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Opening Time of Brittle Shock-Tube Diaphragms for Dense Fluids

P. A. Thompson and W. F. Loutrel

Division of Fluid, Chemical, and Thermal Processes, Rensselaer Polytechnic Institute, Troy, New York 12181

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Metal diaphragms have proved unsuccessful for use with dense fluids. Thin mechanically fractured diffusion-strengthened glass diaphragms are successful and have opening times which correlate well with a simple theory.

Basic fluid properties can be investigated by studying the rarefaction wave produced in the high-pressure section of a simple shock tube. In our experiments the high-pressure test fluids are various dense high-molecular-weight gases, at temperatures and pressures of the order of the critical values (e.g., $T\sim600$ K, $P\sim20$ bars). The low-pressure fluid is an inert buffer gas, usually nitrogen. The shock tube has an internal diameter of 59 mm, a high-pressure (test) length of 2.3 m, and a low-pressure length of 0.7 m.

Conventional scribed metal diaphragms proved to be unsatisfactory in that they open incompletely and unrepeatably. Typically, a small slit opened along the scribe or only one petal folded open. We attribute this behavior mainly to the large acoustic impedance ρc of the test fluid ($\sim10^4$ kg/m^2-sec); according to the linear relation $\delta P=\rho c\delta u$, a small average velocity δu, corresponding to the flow through a small fissure, will yield a large pressure relief δP if ρc is large.

Thin glass diaphragms, both flat and concave ground, were also unsatisfactory under pressure burst in that petalling was incomplete, yielding a small opening, and burst pressure was unpredictable.

Flat diffusion-strengthened Chemcor glass[1] diaphragms, fractured by means of a striker as shown in Fig. 1, are found to be suitable. These are similar in principle to the tempered glass diaphragms used by Terner[2] in his experiments with water, but have the advantage of both high-compression surface layers and small total thickness (2.2 and 1.3 mm in our experiments), leading to complete fracture into very small fragments and relatively short opening times.

Fracture of the glass diaphragm is accomplished by a simple striker mechanism, consisting of a rod of total mass of 1.3 kg, which extends from the diaphragm through a bushing in the end of the low pressure test section. The rod end is struck with a hammer. The impact is sensed by a trigger transducer, located near the diaphragm. The transducer output in turn triggers an electronic circuit, supplying a voltage step to the oscilloscope sweep trigger. Following fracture initiation by this means the glass fragments are formed in negligible time (crack propagation velocity ≈1500 m/sec) and can be viewed as a frictionless piston with mass equal to that of the glass. The opening times of these diaphragms can then be rationalized by a simple theory. Applying Newton's second law to the piston, with the method of characteristics for simple waves for the fluid on either side of the piston, yields a solution for the piston velocity $u(t)$,

$$u/u_\infty=e^{-t/\tau}, \tag{1}$$

where u_∞ is the velocity which corresponds to equal pressures on the two sides of the piston. The characteristic time τ is

$$\tau\equiv\rho_g a/[(\langle\rho c\rangle)_t+(\langle\rho c\rangle)_b], \tag{2}$$

where ρ_g is glass density (2.3 g/cm^3), a is diaphragm thickness, $(\langle\rho c\rangle)_t$ and $(\langle\rho c\rangle)_b$ are the acoustic impedances of the test and buffer gases, respectively, averaged between the initial and final states. The averaging of the acoustic impedance results in a linearized form of the method of characteristics, with the simple solution (1). $(\langle\rho c\rangle)_t$ and $(\langle\rho c\rangle)_b$ are found in terms of the initial values from

$$\begin{aligned}(\langle\rho c\rangle)_t&=(\rho c)_t-k\Gamma_t\Delta P/(2c_t),\\(\langle\rho c\rangle)_b&=(\rho c)_b+(1-k)\Gamma_b\Delta P/(2c_b),\end{aligned} \tag{3}$$

where c is sound speed, the dimensionless quantity Γ is the fundamental gas dynamic derivative[3] defined by

$$\Gamma\equiv c\left(\frac{\partial(\rho c)}{\partial P}\right)_s$$

of order unity, ΔP is the diaphragm pressure difference, and the dimensionless quantity k ($0\leq k\leq1$) is defined such that $k\Delta P$ is the pressure amplitude of the rarefaction wave,

$$k\equiv\frac{2(\rho c)_t}{(\rho c)_t+(\rho c)_b+p+\{[(\rho c)_t+(\rho c)_b+p]^2-4p(\rho c)_t\}^{\frac{1}{2}}},$$

in which $p\equiv(\Gamma_t/2c_t+\Gamma_b/2c_b)\Delta P$.

The experimentally measured opening time Δt is plotted against τ in Fig. 2. The opening time is arbitrarily defined to be the interval in which 90% of the pressure change

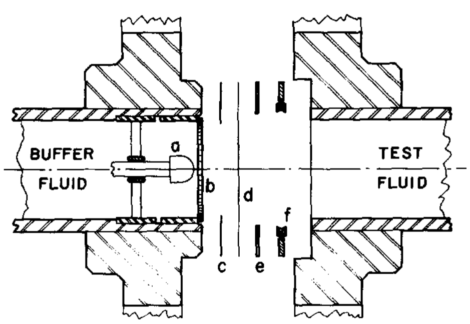

FIG. 1. Glass diaphragm assembly. (a)—Striker ball and rod; (b)—glass diaphragm with silicone adhesive bead; (c)—aluminum foil washer; (d)—aluminum foil sealing sheet; (e)—aluminum compression washer; (f)—spiral-wound gasket.

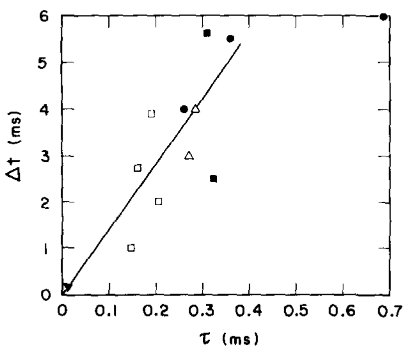

FIG. 2. Diaphragm opening Δt vs characteristic time τ. □, perfluoromethyldecalin. △, fluorinated ether $C_{14}F_{29}HO_4$. ○, perfluorodimethylcyclohexane. ▼, liquid water (Terner[2]). Filled symbols correspond to diaphragm thickness $a=2.2$ mm, unfilled symbols to $a=1.3$ mm.

in the rarefaction wave occurs. The pressures $P(t)$ were measured in the test section by two piezoelectric transducers (Kistler model 601R) located 1 and 1.5 m from the diaphragm. Since the characteristics of simple waves are straight lines, the burst time was calculated by a linear extrapolation of the $P(t)$ rarefaction wave duration back to the diaphragm section.

Figure 2 suggests that there is good correlation between theory and experiment for a variety of large impedance test fluids, including water, and for a variety of prestressed diaphragms. For the longer burst times, reflected waves from the closed end of the buffer gas section have reached the diaphragm and simple wave theory is no longer applicable. We should also mention that experiments with a light test gas (nitrogen) yield opening times substantially shorter than would be predicted on the basis of Fig. 2, possibly because the test gas is penetrating the glass particle screen.

The use of glass diaphragms is far from new. Vieille[4] experimented with glass in the very first shock tube: "The rupture pressures of these diaphragms [collodion] showed a regularity much superior to that of the glass diaphragms, both tempered and nontempered. . . ." In our experiments, the mechanical striker overcomes this difficulty.

Making use of the opening-time predictions presented here, we are designing a new shock tube for the experimental measurement of the fundamental gasdynamic derivative Γ.

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[1]Corning Glass Works (glass similar to Corning Code 0315).

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