Dynamic Performance of Valve in Reciprocating Compressor Used Stepless Capacity Regulation System

Guangbin Liu
State key laboratory for compressor technology, Hefei General Machinery Research Institute, People's Republic of China,
guangbin0805@163.com

Yuanyang Zhao
State key laboratory for compressor technology, Hefei General Machinery Research Institute, People's Republic of China,
yuanyangzhao@163.com

Le Wang
State key laboratory for compressor technology, Hefei General Machinery Research Institute, People's Republic of China,
wangle4127@163.com

Qichao Yang
State key laboratory for compressor technology, Hefei General Machinery Research Institute, People's Republic of China,
qichaoyang@163.com

Bin Tang
State key laboratory for compressor technology, Hefei General Machinery Research Institute, People's Republic of China,
tangbinsoddy@126.com

Authors
Guangbin Liu, Yuanyang Zhao, Le Wang, Qichao Yang, Bin Tang, and Liansheng Li

Dynamic Performance of Valve in Reciprocating Compressor Used Stepless Capacity Regulation System

Guangbin LIU*, Yuanyang ZHAO, Le WANG, Qichao YANG, Bin TANG, Liansheng LI
State key laboratory for compressor technology, Hefei General Machinery Research Institute,
Hefei, Anhui, P.R.China

* Corresponding Author
Phone: +86-0551-65335770, guangbin0805@163.com

ABSTRACT

Capacity regulation system by controlling suction valve is useful for large scale reciprocating compressor in petrochemical engineering field. The dynamic performance of adjustment device influences the stability and accurancy of this system. In this paper, a mathematical model of adjustment device coupled with the motion of suction valve is built, and the dynamic performances of valve plate are simulated. The results show that the displacement of actuator increases with the hydraulic oil pressure until the valve plate is keeped to be opened. The closing process of valve plate is delayed when the hold time of actuator is larger enough. Although the gas flow rate and power consumption of comresssor decrease with the relax angle of actuator, the power is also consumed when the gas is not discharged through the discharge valve. The closing time decreases with the reset spring stiffness but increases with the diameter of hydraulic.
Keywords: Stepless; Capacity regulation; Dynamic

1. INTRODUCTION

Large reciprocating compressor is a mainly energy consumption equipment in petrochemical and refineries industries. It is inevitable to adjust the capacity of compressor in order to adapt to the system condition. Usually, the redundant gas is returned to suction pipe through bypass throttle, which causes much energy waste. Hence, a capacity regulation system is needed to keep the stable gas flow rate and lower energy consumption. Adjusting capacity by controlling suction valve has a good application prospect because the power consumption of compressor can be reduced with the decrease of gas flow rate. Presently, some researchers focus on the thermodynamic performance of compressor influenced by the capacity regulation systm and some mathematical model is built to predict the adjusting performance (*Weirong et al., 2, 2009, Jiangming et al., 2009 and Jiangming et al., 2012*). The programmable logic controller has been used in this system to controll the motion of suction valve in order to simplify the system structure and reduce the cost (*Dacheng et al., 2011*). The simulation software named AMESim is also be used to simulate the dynamic performance of suction valve and actuator (*Bin et al., 2013*), but the compression process and hydraulic system are not coupled.

The motion law of suction valve is affected by the actuator and the working process of compressor is also changed, hence the stability and accuracy of this system are decided by the dynamic performances of actuator and suction valve plate. In this paper, a methematical model is built to simulate the movement of actuator and suction valve plate, and the performances influenced by some parameters are discussed. The resulsts are useful for designing and developing this system.

2. THEORETICAL ANALYSIS

The capacity regulation system includes oil station, solenoid valve, actuator, controller and other accessories. The controller controls the flow direction of hydraulic oil to change the movement of actuator and suction valve plate. The closing process of suction valve is delayed by actuator and some gas flows back to the suction pipe through the suction valve, which reduces the gas flow rate and compression power. The hydraulic cylinder, hydraulic piston and reset spring are needed in this system. The high pressure oil in hydraulic cylinder pushes down the actuator and maintains the suction valve to be opened. When the oil pressure is reduced, the reset spring pushes upward the actuator and valve spring pushes upward the valve plate at the same time, which leads to the closing process of suction valve. The diagram of this system is shown in figure 1.

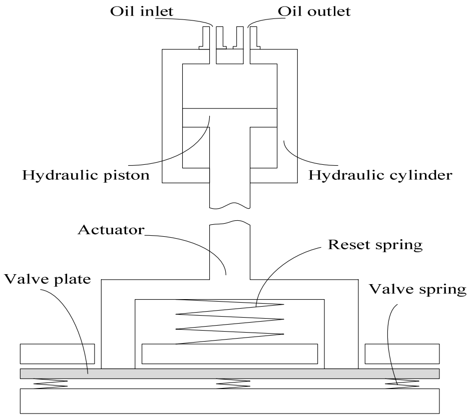

Figure 1: Schematic diagram of capacity regulation system

The mass flow rate of hydraulic oil is influenced by the flow area, differential pressure, and the property of oil. The process of hydraulic oil inflows or outflows hydraulic cylinder can be descirbed by following equation [6].

$$\frac{dm_{oil}}{dt} = fA_{val}\sqrt{\frac{2\left(p_H - p_L\right)}{v_{val}}} \qquad (1)$$

The displacement actuator is decided by the quantity of hydraulic oil, which can be shown as following equations.

$$\frac{dh_{act}}{dt} = \frac{4v_{oil}}{\pi D_{op}{}^2}\frac{dm_{oil}}{dt} \qquad (2)$$

When the suction valve plate is not contacted by actuator, the movement of suction valve is influenced by the valve structure, gas pressure and rotating speed [7].

$$\frac{d^2 h_{sv}}{d\theta^2} = \frac{\beta_{sv}A_{sv}\Delta p - zK_{sv}(h_{sv} + H_{sv})}{\omega^2 m_{sv}} \qquad (3)$$

When the actuator limits the motion of valve plate, the motion process of valve plate can be simplied as the following equation.

$$\begin{cases} h_{vp} = h_{act} \\ u_{vp} = \alpha du \end{cases} \qquad (4)$$

The chamber of compressor is chose as control volume and the energy conservation can be decribed, which includes the leakage and heat transfer process [6].

$$\frac{\partial T}{\partial \theta} = \frac{1}{mc_v}\left\{-T\left(\frac{\partial p}{\partial T}\right)_v\left[\frac{\partial V}{\partial \theta} - \frac{v}{\omega}\left(m_i - m_o\right)\right] - \sum\frac{m_i}{\omega}\left(h - h_i\right) + \frac{Q}{\omega}\right\} \qquad (5)$$

The clearance between cylinder and piston ring influences the working process of compressor, and it can be shown as following equations [6].

$$\frac{dm}{d\theta} = \begin{cases} f\dfrac{A_l}{v_i\cdot\omega}\left[\dfrac{2k}{k-1}p_i v_i\left(\left(\dfrac{p_H}{p_L}\right)^{\frac{2}{k}} - \left(\dfrac{p_H}{p_L}\right)^{\frac{k+1}{k}}\right)\right]^{1/2} & if \quad \dfrac{p_H}{p_L} \ge \left(\dfrac{2}{k+1}\right)^{\frac{k}{k-1}} \\ f\dfrac{A_l}{v_i\cdot\omega}\left[\dfrac{2k}{k-1}p_i v_i\left(\left(\dfrac{2}{K+1}\right)^{\frac{2}{k-1}} - \left(\dfrac{2}{K+1}\right)^{\frac{k+1}{k-1}}\right)\right]^{1/2} & if \quad \dfrac{p_H}{p_L} < \left(\dfrac{2}{k+1}\right)^{\frac{k}{k-1}} \end{cases} \qquad (6)$$

3. RESULTS AND DISCUSSTION

In this simulation on the dynamic performance of this system, the suction pressure is 310 kPa, the suction temperature is 40℃, the discharge pressure is 900 kPa and the oil back pressure is 100 kPa. There are eight valve springs in the suction valve and the siffness of every one is 2.7 kN/m. The dynamic performances of actuator and valve plate are discussed.

Figure 2 shows the displacement of suction valve plate and actuator influenced by hydraulic oil pressure. After the high pressure oil flowing into the hydraulic cylinder, the hydraulic pressure force overcomes the reset spring force and pushes down the hydraulic piston. However, the actuator and valve plate is pushed upward by reset and valve springs when the oil pressure is lower. The maximum displacement of actuator is decided by the oil pressre and springs. In this simulation, the actuator is motionless at the oil pressure of 100 kPa, but it moves a little distance at the oil pressure of 700 kPa. At this moment, the valve plate impacts on the actuator and the suction valve keeps partially opened a little time in the closing process of valve plate. The valve plate is keeped on the lift limiter totally when the oil pressure is 1000 kPa. Then the valve plate returns with the actuator at the same time.

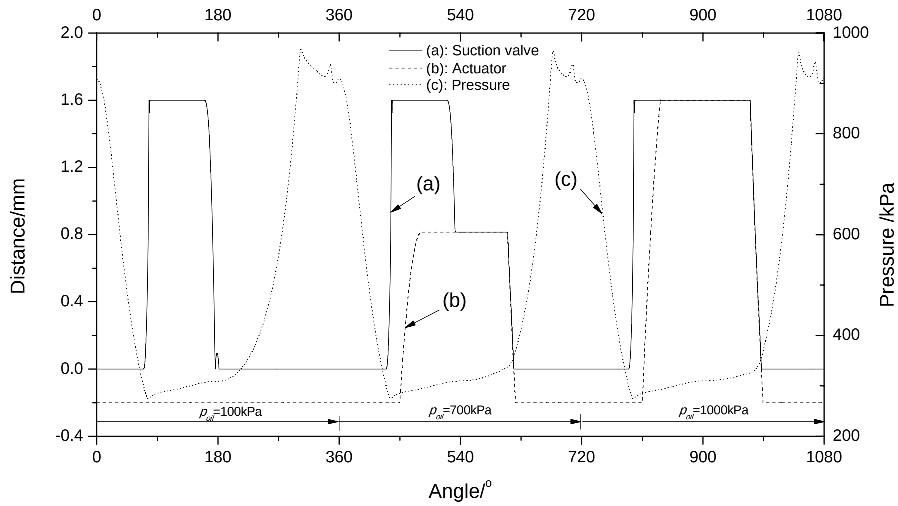

Figure 2: Dynamic performance influence by oil pressure

The hold time of actuator influences the movement of suction valve. Because the larger hold time leads to more gas flowing back through the suction valve, it influences the regulation capacity directly. The valve plate is affected gradually with the increase of hold time. The larger hold time means smaller compression process in the cylinder, lower mass flow rate and power consumption. The open process of sucton valve is not affected by the actuator because the actuator moves after the suction valve plate is opened.

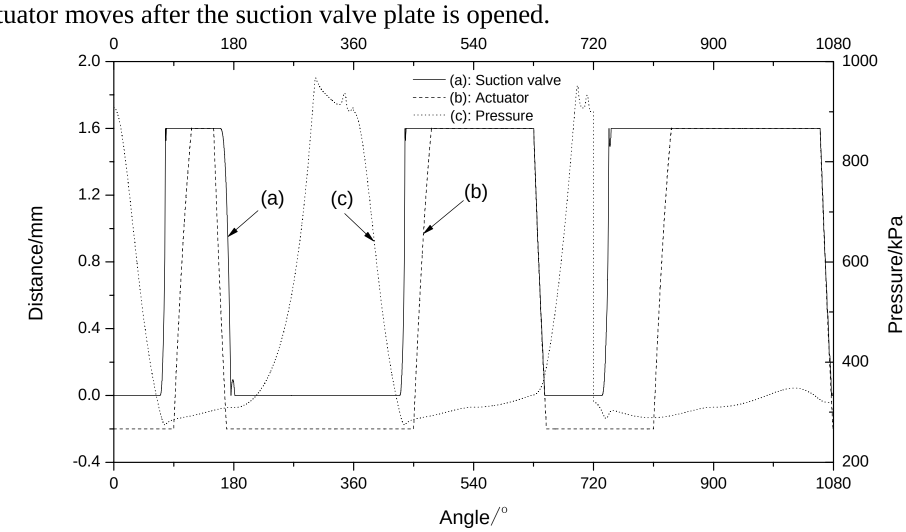

Figure 3: Dynamic performance influence by dely time

The relax angle of actuator influences the power and mass flow rate of compressor. With the increase of relax angle, the compressed gas in cylinder is lower until the discharge valve can not be opened, which means there is no gas outflow. A little gas in the cylinder is also compressed due to the clearance volume, so the power is also consumed. According to the figure, there is no gas outflow through the discharge valve when the relax angle is 287°, but the power consumption is also above 10% of full load.

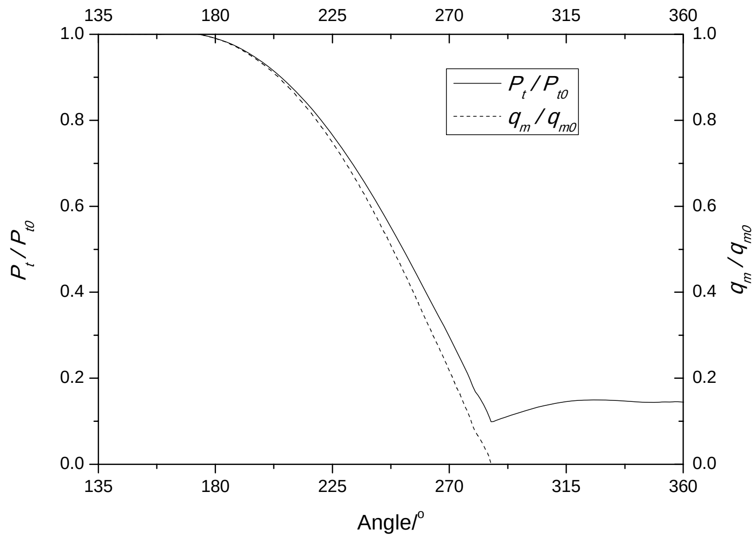

Figure 4: Power and mass flow rate influenced by relax angle

The reset spring stiffness influences the closing time of valve plate and mass flow rate of compressor. The closing time decreases but the mass flow rate increases with the reset spring stiffness. According to the figure, the closing time decreases from 13.43ms to 5.38 ms and the mass flow rate increases from 0.049 kg/s to 0.073 kg/s when the reset spring stiffness changes from 20kN/m to 100 kN/m. Increasing the reset spring stiffness is useful for improving the respons time of suction valve.

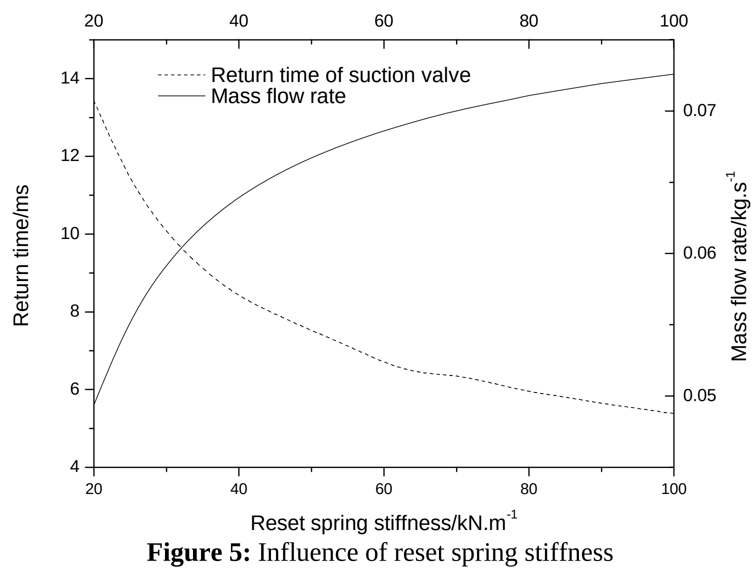

Figure 5: Influence of reset spring stiffness

The diameter of hydraulic cylinder also influences the dynamic performance of sucntion valve. Although the force on the actuator increases with the diameter of hydraulic cylinder, the oil needs more time to inflow or outflow the hydraulic cylinder. According to the figure, the closing time increases from 2.9 ms to 27.8 ms and the mass fow rate decreases from 0.08 kg/s to 0.004 kg/s when the diameter of hydraulic cylinder is changed from 10 mm to 24 mm. Hence, the design of hydraulic cylinder needs to consider the driving force and the response time of valve plate.

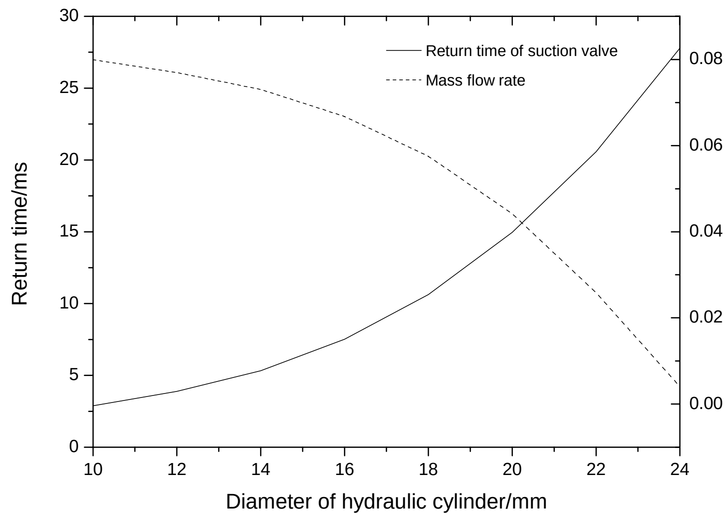

Figure 6: Influence of diameter of hydraulic cylinder

4. CONCLUSION

In order to simulation the dynamic performance of suction valve and actuator in reciprocating compressor, a mathematical model on suction valve and actuator is built, and some conclusions have been gotten.

- The displacement of actuator increases with the hydraulic oil pressure until the valve plate is keeped to be opened. The closing process of valve plate is delayed when the hold time of actuator is larger enough, and the larger hold time leads to more gas flowing back from suction valve.
- Although the gas flow rate and power consumption of comressor decrease with the relax angle of actuator, the power is also consumed when the gas is not discharged through the discharge valve.
- The closing time decreases with the reset spring stiffness but increases with the diameter of hydraulic. The proper reset spring stiffness and diameter of hydraulic cylinder influence the response time of suction valve obviously.

NOMENCLATURE

A	Area	(m^2)
c	specific heat	($J.kg^{-1}.K^{-1}$)
D	Diameter	(m)
f	Flow coefficient	
h	Displacement	(m)
H	Displacement of precompression	(m)
k	Ratio of specific heat	
K	Stiffness of spring	($N.m^{-1}$)
m	Mass	(kg)
p	Pressure	(Pa)
Q	Heat	(W)
t	Time	(s)
T	Temperature	(K)
u	Speed	($m.s^{-1}$)
v	Specific volume	($m3.kg^{-1}$)
V	Volume	(m^3)
z	Number of valve sping	
α	Impact coefficient	
β	Thrust coefficient	

θ	Angle	°
ω	Angular velocity	(rad.s^{-1})
Subscrips		
act	Actuator	
H	High pressure	
i	In	
L	Low pressure	
o	Out	
oil	Hydraulic oil	
op	Oil piston	
v	Constant volume	
val	Valve	
vp	Valve plate	
sv	Suction valve	

REFERENCE

Weirong H, Jiangming J, Rongren W, Bingyuan Z. Theoretical analysis and realization of stepless capacity regulation for reciprocating compressors. *Pro. IMech, Part E: Journal of Process Mechanical Engineering*. 2009, vol.223, no.E4: p.205-213.

Jiangming J, Weirong H, Lingbo T. Improved stepless capacity regulation for reciprocating compressors. *Hydrocarbon Processing*, 2009, no.8: p.43-47.

Jiangming J, Weirong H. Valve dynamic and thermal cycle model in stepless capacity regulation for reciprocating compressor. *Chinese journal of mechanical engineering*. 2012, vol.25, no.6: p.1-10.

Dacheng L, Zhinong J, Lihua C. Design of Capacity Regulation System for Reciprocating Compressor Based on Programmable Logic Controller. *Journal of Computational Information Systems*, 2011, vol.7, no.12, p.4409-4416.

Bin T, Yuangyang Z, Liansheng L, Guangbin L. Thermal performance analysis of reciprocating compressor with stepless capacity control system.*Applied Thermal Engineering*. 2013, vol.54, no.2: p.380-386 .

Wang Le, Tang Bin and Li Liansheng.A Novel Mathematical Model for Reciprocating Compressor of Domestic Refr igerator. *Proceedings of 11th Asian International Conference on Fluid Machinery*. IIT Madras, Chennai India, 2 011: AICFM_TM_024.

Kato M, Kurohashi M. Dynamic behavior of valves with pneumatic chamber for reciprocating compressors. *Journal of Vibration and Acoustics*, Transactions of the ASME, 1993, vol.115, no.4: p.371-376.

ACKNOWLEDGEMENT

The work is fund by the National Key Basic Research program of China (2012CB026000) and the National Science & Technology Pillar Program (2013BAF01B02)