ADJUSTABLE RESPIRATORY VALVES OFFERING LOW RESISTANCE TO FLOW OF GAS

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This study was undertaken to investigate the factors controlling the operation of low resistance respiratory valves in which gas flow is limited to one direction. The model used consists of a tube with a built-in valve seat, as shown schematically in figure 1. It includes a valve disc mounted on a stem which slides through fixed bearings, and a spring, designed to automatically close the valve when the gas flow is stopped. In operation the flow of gas forces the valve to open. The gas pressure at the outlet side of the valve is always lower than the pressure at the inlet side. This drop in pressure between inlet and outlet ($p$) is commonly used as a measure of the resistance of a valve to the flow of gases and will be used in that sense in this paper.

In 1954, Mushin and Mapleson (1) tested 8 movable valves of this type. They found that when the gas flowed at a rate of 35 liters per minute, the pressure difference $p$ varied from 15 to 95 mm. of H$_2$O and that $p$ was about 15 mm. of H$_2$O for a molded rubber valve.

Hunt (2) in 1955 experimented with a stationary horizontal valve without springs. He showed that by reducing the weight of the valve and increasing the size of the valve seat orifice, $p$ could be reduced to about 3 mm. of H$_2$O.

The purpose of this paper is to describe the design of a small, lightweight valve, which presents a negligible resistance to the flow of gases, regardless of its physical orientation.

FACTORS AFFECTING RESISTANCE

The resistance to gas flow in a valve arises from three sources: (1) impedance of the flow by the valve seat orifice and the valve disc, (2) stiffness of the spring and weight of the valve disc and stem, and (3) friction in the bearings. These three sources of resistance are treated separately in the following discussion. A fourth source of resistance is adhesive strength which, however, only affects the opening of the valve and will not be treated in this paper.

We have found experimentally that when gas flows through a circular orifice at a rate of 50 liters per minute, the orifice offers a resistance of less than 1 mm. of H$_2$O when the diameter of the hole is larger than 1.4 cm., or its area is larger than 1.54 cm.$^2$. This implies that if the valve seat in figure 1 has an aperture of this size, its resistance will be negligible.

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In order not to increase the valve resistance above this small value, it is necessary to choose the other components of the valve of such a size that at no point between inlet and outlet of the valve is the gas forced to pass through any area smaller than the valve seat aperture (2). Two results of this restriction are given in the following.

First, the cross sectional area of the tube minus the area of the disc must be at least 1.54 cm.$^2$ The diameter of the disc was taken to be 1.7 cm., 3 mm. larger than the diameter of the seat orifice to ensure that the valve will close even if the bearings are slightly misaligned. Consequently, the disc area was 2.27 cm.$^2$, and the required tube cross section 3.81 cm.$^2$ This means that the inside diameter of the tube must be at least 2.2 cm. To protect against additional resistance produced by the enforced change in the direction of flow of the gas as it curls around the edge of the disc, its diameter should be increased somewhat, perhaps to 2.4 cm.

Second, immediately after the gas flows through the valve seat orifice, 1.4 cm. in diameter, it is forced through an area of $1.4 \pi z$, where $z$ is the distance the valve disc moves away from the seat during operation (the valve stroke). For this area to be 1.54 cm.$^2$, the valve stroke must be 0.35 cm.

For the valve to operate in all orientations with low resistance, it must maintain a stroke of at least 0.35 cm. when tilted either above or below the horizontal by an angle $\alpha$ as shown in figure 2. In the former case, the weight of the disc tends to close the valve, and in the latter, to open it. The following equation relates the pressure drop across the valve $p$ and the area on which the incoming gas exerts a force $a$ to the compressive force of the spring $T$, and the weight of the valve disc-stem combination $G$ as a function of the angle of tilt $\alpha$:

$$p \times a = T + G \times \sin \alpha$$

The requirement that when no gas flows, the valve must remain closed in all orientations, sets a lower limit on the value of the spring force when the valve is closed. Thus $T_{(\text{closed})}$ cannot be smaller than $G$, or the

![Diagram of Adjustable Respiratory Valve](https://example.com/diagram.png)
valve would open when the disc was hanging under the seat ($\alpha = -90$ degrees). To protect against the natural aging and weakening of a spring, $T_{\text{closed}}$ should be larger than $G$.

$$T_{\text{closed}} = b \times G \quad \text{(where the constant } b \geq 1)$$

When the gas flows, the valve opens a distance $z$ and the spring compressive force increases:

$$T_{\text{open}} = T_{\text{closed}} + f \times z = b \times G + f \times z$$

(where $f$ is the force constant, or stiffness, of the spring). Then with gas flowing:

$$p \times a = (b + \sin \alpha)G + f \times z$$

It follows from this equation that for the valve to open a distance $z$ in all orientations, the pressure drop must be at least:

$$p = \frac{(1 + b)}{a} G + \frac{f}{a} z$$

![Fig. 2. Possible orientations of respiratory valve.](image-url)

The values substituted in this equation come from the previous section, $a = 1.54 \text{ cm.}^2$ and $z = 0.35 \text{ cm.}$, and from the following assignments. Since springs rarely lose more than half their strength through continuous use, a safety factor $b = 2.5$ seemed adequate. The spring stiffness cannot be reduced much below $f = 0.35 \text{ Gm. per cm.}$ without making the spring too unstable and wobbly for practical use. Simple calculations indicate that a practical minimum for the weight of the valve disc-stem combination is $G = 0.2 \text{ Gm.}$ Inserting these values in the last equation, it is found that the minimum valve resistance caused by the spring stiffness and valve disc weight is of the order of $p = 0.53 \text{ Gm. per cm.}^2$, or its equivalent, $p = 5.3 \text{ mm. of } H_2O$.

The foregoing discussion has neglected friction in the bearings, which will increase the resistance of the valve to gas flow. The frictional force, which tends to inhibit motion of the valve disc, is:

$$F = \mu \times G \times \cos \alpha$$
where $\mu$ is the coefficient of friction between the valve stem and the bearings, $G$ is the combined weight of the valve disc and stem, and $a$ is the angle the valve is tilted from the horizontal as in figure 2. For the valve to open, the inlet gas pressure $p$ must be large enough to exert a force on the valve disc, $p \times a$, which can overcome this frictional force for all valve orientations. In other words, $p$ must be:

$$p \geq \frac{\mu \times G}{a}$$

Using $G = 0.2$ Gm. and $a = 1.54$ cm.$^3$ from above, a value of $\mu$ as small as 0.2 would mean that friction could be overcome by a pressure drop as small as $p = 0.3$ mm. of H$_2$O (0.01 Gm. per cm.$^2$). Since a coefficient of friction $\mu = 0.2$ can easily be obtained, it appears that the additional resistance caused by friction is negligible.

There is one possible complication which could increase the frictional resistance. As the gas flows through the valve, its direction of flow is drastically altered several times. This would produce turbulence in the gas, which in turn means that the exposed valve stem will be buffeted by the gas and will experience a succession of forces of short duration and random direction. This will momentarily increase or decrease the effective weight of the valve disc-stem combination $G$, depending on the momentary direction of the forces. From the equation in the preceding paragraph, it can be seen that this will affect the valve resistance. Only a detailed experimental treatment can indicate whether or not this additional resistance is negligible.

Summary and Conclusions

The factors controlling the operation of a physically compact respiratory valve which has a low resistance to gas flow in any orientation and which automatically closes when the flow of gas is stopped have been described. Specific results of this analysis are:

The valve resistance caused by the impedance to gas flow of the valve seat orifice and valve disc could be reduced to about 1 mm. of H$_2$O by designing the valve with the following dimensions: 1.4 cm. for the diameter of the valve seat orifice; 1.7 cm. for the diameter of the valve seat disc; 2.4 cm. for the inside diameter for the tube; and 0.35 cm. for the valve stroke.

The gas pressure required to hold the valve open against forces exerted by the spring and gravity in all orientations was found to have a minimum value of 5.3 mm. of H$_2$O, using a weight of 0.2 Gm. for the valve disc-stem combination, and a spring stiffness of 0.35 Gm. per cm.

The valve resistance offered by friction in the bearings could easily
be reduced to a negligible level \((p = 0.3 \text{ mm. of } H_2O)\). Frictional resistance caused by turbulence in the gas was recognized but not evaluated.

This analysis indicates that for such a valve, the maximum pressure difference between the inlet and outlet will be about 6.6 mm. of \(H_2O\), the sum of the 3 pressure drops deduced above. This value should be considered as a theoretical optimum, rather than a practical fact. A practical application of these results will be described in a later paper.

REFERENCES


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