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Combustion characteristics analysis of a free-piston engine generator coupling with dynamic and scavenging

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ABSTRACT

Free-piston engine generator is an unconventional engine, which abandons the crank and connecting rod mechanism. This paper focused on a numerical simulation for the research on the combustion characteristics of a free-piston diesel engine generator. An iteration numerical simulation method was presented by adopting coupled models of zero-dimensional dynamics, multidimensional scavenging and combustion. According to the coupled parameters of these models, the effects of the piston motion on combustion process were investigated compared with a corresponding traditional crank engine. The results indicate that compared with the conventional engine, the free-piston engine generator has a longer combustion duration due to its faster piston mean velocity in combustion process. While the heat release before top dead center, the isochoric heat release, and the heat release during the premixed combustion period both were lower than the traditional engine, and the post-combustion became more intense for the free-piston engine, thus a slight disadvantage of indicated efficiency was found. In addition, the in-cylinder average gas temperature and pressure were generally lower than the traditional engine, which contribute to the distinct advantages in NO discharge of the free-piston engine generator.

1. Introduction

FPEG (Free-piston engine generator) is a new engine type, which has attracted considerable research interests recently as a promising new energy conversion device for energy and environment crisis [1,2]. Common for the new engine is that the piston motion is not restricted by the motion of a rotating crankshaft, as known from traditional reciprocating engine, but that the piston is free to move between its endpoints, only influenced by the gas and load forces acting upon it [3,4].

This special 'crankless' configuration allows the novel engine to operate with variable stroke length and compression ratio, which gives extensive performance advantages, such as multi-fuel possibilities, lower friction loss from fewer motion parts, and combustion optimization flexibility [3–7]. While the 'free' piston motion of the novel engine is different from the piston motion of crank mechanism in traditional engine. This induces the special combustion process for the free-piston engine, and many researchers have focused on the combustion research of the new engine [8–13]. However, most researchers generally applied zero-dimensional empirical models (such as Wiebe model) to modeled the combustion process of free-piston engine generator, they simulated the gas motion and heat release of combustion process with simplified functions, ignored or weakened the influence of gas motion and species distribution. This is mainly due to the piston motion of the free-piston engine cannot be described with a fixed mathematical expression referring to variable working conditions, which makes it is difficult to investigate the details of the combustion process using multi-dimensional tools, and only few studies have been reported.

Mikalsen and Roskilly, at Newcastle University, investigated the in-cylinder gas motion, combustion process and nitrogen oxide formation of a free-piston diesel engine and compared the results to those of a conventional engine using CFD (computational fluid dynamics) engine model with OpenFOAM [14,15]. The piston motion profile was fitted to a high-order polynomial through least square error fitting and implemented into the CFD code. The results indicated that enhanced radial gas flow (squish and reverse squish) around TDC (top dead center) was found for the free-piston engine compared with conventional engine, and it had only minor influence on the combustion process. While a higher heat release rate

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from the premixed combustion phase due to an increased ignition delay was found, along with potential reductions in NOx emissions formation for the free-piston engine.

Fredriksson and Bergman et al., investigated the effects of varying the injection timing on the combustion process in free-piston engine using the KIVA-3V CFD code [16,17]. 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 simulation results illustrate that the combustion process can be optimized, leading to high combustion efficiency and stable engine operation by changing injection timing. High efficiencies and moderately low emissions can also be achieved if the injection schedule is carefully chosen. Moreover, they recently presented a CFD based optimization of diesel-fueled, uniflow scavenged, free-piston engine [18]. The piston dynamics, combustion process and gas exchanging system dynamics were solved using Matlab/Simulink, KIVA-3V and GT-Power respectively. The effects of varying parameters such as compression ratios, power supplied to the compressor, fuel injection timings and injection pressures were studied in both conventional and HCCI (homogeneous charge compression ignition) modes to find out the optimal conditions for the free-piston engine generator. In order to simplify calculation, the piston position curve was fixed when the only ignition timings were changed. The results illustrate that a low compression ratio is required to obtain low indicated specific fuel consumption with low emissions for conventional combustion, while the recommended strategy for HCCI combustion in order to obtain a low NOx regime ($<$0.5 g/kW.h) is a single injection with an injection pressure of 1600 bar, start of injection at 100 before TDC and low compressor power.

Feng et al., at Beijing Institute of Technology, calculated the combustion performances of a free-piston engine generator using CFD software AVL_Fire to define its combustion efficiency when designing a prototype of the engine [19,20]. In recently, they 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, the simulation was validated with tested data from a running free-piston engine generator prototype. Then they studied the exothermic properties of the engine during the combustion process through iterative computation between the dynamic and combustion. The authors indicated that, combustion in the free-piston engine lasted for a longer time compared with that in the traditional crank engine. While the maximum combustion pressure and temperature of the free-piston engine both were lower and lasted for a shorter time than the traditional reciprocating engine.

Globally, the piston motion of free-piston engine generator differs much from traditional crank engine, the zero-dimensional empirical models may be sufficient for the combustion predications in early stage of research process, while some multi-dimensional CFD simulations generally adopt the simple simulated piston motion profile to study the combustion process, but the coupled effects of the piston dynamics and combustion process were not considered in detail, especially, the scavenging performance was generally ignored. Moreover, it is widely recognized that the combustion performances of the two-stroke engine are directly dependent on the effectiveness of the scavenging process. Furthermore, the free-piston engine generator is a special two-stroke engine which abandons the crank connecting rod mechanism; the combustion and scavenging may have many different characteristics compared with traditional two-stroke crank engine. Thus a more comprehensive study on combustion process need be presented. This paper aims to investigate the details of the combustion process in a loop scavenged free-piston diesel engine generator coupling with piston dynamics and scavenging; the different combustion characteristics between the free-piston engine generator and a corresponding traditional two-stroke crank engine with same initial boundary conditions will be introduced; the mechanisms and reasons for the different combustion characteristics in the two engines also will be discussed.

2. The engine and research method

2.1. Configuration of engine

There are many types of free-piston engine generator, but the one under consideration in this study is of the dual piston type with a tube permanent magnet linear generator integrated in between the two cylinders, as can be seen in Fig. 1. This engine employs a special designed loop scavenging system, and constant super charged boost pressure that is generated by an external compressor is used to obtain the best possible scavenging performance. Electronically controlled common-rail fuel injection system is used to avoid short-circuiting of the air/fuel mixture. As a result of the lack of mechanical linkage, a shallow dish-shaped bowl is designed to enlarge the security distance between the piston and cylinder head at TDC. In operation process, the linear electric machine is used as a motor to start the engine, when the unconventional engine finishes the starting process; the linear electric machine is switched to a generator state. Then, combustion at alternating cylinder ends drives permanent magnets fixed on the connecting rod back and forth through the coils of the generator. The main specifications of the free-piston engine generator are listed in Table 1.

2.2. Coupling research method

Since the piston motion of the free-piston engine is not mechanically restricted by a crank mechanism, and it is only influenced by the gas and load forces acting upon it, thus the piston motion and combustion interact in a very complex way. Moreover, the combustion performances are directly dependent on the effectiveness of the scavenging process, if fluctuation occurs in the scavenging process, there will definitely be circulation differences. Therefore there is a coupled relationship between the piston motion, scavenging and combustion process. If using the traditional CFD numerical simulation method for traditional crank engines to calculation the combustion process of the free-piston engine, it will be difficult to define the boundary conditions and the result will be inaccurate [21,22]. So that, the CFD simulation of combustion process in free-piston engine cannot adopt the traditional modeling method which obtain the piston movement by crank mechanism and pre-given parameters (stroke, connecting rod, and speed). The accurate free-piston movement must be used for the establishment of motion mesh model in multi-dimensional CFD model. However, it is impossible to obtain the accurate piston motion for only one time simulation of the piston dynamic model because of the different parameters in combustion model, dynamic model, and scavenging model were coupled. Thus, an iterative research of the combustion was carried using a coupled model, mainly focused on the piston dynamic, combustion process, and scavenging process.

The iterative research started when the engine began to work, and ended when it meets the convergence condition, in which the deviation between in-cylinder gas pressures obtained from zero-dimension calculation and the CFD calculation was less than 5%. The detailed coupling iteration procedure is shown in Fig. 2, and each step can be further introduced as follows: (1) An empirical heat release model of Wiebe function was used to calculate the piston motion profile based on the initial boundary conditions. (2) A Scavenging CFD model is presented to calculate the gas exchange performances according to the calculated piston motion. (3) A