Key issues in theoretical and functional pneumatic design

Z G Xu1, D Y Yang2, W M Liu1 and T T Liu1

1 Shenzhen Research Institute of Shandong University, 518057, High-tech Zone A301, Virtual University Part, Shenzhen, China.
2 School of Mechanical Eng, Shandong University, 250061, No 17923, Jingshilu, Lixiaqu, Jinan, Shandong, China.

zhgxu@sdu.edu.cn

Abstract. This paper studies the energy release of the pneumatic engine in different thermodynamic processes, the isothermal process is the highest power output process, while adiabatic process is the lowest energy output process, and the energy release of the pneumatic engine is a multi-state thermodynamic process between them. Therefore heat exchanging should be increased between the pneumatic engine and the outer space, the gas expansion process in the cylinder should be as close as possible to the isothermal process. Heat exchange should be increased between the cylinder and the external spaces. Secondly, the fin structure is studied to increase the heat exchanging between the cylinder body and the outside space. The upper part has fin structures and the lower cylinder has no fin structure, this structure improved the working efficiency of pneumatic engine. Finally the cam and the hydraulic bottle of pneumatic engines are designed. Simulation and theoretical calculation are used to the analysis of the whole structure, which lay the foundation for the manufacturing and design of the pneumatic engines.

1. Introduction

In recent years, due to the deterioration of the natural environment, especially the impact of fog and haze, new energy vehicles are becoming more and more concerned. Researchers in Hefei University of China, converted a R715 type diesel engine to a two-stroke pneumatic engine[2]. Also, H Wang, and J Zhou, in the Chinese University of science and technology did the research of heat exchange of the air in the pneumatic engine with the outer-space[3]. W, He in Beijing Industrial University, did the research of the performance of the single-screw pneumatic engine[4]. C, J, Marquand designed a experimental two-stroke eccentric vane-type pneumatic engine. Terry Millers, a French company called MDI etc, have also done many works on pneumatic engine.

2. Working principal for air powered vehicles

The working principle of an air powered engine is similar to that of an internal combustion engine, however, there are differences, the structure is shown in figure1. When compressed air enters the cylinder, the piston moves back and forth under the pushing force of the compressed air, which drives the crankshaft to rotate continuously, to move the car. High pressure gas in compressed air bottle 1
flows into the mechanical valve 2 through the air inlet of the mechanical reversing valve 2, then enter the first cylinder 3 through the first reversing interface. It pushes the piston 3 of the first cylinder 5 downward, drives the crankshaft 8 to rotate [5].

Figure 1. Working principal of air-powered engine.

Crankshaft 8 drives the second cylinder piston upward. Cam 9 reverses valve 2 through the ejector rod 10. The second piston in cylinder discharge the gas in into the atmosphere, through the second reversing interface of the mechanical reversing valve 2. When the first cylinder piston moves down to the lower stop point, the second cylinder piston moves up to the top stop point, cam 9 reverses the mechanical reversing valve 2 through the ejector rod 10.

High pressure gas in compressed air bottle 1 flows into the second cylinder 4, through the mechanical valve 2, pushes the second cylinder piston downwards, to rotate the crankshaft 8. Crankshaft 8 drives the first cylinder piston upwards, Cam 9 Make mechanical reversing valve 2 change direction, through the ejector rod 10.

The pressure/ volume change of the gas in the cylinder is shown in fig 4. During the intake stroke, high pressure gas first enters the cylinder with pressure P1, push the piston down, performs works. When the piston moves to position 3, the mechanical reversing valve stops the inlet air. The cylinder becomes a closed system, the high-pressure gas inside the cylinder expands, pressure energy releases, and pushes the piston downward to continue to work outside.

Figure 2. Gas expansion process P-V diagram. Figure 3. P-V curves of gas in cylinder.

When the piston reaches the bottom dead point, i.e. point 4 in the picture, the mechanical reversing valve controls the cylinder to exhaust, reduced the inner pressure to atmospheric pressure P0, in the meanwhile, the piston moves upward to discharge low-pressure gas in cylinder. The enclosed area by
1-2-3-4-5-1 in the chart is the theoretical work of high pressure gas \( V_0 \), during the intake and exhaust processes, pneumatic engine exchanges the refrigerant with the outside world. In an ideal state, gas pressure has no change, the output function by the cylinder equals to gas technical work \( W_s \) [2]; i.e.

\[
W_s = P_1V_1 - P_0V_2
\]

When the cylinder is a closed system, i.e. the mechanical reversing valve closed completely. Gas expansion performs the external work. The Cylinder output function is the expansion function \( W_v \):

\[
W_v = \int_{V_1}^{V_2} pdV
\]

Power generated by the compressed air \( W \) equals the sum of the technical power and the expansion power.

\[
W = W_s + W_v
\]

3. **High pressure gas design**

The power source of air powered vehicle is the high pressure tank. Because the air powered vehicle is a high-speed moving vehicle, so compared with the ordinary pneumatic equipment, the high pressure tank should be high in pressure, light in weight, good in safety, small in size etc. So steel tank is replaced with aluminum alloys, and is wrapped with glass fibers, which can increase 30% in capacity, reduce 30% in weights. 100% carbon fiber can also be used, so high in pressure and light in weight. This tank equipped with high-pressure gas has been tested under the condition of shooting test, fire test, falling down and explosion test etc.

The heat capacity molar ratio \( K \) of the pneumatic engine gas is, the ratio of \( C_p \) (the molar constant heat capacity of gas), to the \( C_v \) (molar constant heat capacity), i.e.

\[
k = \frac{C_p}{C_v}
\]

Molar heat capacity ratio of monatomic molecular gas:

\[
k = \frac{5}{3}
\]

Molar heat capacity ratio of diatomic molecular gas:

\[
k = \frac{7}{5}
\]

Molar heat capacity ratio of polyatomic molecular gas:

\[
k = \frac{4}{3}
\]
The external work of isothermal expansion has nothing to do with the molar heat capacity ratio of gas. However under the adiabatic expansion condition, the output expansion work is related to the molar heat capacity ratio of gas, i.e.

\[ W_v = \left( \frac{p_1 V_1}{k-1} \right) \left[ 1 - \left( \frac{V_1}{V_2} \right)^{k-1} \right] \]

For the convenience of calculation, the expansion ratio is expressed by e, i.e.

\[ W_v = \left( \frac{p_1 V_1}{k-1} \right) \left[ 1 - e^{1-k} \right] \]

The molar heat capacity of a monatomic molecule is the largest, with the worst expansion effect. The polyatomic molecule is the best in expansion effect, while the diatomic molecule is between them.

4. Cam design

For a four stroke internal combustion engine, for every one work needs two strokes, while for a two stroke internal combustion engine, for every one work needs one stroke. The air powered engine can be re-manufactured by the existing internal combustion engine, the motion law of the cam follower is showing in table 1.

The cam contour for intake and exhaust of internal combustion engine is designed for four stroke gas distribution, cam contour should be redesigned for two stroke gas distribution in order to adapt to the set of air powered engine. Mechanical valve is used in the control of intake and exhaust of the air powered engine, which usually rely on cam, block or other mechanical external forces.

| movement | Shock property | \( v_{\text{max}}/(h\omega/\Phi) \) | \( a_{\text{max}}/(h\omega^2/\Phi^2) \) | \( j_{\text{max}}/(h\omega^3/\Phi^3) \) | application |
|----------|----------------|-------------------------------|---------------------------------|---------------------------------|--------------|
| Constant speed | Rigidity | 1.00 | \( \infty \) | -- | Low speed light load |
| Equal acceleration, deceleration | Flexibility | 2.00 | 4.00 | \( \infty \) | Medium speed light load |
| Cosine acceleration | Flexibility | 1.57 | 4.93 | \( \infty \) | Medium speed, medium load |
| Sinusoidal acceleration | NONE | 2.00 | 6.28 | 39.5 | High speed light load |
| 3-4-5 degree polynomial | NONE | 1.88 | 5.77 | 60.0 | High speed, medium load |

The cam mechanism has the advantages of simple in structure, compact in assembly, reliable in performance etc. The cam contour can be designed to drive the follower accurately to realize various
anticipated movement. Roller type mechanical control valve has a roller at the top of the valve core, the roller has a direct contact to the end of the cam, the roller transfers forces to the core of the cam.

One of the advantages of this roller control is that, it can reduce the lateral force of the cam core, improved the loading conditions between the cam core and the valve body, the life and reliability of the valve is increased. The motion of the follower is decided by the cam contour, i.e. different motion laws of follower require that the cam has different shapes and contours:

Sinusoidal acceleration is selected for the follower motion to meet for the high speed, light load of the mechanical valve to control the air powered engine. The cam contour is designed according to the motion law of the engine follower. The cam contour equation is as the followings. Where, $e$ is the offset , $R_b$ is the basic radius , $R_R$ is the radius of the roller, $s=s(\varphi)$, $s$ is the motion law of the follower.

\[
x_B = (s_0 + s) \sin \varphi + e \cos \varphi \tag{10}
\]

\[
y_B = (s_0 + s) \cos \varphi - e \sin \varphi \tag{11}
\]

Where $s_0$ is:

\[
s_0 = \sqrt{r_b^2 - e^2} \tag{12}
\]

The actual contour curve equation is:

\[
x_A = x_B + r_r \frac{dy_B}{d\varphi} d\varphi \sqrt{\left(\frac{dx_B}{d\varphi}\right)^2 + \left(\frac{dy_B}{d\varphi}\right)^2} \tag{13}
\]

\[
y_A = y_B - r_r \frac{dx_B}{d\varphi} d\varphi \sqrt{\left(\frac{dx_B}{d\varphi}\right)^2 + \left(\frac{dy_B}{d\varphi}\right)^2} \tag{14}
\]

Based on the above formula, the theoretical contour curve equation and the actual contour curve equation can be calculated by using the correlation function in MATLAB. The MATLAB graphical user interface (GUI for short) can be embedded in the written programs, and the running results can also be presented to the operator or customer in a man-machine interactive way. And the results can be data or graphics, and the code can also be invisible. MATLAB/GUI is composed of the cursor, window, menu, button, text and other objects (Object) consisting of a user interface. These graphical objects can be activated through mouse or keyboard operation, so as to control some parameters in the program, for the ultimate calculation, drawing and other functionaries.

5. Cylinder design

The different thermodynamic energy release properties have been studied for the pneumatic engine, the isothermal process is the highest power output expansion thermodynamic process, while the
adiabatic process is the lowest power output process, and the pneumatic engine is polymorphic process between them.

The heat exchanging should be increased for the pneumatic engine with the external space, and the gas expansion process in the cylinder should be as close as possible to the isothermal thermodynamic process, where the working efficiency of the pneumatic engine can be effectively improved. The outer part of the cylinder should be heated to increase the temperature or absorb energy from the outer space.

“Temperature increasing” effects have many examples, i.e. electromagnetic induction effect, dielectric effect, Joule-Lenz effect, arc discharge effect, “absorption” effect, emission-focusing effect, thermal radiation effect, Perle effect, hot electron emission effect, Thomson effect and thermo-electric phenomena etc.

From the above effects, "absorption" effect is specified. “Absorption” effect refers to the process of energy absorption of one material from the other objects or processes etc. There are many "absorption" effects, i.e. heat sink, heat exchanger, noise absorption, X-ray absorption etc, which can be combined with the actual situation of the cylinder. The fin structure is combined with the heat exchanger to complete the effect of “temperature increasing”. The actual structure corresponding to the heat sink is the fin, which can appropriately increase the heat transfer effect between the cylinder body and the outside. The preliminary design of the cylinder is as in figure 4 (a).

When high pressured air enters the cylinder, the gas in the cylinder are compressed, and the piston did not immediately move down, which results in the gas temperature in the cylinder rises rapidly. If heat exchanging is increased, the energy in the cylinder will loss.

So when the cylinder fin need to absorb heat from the out space, it will also cause heat loss when the gas temperature is higher than the outside. So from the physical conflict in the TRIZ theory, the fins should be exit, and not be exit. The solution are as the follows: separation in space, separation in time, and conditional separation.

In this paper, the inventive principle of space separation is utilized. According to the innovative idea given by the above principle, a cylinder with no fin at the upper part of the outer wall of the cylinder is designed as in figure 4 (b). When the pneumatic engine works continuously, the gas in the cylinder experienced a poly-morphism process, the gas temperature is lower than the outside space, so extra heat needs to be absorbed from the outside mainly by convection and heat transferring. A heat exchanging simulation is carried out under the following conditions. The cylinder material is Aluminum Alloy, its thermal conductivity is λ=204W/(m·K)/ (M - K), and the heat transferring
The convection coefficient is 25 W/(m² - K), the ambient temperature is 293 K. The simulation result of heat transferring of the finned cylinder is shown in figure 4(c).

From the simulation result, it could be found that, the gas temperature is still very low, due to the reason that the heat transferring effect is poor, because the fin structure is small in size for the sake of compact structure. The compressed air consume too much energy in the work process due to heat transferring. In the practical work, the engine has a larger power output, the temperature of the environment is not high enough, so the fin structure has limited effects, so other heat exchanging methods must be considered.

6. Conclusions
The air powered vehicle can be used in the short distance transport to meet the urgent need of more serious air pollution in the city. In the first-order phase transition, compressed air is used as the power source to drive the vehicle. Compressed air is used to push the piston and the crankshaft to move the vehicle to achieve zero emissions. Some key components of air powered cars have been designed in this paper. The theoretical and actual cam profile have been drawn by MATLAB. Heat exchanging effect have been improved by using TRIZ theory.

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