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Design of a High-Speed Valve*

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A high-speed valve has been designed for opening a deLaval nozzle in times less than 10^{-3} sec.

In connection with current experimental studies on the recombination rates of atoms in deLaval nozzles, it became necessary to develop a valve for opening the nozzle in times less than about 10^{-3} sec. The material had to be chosen in such a way that the valve could withstand temperatures up to 100°C.

The construction of the valve is shown in Fig. 1. In order to shut the nozzle-exit area (1), the plug-valve (2) is located at the bottom of a movable differential piston (3). An O-ring made of silicone (4) is used as a gasket between the plug and the nozzle. Compressed air flows into the valve through the inlet pipe (5) which is closed at the free end with a plastic diaphragm (6). The volume (7) above the piston area F is connected to the annular volume (8) through a small hole (9). By raising the pressure in volumes (7) and (8) slowly, a uniform pressure p is maintained and the force pf forces the piston with the plug-valve onto the nozzle exit area. If the pressure exceeds the burst pressure of the diaphragm, the gas from volume (7) passes out of the valve and the force $p(F-f)$ moves the piston upward, opening the valve. A strong spring (10) above the piston decelerates the motion of the piston.

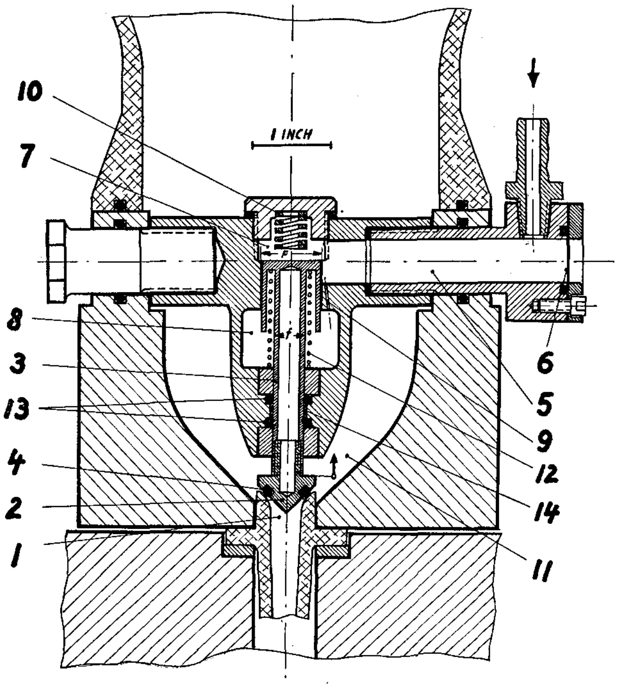

Fig. 1. Schematic diagram of a valve designed for opening in times less than one millisecond.

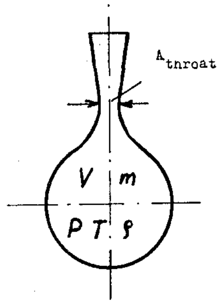

Fig. 2. Schematic diagram of the apparatus used for nozzle flow studies.

After equilibrium has been reached in volume (8) at atmospheric pressure, volume (11) is still at sub-atmospheric pressure and the piston shaft is held with a force Δpf. However, movement of the piston is prevented by a weak counter-spring (12). Two O-rings (13) maintain the piston shaft; the gas volume (14) between these O-rings can either be connected to the atmosphere or else may be evacuated.

Because of the short times involved, the treatment of the rate of discharge may be based on the use of adiabatic relations. The rate of discharge of mass in unit time is

$$-dm/dt=-d/dt(\rho V)=v_t\times A_t\times\rho_t,$$

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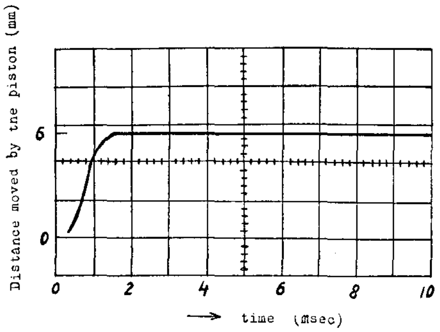

FIG. 3. The distance moved by the piston as a function of time.

where m is the mass of gas in the volume V, t equals the time, v_t is the velocity at the nozzle throat, A_t represents the cross-sectional area of the throat, and ρ_t is the corresponding density (see also Fig. 2). Furthermore,

$$\frac{\rho_t}{\rho}=\left(\frac{2}{\gamma+1}\right)^{1/(\gamma-1)},\quad \frac{T}{T_0}=\left(\frac{\rho}{\rho_0}\right)^{\gamma-1},$$

$$\frac{v_t}{v_{t0}}=\left(\frac{T}{T_0}\right)^{\frac{1}{2}},\quad \frac{p}{p_0}=\left(\frac{\rho}{\rho_0}\right)^{\gamma},$$

where the subscript 0 identifies initial conditions, the subscript t identifies throat conditions, p is the pressure, T represents the temperature, and γ is the (assumed constant) heat capacity ratio. From the preceding expressions we find that

$$t=\frac{2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{-1/(\gamma-1)}\frac{V}{v_{t0}\times A_t}\left[\left(\frac{p_0}{p}\right)^{(\gamma-1)/2\gamma}-1\right].$$

Here t is the time at which the pressure has dropped from p_0 to p in a volume V when the initial gas velocity at the throat of area A_t is v_{t0}. For proper functioning of the valve, it is necessary that the pressure change in the annular volume (8) be of the same order as the pressure decrease in the vessel. Therefore, neglecting differences in γ and v_{t0},

$$(V/A_t)_{\text{vessel}}\approx(V/A_t)_{\text{ring}}.$$

The volume of the reaction vessel is 1000 cm^3, the throat diameter of the nozzle is 2.9 mm, and the annular volume is about 15 cm^3. Hence, the diameter of the connecting hole should be

$$d\approx 2.9\left(\frac{15}{1000}\right)^{\frac{1}{2}}=0.35\text{ mm}.$$

During the time required for opening of the valve, the change of pressure in the annular volume may be neglected in estimating the time of opening. The acceleration of the piston has been calculated by neglecting frictional losses. Thus

$$\ddot{\xi}=\frac{p\times(F-f)}{m_{\text{piston}}}.$$

For the mass of the aluminum piston we use 7 grams, the burst pressure p is 11 atm, the ring area $(F-f)$ is 2.36 cm^2; the acceleration is now found to be

$$\ddot{\xi}=\frac{11\times 2.36}{0.007}g=3720g,$$

where g represents the gravitational acceleration. The valve stroke length is $s=6$ mm. Therefore, the time for complete opening of the valve becomes

$$t=\left(\frac{2s}{\ddot{\xi}}\right)^{\frac{1}{2}}=\left(\frac{2\times 0.006}{3720\times 9.81}\right)^{\frac{1}{2}}=0.57\times 10^{-3}\text{ sec}.$$

A direct optical measurement of the time required for opening of the valve led to the value 1.1×10^{-3} sec (see Fig. 3). The difference between theory and practice should be ascribed mainly to the neglect of frictional losses produced by the O-rings and deceleration of piston movement by the spring. The valve was fully opened for more than 0.1 sec. No oscillations were observed in the valve motion.

By using higher burst pressures, enlarging the effective piston area, decreasing the piston, and minimizing friction, it should be possible to construct valves that open in 10^{-4} sec by using the design principles employed by us.

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