EXPERIMENTAL AND NUMERICAL MODELING OF SHOCK WAVE INTERACTION WITH A DUST LAYER

A.A.BORISOV, S.I. SUMSKOI, and P.V. KOMISSAROV
Moscow Physical Engineering Institute, 31 Kashirskoe Chaussee Moscow, Russia
e-mail: borisov@center.chph.ras.ru

Investigations of the mechanism of lofting of dust and liquid behind a shock wave spreading over a layer and their subsequent mixing with air to form of an explosive mixture are important for solving many problems of explosion safety, therefore they were an objective of many works both experimental and theoretical. Most of the previous studies considered shock waves with Mach numbers not very much different from unity, however it is strong shock waves that are interesting for explosion safety. This work was undertaken to get quantitative information about the rate of mass transfer behind strong shock waves and to ascertain the key processes responsible for dust lofting and mixing with the gas.

Experiments were conducted in a special shock tube comprised (i) high pressure section 1.2 m long filled with an ethylene - oxygen mixture at 2 atm, (ii) test section 2 m long filled with air at atmospheric pressure, (iii) receiver section. The high pressure section is 70 mm i.d., the test section has a 50´80 mm^2 rectangular cross section, it is equipped with two pressure gauges to measure the shock velocity and trigger the X-ray flash camera and a window made of a plastic reinforced with carbon fibers. The window size was 80´190 mm^2. Powder lofting was studied from X-ray snapshots taken through the window. The powder chosen for studies was lead fluoride well absorbing X-rays. The particle size was 40-50 mm. The flash duration was a couple of microseconds. The discharge voltage in the X-ray tube was 100-120 kV. All experiments were performed at one and the same shock wave velocity of about 1500 m/s. Lofting of powder from a 2-mm thick layer put on the floor of the test section visualized through the window and from a hemicylindrical bed oriented along the shock wave front was studied. The photographs were processed on a scanner. To calibrate the scanner data, photographs were taken of a wedge filled with a mixture of wheat flour and lead fluoride of known concentration. A special computer program was developed to average the scanner readings over several cells in order to diminish the influence of film defects.. Processed were shots taken at different time instants after the shock wave arrives at the beginning of the dust layer or passes the bed.

X-ray pictures of a 2-mm powder layer were taken at 194, 284, and 340 ms after shock wave arrival at the face edge of the layer. In the first photograph the lofted powder forms a wedge with an angle at the vertex (positioned near the shock front) of about 20°. The wedge has an irregular shape of its upper boundary which could be attributed to both development of the instability waves and to oblique shock waves in the gas phase formed due to interaction between the supersonic flow behind the shock wave and the rising powder. In 340 ms after beginning of interaction between the shock induced flow and the layer the powder fills the entire tube section and is suspended more or less homogeneously. At later stages local areas completely free of the powder are seen near the wall, indicating that at some sites the powder particles bounce to depart from the wall surface and clear it. The photographs show also striations in the two-phase mixture, which are most likely produced by transverse compression waves travelling between the top and bottom tube walls. The most important parameter which can be extracted from these photographs is the mass transfer rate behind the shock front. Processing of the photographs yielded an approximately constant rate of powder lofting in the tube equal to 0.2 g/ms. Constancy of the mass transfer rate is vividly demonstrated by lifted powder mass versus time plotted in Fig. 1.

The density field of the lofted dust is shown in Fig.2.

The above results suggest that lofting of powdered fuel occurs at a too low rate which can not allow detonation waves in stratified systems to be initiated at least in large-diameter tubes. This process can be used only for suspending the particles and preparing homogeneous two-phase mixtures which then can detonate..

Photographs of hemicylindrical beds show that the gas flow is capable of tearing off from the bed not only individual particles but clusters of particles as well. From these observations we can infer that intensification of the lofting process takes place at the front surface of the bed, and hence, arranging the powder layer in the form of individual cylindrical beds can hardly enhance drastically the mass transfer rate as compared to layers.

The above results suggest that lofting of powdered fuel occurs at a too low rate which can not allow detonation waves in stratified systems to be initiated at least in large-diameter tubes. The lofting process can only be used to suspend particles and prepare homogeneous detonable two-phase mixtures.

Photographs of hemicylindrical beds show that the gas flow is capable of tearing off from the bed not only individual particles byt clusters of particles as well. From these observations we infer that intensification of the lofting process takes place at the front surface of the bed, and hence, arranging the powder layer in the form of individual cylindrical beds can hardly enhance the mass transfer arte as compared to layers.

In this work we attempt, using numerical modeling, to elucidate the mechanism of layer lofting when a shock wave spreads over the dust material and to determine the characteristics of this process. The major attention was concentrated on propagation of waves in the layer itself and on the behavior of the gas-dense medium interface (instability of this interface).

The process considered was simulated using Eiler's equations governing flows of an inviscid multicomponent compressible fluid. The ambient air was described by the equation of state of an ideal gas. The dust layer was considered as a heavy gas with an adiabatic exponent $\gamma = 1.4$. Its density was set at 500 kg/m^3, which corresponds to the density of many real loose-packed dusty materials. This approximation enabled us to adequately model not only the mass distribution in the system, but low velocity waves spreading in the layer as well (the acoustic velocity in the medium is 17 m/s which is close to its experimental values measured in loose-packed layers at 15 or 20 m/s).

The assumption does not contradict the physical nature of the flow either, indeed, ($_i$) dust in a layer istracting with a gas flow resembles a fluidized bed because particles move chaotically driven by the pas permeating in the layer and (*ii*) lofted particles acquire quite rapidly the gas velocity, therefore gasdynamically the suspension can be treated as a heavy gas in which particles behaves like large molecules.

Clearly, with this formulation of the problem, we rule out the factors related to the two-phase nature of the flow, but on the other hand, this simplification allows one to trace the role plyed by gasdynamic factors, i.e., processes associated with spreading compression and rarefaction waves in the layer and instability of the interface. Both shock wave intensity and layer depth were valied in calculations.

We illustrate the results of calculations performed under the following conditions. A 1-mm dust layer is placed on a rigid support, the initial pressure is 1 bar, the adiabatic expponent of the heavy gas is 1.4. The layer length is 0.117 m. The front and rear boundaries of the layer are rigid planes. The height of the air layer above the dust equals four dust layer thickness values. This restriction, although not so important for the early stages, was dictated by the limited computer resource. Initially, at one of the duct ends an air flow with the following parameters: pressure $2.13 \cdot 10^5$ Pa, velocity 215 m/s, and density 1.69 kg/m^3 is generated above the dust layer. This flow produces a shock wave spreading at a velocity of 526 m/s. The shock wave propagating over the layer generates a set of compression and rarefaction waves sequentially reflected fronm the rigid support and free surface. These waves disturb the layer surface and induce initial particle velocity in the vertical direction. Calculations were performed using the Godunov-Kolgan [1] scheme of high-order accuracy. The computational grid is 150×3500 cells, the time step is 10^{-8} s. The calculated field of the mass fraction of the dense material at 360 μs is illustrated in Fig.3. The frames should be considered from left to right and from top to bottom. The length of frames is 1.17 cm. The dense material layer is positioned on the left hand side and is dark, air is dark grey. Various combinations of withe and grey color pertain to smeared contact boundaries between dense material and air. The shock wave spreads downward.

Calculations show that the shock wave spreading over the layer produces periodical perturbations of the layer surface. The periodicity of perturbations is consistent with arrival of reflectet waves to the free layer surface (their length is about 17 mm). At the layer beginning, a protuberance of the dense material is observed which eventually form a vortex. As the vortex grows, thin long jets (tentacles) of the material are formed in front of it, they are tilted toward the shock front. Then these jets are transformed into votices. This flow pattern repaeats: first tentacles form then they are transformed into vortices. The vortices break-up to produce smalle vortices.

Interestingly, the size of the coarse vortices formed is about four or six times as smaller as the size of perturbations generatin in the layer by the sequence of waves spreading within the layer.
The velocity of the upper boundary of the lofted material assessed from calculations is about 10 m/s which is consistent with experiment.

To check how adequate our modeling is, that is, how accurately we resolve the structure of the turbulent flow, we compared the size of the smallest vortices in the turbulent flow (Kolmogorov's scale) and the computational cell size (0.0333 mm). Kolmogorov's scale λ is calculated by the formula [2]

$$\lambda = l_0/(\mathrm{Re})^{3/4},$$

where l_0 is the size of the coarse vortex in the flow, Re is the Reynolds number calculated by the vortex size and the fluctuation velocity. If the vortex size is set at the air layer thickness (4 mm) and the fluctuation velocity, at 50 m/s, the value of $\lambda = 3.2 \cdot 10^{-6}$ m, this is an order of magnitude less tahn the cell size. Hence we disregard small-scale turbulence. To assess how seriously this neglect affects the results of simulation, we solved the same problem taking into account the turbulence (the set of Reynolds equations for averaged quantities and modified k - ε model of turbulence [3] were used). The results of this solutiondiffer only insignificantly from those discussed above. This is because the fluctuation velocity of vortices commensurate with the cell size amounts to 1 m/s, which is much lower than the fluctuation velocity in coarse vortices responsible for dust lofting.

Calculations with various layer thickness have revealed that as the layer thickness diminishes so does the initial perturbation of the interface, because the time of wave jorney in the layer reduces. The rate of perturbation growth and, hence of the mass dust lofting rate in thinner layers is higher.

The work was supported by the Russian Foundation for the Basic Research (project 99-01-01134).

REFERENCES

1. V.P.Kolgan, *Application of the MInimum Derivative Value Principle to Constructing Finite-Difference Schemes Used to Calculate Discontinuous Solutions in Gasdynamics*, Uchenye Zapiski TsaGI, Vol.3, No.6, pp 68-77 (1972).

2. P.A.Libby, F.A.Williams, *The Basic Aspects of the Problem* , in: Turbulent Reacting Flows, P.A.Libby and F.A.Williams, Eds., Topics in Appl. Phys. Vol. 44 (Springer Verlag, Berlin, 1980).

3. A.A.Borisov and S.I.Sumskoi, *Modeling of High-speed Turbulent Flows with Energy Release*, in: Advanced Computation and Analysis of Combustion, G.D.Roy, S.M.Frolov, and P.Givi, Eds. (ENAS Publ., Moscow, 1997).

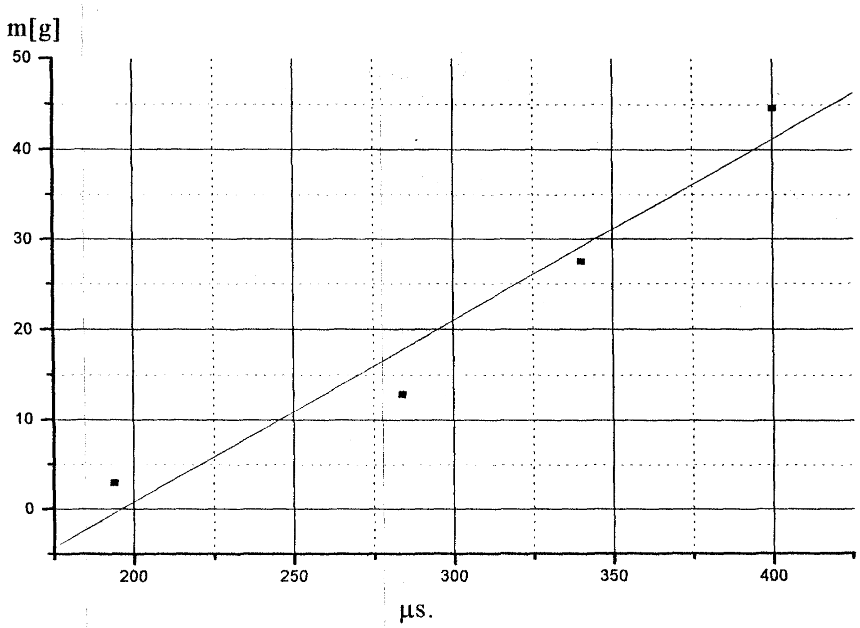

Fig. 1. Rate of mass transfer from a dust layer to tube volume.

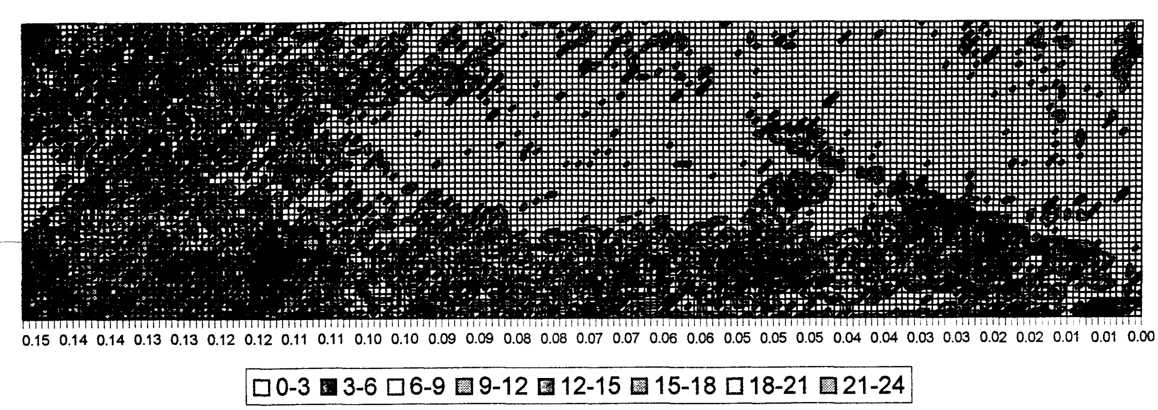

Fig. 2. Computer treating of the snapshot showing shock wave interaction with a 1,5-mm dust layer. Concentration are given in kg/m^3, t=284 μs. Wave moves from left to right.

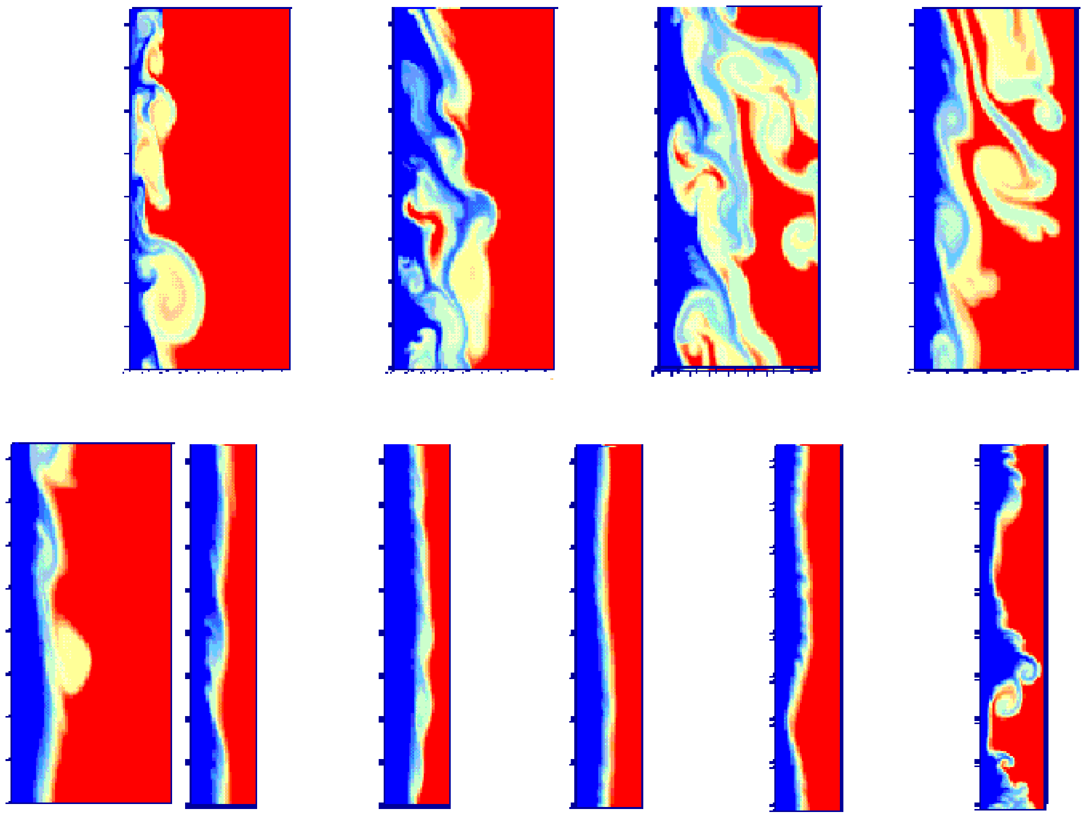

Fig. 3. Distribution of the mass fraction of air and dense medium at t=360 μs.