# An Analysis of Significant Differences Between Suction and Discharge Valves in Reciprocating Air Compressors

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# AN ANALYSIS OF SIGNIFICANT DIFFERENCES BETWEEN SUCTION AND DISCHARGE VALVES IN RECIPROCATING AIR COMPRESSORS

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## ABSTRACT

Using the valve pressure loss equation, the suction valve power loss derived is about 64.3% of total valve power loss, while the discharge valve power loss only 35.7% of it. In addition, differences lie between the structures and operating conditions of suction and discharge valves. Analysis shows that the major requirement for suction valve is to reduce power loss and the requirement for discharge valve is higher than that for suction valve in sealing, strength and service life. Based on the experimental result, synthetical economical efficiency being considered, a combined plan of valve arrangement in a range of reciprocating air compressor for pneumatic power is discussed.

## INTRODUCTION

For a rationally-designed and well-made air compressor with the ring type valves, by means of modern design method and experimental technique, the parameters of valve are adjusted close to the optimun operating conditions, and the compressor is accompanied with lower specific power consumption. The question is whether the specific power consumption could be further reduced through improving the valve again. The auther thought of the straight-flow valve since in this type of valve the pressure loss is the smallest among the valves of same diameter. The experimental investigation has shown that the suction straight-flow valve substituted for ring type valve can obviously decrease the specific power, which depends mainly on Mach number in ring type valve: the greater Mach number is, the more obvious the effect will be. But the discharge straight-flow valve substituted for ring type valve shows almost no effect, in particular, when Mach number is comparatively small, the performence of straight-flow valve is even worse than that of ring type valve. This phenomenon shows that some significant differences lie between the suction and discharge valves, as analysed in the following.

In this paper, some macro analyses with regard to these differences are made;and an economical plan of valve arrangement is discussed on the basis of the experimental results.

## DISTRIBUTION PERCENTAGE OF LOSS WORK IN SUCTION AND DISCHARGE VALVES

There are already new methods for calculating valve loss work and the experimental data obtained by means of modern measurement technique has rather high accuracy, but for general purpose of comparison, in this paper, the values of ratio of loss work in suction and discharge valves to total loss work of the valves are calculated by approximate equation suggested in Reference(1)without using the accurate methods. Two-stage air compressor for pneumatic with 7 bar of discharge pressure is made as a target for calculation since this type of compressor is typical and produced in large amounts.

### Simplified Assumption

(1) The valves open fully for the complete valve event and close at piston dead centre.

(2) According to the statistics data of air compressor for pneumatic in our national L-type series (double-action, water cooling) and V-type series (single-action, air cooling), when 7 bar of discharge pressure, two-stage compression and plate valve(ring type) are used, the suction valve action time is equal to about 140 degree of crank angle, and discharge valve action time is equal to about 70 degree of crank angle in a cycle.

(3) The through-flow areas of suction and discharge valves are equal.

(4) There is a same pressure ratio in both the first and second stages, Let the pressure ratio $=\sqrt{8} = 2.828$.

(5) Mach numbers in the suction and discharge valves are calculated respectively under the suction temperature 20°C, and the corresponding discharge temperature, about 120°C.

Thus, the values of ratio of loss work in the suction and discharge valves to total loss work of the valves can be calculated easily by means of pressure loss equation. A derivation is given in Appendix.

Calculating Results

(1) In the double-action cylinder the valve loss work is about 64.3% of total loss work of valves and discharge valve loss work about 35.7% of it.

(2) For the single-action cylinder (head side) the percentages of loss work of suction and discharge valves are about 57% and 43% respectively.

The above calculation is certainly quite approximate since some assumptions are made. In practice, as a result of complicated dynamic behaviour in valves and differences in the parameters and operating conditions, the measured percentage of loss work is not fully consistent with above-calculated value. In particular, when valve dynamic behaviour is not ideal, the inconsistency is shown obviously. But the above calculation at least provides a significant concept, i.e. when through-flow capability in suction valve is equal to that in discharge valve, the suction valve power loss will be obviously greater than discharge valve power loss. This concept is consistent with the experimental results.

## STRUCTURAL DIFFERENCES

As is well known, the clearance volume has influence on performence of compressor, in particular, the first-stage clearance volume will reduce volume efficiency of compressor and cause higher specific power consumption of it, hence, a small clearance volume in the valve assembly is desirable.

The major structural difference between suction and discharge valves is that the values of their clearance volume are not equal, and they are depended on the type of valve, operating conditions, etc..

In typical plate valve design, according to the strength requirement, for air compressor for pneumatic with 7 bar of discharge pressure, the seat height is so small that the clearance volume of suction valve is greater than that of discharge valve. Take the well-known Hoerbiger type plate valve (8) as an example, only when the seat height is about 35-40 mm, the two clearance volume values are nearly equal. But in air compressor for pneumatic the seat height usually is about 20mm so that the clearance volume of discharge valve is about 60% of suction valve clearance. In addition, in our national air compressor series with ring type valve, the value of ratio of discharge valve clearance to suction valve clearance is about 0.7-0.85.

Just as opposed to the plate valve, in the straight-flow valve, the suction valve clearance volume is much smaller than the discharge valve clearance volume and usually it is about 60% of the latter.

## DIFFERENCES IN OPERATING CONDITIONS

The operating condition of discharge valve is more critical than that of suction valve. Major differences display in

(1) Discharge valve opens and closes under the extremely rapid pressure change so that the impact velocity in general is higher than suction valve. There is no doubt that the stress of discharge valve is also higher.

(2) The operating temperature of discharge valve is higher. Though it has no direct influence on fatigue strength, heat strain and store-up carbon are more surious than those in suction valve, which will cause more failures in operation.

(3) The leakage of discharge valve is greater than that of suction valve because of the following reasons: the acting time of discharge valve in a cycle is shorter than that of suction valve, hence, the leakage time is longer; the average sealing pressure is higher; and the heat strain reduces sealing ability.

The statistics data shows that the life of discharge valve usually is lower than that of suction valve. And discharge valve meets with more failures than suction valve, in particular, when lower quality material is applied.

## QUESTION OF INTEREST

(1) The obvious differences between the suction and discharge valves determine the distinct requirements for them. As analyzed above,the major requirement for suction valve is to reduce power loss and the requirement for discharge valve is higher than that for suction valve in sealing, strength and service life. However, to have a small clearance is the common requirement.

(2) There is a great variety of valve type, however, absolutely evaluating good or bad valve types is not proper. In fact, the features of each valve type determine a suitable range of operating condition. Certainly, some of them have a wide range of suitability (e.g., ring type valve) and others have a narrower one (e.g., read type valve).

(3) The above analyses show that using the same type of suction and discharge valves appears to be imperfect. When the suction valve is of straight-flow type and the discharge valve plate type, not only the power loss in the suction valve is decreased effectively, but also the total clearance volume of the valves is rather small, hence, increasing the volume efficiency of the compressor. The experiment we made in some air compressors with different speeds has, to a certain extent, demonstrated the above tendency. For example, the experimental result obtained in a V-type air compressor (capacity 9 $M^3$/min, discharge pressure 6.86 bar, speed 1490 rpm, air cooling) shows that the specific power is reduced from 6.01 to 5.76 kw/($M^3$/min).

(4) The economical plan of valve arrangement is related to the valve power loss, the cost of production, the service life and compressor operating time rate, the magnitude of annual production, and its operating conditions, etc.. For the compressor with high speed and great Mach number, both the suction and discharge valves are arranged by straight-flow type valve, which will be advantageous, but when Mach number in the valve is of average or small value, selecting combined plan of straight-flow type and plate valve will be economical, in particular, when the compressor operating time rate is high and annual production is great. In this case, both suction and discharge valves should have a long and the same service life to avoid much maintenance work. Certainly, production of the valve assembly must be commercial.

## APPENDIX

## CALCULATING THE PERCENTAGE OF LOSS WORK IN THE SUCTION AND DISCHARGE VALVES

NOTATION

| | |
|---|---|
| $A_p$ | piston area |
| $a$ | acoustic velocity |
| $k$ | ratio of specific heat (air, k=1.4) |
| $M$ | average Mach number in the valve |
| $p$ | average pressure in plenum chamber |
| $\Delta p$ | instantaneous pressure loss across valve |
| $R$ | gas constant |
| $S$ | piston stroke |
| $T$ | gas absolute temperature in valve |
| $V$ | instantaneous cylinder volume |
| $V_{eq}$ | average equivalent velocity in valve |
| $V_{sw}$ | cylinder swept volume |
| $X$ | piston displacement from head end centre |
| $W$ | loss work in the valve |
| $\lambda$ | pressure ratio |
| $\theta$ | crank angle measured from head end centre |
| $\varepsilon$ | crank/connecting rod length ratio |

Subscripts

| | |
|---|---|
| d | discharge |
| s | suction |

Abbreviations

| | |
|---|---|
| CESV | crank end suction valve |
| CEDV | crank end discharge valve |
| HESV | head end suction valve |
| HEDV | head end discharge valve |

Calculating

When the average Mach number in valve is smaller, the instantaneous pressure loss can be calculated according to the following equation

$$\Delta p = \frac{k\pi^2 p}{8}\left(\sin\theta + \frac{\lambda}{2}\sin 2\theta\right)^2 M^2 \tag{1}$$

The loss work in suction and discharge valves can be illustrated using the shaded area of p-v diagram in Figure 1. For simplicity, the areas can be calculated using the following integration.

$$W = \int_{V_1}^{V_2} \Delta p \, dv = A_p \int_{X_1}^{X_2} \Delta p \, dx \tag{2}$$

where $x_1$ and $x_2$ are piston displacements corresponding to $v_1$ and $v_2$.

$$X = \frac{S}{2}\left[(1-\cos\theta + \frac{\lambda}{4}(1-\cos 2\theta)\right] \tag{3}$$

$$dX = \frac{S}{2}\left(\sin\theta + \frac{\lambda}{2}\sin 2\theta\right) d\theta \tag{4}$$

Substituting (1), (4) into (2), we have

$$W = \frac{k\pi^2}{16} p V_{SW} M^2 \int_{\theta_1}^{\theta_2} \left(\sin\theta + \frac{\lambda}{2}\sin 2\theta\right)^3 d\theta \tag{5}$$

where $\theta_1$ and $\theta_2$ are crank angles corresponding to $x_1$ and $x_2$

$$\because \left(\sin\theta + \frac{\lambda}{2}\sin 2\theta\right)^3 \approx \sin^3\theta + 3\lambda \sin^3\theta \cos\theta \tag{6}$$

In equation (6), the terms with $\lambda$ higher than second-order are neglected. Substituting (6) into (5) and integrating it, we have

$$W = \frac{k\pi^2 p}{16} V_{SW} M^2 \left[\left(\frac{-\sin\theta\cos\theta}{3} - \frac{2}{3}\cos\theta\right)\Big|_{\theta_1}^{\theta_2} + \left(\frac{3}{4}\lambda \sin^4\theta\right)\Big|_{\theta_1}^{\theta_2}\right] \tag{7}$$

The values of $\theta_1$ and $\theta_2$ for integration limit are listed in Table 1 on the basis of assumption (2). Let $\lambda = 0.2$, substituting the value of $\theta$ in Table 1 into (7), the loss work of the corresponding valve can be calculated, as well listed in Table 1

Table 1.

| valve names | $\theta_1$ deg. | $\theta_2$ deg. | $\theta_2-\theta_1$ deg. | W |
|---|---|---|---|---|
| CESV | 220 | 360 | 140 | $W_{CES} = 1.1300\, P_s V_{sw} M_s^2$ |
| CEDV | 110 | 180 | 70 | $W_{CED} = 0.1909\, P_d V_{sw} M_d^2$ |
| HESV | 40 | 180 | 140 | $W_{HES} = 1.0858\, P_s V_{sw} M_s^2$ |
| HEDV | 290 | 360 | 70 | $W_{HED} = 0.3929\, P_d V_{sw} M_d^2$ |

in Table $p_d = \varepsilon p_s = 2.828\, p_s$

For double - action cylinder, the average loss work in the suction valve and that in the discharge valve are respectively

$$W_s = \frac{W_{CES} + W_{HES}}{2} = 1.1079\, P_s V_{sw} M_s^2$$

$$W_d = \frac{W_{CED} + W_{HED}}{2} = 0.8255\, P_s V_{sw} M_d^2$$

For single - action cylinder (head side) the loss work of HES valve and that of HED valve are respectively $W_{HES}$ and $W_{HED}$ .

For double - action cylinder the percentage of the discharge valve loss work to the total loss work of valves is

$$\frac{W_d}{W_d + W_s} = \frac{0.8255 M_d^2}{0.8255 M_d^2 + 1.1079 M_s^2} \quad (8)$$

where $M_d^2 = \frac{V_{deq}^2}{a_d^2} = \frac{V_{deq}^2}{kRT_d}$ (9)

$$M_s^2 = \frac{V_{seq}^2}{a_s^2} = \frac{V_{seq}^2}{kRT_s} \quad (10)$$

According to assumption (3), $V_{deq} = V_{seq}$ , substituting (9), (10) and T = 393.2, $T_s$ = 293.2 into (8), we have

$$\frac{W_d}{W_d + W_s} = \frac{0.8255 \times \frac{1}{393.2}}{0.8255 \times \frac{1}{393.2} + 1.1079 \times \frac{1}{293.2}} = 0.357 = 35.7\%$$

then,

$$\frac{W_s}{W_d + W_s} = 64.3\%$$

Using the same method as for the single-action cylinder, the percentage of suction valve loss work and that of discharge valve loss work are about 57% and 43%respectively

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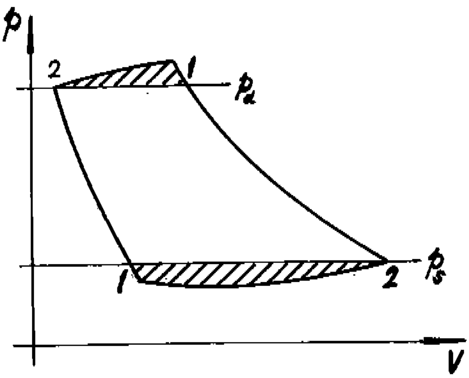


Fig. 1. Pressure-volume diagram calculating idealized valve loss work