

Numerical Simulation of Low Temperature on Performance of Pneumatic Piston Motor

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Abstract

To improve working capacity of pneumatic piston motor in very low temperature environment. Based on the thermodynamics analysis, the mathematical model of pneumatic piston motor working process is established in this paper. Based on the model, the effects of the low temperature on the performance of pneumatic piston motor performance is simulated. The results show that the low temperature has some significant effects on performance of pneumatic piston motor. The gas consumption increased by about 40%, effective power and working efficiency decreased, when ambient temperature dropped from 20 °C to -65 °C. Therefore, those results can be taken as important reference for follow-up research and development to improve performance of pneumatic piston motor, which works in very low temperature environment.

Keywords: Pneumatic motor, Performance, Low temperature, Mathematic model

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I. INTRODUCTION

The pneumatic piston motor is an air power device which can turn gas pressure into rotary mechanical energy output. The pneumatic motor has been widely applied in industry with compressed gas as working medium, the working process safety and non-polluting. It can start at full capacity and can be loaded with full work for a long period of time [1]. Its working process has a lot of advantages, such as dustproof, fireproof and explosion prevention. In the higher latitudes, ambient environment temperature is very low in winter. Through the study of pneumatic piston motor work process analysis, the outputs dynamic characteristics and the compressed gas instantaneous change in state law can be derived by mathematic model, which can be taken as important reference for follow-up research and development to improve the performance of pneumatic piston motor at very low temperature environment [2,3].

1.1 Methodology

Pneumatic piston motor outputs the mechanical energy transformed from the compressed gas energy into torque. The change of pressure and temperature is accompanied by the change of the gas in the cylinder [4]. There is a large temperature difference between the gas in cylinder and external environment. Therefore, heat exchange is carried out with the external environment through the cylinder wall of the motor.

1.2 Gas Pressure Energy Analysis

Fig.1 shows the of pressure energy distribution of compressed gas, In the working process of piston pneumatic motor, some energy is converted to mechanical energy, the other part is lost directly.

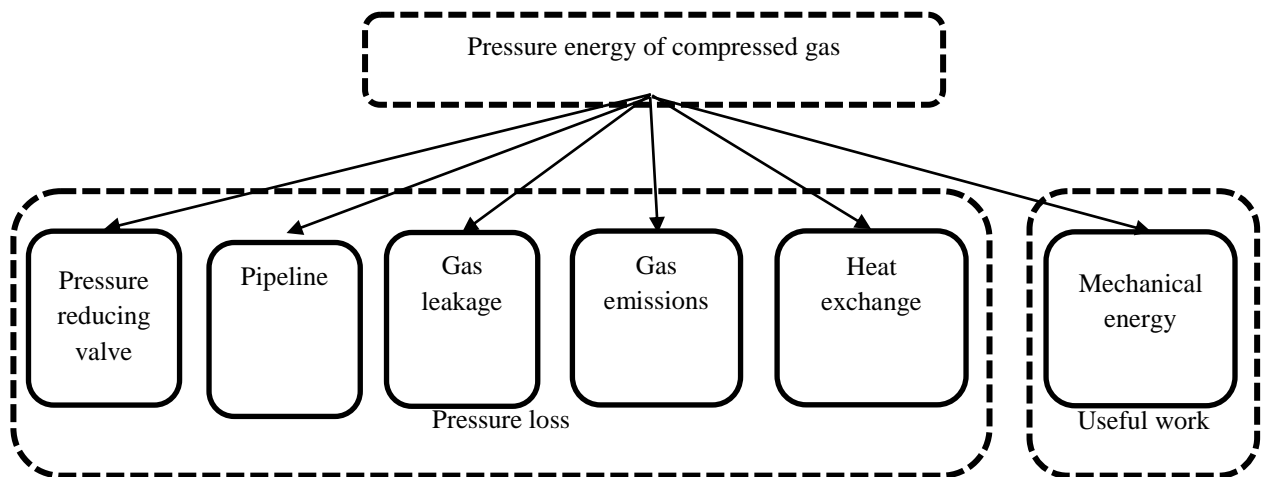


Figure 1. The gas pressure energy distribution

1.3 Thermomechanical Analysis

Fig.2 shows the thermomechanical analysis of the pneumatic piston motor. Take a cylinder as the research object. Establish mathematical model of pneumatic piston motor working process.

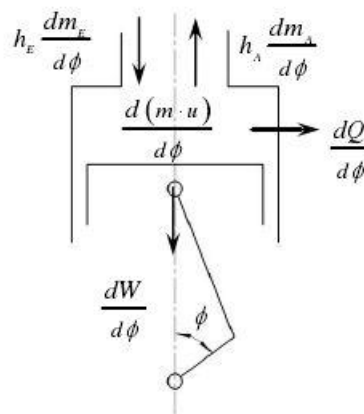


Figure 2. The thermomechanical analysis of the pneumatic piston motor

Therefore, it is necessary to establish a thermodynamic modal, and to analyze the energy efficiency of the pneumatic piston motor. To simplified the theoretical analysis, the following assumption are used:

Air can be regarded as ideal gas and meets ideal gas state equation.

The changes of kinetic and gravitational energy are negligible.

Heat loss and pressure drop in the pipes are negligible.

The transient change of in-cylinder gas conforms to the energy conservation equation.

$$dU = dQ + dW + h_E dm_E + h_A dm_A \quad (1)$$

where U is the system energy, Q is the exchange energy, W is the mechanical energy on the piston, h_E is inlet gas specific enthalpy, m_E is inlet gas mass, h_A is exhaust gas specific enthalpy, m_A is exhaust gas mass.

In general, The specific internal energy of the compressed gas in the cylinder changes simultaneously with the instant mass of gas,

$$\frac{dU}{d\phi} = \frac{d(m \cdot u)}{d\phi} = u \frac{dm}{d\phi} + m \frac{du}{d\phi} \quad (2)$$

Simplify the specific internal energy of the compressed gas down to gas pressure P and generalized gas composition factor α_ϕ . The total differential of u is

$$\frac{dU}{d\phi} = \frac{\partial u}{\partial T} \cdot \frac{dT}{d\phi} + \frac{\partial u}{\partial \alpha_\phi} \frac{d\alpha_\phi}{d\phi} \quad (3)$$

It can be derived,

$$\frac{d(m \cdot u)}{d\phi} = u \cdot \frac{dm}{d\phi} + m \left(\frac{\partial u}{\partial T} \cdot \frac{dT}{d\phi} + \frac{\partial u}{\partial \alpha_\phi} \frac{d\alpha_\phi}{d\phi} \right) \quad (4)$$

Because of $\frac{\partial u}{\partial a_{\varphi}} = 0$, substituting Eq.2 and Eq.4 into Eq.1,

$$\frac{dT}{d\varphi} = \frac{1}{mC_v} \left[\frac{dQ}{d\varphi} + \frac{dW}{d\varphi} + h_E \frac{dm_E}{d\varphi} + h_A \frac{dm_A}{d\varphi} - u \cdot \frac{dm}{d\varphi} \right]. \quad (5)$$

The Exchange Heat Between Cylinder and External Environment

During the running of motor, the heat of in-cylinder gas main come from the heat of the gas itself and external environment. The total exchange heat can be derived:

$$\frac{dQ}{d\varphi} = \frac{1}{\omega} a_W A_W (T_W - T). \quad (6)$$

Where ω is gas transient heat-transfer coefficient, A_W is the total heat-transfer area of cylinder, T_W is external environment temperature, T is the in-cylinder gas transient temperature.

In the working process, because of the transient pressure, transient density and transient flow rate of the in-cylinder gas change with real-time adjusting of the crankshaft rotates. Heat-transfer coefficient can be derived:

$$a_W = 0.1129 D^{-0.2} P^{0.8} V_p^{0.8} T^{-0.594}. \quad (7)$$

Where D is the diameter of cylinder, V_p is piston average speed.

Heat exchange surface area is constantly changing with the rotation of the crankshaft and displacement of the piston, the heat exchange surface area can be derived:

$$A_W = A_p + A_h + \frac{\pi}{2} DS \left[1 - \cos\varphi + \frac{1}{\lambda_s} \left(1 - \sqrt{1 - \lambda_s^2 \sin^2\varphi} \right) \right]. \quad (8)$$

Where A_p is area of the piston head, S is the piston displacement, λ_s is connecting rod length/crank radius ratio.

The Ideal Gas State Equation

Under arbitrary conditions, in-cylinder compressed gas meets the ideal gas state equation.

$$PV = mRT. \quad (9)$$

Where R is gas constant.

Gas Consumption

When the inlet gas expands, expansion ratio $\epsilon = V_2/V_1, P_1 V_1^n = P V_2^n, P_2 V_2^n = P_3 V_1^n$,

$$P' = P_1 \left(\frac{V_1}{V_2} \right)^n = P_1 \frac{1}{\epsilon^n}. \quad (10)$$

$$M = Z V_1 n' \frac{P_1}{T_1} \times 293 = Z V_2 n' \frac{P_1}{\epsilon T_1} \times 293. \quad (11)$$

Where M is gas consumption, V_1 is gas intake volume, T_1 is absolute temperature of the gas.

Considering the leakage, excess volume and throttling pressure drop, the actual gas consumption is:

$$M_g = \mu_1 \mu_2 M. \quad (12)$$

Where μ_1 is leakage and clearance volume impact factor, generally take 1.2~1.6. μ_2 is throttling pressure drop, generally take 0.7~0.8[5].

Circulatory Indicated Work

$$W_i = \int_0^{2\pi} P dV. \quad (13)$$

Where P is in-cylinder gas transient pressure, V is in-cylinder gas transient volume.

Mean Indicated Pressure

$$P_i = \frac{W_i}{V_h} = \frac{W_i}{\pi S D^2 / 4}. \quad (14)$$

Where V_h is the displacement of cylinder, S is throw of a piston, D is the diameter of cylinder.

Mean Active Pressure

$$P_e = \eta_m \cdot P_i. \quad (15)$$

Where η_m is mechanical efficiency.

Mean Indicated Temperature

$$T_i = \frac{1}{2\pi} \int_0^{2\pi} T d\varphi. \quad (16)$$

Where T is in-cylinder gas transient temperature.

Theoretical Power in Gas Adiabatic Expansion Process

$$W_a = RT_1 \frac{(m_{max} - m_{min})}{k-1} \left[1 - \left(\frac{P_0}{P_1} \right)^{\frac{k-1}{k}} \right]. \quad (17)$$

Where R is gas constant, T_1 is intake temperature, P_0 is atmospheric pressure, P_1 is intake gas pressure, K is gas specific heat ratio, m_{max} is the maximum mass of in-cylinder gas, m_{min} is the minimum mass of in-cylinder gas [6].

Working Efficiency

The working efficiency η_e of pneumatic piston motor can be derived:

$$\eta_e = \frac{W_i}{W_a} \eta_m \tag{18}$$

II. RESULT AND DISCUSSION

The results gathered from the simulation are presented and discussed in this section. Based on the above mathematical model of pneumatic piston motor, use the classical Runge-kutta method to calculate the numerical simulation. Table 1 shows the selection of simulation parameter.

Table 1. The basic parameters of the cryogenic temperature pneumatic motor

Items	Number of cylinders	Cylinder diameter [mm]	Connecting rod length [mm]	Crankshaft eccentricity [mm]	Rated Pressure [MPa]
Parameters	5	135	168	38.3	0.8

Fig.3 shows effect of low temperature on gas consumption of pneumatic piston motor. The gas consumption increased by about 40%, when ambient temperature dropped from 20°C to -65°C.

Fig.4 shows effect of low temperature on gas consumption of pneumatic piston motor. Fig.5 shows effect of low temperature on working efficiency of pneumatic piston motor. Both effective power and working efficiency are dropped, when ambient temperature dropped from 20°C to -65°C.

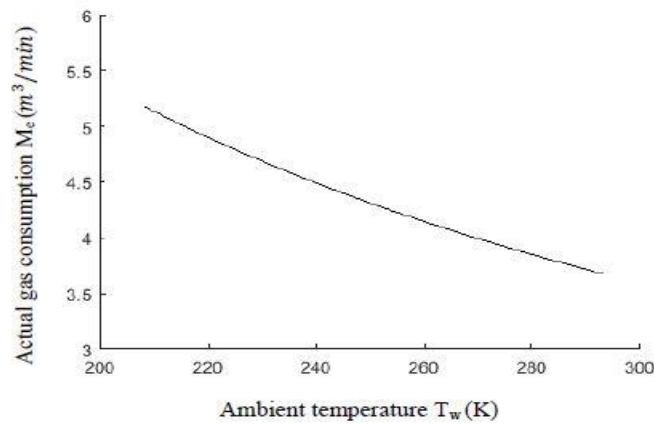


Figure 3. Effect of low temperature on gas consumption of pneumatic piston motor

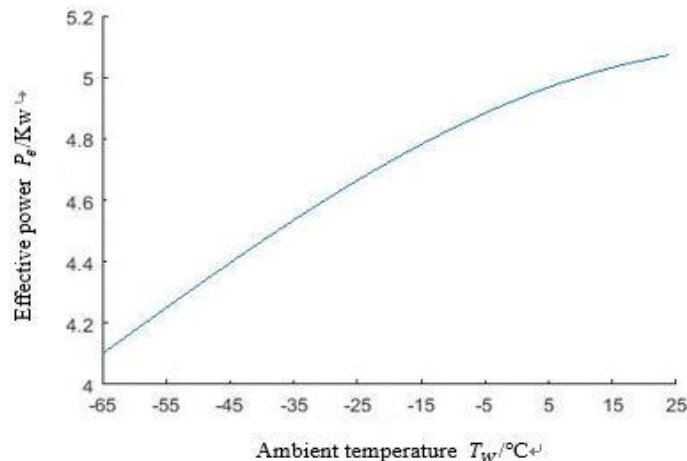


Figure 4. Effect of low temperature on effective power of pneumatic piston motor

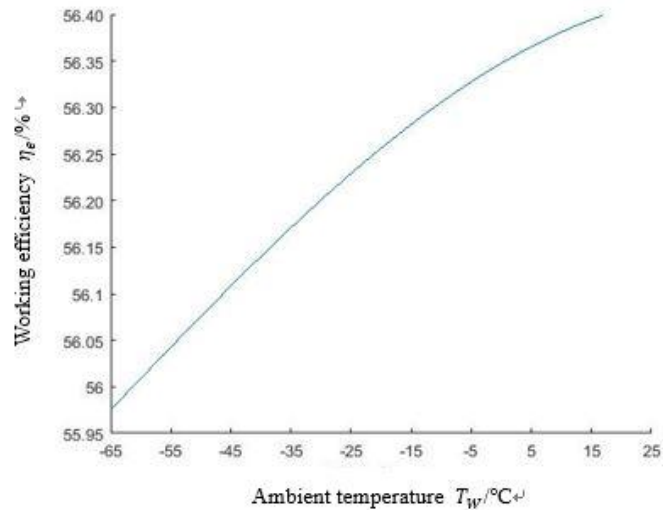


Figure 5. Effect of low temperature on effective power of pneumatic piston motor

III. Conclusion

In this paper, the mathematical model of pneumatic piston motor working process is established. Based on the thermodynamics analysis, the effects of the low temperature on the performance of pneumatic piston motor performance were investigated. The low temperature could increase gas consumption, the effective power and working efficiency of the motor will decrease. Therefore, those results can be taken as important reference for follow-up research and development to improve performance of pneumatic piston motor, which works in very low temperature environment.

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