Blast Wave Reflection from Solid, Liquid, and Gaseous Surfaces

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Abstract. This paper presents first results of an experimental and numerical investigation of the unsteady process of blast wave reflection from straight surfaces. One purpose of this preliminary study is to demonstrate that basic blast wave phenomena such as the transition from regular to irregular wave reflection can be adequately studied by using small charges with masses in the milligram range. These trials can be performed in a laboratory environment, which enables one to make use of a number of diagnostic techniques that are not applicable in large-scale experiments. The present tests reveal that energy losses that occur during the impingement of the blast wave on the surface of a second medium do not lead to a noticeable change of the reflection pattern. Furthermore, from a comparison of the numerical and experimental data it becomes obvious that the experimental determination of the transition point from regular to Mach reflection – both in small-scale and large-scale trials – is rather difficult and possibly inaccurate because of the initially small size and gradual growth of the Mach stem.

1 Introduction

Blast waves represent one of the most common forms of "non-constant velocity shock waves". The reflection of these waves from straight surfaces is a truly unsteady process, which has received less attention in the open literature than the case of steady or pseudo-steady reflection phenomena [1], even though blast waves have been thoroughly investigated over the last few decades [2–4]. One of the reasons for the limited amount of data about the basic characteristics of the reflection process is the fact that considerable measurement difficulties exist when charges with masses ranging between a few hundred grams and several thousands of kilograms are used. Even though a great variety of special instruments and sophisticated diagnostics have been developed, the inherently destructive nature of these tests has imposed severe restrictions to the applicable diagnostics. In large-scale tests, the diagnostic systems may easily become very complex unless one limits the measurement and observation range. Although in principle possible, it is usually very difficult in these trials to visualize the whole flow field generated by the blast wave. Cost and turnover time in large-scale tests present two other constraints, which reduce the overall number of feasible tests.

Small-scale tests, on the other hand, have the advantage that they can be safely performed in a laboratory-environment, if the charge masses are only of the order of a few milligrams. In a preliminary test series it was shown [5] that the blast waves generated by such small charges follow the well-established scaling laws [2–4] and that they can be used to simulate the flow fields observed for charges that are several orders of magnitude larger. With the baseline provided by these tests [5], in which complete "maps" of the small-scale blasts were established and the TNT equivalence factor of the used explosive (silver azide, AgN_3) was determined, the miniature charges can be taken as an instrument to study in greater detail general blast wave phenomena on a convenient model scale.

Changing to a laboratory environment has shortcomings and advantages with respect to the applicable diagnostics: Some very informative techniques used in large-scale trials (such as tracer methods) become mostly inapplicable, while the laboratory can easily provide other options, such as the full visualization of the flow field by several density-sensitive visualization techniques [6], which are only of limited use in large-scale tests. Another point to be considered is that in scaled-down experiments the observation time is also reduced in similar fashion as the charge masses and distances. In large-scale tests, recording devices such as framing cameras with the ability to take several thousand frames per second suffice for observation and measurement purposes, but in small-scale experiments such devices have to be orders of magnitude faster. Finally, small-scale trials have a major advantage in terms of cost and turnover time – depending on the complexity of the setup, it is possible to perform more than 20 experiments per day with minimal operational cost.

2 Reflection Processes

No theory exists for the process of blast wave reflection from a straight surface, which is schematically shown in Fig. 1. The wave initially reflects regularly, but at a certain horizontal distance x_{tr} from the explosion center, the pattern changes into an irregular reflection [1–4]. It has been postulated [4,7] that the transition from regular to irregular reflection can be described using the same criteria as for the pseudo-steady case of planar waves reflecting from wedges, which has been the subject of an abundance of theoretical, numerical, and experimental investigations [1]. Experimental evidence, however scarce, seems to give inconclusive results, which are unfortunately not extensively elaborated on.

When a blast wave reflects from a surface, the reflection process causes an energy transfer: A part of the blast-inherent energy is transmitted into the medium from which the wave reflects while another part is continuously redistributed within the flow field as a consequence of the interaction of the wave with elements of the surface [8].

It appears plausible to assume that these energy transfer processes influence the transition from regular to irregular reflection and that, for instance, a change of their relative magnitudes may change the reflection pattern. It has been shown in other experiments (mostly for planar shock waves) that the condition of the

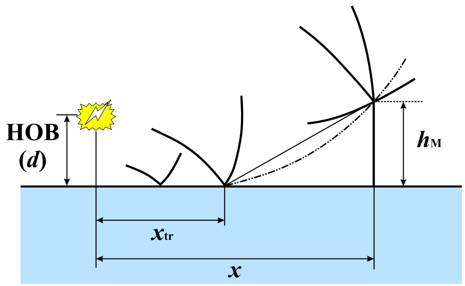

Fig. 1. Reflection of a blast wave from a straight surface

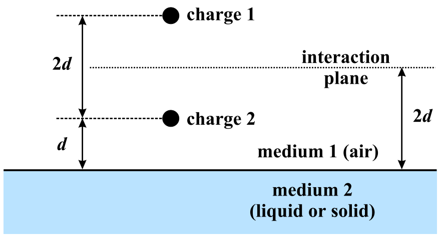

Fig. 2. Charge configuration

surface (smooth, rough, porous, slit etc.) can significantly modify the transition process and the shape of the evolving wave systems [1]. These effects are also important for the reflection of blast waves, but they shall not be investigated here and they shall be eliminated as much as possible by only considering smooth surfaces. The ultimate goal of this study is to determine, whether the energy losses that inevitably occur when a blast wave impinges on a reflecting surface also have an effect on the transition behavior. Such energy losses can be envisioned to appear in the form of transmitted waves (e.g., seismic waves or ground shock) or as a result of the displacement of a yielding surface (e.g., cratering). It may be assumed that, as a consequence of these losses, the blast wave is weakened, which should affect the moment of transition to irregular reflection and equivalently the formation process and growth of the Mach stem.

In a small series of large-scale experiments [8] such effects were indeed observed, although the number of experiments and the amount of collected data may be considered too small for a general clarification of the issue. In these experiments, two charges were simultaneously ignited, one at a distance d from the ground and the other at a distance $3d$, located directly over the first charge (see Fig. 2). The reflection from the ground of the blast wave generated by the lower charge was then compared with the interaction between the two blast waves in mid-air at a vertical distance of $2d$ from the ground. The latter pattern is considered an ideal reflection process inasmuch as it may be postulated that no energy is lost in this process [8].

3 Experiments

In the present experiments, the test scenario is very similar to that described in [8]. Two charges, aligned along a line perpendicular to a straight, smooth surface at vertical distances d and $3d$, respectively, were fired simultaneously by laser ignition. The charge mass was kept constant at 10 mg AgN_3 while d was chosen to be either 20 or 30 mm. The propagation of the blast waves was monitored by means of time-resolved omni-directional monochrome and single-shot direction-indicating color schlieren pictures. In the time-resolved mode, a high-speed image converter camera (IMACON 200, Hadland Inc.) allowed one to take up to 16 frames of the process with image separations between 2 and 10 microseconds (both shorter and longer separations are possible, but not necessary or useful for this investigation). The color schlieren pictures were taken at selected instants based on the previously obtained time-resolved records in order to get higher resolution images and additional information about the density gradient direction. Both recording setups are essentially conventional schlieren systems, which are described in [5,6].

These experiments can be understood as scaled-down versions of the large-scale tests described in [8], although for the cases presented here the configuration of the large-scale experiments has not been exactly duplicated. One further difference is the fact that in one half of the experiments the reflecting surface is liquid rather than solid. If energy losses play a role in the transition process, their effect should be more pronounced for a liquid reflecting surface. The acoustic impedances of air, water, and metal (aluminum) are several orders of magnitude apart (the ratio is approximately 1:4500:40000), which indicates that even though most of the energy imparted by the impinging wave will be found in the reflected wave, there should be about one order of magnitude difference between the strengths of the transmitted waves in liquid and in metal. In fact, in the case of a liquid one can visualize the transmitted wave and from an adequate visualization, with some assumptions concerning the symmetry of the wave and the properties of the liquid, one may even give an estimate for the amount of transmitted energy. A liquid surface, however, presents the technical difficulty that its exact position is partially veiled in the visualization since the meniscus effect at the windows of the test section deflects some of the light. With the help of a calibration, the resulting inaccuracy of measurement can be reduced to about ±0.2 mm.

The described test scenario can be expected to yield reliable results if the following conditions are met:

- The charges are fired and ignited simultaneously.
- The explosive yield of both charges is identical.
- The charges are exactly aligned as seen in Fig. 2.

In reality, none of these conditions can be exactly fulfilled. It is important to clarify at an early stage of the investigation to what extent inevitable experimental inaccuracies and uncertainties may affect the results. Synchronized ignition (within fractions of 1 μs) is the least critical factor for the used laser ignition system (see [5] for details). The explosive yield, on the other hand, cannot be fully controlled, even for charge masses that are identical within measurement accuracy – only by analyzing the results of a performed test may one determine in retrospect whether this condition has been met. This task is somewhat simplified if a visualization of the full flow field is available, as asymmetric structures resulting from unequal explosive yields would become obvious on such records. On the other hand, deviations in the charge positioning such as the ones indicated in Fig. 3 may be considered as the main source of errors. In the present arrangement, the position uncertainties given in Fig. 3 are $\Delta x \approx \Delta y \approx \Delta z \approx 0.25$ mm.

Changes Δz in the vertical distance d (i.e., the height of burst) can be assumed to have the strongest influence on the results.

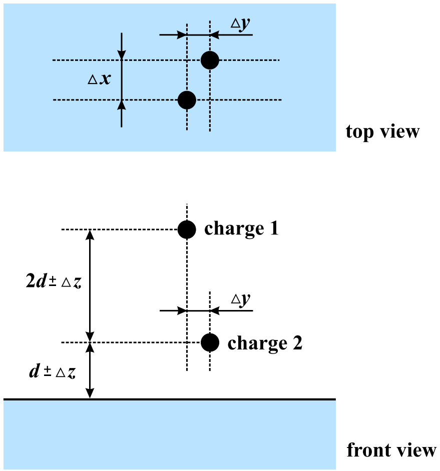

Fig. 3. Possible alignment errors

Fig. 4. Influence of variations of the height of burst on the Mach stem height; results from numerical simulation; nominal height of burst: 20 mm; charge mass: 10 mg AgN_3

4 Numerical Simulation

In order to clarify how much influence the aforementioned small changes Δz in the height of burst have on the wave pattern, the reflection process was simulated numerically. The propagation of the blast wave was modeled according to the experimentally obtained x-t diagrams [5]. An ideal reflecting surface was assumed. The calculations were carried out using a 2-D locally adaptive unstructured Euler code [9] with the minimum grid spacing equal to $\approx 0.00078\, d$.

The simulation, which yielded the height h_M of the Mach stem as a function of the horizontal distance x from the explosion center was performed for the nominal height of burst ($d = 20$ mm or 30 mm) and in addition for the cases with the highest expected deviations from this nominal value, i.e., $d \pm 0.5$ mm. From the results (see Fig. 4 for $d = 20$ mm) it is obvious that the Mach stem height may vary by approximately 10% just as a result of these changes in the height of burst. Consequently, for the interpretation of experimental results, it may be concluded that variations in Mach stem height below this value of 10% cannot clearly be attributed to wave reflection phenomena other than shifts in the transition history caused by uncertainties in the height of burst.

5 Results and Discussion

The height of the Mach stem as a function of the horizontal distance x of the reflection point from the explosion center was determined from the experimental records such as the one given in Fig. 5 and compared with the numerical prediction presented in Fig. 4. The result of this comparison is shown in Fig. 6. The experimental data follow the trend indicated by the simulation, however, the scatter is generally quite large and mostly exceeds the range of predicted Mach stem heights for the considered variations of height of burst. This can be attributed to general measurement inaccuracies (the measurement of the Mach stem dimensions on the time-resolved records is usually less accurate than on the single-shot pictures because of the significantly lower image resolution of the former visualization) and to variations in the explosive yield, which was considered as constant in the calculations. Furthermore it appears that at larger horizontal distances x the experimentally determined Mach stem height is consistently below the predicted value. This may have been caused by small discrepancies between the numerical modeling of the blast wave propagation and the experimentally determined blast wave trajectory. A very recent analysis of the experimental x-t data also indicates a variation of the equivalence factor with shock radius. It can be seen that the blast wave from silver azide is weaker, relative to TNT, close to the charge, and relatively stronger at greater distances [10]. The exact cause of the differences in measured and calculated Mach stem height is the subject of further studies.

More significant than the differences between the numerical and the experimental data is the fact that within the given measurement accuracy there is hardly a noticeable discrepancy between the Mach stem heights measured at the reflecting surface and in mid-air, irrespective of the material of the reflecting surface. This means that the reflection from a smooth liquid or solid surface eventually yields the same reflection pattern as that from the "ideal" surface in mid-air. This result is largely consistent with the findings in [8], where the differences in Mach stem trajectory were found to be very small for the "ideal" gaseous and a smooth solid surface. The present results indicate that the change in acoustic impedance does not significantly influence the reflection pattern.

Another important result concerns the determination of the transition point x_{tr} from regular to irregular reflection. From conventional flow visualization records it is not possible to detect directly the onset of irregular reflection before the Mach stem has attained a recognizable size (about 1 mm in the present experiments). The location of the transition point may be obtained from an extrapolation of an experimentally determined triple point trajectory, however, unlike in the case of planar waves reflecting from wedges, the trajectory is tangential to the reflecting surface, which introduces large potential errors (note that in Fig. 1 the initial angle has been strongly exaggerated for the sake of clarity). The results of the numerical simulation indicate that the actual transition has occurred much earlier – at a distance $x \approx 17$ mm for $d = 20$ mm – than the instant at which experimentally a Mach stem is first observed ($x \approx 27$ mm, see Fig. 6) . In a log-log plot of h_M vs. x, the differences become even more obvious. It appears mandatory that a new set of experimental techniques be developed that may overcome this problem, which is caused by the initially small size and the very gradual growth of the Mach stem. This observation holds true both

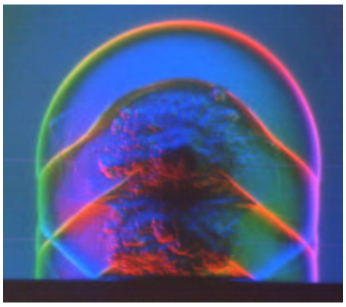

Fig. 5. Color schlieren visualization of the flow; nominal height of burst: 20 mm; charge mass: 10 mg AgN_3; visualized instant: 122 μs after ignition

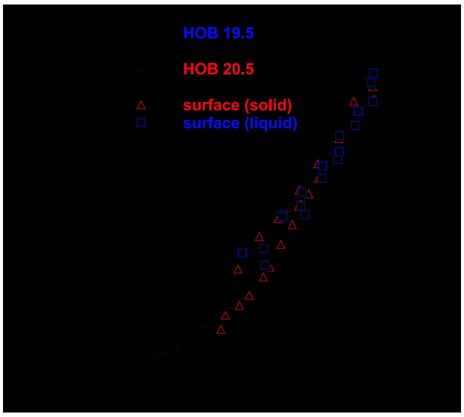

Fig. 6. Experimental and numerical data for the Mach stem height vs. distance from the explosion center; height of burst: 20 mm; charge mass: 10 mg AgN_3

for small-scale and large-scale experiments. The full visualization of the flow in the small-scale trials may, however, offer one possible alternative: The slip lines formed by the triple point trajectories of the mid-air interaction are usually visible if the combustion products do not veil this part of the flow. Since the effect of the blast wind is very small for the used charges, it may be assumed that the displacement of this wave pattern by the flow following the blast front is negligible, so that one might define the onset of transition as the location where the slip lines first become visible. This subject is currently being investigated.

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