Shock Loading of Stratified Dusty Systems

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The paper reports a detailed study on the parameters of pressure waves interacting with a rigid wall covered with various dusty materials. Both normal reflection of shock waves at the layer surface and propagation of shock waves over it are investigated.

The problems of risk assessment and explosion safety of technological processes in industrial enterprises dealing with dusty materials are connected to a great extent with appraisal of detrimental action of blast waves generated by accidental explosions. Situation in which a blast wave produced by a dust explosion propagates through a volume with a dust layer on the confining walls is rather typical under industrial conditions.

Blast wave propagation over a dust layer was studied in a number of works. The authors of Ref. [1] have shown that the pressure profiles at a wall change appreciably when the wall surface is covered with dust.

In the present work a detailed study is performed of the parameters of pressure waves interacting with a rigid wall covered with various dusty materials. Both normal reflection of shock waves at the layer surface and propagation of shock waves over it are investigated. Based on a simple mechanistic model of shock wave interaction with dust layers dimensionless pressure — impulse diagrams are plotted for shock loading of a construction element covered with dust.

1. Normal Incidence of a Shock Wave on to a Layer

Experiments were performed employing a vertical shock tube 3 m long and 50 mm in internal diameter. The schematic of the setup is shown in Fig. 1.a. The high pressure chamber (1) 1.5 m long is separated from the low pressure chamber by a diaphragm. The low pressure chamber is equipped with piezoelectric pressure gauges, (4) to (6). Dust layers were put on the end plate of the test section.
Pressure gauge 6 is mounted in the end plate. The parameters characterizing dusts under investigation, viz. the density of the particle material \( \rho_p \), overall layer density \( \rho \), volumetric solid-phase fraction \( \varphi \), and mean particle size \( d \) are presented in Table 1. The powders were graded using sieves with calibrated mesh sizes. The sensing element of the pressure gauges was 1 cm in diameter, which is much greater than \( d \). Gauge 5 was mounted near the layer surface and gauge 4 triggered the oscilloscope. Nitrogen and helium were used as driver gases. The low pressure chamber was filled with air at \( p_a = 0.1 \) MPa. The overpressure in incident shock waves \( p = p_i - p_a \) \( (p_i \) is the pressure at the shock front) varied from 0.05 to 1 MPa.

The experiments showed that the pressure pulse at the end plate surface with a dust layer on it differs from that at a rigid wall. After reflection of a shock wave at the free dust surface the transmitted compression wave propagating through the layer produces a pressure pulse at the rigid wall surface which is characterized by an overshoot at the front and by oscillatory decay to the pressure in the wave reflected at the free layer surface \( p \). Duration of the overshoot is proportional to the layer thickness and its amplitude in some cases is 8-9 times that of the

<table>
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<th>No.</th>
<th>Material</th>
<th>( \rho_p ), g/cm(^3)</th>
<th>( \rho ), g/cm(^3)</th>
<th>( \varphi )</th>
<th>( d ), mm</th>
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<td>5</td>
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<td>0.55</td>
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"steady-state" reflected-wave pressure pulse \( p \), that is 10-20 percent lower than the pressure in the wave reflected from a rigid wall.

To clarify the nature of the phenomenon observed we performed pressure measurements in a setup shown schematically in Fig. 1b. This technique allowed discriminating between the effects of a powder and gas in voids on the pressure records. We mounted two pressure gauges in the end plate. Gauge 1 was in direct contact with the powder particles (like gauge 6 in Fig. 1a). The sensing element of gauge 2 was protected with a perforated gas permeable plate precluding its contact with the powder. Preliminary tests have shown that the presence of a perforated plate does not lead to distortion of the pressure signal, provided that the plate is positioned close enough to the sensing element surface.

Pressure records from the two gauges are displayed in Figs. 2a and b, for a layer of powder 3 (see Table 1) of the thickness \( h = 20 \) mm. Time scale is 0.5 ms/div (for Figs. 2a and b) and pressure scale is 0.23 MPa/div in Fig. 2a. Pressure scales in Fig. 2b are 0.23 MPa for the upper trace and 0.3 MPa for the bottom one. Figure 2a demonstrates a pressure profile in a reflected wave at the layer surface recorded with gauge 3 (see Fig. 1b). The incident-wave overpressure in this case was \( \Delta p = 0.1 \) MPa. The upper trace in Fig. 2b represents pressure recorded with gauge 1 and the bottom trace is a signal from gauge 2. As seen in Fig. 2b the signals from these two gauges are quite different. The gauge whose sensing element contacts with dust particles produces a signal that exhibits a strong overshoot at the front with the amplitude \( p_m \) and then rapid oscillatory decay of the pressure to the pressure at the free layer surface \( p \). With no contact

Fig. 2. Pressure records for normal incidence of shock waves:
a) step-wise shock wave
b) pressure at the support surface
c) shock wave of a triangular shape
d) pressure (the bottom trace) and impulse at the support surface
between the sensing element and the solid phase the signal indicates a relatively slow pressure growth at the front. This apparently is due to slow filtration of the shocked gas inward the layer bulk.

Although the first pressure spike is rather short (its duration is 300 µs in the run shown in Figs. 2 a and b) its mechanical effect can be significant in certain cases. This is demonstrated by the following test. A copper diaphragm 0.1 mm thick was mounted in be the end in place of the end plate. An incident shock wave with an overpressure of 0.1 MPa did not rupture this diaphragm. However when a 20 mm layer of powder 2 was placed on the diaphragm a shock wave of the same intensity ruptured it quite easily.

Now we discuss dependence of the maximum overpressure at the layer support $p_n$ on the parameters of the dust layer: its thickness $h$, size and material of particles, and overall density of the powder. For the sake of convenience we introduce a relative loading coefficient $\delta_m$ equal to the ratio of $p_n$ to the overpressure in the shock wave reflected at the free layer surface, $\delta_m = p_n/p$. The upper part of Fig.3 shows $\delta_m$ as a function of the layer thickness for various powders. The overpressure in incident waves is the same in all the runs and equal to 0.1 MPa. The numbers labeling the curves correspond to the numbers of powders in Table 1. As is seen from Fig.3 there exists an "optimal" layer thickness $h$ at which the loading coefficient is maximal. Coefficient $\delta_m$ increases with the particle size diminishing. Comparison of curves 3 and 4 allows one to believe that shock loading depends on the particle material only insignificantly.
The value of $\delta_n$ is strongly affected by the initial state of the powder layer. It was found to be lower in the case when the layer was precompressed either mechanically or by shock waves. For example, in experiments with a layer of powder $l$ of a fixed thickness $h = 20$ mm we increased the volumetric solid phase fraction in the layer from 0.29 to 0.41 by mechanically compacting it. This reduced $\delta_n$ 2.5 times.

Impulse determined as an area of the positive compression phase of the recorded pressure-time history is one of the principal characteristics of blast wave effect on constructions.

In order to investigate how the blast wave impulse is affected by a dust layer we performed experiments with shock waves of a finite duration. A setup similar to the shock tube shown in Fig. 1a was employed for that purpose however its high pressure chamber was only 1 cm long and was filled with He at a pressure of about 5 MPa. Under these conditions a shock wave of a triangular shape with $\Delta p = 0.1$ MPa and compression-phase duration of 1.2 — 1.4 ms arrived at the end plate of the low pressure chamber. Both manual integration of the pressure profile and electronic integrator of the signal of the end-plate pressure gauge were used. The maximal impulse transferred to the solid support in the presence of a layer of powders 4 and 5 (sand and polyethylene grains) exceeds that with no powder by 15-20%. The effect is even greater with powders 1 through 3.

Representative pressure records for a 20 mm layer of powder 3 are shown in Figs. 2c and d. Figure 2c presents a pressure record at the layer surface which corresponds to a reflected shock wave with a triangular pressure profile (the time and pressure scales are 0.2 ms and 0.2 MPa per division respectively). The bottom trace in Fig. 2d is a pressure signal recorded with the end-plate gauge and the upper trace is the same signal transformed by the electronic integrator. Here the time scale is 0.5 ms/div, impulse scale is 115 Pa·s/div, and pressure scale is 0.5 MPa/div. It is seen that pressure loading of the support still persists when the overpressure in the gas phase at the layer surface drops to zero. In accord with this the impulse recorded at the support surface is increased and may significantly surpass that in the wave reflected at the layer surface. Microscopic studies showed that in contrast to sand and polyethylene particles the surface of the plexiglas and polystyrene ones becomes rough. Interaction of these latter particles between each other and with the tube wall surface may give rise to significant cohesive forces that will result in irreversible compaction of the powder and consequently to residual pressure loading of the support.

2. Shock Wave Propagation Over a Layer

Generally blast waves generated by an external energy source may interact with the dust layer surface at different incidence angles. For this reason we studied shock waves propagating over the layer surface. Schematic of the
experimental setup is presented in Fig. 4a. Layers of the powders to be studied of various thickness were placed on the bottom wall of the low pressure chamber of a horizontal shock tube of square cross-section (40 x 40 mm$^2$) and 2 m long. The layer length was about 40 cm. The distance from the diaphragm 3 to the beginning of the layer was 45 cm. The 0.5 m long high pressure chamber was filled with nitrogen or helium. The pressure gauges were mounted as shown in Fig. 4a under and above the layer respectively. This allowed measuring pressure in the gas phase and at the solid-support surface. The gauges were positioned 20 cm apart from each other along the tube.

Pressure records in a run with a sand layer, $h = 25$ mm, are displayed in Fig. 5a. The pressure scales are 0.08 MPa/div and 0.12 MPa/div for the upper and bottom traces respectively, the time scale is 0.2 ms/div. The bottom trace represents the gas pressure over the layer and the upper one is the pressure under the layer in the same cross-section. The pattern of the pressure signal at the support surface is similar to that in the case of normal incidence of the shock wave (compare with the upper trace in Fig. 2b). The specific feature of the process consists in the fact that the pressure perturbation arrives at the support with a delay $\tau$ as compared to the pressure pulse in the gas. This delay is proportional to the layer thickness which is consistent with the results of Ref.[1]. It is noteworthy that $\tau$ defines also the duration of the pressure spike at the front. Similarly to normal reflection we introduce coefficient $\delta_m$ equal to the ratio of the pressure spike at the support to the shock overpressure in the gas.

The values of $\delta_m$ and $\tau$ as functions of the layer thickness for powder 4 are shown in the bottom part of Fig. 3. The overpressure in the shock waves propagating over the layer were $\Delta p = 0.15 - 0.2$ MPa. The maximal relative loading coefficient versus layer thickness in this case is quite similar to that for reflected shock waves. One may reasonably assume that the mechanism of pressure spike generation at the support surface is the same in both cases.

The effect of the pressure profile in a shock wave propagating over a dust layer on the pressure behavior at the support is illustrated in Figs. 5b and c. Shock waves with triangular pressure profiles (the bottom trace in Fig. 5b) are obtained in a shock tube with 1 cm long high pressure chamber filled with helium. The topmost trace corresponds to the pressure under neath a 20 mm thick sand layer. The pressure and time scales are 0.06 MPa and 0.2 ms per division.

Pressure records in weak spherical shock waves propagating through a layer are presented in Fig. 5c. The experiments were conducted on a setup described in Ref. [2] and shown schematically in Fig. 4b. A semispherical diaphragm (1) 150 mm in diameter and pressure gauges 3 and 4 were mounted in the same plate. A dust layer (5) was placed onto pressure gauge (4). After the diaphragm has burst a shock wave with a rarefaction phase and secondary pressure jump characteristic of blast waves generated by bursting high pressure vessels [3] is formed. The upper trace in Fig. 5c represents the gas pressure, the bottom trace is the pressure under a plexiglass powder layer 15 mm thick. The time scale is 0.5
Fig. 4. Schematic of a setup designed for investigations of shock wave propagation over the layer surface: a) plane shock waves, b) spherical shock waves

Fig. 5. Pressure records in the gas and at the support surface for shock waves propagating over the layer surface: a) plane shock wave with a step-wise pressure pulse, b) plane shock wave of a triangular shape, c) spherical shock wave
ms/div and the pressure scales are 5 kPa/div and 7 kPa/div for the upper and bottom traces respectively. The polarity of the gauge measuring pressure at the support surface is negative.

An analysis of the experimental results shows that unlike plane shock waves (Fig. 5 and 6) a spherical wave propagating through the layer exhibits a secondary pressure spike whose amplitude sometimes exceeds the primary pressure jump. The pressure signal at the support surface is of the oscillatory nature with intense rarefaction phases.

3. A Model of Shock Loading in Systems with Dust Layers

The above data indicate that the process of shock loading of a surface covered with a dust layer is quite similar to interaction of shock waves with walls protected with a porous compressible material (e.g. polyurethane foam of a moderate density 30 — 50 kg/m³) [4,5]. A model that represents a porous compressible material as an equivalent “gas” with “equilibrium” parameters has been suggested in Refs. [6,7] to describe shock loading of protected walls. This model can not be applied directly to layers of loose-packed powder materials because of several reasons. As shown in the work [8] “equilibrium” parameters provide for an adequate description of shock loading of dust layers only if the particle size is below 20 µm. Furthermore it is not clear how one can account for the dependence of δm on the layer thickness within the framework of the equivalent-gas model. We consider a model of the process that is different from the model proposed in Refs. [6,7]. This model is based on an assumption that the dust layer moves as a whole driven by an instantaneously applied load.
As shown above (Fig. 2b) the main contribution to the recorded pressure spikes is due to the solid phase motion. Because of this we describe the essential features of the process as follows. Prior to the arrival of a shock wave at the layer the powder particles are held in the „equilibrium” state by the friction forces. A shock wave reflected at the gas-layer interface is equivalent to a gas piston which loads the layer instantaneously with overpressure \( p \). This overpressure displaces the powder particles from their equilibrium state to a new position, thus compacting the layer. The particles start moving under not very high overpressures [9]. Further deformation of the layer causes an increase in the resistance force which depends primarily on the elastic properties of the powder particles. According to the scheme considered above we assume that a column of mass \( m \) with a unit cross-section area „cut” in a powder layer of thickness \( h \) can be replaced by a mechanical system comprising a point mass \( m \) and a combination of an ideally plastic Coulomb element with a zero restoring force (section 1 in Fig. 6a) and an elastic element with the elasticity coefficient \( k \) and damping coefficient \( c \) (section 2 in Fig. 6a). Under action of an instantaneously applied force the mass \( m \) acquires velocity \( \nu_0 \) within section 1. The further motion of the mass is governed by the equation

\[
mx'' + cx' + kx = p
\]

with the initial conditions

\[
x(0) = 0 \text{ and } x'(0) = \nu_0.
\]

There are three types of solutions of Eq. (1) depending on \( c \) and \( c_o = 2(km)^{1/2} \) \((c_o \) is the critical damping coefficient). For the problem under consideration the case \( c < c_o \) is realized. Pressure loading of a rigid support at an arbitrary time \( t > 0 \) is \( R = kx \). The relative loading coefficient \( \delta = R/p \) is found from the solution of Eqs. (1) and (2) to be

\[
\delta = \exp(-\alpha t) \left[ (\gamma - \alpha) \beta^{-1} \sin \beta t - \cos \beta t \right] + 1
\]

where \( \alpha = c/2m; \beta = (k/m - \alpha^2)^{1/2}; \) and \( \gamma = k\nu_0/p \).

The maximal value of the relative loading coefficient \( \delta_m \) is attained at

\[
t_m = \beta^{-1} \arctan \left\{ \beta \gamma \left[ (\gamma - \alpha) \alpha - \beta^2 \right]^{-1} \right\}
\]

The main difficulty in application of this „mechanistic” model to shocked dust layers lies in determination of quantities \( k, c, \) and \( \nu_0 \). Based on the results of one of the runs (powder 4, \( h = 14 \) mm, and \( p = 0.32 \) MPa) and Eq. (3) we found approximate values of \( k, c, \) and \( \nu_0 \). The dashed line in Fig. 6b represents this run. The solid line is the calculated \( \delta = \delta (t) \) dependence for \( k = 3.3 \cdot 10^{10} \) N/m³, \( c = 0.2 \) \( c_o \) and \( \nu_0 = 0.6 \) m/s in Eq. (3). Figures 7 a and b demonstrate the
experimental results (dashed lines) and calculations (solid lines) for the same powder (No.4) at $p = 0.32$ MPa and $h = 20$ and $5$ mm respectively. The values of $k_c$ and $v_c$ found in experiments with $h = 14$ mm are used in the calculations. The calculated parameters are seen to be fairly well consistent with the experimental data and describe correctly the amplitude — frequency dependences.

![Graph](image)

**Fig. 7.** Calculated pressure profiles

If the mass $m$ (Fig. 6, a) is assumed to be located at the mass center of the initial powder column the maximal velocity of the layer free surface should be equal to $2v_c$. Moreover given a value of $v_c$ one may calculate the distance over which the free surface is displaced before the elastic layer compaction starts, i.e. over the length of section 1 in Fig. 6a. The ratio of the length of section 1 to the thickness $h$ of the initial column we denote as $\varepsilon$. The velocity $v_c = (6p/\rho_c)^{-1.12}$ is independent of the layer thickness. For the conditions of the run shown in Fig. 6, the calculated $\varepsilon \approx 0.0025$ i.e. a displacement of the layer surface is no more than 0.01 of the initial layer thickness. We attempted to measure the movement of the layer-gas interface employing a high-speed framing camera. No detectable change in the position of the interface was observed.

If should be noted that the mechanistic model proposed is based on too simple assumptions therefore it is inevitably restricted, in particular, more or less correct dependence of $\delta_m$ on the layer thickness may be obtained with this model only for relatively low values of $h$ ($h \leq 20-25$ mm). To refine the governing equations one must take into account the specific properties of a given powder. For example, one should take into consideration compaction of a layer due to gravity for very thick layers. The value of $\varepsilon$ in this case drops which leads to a decrease of coefficient $\delta_m$. 
As is obvious from Eq. (3) the maximal relative loading coefficient diminishes as pressure grows. However, for very strong shock waves (above 10 GPa) there is observed [10,11] pressure pulse amplification in a porous layer associated with the dynamic rigidity of the medium and its strength properties.

The desisive contribution of solid-phase motion to shock loading of a rigid wall with a dust layer on it can be seen from a comparison of the above calculations with those performed for a wall with a fixed nondeformable layer. One-dimensional gasdynamic equations for an inviscid compressible gas involving terms that account for the loss of momentum due to interaction of the gas with fixed powder particles were used in the calculations. The friction coefficient was estimated according to relationships suggested in Ref. [12]. The calculated pressure at the support surface grows monotonically after the arrival of a shock wave at the layer surface, no pulsations are observed. Calculated pressure pulses are analogous to that presented in Fig. 2b (the bottom trace).

4. Pressure-impulse Diagrams for a Construction Element with a Dust Layer

The presence of a dust layer on a wall gives rise to a nonsteady pressure spike at the wall surface and oscillatory behavior of pressure. The overall mechanical effect of a shock wave in these conditions may be most conveniently demonstrated using a well known method of dimensionless pressure-impulse diagrams [3].

A construction element is simulated in Fig. 8 by an elastic oscillator (section II) with one degree of freedom. The oscillator comprises mass $m_2$ and a spring

![Diagram](image)

Fig. 8. Pressure — impulse diagrams for a construction element covered with a dust layer
with the strength constant $k_2$. A dust layer is represented by its mechanical equivalent (section 1) with the following parameters: $m_1$, $k_1$, and $r$, where $r = \sqrt{h/k_1}$. The pressure pulse of a blast wave at the layer surface is assumed to be exponential: $p(t) = p_0 \exp(-rt)$.

Figure 8 presents an example of a calculated pressure-impulse dependence. Dimensionless coordinates, pressure (force) $p = 2p_0 \sqrt{k_1/k_2}$ and impulse $I = 1/2\pi m_1(k_1/k_2)$, are used for presentation of the data. Here $m_1$ is the maximal displacement of mass $m_2$ from the original position and $I = \int p(t) dt$. The dashed line corresponds to shock loading of a wall without a layer. Curves 1—3 are plotted for $r = 0.1$, 10, and 100 respectively ($m_1 = m_2$ and $k_1 = k_2$). As is seen from the graphs a dust layer may both impair and enhance the mechanical effect of shock loading for dynamic and quasistatic loading modes [3]. In the region of essentially pulsed loading curves 1 to 3 have a vertical asymptotic line which lies to the right from the asymptotic line of the dashed curve plotted for a nondusted wall.

It follows that for $r < 1.08$ the dust layer protects the structural element against the blast wave effect. As the ratio $m_2/m_1$ grows the asymptotic lines shift to the left and the protection effect vanishes. It is worth noting that the pressure-impulse diagrams for $m_2/m_1 = 100$, $k_1 = k_2$ and $r = 0.4$ practically coincide with the dashed curve, i.e., shock loading in this case is the same as with no layer.

Hence the results of experimental studies and calculations indicate that one has to take into account mechanical and physical properties of a layer and support when assessing the destruction hazard for stratified systems and dusty-covered constructions.

References


