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Research on combustion process of a free piston diesel linear generator

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HIGHLIGHTS

- We study the exothermic properties of the FPDLG during the combustion process.
- We compare the combustion of TRE with FPDLG, and reveal the heat releasing characteristics of FPDLG.
- We validate the model with test data from a running FPDLG prototype.

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ABSTRACT

The piston motion of a free-piston diesel linear generator (FPDLG) is different from the traditional reciprocating engine (TRE). Here we focused on a numerical simulation for the research on the combustion process of an FPDLG by adopting coupled models of zero-dimensional dynamics and multi-dimensional computational fluid dynamics (CFD). Piston dynamics model and CFD model to simulate the combustion process were set up based on the calculated results of free-piston motion, which were validated with tested data from a running FPDLG prototype. According to the coupled parameters of these two models, we studied the exothermic properties of the FPDLG during the combustion process through iterative computation, and compared the simulation results of a TRE to a FPDLG with comparable and similar structural parameters. The results indicated that, combustion in the FPDLG lasted for a longer time compared with that in the TRE. While the heat release before top dead center (TDC), the isochoric heat release, and the heat release during the rapid combustion period were low, the post-combustion became more intense. Furthermore, the average temperature in the cylinder was generally lower, while became higher in the end of expansion stroke. In addition, the maximum combustion pressure was lower and lasted for a shorter time.

1. Introduction

The free-piston diesel linear generator (FPDLG) is a new engine type with the advantages of both environmentally friendly and energy saving. It is a combination of free-piston engines and a linear generator, with merits such as structural simplicity, fast transient response, high efficiency as well as high power density etc [1–6]. The FPDLGs could be divided into three categories, namely, the opposed piston free-piston engine, single-cylinder free-piston engine, and dual piston free-piston engine. In this research, a dual piston type FPDLG is selected due to its potential character of higher power-to-weight ratio, and the schematic diagram of the designed prototype is shown in Fig. 1. However, the prototype is unable to operate smoothly on this stage. The reason is because its special dead center movements are lack of mechanical restraint, and the working process of the whole system is very sensitive to the combustion fluctuations occurred in the two cylinders, which restricts its further development.

The free-piston internal combustion engine was first introduced in the 1920s, when Pescara put forward the free-piston internal combustion engine model [7]. The free piston engine, however, developed slowly at the early stage for various reasons. The last two decades have witnessed the advancement of technologies such as computer control, microelectronics, and the design of modern internal combustion engine. The FPDLG has now been investigated by many researchers, and continuous progresses have been made

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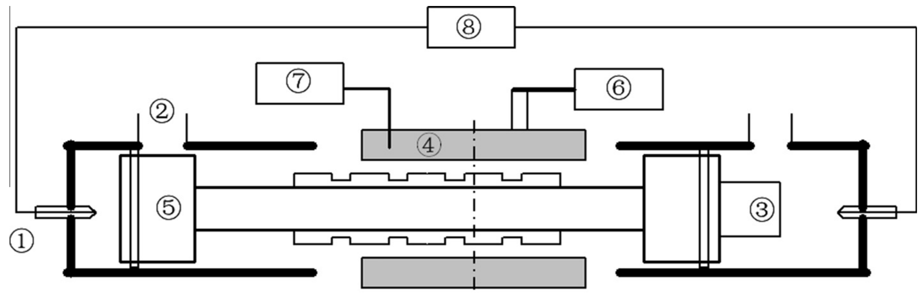

Fig. 1. Schematic diagram of the FPDLG prototype.

on modelling, simulation, controlling strategy, as well as experimental techniques [8,9].

Houdyschell et al. at West Virginia University studied the main features of a spark ignited free piston linear generator (FPLG) by numerical simulations [10]. Numerical models were set up to calculate and analyse the compression, combustion, and ventilation processes of the whole system based on related thermodynamics theories. Their study aimed to obtain operating parameters while the FPLG was under stable operation. They also discussed the influence of structural parameters, including bore-to-stroke ratio, external load, air-to-fuel ratio, and the length of ignition period, on major operation parameters by adopting dimensionless analysis method.

Roskilly and Mikalsen at Newcastle University studied the thermodynamic characters and the performance of the engine subsystem, dynamics as well as the controlling strategy based on mathematical modelling and numerical simulations [11,12]. They analysed the gas exchanging and in-cylinder combustion processes by carrying out coupled multi-dimensional numerical simulations. It was found that the designed FPLG had many potential advantages, particularly its flexibility of combustion optimisation, variable compression ratio, and lower heat transfer losses.

Goldsborough at Sandia National Laboratories simulated the operation of the FPLG by applying a zero-dimensional model, and described the heat transfer, scavenging process, and friction force based on a set of empirical formulas [13–16]. After the initial simulation, they built more detailed thermodynamic models to compare the influences of each parameter on the emission performance and heat efficiency of the engine.

Mao et al. at Beijing Institute of Technology conducted a zero-dimensional numerical simulation on the operation of the FPLG [17–21]. They analysed the influences of the main controlling parameters on system operation, and offered insights into the scavenging process and combustion process by using CFD method, based on numerically simulated piston motion profiles. Thus, they observed the effects of the main parameters in the scavenging system on the scavenging efficiency and short-circuit losses, and the impacts of the FPLG operation profile on the combustion of the engine sub-system.

The FPLG prototype developed by researchers at Toyota Central R&D Labs Inc. consisted of a two-stroke combustion chamber, a linear generator, and a gas spring chamber [22,23]. A power generation experiment was carried out, and the results demonstrated that the prototype operated stably for quite a long period of time, despite of the abnormal combustion during the test. The unique piston motion and its effect on combustion and power generation in the FPLG prototype were experimentally analysed.

Researchers at Nanjing Institute of Technology proposed a novel new FPLG design, which was consisted of a single cylinder operating on four-stroke cycle, a linear electric generator, and a mechanical spring kickback system [24]. Scavenging was completed through electromagnetic valves at the cylinder head. A reversible energy storage device was used to store the electric power output, and a bi-directional power converter was applied to match the linear generator and energy storage device. A 2.2 kW average power output was obtained with an efficiency of 32% [24]. The feasibility and performance of the proposed design were verified and detailed test results were analysed, giving insight into the performance and dynamic behaviours of the novel power system.

Globally, researchers have preliminarily mastered the piston operation mechanism. They found the key reason why FPDLG was difficult to run smoothly was due to the difficulty in controlling the TDC, which was mainly caused by unstable combustions. As a result, further research on the features of the FPDLG during the combustion process is required [25–28]. The research work presented in this paper described a piston dynamics model and a CFD model for a FPDLG during the combustion process, in accordance with the characteristics of free-piston motion. Based on the coupled parameters of these two models, the exothermic properties of the FPDLG in the combustion process through iterative computation were presented, and the results with the combustion process in a TRE with the same structural parameters were compared.

The motion of the piston is determined by the forces acting on the FPDLG. If fluctuation occurs in the scavenging process, there will definitely be circulation differences. While the combustion differences in the divergent circulations will exert effects on the motion of the FPDLG, which will in return affect the scavenging process of the engine. As a result, strong coupling effects between the motions of the FPLG components and scavenging exist, as well as combustion processes. If the current CFD numerical simulation of the TRE is used to calculate the scavenging and combustion processes of the FPDLG separately, it will be difficult to define the boundary conditions and the result will be inaccurate. As a result, in response to the simulation of the FPDLG combustion process, it is essential to set up a dynamic mesh model based on accurate free-piston motion rules, rather than the given parameters of the TRE, such as piston stroke and ratio of stroke and cylinder diameter. In order to obtain the precise combustion features of the FPDLG, an iterative calculation of the combustion process was carried out using a coupled model, mainly focused on the dynamic and combustion processes [29]. The calculation started when the engine began to work, and ended when it meet the convergence condition, in which the deviation between in-cylinder pressures got 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 is further explained as follows: