Characteristics of blast waves generated by milligram charges

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Abstract. Large-scale explosions have been investigated intensively by many researchers for several decades. It was found that many blast wave parameters can be scaled for charge masses varying from a few grams up to several tons. In this study it could be shown that the same scaling law can be applied even if the charge mass is only of the order of a few milligrams. Furthermore, based on pressure measurements and flow visualization, the TNT equivalence factor of the used explosive (silver azide) was found to be approximately 0.45. From the visualization results, the propagation of the primary and secondary shock wave could be mapped in corresponding x-t diagrams.

1 Introduction

The study of explosion phenomena is an important research field for safety assessment and prediction of explosion disasters. Blast waves are produced by the sudden release of energy from sources such as a chemical detonation, a nuclear explosion, or the rupture of a pressurized vessel. These waves are characterized by a supersonic shock front followed by an exponential-type decay of the physical properties of the gas [1].

In large-scale experiments, which have been intensively carried out over the last decades, many diagnostic techniques have been developed to measure the physical properties of a gas subjected to a blast wave [1] [2]. In small-scale laboratory experiments, on the other hand, different diagnostics are available, which may be difficult to implement in large-scale tests. This concerns mainly density-sensitive flow visualization techniques such as shadowgraph, schlieren methods and interferometry. These techniques allow one to visualize and - to some extent - quantify the full flow field including primary and secondary shock waves and the contact surface enveloping the cloud of combustion products [3]. Apart from significantly reduced cost, another major advantage of small-scale tests is the low turnover time between experiments - more than 30 trials per day can be performed without difficulty. The gathered information is useful for a thorough validation of computer codes for blast wave simulation, since the experimental and numerical results can easily be brought to the same format for comparison.

The intensive investigation of large-scale explosions has led to the result that many blast wave parameters can be scaled for charge masses varying from a few grams up to several tons [1] [2] [4]. In this study it was to be shown that the same scaling law can also be applied for much lower charge masses of the order of a few milligrams.

2 Experiments

Two sets of experiments were conducted, namely measurement of face-on overpressure and time-resolved schlieren visualization of the blast wave flow fields. From these records, the TNT equivalence factor of the used explosive (silver azide) could be determined and the propagation of the generated blast waves could be mapped in corresponding x-t diagrams.

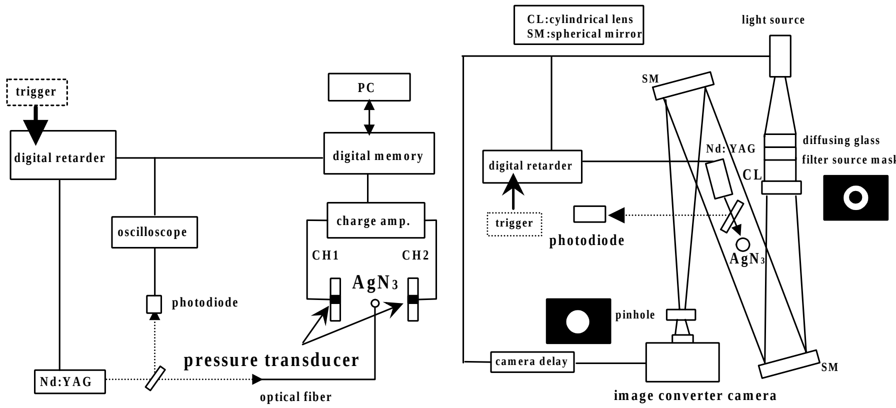
2.1 Overpressure measurements

The blast waves were generated by the detonation of silver azide (AgN_3) pellets with masses of 0.5mg, 1mg, 5 mg, and 10mg. In the overpressure tests, the charge was glued to an optical fibre and ignited by the irradiation of a pulsed Nd:YAG laser(1064nm, 7ns pulse duration, 25mJ/pulse) fed through this fibre. Fig. 1 (a) shows the schematic of the overpressure measurement setup. The charge was placed between two plates (diameter: 150mm), each of which was equipped with one piezo-electric pressure transducer (Kistler603B). The transducers were facing each other and aligned on one axis with the charge. Distances between the center of the charge and the transducer ranged from 15mm to 200mm. For smaller distances, the size of the pressure transducer becomes too large with respect to the radius of the blast wave; for larger distances, the signal-to-noise ratio increases due to weak pressure signals; for distances larger than 200 mm one also has to consider that the size of the plate is insufficient for recording the whole pressure history as corner signals may reach the transducer before the blast wave profile is completed. Further details concerning the charges, the ignition system, and the characterization of the resulting blast waves are given in [3] [5].

In a set of preparatory experiments [5] the ignition threshold of silver azide had been found to be around $100\mu J$ with an ignition delay of less than $1\mu s$. The instant of ignition therefore corresponds with sufficient accuracy to the instant when the Nd:YAG laser is fired, which can be measured by means of a photodiode as indicated in Fig. 1 (a).

2.2 Visualization

In these tests, the charge was glued to a nylon thread and ignited by direct irradiation of the Nd:YAG laser. Visualization was performed using time-resolved monochrome schlieren, shown schematically in Fig. 1 (b). Analogous to the configuration in a colour schlieren apparatus [6] a diffusing screen with a circular source mask was illuminated by a light source (a flashlamp that provided intense illumination for about 1 ms), while a pinhole was used as cutoff device. This resulted in a system that was equally sensitive to gradients in all directions. A



(a) pressure measurement (b) time-resolved schlieren method

Fig. 1. Schematic of experimental setup

cylindrical lens in front of the source mask was required for astigmatic correction [6]. The images were recorded with an image converter camera, which could take 6 frames per test with individual exposure times of 200ns.

3 Results and Discussion

3.1 Overpressure

The arrival of the shock front leads to a pressure jump from atmospheric pressure P_1 to the shock-generated pressure P_2. The pressure increment $P_2 - P_1$ is termed side-on overpressure. If the shock reflects from a rigid surface, the pressure increases from P_1 to the reflected pressure P_5. The corresponding pressure increment $P_5 - P_1$ is termed face-on overpressure.
The changes of the thermodynamic properties of the gas can be determined using the Rankine-Hugoniot relations. These relations can be written in a form that links the jump in pressure, density, temperature etc. immediately behind the shock front to the speed of the shock front, V_s, usually expressed in form of the shock Mach number M_s:

$$M_s = \frac{V_s}{a_1} \tag{1}$$

where a_1 is the speed of sound in the gas ahead of the shock.

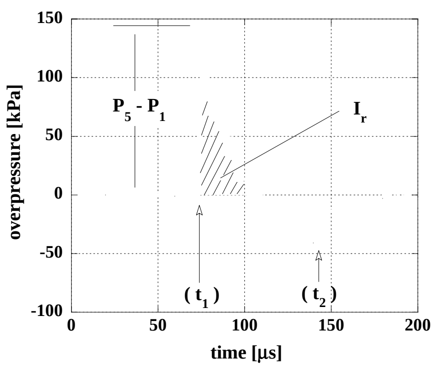
The normalized side-on overpressure immediately behind the shock, in terms of the shock Mach number, is given by

$$\frac{P_2 - P_1}{P_1} = \frac{2\gamma M_s^2 - 2\gamma}{\gamma + 1} = \Delta P_{21} \tag{2}$$

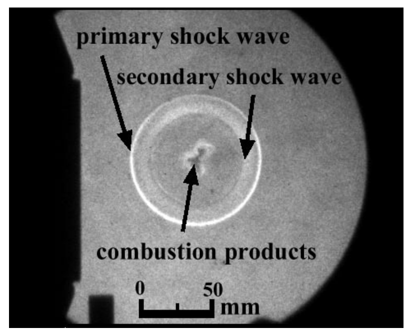
and the normalized reflected overpressure follows as [1]

$$\frac{P_5 - P_1}{P_1} = 2\Delta P_{21} + \frac{(\gamma+1)\Delta P_{21}^2}{(\gamma-1)\Delta P_{21} + 2\gamma} = \Delta P_{51} \tag{3}$$

Fig. 2 (a) shows a typical face-on overpressure-vs.-time trace of a blast wave, from which three essential blast wave parameters (face-on overpressure $P_5 - P_1$, reflected impulse I_r, time of arrival t_1) can be obtained. From the complete series of experiments, an overpressure-vs.-range diagram of the type of Fig. 4 can be established. Following the initial pressure jump at t_1 and the subsequent decay, at time t_2 a second but significantly smaller pressure jump is observed, caused by the so-called secondary shock, which is a common (but usually weak and therefore mostly neglected) blast wave feature [1] [2]. The time of arrival data from these tests were included in the x-t diagrams (Fig. 3) and were seen to be in excellent agreement with the corresponding data from the independently carried out visualization.



(a) face-on overpressure vs. time

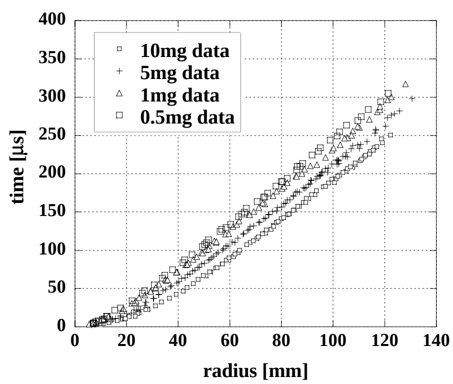


(b) schlieren visualization

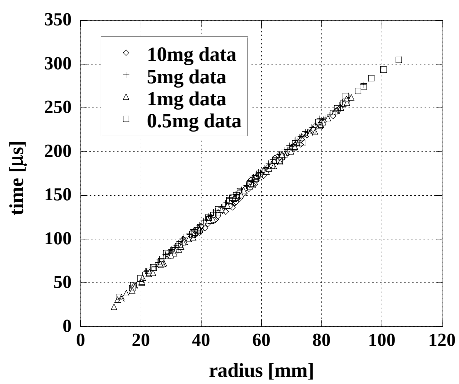
Fig. 2. (a) Typical face-on overpressure-vs.-time trace for a blast wave generated by 5 mg of silver azide at a distance of 45 mm from the transducer (b) One frame of a sequence of photos obtained with the time-resolved schlieren system. Instant of photography: 156μs after ignition of a 1mg silver azide charge.

3.2 Visualization data

From series of photos of the type of Fig. 2 (b) it is possible to measure with sufficient accuracy the loci of the discontinuities (primary shock wave, secondary shock wave, and the cloud of combustion products) and to establish an x-t diagram for all investigated charge masses (Fig. 3). The decay in shock speed for the primary blast wave is - as expected - more rapid for smaller charges than for large ones so that distinct x-t curves are established for each charge size. The propagation speed of the secondary shock, however, appears to be essentially constant for all investigated charge masses, at least within the accuracy of this measurement. The reason for this feature is currently being further investigated. Since the jump of the thermodynamic properties is intimately linked to the speed of the shock front, the time-of-arrival data can be used to independently obtain pressure values [2] [4]. Based on the x-t data from visualization and pressure measurements an appropriate curve fit $x = x(t)$ can be found. The form of this fit is critical and a strictly monotonous function should be used [2]. Corresponding functions were determined for the x-t curve of all primary blast waves associated with each charge mass. Differentiation of these functions yields the charge-specific shock speed V_s from which according to the above relations the face-on overpressure can be determined. The results are presented together with the pressure measurements in Fig. 4.



(a) primary shock wave



(b) secondary shock wave

Fig. 3. x-t diagram of primary and secondary shock waves

3.3 Overpressure vs. scaled distance

The most common form of blast scaling is the "cube-root" scaling [7] [8]. This states that at identical scaled distances self-similar blast waves are produced when two explosive charges of similar geometry and of the same explosive, but of different sizes, are detonated in the same atmosphere. It is customary to plot the blast property of interest (e.g., the overpressure) against the scaled distance Z_{HC} defined as

$$Z_{HC} = \frac{x}{W^{1/3}} \quad (4)$$

where x is the distance from the center of the explosive source and W is the charge mass. The scaling law has been extended to account for differences in atmospheric conditions [9]. In this case, the previously defined overpressure ratios ΔP_{21} or ΔP_{51} are plotted against the scaled distance

$$Z_S = \frac{x}{W^{1/3}} \times P_1^{1/3} \tag{5}$$

A great amount of reference data exists for TNT as 'standard' explosive. These data are normalized to standard atmospheric conditions ($P_0 = 101.25$ kPa, $T_0 = 288.15$K) and are available in tabulated form [1], as curve fits [4], or in databases [2]. In order to compare an explosive other than TNT with these reference data, W is to be interpreted as the equivalent TNT mass of the charge, i.e., the mass of TNT that would be necessary to generate a blast wave of the same characteristics as the one generated by the investigated charge (here: silver azide). This can be written as

$$W = W_{TNT} = \eta \times W_{silverazide} \tag{6}$$

with η as the TNT equivalence factor. An explosive is said to follow the scaling laws [7] [8] [9] if its overpressure-vs.-scaled distance curve coincides with that of the reference explosive. Figure 4 shows the experimentally obtained face-on overpressure data vs. scaled distance in comparison with TNT reference data from [4] for an equivalence factor of 0.45. The experimental data points, which represent about 1500 measurements obtained in more than 300 trials, lie reasonably close to the reference curve. Pressure and visualization data were found to be in very good agreement and give virtually identical results. The value of η found in these experiments lies significantly below the value given in the literature [10], which was, however, determined for larger charges by the entirely different sand crush test method ($\eta_{lit} = 0.88$). The exact determination of η depends to a large extend on the blast property chosen for comparison and also on the selected set of reference data. Slight deviations from the value obtained here are possible if other blast properties (e.g., impulse or energy) and different reference sources (e.g., [1] [2]) are used. These differences will, however, be minor and would not account for the significant discrepancy between the value found here and the one given in the literature.

4 Conclusions

In order to characterize the properties of blast waves generated by milligram charges in free-air, extensive flow visualization and pressure measurements were conducted. The results of these tests can be summarized as follows:

1. The propagation of primary and secondary blast waves for four different charge masses (0.5mg, 1mg, 5mg, and 10mg) was mapped in corresponding x-t diagrams.
2. Independently obtained pressure measurements and visualization data were found to be in very good agreement.
3. The blast waves generated by the investigated charges follow the scaling laws introduced in [7] [8] [9].

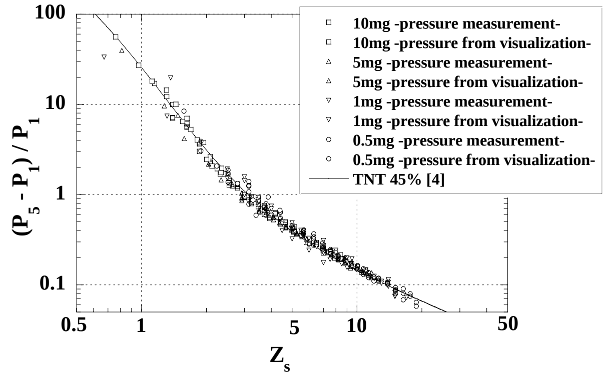


Fig. 4. Normalized face-on overpressure vs. Sachs-scaled distance

4. Based on pressure and visualization records, the TNT equivalence of silver azide was found to be approximately 0.45.
5. The propagation speed of the secondary shock wave appears to be essentially constant for all investigated charge masses.

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