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DYNAMIC SIMULATION AND EXPERIMENTAL RESEARCH ON CHARGE OF GAS BOOSTER

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ABSTRACT

Based on the analysis of principle and structure of the gas booster, this paper studied on its charging process from low-pressure gas bottle to high-pressure one, considered the effect of some facts, including the changing of inlet and outlet pressure, clearance space, friction, according to the principle of kinematics, gas dynamics and thermodynamics ,established the mathematical and dynamics model of a gas booster system, which includes pressure differential equation of each chamber, flow rate equation, as well as the temperature equation and piston acceleration equation. The system is simulated with M-File of MATLAB software, and we got the pressure change curves, flow characteristic curve and time of charging gas, and the experimental data proved the correctness of simulation result, and provide theoretical basis for model selection and overall design.

KEY WORDS

Gas booster, Mathematical model, MATLAB, Numerical simulation

NOMENCLATURE

A_e : Effective area of pipeline system;
b : Critical pressure ratio;
k : Adiabatic exponent;
M : Mass of the piston;
R : Molar gas constant;
S : Stroke of the piston;
X : Displacement of the piston;
X_{10} : Clearance of chamber 1.

INTRODUCTION

Gas booster is an equipment of compressing low-pressure gas to high-pressure, which has wide applications in gas bottle charging and compression fields. The working principle of gas booster abide by Pascal's Law, if there is a smaller force acting on the big end of piston, there will be a bigger force on the small end. Based on the analysis of principle and structure of gas booster, a mathematical model was set up, and we solved the problem of reciprocating motion of piston in the simulation, the experimental data verified the correctness of this simulation, and provide theoretical basis for model selection and overall design.

MATHEMATICAL MODEL

In the experiment, we use a single acting gas booster to pressurize the gas, whose pressure ratio is up to 30. Aiming at the course of charging, we established the

mathematical model. The model of gas booster system is shown in Figure 1.
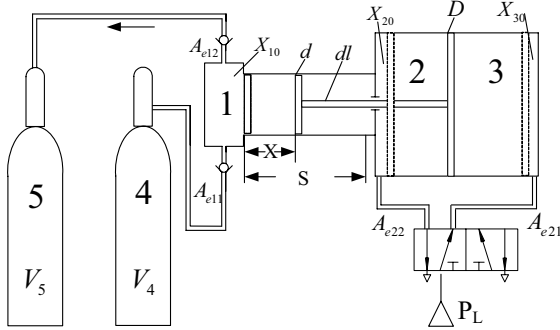

Figure 1 Physical Model of Gas Booster System

For the physical model of gas booster system, we suppose the working media is ideal gas, and there is no leakage in the course of charging; the temperature field and pressure field is uniform in the same chamber, and the state parameters of gas are equal at any point and any time; the gas flowing through a throttle was supposed to be one-dimension adiabatic steady flowing. Take chamber 1 to 5 as control body respectively, and the gas obeys the first law of thermodynamics and the flow rate continuation equation, so we got the pressure equation of each chamber.

Pressure Differential Equation of Chambers
Take five chambers as control body separately, and the volume of gas booster could easily get as shown in Figure.1, according to the first law of thermodynamics, the gas state equation and the flow rate continuation equation, we got the pressure differential equation of each chamber

$$\frac{dp}{dt} = \frac{k \cdot R}{V}(T_{in} \cdot Q_{in} - T \cdot Q_{out}) - \frac{k \cdot p}{V} \cdot \frac{dV}{dt} \qquad (1)$$

Temperature Equation
Based on the course of adiabatic inflation for each chamber, suppose its pressure change from P_0 to P, temperature from T_0 to T and volume from V_0 to V, the temperature of gas source is T_s, then the temperature of the chamber after inflation

$$T = \frac{kT_s}{(k+1) + k(\frac{p_0}{p} - 1)\frac{V_0}{V} - \frac{p_0}{p}} \qquad (2)$$

Based on the course of adiabatic deflation for a chamber, suppose its pressure change from P_0 to P, temperature from T_0 to T, then the temperature of the chamber after

deflation can be calculated as follows, in which `adiabatic exponent k is 1.4`.

$$T = T_0 \left(\frac{P}{P_0}\right)^{\frac{k-1}{k}} \qquad (3)$$

Flow Rate Equation
According the study of Sanville F.E., the calculation formula of the mass flow rate for the real pneumatic component can be calculated as follows,

$$Q_m = \frac{A_e p_u \sqrt{1-b}}{\sqrt{RT_u}} \omega(\sigma, b) \qquad (4)$$

$$\omega(\sigma, b) = \begin{cases} 0, & \sigma = \frac{p_e}{p_u} > 1 \\ 1, & \sigma = \frac{p_e}{p_u} \le b \\ \sqrt{1 - \left(\frac{\sigma - b}{1-b}\right)^2}, & b < \sigma \le 1 \end{cases} \qquad (5)$$

In the equation, A_e is the total effective area of inlet and outlet pipeline system, T_u, P_u, P_e are respectively the upstream temperature, upstream pressure and downstream pressure, according to upper equation, we got the flow rate equation of every chamber of gas booster and gas bottle.

Piston Motion Differential Equation
The reciprocating motion of the piston is mainly due to the gas force of each chamber as well as the friction force between the piston and the cylinder wall. The force diagram of the piston is shown in Figure 2.
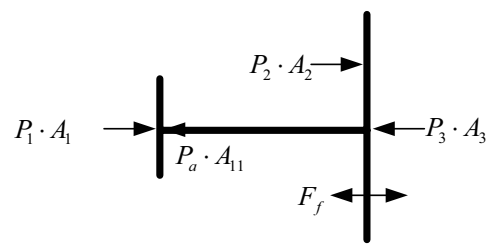

Figure 2 Force diagram of the piston

Take rightward as the positive direction of vector, its value can be calculated as follows:

$$F = P_1 A_1 - P_a A_{11} + P_2 A_2 - P_3 A_3 - F_f \qquad (6)$$

In the equation, F_f is the friction between the piston and

the cylinder wall, including the static friction when still and the sliding friction when moving, the direction of which is judged by the velocity or acceleration of the piston, which could be explained as follows

$$F_f = \begin{cases} F_{fs} & v = 0 \\ \left(F_{fc} + B_e|v|\right) \cdot \text{sgn}(v) & v \neq 0 \end{cases} \quad (7)$$

In the equation, B_e is damping coefficient, F_{fs}, F_{fc} are respectively the maximum static friction and Coulomb friction.

When piston is at the most left and the direction of resultant force is rightward or at the most right and the direction of resultant force is leftward, as well as when piston is in the stroke, the acceleration of piston can be described as follows:

$$\begin{cases} \dfrac{d^2X}{dt^2} = \dfrac{F}{M}, & (X = 0 \cap F > 0) \cup (0 < X < S) \\ & \cup (X = S \cap F < 0) \\ \dfrac{d^2X}{dt^2} = 0 & , (X = 0 \cap F \leq 0) \cup (X = S \cap F \geq 0) \end{cases} \quad (8)$$

NUMERICAL SIMULATION

The core of the simulation is to solve the differential equations, in Matlab, the type of the solver we used is as follows

[T,Y,TE,YE,IE] = ode45(odefun,tspan,y0,options)

In the mathematical model, the equation of pressure of each booster chamber and flow rate are not the same when piston move rightwards or leftwards, in order to judge the direction of the piston movement, we use the output arguments of the solvers-IE, which is got in the "options" of events. In simulation procedure, the events function is set as follows:

Function [value, isterminal, direction] = events(t, y)
  global S;
  value =[y(1) y(1)-S];   % detect value = 0
  isterminal =[1 1];   % stop integration
  direction =[-1 1];   % direction of value change

SIMULATION RESULTS

Run the simulation procedure in Matlab, simulate the charging process from a low pressure gas bottle of volume and pressure are separately 40L and 7MPa to a high pressure bottle of 30L and 12.9MPa. The driven air pressure p_1 is 0.6MPa, the initial temperature is 20℃. We got the curve of the displacement of the piston and pressure of each chamber. The results are shown in Figure 3 and Figure 4.

Figure 3 indicates that the frequency of piston circle is about 1.4 circles per second, and the displacement of piston in each circle is from zero to maximum stroke

and back to zero. On this basis, the consumption of driven air can be obtained.
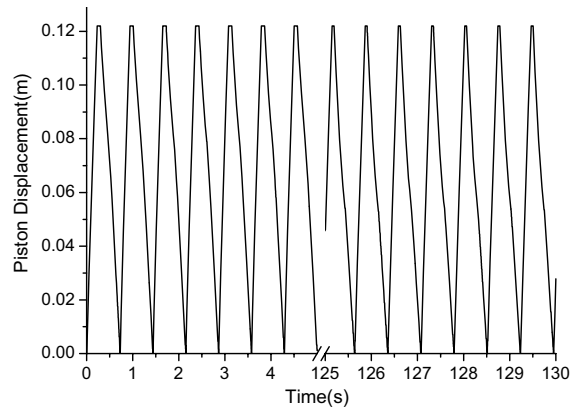

Figure 3 Displacement of piston

Figure 4 shows that the charging time from 12.9MPa to 14MPa is different. The simulation result is 132 seconds, and the experimental result is 140 seconds. There is a good agreement between experimental and simulation results.
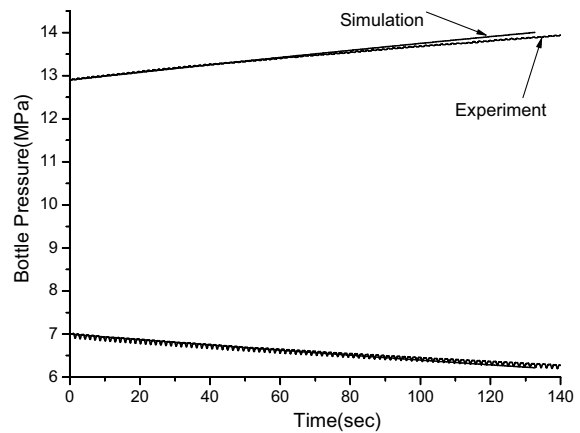

Figure 4 Pressure of two gas bottles

CONCLUSIONS

In this paper, the mathematical model was founded for the course of gas bottle charging, which mainly including the pressure differential equation, piston movement differential equation, as well as temperature and flow rate equation of each chamber. In the simulation process, the problem of reciprocating motion of piston was solved. By comparing with the experiment,

the mathematic model was proved to be able to reflect the work process of gas booster correctly. The error of two results is due to the given parameter values. The research provides theoretical basis for model selection, overall design, and for structure optimization.

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