Thermodynamic modeling and simulation of working process of high efficiency two-stroke engine

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Abstract. In this paper, the thermodynamic modeling and simulation of high-efficiency two-stroke engine are studied. Based on the assumptions of uniform distribution of working fluid, adiabatic process and complete combustion, key parameters such as initial volume and compression ratio are set, and the model is established according to the ideal gas law. The model includes energy and mass conservation equations and state equations, and is used to describe the thermodynamic behavior of the engine. Using MATLAB/Simulink platform, the influence on performance was evaluated by adjusting the parameters such as fuel injection time and quantity, inlet size and combustion chamber shape. The results show that optimizing fuel injection strategy can balance power output and fuel economy, increasing inlet size can improve charging efficiency, and improving combustion chamber shape is beneficial to enhance flame propagation and combustion stability. The performance of the engine under different working conditions is analyzed, and the design optimization suggestions are put forward accordingly, aiming at improving the engine performance in an all-round way and providing theoretical and practical guidance for the design of high-efficiency and environment-friendly two-stroke engine.

Keywords: two-stroke engine, Thermodynamic modeling, simulation, high efficiency.

1. Introduction

It is particularly important to improve the efficiency of power machinery, especially engines. Two-stroke engine, as an important power equipment, is widely used in various vehicles and industrial machinery. However, the efficiency and emission of the traditional two-stroke engine still need to be improved, which urges us to study its working process in depth and seek ways to optimize its performance [1-2]. In this study, the working process of high-efficiency two-stroke engine is deeply explored by establishing accurate thermodynamic model and detailed simulation analysis. Through this research, we can not only reveal the key influencing factors of engine performance, but also provide scientific theoretical support and practical guidance for the design and optimization of efficient and environmentally friendly two-stroke engine.

2. Thermodynamic modeling

2.1. Model hypothesis

According to the working characteristics of two-stroke engine, the following reasonable assumptions are made [3-5]: It is assumed that the working medium in the cylinder, that is, the mixture of air and fuel, can be evenly distributed in the whole cylinder volume at any time, which means that the temperature, pressure and composition of the working medium are uniform; Considering the energy conversion efficiency, assuming that there is no heat exchange between the cylinder wall and the outside, the compression and expansion processes of the engine can be regarded as adiabatic processes; For the combustion stage, it is assumed that the fuel can be burned immediately and completely, producing carbon dioxide and water vapor as combustion products, without considering any incomplete combustion and the formation of emissions due to insufficient combustion.

Follow the ideal gas law, namely:

$$PV = nRT \tag{1}$$

Where P is the pressure, V is the volume, n is the number of moles, R is the ideal gas constant and T is the absolute temperature.

2.2. Key parameter setting

The initial volume (that is, the volume at the end of scavenging) V_1 depends on the design of the engine, and its range is between 0.1 and 1.0 liters; The volume V_2 at the end of compression is calculated by the compression ratio, and the calculation formula is $V_2=V_1/\gamma$, where the compression ratio γ is between 5 and 20 [6].

The fuel injection quantity is determined according to the circulating fuel supply m_f and estimated according to the empirical formula, such as: m_f = power (kW)× fuel consumption rate (g/kWh)/ speed (rpm)×60.

The initial temperature is T_1 ambient temperature, about 298 K (25°C). The initial pressure P_1 is set according to the intake conditions, which is close to atmospheric pressure, about 101.3 kPa.

2.3. Establishment of mathematical equation

Based on the first law (conservation of energy) and the second law (entropy increasing principle) of thermodynamics, the following equations are established:

Energy conservation equation:

$$\Delta U = Q - W \tag{2}$$

Where ΔU is the internal energy change of the system, Q is the heat exchange ($Q = 0$ under adiabatic conditions), and W is the work done by the outside to the system. For the compression and expansion process, it can be further expressed as:

$$m(u_2 - u_1) = -P_1 V_1 \ln\left(\frac{V_2}{V_1}\right) \tag{3}$$

Where, m is the mass of working medium, u is the specific internal energy, and subscripts 1 and 2 respectively indicate the state at the beginning and end of the process.

Mass conservation equation:

$$m = m_{air} + m_f \tag{4}$$

Where m_{air} is the intake air mass and m_f is the fuel mass.

Equation of state (ideal gas equation):

$$\begin{aligned} P_1V_1 &= n_1RT_1 \\ P_2V_2 &= n_2RT_2 \end{aligned} \tag{5}$$

Where n is the number of moles and subscripts 1 and 2 correspond to different states respectively. In the combustion process, the change of gas composition before and after chemical reaction is considered.

Combustion exothermic equation:

Assuming complete combustion, the released heat Q_{comb} can be calculated from the fuel low calorific value LHV:

$$Q_{comb} = m_f \times LHV \tag{6}$$

Using the conservation of energy and the equation of state to solve the temperature change simultaneously, such as the compressed temperature T_2:

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{\frac{R}{c_v - R}} \tag{7}$$

Where c_v is the specific heat capacity of constant volume.

3. Simulation analysis and discussion

3.1. Introduction of simulation platform

In this study, MATLAB/Simulink is used as the simulation platform, which is a powerful numerical calculation and visualization software, especially suitable for modeling, simulation and analysis of complex systems. MATLAB provides a rich toolbox and function library, which can efficiently handle mathematical operations, data analysis and graphic display. Simulink, on the other hand, through modular design, allows users to build a system model in a graphical way and carry out simulation analysis of dynamic systems. In the aspect of engine performance analysis, MATLAB/Simulink provides a special engine modeling toolbox to support the simulation of combustion process, thermodynamic cycle, fluid dynamics and other aspects, which is very suitable for the thermodynamic modeling and simulation of the working process of two-stroke engine in this study.

3.2. Simulation experiment design

The initial volume V_1 is set to 0.5 liters. The compression ratio γ is set to 10. The volume V_2 at the end of compression is calculated, that is, $V_2 = \frac{0.5}{10} = 0.05$ liters. For the fuel injection quantity m_f, assume that the engine power is 10 kW, the fuel consumption rate is 250 g/kWh, and the rotation speed is 3000 rpm, then $m_f = \frac{10 \times 250}{3000 \times 60} = 0.014$ kg/ cycle. The initial temperature T_1 is set to 298 K. The initial pressure P_1 is set to 101.3 kPa.

Adjust the fuel injection time (before TDC, TDC or BDC) and injection quantity (0.01 kg/ cycle, 0.015 kg/ cycle), and record the combustion efficiency, power output and emission characteristics under various combinations.

By changing the inlet length (50 mm, 75 mm, 100 mm), diameter (25 mm, 30 mm, 35 mm) and the opening and closing timing of the valve, the influence on the charging efficiency, scavenging effect and power loss was evaluated.

Simulate the influence of different combustion chambers (spherical, ellipsoidal and conical) on flame propagation speed, combustion stability and heat loss, and optimize the combustion chamber design.

Simulation tests were carried out under different working conditions, including load from 25% to 100% of rated load, speed from 2000 rpm to 3500 rpm and ambient temperature changes (-10°C, 25°C, 40°C), corresponding power output, fuel consumption rate and exhaust temperature were recorded, and adaptability and performance stability were evaluated.

3.3. Results analysis and discussion

As can be seen from Figure 1, when the fuel injection timing is at a certain angle (-30 degrees to -10 degrees) before the top dead center, with the delay of the injection timing, the fuel consumption rate gradually decreases and reaches the lowest value near the top dead center. This is because proper early injection can make fuel and air have more sufficient time to mix and form a more uniform mixture, thus improving combustion efficiency and reducing fuel consumption. However, when the injection time continues to be delayed to the top dead center, the fuel consumption rate begins to rise, which may be because the fuel mixing is uneven and the combustion is incomplete due to the late injection, thus increasing the fuel consumption. With the increase of fuel injection quantity, the power output of the engine first increases and then decreases, and there is an optimal injection quantity to make the power output reach the maximum. This is because when the injection quantity is too small, the mixture is too thin and the combustion is incomplete, resulting in insufficient power output; When the injection quantity is too large, the mixture is too rich, which will also lead to incomplete combustion, and at the same time increase the burden of the engine and reduce the power output. Therefore, in practical application, it is necessary to find the best fuel injection quantity to achieve the best balance between power output and fuel economy.

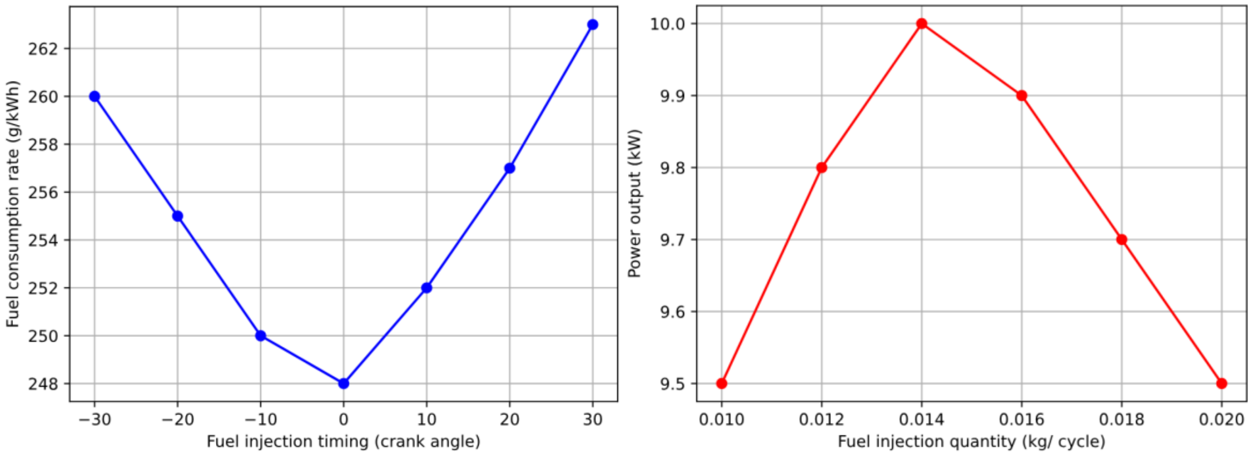

Figure 1. The variation of fuel consumption rate with injection time and power output with injection quantity

With the increase of inlet length from 50mm to 100mm and diameter from 25mm to 35mm, the inflation efficiency is improved. For example, the inflation efficiency of Scheme 3 (100mm in length and 35mm in diameter) is 82.345%, which is better than that of Scheme 1 (50mm in length and 25mm in diameter) by 78.123%. This shows that increasing the inlet size can reduce the inlet resistance and improve the inflation efficiency. Similarly, under the condition of keeping the design of the intake and exhaust system unchanged, different combustion chamber shapes significantly affect the combustion efficiency. Ellipsoidal combustion chamber performs better than spherical combustion chamber in schemes 1, 4 and 5, while conical combustion chamber shows the highest combustion efficiency in schemes 3 and 6. Optimizing the shape of combustion chamber is helpful to enhance flame propagation and combustion stability. On the whole, Scheme 3 (length 100mm, diameter 35mm, conical combustion chamber) is excellent in terms of charging efficiency, combustion efficiency, power output (10.123kW) and fuel consumption rate (250.789g/kWh), which is more efficient and lower in fuel consumption than other schemes. Scheme 2 (inlet length 75mm, diameter 30mm, ellipsoidal combustion chamber) shows excellent charging efficiency and combustion efficiency, and its power output is close to the optimal level; Schemes 4 and 5 show that the engine performance can be effectively improved by changing the shape of the combustion chamber even if the length or diameter of the intake port remains unchanged. In addition, scheme 6 (inlet length 50mm, diameter 35mm, conical combustion chamber) has a shorter inlet length, but its performance exceeds some other design schemes because of the larger diameter and the application of conical combustion chamber. The significant effects of different intake and exhaust system designs and combustion chamber shape combinations on engine performance indicators are shown in Table 1.

Table 1. Performance indicators under different schemes

plan	Inlet length (mm)	Inlet diameter (mm)	Inflating efficiency (%)	Combustion chamber shape	Combustion efficiency (%)	Power output (kW)	Fuel consumption rate (g/kWh)
1	50	25	78.123	sphericity	92.456	9.870	255.123
2	75	30	80.567	spheroidicity	93.789	10.012	252.456
3	100	35	82.345	cone	94.678	10.123	250.789
4	75	25	79.234	sphericity	92.890	9.934	254.321
5	100	25	78.678	spheroidicity	93.123	9.956	253.678
6	50	35	81.012	cone	94.234	10.078	251.567

Figure 2 reveals the spatial distribution characteristics of temperature and pressure in the internal working state of the engine. It can be seen from the temperature nephogram that the central area inside the engine presents the highest temperature value, which indicates that the fuel is ignited here at the end of the compression stroke and at the beginning of combustion, generating a lot of heat and forming a core high temperature area. With moving outward from the center, the temperature shows an obvious downward trend. This is because the heat energy diffuses to the surrounding lower temperature area by conduction and radiation, resulting in a relatively lower temperature at the edge. Similarly, there is a high-pressure area near the geometric center of the engine, because the gas generated in the combustion process expands rapidly, which makes the local pressure increase sharply. Similar to the temperature distribution, the pressure decreases with the distance from the center. This reflects the process that the combusted gas diffuses to the external space along the cylinder wall with the help of piston movement and crankshaft rotation.

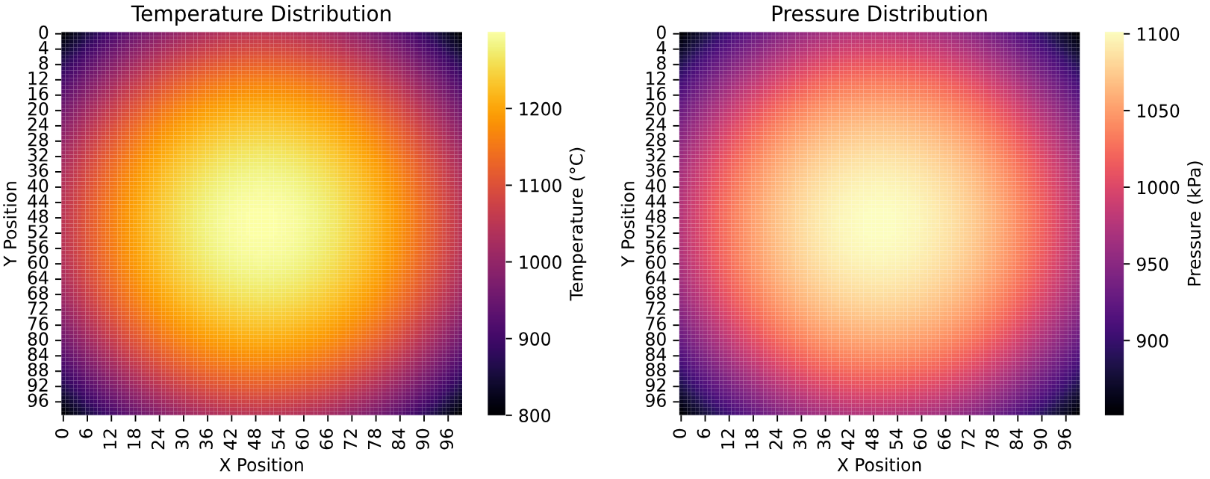

Figure 2. Distribution of internal temperature and pressure parameters of engine

The central area is both a high temperature and a high-pressure area, which embodies the core of the engine working principle-promoting mechanical movement through the energy released by fuel combustion. Higher central temperature is helpful to improve thermal efficiency, but it also brings thermal stress challenges; Reasonable pressure distribution is beneficial to balance the engine load and avoid local overload.

Based on the comprehensive simulation results, the following optimization suggestions are put forward: further optimizing the fuel injection strategy, combining with the improvement of intake and exhaust system and combustion chamber design, and considering the adoption of advanced combustion control technology, such as the optimization of electronic control unit (ECU), in order to realize the overall improvement of engine performance.

4. Conclusion

In this study, the working process of an efficient two-stroke engine is deeply discussed by establishing and simulating its thermodynamic model. It is found that the performance of the engine can be significantly improved by optimizing the fuel injection strategy and improving the intake and exhaust system and combustion chamber design. In addition, adopting advanced combustion control technology, such as the optimization of electronic control unit (ECU), is expected to further improve the engine performance. These findings provide important theoretical support and practical guidance for the design and optimization of efficient and environmentally friendly two-stroke engines.

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