Substance-Field Model for Functional Pneumatic Design

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Abstract. The Substance-field analysis is put forward. The functional analysis method is studied to find out the problem, and an improved algorithm is put forward. The internal combustion engine is taken as an example, the harmful function is recognized, and is improved, i.e, high pressure gas is introduced to remove polluted air. The working principle of pneumatic engine is described, the thermodynamic engineering is analyzed, the energy release amounts are analyzed in the isothermal, polymorphism and adiabatic processes. It is concluded that, the isothermal process releases the most energy than the others. The expansion process of the pneumatic engine should be as close as possible to the isothermal process.

1. Introduction
With the increasingly serious environmental problems, the transformation and upgrading of China's auto industry is becoming more and more urgent. 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. Y. Shimomura, 1998 [1] suggested a functional body, functional modification and target entity building method, a FBS/M graph is to describe a function-behavior-form model, and to describe the design intent. J. S. Gero, 2002, [2] put forward 8 extended original frame models to rebuild the functional model. S. B. Tor, 2002, [3] put forward the B-FES model based on the FEBS, three levels of function, behavior and environment are put forward. University of Washington developed a liquid nitrogen powered vehicle prototype[4]. Their energy source is liquid nitrogen. University of North Texas did the study of liquid nitrogen powered vehicle. A team by Dr. Carfós Ordonez,[5] uses liquid nitrogen as power source, to drive vane type pneumatic motor. Tsu-Chin Tsai [6] from the University of California, Los Angeles, lead a R & D team, funded by Ford Motor Company. developed a hybrid power engine with no cam shaft. In China, Liu Hao of Zhejiang University studied the working principle of a pneumatic engine, The characteristics of energy release of high pressure air under different conditions are analyzed, A number of experiments have been carried out on the pneumatic engine, It provides the theoretical basis and experimental data for the design and manufacture of pneumatic engine.

2. Heat exchanging for air powered vehicles
In the TRIZ based functional analysis, two kinds of material and a field are used to represent the function. In order to make the functional model more understandable, the field is replaced by "action". The standard function is to determine the designer based on the user's current or potential needs; harmful effects are the adverse effects on the whole system, which should be eliminated as far as possible. Any component in the system has its functional uses, to complete one or more functions.
Through functional analysis, functions of each component are recognized, problems with the elements are recognized, thereby the system is improved. The establishment of functional model is composed of the following two steps: Recognizing component, product, and super-system;

Recognizing the relationship among component, product, and super-system.

**Figure 1.** Combustion engine function model **Figure 2.** Function model of air powered vehicle

The use of internal combustion engines is the "explosion" effect, high pressure gas generated by explosion of air and fuel to drive cylinder; the use of "magnetic" effect and electromagnetic induction can be made of electric vehicles; the steam engine uses a "thermal expansion" effect. It can be seen that different effects can be used to design different products.

The most harmful effect of an internal combustion engine is air pollution, its biggest function is to drive the cylinder an the car. The key word for searching is in a "Verb + noun" format, in the paper, "produce force" is used. In order to simplify the engine, and do not pollute the air, first order phase transition effect is utilized. When the phase change occurs, there are volume changes at the same time, having the same amount of heat absorption or releasing. Combined with the actual situation in the project, the production of compressed air is utilized, the engine piston is driven by compressed air. Its functional model is shown in Figure2.

**3. Working principle of air powered engine**

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 Figure3. 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 though the first reversing interface. It pushes the piston 3 of the first cylinder 5 downward, drives the crankshaft 8 to rotate. 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 first cylinder piston discharges the gas in the first cylinder 3 into the atmosphere, through the mechanical valve 2. A work cycle finished. In order to make the engine more stable, four or six cylinders could be set, which can be in a straight line, “V” or “asterisk” shaped arrangement. The air powered engine has the following two strokes. Intake stroke, in this process, high pressure gas enters the cylinder from the gas tank, expansion works, which is equivalent to the internal combustion engine intake stroke and power stroke; Exhaust stroke, in this process, low pressure gas is discharged from cylinder, which is equivalent to the compression stroke and exhaust stroke of an internal combustion engine.

Figure 3. Schematic diagram of 4-air powered engine

The pressure/volume change of the gas in the cylinder is shown in Figure 4. During the intake stroke, high pressure gas first enters the cylinder with pressure \( P_1 \), 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 4. gas expansion process

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 \( P_0 \), in the mean while, 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 \( W_0 \), during intake and exhaust, pneumatic engine exchange 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 \( W_s \); 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 $W_v$:

$$W_v = \int_{V_1}^{V_2} pdv$$  \hspace{1cm} (2)

Power generated by the compressed air $W$ equals the sum of the technical power and the expansion power.

$$W = W_s + W_v$$  \hspace{1cm} (3)

**Thermodynamic analysis of air powered engine**

When the gas varies in different conditions, the thermodynamic processes are different. Under the same pressure and expansion ratio, different thermodynamic processes affect the energy efficiency of an air powered engine. In the process of high pressure, gas expanded from $V_1$ to $V_2$, the thermodynamic processes are different, the expansion work of the high-pressure gas is also different. The P-V curves of the high-pressure gas through different thermodynamic processes are shown in Figure 5. In this paper, three cases are discussed in the thermodynamic process of high pressure gas expansion.

$$\frac{P'}{P_1} = \left(\frac{V_1}{V}\right)^k$$  \hspace{1cm} (4)

1. Heat insulation process, as shown in the Figure5, curve 3-4'. In this process, gas does not absorb ambient heat, gas pressure decreased from $P_1$ to $P_2''$, the gas pressure $P'$ decreases rapidly with the change of volume, therefore, the external output expansion power of is less, equals to the area of 0-3-4 (-0) of the dotted line and the axis. In this process, the relationship between the gas pressure and volume is as follows. Where, $K$ is the molar heat capacity ratio, the formula (4) is added to the formula (2) to obtain the expansion work of the adiabatic process:

$$W_v = \left(\frac{P'}{k-1}\right) = \left(\frac{V}{V}\right)^k [1 - \left(\frac{V}{V}\right)^{k-1}]$$  \hspace{1cm} (5)

2. Isothermal process, as shown in figure 3-4. In this process, high pressure gas absorbs ambient heat, gas pressure decreased from $P_1$ to $P_2''$, the gas pressure $P''$ decreases gradually with the volume change, therefore, the expansion of external output power is larger, i.e. the area of 0-3-4'-4''-0, the circumference of the dotted line and the axis. In this process, the equation of the gas pressure and volume are as follows.

$$\frac{P''}{P_1} = \left(\frac{V_1}{V}\right)^n$$  \hspace{1cm} (6)

The isothermal output power can be obtained by putting formula (4-6) into the formula (7).

$$W_v = P'V_1 \ln(\frac{V_1}{V_2})$$  \hspace{1cm} (7)

3. Polymorphic process, in the actual operation of the pneumatic engine, affected by various external conditions, the heat absorbed from the environment is between adiabatic and isothermal processes. Gas pressure decreased from $P_1$ to $P_2$, as shown in Figure 3. At this time the output power of mechanical work is also between the above two conditions. i.e. the area of 0-3-4-4'-0, the fine solid line and axis. In this process, the equation between the gas pressure and volume is as follows.

$$\frac{P}{P_1} = \left(\frac{V_1}{V}\right)^n$$  \hspace{1cm} (8)

Where, $n$ is the polymorphism index, putting the formula (8) into the formula (8), the output expansion power for polymorphic process is obtained.
\[ W_v = \frac{PV}{n-1} \left[ 1 - \left( \frac{V_1}{V_2} \right)^{n-1} \right] \]  

(9)

In order to compare the differences of energy output in different thermodynamic processes, the ratio of the output to the mechanical work of isothermal and adiabatic processes is set to \( Zw_1 \). So,

\[ Z_{w_1} = \frac{(k-1) \ln \left( \frac{V_1}{V_2} \right)}{1 - \left( \frac{V_1}{V_2} \right)^{k-1}} \]  

(10)

\( Zw_2 \) is set as the ratio of the output power of the polymorphic process and adiabatic process. So,

\[ Z_{w_2} = \frac{(k-1)(1 - \left( \frac{V_1}{V_2} \right)^{n-1})}{(n-1)(1 - \left( \frac{V_1}{V_2} \right)^{k-1})} \]  

(11)

In the normal working of the engine, the total cylinder volume and the air intake are constant. In the process of gas expansion, the polymorphism index \( n \), changes with the condition of gas and external environment. Because the volume expansion ratio is a fixed value, the formula is simplified as the follows,

\[ e = \frac{V_2}{V_1} \]  

(12)

So, the calculation of \( Zw_1, Zw_2 \) are as the follows.

\[ Z_{w_1} = \frac{(k-1) \ln(e)}{1 - e^{(k-1)}} \]  

(13)

In the above three thermodynamic processes, due to the absorption of energy from the outside world, therefore, the expansion process releases the most energy.

\[ Z_{w_2} = \frac{(k-1)(1 - e^{(n-1)})}{(n-1)(1 - e^{(k-1)})} \]  

(14)

The following table lists the energy released by gas at different expansion ratios. From table 1, it could be found that, increase the heat exchange between the pneumatic engine and the outside air, make the expansion of the high pressure gas in cylinder approximately equals to the isothermal process.

| Expansion ratio | 10   | 20   | 30   |
|----------------|------|------|------|
| When the polytropic index is 1.2, the surplus expansion power issued by the polymorphic process than that of the adiabatic processes | 22.63% | 29.09% | 32.76% |
| the surplus expansion power issued by the isothermal process than that of the adiabatic processes | 53.02% | 71.6% | 82.99% |

4. Conclusions

When solving the practical problems using sub-F model, first of all, it is necessary to analyze the improved technology system, find out the elements and their relationships, then the sub-F model is established. The transformed system consists of 3 basic elements and two material and field elements, according to the completeness of the three elements, four categories are classified, i.e. ideal sub-F model, incomplete sub-F model, sub-F model with insufficient effect and the harmful sub-F model. In this paper, the function model of the internal combustion engine is established. The harmful function is recognized, and the cutting method is used to improve, i.e. high pressure gas with pollution are removed. Use high pressure air as an energy source to drive a car, the working principle of pneumatic...
engine is described, the thermodynamic engineering properties are analyzed, energy release under different conditions are compared, i.e. isothermal process, polymorphic process, and adiabatic process. It could be concluded that, the isothermal process releases the most energy, the expansion process of the pneumatic engine should be as close as possible to the isothermal process.

Acknowledgment
The above-mentioned research work is supported by the Science, Technology and Innovation Commission of Shenzhen Municipality, JCYJ20160510165328965 and the Chinese NSFC, 61272017, P.R. China.

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