Optimum Operating Technique of Two-Stage Hypersonic Gun Tunnel

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An operating technique of a two-stage hypersonic gun tunnel is presented. The two-stage gun tunnel differs from a conventional gun tunnel in that a free-piston compressor is used as a high-pressure source. Although the free-piston technique has previously been applied successfully to ballistic ranges, shock tubes, and shock tunnels, it has been difficult to adapt it to operate a gun tunnel. In this paper, an optimum operating condition of the two-stage gun tunnel is obtained by matching the gun tunnel diaphragm rupture with the position of the heavy piston in the compressor. It is concluded that the stagnation pressure and temperature become higher by 60% and 10%, respectively, than those of a conventional gun tunnel.

Nomenclature

A	= cross-sectional area
i	= initial position of heavy piston
k	$= (p_r - p_b) V_r g / W U_r^2$
M_A	= Mach number at end of pump tube
p	= driver gas pressure
p_b	= pressure at rear face of heavy piston
p_0	= initial barrel pressure
p_p	= initial pump tube pressure
p_r	= driver gas pressure at diaphragm rupture
p_R	= initial reservoir pressure
r	= position of heavy piston at diaphragm rupture
u	= flow velocity of driver gas into gun tunnel
U	= heavy piston velocity
V	= volume
V_r	= driver gas volume at diaphragm rupture
W	= heavy piston weight
x	= coordinate of heavy piston
x_p	= pump tube length
x_R	= equivalent reservoir length $= V_R / A_p$
Z	= nondimensional time $= A_p U_r t / V_r$
α	= factor of piston striking at end of pump tube
β	= time factor required to drive light piston
τ	= duration time of gun tunnel

Subscripts

A	= end of pump tube
b	= conditions at rear face of heavy piston
conv	= values of conventional gun tunnel
0	= initial conditions in barrel
p	= initial conditions in pump tube
r	= conditions at diaphragm rupture
R	= initial conditions in reservoir
T	= conditons in driver gas when $U = u_r$

I. Introduction

THE light-gas gun tunnel has been reported by many investigators.[1-3] Generally, the conventional gun tunnel has a single-stage gun barrel, in which the nozzle supply pressure is compressed by a light piston. In the single-stage gun tunnel, higher stagnation pressures have been generated by using hydrogen as the driver gas[4] or helium preheated by an electric heater.[5] Longshot tunnels,[6-8] using a heavy piston and a system of check valves in the barrel, have been developed at VKI and Republic Aviation, and the stagnation pressure of 60,000-200,000 psi is obtained there. These techniques are applicable to the single-stage gun tunnel in which a conventional compressor is used as a pressure supply.

The two-stage type of hypervelocity facility has been developed, in which a free-piston compressor is used as a pressure supply instead of a conventional compressor. That is, the free-piston technique has previously been used successfully in ballistic ranges,[9,10] shock tubes,[11] and shock tunnels.[12] Since the free-piston compressor produces unsteady peak pressure in the pump tube, a special technique must be required to adapt it to the gun tunnel. In this paper, the technique is discussed theoretically, and the optimum operating condition is researched experimentally.

II. Theory of Free-Piston Compressor

A schematic diagram of a two-stage hypersonic gun tunnel is shown in Fig. 1a. Initial pressures are p_R at the reservoir, p_p at the pump tube, and p_0 at the barrel. A heavy piston, which is initially at position i, is driven down the tube by rupturing the first diaphragm. When the piston reaches position r, the second diaphragm ruptures and the light piston is driven

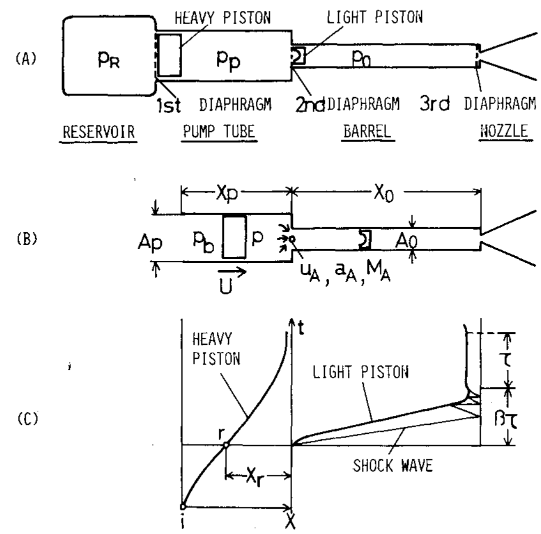

Fig. 1 Operation diagram of piston driven gun tunnel. a) Initial conditions, b) Conditions after diaphragm rupture, c) Wave diagram.

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down the barrel. The notation of the flow parameters and the $x-t$ wave diagram are shown in Figs. 1b and 1c.

The motion of double pistons in the two-stage gun barrel was investigated by Carter et al.[9] In their paper, the piston trajectories and the flow parameters are solved numerically by a computer. Since the purpose of our paper is to obtain experimental data on the optimum operating conditions of the two-stage gun tunnel, a functional relation on the gun tunnel flow is needed rather than the numerical solution. Therefore, an approximation to the two-stage gun barrel is considered as follows.

The motion of heavy piston before diaphragm rupture is obtained from the relation of steady, adiabatic compression.

$$\frac{U}{a_R}=\sqrt{\frac{2}{\gamma-1}\frac{gp_pA_px_p}{wa_R^2}}\times\sqrt{1+\frac{x_R}{x_p}\frac{p_R}{p_p}-\left(1+\frac{x}{x_R}\right)^{1-\gamma}\frac{p_R}{p_p}\frac{x_R}{x_p}-\left(1-\frac{x}{x_p}\right)^{1-\gamma}} \tag{1}$$

where A_p and x_p indicate the cross-sectional area and the length of pump tube, respectively, and x_R is the equivalent length of reservoir, i.e., $x_R=V_R/A_p$.

The pressure in the pump tube, p, is given by

$$\frac{p}{p_p}=\left(1-\frac{x}{x_p}\right)^{-\gamma} \tag{2}$$

The piston velocity U_r, the pressure in pump tube p_r, and the driver gas volume V_r at diaphragm rupture are calculated by putting $x=x_r$ into Eqs. (1) and (2).

The variation of pressure in the pump tube after diaphragm rupture was given by Stalker.[12] The approximate equation of piston motion is assumed as $(W/A_pg)\mathrm{d}U/\mathrm{d}t=-(p_r-p_b)$, where the pressures at the front and rear face of the piston, p_r and p_b are nearly constant. Then the pressure in the pump tube is given by

$$\frac{p}{p_r}=\left[(1-Z+\frac{k}{2}Z^2)^{-1}\exp\left\{-\frac{u_r}{U_r}\frac{2}{\sqrt{2k-1}}\times\left(\tan^{-1}\frac{kZ-1}{\sqrt{2k-1}}+\tan^{-1}\frac{1}{\sqrt{2k-1}}\right)\right\}\right]^{1/\gamma} \tag{3}$$

where $k=(p_r-p_b)V_rg/WU_r^2$, $Z=A_pU_rt/v_r$ and it is kept nearly constant, i.e., u equals approximately u_r.

When $U=u_r$, the maximum pressure is obtained and a subscript T is used to indicate the driver gas conditions. Putting $(p_T-p_b)V_T=\alpha Wu_r^2/g$, if $\alpha>1$ in case that $U_r>u_r$, then the heavy piston will not strike the end of the pump tube. On the contrary, if $\alpha<1$, the piston will strike the end of the pump tube.

Assuming the end of the pump tube (i.e., the diaphragm section) as a convergent nozzle with the entrance area A_p and exit area A_0, u_r can be calculated from the theory of steady nozzle flow. That is, $M_A=u_r/a_A$ is obtained from A_p and A_0. Moreover, the following equation is given

$$\frac{u_r}{a_A}=\frac{1}{\gamma-1}\left[\left(\frac{p_r}{p_A}\right)^{(\gamma-1)/2\gamma}-1\right]=\frac{2}{\gamma-1}\left(\frac{a_r}{a_A}-1\right) \tag{4}$$

where the subscript A indicates conditions at the entrance of the nozzle.

Figure 2 shows theoretical results of the variation of the driver gas pressure p/p_r in case that $\alpha=0.6$. When α is smaller than unity, the driver gas pressure becomes greater compared with the case that $\alpha>1$, although it is dangerous for the equipment because the piston strikes the end of the pump tube.

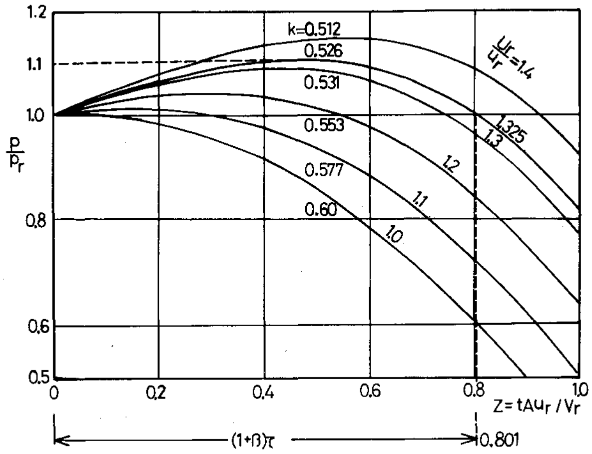

Fig. 2 Variation of driver gas pressure, $\gamma=1.4$, $(p_T-p_b)V_T=\alpha Wu_r^2/g$, $\alpha=0.6$.

III. Optimum Operating Condition

In the two-stage gun tunnel, the pressure in the pump tube which varies with time is used for driving the light piston in the barrel. Approximately constant driver pressure must be used in order to obtain steady stagnation values in this tunnel. In this paper, we assume that the driver gas pressure can be regarded as nearly constant if the variation of driver gas pressure is less than 10%. Then, as shown in Fig. 2, the pressure curve where $k=0.526$ and $U_r/u_r=1.325$ can be considered approximately steady within $Z=0\sim0.801$. When this pressure curve is used as the driver condition, we regard it as the optimum operating condition. On the other hand, the other pressure curves cannot be considered as the optimum operating condition because the duration time of steady state is much shorter than the optimum one. Figure 3 shows experiments about the optimum operation of a gun tunnel, under the conditions that $p_R/p_p=16/3$ and $W=4$ kg. In these experiments, stagnation pressure at the end of the barrel and pitot pressures in the test chamber were measured. Figure 3b shows an example of the optimum operation, where the piston position at diaphragm rupture x_r is 1.63 m and the operating condition corresponds to the curve of $U_r/u_r=1.325$ in Fig. 2. In the photograph, a steady stagnation pressure obviously exists.

Figures 3a and 3c show that there is not steady state because of fast diaphragm rupture ($x_r=0.95$ m) and late diaphragm rupture ($x_r=1.9$ m), respectively, and these operating conditions correspond to the curves of $U_r/u_r=1.4$ and 1.0.

The driver pressure in the pump tube is propagated toward the end of the barrel along positive characteristics $\mathrm{d}x/\mathrm{d}t=u+a$. Therefore, the duration time of a gun tunnel τ must be calculated graphically by networks of the characteristics, as shown in Refs. 8 and 9. In this paper, however, considering that the steady driver pressure contributes not only the duration time τ but also the time required to drive the light piston including multiple shock reflections $\beta\tau$, the duration of the steady driver gas pressure (e.g. $Z=0.801$ in Fig. 2) is expressed by $(1+\beta)\tau$, where β should be evaluated by experiments.

Theoretical optimum operating conditions are obtained by Eqs. (1-4). An example of the results is shown by solid lines in Fig. 4, where $p_r=16$ atm, $W=1.5$ kg, $\alpha=0.6$, and $\beta=1$. An optimum operating condition is shown by x_r/x_p. This means that it can be obtained by rupturing the second diaphragm when the heavy piston reaches the position x_r. The stagnation pressure $p_t/p_{t,\mathrm{conv}}$ and the duration time $\tau/\tau_{\mathrm{conv}}$ are also shown in this figure, where the subscript conv means the values obtained by a conventional gun tunnel. At present, $p_{t,\mathrm{conv}}=19.5$ atm and $\tau_{\mathrm{conv}}=15$ ms. Theoretical stagnation pressure p_t is given by Winter et al.[3,13]

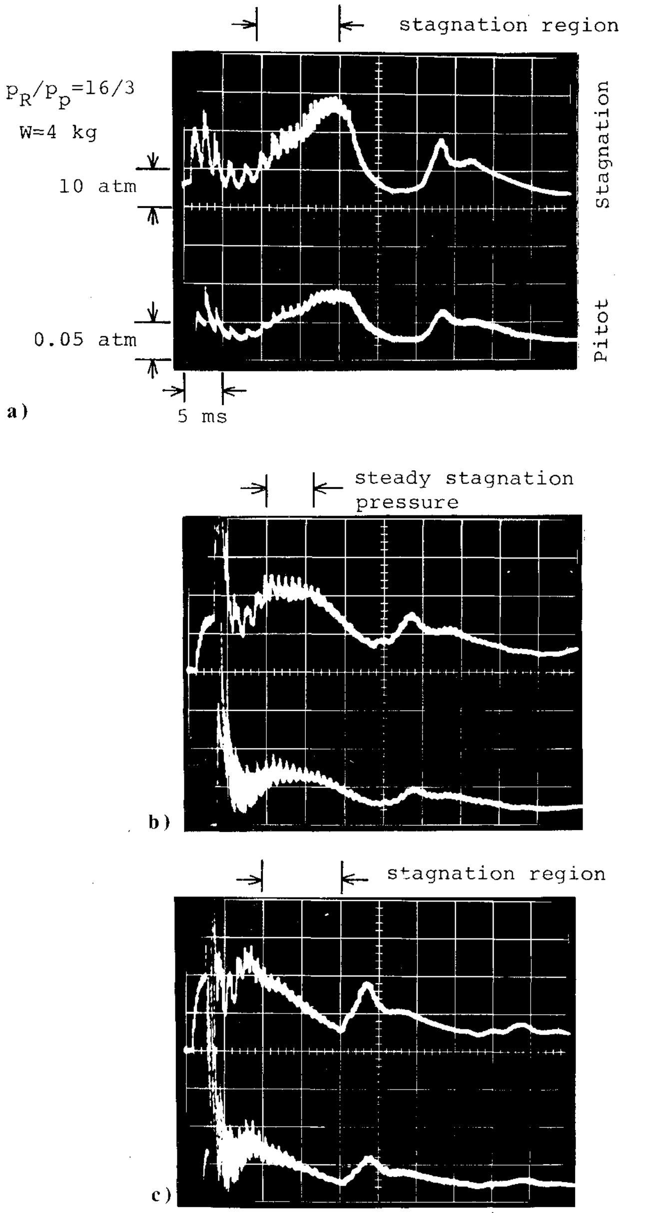

Fig. 3 Stagnation pressure and pitot pressure $p_R/p_p = 16/3$, $W = 4$ kg. a) Fast diaphragm rupture, $x_r = 0.95$ m, b) Optimum operation, $x_r = 1.63$ m, c) Late diaphragm rupture, $x_r = 1.90$ m.

IV. Equipment

The two-stage hypersonic gun tunnel used in this experiment has a reservoir (diam = 0.3 m, length = 0.6 m), a pump tube (diam = 8 cm, length = 2.6 m), a barrel (diam = 4 cm, length = 3 m), a hypersonic nozzle (angle of apex = 20 deg, exit diam = 15 cm, and nominal Mach number = 10), a test chamber (diam = 1.05 m, width = 1 m) and a dump tank (diam = 1.05 m, length = 2 m). The free-piston compressor consists of the reservoir and the pump tube, in which a heavy piston (1.5, 2, 3, and 4 kg in weight) made of duralumin is inserted. In the barrel is a light piston (10 g in weight) made of nylon.

According to the theory, the stagnation value becomes greater as α becomes smaller. Since the heavy piston strikes at the end of the pump tube when $\alpha < 1$, the shock absorber is used to protect the pump tube, as shown in Fig. 5.

V. Experimental Results and Discussions

The reservoir pressure $p_R = 16$ atm and the barrel pressure $p_0 = 1$ atm were used in all of the experiments. The other conditions were as follows: the piston weight $W = 1.5$, 2, 3, and 4 kg and the pressure ratio of reservoir vs pump tube $p_R/p_p = 16/3$, 16/4, and 16/5. The optimum operation was obtained by searching an appropriate position of the heavy piston x_r at diaphragm rupture. The position x_r was decided by changing a thickness of the second diaphragm. Results of the position at the optimum operation x_r/x_p, stagnation pressure $p_t/p_{t,\text{conv}}$, and duration time τ/τ_{conv} are shown in Table 1.

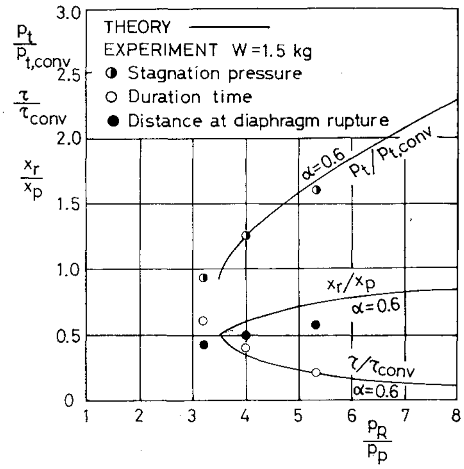

Fig. 4 Theoretical and experimental results of optimum operation, $W = 1.5$ kg, $\alpha = 0.6$.

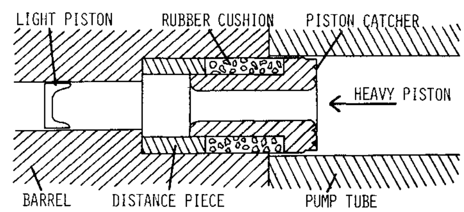

Fig. 5 Shock absorber.

From these results, the following are discussed: stagnation pressure p_t becomes greater as p_R/p_p is larger and W is smaller, while the duration time τ becomes longer as p_R/p_p is smaller and W is heavier. As for the stagnation value, the result of $W = 1.5$ kg and $p_R/p_p = 16/3$ is the most excellent among these results, where p_t is greater by about 60% than $p_{t,\text{conv}}$, although τ is smaller than τ_{conv}. The experimental results of $W = 1.5$ kg are plotted in Fig. 4, and they agree well with the theoretical ones. As for stagnation temperatures, calculating methods are given by Winter et al.[3,13] One of the calculating results is $T_t/T_{t,\text{conv}} = 1.1$ in case that $W = 1.5$ kg and $p_R/p_p = 16/3$. A Mach number of 9.8 is obtained by the stagnation pressure and the pitot pressure.

Table 1 Results of optimum operating conditons

	p_R/p_p	W, kg 1.5	2.0	3.0	4.0
x_r/x_p	16/3	0.55	0.62	0.65	0.63
	16/4	0.49	0.56	0.59	0.58
	16/5	0.45	0.52	0.53	0.53
$p_t/p_{t,\text{conv}}$	16/3	1.59	1.33	1.23	1.02
	16/4	1.23	0.97	0.92	0.87
	16/5	0.92	0.92	0.92	0.92
τ/τ_{conv}	16/3	0.20	0.27	0.33	0.40
	16/4	0.40	0.47	0.47	0.67
	16/5	0.60	0.67	0.67	0.67

VI. Conclusion

An operating technique of a two-stage hypersonic gun tunnel is presented. The two-stage gun tunnel differs from a conventional gun tunnel in that a free-piston compressor is used as a pressure source. Although the free-piston technique has previously been applied successfully to ballistic ranges, shock tubes, and shock tunnels, it is difficult to adapt it to operate a conventional gun tunnel. Thus, the operating condition was investigated in this paper. The optimum operating conditions were discovered experimentally by matching the gun tunnel diaphragm rupture with the position of the heavy piston. The piston trajectory and the flow parameters in the gun tunnel were calculated by an approximate theory, and the results agreed well with the experimental ones. It was concluded that the stagnation pressure and temperature became higher by 60% and 10%, respectively, than those of a conventional gun tunnel. It is also predictable that this technique is applicable not only to conventional gun tunnels but also to the other single-stage guns.

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