2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring

Experimental Study on Hydraulic Free-piston Diesel Engine

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***Abstract*—Free-piston engines are investigated by a number of research groups worldwide, with potential advantages of high-efficiency and low-emissions. Hydraulic free-piston diesel engine, which combines a two-stroke diesel engine and a hydraulic pump, could be an alternative to conventional technology in applications. It can fulfill the power requirements of vehicle under optimum operation conditions, only by change the operation frequency. The piston dynamics of the free-piston engine differ from those of conventional engines, and this may influence the combustion process and power output. This paper introduces the design of a single piston hydraulic free-piston diesel engine. The piston dynamics and combustion process were investigated from test data. Different from conventional engine, the main combustion phase of hydraulic free-piston diesel engine is pre-mixed combustion phase. Most of the fuel burns in the pre-mixed phase, resulting in a very high rate of heat release. Finally, the pumping process of hydraulic free-piston diesel engine has been discussed. It is seemed that the response lag between the pump chamber pressure and the piston displacement at the start of the expansion stroke is mostly determined by the close action of the suction valve. Improving response performance of the suction valve will increase the total efficiency of the hydraulic free-piston diesel engine.**

Keywords-Free-piston engine; Diesel engine; Dynamics; Combustion

I. INTRODUCTION

Extensive use of hydrocarbon fuels as an energy source for power leads to significant environmental impacts. Much research, particularly within the automotive industry, is being undertaken to develop more environmental friendly power source, and the free-piston engines stand out as a potential technology for the future applications such as hybrid electric vehicle and off-road vehicle.

Since the free-piston engine was first developed around 1930, a number of different designs have been proposed using the free-piston concept. A number of investigations were focus on the operation characteristics of free-piston engine, with the aim of high-efficiency and low-emissions.

Free-piston engines are linear, 'crank-less' engines, in which output power is extracted by a linear load device directly coupled to the moving piston. The free-piston concept has potential advantages over conventional technology due to its simplicity and flexibility, which allows a more compact unit with less maintenance costs and energy losses [1].

As show in Fig. 1, free-piston engines are usually divided into three categories based on the piston/cylinder configuration. A fourth category, free-piston gas generators, identifies engines where the load is extracted purely from an exhaust turbine and not from a load device mechanically coupled to the engine [2].

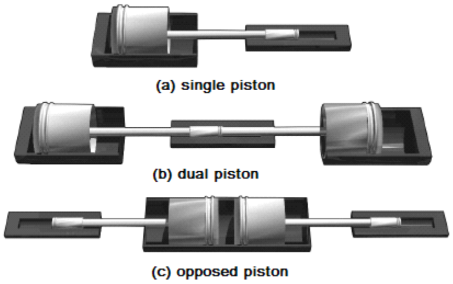


Figure 1. The free-piston concepts.

A single piston free-piston engine consists of three parts: a combustion cylinder, a load device, and a rebound device to store the energy required to compress the next cylinder charge [2]. The single piston free-piston engine is easier to accurately control the amount of energy put into the compression process and thereby regulating the compression ratio and stroke length, but it needs a rebound device.

The dual piston free-piston engine configuration eliminates the need for a rebound device, as the working piston provides the work to drive the compression process in the other cylinder. This allows a simple and more compact device with higher power to weight ratio [2]. However, the control of piston motion, in particular stroke length and compression ratio, is a challenge.

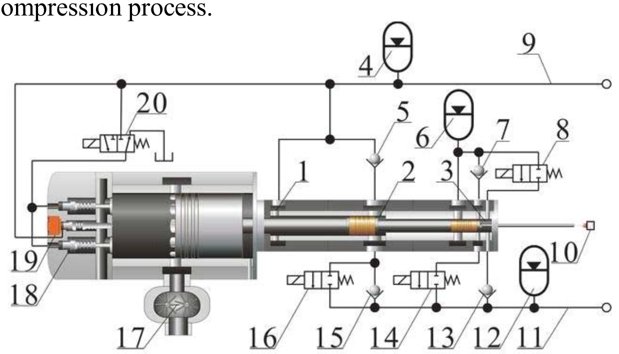
An opposed piston free-piston engine essentially consists of two single piston units with a common combustion chamber. Each piston requires a rebound device, and a load device may be coupled to one or both of the pistons. The main advantage of the opposed piston configuration is the perfectly balanced and vibration-free design. However, the absolute need for a piston synchronization mechanism is the most important disadvantage of the opposed piston design. And the need for a dual set of the main components also makes the engine complicated and bulky [2].

Most modern applications of the free-piston engine concept are using a hydraulic cylinder or a linear electric machine as load device. No matter which kind of free-piston engines is, as the piston motion is not mechanically restricted by a crank mechanism, the free-piston engine has the valuable feature of variable compression ratio, which may provide extensive operation optimization and multi-fuel possibilities.

978-0-7695-4350-5/11 $26.00 © 2011 IEEE
DOI 10.1109/CDCIEM.2011.99

II. HYDRAULIC FREE-PISTON DIESEL ENGINE CONFIGURATION

The configuration of hydraulic free-piston diesel engine (HFPDE) is shown in Fig. 2. Based on the concept firstly proposed by INNAS BV [3], the hydraulic chambers are set up by the HFPDE operations which contain start operation, stable operation and misfire operation. The HFPDE internal-combustion system also needs fuel injection, intake and exhaust system. The hydraulic chambers achieve hydraulic power output, resetting of the piston after misfire and engine compression process.



1-Check chamber 2-Pump chamber 3-Compression chamber
4-High pressure accumulator 5-Check valve
6-Compression accumulator 7-Check valve
8-Frequency control valve 9-High pressure rail
10-Piston displacement transducer 11-Low pressure rail
12-Low pressure accumulator 13-Suction valve
14-Reset valve 15-Suction valve 16-Reset valve
17-Roots pump 18-Electrohydraulic exhaust valve
19-Hydraulic-electronic unit injector
20-Exhaust control valve

Figure 2. The configuration of HFPDE.

The pause of the piston at bottom dead center (BDC) is mainly determined by the hydraulic chamber pressures, in particularly the force brought by the check chamber pressure. The pump chamber takes charge of the suction of low pressure oil from the low pressure rail and the output of high pressure oil to the high pressure rail. The pumping action of the pump chamber needs the cooperation of the check valves connected to the pump chamber as shown in Fig. 2. The compression power is offered by the hydraulic power stored in the compression accumulator.

According to the principle of HFPDE, a prototype as shown in Fig. 3 has been designed and constructed in Beijing Institute of Technology.

The basic engine design parameters as below:

- Single piston, direct injection, compression ignition.
- Flow control by means of the pulse pause modulation of the piston frequency.
- Two-stroke, uniflow scavenged by roots pump.
- Variable compression ratio.
- Cylinder bore: 98.5mm.
- Piston mass: 4.2Kg.
- Piston cross-sectional area in the check chamber: 102mm^2.
- Piston cross-sectional area in the pump chamber: 204mm^2.
- Piston cross-sectional area in the compression chamber: $440\ \text{mm}^2$.
- Variable stroke: 119-130mm.
- Position of the intake ports: 95.4mm.
- Rated pump pressure: 25MPa.
- Piston frequency: 0-28Hz.
- Net effective flow output: 0-42L/min.

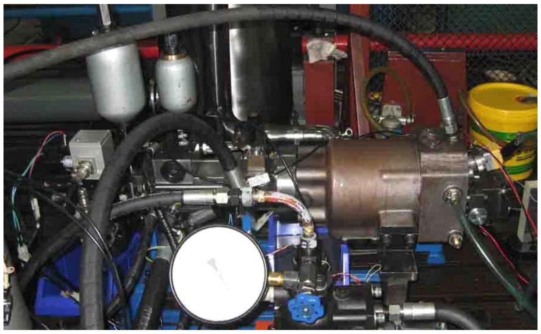


Figure 3. The HFPDE prototype.

A. *Internal-Combustion System*

The internal-combustion system of the HFPDE is a two-stroke diesel engine with uniflow scavenging and direct fuel injection. For the injection system, as show in Fig. 4, a hydraulic-electronic unit injector (HEUI) from Caterpillar is used. The HEUI is directly driven by the high pressure oil which called the injection actuation pressure.

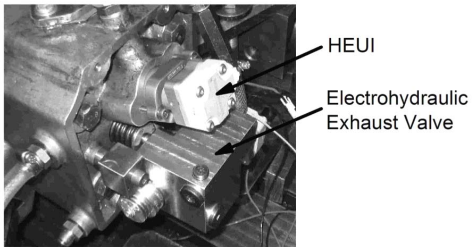


Figure 4. Fuel injection system and electrohydraulic exhaust valve.

The HEUI uses lubrication oil that is pressurized from 6 MPa to 28 MPa in order to pump fuel from the injector. It operates in the same way as a hydraulic cylinder in order to multiply the force of the high pressure oil. This multiplication of pressure is achieved by applying the force of the high pressure oil to a piston. The piston is larger than the plunger by approximately six times. So that injection pressure is greater than actuation pressure of the oil by approximately six times.

As show in Fig. 4, the exhaust valve is controlled by a hydraulic cylinder and a high speed triple valve. The valve is closed by a valve spring with the hydraulic cylinder connected to the low pressure rail. When exhausting, the high speed triple valve makes the hydraulic cylinder connect to the high pressure rail. Then the hydraulic cylinder piston moves downward to open the exhaust valve. The valve stroke is determined by the signal pause width and the actuating pressure.

B. Hydraulic Circuit

The hydraulic chambers are made up by sleeves and then fit on the engine body as shown in Fig. 2. The frequency control valve (FCV) is used to control the engine working frequency. The start of the engine compression process needs to be controlled when the engine working frequency is under its self-excited vibration frequency. The piston bouncing movement at BDC should be properly limited at that time. The bouncing is mainly affected by the hydraulic chamber pressures, which are determined by dead zone volume, oil bulk modulus, and hydraulic valve dynamics. The piston will stop at top dead center (TDC) after misfire. Then the reset valves are prepared for the reset of the piston to BDC. The piston extreme displacement at BDC is limited by throttle effect and hydro-elastic effect, in order to protect the engine mechanical structure [10].

As Fig. 5 shows, the hydraulic circuit is built up by a chief-port, a sub-port, an FCV-port, a reset port, a feed-port and a compression piston. The chief-port is directly connected to the compression accumulator. It is closed by the compression piston when the piston locates at BDC. The clearance between the compression piston and the sleeve should be suitable to satisfy requirement of the start operation. The sub-port is connected to the compression accumulator through a check valve. The FCV-port connects the FCV and the compression chamber. When the FCV is closed, the piston can stop at BDC for a certain moment at the end of the expansion stroke.

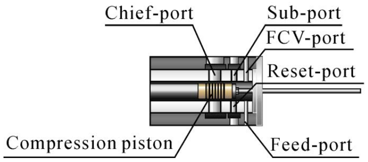


Figure 5. Main parts in the compression chamber.

C. Control Strategy

In conventional engines, the crank-link mechanism controls the dead centers and the piston motion profile, which are not influenced during engine operation. The control of free-piston engines is a special challenge and the volume of published research on free-piston engine control issues is very limited [4]. Johansen et al. [5] studied the feasibility of decentralised PID control of TDC and BDC position in a single piston free-piston gas generator, with variable gas pressure bounce chamber. Experimental results indicated that a satisfactory performance could be achieved using this control strategy. Tikkanen et al. [6] investigated the control of a dual piston hydraulic free-piston engine with a feedforward propagation of the disturbance. A acceptable compression ratio control was gained. Mikalsen et al. analyzed the control of piston dead centre positions of a single piston free-piston engine generator. The influences on position control of different variables were given. Standard feedback ideas were used in the controller to get an adequate performance for moderate load changes. A predictive control system was also proposed to improve the dynamic response under highly varying loads [7, 8].

The HFPDE control strategy is a standard feedback control method. It contains different functions for its different operations. The starting operation takes charge of the first cycle of the engine. It needs to adjust the compression pressure and the reset valves should cooperate with the FCV to avoid squirm of the piston for hydraulic leakages. The stable operation offers the working frequency control and the working pressure control. The working frequency has a linear relationship with the output horsepower and the output flow. The working pressure determines the quantity of fuel injected and the energy balance between them is the foundation of the stable operation. Misfire of the HFPDE causes risky cases, such as decrease of the working frequency and pressure. The misfire operation should accomplish the restarting of the HFPDE and the time cost must as short as possible. A program for protecting the exhaust valve from hitting by the piston is running on all operations. The program uses both piston displacement and velocity feedback. An inaccurate response may damage the mechanical structure of the engine [10].

III. EXPERIMENTAL SET-UP

The measuring devices are mentioned in table Ⅰ and the control parameters are mentioned in table Ⅱ.

TABLE I. MEASURING EQUIPMENT

Test parameters	**Type of the sensor**
Cylinder pressure	Kistler 6055BB, charge amplifier
Piston displacement	Laser displacement sensor, ZLDS100
Valve lift	Laser displacement sensor, LD1607-200
Hydraulic pressure	HYDAC-600
Data acquisition	National Instruments DAQ device with LabVIEW

TABLE II. CONTROL PARAMETERS

Control parameters	**Value**
Compression chamber pressure (MPa)	16.5
High pressure rail pressure (MPa)	13
Low pressure rail pressure (MPa)	1
Driving pressure of HEUI and valve (MPa)	16.5
Scavenging pressure (bar)	1.2
Fuel-injection timing (mm BTDC)	24
Cycle Fuel injection quantity (mg)	21.9
Exhaust valve timing(mm ATDC)	58
Exhaust valve signal pulse width(ms)	10

Working frequency(Hz)	8.7

IV. TEST RESULTS AND DISCUSSION

A. Piston dynamics

The piston dynamics of the HFPDE was studied by experiment. It was found that the piston motion profile of the hydraulic free-piston diesel engine differs from that of conventional engines, with the main difference being significantly higher piston velocity and acceleration around TDC, and other papers confirmed that [1, 3].

Fig. 6 gives test piston motion in the stable operation of the prototype. The working frequency of the prototype is about 8.7Hz. As shown in Fig. 6, in the stable operation, the differences of piston motion profile between each cycle is observable. A stroke uniformity is achieved more easily in compression stokes, because the piston stroke in the expansion stroke is longer than that in the compression stroke considered the rebound.

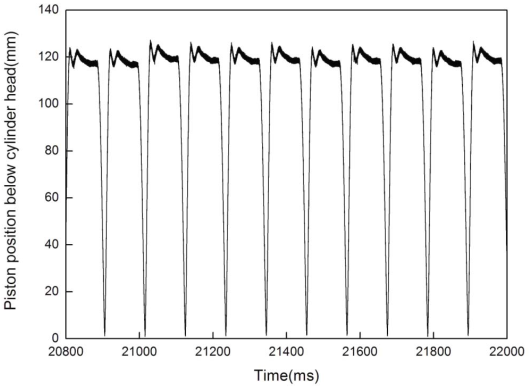
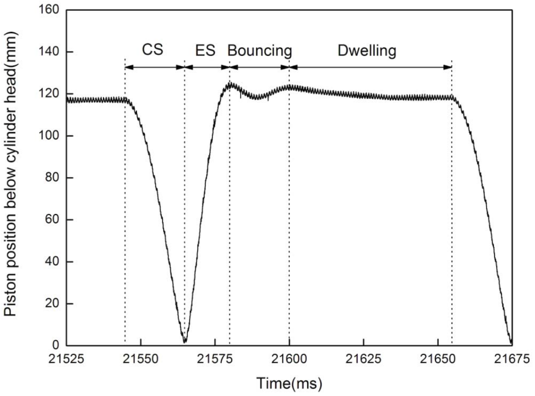


Figure 6. Test of piston displacement.

As can be gathered from Fig. 7, a single cycle of HFPDE consists of four processes: compression stroke, expansion stroke, bouncing, and dwelling. The compression stroke takes 23ms, and the expansion stroke takes 15ms.In conventional engines, the piston motion profile is determined by crank system, and that makes the time of one cycle almost constant. In the free-piston engine, the piston motion at any point in the cycle is determined by the instantaneous force balance on the piston. It can be noted that the piston motion profile of HFPDE is asymmetrical around TDC, leading to the engine spending slightly more time in the compression stroke than in the expansion stroke.

Furthermore, different from the crankshaft engine, the single cycle of HFPDE comprises bouncing and dwelling process. When the piston reaches the BDC, the compression accumulator will be closed. The piston will be pushed back in the direction of the TDC. The pressure in compression chamber will decrease rapidly because of the increase of compression chamber volume. Meanwhile, due to the control chamber pressure, the piston will stop after several rebounds, until the next frequency control signal.

Fig. 8 shows the piston speed during a single engine cycle. The peak piston speed during the expansion stroke is 50% higher than that during the compression stroke.



CS-Compression stroke, ES-Expansion stroke.

Figure 7. Piston displacement of single cycle .

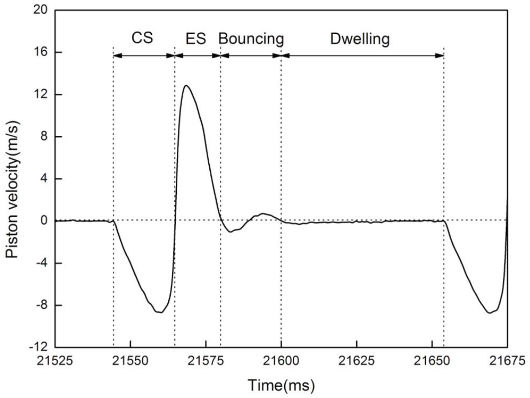


Figure 8. Piston velocity of single cycle.

As shown in Fig. 9, it seems that the HFPDE has significantly higher piston acceleration shortly around TDC. The accelerating forces on the piston are at maximum around TDC, consequently the acceleration has a maximum value around TDC [3]. In comparison to the crankshaft engine, the piston acceleration in HFPDE is about 3 times higher.

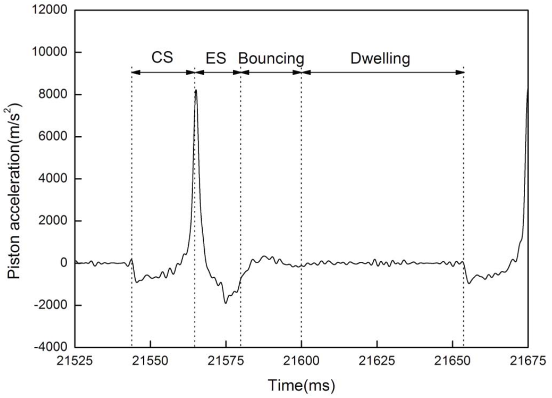
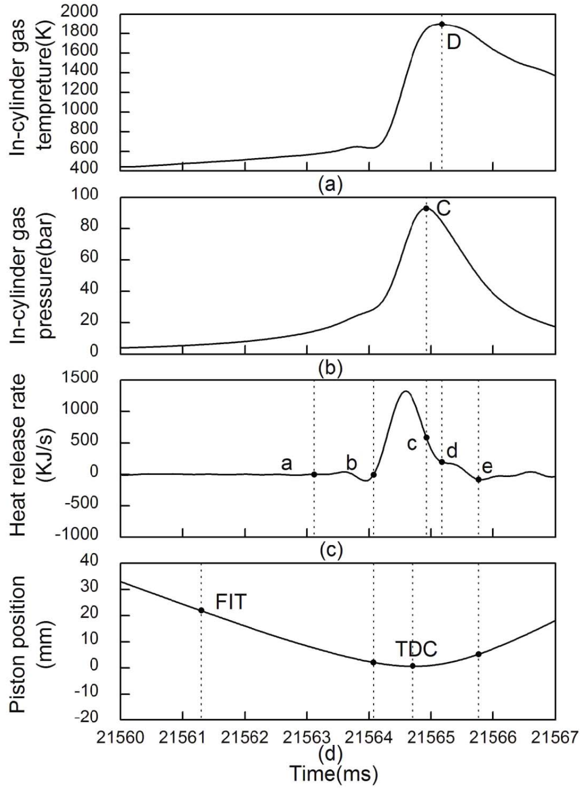


Figure 9. Piston acceleration of single cycle.

B. *The combustion process*

Having investigated piston dynamic, the combustion process was studied in order to identify effects of the piston motion profile on the combustion process in the free-piston engine.

As shown in Fig. 10, combustion analysis has been done by calculating the rate of heat release from measured data. The typical heat-release-rate diagram for free-piston engine is shown in Fig. 10(c). According to the definition of the conventional compression-ignition diesel combustion stages, the combustion process of HFPDE can also be defined four stages: Ignition delay (ab), Pre-mixed combustion phase (bc), Mixing-controlled combustion phase (cd), and Late combustion phase (de).



FIT-fuel injection timing, TDC-top dead center.

Figure 10. Heat release rate of HFPDE calculated from measured data.

It seems that most of the fuel burns in the pre-mixed phase, resulting in a very high rate of heat release with pressure gradients of two times those of a comparable conventional engine. Similar results were also found by Somhorst and Achten [12]. Different from conventional engine, HFPDE doesn't have crank and connecting rod, so the kinematic principle is different. As in conventional engine, a change of the cylinder volume results in a change of the cylinder pressure. But, in HFPDE, an increase of the cylinder pressure also results an increased piston acceleration and a faster change of the cylinder volume. That makes in-cylinder pressure and temperature decreased rapidly. So the mixing-controlled combustion phase and late combustion phase are very short in HFPDE. That demands higher requirement of the combustion organization of HFPDE.

In Fig. 10(c), the combustion duration in HFPDE is very short, 1.14ms. The main combustion phase is Pre-mixed combustion phase, and 60% fuel burns before TDC. In this test, the indicated efficiency is about 42.7%. It is seemed that the indicated efficiency can be increased by optimizing the combustion process. As can be seen in Fig. 10(a) the average temperature in the combustion chamber dropped rapidly. That will reduce the heat losses and make HFPDE have potential advantages on fuel efficiency and emissions reduction.

C. The pump chamber pressure

Fig. 11 shows the measured pressure output of pump chamber with piston displacement. In the compression stroke, due to the pump chamber volume increases, the pump chamber pressure decreases. Soon after the piston has reached the BDC, the suction valve in the pump chamber will open. The oil in the low pressure tail will start to flow into pump chamber. After the piston reached TDC, because of the response lag of suction valve, the pump chamber pressure increased slowly at first. And the pump chamber pressure rise rapidly when the suction valve is fully closed. It is seemed that the response lag between the pump chamber pressure and the piston displacement at the start of the expansion stroke is mostly determined by the close action of the suction valve. This possibly reduces in-cylinder heat transfer losses and temperature dependent emissions formation [9].

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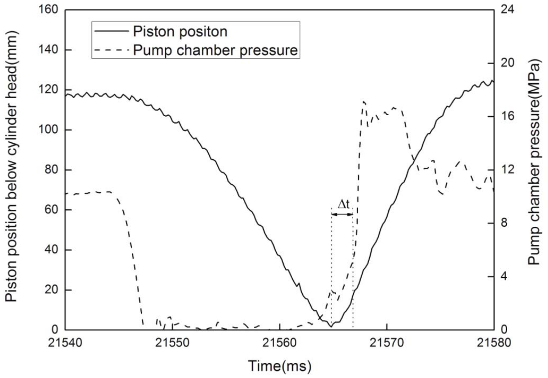

Figure 11. Piston displacement and pump chamber pressure vs. time.

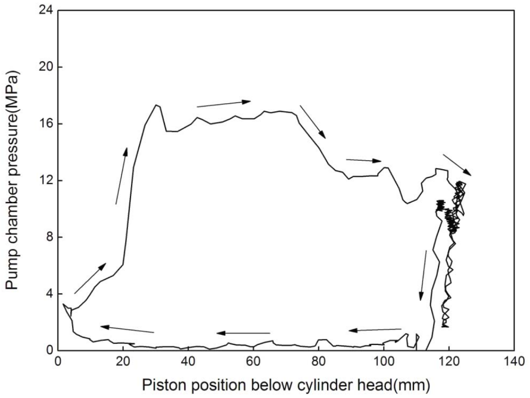

Figure 12. Test pump chamber pressure vs. piston displacement.

So far total efficiency of the HFPDE could reach nearly about 38% [10] in one engine cycle, based on simulation. And the test total efficiency is about 37% [11], without considering the power loss brought by the driving system of fuel injection, valve control and Rooth blower. A motor about 3.7 kW is used to drive the Rooth blower in the test and the power calculated by simulation is about 0.8kW. The energy used for scavenging costs about 5% of the engine indicated work. The main power loss is brought by power losses in the fuel combustion process and the response lag of the suction valves on the pump chamber. An optimization on combustion process and suction valves is significant for the performance of the engine.

V. CONCLUSIONS

The design of a single piston hydraulic free-piston diesel engine was given and a discussion on the basic test results was presented to give insight into the basic performance and operation of the hydraulic free-piston diesel engine. The piston dynamics, the combustion process and pressure output were investigated from test data.

The basic characteristics of HFPDE were found to be similar with the results of the previous researches. The HFPDE has significantly higher piston speed and acceleration shortly around TDC. Different from conventional engine, the main combustion phase is Pre-mixed combustion phase. Most of the fuel burns in the pre-mixed phase, resulting in a very high rate of heat release. The average temperature in the combustion chamber is lower than comparable conventional engine. It makes HFPDE have a potential advantage on emissions reduction. The HFPDE spends more time in compression stroke, which is a better state for the low pressure oil suction of the pump chamber. The fast commutation of the piston motion at TDC demands a fast close action of the suction valve on the pump chamber. The response lag leads a much faster power stroke expansion. This results in a decrease of volumetric efficiency of the pump chamber. Furthermore, it causes power loss and fuel economy becomes lower.

The results can be used for the design and optimization of a single piston hydraulic free-piston engine. Other free-piston engine topics that should be further investigated include the effects of fuel injection timing and the potential for operation optimization, along with the use of alternative or low-quality fuels.

ACKNOWLEDGMENT

This work is supported by the National Ministry Fundamental Research Foundation of China (Grant no. A2220060053). The authors wish to thank the INNAS BV for their creative work on the hydraulic free-piston engine.

The authors also wish to thank referees for the quality improving of the paper.

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