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# An experimental research on the combustion and heat release characteristics of a free-piston diesel engine generator

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ABSTRACT

Free-piston engine generator (FPEG) is an unconventional engine; which is characterized by freely moving pistons without crankshaft system. This paper focused on an experimental analysis for the combustion and heat release characteristics of a free-piston diesel engine generator. An experimental prototype was established to test the operation performances of the new engine under different injection conditions. Experimental results show that the actual compression ratio of the FPEG is influenced by the injection advance position (IAP), which decreases with injection position advancing; but the peak in-cylinder gas pressure varies in positive correlation with the IAP. Moreover, the heat release characteristics of the unconventional engine were also analyzed using the experimental data. The results indicate that at the optimum injection position, the ignition delay of the FPEG prototype is 0.86 ms and generally shorter than a corresponding conventional crank engine due to its faster piston motion around the top dead center; and the heat release process has more significant pre-mixed combustion, which differs from the conventional engine situation. The heat release center of the FPEG at all injection position lags a stable time after injection; and the departure time of heat release center (DTHC) is increased significantly with the retarded injection. Meanwhile, a particular feature was found that the optimum efficiency of the FPEG does not occur in the lowest DTHC condition due to its variable compression ratio.


## 1. Introduction

Free-piston engine generator (FPEG) is a novel crankless reciprocating internal combustion engine. Unlike conventional reciprocating engine, the new engine is characterized by a purely linear piston motion that is not restricted by a crankshaft mechanism [1–3]. It has attracted considerable research interests recently as a promising new energy conversion device for the energy and environment crisis due to its special configuration and potential performance, such as structural simplicity, fast transient response, and high efficiency as well as high power density [1–5].

The most important process taking place in an internal combustion engine is the combustion process; the free piston engine generator is of no exception. In addition to its obvious importance in the generation of power, it provides a key driving input to the heat transfer which originates in the in-cylinder gases. Therefore, the features of combustion are an important part of FPEG research in order to understand the work of the new engine. Many efforts have been devoted to reveal the combustion performances and characteristics of the FPEG by many researchers.

The combustion characteristics of free-piston engines are commonly simulated using zero-dimensional, single zone models developed for conventional crank engines. Houdyschell and Clark et al. at West Virginia University studied the main features of a direct injection compression ignition FPEG by numerical simulations [6,7]. The combustion process of the FPEG was divided into two stages, and the heat release model was based on the two primary forms of traditional compression ignited combustion, the premixed combustion and the diffusive combustion. The burned mass fraction was expressed by a Wiebe function of time explicitly rather than implicitly the conventional crank angle. They indicated that the empirical value of the combustion duration in the Wiebe function influences the peak pressure, engine frequency, and displacement. In addition, they also found that high engine performance can be easily obtained by optimizing some key parameters of the Wiebe function. Meanwhile, other similar researches about the combustion in the FPEGs were also presented. Such as Kim at Seoul National University [8], Blarigan at Sandia national laboratories [9], Li at Shanghai Jiaotong University [10], and Hung at

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**Nomenclature**

| | |
|---|---|
| $A_{cyl}$ | the in-cylinder surface area in contact with gas |
| $C_p$ | specific heat capacity at constant pressure |
| $C_v$ | specific heat capacity at constant volume |
| $m$ | gas mass |
| $p$ | in-cylinder gas pressure |
| $Q$ | total heat |
| $Q_c$ | heat released from combustion |
| $Q_w$ | heat transferred to cylinder wall |
| $R$ | gas constant |
| $t$ | time |
| $t_s$ | the starting time of combustion |
| $t_e$ | the ending time of combustion |
| $T$ | in-cylinder gas temperature |
| $T_c$ | the center time of heat release |
| $T_w$ | average cylinder wall temperature |
| $V$ | in-cylinder gas volume |
| $v_m$ | mean piston velocity |
| $V_s$ | working volume of engine |
| $U$ | gas internal energy |
| $W$ | in-cylinder gas work |
| $W_i$ | indicated work |

*Abbreviations*

| | |
|---|---|
| FPEG | free-piston engine generator |
| CFD | computational fluid dynamics |
| TDC | top dead center |
| DAQ | data acquisition |
| IAP | injection advance position |
| IMEP | indicated mean effective pressure |
| DTHC | departure time of heat release center |
| NI | National Instrument |

University of Ulsan [11,12], also used zero-dimensional empirical models to study the combustion of the FPEGs.

These zero-dimensional models may be sufficient for the combustion predications in early stage of research process, while they can be useful for investigating basic engine performance and piston dynamics, but they simulates the gas motion and heat release of combustion process with simplified functions, ignoring or weakening the influence of gas motion and species distribution. To overcome the weaknesses of the zero-dimensional models, some researchers presented a more advanced approaches using multidimensional simulation models to obtain combustion performance and heat release rates and combining these with a dynamic piston motion model. Mikalsen and Roskilly, at Newcastle University, investigated the combustion process and nitrogen oxide formation of a free-piston diesel engine using CFD (computational fluid dynamics) engine model with OpenFOAM [13,14]. The piston motion profile was fitted to a high-order polynomial through least square error fitting and implemented into the CFD code. Fredriksson and Bergman et al. investigated the effects of varying the injection timing on the combustion process in free-piston engine. The piston dynamics, combustion process and gas exchanging system dynamics were solved using Matlab/Simulink, KIVA-3V and GT-Power respectively [15–17]. The piston speed and position as a function of time obtained from the dynamic model were coupled with the piston motion routine of the KIVA-3V code in the CFD simulation. The results illustrated that a low compression ratio was required to obtain low indicated specific fuel consumption with low emissions for conventional compression ignited combustion. Feng and Yuan et al., at Beijing Institute of Technology, focused on a numerical simulation for the research on the combustion process of a free-piston diesel engine generator by adopting coupled models of zero-dimensional dynamics and multi-dimensional CFD combustion [18,19]. They studied the exothermic properties of the engine during the combustion process through iterative computation between the dynamic and combustion. Their results indicated that the heat release before the top dead center (TDC), the isochoric heat release, and the heat release of the FPEG during the premixed combustion period were both lower than a corresponding conventional crank engine, and the post-combustion became more intense for the free-piston engine, thus a slight disadvantage of indicated efficiency was found.

In recent years, some experimental works on FPEGs have been carried out sporadically. Lim et al., at University of Ulsan, presented an experiment to study the effects of spring stiffness on dynamic and combustion in a free-piston spark ignition engine [20]. The engine was fueled with a pre-mixture combined with liquid propane gas and air. Their measured results showed that the larger spring stiffness affected combustion efficiency and maximum in-cylinder pressure. In recently, to study the influence of motion on the combustion, Feng et al. performed an experiment to measure the pressure-volume diagram of a free-piston diesel engine, and using equivalent crank angle as the unit of measurement to express combustion process [18,21]. Their results showed that the free piston motion is favorable to evaporation and oil-gas mixture leading to pre-mixed combustion ratio up to 80%. The authors stated that the ignition delay time was decreased due to the high piston velocities around the TDC, increasing in-cylinder gas motion and turbulence levels.

The published papers show that the combustion and heat release characteristics of FPEGs have been investigated by many researchers, and continuous progress has been made on modeling, as well as simulation techniques. Although zero-dimensional and multi-dimensional models have been developed for and validated against conventional engines, it is questionable whether they are suitable for modeling free-piston engines without modification. Meanwhile the experimental research of combustion process in free-piston engine generator has not been concerned enough, only discussed briefly by some researchers [20,21]. To accurately obtain the combustion performance and potential heat release characteristics of the free-piston engine, a comprehensive experimental study on combustion process needs to be presented. Therefore, this paper establishes a prototype of free-piston diesel engine generator for the experimental research of combustion characteristics. The in-cylinder gas pressures and piston motions of the prototype are measured under different injection conditions. Moreover, the heat release characteristics of the engine are also analyzed based on the experimental data, which is benefit to understand the special combustion performance in the FPEGs.

## 2. Experimental setup and methods

### 2.1. Experimental prototype

The schematic diagram of this free-piston diesel engine generator can be seen in Fig. 1. This new power device uses opposed twin-cylinder arrangement with two free-piston engines placed at both ends and a linear electrical machine placed in the middle. It essentially consists of main five parts: two combustion cylinders, two free pistons, a permanent magnet, an electromagnetic coil, and a