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OPTIMIZATION STUDIES OF A THREE-STAGE LIGHT GAS GUN

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ABSTRACT

A new gasdynamic launcher is described, in which intact projectiles weighing at least 1 gram can be accelerated to mass velocities of 15-20 km/s. The system employs a conventional 2--stage light gas gun, with the barrel modified and filled with helium to act as a pump tube for a third stage. The key feature of the launcher is that the peak pressure in the third stage can be maintained below 2.5 GPa, thus assuring high efficiency and the integrity of the projectile.

INTRODUCTION

The maximum velocity attainable in a gasdynamic launcher is limited by the maximum sound speed in the driver gas. For a conventional 2--stage light gas gun, the limit is ~ 10 km/s. To achieve higher velocities requires adding additional stages. Staging methods have been reported whereby a pusher of high shock impedance impacts a stack of target plates in which the impedance decreases from plate to plate in the desired direction of motion (1, 2), and velocities up to 14 km/s have been obtained in this manner. Chhabildas and his colleagues at Sandia National Laboratory have reversed this strategy with a graded density pusher, and they have demonstrated velocities up to 15.8 km/s with a 6 mm-diameter $\times$ 0.56 mm thick titanium projectile (3). A difficulty with this method is that the loading pulse is applied in a very short period of time and to achieve such a high velocity in this period requires a very high pressure, up to 100 GPa or even more. This means that the projectile thickness must be kept very thin to prevent spall fracture, and the impactor design is highly constrained to avoid shock-melting or even vaporizing the projectile. Also, such high pressures effect large energy

losses via pdV work on the walls of the launcher; in the 15.8 km/s experiment cited above, the kinetic energy efficiency of the third stage (ratio of the kinetic energy of the flyer to that of the impactor) was only 0.6%.

It may be possible to avoid many of these problems by slightly modifying the configuration of the conventional 2--stage system, as shown in Fig. 1. Normally, a vacuum is drawn in the 2nd stage launch tube of the gun, so that after the burst diaphragm is broken by the compressed hydrogen, the 2nd stage projectile is accelerated with no downstream resistance. If instead, this launch tube is closed at the downstream end with a second burst diaphragm, and filled with an appropriate mass of light gas, the second-stage projectile will act to compress the gas in much the same manner as does the piston in the first stage. The third stage projectile is placed downstream of the second burst diaphragm in a smaller diameter barrel, which now becomes the final launch tube.

We are interested in the solution of the following problem: Given the fixed characteristics of a two-stage light gas gun (pusher mass and velocity, m_2

FIGURE 1. Sketch of the three-stage light gas gun.

and v_2 , cross sectional area and length of barrel, A_2 and L_2), find the largest projectile mass, m_3 , that can be accelerated to a final velocity, v_3 , subject to the constraint that the maximum pressure on the projectile, $\hat{p}$ is less than some prescribed value. It is required to also find the corresponding third stage characteristics, A_3 and L_3 , and the interstage gas mass, m_g . Under certain simplifying assumptions, it can be shown that an exact solution to the above-posed problem exists (4). Our approach in what follows will be to use the analytical results to derive the approximate solution space and then to perform hydrodynamic code calculations to assess the effects of removing the simplifying assumptions.

ANALYTICAL MODEL

If it is assumed that 1) the walls of the gun tubes remain rigid, 2) there is a step change in cross section between stages and the pusher mass, m_2 , is brought to rest precisely at this location, 3) pressure gradients in the interstage gas can be ignored, 4) a monatomic γ -law equation of state describes the gas, and 5) after the first shock, the gas is effectively isentropically compressed, then the following solution for the third stage mass is derived in (4):

$$m_3 = \frac{4k}{3} \frac{m_g}{g^2} \left[\left(1 + \frac{1}{\alpha} \right) - \frac{1}{k} \left(\frac{\Phi}{1 + \Phi} \right) \right] \quad (1)$$

where g is the velocity gain, v_3/v_2 , k is the fraction of the peak internal energy of the gas that goes into increasing the kinetic energy of the projectile from its value at the time of peak pressure to its final value; k is essentially a free parameter, however, choosing a value of k much larger than 0.75 leads to diminishing returns, the energy saved being at the expense of greatly increased barrel length. The quantity, α , derives from solution of the equation:

$$\left(\frac{1 + \alpha}{\alpha} \right)^{5/2} \frac{\alpha(1 - \alpha)}{1 - \alpha + [\alpha(1 + \alpha)]^{1/2}} = \frac{3A_2 L_2}{4} \frac{\hat{p}}{m_2 v_2^2} \quad (2)$$

All the quantities on the right-hand side of equation (2) are given, so that α is readily evaluated. The quantity, Φ in equation (1) is then found from the relation:

$$\Phi = \frac{[\alpha(1 + \alpha)]^{1/2}}{1 - \alpha} \quad (3)$$

and the gas mass, m_g , is determined by:

$$m_g = \frac{3}{4} m_2 \left(\frac{\alpha}{1 + \Phi} \right) \quad (4)$$

The cross sectional area of the third stage launch tube, A_3 , is then found from the relation:

$$A_3 = \left(A_2^2 \Phi \frac{m_3}{m_2} \right)^{1/2} \quad (5)$$

and finally, the length of the third stage launch tube, L_3 , is given by:

$$L_3 = \frac{\left(\frac{1 + \alpha}{1 + \Phi} \right) m_2 v_2^2}{3A_3(1 - k)^{3/2}} \quad (6)$$

To illustrate, the intermediate LLNL two-stage light gas gun has been shown to fire a projectile, $m_2 = 37$ g at a velocity $v_2 = 6.2$ km/s. The launch tube bore diameter is $D_2 = 28$ mm (so that $A_2 = 6.16$ cm²) and the length is $L_2 = 9$ m. Assuming it is desired that the projectile velocity from the added third stage be $v_3 = 20$ km/s, $g = 3.23$. If the third stage projectile is made of titanium alloy ($\rho_3 = 4.51$ g/cm³), we choose $\hat{p}$ to be 2.5 GPa, less than half the ~ 5.5 GPa spall strength. Equations (1)-(6) then yield $\alpha = 0.267$, $\Phi = 0.793$, $m_3 = 1.65$ g, and $A_3 = 1.158$ cm², so that the bore diameter of the third stage barrel is 12.1 mm and the projectile length is $m_3/A_3\rho_3 = 3.16$ mm. Also, $m_g = 4.13$ g, which leads to a fill pressure of 0.46 MPa assuming helium is employed, and $L_3 = 9.3$ m. Although this represents a quite acceptable parameter set, it might be desirable to reduce the barrel length. This could be accomplished by reducing the projectile mass (length) somewhat. Another alternative is to accept a slightly lower final projectile velocity. Code calculations show that the 1.65 g projectile attains $0.95 v_3$ in the first 3.9 m, and is already at $0.9 v_3$ in 2.7 m.

We have not accounted for losses thus far. These are from three principal sources, gasdynamic drag, heat loss to— and pdV work done by the gas on the walls. We intend to choose $\hat{p}$ well below the spall strength of the projectile material, so as to minimize pdV work on the walls. Heat loss by radiation transport can be shown to be insignificant as long as the gas temperature remains below ~ 10 eV. Gasdynamic drag and convective heat transport from the turbulent boundary layer adjacent to the wall are discussed below.

HYDROCODE CALCULATIONS

GGUN2 is an extension of earlier codes (GGUN(5) and IGUN(6,7)) employed to study the performance of the two-stage light gas gun and various implosion and multistage launchers. It is an arbitrary Lagrange-Eulerian (ALE) code that solves the equations of motion in one dimension, but takes into account arbitrary flow cross section (including discontinuities), convective heat transport to the walls, and gasdynamic wall drag. Tabular equations-of-state can be employed, as well as Grüneisen, polynomial, and γ -law models, and JWL-explosive and Noble-Abel propellant burn packages have recently been added. There is also a coupled wall motion algorithm that allows the gun-barrel walls to move in response to the developing internal pressure. The equations of motion and other details have been described earlier (7).

The GGUN2 code was validated by comparing the computational results with experimental data from the first two stages of the three-stage light gas gun discussed in the previous section; it was shown in (4) that excellent agreement was obtained. Excellent agreement was also obtained by comparing third stage calculations with 2D simulations performed with the CALE code (8).

Helium is the preferred working fluid for all stages beyond the second because a higher final sound speed can be produced for given initial and final pressures. This is true also for the second stage. For example, when we recalculated the two-stage launcher discussed above, using helium in place of hydrogen (all other parameters remained the same, including the initial gas density and temperature), the final velocity increased by about 3%, notwithstanding the lower atomic mass of the hydrogen. However, practical considerations preclude the use of helium in the second stage. Although the velocity was slightly higher, the peak gas temperature in the AR (transition) section with helium was 6360 K compared with 1880 K with hydrogen. The slight increase in performance is more than countered by the potentially severe erosion that would be engendered by repeated use of the gun with helium. In the third stage, however, this is no longer a problem since the barrel in this stage

cannot be salvaged and must be replaced after each shot.

Figure 2 shows the performance when the results of the analytical model are used to design the third stage. Both the velocity of, and the peak pressure on, the third stage projectile are shown for 3 cases. All 3 calculations employed tabular equations of

FIGURE 2. Calculated velocity of and peak pressure on third stage projectile. Solid curve includes radial wall motion, dashed curve adds convective heat transfer, and dotted curve adds gasdynamic drag.

state for both the hydrogen in the second stage and the helium in the third. The solid curves depict the results when wall motion is included, but not heat transfer or drag. Assuming fully developed turbulent flow, the dashed curves include convective heat transfer from the helium plasma to the walls, and the dotted curves include both heat transfer and gasdynamic drag.

DISCUSSIONS & CONCLUSIONS

The calculated results exhibit the effects of all important loss mechanisms, pdV work on the walls (kept small by maintaining relatively low pressures in the system), heat transfer, and

turbulent drag. The latter effect appears most important, and reduces the maximum velocity from 20 to 16 km/s. At the same time, the peak pressure on the projectile drops from 2.5 GPa to approximately 0.8 GPa. Subsequent calculations have shown that shaving the length of the projectile to decrease the mass to 1 g (all other parameters fixed, and all loss mechanisms activated) increases the predicted velocity to 18 km/s and decreases the peak pressure to less than 0.5 GPa.

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