Performance Comparison of Capacity Control Methods for Reciprocating Compressors

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Abstract. Different capacity control methods are used for adjusting suction flow of reciprocating compressors to meet process need. Compared with recycle or bypass and suction throttling, three capacity control methods of speed control, clearance pockets and suction valve unloading are preferred due to their energy-saving at operating condition of partial load. The paper reviewed state of the art of the current capacity control technologies and their principles. A comprehensive mathematical model was developed to predict thermodynamic and dynamic performance of reciprocating compressors equipped with the capacity control systems of four above-mentioned methods. Comparison of shaft work and mechanical efficiency were conducted for different capacity control methods at the same condition. In addition, their influence on p-v diagram and valve motion were also studied, which is important for reliability and life of the reciprocating compressors. These results were helpful for selection of the capacity control systems by end-users and optimum design by manufacturers.

1. Introduction
Reciprocating compressors play a major role in the chemical, petrochemical, gas, and general industry processes. Unlike centrifugal pumps, the reciprocating compressor cannot self-regulate its capacity against a given discharge pressure, it will simply keep displacing gas until it is turned off. However, in the real processes of refineries, chemical plants, and gas transmission lines, we find that we have specific parameters within which to work, and that capacity is a unique quantity at any point in time. Thus, compressor capacity control methods are utilized to maintain a required delivery under variable process conditions.

The principle of several capacity control methods was presented early since 1930s [1]. In recent years, some innovation was introduced to the traditional capacity control methods. Automated, variable volume unloaders for clearance pocket capacity control provide the ability to smoothly load/unload reciprocating compressors to maintain ideal operations in ever-changing environments [2]. Stepless capacity regulation utilizes a very fast, digitally controlled, hydraulic solenoid valve to control suction valve opening time [3]. Some new concepts of capacity control were developed. Based on the pulse signal concept, a duty cycle regulation method for capacity control was introduced [4]. The Southwest Research Institute (SwRI) considered that the capacity control method which used linear motor to change length of piston stroke would be very promising [5].

2. Model formulation for capacity control methods
A comprehensive mathematical model is proposed to evaluate the compression work and the friction losses for reciprocating compressors. The paper reviews the basic theories and the state of the art of the five capacity control technologies, namely recycle or bypass throttling, speed control, clearance pockets and suction valve unloading. Each of the capacity control methods is modeled respectively and the pressure-volume relationship and the valve displacement-angle relationship are obtained.

2.1. Modelling of compressor performance

The basic models describing the working process of reciprocating compressor include governing equations, internal leakage model and valve motion model [6]. The governing equation group is based on energy and mass conservation as well as equation of state as following:

\[
\frac{dT}{d\theta} = \frac{1}{mC_v} \left\{ -T \frac{\partial P}{\partial T} \left[ \frac{dV}{d\theta} - \frac{v}{\omega} (m_{in} - m_{out}) \right] - \sum \frac{\dot{m}_{in}}{\omega} (h_{in} - h_{out}) + \frac{\dot{Q}}{\omega} \right\} 
\]

\[
\frac{dm}{d\theta} = \sum \frac{\dot{m}_{in}}{\omega} - \sum \frac{\dot{m}_{out}}{\omega} 
\]

\[
P = P(v, T) 
\]

By solving the governing equations considering the internal leakage and the valve motion simultaneously, some parameters such as the mass, temperature, pressure of working fluid and the valve displacement with respect to the orbiting angle at any working condition can be obtained. Thus, compression work \( P_c \) is calculated from \( p-V \) diagram by means of integrating the volume by the change of the pressure over the whole working process:

\[
P_c = \int V dp 
\]

In addition, a novel friction model basing on journal bearing theory for reciprocating compressor is used to evaluate friction losses [7]. Hydrodynamic lubrication theory is applied to calculate the friction losses \( P_f \) of the journal bearings supporting the crankshaft and the connecting rod. Thus, mechanical efficiency \( \eta \) is ratio of the compression work to the shaft work \( P_c \):

\[
P = P_c + P_f 
\]

\[
\eta = \frac{P_c}{P_c + P_f} 
\]

2.2. Recycle or bypass

One of the simplest methods of controlling capacity is to recycle, or bypass. To reduce the flow to process, one simply opens up the bypass line through some type of control valve and diverts the excess flow back to the compressor suction. This control scheme is extremely inefficient because the backflow gas is recompressed and the compression work is totally wasted. As a result this control technique is rarely used. Only in case of failure of other control methods, the control method of recycle or bypass is activated for safety. This control method does not make any changes to the working process of the reciprocating compressor.

2.3. Suction throttling

The gas suction pressure is reduced by throttling of a control valve into the compressor inlet. The density of the gas will be reduced at this lower pressure, thus helping to reduce the mass flow delivered. As a rule, the gas suction pressure is controlled as a function of either discharge pressure or flow. It is assumed that the process of the throttling is isenthalpic and the gas temperature is gotten by the equation of state.
Figure 1 and 2 show $p$-$V$ and $h$-$\theta$ relationship under different suction pressure. As the suction pressure is reduced and the discharge pressure held constant, the compression ratio is increased. Suction throttling moves the characteristic curve of $p$-$V$ to the left, indicating a lower volumetric efficiency and thus less flow. The valve motion is also altered by the increase of the compression ratio. A sizable reduction in capacity means a dramatic increase of the compression ratio. This causes higher discharge temperatures. In the case, the discharge temperature is rising from 92°C to 210°C as the compression ratio rising from 2 to 5 for air.

![Figure 1](image1.png)  ![Figure 2](image2.png)

**Figure 1.** $p$-$V$ diagram under different flow rates for suction throttling  
**Figure 2.** $h$-$\theta$ diagram under different flow rates for suction throttling

### 2.4. Speed control

Inverter-driven motors make it possible that the capacity is matched to the load by regulating the speed of the compressor. This method is widely used for refrigeration and air-conditioning system. However, it is rarely used in process compressor due to the problems of the cost and the reliability of the large-scale inverter-driven motors.

As shown in figure 3, the gas mass flowing into the compressor during one resolution is nearly equal for different orbiting speeds. Thus, the gas mass flow rate is approximately proportional to the orbiting speed. As shown in figure 4, the orbiting speed influences the valve motion. When the orbiting speed decreases, the status of both the suction and discharge valves gets worse.

![Figure 3](image3.png)  ![Figure 4](image4.png)

**Figure 3.** $p$-$V$ diagram under different flow rates for speed control  
**Figure 4.** $h$-$\theta$ diagram under different flow rates for speed control
2.5. Clearance pockets
Volume pockets vary the compressor capacity by adding clearance to the piston area. Recently hydraulically controlled variable-volume clearance pocket instead of having fixed-steps is equipped in more and more process reciprocating compressor.

As clearance is increased, figure 5 illustrates that the effective suction volume (volumetric efficiency) decreases, thus reducing the amount of flow to process. Figure 6 illustrates that the time for the opening of both the suction and the discharge valve also decreases. It should be noted that the volumetric efficiency is not only affected by increased clearance but also is governed by the compression ratio. When the clearance volumetric coefficient is 0.8 for the compression ratio of 2.0, the flow rate is only 45% of the rated one. So, clearance pockets are ineffective and not useful with low compression ratios.

![Figure 5. p-V diagram under different flow rates for clearance pocket](image1)

![Figure 6. h-θ diagram under different flow rates for clearance pocket](image2)

2.6. Suction valve unloading
Many researchers pay attention to the stepless capacity control system [7]. This system uses finger-type unloaders that are pneumatically actuated. It is to physically keep the cylinder from compressing gas by maintaining the suction valve opening for only a portion of one stroke. It is assumed that when suction valve unloading takes effect, the suction valve displacement $h_s$ is equal to the valve stop $H$ as follows:

$$\theta_0 \leq \theta \leq \theta_1, \quad h_s = H$$  \hspace{1cm} (3)$$

$\theta_0$ and $\theta_1$ is the starting and ending orbiting angle for the suction valve opening respectively.

As shown in figure 7, suction valve unloading makes the curve of $p-V$ move to the left, which means that the time for the suction process is extended and that for the compression process is shortened. As shown in figure 8, the displacement of the suction valve is set to the valve stop since the orbiting angle of 90 degree.
3. Performance comparison of different capacity control methods

Figure 9 plots the relationship between the shaft work (dimensionless) and the flow rate (dimensionless) for different capacity control methods. Except for the suction throttling, the shaft work is nearly linear to the flow rate for other three methods. The speed control is most efficient. The shaft work of the suction valve unloading is almost close to that of clearance pocket. The shaft work of the suction valve throttle is even a litter larger than the rated one at the rated flow rate of 60% to 100%.

The mechanical efficiencies (dimensionless) in terms of the flow rate (dimensionless) for different capacity control methods are plotted in figure 10. The mechanical efficiency increases with the decrease of the rotation speed and is more than 1, which is attributed to reduction of friction losses. The mechanical efficiency for other three capacity control is less than 1, because the isentropic efficiency of the compression process decreases, which caused by the increase of the volumetric efficiency. Similar to figure 9, the mechanical efficiency for both the suction valve unloading and the clearance pocket shows the same behaviour.
4. Conclusion

Different capacity control methods are reviewed and simulated and their characteristics of \( p-V \) and \( h-\theta \) curve are studied. The speed control is most efficient and its mechanical efficiency increases with the decrease of the rotation speed. The behaviour of the suction valve unloading and the clearance pocket for the shaft power and the mechanical efficiency are similar to each other.

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\[ \textbf{Nomenclature} \]

\begin{tabular}{ll}
\( h \) & Enthalpy of working fluid, Valve displacement \\
\( p \) & Pressure of working fluid \\
\( T \) & Temperature of working fluid \\
\( H \) & Valve stop \\
\( m \) & Mass of working fluid \\
\( m_i \) & Working fluid mass flow rate \\
\( \dot{Q} \) & Heat flow rate into the control volume \\
\( t \) & Time \\
\( C_v \) & Specific heat capacity at constant volume \\
\( v \) & Specific volume of working fluid \\
\( V \) & Volume of the control volume \\
\( \eta \) & Efficiency \\
\( \theta \) & Orbiting angle \\
\( \rho \) & Density \\
\( \omega \) & Angel speed \\
\( P_f \) & Friction power \\
\( P_c \) & Shaft power \\
\( P \) & Power input \\
\end{tabular}

\[ \textbf{Subscripts} \]

\begin{tabular}{ll}
\( v \) & Flow in \\
\( \text{in} \) & Flow in \\
\( \text{out} \) & Flow out \\
\end{tabular}

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