OPTIMIZATION OF TWO-STAGE GAS GUN FOR FUSION REFUELING PELLET INJECTION WITH CONSIDERATION OF REAL EFFECTS

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ABSTRACT

Analytic expression of pellet acceleration by constant base pressure with consideration of gas-wall friction, heat transfer and viscous dissipation that important for high speed injection is obtained. The process of compression stage is formulated by a set of governing equations and can be numerically integrated. Excellent confirmation with experiments is obtained and the ways to optimum match the compression stage with the launch stage are suggested.

1. INTRODUCTION

It is estimated that the speed of fusion refueling pellet should attend 5km/s or more in order to penetrate into the core of burning plasmas[1]. The only practical way now to get this speed range is launched by two-stage gas gun. This kind of gun is different from those for space flight simulation in at least three ways: 1. the base pressure is much lower for iced D_2 pellet as compared to that of metallic pellet. even sabot is used 2. the inner diameter of launch stage is only few millimeters, so real effects, friction and heat transfer between gas and wall are so important for high speed pellet injection that should be considered. 3. the free piston of compression stage is not replaced after each launch.

The best process to push the pellet from rest to high speed is constant base pressure acceleration (CBPA) obviously due to the stress limit of the iced pellet. The inlet pressure programming for CBPA with consideration of real effects is analysed. Since the inlet pressure for launch stage is supplied by compression stage, the key problem is how to reach the optimum match between these two stages.

The results of these investigations will be shown as follows.

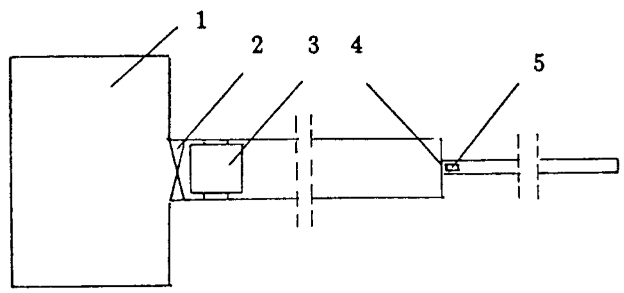

Fig. 1. Schmatic drawing of a two stage gas gun 1—driving gas reservoir, 2—fast valve, 3—free piston, 4—diaphragm, 5—pellet

2. STATIC PRESSURE PROGRAMMING AT THE INLET OF THE LAUNCH STAGE

The basic philosophy for CBPA is that all the gas follow the pellet is to be kept at the same speed as that of the pellet. Since a pressure gradient is needed to accelerate the gas, the pressure gets higher and higher at the inlet during the acceleration process.

The motion of the pellet in the launch stage is described by

$$M_p \frac{dV_p}{dt} = P_b A_p \tag{1}$$

If base pressure remains constant, acceleration of pellet

$$a_p = \frac{dV_p}{dt} = \frac{P_b A_p}{M_p} = \frac{P_b}{\rho_p \ell_p} = const. \qquad (2)$$

the flow of the driving gas can be approximately described by

$$\rho_g \frac{dV_g}{dt} = -\frac{dP_g}{dL} - f\rho_g \frac{V_g{}^2}{2}\frac{1}{d} \qquad (3)$$

M, V, p, ρ, A, ℓ denote mass, velocity, pressure, density, area, length respectively, subscripts p, b, g denote pellet, pellet base, gas respectively. t is time, L is along the launch tube. f is the friction coefficient between gas and wall which depends on Reynolds' number and surface roughness for viscous flow and d is the diameter of the launch tube. Assume the existence of a polytropic relation between the pressure and density as the simplified way to take account of heat transfer and viscous dissipation, their importance and detailed analysis could be found elsewhere[2]

$$\frac{P_g}{P_b} = \left(\frac{\rho_g}{\rho_b}\right)^n = \left(\frac{T_g}{T_b}\right)^{\frac{n}{n-1}} \qquad (4)$$

integrate

$$\frac{P_{g,L=0}}{P_b} = \{1 + [(f' \frac{\rho_p l_p}{\rho_b d})\frac{k}{8}\bar{V}_p^4 + \frac{1}{2}\bar{V}_p^2]\frac{k(n-1)}{n}\}^{\frac{n}{n-1}} \qquad (5)$$

and the stagnation pressure at the entrance of the launch tube to the base static pressure of the pellet is

$$\frac{P^*_{g,L=0}}{P_b} = \{1 + \frac{k-1}{2}\bar{V}_p^2 \times \frac{1}{[1+[f^{*}\frac{k}{8}\bar{V}_p^4 + \frac{1}{2}\bar{V}_p^2]\frac{k(n-1)}{n}]}\}^{\frac{k}{k-1}}$$
$$\times\{1 + [f^{*}\frac{k}{8}\bar{V}_p^4 + \frac{1}{2}\bar{V}_p^2]\frac{k(n-1)}{n}\}^{\frac{n}{n-1}} \qquad (5a)$$

here $\bar{V}_p = \frac{V_p}{C_b}$, $C_b = (kRT_b)^{\frac{1}{2}}$ is the sonic speed. k—specific heat ratio, R—gas constant, T—temperature, n—polytropic factor, f'—average friction coefficient, $f^{*} = f' \cdot \frac{\rho_p l_p}{\rho_b d}$ —equivalent friction coefficient

Typical results of eq.(5) & (5a) are shown in fig.2 and 3

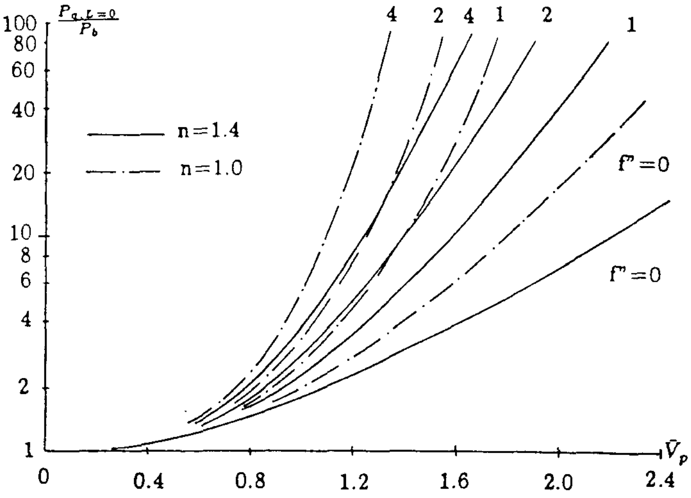

Fig. 2. Static pressure programming for CBPA $\bar{V}_p$—dimensionless pellet speed, f"—equivalent friction coefficient, $P_{g,L=0}/P_b$—ratio of static pressure at entrance of launch stage to pellet base pressure

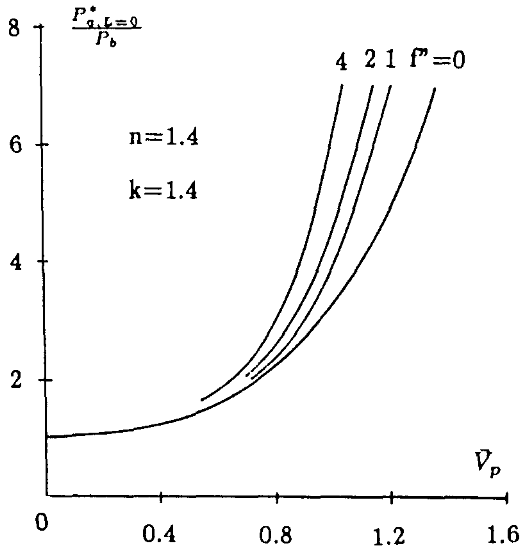

Fig. 3. Stagnation pressure programming for CBPA $P^*_{g,L=0}/P_b$ —ratio of stagnation pressure at entrance of launch stage to pellet base pressure

For CBPA of iced D_2 pellet with diameter of few millimeters, it is shown: 1, pressure loss due to turbulent friction could be a dominant part of the total pressure gradient for high speed pellet injection for example[3], $f' = 10^{-2}$, base pressure 100 bar, base temperature $2000° k$, V_p=5km/s with $\frac{\ell p}{d} = 1$ of iced D_2 pellet it can be shown in fig. 2 and 3, the highest pressure needed at entrance of the launch stage is about 60% higher that that for frictionless case. 2, in order to keep the maximum pressure at a tolerable level, the gas temperature T_b should be kept high enough when high pellet speed is needed.

3. WORKING PROCESS OF THE COMPRESSION STAGE

The driven gas is hydrogen and the driving gas can be either hydrogen or other gases though helium is always used. The whole compression process contains two periods: period 1, adiabatic compression by a free piston driven by driving gas with constant compressed mass before the diaphragm breaks, period 2, adiabatic compression with variable compressed mass since the diaphragm is broken and the gas leaks into the launch stage in the supercritical state to match with the pellet acceleration process.

Period 1. the free piston is pushed by driving gas and compresses the driven gas, that is

$$M_{fp}\frac{dV_{fp}}{dt} = (P_d - P_c)A_c \qquad (6)$$

subscripts fp, d, c denote free piston, driving gas and compressed gas respectively the driving gas undergoes an adiabatic process

$$P_d = P_{do}[\frac{1}{1+\frac{L_{co}A_c}{V_o}(1-\frac{L_c}{L_{co}})}]^{k_1} \qquad (7)$$

here V_o is the volume of driving gas reservoir and driven gas undergoes an adiabatic compression process

$$P_c = P_{co}(\frac{L_{co}}{L_c})^{k_2} \qquad (8)$$

integrate eq.(6)

$$\bar{V}_{fp} = [2\{[\frac{1}{C_1(k_1-1)}(1-\frac{1}{1+C_1(1-\frac{L}{L_o})})^{k_1-1}] - \frac{C_o}{k_2-1}[(\frac{L}{L_{co}})^{1-k_2}-1]\}]^{\frac{1}{2}} \qquad (9)$$

$$= f(k_1, k_2, C_o, C_1, \frac{L}{L_{co}})$$

here k_1, k_2 are specific heat ratio of driving and driven gas respectively, $\frac{L}{L_{co}}$—ratio of compressed gas volume to initial gas volume.

$C_o = \frac{P_{co}}{P_{do}}$ initial filling pressure of driven gas over initial pressure of driving gas.

$C_1 = \frac{L_{co}A_c}{V_o}$ volume of compression cylinder over volume of reservoir for driving gas.

$\bar{V}_{fp} = \frac{V_{fp}}{V_o}$ with $V_o = (\frac{L_{co}P_{co}A_c}{M_{fp}})^{\frac{1}{2}}$. A typical case with $C_o = 0.01, C_1 = 4, k_1 = 5/3, k_2 = 1.4$ is shown in fig.4 it is shown the free piston gets it maximun velocity near the middle of the compression stroke, and then is decelerated by the higher pressure ahead of it, transfer its kinetic enegy to continue compressing the driven gas. At last the free piston stops with the maximun pressure ratio 4234 if the diaphragm does not break.

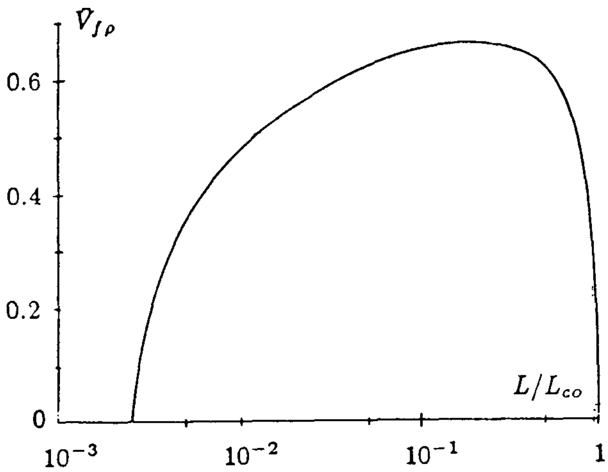

Fig. 4. Working process of a typical compressure stage with unbroken diaphragm
$\bar{V}_{fp}$—dimensionless free piston speed, L/L_{co}—position of free piston

In the real case, the diaphragm will be broken at a certain pressure by carefully cut slots of the diaphragm to a definite thickness. Then the process will be different from the unbroken diaphragm case. It will be shown in the next section.

Period 2, After the diaphragm breaks, the free piston continue to compress the driven gas with variable mass since the driven gas leaks into the launch stage in supercritical state owing to much higher pressure ratio than that for critical flow. the set of governing equations is

$$\begin{cases} \frac{d\bar{V}_{fp}}{d\bar{t}} = [1 + \frac{L_{co}A_c}{V_o}(1 - \frac{L_c}{L_{co}})]^{-k_1} - C_o(\frac{G}{G_o}\frac{L_{co}}{L_c})^{k_2} \\ \frac{dL_c}{d\bar{t}} = -\bar{V}_{fp} \\ -\frac{d\bar{G}}{d\bar{t}} = C_1(\frac{G}{G_o}\frac{L_{co}}{L_c})^{\frac{k_2+1}{2}} \end{cases} \quad (10)$$

$$\text{with } C_1 = [\frac{(\frac{2}{k_2+1})^{\frac{k_2+1}{k_2-1}} k_2 R T_{co}}{\frac{P_{po}}{\rho_{fp}}} \frac{l_{fp}}{L_{co}}]^{\frac{1}{2}} \frac{A_b}{A_c}$$

here A_c and A_b are cross section area of compression stage and launch stage respectively

$$G_o = \rho_{co} A_c L_{co}$$

$$\bar{t} = \frac{t}{\tau}, \tau = (\frac{L_{co}\rho_{fp} l_{fp}}{P_{po}})^{\frac{1}{2}}$$

the initial state of period 2 is the end state of period 1, so the set of equations (10) can be numerically integrated. Compared with several experimental cases[4], excellent confirmations were obtained, a typical case can be shown in fig. (5).

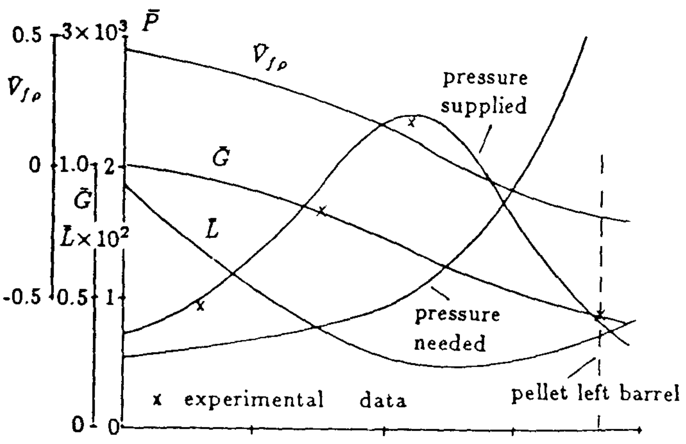

Fig. 5. Performance of a JET two-stage gas gun before modification with $M_{fp} = 5.3kg$, $\frac{P_{co}}{P_{4o}} = \frac{0.7}{65}$, $V_p = 3.7km/s$

4. MATCH COMPRESSION STAGE WITH LAUNCH STAGE

Theoretically, the optimum match compression stage with launch stage is the pressure supplied by compression stage is just consisted with the pressure needed for launch stage with CBPA, but perfect match could not always be reached, practically the "optimum" match is reached by choosing the parameters of the compression stage properly to match the launch stage with CBPA as close as possible. from fig (5) it is shown a large deviation existed between the supplied pressure and the needed pressure, the supplied pressure rose too fast in the initial period and the free piston bounced back too early to cause the supplied pressure sharply dropped in the late period instead of continued to increase that needed for CBPA.

Obviously these results were caused by too light the weight of the free piston, too low the pressure ratio of the initial driving pressure to filling driven pressure etc. The parameters of the compression stage should be modified and the process of compression stage was recalculated by the set of governing equations (10). After several numerical tests by choosing different parameters, the supplied pressure could be obtained very close to that the CBPA needed. one of the results is shown in fig.6.

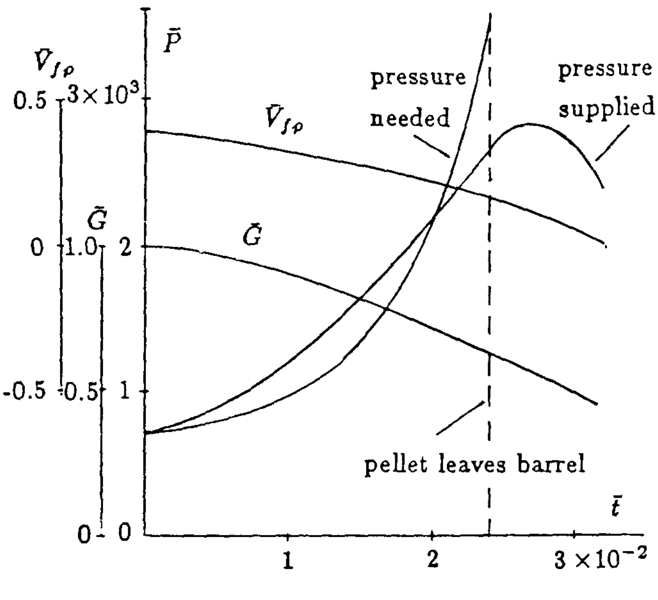

Fig. 6. Suggested process for improving performances with $M_{fp} = 26.55kg$, $\frac{P_{co}}{P_{4o}} = \frac{1}{150}$, $V_p = 5km/s$

5. CONCLUSION:

Optimum matching between stages is the key problem for two stage gas gun. The processes of either compression stage and launch stage could be known by numerially integration of governing equations and confirmed excellent with experimental data. It was helped to modify several versions of two stage gas guns to improve their performances.

Helpful discussion with Dr. P. Kupschus is deeply appreciated.

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