly 3 times higher than the density of sand material. Beside of this the metal rubber actually has a skeleton with high modulus of elasticity while sand layer has the property of compliance until an individual particles to be packed dense. The observed phenomena are in accordance with the experimental findings and simulations by Gelfand et al (1989) in spite of the fact that the considered values of the shock overpressure were one order lower than in the case of a detonation wave.

Figure 3 represents the dependence of the relative values of impulse $I_4/I_{4(h=0)}$ on the layer thickness. Considering Figs. 2 and 3 one can conclude that porous covers made from metal rubber with a thickness of nearly 50 mm provides a favorable condition for significant mitigation of the loading in the case of a detonation wave reflection.

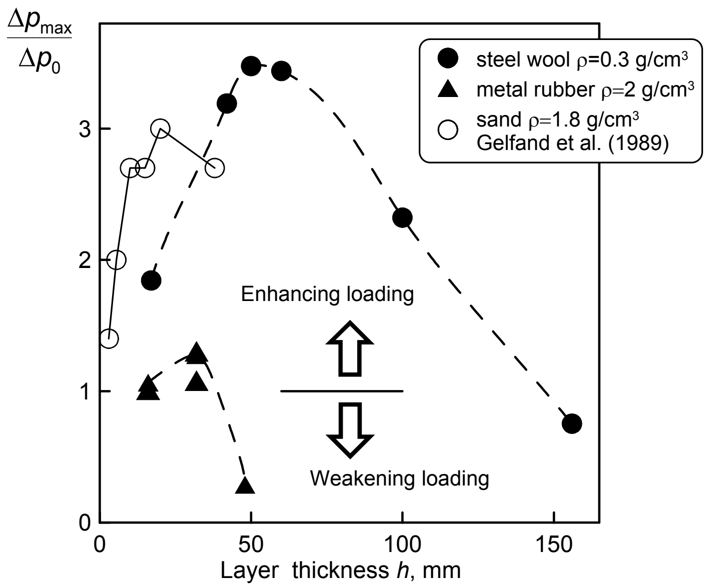

Figure 2. Maximum relative loading coefficient as a function of layer thickness.

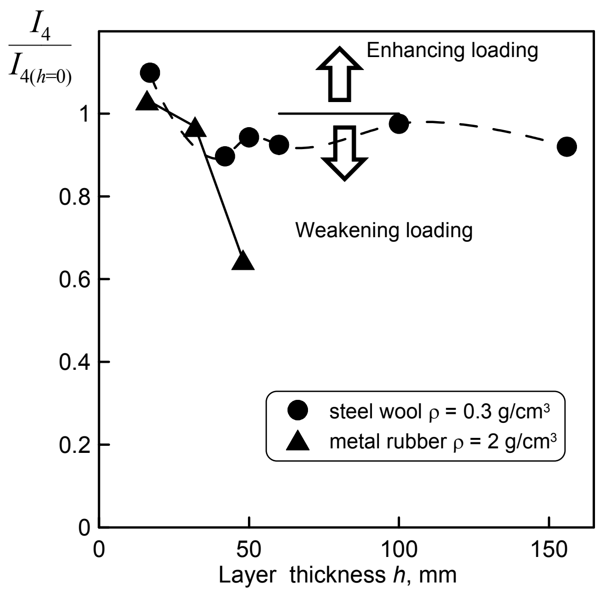

Figure 3. Maximum relative impulse as a function of layer thickness.

Conclusion

The investigation of interaction of a detonation wave with a rigid wall covered by porous materials was performed in the 141 mm diameter detonation tube. The porous materials consisting of compressed steel wool and metal rubber were placed onto the rigid surface (endflange) equipped by pressure transducer. The incident detonation wave was initiated in 30% hydrogen in air mixture at an initial pressure of 1 bar.

The experiments revealed a strong dependence of the maximum overpressure (measured in the substrate) on the layer thickness. There exists a proper value of depth of the layer at which the peak overpressure attains a maximum value. This value can be of 3-4 times higher than the maximum overpressure in the case of an uncovered surface. Therefore depending on the covering thickness the loading can be both enhanced and weakening. It was shown that a more dense covering material is more effective for the purposes of detonation loading mitigation.

Acknowledgements

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