Letter

Traveling liquid charge accelerator for hypervelocity

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Abstract

This letter analytically considers the motion of projectile in the traveling liquid charge accelerator to obtain mathematical criterion among parameters of both propellant and accelerator. And it is understood from this criterion that a liquid propellant is the key tool to realize hypervelocity of order more than 10 kms^{-1}, provided that the explosion of traveling liquid charge is securely choked by a certain means. An example of a structure of this accelerator is also pictured from this criterion with a little exaggeration.

1. Introduction

There are two concepts of projectile accelerator which is already proven to attain around 8 km s^{-1}. One is the two stage light gas gun[1)] with low repetition rate operation because the plastic piston has to be employed for the compression of light gas and the long , tedious time is necessary to exchange the used piston to the new one. The other is the electromagnetic rail gun[2)] which can obtain that high speed given above by the Lorentz force with a fatal damage to accelerator rails by the arc plasma of temperature around 5000 ℃. Because of this rail damage , repetitive use of a set of the accelerator rails is, at best, several times under the present technology.

Fortunately, however, there is one more hopeful idea still remained to be investigated thoroughly. This is the traveling liquid charge accelerator ,which is already but briefly introduced in the textbook written two decades ago by Bailey and Murray[3)], although the liquid charge has been discussed just from the view point of tactical advantages at that time. In the accelerator, liquid propellant is loaded in the room between a projectile and a perforated piston by a special pump from reservoir tank of the charge. The loaded propellant is ignited from the rear side of the perforated piston by an ignition device. Then the piston begins to move forward by the hot gas pressure from the ignited charge. While a little bit of the liquid is spilt backward into the burning chamber through the perforation, most of the liquid charge driven by the piston is able to play a role of cue to propel projectile forward.

This operation is difficult to expect for any solid charge because the solid propellant is hard to play a role of cue to propel projectile since the material strength against stress is not so high for the solid charge. Also, the friction between the guide tube and the solid can generate heat which can explode the solid. Even if the guide tube is tough against such explosion, the traveling solid would change into hot gas after such explosion. Then, the projectile is accelerated just by this gas pressure like a conventional gun. The maximum attainable velocity then becomes the thermal speed of the hot gas. Since the average weight of the reaction products is hard to lower than 14[4)], the speed to be expected is less than 2.5 km s^{-1}.

The situation changes dramatically, once a liquid propellant is successfully employed in stead of solid one. Because this propellant is an incompressible fluid, it is tough enough against stress in a stiff guide tube and the friction problem should also be greatly relaxed hydrodynamically. As you will see later, the liquid propellant is a potential tool to realize high velocity of more than 10 km s^{-1} which could not be realized even by the two stage light gas gun[1)] and the rail gun[2)]. From both of this historical evidence the experimental research on impact fusion[5, 6)] was left for a future study until a new invention of projectile accelerator, because the thermonuclear burn by hypervelocity impact[7)] needs at least 20 km s^{-1}.

This work analytically considers motion of projectile in the traveling liquid charge accelerator using a mathematically tractable model in order to obtain mathematical criterion among parameters of both accelerator and propellant in order to clarify the potentiality of attaining hypervelocity. Also a way to avoid the explosion of the traveling liquid charge is briefly discussed.

2. Analytical consideration of the traveling liquid charge accelerator

In order to get an idea of the dynamics of projectile, we will treat an idealized case as a start of thorough consideration of this concept since analytical information of this accelerator is not seen even in the textbook[3)].

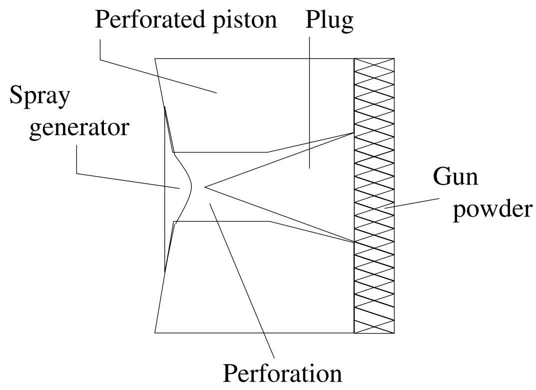

Fig. 1 Perforated piston with plug and a spray generator.

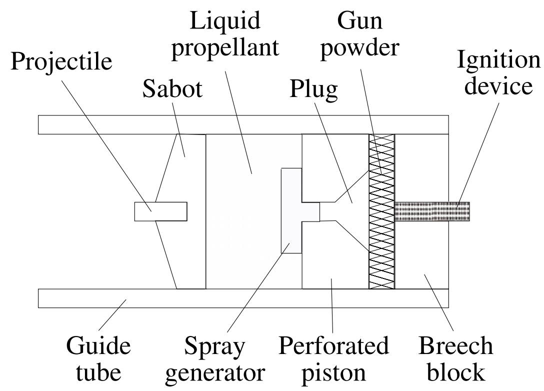

Fig. 2 Travelling liquid charge accelerator with ignition device.

The equation of motion of the projectile with the liquid charge is written by

$$\mathrm{d}\,(M\,v)\,/\,\mathrm{d}t = F. \quad (1)$$

Here, the frictional problem between the guide tube and the charge is assumed to be negligible because of hydrodynamical reason. Also resistive force from the tube wall against the projectile is set at naught for simplicity. The notation v is the velocity of the projectile, M represents the total mass of the projectile together with the charge, and the time is expressed by t.

To facilitate analysis we assume that the expression F is the constant force from the gas pressure since the propellant is assumed to be supplied constantly in time during the burn time T from the diminishing charge through a thin channel of the perforated piston. This assumption is acceptable if the channel flow of the propellant is obeyed by the viscous interaction between the fluid and the wall of the thin channel. Then the mass of the traveling charge is diminishing constantly in time.

Therefore, the time-dependent expression of this traveling mass, M, is able to be described by

$$M = m_B + m_f\,(1 - t\,/\,T). \quad (2)$$

where m_B is the mass of the projectile with related parts such as sabot and perforated piston etc., and m_f corresponds to that of propellant.

Before carrying out mathematical work we should recognize the structure of perforated piston and accelerator. Figure 1 shows an example of the perforated piston with plug from the rear side and spray generator at the front side. Also, a gun powder of thin circular shape is attached to the rear side of the piston. This gun powder works to give initial motion to the piston once it is ignited. This piston together with a projectile ,sabot and liquid propellant are loaded in a guide tube in order to form an accelerator which is depicted in Fig. 2 with a little exaggeration. The rear side of the guide tube is closed by a breech block with an ignition device to ignite gun powder. The three components, i.e. wall of guide tube , rear side of projectile and front side of piston, works as a traveling container of propellant. Although the propellant should be designed to be pumped directly into a chamber from a reservoir tank through a valve and so on, they are not shown to simplify this picture.

To start this accelerator, an ignition device as shown in Fig. 2 should work to ignite gun powder also shown in the same figure. Then, high pressure gas from the gun powder just give the initial motion to the piston and the plug, and the gas penetration into the traveling container through the channel at the initial moment is securely avoided by this plug. Once the piston begins to move the plug is pushed back in the inverse direction by the reaction of hydrodynamical motion of this incompressible fluid. And sooner or later the plug falls off from this thin hole. At the moment of open perforation the charge abruptly flows in the rear side of the piston through the thin channel. At the same time the spray generator (precise structure is not described here) also starts to work converting the incompressible liquid into a numerous number of tiny grain, i.e. spray. As long as the temperature of the grain surface is raised over the ignition point by any means, it burns. Then the pressure at the side of the piston will begin to increase giving forward thrust to projectile by incompressible but diminishing propellant. Also, the jet stream of spray continues to flow in from the traveling container through the perforation until the last drop of liquid is spent while preventing heat wave from burning spray into the diminishing propellant. In this way, the propellant securely burns to the last drop during the burn time T.

Armed with the knowledge of the perforated piston and the accelerator given above together with the assumption of the viscous channel flow through the perforation of the piston, Eq. (1) is straight forwardly integrated for the propagation distance, z, of the projectile with the initial condition $z = 0$ at $t = 0$ as follows since $\mathrm{d}z\,/\,\mathrm{d}t = v$.

This treatment is true as long as the cross section of perforation is quite less than that of the guide tube. By this assumption difference of velocity between projectile and perforated piston can be negligible in calculating their motion.

We then have by (1) with (2) as follows.

$$z = [(FT^2\,/\,m_B)(1 + R)\,/\,R^2] \cdot \ln\,[(1 + R)\,/\,\{1 + R\,(1 - \tau)\}] - \tau\,(FT^2)\,/\,(m_B R). \quad (3)$$

Here the notations R and τ are defined by $R = m_f\,/\,m_B$ and $\tau = t\,/\,T$.

We will call R the mass ratio hereafter in this work.

It may be convenient to define the length of the acceleration by $z = L$ at $t = T$ from (3). Then, we have the following relation for L.

$$L = (FT^2 / m_B)\, G. \tag{4}$$

where G is the figure of merit of the traveling charge accelerator given by

$$G = \{(1 + R) \ln (1 + R) - R\} / R^2. \tag{5}$$

which means that less G needs less acceleration length to its final state.

The velocity of the projectile attained at $t = T$ is written simply from (1) and (2) by

$$v = FT / m_B. \tag{6}$$

This is the maximum velocity obtained by this accelerator. After this time, T, the projectile is shot into an experimental chamber to impact on a target.

By vanishing F from (4) and (6), we have the criterion among the parameters L, T and v as follows.

$$v = L / (TG). \tag{7}$$

In case the mass ratio R is less than 1, G is approximated by 0.5. In this case (7) means that we can attain high velocity if a dangerous high explosives is chosen. Otherwise, L becomes prohibitively large.

The other extreme is that the propellant is very much heavier than the projectile. In this selection, G can be approximated by $G = (\ln R) / R$. And the criterion (7) can be rewritten by

$$v = RL / (T \ln R). \tag{8}$$

This expression means that the mass ratio R is not only to give us a great bonus of attainable velocity but also to give us a motivation to choose voluminous but safer charge than high explosives ,although this massive propellant remind us of a space rocket ,where the payload is quite less than its fuel tank. The choking of propellant explosion is a must for both the rocket and this accelerator in order to achieve required velocity.

From now on, any designer of this accelerator can see the necessary force F from the propellant by (4) or (6) with the help of (7). Using this force F and the mass of projectile we recognize both the power of propellant to develop and a proper perforation to drill through the piston.

By taking advantage of the mass ratio, it may be interesting to see two cases whose velocity is not attained by the conventional gun accelerator. Here, the burning time T is taken 10^{-2} s.

The first example is v = 3 km s^{-1} by L = 5 m. Then G becomes 0.16, which means the mass ratio must be 9.5 from (5). This means that the length of propellant in the guide tube should be quite longer than that of projectile. An important point to notice is that the velocity 3 km s^{-1} could not be attained by the conventional gun accelerator in principle. However, it can be done by the traveling liquid charge accelerator.

The second example is to attain 10 km s^{-1} by the accelerating length 10 m. In this case figure of merit of this accelerator G becomes 0.1 which means that the propellant has to be 25 times heavier than the projectile. Therefore, the length of propellant becomes roughly twice of the first example. These two examples are suggesting that the length of accelerator is not L, but it should be the length of acceleration in addition to the length of propellant in the guide tube.

3. Discussions and conclusion

In this analysis we have considered the case where a steadily diminishing mass of charge is generating constant force, because this is the simplest, consistent example of the burn dynamics of liquid propellant. The future work has to take into account both the time-dependent supply of charge and the resultant force to propel projectile in order to understand optimum operation. Even from this simplest case, we are able to point out that the traveling liquid charge accelerator has potentiality to obtain high velocity more than 10 km s^{-1} because of the result (8), provided that the perforated piston could choke explosion of spending propellant during the burn time T and that the mass ratio R were chosen arbitrarily through a proper design of the perforation of the piston. These secure burn and viscous flow through the thin channel must be proven by experiment, though.

Therefore it is understood that the most important technology to realize hypervelocity more than 10 km s^{-1} is a development of proper liquid propellant together with the knowledge of the maximum limit for the mass ratio which guarantees viscous flow through the perforation of the piston. Once this is done, we emphasize that the experimental research of the impact fusion[5, 6, 7] will be able to restart in the very near future with a traveling liquid charge accelerator having a reasonable size by optimizing the figure of merit G given by (5).

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超高速液体移動装薬加速器

生田一成

このレターは液体移動装薬加速器内の飛翔体の運動を解析的に熟慮して加速器のパラメーターと装薬の特性指数間の数式上の基準を求める。この基準は適正なる燃焼時間と出力を持つ液体発射薬が10km／sの超高速を発現する基本的道具である事を示す。そして、この基準による加速器の概略図を少し誇張を加えて示す。

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