Applied Energy 211 (2018) 921–928

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Study on adaptive behavior and mechanism of compression ratio (or piston motion profile) for combustion parameters in hydraulic free piston engine

Heming Geng[a], Yang Wang[a,*], Xudong Zhen[b], Yu Liu[a], Zhiyong Li[a]

[a] State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China
[b] School of Automobile and Transportation, Tianjin University of Technology and Education, Tianjin 300222, China

HIGHLIGHTS

- The HFPE CR is self-adaptive for the change of combustion parameters.
- The self-adaptive adjustment can avoid knocking or post-combustion.
- The self-adaptive adjustment can extend the operation range of the HCCI combustion.
- The self-adaptive features are analyzed by dynamic calculations and a prototype test.
- A glow plug was used to assist the ignition of HCCI combustion in a HFPE.

ARTICLE INFO

Keywords:
HFPE
Compression ratio
Combustion parameters
Piston motion profile
HCCI
Self-adaptive features

ABSTRACT

The Hydraulic Free Piston Engine (HFPE) piston motion profile is controlled by the composite force of the in-cylinder gas and hydraulic fluid. Based on the analysis of HFPE piston motion by dynamic calculations, it is found that the piston motion profile and compression ratio (CR) are self-adaptive for the variation of combustion parameters. As the combustion timing is advanced, the piston commutation time is advanced, and the CR is decreased. Further, the existence of this self-adaptive features are demonstrated by a prototype test of HFPE, and it also proves that HFPE has self-adaptive features for the variation of mixture concentration. The self-adaptive features can make HFPE effectively avoid the phenomenon of knocking or post-combustion, make it stable of the maximum in-cylinder gas pressure and maximum value of heat release rate, reduce the loss of indicated work, and keep the output power relatively stable.

1. Introduction

Homogeneous charge compression ignition (HCCI) is an advanced combustion technology which can get high efficiency and create less pollution [1]. However, it has a challenge of the absence of direct control over combustion, as combustion is not initiated by a spark or injection. The control flexibility and accuracy of the combustion timing and combustion rate are relatively low [2,3]. If the combustion timing is too advanced, it will lead to rough work, even knocking. If the combustion timing is too delay, it will cause a post-combustion, even a flameout [4–7]. This causes the HCCI combustion to a large extent to have a narrow operating region, and it is difficult to switch into the traditional combustion mode, or vice versa [8], thus hindering the practical application of this clean and efficient combustion method [9–12].

Hydraulic free-piston engine (HFPE) is a new type of power unit in which the combustion piston is directly coupled to hydraulic pump. It is a linear internal combustion engine. The energy is stored and transferred by hydraulic oil pressure, and ultimately output the power through hydraulic motor or other institutions, which can be off from the engine load. In addition, different HFPE operating frequencies can also be used to meet different power requirements for the engine. The piston motion profile is determined by force generated by the in-cylinder gas and hydraulic fluid in the plunger chamber. Thus it has advantages of a variable CR and less heat loss near the top dead center [13–15]. However, it has some disadvantages, for instance, the constant volume of the combustion process is low, as the piston near the top dead center residence time is short [16,17].

Once HCCI combustion mode is used on the HFPE, the characteristic of fast heat release can make up the defects of HFPE in piston motion profile [8,18–23]. Furthermore, it is a valuable research to use the unique piston motion profile of HFPE [18,24,25] to solve HCCI

---

[*] Corresponding author.
E-mail address: wang_yang@tju.edu.cn (Y. Wang).

https://doi.org/10.1016/j.apenergy.2017.11.100
Received 11 October 2017; Received in revised form 22 November 2017; Accepted 27 November 2017

modeling problem of the fluctuation and uncertainty of combustion state parameters aroused by the indirect control.

Jia et al. [26] studied the disturbance analysis of a free-piston engine generator using a validated fast-response numerical model. The result indicated that the injected fuel amount could affect the target TDC. Li et al. [27] presented a parametric study of an FPLE under the effects of various intake pressures, moving masses, ignition positions, and resistance loads. They found that the maximum piston stroke could easily be changed by adjusting the ignition positions. Goldsborough and Blarigan [28] used a zero-dimensional thermodynamic model of a dual-piston FPLE to analyze the steady-state operation of hydrogen-fueled HCCI at a high CR (30:1) and low equivalence ratio. The simulation results indicated that a variable operating CR particularly dependent on equivalence ratio. In summary, in the HFPE, the injected fuel amount, ignition position and other factors will affect the compression ratio (piston motion profile). In this regard, only a small number of researchers involved, and there is no in-depth study of these phenomena.

In recent years, some researchers have proposed glow plug assisted compression ignition to optimize HCCI combustion. Houdyschell [29] investigated the cold start of a diesel two-stroke linear engine. The results showed that cylinders equipped with glow plugs can aid the cold start of the engine. Ma et al. [30] investigated the combustion in a small homogeneous charge compression assisted ignition engine. It indicated that compared with the ‘cold’ glow plug, ‘hot’ glow plug assisted combustion can effectively reduce cycle-to-cycle variations. Yao et al. [31] analyzed glow plug assisted combustion on a four-cylinder compression ignition (CI) engine fueled with dieseline. It is found that glow plug assisted combustion can avoid misfire at low load conditions and play a role in triggering the auto-ignition of the pre-mixture. It can be seen from the above analyses that glow plug assisted compression ignition can optimize HCCI combustion. However, no research was found that a glow plug was used to assist the ignition of HCCI combustion in a HFPE.

In this paper, a kinematic simulation calculation of the HFPE piston motion profile is established. The coupling relationship between the piston motion profile and combustion timing is revealed. Then, based on the adjustment of the HCCI combustion timing and the change of the mixture concentration, the coupling relationship between the HFPE piston motion profile and the combustion timing is studied, as well as the cumulative heat release. The self-adaptive features between the HFPE piston motion profile and the change of these parameters are explored. Further study would be recommended to elucidate the effect of adaptive behavior for the combustion characteristics. The results of this paper have a reference for understanding the operation mechanism of HFPE and the design and optimization of HFPE.

2. The theoretical analysis of HFPE’s piston motion profile

2.1. Coupling calculation and analysis of piston motion dynamics and combustion

Based on the MATLAB/Simulink simulation environment, the Simulink model consists of two parts. One part is the dynamic model of the interaction between the forces produced by hydraulic oil pressure acting on the plunger in the plunger cavity and in-cylinder pressure acting on the piston. The other part is the model of internal combustion engine, which includes combustion calculation, heat transfer calculation and so on. The model can be used to calculate the real time displacement of the piston under the combined action of the forces. The main mathematical expression is shown below.

As shown in Fig. 1, combined with the piston force characteristics and Newton's second law, the piston motion equation is shown below:

$$m\frac{d^2X}{dt^2} = p_h{\cdot}A_h{-}p{\cdot}A{-}f \tag{1}$$

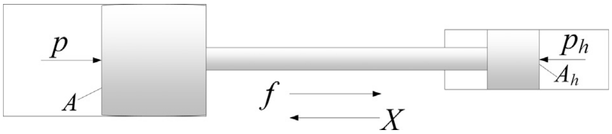

Fig. 1. Piston assembly force analysis.

where X is the piston displacement, m is the piston mass, p is the in-cylinder gas pressure, A is the piston top area, p_h is the hydraulic source driving pressure, A_h is the hydraulic plunger top area, f is the friction and t is time.

The double Wiebe function is used in combustion model for combustion process to simulate the actual heat release rate [32]:

$$\frac{dx}{dt} = \frac{dx_1}{dt} + \frac{dx_2}{dt} \tag{2}$$

$$\frac{dx_1}{dt} = \left[(m_p + 1)6.908{\cdot}\left(\frac{1}{t_{Zp}}\right)^{m_p+1}(t{-}t_B)^{m_p}{\cdot}e^{-6.908\left(\frac{1}{t_{Zp}}\right)^{m_p+1}(t-t_B)^{m_p+1}}\right]{\cdot}(1{-}Q_d) \tag{3}$$

$$\frac{dx_2}{dt} = \left[(m_d + 1)6.908{\cdot}\left(\frac{1}{t_{Zd}}\right)^{m_d+1}(t{-}t_B)^{m_d}{\cdot}e^{-6.908\left(\frac{1}{t_{Zd}}\right)^{m_d+1}(t-t_B)^{m_d+1}}\right]Q_d \tag{4}$$

where x represents the percentage of the original substance that has participated in the chemical reaction in time t, t_z is the end time; m is the combustion quality index, Q is the burning fraction, subscript 1 and p represents the first-stage reaction and subscript 2 and d represents the second-stage reaction.

The heat transfer rate is shown as follows:

$$\frac{dQ_w}{dt} = \alpha_g{\cdot}A{\cdot}(T{-}T_{wi}) \tag{5}$$

Where α_g is the instantaneous average heat transfer coefficient, A is the heat transfer area, T is the instantaneous temperature of charge and T_{wi} instantaneous temperature of heat transfer wall.

2.2. Model research results and analysis

The structure parameters in the calculation are the same as the experimental equipment. The hydraulic oil pressure is 6.4 MPa. The fuel is methanol, and the equivalence ratio is 0.6. By modifying the parameters of double Wiebe function to simulate the adjustment of combustion timing, the displacement curves of the piston motion profile under different combustion timings are obtained, as shown in Fig. 2. Fig. 3 shows the characteristics that the maximum piston displacement and CR automatically adjust with the change of the combustion timing more clearly.

It can be found from Figs. 2 and 3 that as the combustion timing delays, the maximum piston displacement and CR automatically

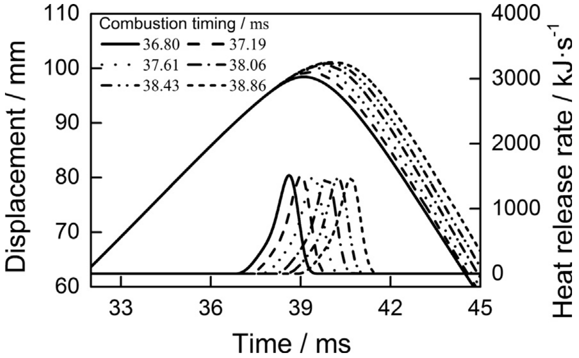

Fig. 2. Curves of piston displacement and heat release rate with different combustion timings.