Research paper

Experimental study on acceleration of projectile by a gaseous detonation-driven gas gun using a light gas

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Abstract

Experiments were conducted to investigate the gaseous detonation-driven gas gun in which the driving source was the high-pressure combustion products behind the detonation waves propagating inside the simple straight tube (called detonation tube), and demonstrated that the acceleration of the projectile reached to the supersonic or hypersonic speeds. As the simplest configuration, the single-stage gun was tested directly connecting the detonation tube with the launch tube. When the detonation wave was driven by the hydrogen-oxygen mixture, the gun could accelerate the spherical projectile of 4.76 mm diameter and 52 mg mass up to 1400 m s^{-1}. The dilution of the hydrogen-oxygen mixture with the helium gas within 30% of the volumetric fraction had an insignificant effect on the projectile acceleration, and the reason was explained from the thermodynamic properties of the combustion products. However, the increase of the dilution rate to 40% caused to increase the projectile velocity up to 1600 m s^{-1}. This was owing to the arrival of the over-driven detonation at the launch tube, because the location of the detonation transition shifted to the downstream section of the detonation tube. In these experiments, the detonation-driven gas gun could obtain experimentally two to three times the projectile velocities compared to the theoretical velocities of the conventional single-stage light-gas gun driven by the pure hydrogen or helium gas under the same gun geometry and the filling pressure. The two-stage gun driven by the hydrogen-oxygen detonation was also tested by using the same detonation tube. The pump tube was added downstream of the detonation tube to compress the pure helium gas using the free piston driven by the detonation products. The detonation driver successfully established the pumping process of the helium gas in the pump tube. The velocities obtained in this study were up to around 2500 m s^{-1}, and these results were about 1.8 times higher than the velocities of the single-stage gun using the same detonation driver.

Keywords : gaseous detonation, gas gun, shock wave, supersonic combustion, supersonic flow

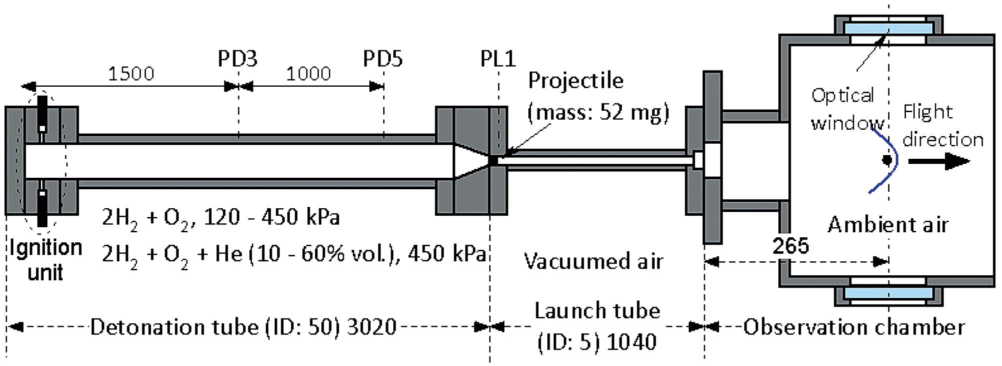
1. Introduction

Gaseous detonation waves propagating in combustible mixtures are characterized by a self-sustained supersonic propagation supported by coupling between a leading shock wave and subsequent combustion wave. The detonation waves are often produced inside simple straight tubes filled with the combustible mixtures, often called as “detonation tubes”. The combustion products behind the detonation wave have much higher pressure and temperature than the initial state of the combustible mixture, because of the strong compression produced by the leading shock wave of around Mach number 4 to 7. Therefore, the detonation waves have received attention as a method to generate combustion products having high-pressure, temperature and velocity for aerospace propulsion1) and industrial uses2). As another application, Presles and Bauer3) suggested the concept of “detonation products gun” which was the high-speed gas gun driven by the high-pressure combustion products behind the detonation wave. The concept was the single-stage gas gun simply consisting of the detonation tube and the launch tube. The detonation wave propagating in the detonation tube acted as “reactive piston” to increase the pressure, temperature and sound speed of the combustible mixture filled as the driver gas at the given initial pressure. Although Presles and Bauer[3] only reported the simple theoretical consideration to estimate the performance of the gas gun, they concluded that such the device would provide opportunities for investigating a wide range of velocities exceeding those of a compressed gas gun or of a powder gun. However, experimental demonstrations and discussions[4] of such the gas gun are extremely limited to date. High speed guns have been used since early times in laboratory studies for investigating hypersonic aerodynamics and hypervelocity impacts associated with atmospheric reentry of space vehicles, properties of solid materials, planet collisions, meteorite impacts etc. Two-stage light-gas guns have been frequently used in these investigations to achieve projectile (test material) velocity from 3 km s^{-1} to above 10 km s^{-1}, which is called as hypervelocity. These guns have precisely designed and manufactured to achieve required velocities in each investigation. The historical development of the two-stage light-gas guns was given in the literature[5]. Recently, we reported the experimental demonstration[6] of the single-stage gas gun driven by the hydrogen-oxygen detonation. The concept of the gas gun is capable of launching a small and lightweight projectile up to the velocity of 3 km s^{-1} by a low filling pressure of several atmospheres, which have been achieved using single-stage gas guns and small-sized two-stage light-gas guns driven by high-pressure gases or gun powders. The present intended purpose of this gas gun is for investigating shock-induced combustions and detonation waves[7] induced around projectiles which are launched with supersonic to hypersonic speeds into combustible mixtures. The required projectile velocity is above around Mach numbers 4 (about 1.4 km s^{-1}) for initiating a chemical reaction behind a shock wave formed around a projectile, and is Chapman-Jouguet Mach numbers up to around 7 (about 2.5 km s^{-1}) for stabilizing a detonation wave around a projectile. This range of the projectile velocity covers aerodynamic researches of supersonic to hypersonic flights in atmospheres. The detonation-driven gas gun is considered to have potential for realizing a laboratory-scale simple high-speed gas gun, reducing inconveniences associated with the regulations to handle a gunpowder or high-pressure gas, although special cares are obviously needed for the manipulation of combustible mixtures.

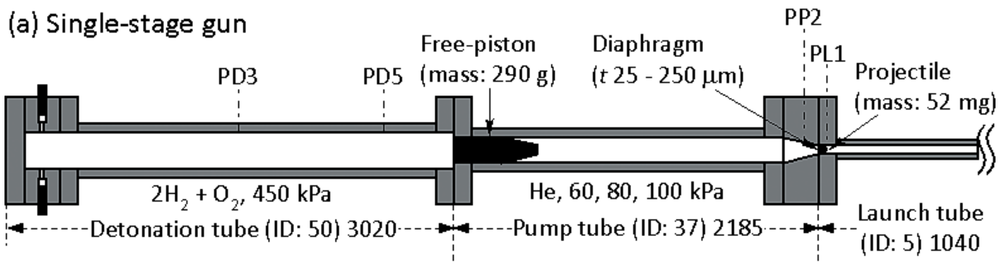
In this study, a helium gas was used as the driver gas in addition to the hydrogen-oxygen mixture, because a high sound speed of helium gas was understood to be suitable for accelerating a projectile. Two types of the gas gun using the helium gas were investigated; the single-stage gun in which the hydrogen-oxygen mixture was directly diluted with the helium gas and the two-stage gun in which the helium gas was compressed using the free piston which was driven by the pure hydrogen-oxygen detonation. The acceleration performances of the projectile in these gun configurations were reported.

2. Experimental setups and conditions

Figure 1 shows schematic of the experimental setup. In the single-stage gun shown in Figure 1 (a), the detonation tube and the launch tube were simply connected. Therefore, high-pressure combustion products directly accelerated the projectile. The observation chamber was coupled downstream of the launch tube. The chamber had a pair of optical windows to directly observe the projectile in free-flight. Thin diaphragms were used to separate each tube and chamber. The detonation tube was simple straight tube having 50 mm inner diameter and 3020 mm length. The detonation tube was filled with the combustible mixture, and the mixture was ignited in the vicinity of the closed end by using the ignition unit. The combustible mixtures were stoichiometric hydrogen-



(a) Single-stage gun



(b) Two-stage gun

Figure 1 Schematic of the detonation-driven gas gun (unit of lengths: [mm]).

oxygen mixture in 120 to 450 kPa of the filling pressures, or stoichiometric hydrogen-oxygen mixture diluted with the helium gas in 10 to 60 % by volumes maintaining the total filling pressure as 450 kPa. These mixtures were prepared directly in the detonation tube just before the ignition, in order to minimize the existence time of the combustible mixture in the apparatus. The hydrogen and oxygen (and helium) gases were filled in this order using a method of partial pressure, and the mixture was ignited about 30 minutes after the filling in order to form the premixed gas by a molecular diffusion. Our previous study[6] showed that the gases were sufficiently premixed for the detonation propagation using this method. The power supply of the ignition circuit was started up immediately before the ignition to avoid unexpected ignition, and the final ignition switch was turned on after the all people taking in shelter. The special cares are needed for the manipulation of the combustible mixtures in these experiments. The launch tube had 5 mm inner diameter and 1040 mm length. Between the detonation tube and launch tube, there was the taper section having 30 deg. of half angle to connect the inner diameters of the both tubes.

In the two-stage gun as shown in Figure 1 (b), the pump tube for pumping the helium gas was installed between the detonation and the launch tube. The pump tube had 37 mm inner diameter and 2185 mm length, and the free piston of 290 g mass was preliminarily set at the upstream end of the pump tube. Between the pump tube and launch tube, there was the taper section having 31.5 deg. of half angle to connect the inner diameters of these tubes. The experimental setup was almost same as that of the single-stage gun except for adding the pump tube. The combustible mixture filled in the detonation tube was fixed at stoichiometric hydrogen-oxygen mixture and the filling pressure of 450 kPa. The pump tube was filled with the helium gas and the filling pressure was changed as 60, 80, and 100 kPa. Therefore, high-pressure combustion products firstly accelerated the free piston, and the free piston compressed the helium gas filled in the pump tube, and finally the high-pressure helium gas could accelerate the projectile. One of the important parameter for controlling the projectile velocity of the two-stage gun is the thickness of diaphragm between the pump tube and launch tube, and the thicknesses were changed between 25 to 250 μm.

In the two types test of the gas guns, the launch tube was evacuated below 2 kPa, and the observation chamber was kept with the ambient air. The projectile was sphere made of high-density polyethylene, and the diameter and weight were 4.76 mm and 52 mg, respectively. The projectile was preliminarily set at the upstream end of the launch tube. The free-flight projectile passing through the optical window was directly visualized by the time-resolved schlieren imaging using the high-speed camera (nac image technology, ULTRACam HS-106E) with the inter frame time of 2.5 μs and the exposure time of 100 ns. Inside the field of view, the relation of time-location of the projectile was found to be almost linear, therefore the projectile velocity was calculated by the slope of the relation. Also, several pressure transducers were mounted on the side wall of the each tube. As shown in Figure 1, the pressure were measured at PD3 and PD5 of the detonation tube, PP2 near the downstream end of the pump tube, and PL1 near the upstream end of the launch tube.

3. Results and discussion

3.1 Case of single-stage gun using a pure hydrogen-oxygen mixture

The results of the single-stage gun using a pure hydrogen-oxygen mixture were firstly described. In Figure 2, the measured projectile velocities were shown against the filling pressures of the mixture. Opened circles are the results of this study, and the opened triangles and squares are the results of our previous study[6] using the different lengths of the detonation tube. Under the constant filling pressure, the projectile velocity tended to be higher using the longer detonation tube. In our previous study[6], the cause for this tendency was discussed using the pressure histories measured at the inlet section of launch tube. By using the longer detonation tube, the pressure histories represented that the higher driver gas pressure was maintained for the longer duration owing to the longer tail of the expansion wave (so called Taylor wave) existing behind the detonation wave. The results of this study shown in Figure 2 showed the additional evidence of this explanation. The closed symbols with solid lines show the theoretical values[8] for the same gun geometry, assuming the idealized conventional single-stage light-gas gun. The closed triangles and circles represent the theoretical values using a pure hydrogen gas or helium gas as a driver gas, respectively. The detonation-driven gas gun could obtain experimentally two to three times higher projectile velocities compared with the ideal velocities of the conventional single-stage light-gas gun under the same filling pressure. The conventional single-stage light-gas gun requires about 5 MPa of the filling pressure in order to obtain the projectile velocity of 1400 m s^{-1} which is obtained in the detonation-driven gas gun under 450 kPa of the filling pressure. The closed squares represent the theoretical values using the combustion products as a driver gas assuming the isochoric combustion for the hydrogen-oxygen mixture. The idealized modelling was not able to quantitatively reproduce the experimental results, however, the model gave the similar trends of the projectile velocities for the case of the gas gun driven by the combustion products.

3.2 Case of single-stage gun using a hydrogen-oxygen mixture diluted with a helium gas

In this section, the results of the single-stage gun using a hydrogen-oxygen mixture diluted with a helium gas were described. Figure 3 showed the relationship between the measured projectile velocities and the volumetric fraction of the helium gas, maintaining the total filling pressure at 450 kPa. Opened circles are the experimental results, and

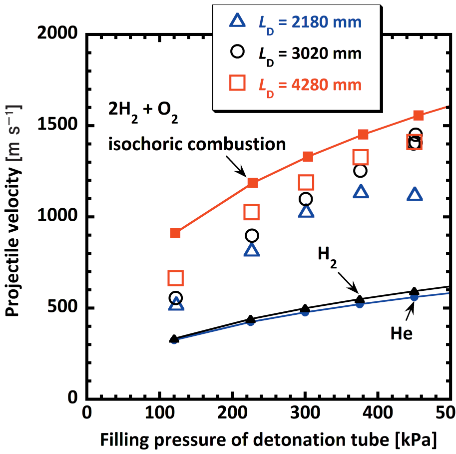


Figure 2 Measured projectile velocities by using different lengths of detonation tubes, L_D. Length of 3020 mm is results of present study, and others are results of our previous study[6]. Symbols with solid lines are theoretical values[8] in single-stage gun using given driver gases.

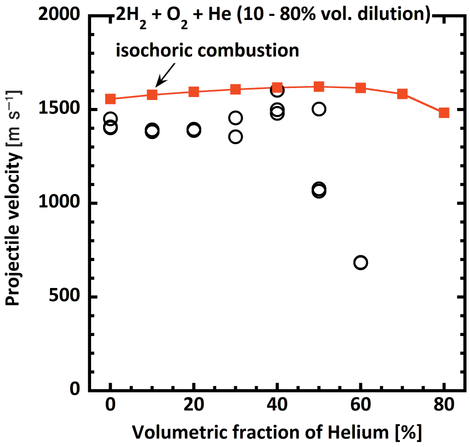


Figure 3 Effect of dilution rate of helium gas on projectile velocity while total filling pressure of mixtures are constant at 450 kPa.

the closed squares with solid line show the theoretical values obtained by assuming the combustion products of the isochoric combustion for the given mixtures. The measured projectile velocities kept almost constant value for the dilution rate below 30%, and the velocities showed certain increase for 40%, and then rapidly decreased above 50%. The maximum projectile velocity was around 1600 m s^{-1} for the dilution rate of 40%. On the other hand, the theoretical velocities had not largely changed against the dilution rate compared with the experimental ones. For explaining this weak dependence against the dilution rate, the thermodynamic properties of the combustion products assuming the isochoric combustion are calculated using the chemical equilibrium software[9], and they are shown in Figure 4. This figure indicates the pressure, p_{CV}, sound speed, a_{CV} and specific heat ratio, γ_{CV} against the dilution rate of the helium gas, and each value is normalized by the values of non-dilution. By substituting these parameters to Equation 1[8], the theoretical projectile velocity could be calculated as shown in Figures 2 and 3. This equation relates the velocity, u_p and location, x_p of the projectile with the mass, m_p accelerating inside the launch tube with the cross-sectional area, A.

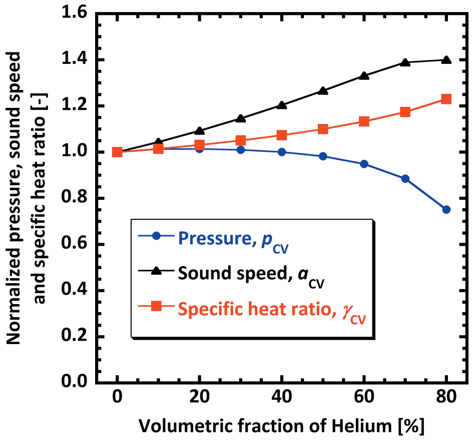


Figure 4 Effect of dilution rate of helium gas on thermodynamic properties of combustion products by assuming isochoric combustion, while total filling pressure of mixtures are constant at 450 kPa. Each value is normalized by values of non-dilution; p_{CV} = 4.59 MPa, a_{CV} = 1590 m s^{-1} and γ_{CV} = 1.21.

$$x_p = \frac{m_p}{A p_{CV}} \frac{2 a_{CV}^{2}}{\gamma_{CV}+1}\left[\frac{\frac{2}{\gamma_{CV}-1} - \frac{\gamma_{CV}+1}{\gamma_{CV}-1}\left(1-\frac{\gamma_{CV}-1}{2a_{CV}}u_p\right)}{\left(1-\frac{\gamma_{CV}-1}{2a_{CV}}u_p\right)^{\frac{\gamma_{CV}+1}{\gamma_{CV}-1}}} + 1\right] \quad (1)$$

Equation 1 is obtained using two relations; the equation of motion for the projectile, and the relation of pressure-particle velocity of the gas immediately behind the projectile assuming the isentropic expansion. Equation 1 is not explicit about the projectile velocity, u_p, however, the higher pressure, p_{CV} of the combustion products apparently gives positive effect for the projectile velocity. From a parametric examination for the Equation 1, the higher sound speed, a_{CV} also gives positive effect. On the other hand, the higher specific heat ratio, γ_{CV} gives negative effect. These tendencies base on the simple characteristic of the pressure-particle velocity relation as in a gasdynamics textbook[10]. In the idealized model, the combustion product assuming the isochoric combustion is initially at rest. Along with the acceleration of the projectile, the combustion product is accelerated to the certain particle velocity which is equal to the projectile velocity, and the pressure gradually decreases. The higher sound speed, a_{CV} suppresses the pressure drop of the combustion product, and the higher specific heat ratio, γ_{CV} intensifies it. These effects on the pressure drop of the combustion product directly affect the driving pressure of the projectile. From the Figure 4, the pressure of p_{CV} gradually decreases as the volumetric fraction of helium increases, however, the pressure keeps above 95% of that in the non-dilution when the volumetric fraction is below 60%. This pressure trend is characteristic with respect that the helium dilution maintains the pressure of the combustion product as far as the dilution rate is below 60% while decreasing the amount of the hydrogen-oxygen mixture (i.e. the heat release energy). The helium dilution decreases the temperature of the combustion product while increasing the sound peed of the combustion product. This may reduce the heat loss of the combustion product during the processes of the combustion and the

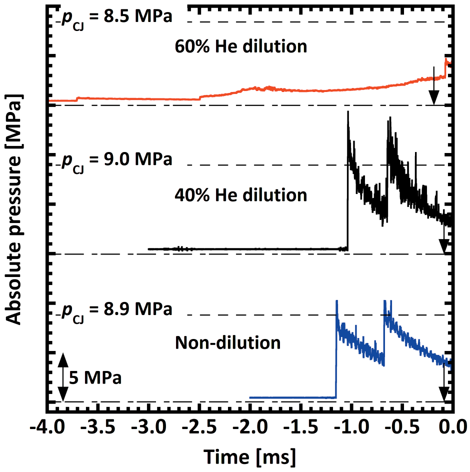


Figure 5 Pressure histories recorded on side wall of detonation tube obtained at 500 mm upstream from inlet of launch tube. Results using $2H_2+O_2$, $2H_2+O_2+40\%$ He and $2H_2+O_2+60\%$ He are shown with calculated C-J pressure for each condition. Down-pointing arrows show estimated launch time of projectile.

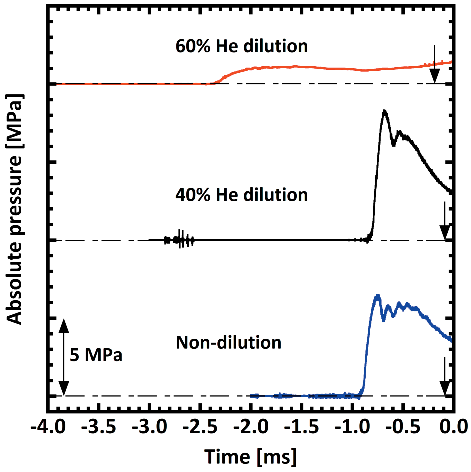


Figure 6 Pressure histories recorded at inlet of launch tube. Results using $2H_2+O_2$, $2H_2+O_2+40\%$ He and $2H_2+O_2+60\%$ He are shown. Down-pointing arrows show estimated launch time of projectile.

projectile acceleration. These features of the helium dilution might indicate the possibility of the enhancement of the practical capability of the single-stage gas gun, if the geometry and the operating condition of the gas gun are optimized. The filling pressure of the combustible mixture can easily control, and this indicates the possibility that the projectile velocity can easily control in the wide range by controlling the filling pressure. From the Figure 4, the a_{CV} and γ_{CV} increase with the dilution rate. Therefore, these positive and negative effects on the projectile velocity result in the weak dependence on the dilution rate. The experimental results in the cases below 30% of the dilution rate shown in Figure 3 are considered to support this characteristic of the thermodynamic properties of the combustion products. Because in these conditions, the distances required for the detonation transitions were within one third the whole length of the detonation tube from the ignition point, and it was confirmed that the stable Chapman-Jouguet detonation wave arrived at the inlet of launch tube. Dilution of combustible mixtures with inert gases reduces reactivity of the mixtures. Therefore, initiation of detonations becomes difficult in high dilution rates, and the distances required for the detonation transitions become much longer. Therefore, it is predicted that the transient phenomena of the detonation transitions affect the measured projectile velocities in the cases above 40% of the dilution rate. Next, we discuss the effect of the transient phenomena based on the pressure records measured at the detonation and launch tube.

Figure 5 shows the pressure histories in the detonation tube obtained from the pressure transducer at the PD5 as shown in Figure 1. Figure 6 also shows the pressure histories in the launch tube obtained from the pressure transducer at the PL1 as shown in Figure 1. These pressure histories were obtained in the same experiment. These figures show the three different dilution rates of the helium gas ; 0% (non-dilution), 40% and 60%. In Figure 5, the dotted lines show the Chapman-Jouguet pressures, p_{CJ} calculated from the chemical equilibrium software[9]. For each pressure record in Figures 5 and 6, the down-pointing arrows show the launch times at which the projectile was released from the outlet of launch tube. The launch times were estimated by extrapolating the time-location relation of the projectile obtained from the high-speed camera. In the case of non-dilution, the first discontinuous pressure rise as shown in Figure 5 was close to the value of p_{CJ}, therefore, this indicated the arrival of the Chapman-Jouguet detonation wave. The second pressure rise shows the reflected shock wave propagating upstream in the detonation tube. This shock wave originated from the reflection of the detonation wave at the inlet section of launch tube. On the other hand, in the case of 40% dilution, the first discontinuous pressure rise shown in Figure 5 obviously higher than p_{CJ}, therefore, this indicated the arrival of the over-driven detonation wave. In this condition, the distances required for the detonation transitions were more than half the whole length of the detonation tube. An occurrence of an over-driven detonation is a typical behavior just after a detonation transition. Therefore, it was implied that the over-driven detonation wave arrived at the inlet of launch tube. Although the values of p_{CJ} were almost the same value between the cases of non-dilution and 40% dilution as shown in Figure 5, the peak pressure obtained at the inlet of launch tube in the case of 40% dilution was 2 MPa higher than the cases of non-dilution as shown in Figure 6. This result was consistent with the arrival of the over-driven detonation at the inlet of launch tube, and this transient phenomenon was considered to increase the driving pressure of the projectile in the case of 40% dilution. On the other hand, further increase of the dilution rate to 60% caused to decrease the pressures in the detonation tube and launch tube. In Figure 5, the first pressure rise recorded at -3.7 ms was substantially lower than the p_{CJ}, and this pressure rise was attributed to the propagation of the leading shock wave ahead of the flame propagation. The second pressure rise recorded at −2.5 ms was due to the reflected shock wave propagating upstream after the reflection of the leading shock wave at the inlet of launch tube. The gradual pressure increase after this second pressure rise was probably owing to the successive generation of the compression wave associated with the flame propagation, and the behavior was often observed during the flame propagation inside the tube. From Figure 6, the pressure at the inlet of launch tube rose soon after this reflection of the leading shock wave. The projectile was consequently launched by this fairly weak shock wave compared to the detonation wave. Because there was no pressure rise which could be regarded as the onset of the detonation wave during the acceleration process of the projectile inside the launch tube, the distance required for the detonation transition in this condition was longer than the whole length of the detonation tube. This resulted in the apparent reduction of the projectile velocity in the dilution rate of 60% as shown in Figure 3. The wide variation of the projectile velocity observed in the case of 50% dilution was attributed by the stochastic variations of the detonation transition distance between within or over the whole length of the detonation tube.

The discussions through Figures 3 to 6 are summarized as follows. When the combustible mixture was diluted with the helium gas, the effect of the thermodynamic properties of the combustion products on the projectile velocity was small. In other words, the projectile velocity was maintained at almost constant value despite decreasing the energy input (heat release from the combustible mixture) by the dilution. This means that the energy efficiency (ratio of the kinetic energy of the released projectile to the heat release) of the gas gun is improved by using the light gas. Additionally, as a result of the increase in the distance required for the detonation transition in the higher dilution rate, the arrival of the over-driven detonation wave at the inlet of launch tube caused to increase the projectile velocity. However, this transient phenomenon was difficult to control for the operation of the gas gun. By increasing the dilution rate, the detonation transition did not occur in the detonation tube, and this obviously resulted in the significant reduction of the projectile velocity.

3.3 Case of two-stage gun

In this section, the results of using two-stage gun are discussed. The driving source of the two-stage gun was the same detonation tube as that used in the single-stage gun, and the condition was also the same as the case of non-dilution in Figure 3. Therefore, the increase of the projectile velocity directly results in the increase of the energy efficiency as compared to the results of the single-stage gun. Figure 7 shows the typical pressure histories at PD3 and PD5 in the detonation tube, at PP2 in the pump tube and at PL1 in the launch tube during the operation. The first pressure peaks in the PD3 and PD5 show the detonation propagation toward the downstream direction. After the detonation wave reached at the inlet of pump tube, the PP2 gradually increased by the acceleration of the free piston. During the pumping process of the helium gas inside the pump tube, the PD3 and PD5 recorded that the shock wave propagated back and forth by the repeated reflection between the closed end of the detonation tube and the base of the running free piston. The averaged pressure inside the detonation tube gradually decreased over time depending on the displacement of the free piston. During the final phase of the pumping process of the helium gas, the PP2 rapidly increased up to 38 MPa. When the PP2 reached about 10 MPa, the diaphragm between the pump tube and the launch tube was broken and the PL1 started rapid increase up to 26 MPa. This peak pressure obtained at the inlet of launch tube was about 3 times higher than the single-stage gun. The estimated launch time of the projectile was fairly close to the time zero in Figure 7. The pressures inside the pump tube and the launch tube rapidly dropped after the projectile was released. In this condition, the projectile was accelerated to the velocity of about 2 km s^{-1}, and the detonation driver successfully established the pumping process of the light gas. In the two-stage gun, the acceleration process of the projectile was similar to conventional two-stage light-gas guns driven by compressed gases or gun powders. The free piston needs to gain enough inertia for dynamically compressing the helium gas in the operation of the two-stage guns. The temporal evolution of the location of the free piston could be roughly estimated from the pressure history inside the pump tube (PP2) in Figure 7, if the compression process was assumed to be isentropic without the leakage of the helium gas between the free piston and the inner wall of the pump tube. The maximum velocity of the free piston was estimated to be approximately 170 m s^{-1}. This indicated that the detonation tube under the filling pressure of several atmospheres could give sufficient inertia to the free piston by the detonation combustion.

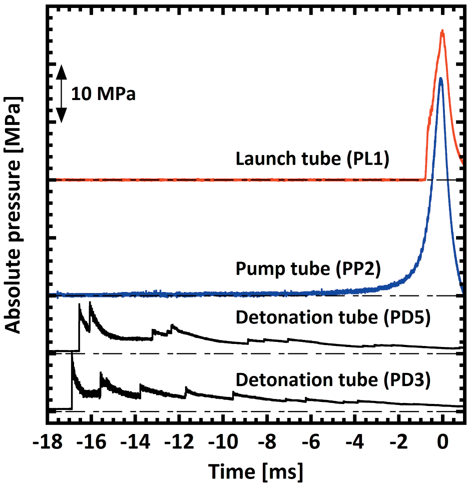


Figure 7 Typical pressure histories in the detonation tube (PD3 and PD5), pump tube (PP2) and launch tube (PL1) during the operation of the two-stage gun driven by the hydrogen-oxygen detonation. Detonation tube: $2H_2+O_2$, 452 kPa, Pump tube: He, 102 kPa, Diaphragm thickness: 125 μm, Projectile velocity: 1920 m s^{-1}.

Figure 8 shows the measured projectile velocities under the various conditions of the pump tube while maintaining the conditions of the detonation tube. The Mach numbers

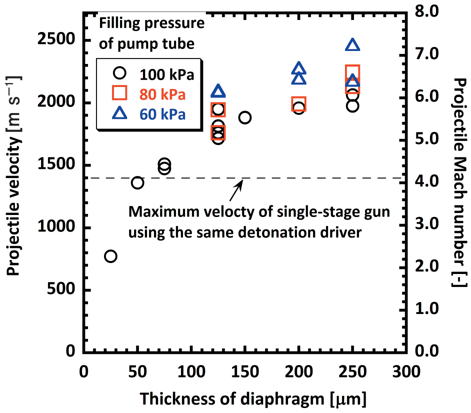


Figure 8 Measured projectile velocities in the two-stage gun. The thickness of the diaphragm located at the exit of the pump tube and the filling pressure of the helium gas inside the pump tube were varied.

of projectile were calculated using a sound speed of air at room temperature as 340 m s^{-1}. The horizontal axis shows the thickness of the diaphragm located at the outlet of pump tube, and the symbols show the pressure of the helium gas filled inside the pump tube. Using the thicker diaphragm turned out to increase the rapture pressure, and the higher pressure drove the projectile to increase the velocity. In addition, the lower filling pressure of the helium gas turned out to increase the pumping pressure because the free piston could be accelerated to the higher velocity, and the projectile velocity was increased. The projectile velocities up to around 2500 m s^{-1} were obtained. These results were about 1.8 times higher than the single-stage gun using the same detonation driver, which was shown as the dotted line in Figure 8, and the kinetic energy of the released projectile became about 3.2 times. In the two-stage gun, the setup and operation of the gas gun lose the simplicity, however, the higher projectile velocities were obtainable compared to the single-stage gun using the same detonation driver.

4. Conclusions

The single-stage gun and the two-stage gun driven by the hydrogen-oxygen detonation or the hydrogen-oxygen-helium detonation were tested. The acceleration of projectiles to the supersonic or hypersonic speeds was demonstrated in the each gas gun.

1. In the single-stage gun driven by the hydrogen-oxygen detonation, the detonation-driven gas gun could obtain experimentally two to three times the projectile velocities (up to 1400 m s^{-1} in this study) compared to the ideal velocities of the conventional single-stage light-gas gun driven by the pure hydrogen or helium gas under the same gun geometry and the filling pressure.
2. In the single-stage gun driven by the hydrogen-oxygen-helium detonation, the effect of the helium dilution on the projectile velocity due to the variations of the thermodynamic properties of the combustion products was small. As the result of the increase in the distance required for the detonation transition in the higher dilution rate (40% vol. of the helium dilution), the arrival of the over-driven detonation wave at the inlet of launch tube caused to increase the projectile velocity up to 1600 m s^{-1}.
3. In the two-stage gun driven by the hydrogen-oxygen detonation, the detonation driver successfully established the pumping process of the light gas in the pump tube. The projectile velocities obtained in this study were up to around 2500 m s^{-1}, and this result was about 1.8 times higher than the single-stage gun using the same detonation driver.

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