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An experimental study of the hydraulic free piston engine

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HIGHLIGHTS

- ▸ A prototype of hydraulic free piston engine is developed.
- ▸ Stable running of the prototype is realized.
- ▸ Detailed studying of an experiment of the prototype is presented and analyzed.
- ▸ The piston dynamics, combustion process and the hydraulic characteristics are verified by experiments.
- ▸ The indicated thermal efficiency and the indicated mean effective pressure have been obtained by the experiments.

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ABSTRACT

A prototype of hydraulic free piston engine has been developed to achieve efficient energy conversion directly from chemical energy of fuel to hydraulic energy. In stable running condition, in order to verify the features of this kind of engine, the piston dynamics, combustion process and hydraulic characteristics are investigated through series of tests of the prototype. The experimental results show that the majority of fuel burns in the rapid combustion phase which is due to the high piston velocity in the final part of the compression stroke. The combustion is characterized by a constant volume process. Furthermore, the indicated thermal efficiency and the indicated mean effective pressure of the prototype presented in this study are 41% and 5.2 bar respectively.

1. Introduction

With the development of industry and technology, the energy crisis and environmental pollution have become two serious societal problems across the world. Consequently, increasing fuel prices and tight environmental legislation present a great challenge for internal combustion engine designers. More research efforts are put into engine technology, aiming at reducing engine emissions and improving efficiency. While some researchers are still struggling to improve and optimize the performance of conventional engines, other researchers are devoted to explore and study more efficient unconventional engines. The free piston engine is a kind of unconventional engine with the characteristics of simplicity and operational flexibility, which draw a great amount of attention from engine researchers. The advanced microprocessor-based control systems and modern engine technologies such as electronically controlled fuel injection and valve actuation systems significantly promote the development of this research as a result of improved operational control of the free piston engine, along with enhanced optimization possibilities for various operating conditions [1].

The free piston engine is a linear “crankless” engine, in which the reciprocating motion piston is coupled directly with a linear load device such as hydraulic pump or electric power [2–4]. The free piston concept was first proposed by Pescara in 1930s [5], and its successful applications are compressors and gas generators in the mid-20th century. A background study on the history of free piston engine, the advantages of the hydraulic free piston engine and free piston generator can be found in Ref. [6], and the authors will not give more description here.

The hydraulic free piston engine integrates the internal combustion engine and the hydraulic pump. And the energy released from combustion process is converted directly into hydraulic energy. This promising approach has potential advantages over conventional technologies due to its simplicity, which allows more compact units with reduced frictional losses, less maintenance costs and higher operational flexibility. Furthermore, the elimination of crank mechanism leads to the valuable feature of variable compression ratio which is suitable for multiple types of fuel.

In the last few decades, researches related to hydraulic free piston engine have been carried out by either research institutions

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or universities. The Dutch company Innas BV developed a single-piston hydraulic free piston engine prototype, and Achten et al. gave a description [7,8]. They compared the piston dynamics of hydraulic free piston engines with that of conventional engines. Higher piston acceleration around top dead center (TDC) was reported, and the piston velocity during the expansion stroke was higher than that in the conventional engines. High part load efficiency due to using the PPM (Pulse Pause Modulation) control and high indicated efficiency were reported. Tampere University of Technology and Helsinki University of Technology [9,10] presented the modeling and simulation of a dual-piston hydraulic free piston engine in detail, comparing the performance characteristics with single-piston hydraulic free piston engine. It is found that the piston velocity and the acceleration of dual-piston engine are lower than that of single-piston engine because of the heavier piston assembly. Cycle-to-cycle variations of compression ratio and cylinder gas pressure were reported. Other research groups such as National Vehicle and Fuel Emissions Laboratory, US EPA, FEV Engine Technology Inc. [11], and Toyohashi University of Technology [12,13], also conducted a series of studies on the hydraulic free piston engine, but only a small number of prototypes have been successfully developed. Up to date, a great many of researches that have been carried out only focused on the performance simulation and the comparison in the piston motion profile between hydraulic free piston engines and conventional engines. The asymmetric piston motion profile relative to TDC, higher piston acceleration around TDC, and higher piston velocity during the expansion stroke than that in the compression stroke were reported as the major differences from the conventional engines. Although the characteristics of the hydraulic free piston engines were discussed briefly by some developers, few research papers have been published concerning the experimental study from a continuous running prototype, especially regarding the details of combustion process, which is one of the most important subjects for studying this kind of engines. The objective of this paper is focused on the experimental methods to investigate the characteristics of the hydraulic free piston engine. The impact of the piston motion profile imposed on the combustion process will be examined and discussed.

2. Principle of the hydraulic free piston engine

The hydraulic free piston engine studied here is a special engine that combines an internal combustion engine and a reciprocating plunger pump without any other mechanical systems. The fuel combustion energy can be directly converted to hydraulic energy through the rigid piston assembly, and the crankshaft commonly found in conventional engines is eliminated. Fig. 1 shows the working principle of the hydraulic free piston engine. Being different from the existing this kind of engine, the internal combustion part is characterized by a uniflow scavenging system that provides a better scavenging quality than a loop scavenging system. But this also presents greater technical challenges. The exhaust valve system cannot be driven by a rotary mechanism like the camshaft timing of conventional engines, for the piston moves freely between its two endpoints, and the reciprocating motion is determined by the instantaneous balance of the cylinder gas pressure, the hydraulic forces and the friction forces. Therefore, the exhaust valves have to be controlled and driven quickly and accurately according to the piston position. In this prototype, the hydraulic exhaust valves system is developed and equipped in the cylinder head [14].

The piston assembly motion is not restricted by a crankshaft. The piston assembly consists of the power piston, pump piston and rebound piston which are rigidly connected by the piston rod. The HEUI (Hydraulic Electronic Unit Injector) is equipped. The accumulator is used as a reversible energy storage device to supply energy for the compression stroke. According to the principle diagram, the working process can be briefly described as follows: During the compression stroke, the piston assembly is driven by the hydraulic energy from accumulator in order to compress the gases in the combustion cylinder. At the same time, the pump piston sucks the low-pressure oil through the suction valve. When the piston assembly approaches TDC, the fuel is injected into the combustion chamber and burns. During the expansion stroke, the energy of fuel is absorbed by the hydraulic system. It pushes the piston assembly towards the bottom dead center (BDC). High-pressure oil is outputted by the pump piston through the pressure valve. Finally the compression piston pushes the compression oil into the accumulator again. The supplied energy from the accumulator to the piston assembly is controlled by the frequency control valve. This valve determines the operational frequency of the engine. As long as this valve is closed, the piston will dwell at the BDC for the high-pressure oil pushing the rebound piston. Whenever the valve opens, a new stroke will commence. The detailed description of the hydraulic free piston engine working process can be found in Refs. [15,16].

3. Prototype of hydraulic free piston engine

3.1. Prototype fabrication and specifications

The prototype of hydraulic free piston engine, which is shown in Fig. 2 and with the specifications given in Table 1, has been built to validate the feasibility of the technical scheme discussed above. The prototype is a single-piston configuration, two-stroke, direct injection and compression ignition diesel engine, uniflow scavenging with the hydraulic driving exhaust valves.

The piston displacement sensor, cylinder pressure sensor, and hydraulic pressure sensors acquire the system running states and provide signals for the controller. Based on these signals, the controller calculates the control parameters, such as the fuel injection

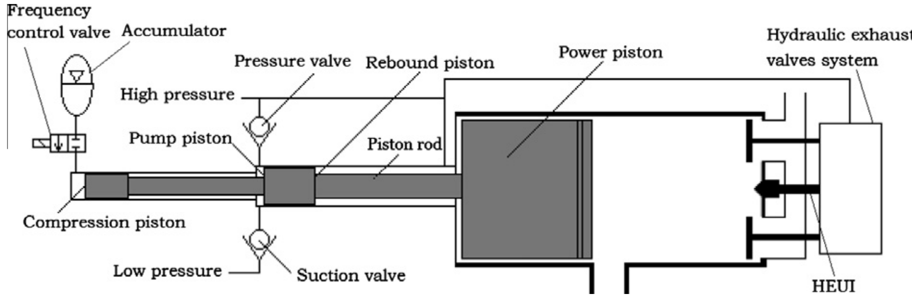

Fig. 1. Schematic diagram of the hydraulic free piston engine configuration.