RESISTANCE IN RESPIRATORY VALVES AND CANISTERS*

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Since some readers may be unfamiliar with the basic concepts of fluid mechanics, the writer has thought it advisable to begin with a simple exposition of the relevant principles. Only thus can the behaviour of disc valves and absorbers be appreciated, and a proper understanding is clearly essential for rational design.

1. *The General Principles of Air Flow (at a Steady Rate) in Ducts*

When a fluid (say air) passes *at a steady rate* along a duct, there will be a loss of energy. For a horizontal duct of uniform cross section, this loss is manifested by a pressure drop along the duct which

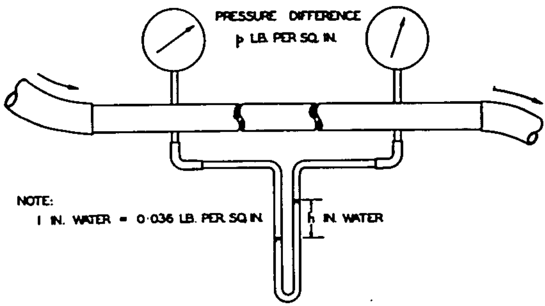

Fig. 1. Methods of measuring the pressure drop along a duct.

can be measured by attaching pressure gauges or the limbs of a manometer to suitable pressure tappings in the duct walls (fig. 1). These pressure tappings should be small holes, which pierce the walls squarely so as to cause the least possible disturbance to the flow; they should be clear of any regions of unsymmetrical flow, that is, bends, changes of section or any form of obstruction.

This energy may be regarded as being lost either by friction or by impact.

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(a) The fluid velocity will be greatest at the center of the duct; successive layers toward the boundary exercise viscous drag on the adjacent layers, the particles actually in contact with the boundary being stationary. On this assumption, the fluid friction in the form of viscous drag causes the energy loss.

(b) Eddies, caused by abrupt changes in section, bends or obstructions in the duct, are composed of fluid particles moving across or opposing the general direction of flow. The impact of these eddies results in dissipation of energy in the form of heat. Careful streamlining, to reduce any abruptness, minimizes this loss.

(c) In a uniform duct, above a certain critical velocity, viscous forces are unable to preserve the orderly motion of the fluid particles in sliding layers. The flow becomes unstable, and the fluid contains eddies superimposed upon its general motion. This type of flow is called turbulent, as opposed to viscous or laminar flow at velocities below the critical.

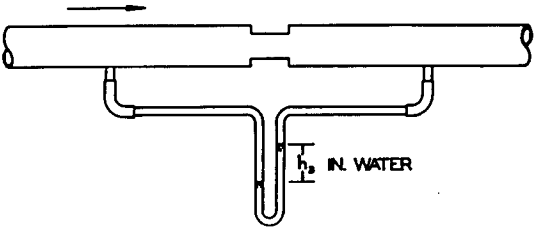

FIG. 2. The pressure drop across an obstruction. The pressure tappings should be sufficiently far from the obstruction to be in regions of undisturbed flow.

Laminar and turbulent flow are, then, very different, and different mathematical laws obtain. In laminar flow the loss of energy is due solely to viscous forces which are exactly proportional to the velocity (as may be proved analytically and verified accurately by experiment). Algebraically, the drop in pressure (expressed in inches of water in a manometer, say) may be written

$$h_1 = k_1 Q. \qquad [1]$$

that is, in a certain length of uniform duct, with a certain fluid flowing, the pressure drop is in direct proportion to the average velocity or to the quantity flowing, Q, the coefficient k_1 remaining constant.‡

In fully turbulent flow, however, the losses are due predominantly to the dissipation of kinetic energy in eddies. Since the kinetic energy

‡ The product (duct cross section, square centimeters) × (average velocity, centimeters per second) is equal to the (quantity flowing, cubic centimeters per second). Hence, for a duct of uniform cross section, the average velocity is proportional to the flow Q.

is proportional to the square of the velocity, the drop in pressure may be written

$$h_2 = k_2Q^2. \qquad [2]$$

This relation is, by the complicated nature of the turbulent flow, not so exact as in [1], laminar flow. The index of Q will be somewhere between 1.7 and 2.0, approaching 2.0 only at very high velocities.

The pressure drop across an obstruction or change of section may be measured in an identical manner (fig. 2). Whether the flow elsewhere in the duct is laminar or turbulent, the drop across the obstruction as a result of the eddies thrown off is given very closely by

$$h_3 = k_3Q^2. \qquad [3]$$

The accurate measurement of the rate of air or gas flow (at a steady rate) in a duct presents many interesting problems. It is not usually desirable to resort to direct measurement of volume or weight

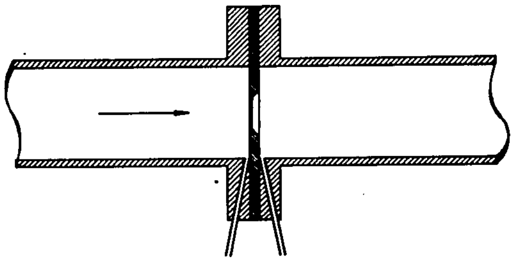

Fig. 3. Typical arrangement of an orifice plate for flow measurement.

—methods that are very suitable for liquids. The orifice plate (fig. 3) provides an ideal laboratory method for continuous flow measurement. An orifice plate is a disc with a central hole, accurately machined and chamfered according to precise standards (1). It is clamped between two flanges in the duct. The pressure difference between tappings immediately adjacent to the plate, on both sides, gives a measure of the gas flow according to a formula

$$h = kQ^2.$$

very closely (as would be expected). The behaviour of flow with standard orifice arrangements has been so closely studied that no calibration is necessary. Accurate details of coefficients (for various gas densities and orifice proportions) may be found by reference to the British Standard Code (1). Reversing the equation, the flow $Q = c\sqrt{h}$. The coefficient c, equal to $1/\sqrt{k}$, may be calculated to give Q in liters per minute if desired.

2. *The Behaviour of Disc Valves and Canisters under Steady Flow Conditions*

(a) Disc-type Valves.

A disc valve is, clearly, an obstruction, but the obstruction is variable, depending on the amount the disc has been lifted off its seat. (See fig. 6 for the usual general form of a disc valve. A helical spring may be added above the disc to assist closure.) It is convenient to investigate the influence on the pressure drop of the free disc separately from the valve structure as a whole.

With the disc held in the position of maximal lift, the valve becomes a fixed obstruction, or rather, a succession of fixed obstructions: bends,

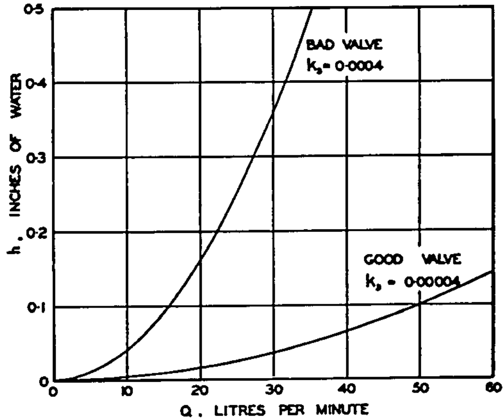

FIG. 4. Typical curves of pressure drop (expressed in inches of water) for disc valves with the discs held at full lift. See the text for the significance of the coefficient k_2.

changes in section, sharp edges and so forth. For all the tests done the drop in pressure was found § to be according to the equation [3] previously given for an obstruction, that is,

$$h_2 = k_2Q^2;$$

k_2 is, of course, lowest for the valve with the most lavish internal proportions (fig. 4). It should be noted that, as the flow approaches zero, so the pressure drop, h, becomes very small, and for $Q = 0$, then $h = 0$.

This last statement is obviously not true when the disc is free. The

§ A simple manometer is clearly not sensitive enough to measure the small pressure differences. Special "Chattock" and "Casella" types of manometer were used. Details of these may be found in many texts on hydraulics and fluid mechanics, for example, A. H. Jameson, "An Introduction to Fluid Mechanics" (Longmans).

disc, resting on its seat, acts as a seal in the duct. Before this seal can be broken, the force acting on the under side of the disc must be sufficient to lift the disc away from its seat. The cross sectional area (A square inches) of the seating is equal to the area of a circle of diameter S inches (fig. 6), that is,

$$A = \frac{\pi}{4} S^2.$$

If the weight of the disc were W pounds, then, for a valve without a spring, the required pressure difference, p_D pounds per square inch required to start lifting the disc is given by the equation

$$(p_D) \times \left(\frac{\pi}{4} S^2\right) = W$$

or

$$p_D = \frac{W \times 4}{S^2 \times \pi}.$$

To measure the pressure difference in inches of water (fig. 1), divide p_D by 0.036. If the disc is weighed in grams, then this may be converted to pounds by dividing by 453.

Therefore the pressure drop, h inches of water, imposed by the valve before any air will pass, is equal to

$$\frac{(\text{disc weight, Gm.}) \times 4}{453 \times S^2 \times \pi} \times \frac{1}{0.036}$$

$$= \frac{(\text{disc weight, Gm.})}{S^2} \times 0.078 \text{ inch of water } (S \text{ in inches})$$

The pressure drop across a valve cannot ever be less than this figure. If it were, then the resultant force on the disc would be downward, and the valve would close. With a well made valve and smooth locating pin, the additional forces due to friction are negligible.

With a free disc (no spring), as the air flow rate is increased the disc tends to rise until, above a certain flow, it reaches the upper end of the thin stem, which is usually provided with some form of a disc stop. The disc usually tends to flutter while in its "floating" region, and the measurement of lift under these conditions is rather meaningless. One interesting point came out of the experiments with discs of different sizes and thicknesses; the drop in pressure remained substantially constant while the disc was floating. This indicates that the eddies around and above the disc account for by far the greater proportion of the total pressure drop under the floating conditions.

So, for a valve of certain fixed proportions, the pressure drop curves for light and heavy discs are as shown in figure 5. If, just after the heavier disc leaves the seat, it is acted on by a spring, then the form of the curve will be roughly as shown — - - — - - —. The drop, 0.092 inch of water, at the point X, corresponds with the air pressure required to hold the disc against the stop in opposition to a downward force made up of the weight of the heavier disc and the compressed spring. Thus, the point X can be located for any chosen setting of the spring used, knowing its stiffness.

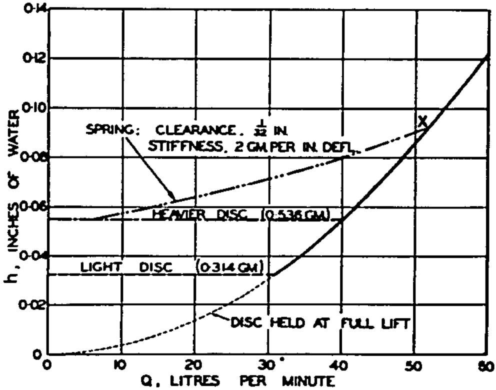

FIG. 5. Curves of pressure drop for an actual valve of the following internal dimensions:

Seat diameter,	0.875 inch	Outlet diameter,	1.000 inch
Disc diameter,	1.000 inch	Body diameter,	1.375 inches

Maximal disc lift, 0.195 inch

(The spring is used in conjunction with the heavier disc.)

The actual steady flow tests were carried out with an experimental disc valve with a cylindrical body (fig. 6) whose internal dimensions could be altered. The cross sections of air flow at all the restricted portions of the valve shown in figure 6 are:

(a) inlet, $\frac{\pi}{4} S^2$ sq. in.

(b) past seating (disc fully lifted), πSL sq. in.

(c) around disc, $\frac{\pi}{4} (B^2 - D^2)$ sq. in.

The common-sense choice of proportions would be to make each of these areas approximately the same as the duct cross section. If, for example, area (a) were increased at the expense of area (c), that is, by inserting a larger seat into the same valve body, the over-all loss would be increased. The energy loss due to eddies from the valve seat (a) will, indeed, be reduced, but the velocity at (c) has been increased. Losses are proportional to (velocity)^2; so the increase in the loss at area (c) is greater than the improvement at area (a).

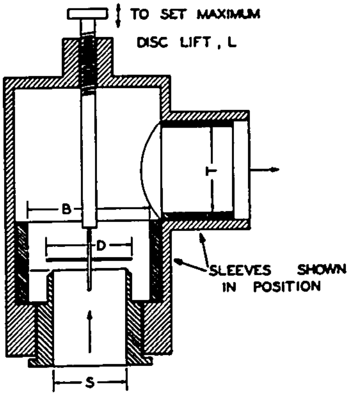

Fig. 6. The test valve actually used is shown diagrammatically. By taking different sleeves, discs and seatings, the following dimensions and disc weights were available for test purposes. (The maximal disc lift could be set at any desired figure.)

		Diameters (inches)		
	S B T	1.000 1.500 1.000	0.875 1.375 0.875	0.750 1.250 0.750
Disc	Dia. D	1.125	1.000	0.875
	Alternative weights	(1.508 gm. 0.690 gm. 0.495 gm.)	(1.227 gm. 0.536 gm. 0.314 gm.)	(0.899 gm. 0.414 gm. 0.260 gm.)

Experiment clearly confirmed this common-sense argument. One obvious means of reducing the pressure drop is by increasing the lift but (fig. 7) there is little to be gained beyond the value which is close to the "common-sense" choice.

The "optimum" valve was chosen with the internal proportions as given below figure 7, with the maximal lift set at 0.195 inch.

(b) Carbon Dioxide Absorption Canisters.

A canister of soda lime is, in the fluid mechanics sense, an obstruction in the duct. At first sight it might be expected that equation 4 (that is, $h_3 = k_4 Q^2$) would hold. In circumnavigating the granules of soda lime, however, the air has to pass through irregular narrow passages at velocities lower than the critical velocity. Therefore, the air will be subjected to a series of very small pressure drops (a) owing

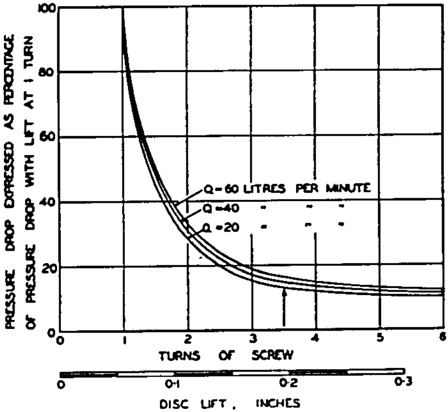

FIG. 7. Curves showing the influence of lift on pressure drop across a valve for which S = 0.875 inch, $B = 1.375$ inches, $T = 1.000$ inch and $D = 1.000$ inch. It is seen that there is little practical advantage in increasing the lift beyond 3½ turns (0.195 inch for the 18 thread per inch screw used) which gives a flow area past the seating of 0.54 square inch. (Inlet area = 0.60 square inch, area round disc = 0.62 square inch, thus confirming the common-sense proportions with approximate equality of areas throughout.)

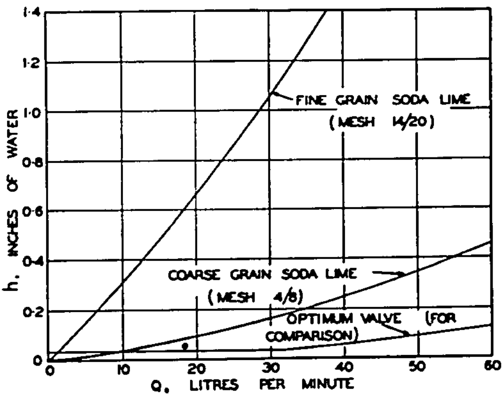

FIG. 8. Curves showing the high pressure drop across standard soda lime canisters compared with the "optimum" valve. The soda lime indentification numbers refer to the mesh sizes between which all granules lie. The curve for 6/8 soda lime is approximately identical with that shown for 4/8.

to the obstruction of granules causing eddies (equation 3), (b) according to the viscous law [1] in the crevices between granules. The resulting curve for pressure drop across the whole canister would be expected to obey a law

$$h_4 = k_4 Q^n,$$

where n lies somewhere between 1 and 2. The faster the flow, or the larger the granules, the greater will be the eddy effect and the higher will n become.

The curves in figure 8 show the pressure drop obtained from different granule size ranges. The fine granules give a slightly lower mean value for the index n and a much higher pressure drop.

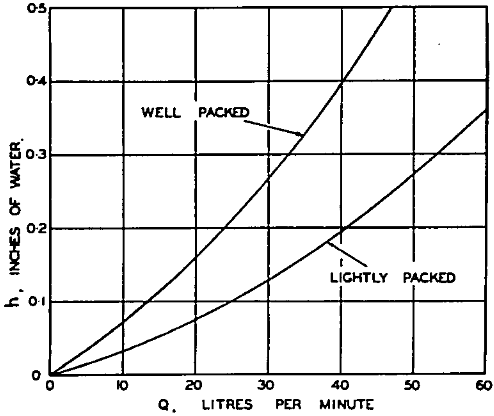

Fig. 9. Comparison of pressure drop for 4/8 soda lime, (a) compacted, by shaking only, and (b) uncompacted.

In carrying out these tests, compaction of the soda lime was kept at an absolute minimum. Vigorous compaction can about *double* the pressure drop (fig. 9). Any figures of pressure drop through canisters are, therefore, only approximate.

The important fact to be gained from these tests (fig. 8) is that the resistance to flow of a canister is very much higher than that of a conventional valve, except at very low velocities. It is clearly best to choose as large a grain size as possible compatible with the absorption rate required. A large grain of irregular shape (that is, of large surface area) would appear to be the best.

Wide, short canisters would give a smaller pressure drop than narrow ones of identical soda lime capacity (fig. 10) (2).

3. *Behaviour of Valves with Pulsating and Intermittent Flow.*

It is clear that, in respiration, the air flow is not steady, but is irregularly pulsating.

It has been shown by Fleisch (3) that the air flow in respiration of man may be taken as varying throughout the inhalation and exhalation half-cycles in the manner depicted in figure 11.

The problem which confronts the experimenter is how to measure the pressure drop across an obstruction when the flow is pulsating and when the pressure, consequently, is varying from one instant to the next. A manometer is useless, owing to the slow response of the liquid

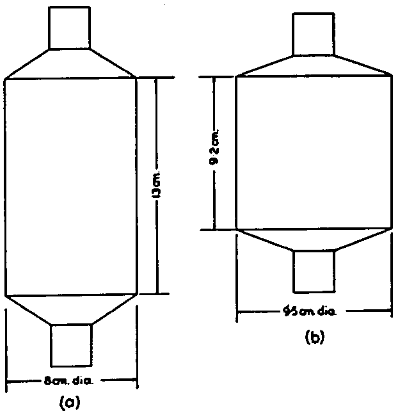

FIG. 10. Comparison of (a) a standard adult canister with (b) a suggested canister of identical capacity and comparable absorptive efficiency which provides just less than half the resistance to flow by reason of (1) lower air velocity between granules and (2) shorter over-all passage through the canister.

column. For many years engineers have had to measure pressures varying more or less rapidly in a cyclical manner. Common instances of this need are in the cylinders of (a) steam engines and (b) the more modern internal combustion engines. For both of these the pressure ranges are large, of the order of several hundred pounds per square inch. In the past twenty years the science of electronics has come to the rescue in the internal combustion engine field where the speeds are far too high to permit the use of a simple plunger and spring, which is a perfectly satisfactory form of pressure indicator in slower steam engines. In one type of electronic indicator, the cylinder pressure acts on a small diaphragm which deflects a fraction of a thousandth of an inch. This diaphragm is itself one plate of a small electrical condenser; the change in capacitance in the condenser is detected electrically and, by means of an amplifier, a spot may be made to move, on a cathode ray oscillograph screen, proportionally to the pressure in the cylinder.

Using a specially designed sensitive capacity pressure element, with an extremely thin, stretched metal diaphragm, it was possible to obtain a full spot deflection for a pressure difference corresponding to ¼ inch of water. This represents a working range of about 0.01 per cent of that of a typical internal combustion engine indicator, and it

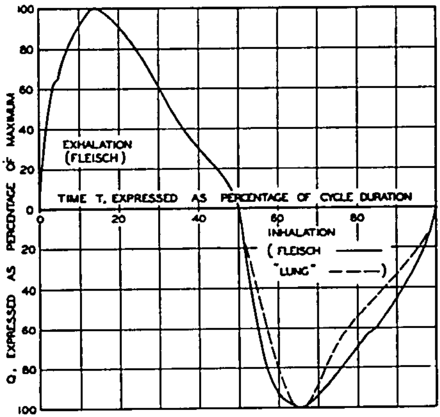

FIG. 11. The "Fleisch" curve, in a form which may be applied to respiration whether it be deep or shallow, slow or rapid. The dotted curve is the inhalation half-cycle obtained from the mechanical lung for a setting of 30 cycles per minute, maximal rate of flow 55 liters per minute.

is not surprising, therefore, that the apparatus proved very difficult to handle and was very susceptible to many outside influences.

Pulsating flow, closely following the "Fleisch" curve, was obtained by means of a mechanical lung. This lung consists of a cylinder containing a plunger of variable stroke. By means of a specially cut cam, the plunger is made to follow a curve approximating that of Fleisch over a wide range of speeds and quantities. The comparison of the performance of this lung, purposely set for rather extreme conditions, with the "Fleisch" curve is shown in figure 11. The lung had previously been calibrated [Adams, Ellis and Kaye (4)] so that, for any chosen setting, the precise curve of rate of discharge (in liters per minute) was known.

If the rate of air flow past an obstruction changes with time, provided such a change is slow, the pressure drop at any instant will be expected to be in accordance with the point (on a previously obtained "steady flow" test curve) corresponding with the instantaneous value of discharge. As the rate of change increases, the error in this method of assessment will become more prominent. In the extreme case, when

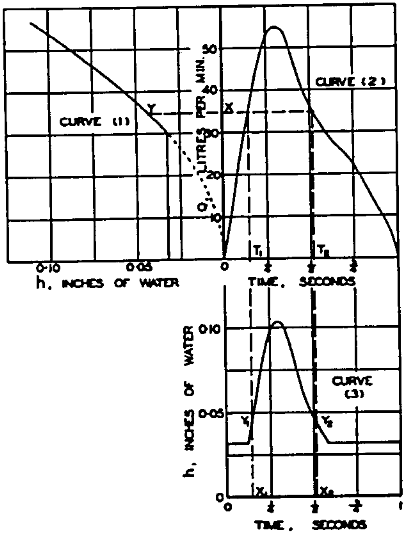

FIG. 12. Method of obtaining the "ideal" curve 3 of performance of a valve, given curves 1 and 2 (see text).

the natural frequency of the air column in the duct is approached, the method is useless. In the case of a valve there is another cause of error in assessment—the disc. There are movement and inertia not only in the air column itself but also in the disc, and so there will probably be some discrepancy while the disc is floating and while it is being forced off its seat. A half-cycle (say inhalation), however, takes the comparatively long time of one to 2 seconds, and thus the method of assessing the pressure drop should not be much in error (fig. 12).

The "steady flow" pressure drop curve for a particular valve—

the "optimum" valve is chosen—is shown tilted (curve 1), adjacent to the "lung" curve for the chosen setting (curve 2). This "lung" curve is plotted using the same "Q" axis. Therefore, at time T_1 the rate of flow (being drawn into the "lung") is X liters per minute, and the pressure drop at this instant should be XY inches of water. Transfer this distance XY to the axes for curve 3 (X_1Y_1). Repeat for time T_2 and at other convenient points on curve 2, to obtain the complete "ideal" curve 3, for the exhalation part of the cycle.

It was then required to check experimentally how closely the actual pressure drop curve agreed with this "ideal" curve 3.

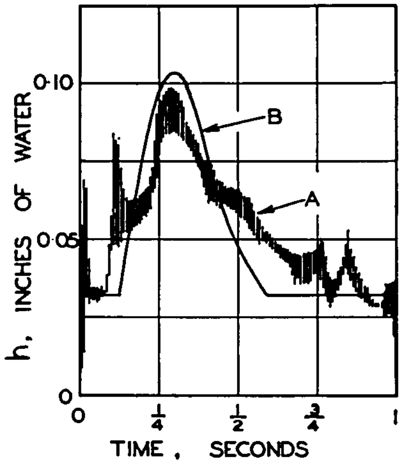

Fig. 13. Comparison of the "ideal" curve 3 (transferred as curve B from fig. 12) with the corresponding pressure trace A obtained experimentally.

In analyzing the experimental results, allowance had to be made for mechanical and electrical vibrations, and also for a high frequency jerkiness in the motion of the "lung" plunger which set up oscillations in the air column. When these spurious effects were compensated for, it was found that agreement with curve 3 was fairly close (fig. 13) except near the ends of the cycle when, as would be expected, the opening, closing and bouncing of the disc cause sudden jumps in the pressure drop. It appears, too, that the disc leaves the stop (as the rate of flow decreases) somewhat earlier than would be expected according to curve 3.

Figure 13 demonstrates that steady flow tests (which can be carried out relatively easily) afford a means of reasonable comparison between valves, or between other obstructions. It is not likely that any additional information of any consequence would result from an actual pulsating flow test. It is to be noted that both the maximal flow rate, of 55 liters per minute, and the rapidity of respiration, 30 cycles per minute, used here are extremes, and that much closer agreement is to be expected at the lower rates usually encountered in anaesthetic work.

The same method of assessment can, of course, be applied to obtain the "ideal" curve for flow through a canister during inhalation (or exhalation).

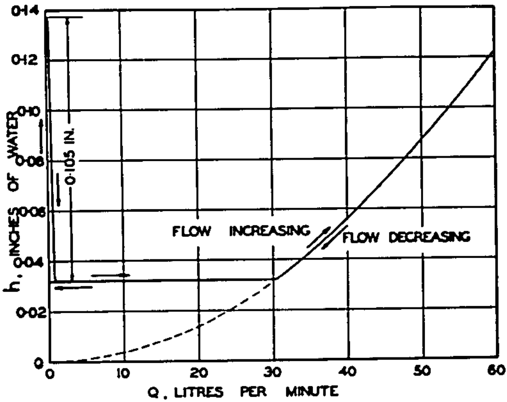

FIG. 14. Curve showing the maximal possible effect of surface tension on a valve (of "optimum" proportions).

4. The Influence of Humidity on the Behaviour of Valves

Humidity of the air will not have any noticeable effect on any ordinary obstruction. If a complete film of water should be formed (by condensation from the exhaled water vapour in the duct) on the under side of a disc, however, the pressure of the air then will have to overcome the surface tension which will tend to act in addition to its weight in holding the disc on to its seat. The surface tension of water (at 90 F.) may be taken as 72.2 dynes per centimeter. With a seating of diameter ¾ inch (1.91 cm.) the total length of the surfaces (on both the inner and outer edges) is $2 \times \pi \times 1.91$ cm. = 12 cm. Thus the force is equal to 12×72.2 dynes, or 865 dynes. (However sharp the knife edge seat is, there is still an inner *and* an outer film surface, both of which are acted on by the surface tension forces.) The air pressure acting below the disc (seating area 0.442 sq. in. or 2.86 sq. cm.) to give this force is 865/2.86 dynes per square centimeter, or 0.0044 pound per square inch (0.122 inch of water). Corresponding figures for three sizes of seatings are given in table 1.

TABLE 1.

Seat Diameter, inches	Pounds per square inch	Inches of Water
$\frac{3}{4}$	0.0044	0.122
$\frac{7}{8}$	0.0038	0.105
1	0.0033	0.092

With a wet disc, the form of the "steady flow" curve (for the "optimum" valve) would be approximately that shown in figure 14. Apart from the slightly increased weight of the disc (due to the condensed water) this is the maximal possible effect that surface tension can have on the pressure drop across a valve, short of actual waterlogging.

Summary and Conclusions

This paper describes:

(1) The general principles of air flow (at a steady rate) in ducts.

(2) Experimental verification of these principles for flow at about atmospheric pressure past (a) disc type valves, and (b) carbon dioxide absorption canisters.

(3) Experimental observations of the behaviour of disc type valves with pulsating and intermittent flow, and a method of deducing, from simple steady flow tests, the manner in which such valves would be expected to behave under the pulsating flow of respiration.

(4) The influence of humidity on the behaviour of valves.

As a result of the foregoing, it is concluded that:

(1) Disc valves should be designed so as to have approximately equal cross-sectional flow areas for air at all the constricted portions, these areas being closely equal to that of the duct. The disc should be as light as practicable, and should have a lift approaching one quarter of the diameter of the duct. Spring loading should be eliminated if possible.

(2) It is not necessary to study the behaviour of valves or canisters under the actual conditions of pulsating flow encountered in respiration. Close approximations to their actual behaviour may be obtained from simple steady flow tests, using the method described in the text.

(3) The resistance to flow imposed by the soda lime in standard absorption canisters is, in general, far greater than that due to well

made disc valves, especially if the granules of soda lime are small. Improvements in granule surfaces and in the shape of canisters are suggested.

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