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Detailed Comparison of Blast Effects in Air and Vacuum

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Abstract.

Although blast mitigation is most often achieved with solid shielding, ambient gas pressure can also affect the coupling of shock waves to solid targets. In this work the role of air as an energy transfer medium was examined experimentally by subjecting identical large-area rectangular witness plates to short-range blast effects in air and vacuum (~50 mtorr) at 25 ºC. The expanding reactant front of 3 kg C4 charges was observed by fast camera to be cylindrically symmetric in both air and vacuum. The horizontal component of the reactant cloud velocity (perpendicular to the witness plates) was constant in both cases, with values of 3.0 and 5.9 km/s for air and vacuum, respectively. As a result of the blast, witness plates were plastically deformed into a shallow dish geometry, with local maxima 30 and 20 mm deep for air and vacuum, respectively. The average plate deflection from the air blast was 11 mm, ~10% deeper than the average vacuum plate deflection. Shock pressure estimates were made with a simple impedance-matching model, and indicate peak values in the 30-50 MPa range are consistent with the reactant cloud density and velocity. However, more detailed analysis is necessary to definitely establish the mechanisms by which air couples shock energy to the plates.

EXPERIMENTAL PROCEDURE

Blast mitigation is conventionally achieved with solid shield materials that absorb energy as they mechanically deform.[1]. However, under certain conditions the blast medium itself can be modified to reduce damage. Here we experimentally examine the role of air as an energy transfer medium by subjecting identical large-area rectangular witness plates to short-range blast effects in air and vacuum.

The experimental setup is shown in Fig. 1. The charge used was a 3-kg, 17.2 cm diameter cylinder of C4 (91% RDX, 9% polyisobutylene), compressed to 1.3 g/cm3 (~80% theoretical maximum density). It was initiated by an RP1 detonator and composition B booster embedded to a depth of 3.8 cm from the top of the C4 charge.

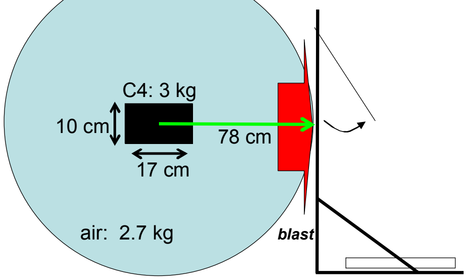

Fig. 1 Experimental configuration for air and vacuum blast experiments. A cylindrical 3 kg C4 charge was positioned 78 cm from the center of a 6061-T651 aluminum alloy plate, 64 mm thick, 610 mm wide and 533 mm high. The plate was allowed to swing freely from a horizontal rod mounted on a stand which was designed to break under horizontal loading.

The charge was positioned 78 cm from the center of a 6061-T651 aluminum alloy plate, 64 mm thick, 610 mm wide and 533 mm high, clamped to a thick metal frame at the edges. The position of plate relative to the charge corresponds to a Hopkinson-Cranz scaled range[2-4], $Z = R/W^{1/3}$, of 0.4 m/kg$^{1/3}$, where R is the range from the explosive to the target and W is the weight of the charge.

The axis of the cylindrical charge was parallel to the vertical axis of the plate. The plate and frame were allowed to swing freely from a horizontal rod mounted on a stand designed to break under loading in a direction perpendicular the surface of the plate. The break-away stand and freely-swinging plate increased the influence of shock and prompt blast effects on the mechanical deformation of the plate, further reducing the relative importance of later-time blast and combustion-related effects.

Experiments were performed in a fully-contained, 56 m^3 spherical firing tank. The air blast was initiated at ~25º C, 750 torr, while the vacuum blast was initiated at ~25 ºC, 50 mtorr. The blast evolution was observed by Phoenix fast camera, imaging at 33 µs per frame. Chamber pressure was measured as a function of time by blast probes positioned ~2.4 meters from the center of the charge, pointing toward the charge.

RESULTS AND DISCUSSION

The evolution of the blast front is shown for the case of air and vacuum in Fig. 2(a) and 2(b), respectively, where each frame in the sequence separated from the previous frame by 33 µs. Combustion of C4 (which is ~45% oxygen deficient[5]) in air makes the blast front highly luminous. The chaotic formation and evolution of combustion cells is evident in air, while the blast front in vacuum is almost translucent. When the vacuum blast front reaches the aluminum plate, a light-generating event is observed, which may be pressure-induced reaction of C4 with itself, or reaction of the explosive with the surface of the aluminum plate. The blast profile in both cases has a pronounced cylindrical symmetry that reflects the geometry of the pressed explosive charge.

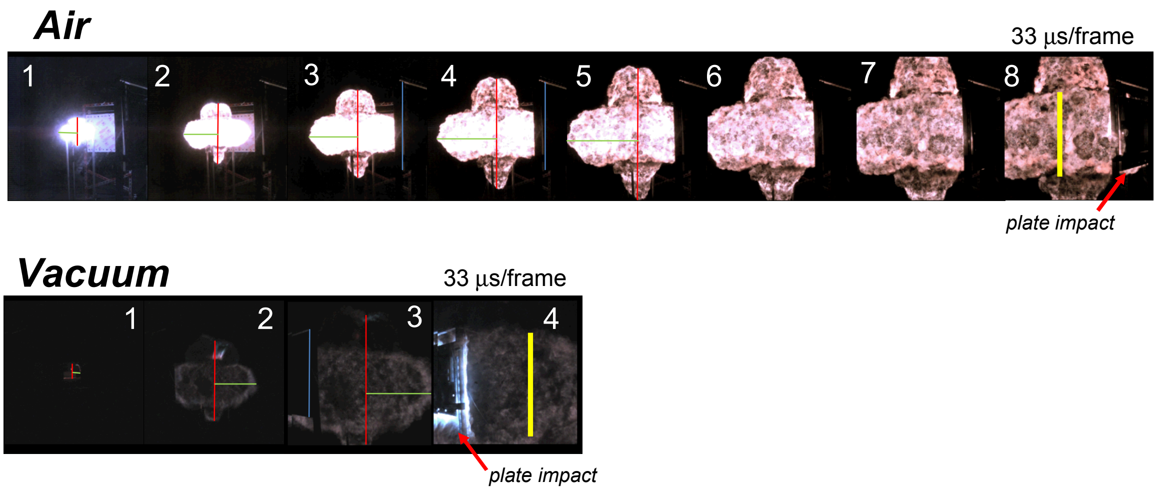

Fig. 2. Evolution of blast wave for (a) air, and (b) vacuum, with frames separated in time by 33 µs.

The final witness plate deflection is shown in Fig. 3(a) and (b) for air and vacuum, respectively, with deflection statistics summarized in Table 1.

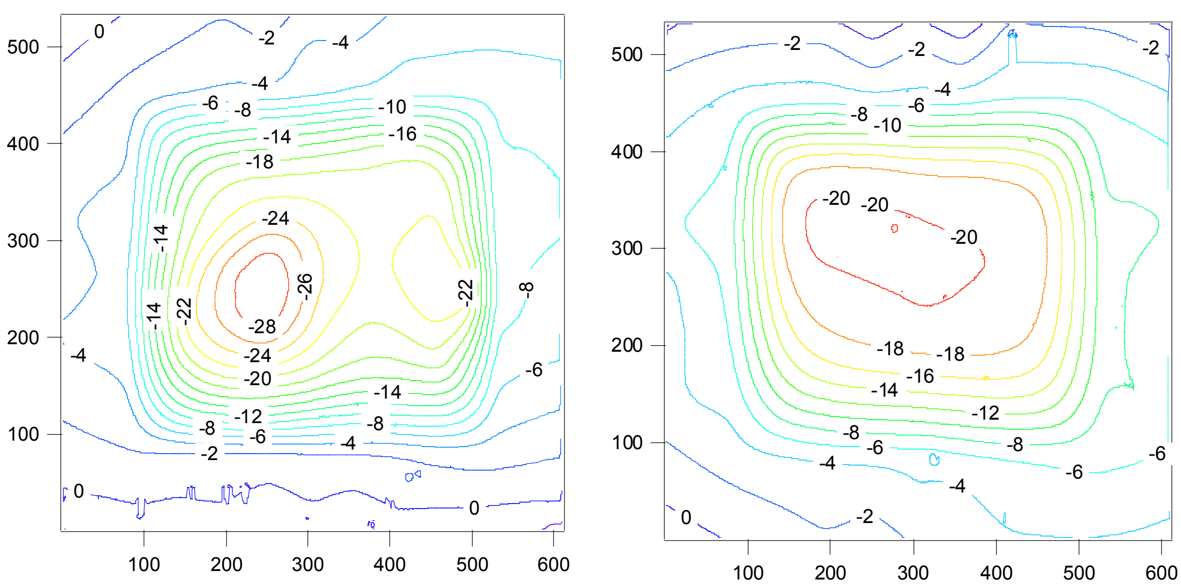

Fig. 3. Depth profiles of aluminum plates subjected to blast loading in (a) air and (b) vacuum.

	Air	Vacuum	% difference
# points	268301	267812	0.2
avg depth (mm)	-11.4	-10.4	8.8
std dev	8.3	6.2	25.3
rms depth	14.1	12.1	14.2
minimum	-29.5	-20.4	30.8
maximum	3.3	2.2	33.3

Table 1. Deflection conditions for 6061-T651 aluminum alloy plate, 64 mm thick, 610 mm wide and 533 mm high after blast loading

The average deflection depth is about 9% larger in the case of air vs. vacuum, while the maximum deflection is 33% larger. In both cases, a smooth dish-like geometry is observed in the plates, indicative of the curved blast fronts. There are two minima in the air blast plate, vs. one in the vacuum blast, but all minima are centrally located on the plates, consistent with the alignment of the cylindrical charge.

Blast pressure as a function of time is shown in Fig. 4, together with polynomial fits to highlight the data trend. As expected, vacuum conditions are effective at suppressing average chamber overpressure, and the combustion-induced pressure rise which develops for air is not observed for vacuum. Early time, shock-induced pressures create a poorly-controlled transient in the pressure transducers which is not visible on time scale shown. The high-frequency pressure oscillations indicate ringing in the 56 m^3 spherical firing tank.

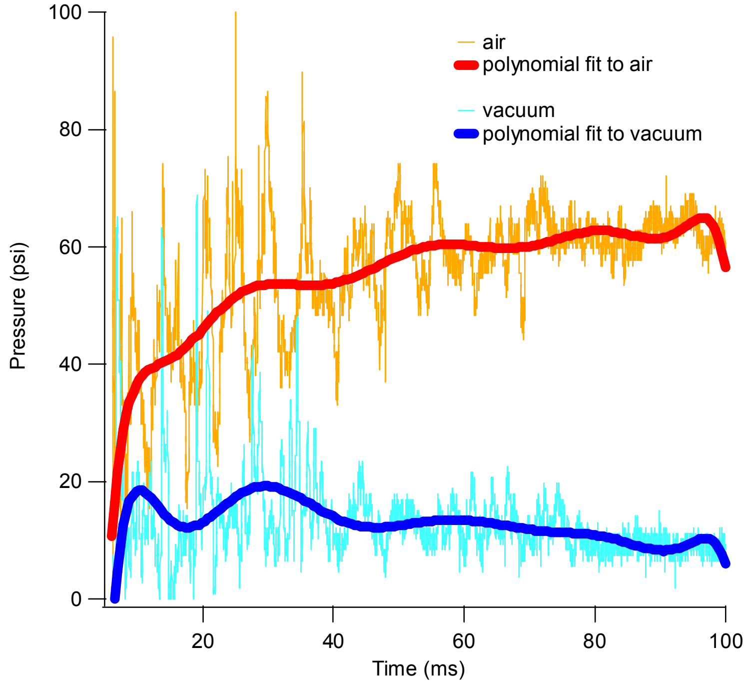

Fig. 4 Blast pressure as a function of time.

The reactant front velocity can be estimated from the images shown in Fig. 2. The position of the front as a function of time is shown in Fig. 5, together with the observed time of plate impact. The velocity appears constant in both cases, with values of 3.0 and 5.9 km/s for air and vacuum, respectively. A Cheetah 4.0 calculation of the Chapman-Jouget condition of C4 at 1.3 g/cm3 in air indicates a shock velocity of 6.8 km/s, which is consistent with the reactant front velocity observed in vacuum.

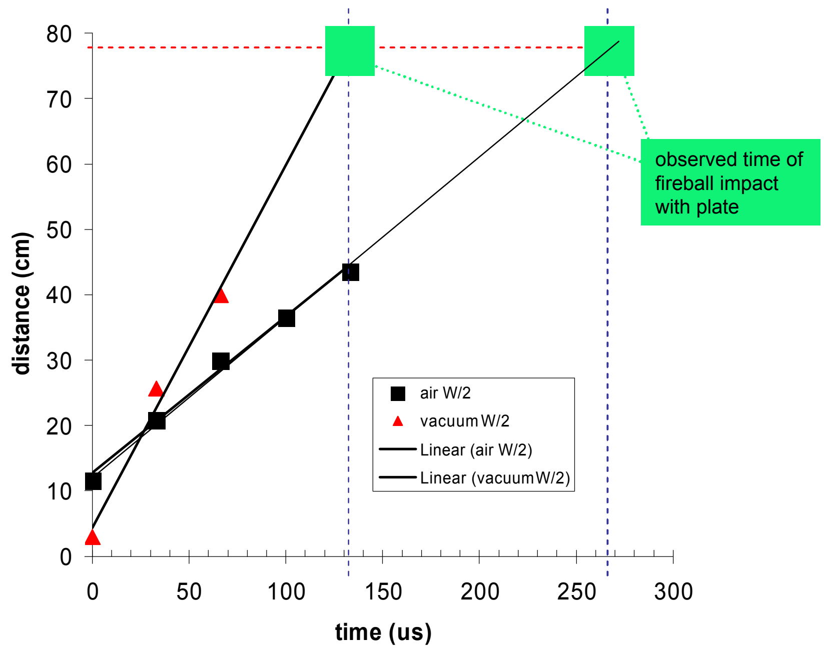

Fig.5. Reactant front edge position vs. time, extracted from fast camera images taken 33 µs apart.

Calculations of prompt shock pressure are complicated by fact that the target plate was allowed to move freely, and by the non-spherical nature of the explosive charge.[6] However, some quantitative pressure estimate can be made by considering the simplified case of an impedance-matched shock interface between two slabs, where one of the slabs is the aluminum target plate, and one of the slabs is the explosively-driven C4 reaction products in air or vacuum. The velocities of the slabs are determined by fast camera images, as shown in from Fig. 4, and slab densities are found by assuming a (simplified) uniform, spherical geometry for the reaction products. Densities calculated in this way are 0.0028 g/cm3 for the air blast (taking into account 2.7 kg of air mass), and 0.0012 in the case of vacuum. For both cases, the Hugoniot speed of sound, C_0, and the s parameter were taken to be 0.9 km/s and 0.94, respectively, which are appropriate for gases.[5] The resulting shock pressures then are 31 and 45 MPa for air and vacuum, respectively.

For spherical shock waves in air, overpressure can also be calculated from[7]:

$$\frac{P-P_0}{P_0}=\frac{2\gamma}{\gamma-1}\left[\left(\frac{V}{a}\right)^2-1\right] \qquad (1)$$

where P is absolute pressure immediately behind the shock front, P_0 is absolute pressure ahead of the shock , V is the velocity of the shock relative to the medium ahead, a is the velocity of sound in the medium and γ is the ratio of specific heats $C_P/C_V = 1.4$.[5] Taking

$P_0 = 1.01\times10^5$ Pa, a = 331 m/s (for air P_0), and shock velocity V as 6.8 km/s (from Cheetah 4.0), then P = 49 MPa. If, however, V is reduced to 5.4 km/s, which is closer to observed reactant propagation in vacuum, then P matches the shock pressure found by impedance-matching for air. Note that although is some uncertainty in γ at these high pressures and temperatures, $\gamma = 1.4$ is a lower limit,[8] and increasing γ leads to larger, not smaller, overpressures.

The similarity of the quantitative pressure estimates obtained by these two methods provides some measure of confidence in the resulting order of magnitude. However, the impedance-matching calculation gives a larger shock pressure for air vs. vacuum, while experimentally we find that the permanent plate deflection is larger for air vs. vacuum. There are two possible explanations for this difference. First, the impulse of the reactants acting on the plate in air is likely greater than the impulse of the reactants acting on the plate in vacuum, because of the longer interaction time of the shock-compressed air shell surrounding the expanding reactants. Alternately, the vacuum density may be lower than assumed with the simplified spherical reactant cloud geometry. It is true that additional energy will be provided by oxygen in air reacting with C4, but this late-time energy is unlikely to be efficient at causing plate deflection.

CONCLUSIONS

The role of air as an energy transfer medium was examined experimentally by subjecting identical large-area rectangular witness plates to short-range blast effects in air and vacuum (~50 mtorr) at 25 ºC. A cylindrical 3 kg charge of C4 was positioned 78 cm from the center of 6061-T651 aluminum alloy plates, 64 mm thick, 610 mm wide and 533 mm high, clamped to a thick metal frame at the edges. The position of plate relative to the charge corresponds to a Hopkinson-Cranz scaled range, $Z = R/W^{1/3}$, of 0.4 m/kg$^{1/3}$. Late time pressures measured by blast gauges were higher on average for air vs. vacuum, and increased as a function of time in air due to combustion effects. The expanding reactant front, observed by fast camera, was cylindrically symmetric. The horizontal component of the reactant cloud velocity (perpendicular to the witness plate) was constant in both cases, with values of 3.0 and 5.9 km/s for air and vacuum, respectively. As a result of the blast, witness plates were plastically deformed into a shallow dish geometry, with local maxima 30 and 20 mm deep for air and vacuum, respectively. The average plate deflection from the air blast was 11 mm, ~10% deeper than the average vacuum plate deflection. Shock pressure estimates of 31 and 45 MPa for air and vacuum, respectively, were made with a simple model which assumed uniform, spherical reactant distribution. The fact that the vacuum plate deflection was experimentally found to be smaller than the deflection of the plate shocked in air may be a result of longer shock pressure interaction of the plate in air, or lower density of the vacuum reactant cloud, neither of which were accounted for in the simple shock pressure model. Future work will apply experiments on complementary witness plate configurations as well as employ finite element analysis to provide a better estimate of shock pressure consistent with the observed plate deflections.

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