Magnetically Driven Fast-Acting Valve for Gas Injection into High Vacua*

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(Received November 12, 1959)

A description is given of a valve suitable for use in studies involving the acceleration of plasmas into regions of high vacua. Valve opening durations of less than 60 μsec may be attained, and amounts of gas lower than 0.01 cc STP may be introduced. Valve performance characteristics and measuring techniques are discussed.

INTRODUCTION

THERE is currently considerable interest in studying the properties of plasmas moving into a vacuum. When a variety of gases are to be studied as sources of electrically produced plasmas, it is desirable to use cold gases in very short pulses compatible in duration with the ringing period of the electrical discharge circuitry. Such short gas pulses can be admitted into an evacuated discharge chamber by means of a quick-acting gas-entry valve. Generally, the valve-operating durations required are in the order of 100 μsec or less.

One such valve, which has been described elsewhere,[1] opens as a result of a longitudinal sound wave created in an anvil at one end of a steel rod and transmitted to a moving valve member at the other end. Thus, the operating time of such a valve has a practical lower limit which is determined by the lower limit of the size of the longitudinal wave packet that can be generated by an anvil of practical size, and by the velocity of the wave (about 5×10^5 cm/sec). In the valve to be described here, the mechanical impulse is imparted directly to the moving valve member, and hence the above limitations do not apply.

CONSTRUCTION AND CIRCUITRY

The brass valve assembly, as shown in Fig. 1, is designed for installation on any smooth surface forming an entrance into a vacuum chamber. The assembly is in two parts, one containing fittings for gas lines and a spring-disk assembly, the other containing a field coil, electrical leads, and a valve seat. The valve seat is a Teflon O-ring mounted in a highly polished groove. With 1 to 4 atmos on the high-pressure side, the valve seals sufficiently well to maintain a pressure of 10^{-7} mm Hg on the low-pressure side. This represents the lower limit of the vacuum system capability with a blind seal in place of the valve. A rubber gasket provides a seal for the assembled sections.

The copper-ribbon field coil is soldered to the valve body at one end, and to a vacuum-tight glass-sealed high voltage lead-through terminal at the other end. It is potted in Sauereisen porcelain cement to prevent electrical breakdown and to avoid deformation and movement caused by its internal magnetic fields.

The steel valve spring is soft soldered to the highly polished brass valve disk. The spring has a mass of 7 g and a constant of 3.5×10^7 g sec^{-2}. The mass of the disk is 10 g. The moving system has a calculated period of approximately 3 msec.

A 10-kv 3-μf General Electric capacitor, charged from 4.5 to 8 kv, provides energy for the opening of the valve. The capacitor energy is held off from the rest of the circuit by a 3-electrode air gap. Breakdown is initiated by applying a timed spark from an induction coil to the trigger electrode.

PRINCIPLE OF OPERATION

The capacitor is discharged through the field coil, creating a magnetic field which, in turn, induces eddy currents in the metallic disk. A mutual repulsion results, forcing the disk away from its O-ring seat and admitting a quantity of gas through one of the two electrodes of the accelerator system.

The valve action is that of a Hooke's Law oscillator which has been preloaded and constrained from passing through the zero-potential point. The mechanism best can be described by considering the potential energy of the system,

$$\tfrac{1}{2}kx^2. \tag{1}$$

The deflection, x, may be expressed in terms of the time

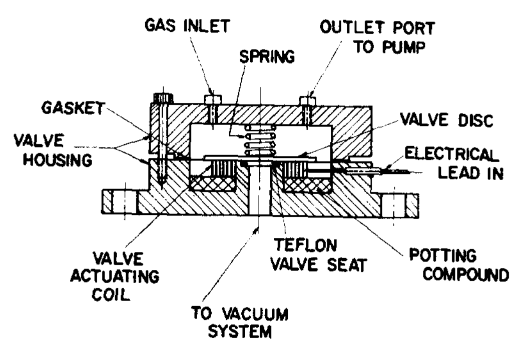

FIG. 1. Detail of fast-acting valve.

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* Based upon work performed under the auspices of the U. S. Air Force, Ballistic Missile Division.

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[1] J. Marshall, "Acceleration of plasma into vacuum," *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy* (United Nations, Geneva, 1958), Vol. 31, p. 341.

as follows:

$$x=(x_0+\Delta x)\cos(2\pi t/\tau), \quad (2)$$

where zero time has been defined as occurring at the point of maximum swing (zero kinetic energy). In operation, the valve spring is precompressed by an amount x_0. The electromagnetic coil action then causes an additional displacement Δx. Thus from Eq. (2) we have

$$t=0, \text{ at } x=x_0+\Delta x$$

and

$$t=(\tau/2\pi)\cos^{-1}[x_0/(x_0+\Delta x)], \text{ at } x=x_0. \quad (3)$$

In operation, a certain fraction, η, of the electrical energy is converted to mechanical energy which, in turn, becomes entirely potential energy at $t=0$ as defined above, i.e.,

$$\tfrac{1}{2}kx^2=\tfrac{1}{2}\eta CV^2, \quad (4)$$

or

$$x=(\eta C/k)^{\frac{1}{2}}V. \quad (4a)$$

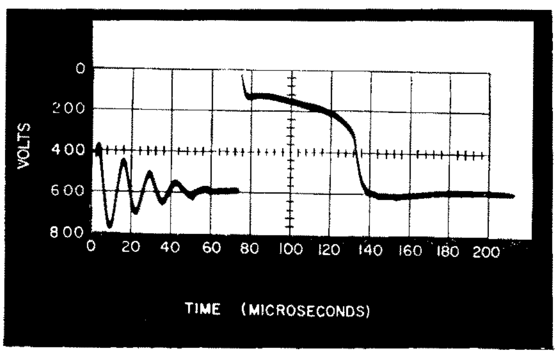

FIG. 2. Determination of valve-operating time by means of discharge type pressure probe. Initial transient from 0–75 μsec is due to pickup from the LRC circuit of the valve solenoid. Subsequent wave form represents the variation of voltage across the discharge pressure probe as the gas is admitted by the valve.

Substituting this value for x in Eq. (3) we obtain

$$t=(\tau/2\pi)\cos^{-1}[V_0/(V_0+\Delta V)]. \quad (5)$$

The actual operating time is just twice this amount, or

$$t=(\tau/\pi)\cos^{-1}[V_0/(V_0+\Delta V)]. \quad (6)$$

It will be noted that in the limit of large ΔV, $\Delta t=\tau/2$.

MEASUREMENTS

Valve-operating times were determined by measuring the duration of a 600-v hollow-cathode discharge through the pulse-injected gas. The discharge assembly consisted of the $\frac{3}{8}$-in. diam, $\frac{7}{8}$-in. deep gas exhaust port in the valve which served as a hollow cathode, and a thin wire, extending centrally into the port to within $\frac{1}{8}$ in. of the valve disk, as an anode. The voltage drop across the discharge was measured as a function of time. A representative oscilloscope record is shown in Fig. 2. A sharp spike will be noted on the leading edge of the discharge pressure probe signal.

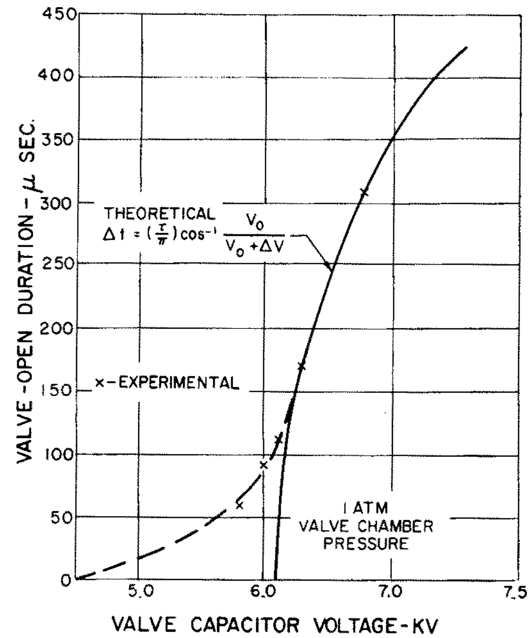

FIG. 3. Valve-opening durations for usual operating voltages. Values are obtained by discharge pressure probe measurements.

Since the width of this spike was found to vary inversely as the valve-operating voltage, it cannot represent the operating time of the valve. Rather, it is probably the breakdown characteristic of the gas in the valve port. With 5000 to 8000 v on the coil capacitor, this discharge technique indicated valve-opening durations ranging from 60 to 750 μsec.

Discharge current measurements also have been carried out. These measurements indicate the same valve-opening durations for a given set of conditions. The lower limit of 60 μsec is determined partly by the fact that a 600-v discharge could not be initiated at shorter opening durations. These data are recorded graphically in Fig. 3. It should be pointed out that the pressure measurements have demonstrated that the valve is capable of opening at lower coil capacitor voltages, and thus, for shorter durations than indicated. The curve of Fig. 3 appears to fit Eq. (6) at the higher operating voltages, with the parameters V_0 equal to 6090 v and τ equal to 2100 μsec. Departure from this relationship at the lower voltages is attributed to a lever-type action of the valve disk in this voltage range. This is a result of the nonrigidity of the spring and the nonparallel attack of the valve disk on the valve seat. Substituting measured values for V_0 (6090 v) and x_0 (0.6 cm) in Eq. (4), the efficiency of conversion η is found to be 1%. The actual operating efficiency of the valve is still lower, since a portion of the energy must be expended in overcoming the potential stored in the compressed spring. However, this inefficiency is of little consequence as far as experimental usage is concerned. In Fig. 3, we have assumed that the valve opening and pressure probe discharge durations are

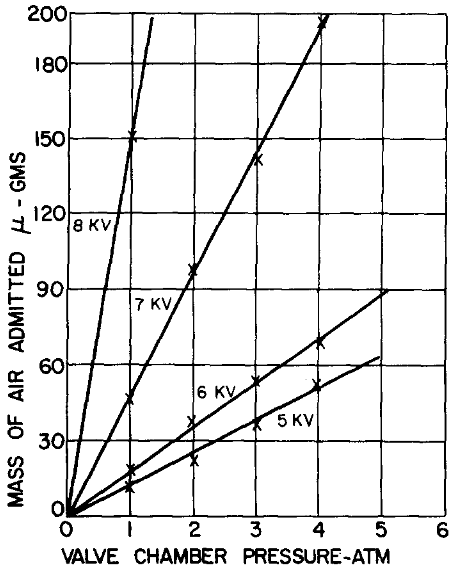

FIG. 4. Mass of air admitted by fast-acting valve *vs* valve chamber pressure.

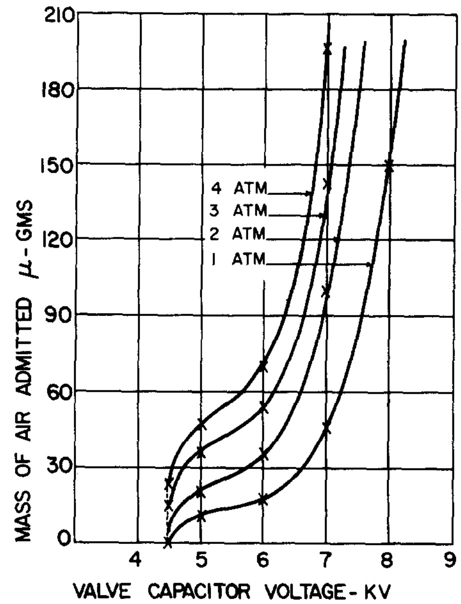

FIG. 5. Mass of air admitted by fast-acting valve for usual operating voltages on valve capacitor.

the same. This does not take into account the time necessary to exhaust the $\frac{7}{8}$-in. long port to pressures sufficiently low for extinguishing the discharge. Thus, at the higher operating voltages, it may be necessary to subtract 60 μsec or more from the recorded times, since this represents the time for a rarefaction wave to traverse the port. At the lower operating voltages, the pressure in the port may drop below the extinguishing pressure before the gas reaches the mouth of the port. Hence, a much smaller correction may be appropriate at these lower voltages.

Depending on the magnitude of the spring constant, pressure conditions in the valve itself may influence the duration of opening. It was found that when springs weaker than the present one were used, the valve-operating durations varied inversely with the back pressure on the valve. Future designs may employ this to admit optimum amounts of gas in the shortest possible times and with the least amounts of electrical energy.

The composition of the valve seat also appeared to have a considerable effect on the manner in which the valve opens. Rubber O-rings, used earlier, required higher capacitor energies to open the valve. The effect probably was caused by a combination of the wasted movement involved in decompressing the rubber and the adhesion of rubber to the metal valve disk.

The amount of gas admitted to the accelerator system was measured with a mercury McLeod gauge which registered the increase of pressure in the entire vacuum system caused by 8 to 10 openings of the valve carried out in rapid succession (1/sec). Average amounts per shot, as determined by dividing the total mass increase by the number of shots, were reproducible over several sets of measurements. These measurements indicated that, with voltages ranging from 4500 to 8000 v and valve pressures ranging from 1 to 4 atmos, 0.3 to 12 μ of air were admitted into the 19-liter vacuum system per capacitor discharge. These amounts are approximately equivalent to 1 to 450 μg of nitrogen, or 0.009 to 0.4 cc STP. Figure 4 shows this in graphic form as the amount of gas admitted *versus* pressure in the valve chamber for various voltages on the coil discharge capacitor. The linear relationship appears to indicate that the closing time of the valve is not influenced significantly by increases in pressure behind the valve disk. As mentioned before, this is not the case with springs significantly weaker than the one used to obtain these data. In Fig. 5, the same data are plotted as amount of gas admitted *versus* valve-capacitor voltage for various valve-chamber pressures.

A Phillips pressure gauge monitoring the vacuum system indicated no noticeable valve opening below 4500 v. It is interesting to note that the same minimum operating voltage is indicated by extrapolating the curve drawn through the valve-opening duration data (Fig. 3) to zero time. It can be seen that the time required to inject a given amount of gas may be shortenend by using lower valve-operating voltages, along with higher pressures in the valve chamber.

NOTE

As the writing of this paper was being concluded, we noticed with interest that a similar means for quickly opening a valve has been developed in Russia.[2] However, the Russian device made no provision for again rapidly closing the valve, with the result that a gas pulse is obtained which has a sharp leading edge, but is also rather extensive in time.

[2] I. S. Shpigel', Instr. and Meas. Eng. U.S.S.R. **1**, 151 (1959).