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Thermal performance analysis of reciprocating compressor with stepless capacity control system

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HIGHLIGHTS

- ► Flow resistance of valve can be reduced and pressure fluctuation can be reduced.
- ► Equivalent Mach number of reverse flow is much higher than that of suction process.
- ► Response of stepless capacity control system is important for regulation accuracy.
- ► Clearance and valve clearance Mach number have influence on thermal performance.

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ABSTRACT

On the basic principle of stepless capacity control system for large reciprocating compressor, the thermal cycle was analyzed. The equations for the process of suction, reverse flow, compression, discharge and expansion of clearance gas were established. According to these equations, p–V diagrams at various situations were simulated. An experimental platform was setup and the compressor with designed stepless capacity control system run well. The experimental results show that the capacity of compressor can be regulated steplessly, and the motor power is reduced proportionally with respect to the reduction of capacity. During the suction process, both the flow resistance of valve and the pressure fluctuation in cylinder can be reduced by opening the suction valves with the actuators. The simulated and experimental results showed good coincidence. The clearance volume and valve clearance Mach number had a negative influence on the thermal performance of compressor with stepless capacity control system.

1. Introduction

Large scale reciprocating compressors have been widely used in the industries of chemical processing, gas transport and storage, refineries, and so on. During their operation, the capacity of compressor needs to be regulated in line with the actual demand of the chemical and petrochemical processes. Various approaches have been used to control the capacity of reciprocating compressors, and by-pass regulation is simple and reliable for large-scale reciprocating compressors. However, the method of by-pass regulation results in much power dissipation because the reflux gas is compressed again [1]. Compared with the by-pass regulation, the method of actively controlling suction valve motion, called stepless capacity control method too, has much better energy-saving performance just because only the gas needed is compressed in the compressing process [2–4]. As this approach could make system more efficient, stepless capacity control system has been applied in large-scale compressors [5].

At present, researches on the stepless capacity control focus not only on the dynamic characteristics of suction valve [6] and how to realize the action of actuator [7], but also on energy-saving performance and economic efficiency both effected by compressor load and shaft power when the stepless capacity control is employed [8]. However, in those researches, fundamental theory and principle of the stepless control system were only qualitatively analyzed, not quantitatively calculated [9,10]. Qualitative analysis could not provide enough theoretic reference. In Ref. [4], the theoretical models of thermal circle with stepless capacity control in described did not consider the influence of actuator and the motion of valve. In this paper, theoretical models of thermal circle

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Nomenclature

a_p	area of holes in valve seat
Cp	piston speed
C_R	valve rebound coefficient
C_s	local speed of sound
h	valve displacement
H	valve lift
H_0	preload distance of valve spring
k	adiabatic coefficient
K	valve spring stiffness
m_f	mass of valve movement part
m	adiabatic compression coefficient
Mv	Mach number in valve clearance
n	adiabatic expansion coefficient
p	pressure in cylinder
p_s	inlet pressure
p_d	discharge pressure
r	crank radius
S_c	effective compression stroke length
S	piston stroke
u_a	flow velocity of valve clearance
V	stroke volume
x_i	displacement of piston
Z	valve springs amount

Greek letters

α	relative clearance volume
β	thrust coefficient of valve
λ	ratio of crank radius to length of connecting rod
ω	rotation speed of compressor
θ	crank rotation angle
θ_0	initial rotation angle of calculation
φ	dimensionless pressure p/p_s
φ_0	initial dimensionless pressure

considering those effect factors were established and an experiment has been done to prove them.

2. Stepless capacity control system

The basic principle of the stepless capacity control system is that the movement of the suction valve is controlled by external force which can delay the closure, so that the redundant gas is allowed to return to suction cavity or pipe through suction valves. Therefore, the capacity of compressor can be controlled by adjusting the delay time, and theoretically a stepless capacity regulating range of 0%–100% could be achieved through this method. The schematic layout of the stepless capacity control system for reciprocating compressor is shown in Fig. 1. A 2/3 way solenoid valve controlled by PLC (Programmable Logic Controller) is used to control the pressure of hydro-cylinder. The actuator moves back and forth under the action of hydraulic pressure. As solenoid valve powers up, the hydraulic cylinder connects with high pressure oil circuit, the hydraulic pressure drives the actuator to move forth, and the valve in contact with the actuator is forced to open. As the solenoid valve powers down, the hydraulic cylinder connects with low pressure oil circuit, the actuator moves back under the force of return spring, and the valve is closed by valve springs and gas force in the cylinder. With the action of actuator, the closing time of suction valve can be delayed, and the redundant gas in the cylinder flows out of cylinder through the suction valve. This is called reverse flow process. Delaying the closure of suction valves could reduce the capacity and power consumption of compressors, and the theory p–V diagram is shown in Fig. 2. The indicated power decreases with the decrease of capacity. Therefore,

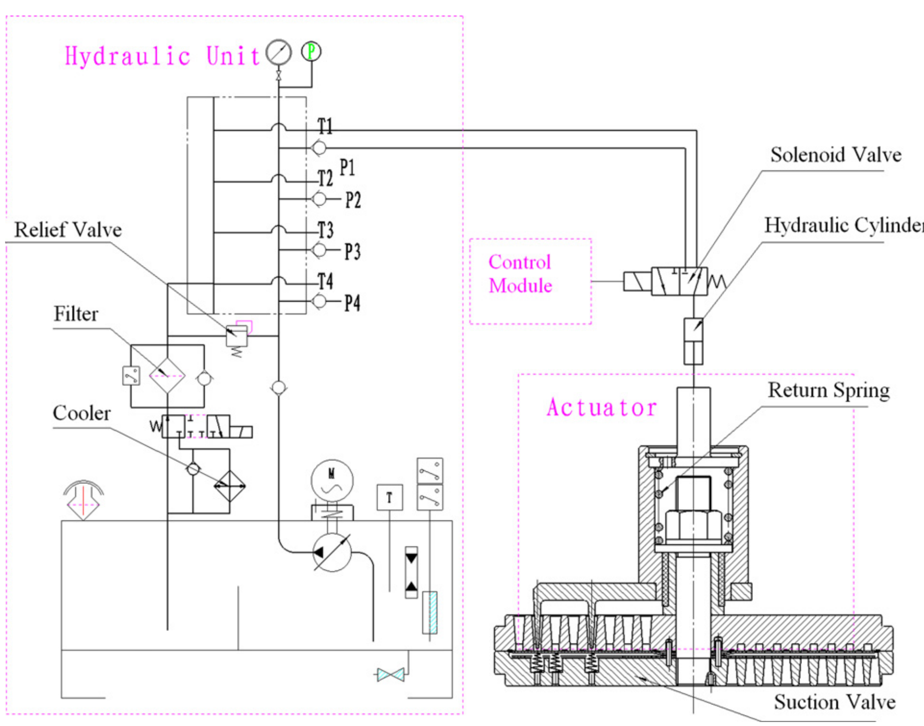

Fig. 1. Structure of stepless capacity control system.