

**DESIGN CALCULATIONS TO EVALUATE PERFORMANCE
PARAMETERS OF COMPRESSOR VALVE**Chaitanya D. Patil¹, Prof. M. R. Khodke², Akash Baheti³¹Mechanical Engineering Department, Vishwakarma Institute of Technology, Pune²Mechanical Engineering Department, Vishwakarma Institute of Technology, Pune³Design and Development Department, Burckhardt Compression India Pvt. Ltd., Kondhapuri

Abstract — Compressor sizing is important process which play vital role in multi-stage reciprocating compressor. Proper selection of compressor and its sizing is significant concern which will give proper compressor efficiency. It covers various performing factors including pressure, temperature, flow, cylinder sizing, power rating, etc. Due to multi-staging there are various factors which have to take into account while sizing of compressor. For sizing some parameters are initially decided and then effective parameters are calculated considering handled gas. Various standards are taken into considerations while sizing.

Keywords- Compressor, Sizing, Pressure, Temperature, Volume flow.

I. INTRODUCTION

A reciprocating compressor or piston compressor is a compressor that uses pistons driven by a crankshaft to deliver gases at high pressure. Reciprocating compressors are typically used where high compression ratios (ratio of discharge to suction pressures) are required per stage without high flow rates, and the process fluid is relatively dry. The reciprocating compressors are standardized in API 618: Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services. Arrangements may be of single-or dual-acting design.

Reciprocating compressors are typically used where high compression ratios (ratio of discharge to suction pressures) are required per stage without high flow rates, and the process fluid is relatively dry. Wet gas compressors tend to be centrifugal types. High flow, low compression ratio applications are best served by axial flow compressors. Rotary types are primarily specified in compressed air applications, though other types of compressors are also found in air service.

H. Bukac presented 6 different mathematical dynamic model of self-acting compressor valve and derived equation of motion. [1] Klaus Brun and Marybeth Nored investigated valve performance in terms of life and efficiency. With the help of experimental procedure, life is calculated. [2] From API standards 618, various factors that are affecting performance of compressor are taken into account while sizing of compressor. [3] Mircea Horia Tieren studied design procedure for compressor valve considering gas flow through valve plates and then thermal behavior is studied. [4] Royce N. Brown analyzed sizing of centrifugal compressor. It also involves selection of compressor with the help of different parameters. [5] H. Ali Marefat investigated process multi-stage centrifugal compressor and design procedure is derived. [6] Tonye K. Jack studied reciprocating process gas compressor with the help of mathematical relationship and computational program is developed. [7] Chris Schmidt presented air compressor energy use to estimate energy savings in compressed air system. [8]

II. COMPRESSOR SIZING

Compressor sizing is many types of compressors are available and can be selected due to peculiarities in their designs. A typical chart of different compressor types are shown in Figure 1, although types other than reciprocating compressor are not discussed in detail. Types of compressors are categorized mainly by positive displacement and dynamic [2].

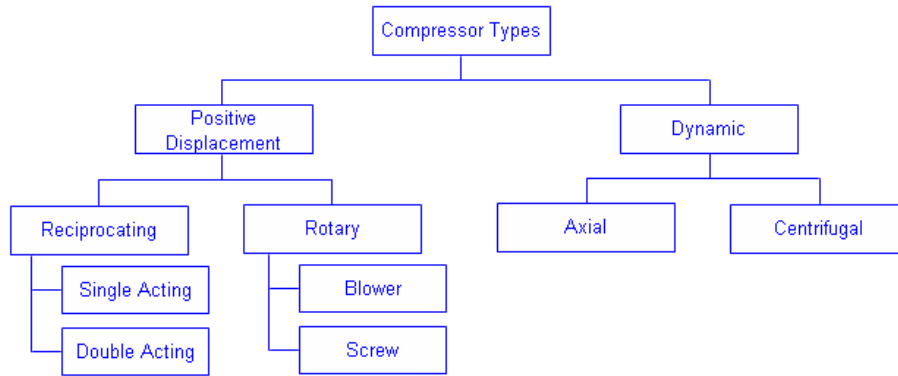


Fig-1: Types of Compressor

2.1 Initial Considerations:

While developing reciprocating gas compressor certain factors need to be fixed before sizing depending on the application and working of compressor. It involves:

- Gas being handled: It may be air or any other gas that is being flown in compressor, but their properties need to be considered while sizing of compressor. Properties like gas composition, molecular weight, density are going to affect the performance of compressor.
- Capacity at suction: It is solely depending on application and customer's requirement. Capacity defines the number of stages and volumetric efficiency.
- Suction pressure and temperature: These are the factors that are decided depending on the working site of compressor. Suction parameters are input to compressor.
- Discharge pressure: Discharge pressure is the output to all process of compressor. It is predefined in order to develop such compressor with specific number of stages. Number of stages vary mainly depending on discharge pressure.

Stroke Length and Speed: Stroke length is given by considering flow of gas being handled and size of compressor. Speed of compressor defined the power rating required for compressor.

2.2 Sizing of Compressor:

Sizing of compressor involves various performing factors to be considered. Proper sizing of compressor is done first in order to have more efficient working. This contains various standards which are followed with API 618 standards fifth edition [3]. The step of procedure for sizing of compressor is given below by considering input data.

Input data:

Capacity at suction(Q) by customer requirement	291	m ³ /hr
Suction Pressure ($P_{amb} = P_s$)	1.013	bar a
Gas handled	Air	-
Suction Temperature (T_s)	45	°C
Discharge pressure (P_d)	401.5	bar a
Discharge Temperature (T_d)	<180	°C
No. of cylinder at suction (n_s)	2	nos.
Stoke length (L)	0.1	m
Speed (N)	1485	rpm

Table 1. Initial recommended conditions

- SELECTING NUMBER OF STAGES FOR COMPRESSOR

It mainly depends of both pressure parameters which are going to be taken into account while designing compressor.

$$\text{Overall pressure ratio} = (P_d/P_s) \quad (1)$$

Where, P_d = Discharge pressure = 401.5 bar a and P_s = Suction pressure = 1.013 bar a
 Overall pressure ratio = 396.35

Compression ratio (R) is the ratio of discharge pressure to suction pressure:

Compressor ratio, $R = (P_d / P_s)^{(1/s)} = 3.308$ when $s = 5$ (2)

Where, s is number of stages.

So in order to maintain compressor ratio below 3.5 the number of stages are decided.

Therefore five-stage air compressor is selected.

- CALCULATE CYLINDER DIAMETER FOR ALL STAGES**

Actual Capacity at suction, $Q = \frac{\pi}{4} * D * D * n_s * L * N * \eta_{vol.} * 60 =$ (3)

$Q = 291 \text{ m}^3/\text{hr}$

So $D = 0.166 \text{ m} \approx 0.165 \text{ m}$

Where, n_s is number of cylinders at first stage

L is Stroke length

N is speed

Therefore, cylinder diameter for first stage is selected as 165 mm.

For rest of the stages in multi-stage cylinder,

Cylinder diameter other than 1st stage, $D_i = \sqrt{\frac{n_s * D(i-1) * D(i-1)}{R}}$ (4)

So cylinder diameter configuration is 165mm, 125mm, 70mm, 42mm, and 25mm.

Note: Cylinder diameters are considered as per availability of standard sizes.

- CALCULATE THE PRESSURE RATIO**

Pressure ratio (R_i) for each stage is given by,

Pressure ratio $R_i = (P_{di}/P_{si})$ (5)

Where, P_{di} and P_{si} are discharge and suction pressure at different stages respectively.

So a single-stage compressor has only single R i.e. Compression ratio.

But multi-stage compressor has one compression ratio R and multiple number of pressure ratios (R_i) values same as number of stages.

- DETERMINE THE ACTUAL VOLUMETRIC EFFICIENCY**

In order to evaluate the energetic quality of a compressor volumetric efficiency is calculated. In the ideal case the complete piston displacement at the end of the suction stroke is filled with gas at inlet condition. It would contain the complete displacement mass. The actual delivered mass after a compression cycle is always smaller than the ideal piston displacement mass [5].

The ratio of the actual delivered to the ideal mass per compression cycle or the respective mass flows is called the volumetric efficiency.

This parameter does not have a direct indication of the energetic efficiency of the compressor. If the piston displacement and the volumetric efficiency of a compressor is known, the volume flow (flow at suction condition) follows [7].

Actual volumetric efficiency is given by,

$\eta_{vol.} = \frac{100 - R_i}{100} - [C * \frac{Z_s}{Z_d} * (R_i^{1/n} - 1)] = 75.18 \%$ (6)

- DETERMINE THE REQUIRED PISTON DISPLACEMENT**

Piston displacement (PD) is a measure of the compressor's size and is dependent on the size, number and type of cylinders, and compressor RPM. Required piston displacement (PDR) is a calculated number that will determine how large a compressor will be required to handle the specified capacity.

$PDR = (Im_3/\text{hr}) / \eta_{vol.} = 387.07 \text{ m}^3/\text{hr}$ (7)

Where, PDR is required piston displacement (m^3/hr)

$\eta_{vol.}$ is Volumetric Efficiency

I_m^3/hr is Capacity (inlet meters cubed per hour)

- DETERMINE THE MINIMUM RPM REQUIRED OF THE SELECTED COMPRESSOR

With the compressor model and Required Piston Displacement known, the minimum RPM required can be calculated.

$$\text{Speed} = 120 * f / P = 1500 \text{ rpm} \quad (8)$$

Where, f is frequency (in Hz)

P is no. of poles

- DETERMINE INTER STAGES PRESSURES

Inter stage pressures are calculated depending upon the cylinder size for each stage. It gives discharge pressure at each stage. Here suction pressure is given as input.

$$\text{So discharge pressure at each stage, } Pd_i = Psi * \frac{ns * Di * Di}{D(i+1) * D(i+1)} \quad (9)$$

At final stage, discharge pressure is calculated with the help of discharge pressure ratio of that stage.

$$\text{I.e. Discharge pressure ratio, } R_i = \frac{Ps * Pd}{Pd(i-1)} \quad (10)$$

Discharge pressure at final stage = $R_i * Pd_{(i-1)}$

Discharge Pressure at every stage is 3.53 bar a, 11.14 bar a, 30.635 bar a, 85.60 bar a, 410.024 bar a.

For safety considerations the safety relief valve is installed with pressure setting of 115% of each inter stage discharge pressure and 110% for final stage discharge pressure. Safety relief valve is given in order to have prevent compressor components with unexpected increase in pressure.

So SRV discharge pressure for each stage (P_{dSRV}) = 115% of inter stage discharge pressure.

And SRV discharge pressure for final stage (P_{dSRV}) = 110% of final discharge pressure.

SRV discharge pressure at each stage is 4.06 bar a, 12.81 bar a, 35.23 bar a, 98.44 bar a, 451.03 bar a.

- DETERMINE ADIABATIC TEMPERATURE AT DISCHARGE.

The compressor's discharge temperature directly affects the life of the piston rings and valves. Here is the formula to calculate the discharge temperature for compressor.

$$\text{Discharge temperature} = [(273+Ts) * \frac{Pd^{(n-1)/n}}{Ps}] - 273 \text{ } ^\circ\text{C} \quad (11)$$

Discharge temperature at each stage is 181.29 °C, 161.66 °C, 165.01 °C, 137.70 °C, 172.03.

For safety relief valve considerations,

$$\text{SRV discharge temperature, } TdSRV = [(273+Ts) * \frac{PdSRV^{(n-1)/n}}{Ps}] - 273 \text{ } ^\circ\text{C} \quad (12)$$

Where, Ts for Stage 1 = 45 °C at stage suction

Ts for rest Stages = 40 °C at stage suction

SRV discharge temperature at each stage is 199.81 °C, 186.59 °C, 190.14 °C, 159.88 °C, 184.32 °C.

- DETERMINE FLOW AT EACH STAGE DISCHARGE.

Flow rate at each stage is important in consideration with compressor performance. Flow at each stage is given by,

$$Q_s = Q_{s-1} * \frac{Ps-1}{Ps} * \frac{(273+Ts)}{(273+Ts-1)} \text{ m}^3/\text{hr} \quad (13)$$

$$Q_d = Q_s * \frac{Ps}{Pd} * \frac{(273+Td)}{(273+Ts)} \text{ m}^3/\text{hr} \quad (14)$$

Q_s for each stage is 291 m³/hr, 83.51 m³/hr, 31.19 m³/hr, 8.81 m³/hr, 2.43 m³/hr.

Q_d for each stage is 119.30 m³/hr, 36.75 m³/hr, 13.47 m³/hr, 4.50 m³/hr, 1.01 m³/hr.

- DETERMINE ISOTHERMAL EFFICIENCY FOR EACH STAGE

The isothermal efficiency is defined as the ratio of the work input to the isothermal process, to the work input to the actual process between the same inlet and exit pressures.

$$\text{Isothermal efficiency, } \eta_{\text{iso.}} = \ln \frac{R_i}{\frac{n}{n-1} \times R_i^{\frac{n-1}{n}} - 1} \quad (15)$$

Where, $R_i = (P_d/P_s)$ & $n = 1.4$

- ADIABATIC SHAFT POWER OF COMPRESSOR

$$P_{\text{ad}} = \frac{P \cdot V}{3600} \times \frac{n}{n-1} \times \left\{ \left[\left(\frac{P_d}{P_s} \right)^{\left(\frac{n-1}{n} \right)} - 1 \right] \right\} \times \frac{1}{\eta_{\text{ad}}} \times 100 \text{ kW} \quad (16)$$

Shaft power at each stage is 14.72 kW, 13.20 kW, 13.58 kW, 10.57 kW, and 14.00 kW.

Total shaft power = 66.08 kW + P_{valve} + P_{mw} + P_{fric} + P_{safety} = 70.13 kW.

Summation of P_{ad} for all stages gives Total P_{ad} .

Then Shaft power includes Total P_{ad} , valve power, friction power, safety factor and others.

- MOTOR RATING

Motor rating is decided from maximum shaft power with 5% tolerance and margin of 10% over shaft power.

Motor rating is given by considering all factors and components which require power as input and finally considering factor of safety the nearest motor rating is selected from standard motor ratings. [8]

Max shaft power = 70.13 + 5% = 73.64 kW max. So nearest motor rating recommended is 79 kW.

Finally by considering these performing parameters compressor machine configuration for piston-cylinder arrangement. It will help to make proper arrangement for positioning of piston-cylinder for all stages.

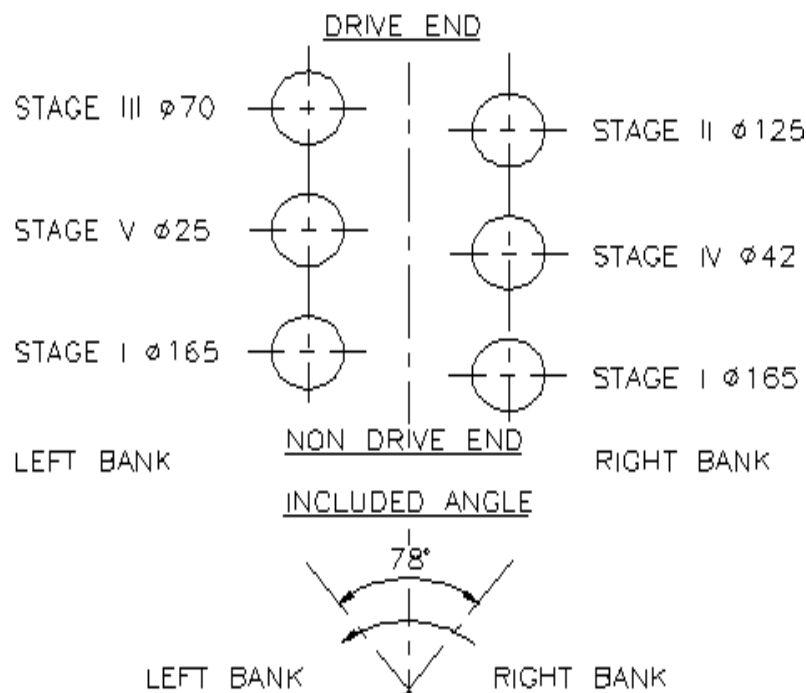


Figure 2: Compressor Machine Configuration for piston-cylinder arrangement

With the help of RecipCalc software P-V diagram for current configuration compressor is developed. It clearly differs actual effective versus isentropic ideal curves.

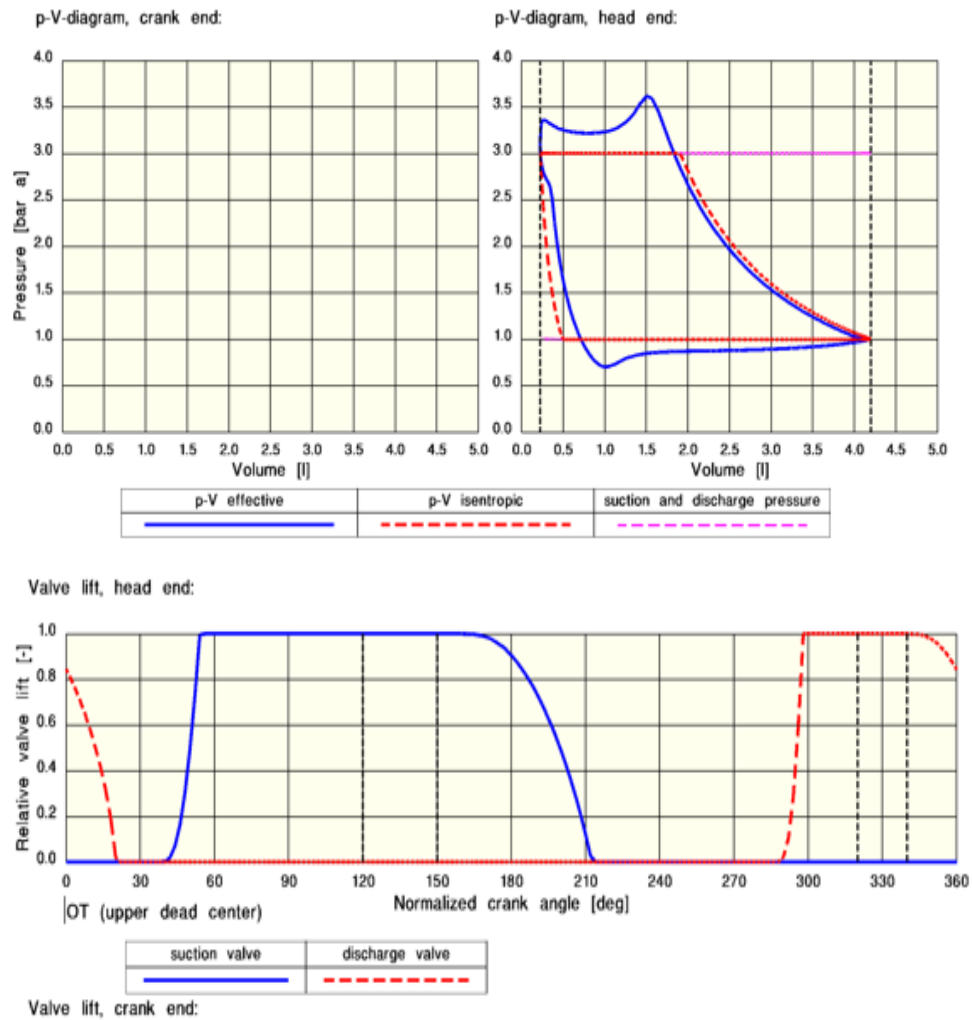


Figure 3: P-V diagram for designed compressor specification

2.3 Experimentation:

For experimentation the compressor arrangement is done and actual testing is done on working compressor. Experimentation results are evaluated and compared with calculated once for validation.

Finally both calculated and experimentation results are validated.

Sr No	Parameter	UOM	Calculated	Expt. Read. 1	Expt. Read. 2	Expt. Read. 3
1.	Compressor speed	RPM	1485	1460	1480	1485
2.	Suction pressure	Bar a	1.013	1.013		
3.	Discharge Pressure stage 1	Bar a	3.53	3.1	3.2	3.1
4.	Discharge Pressure stage 2	Bar a	11.14	10.8	11.2	11.1
5.	Discharge Pressure stage 3	Bar a	30.635	31.1	30.7	30.5
6.	Discharge Pressure stage 4	Bar a	85.60	85.1	86.0	85.9
7.	Discharge Pressure stage 5	Bar g	410.024	405.1	412.2	409.5

Table 2. Validation of design calculation with experimentation

III. CONCLUSION

In this paper, a design procedure is provided for sizing of reciprocating compressor. The procedure for the sizing and performance analysis calculations of reciprocating compressor is simplified in handling various parameters involved. It will be helpful while designing any reciprocating compressor as per required data. With the use of these sizing procedure one can clearly calculate effective parameters and design accordingly. Many factors influence the selection of a reciprocating compressor. It is, therefore, out of scope herein to provide additional guidance beyond the rough estimation stage, which will help to determine how well a reciprocating compressor may fit a process application.

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