Applied Energy 179 (2016) 888–898

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Experimental study of hydraulic electronic unit injector in a hydraulic free piston engine

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HIGHLIGHTS

- A hydraulic electronic unit injector in HFPE is developed and the test bench is established.
- Effect of drive pressure on injection delay of hydraulic electronic unit injector are investigated.
- Cycle fuel injection quantity is tested online and off-line engine operation.
- The BDC control results in HFPE based on feed-forward compensation are acceptable.
- The energy flow in HFPE is analyzed and the hydraulic output energy is optimized.

ARTICLE INFO

Article history:
Received 11 April 2016
Received in revised form 13 July 2016
Accepted 15 July 2016

Keywords:
Hydraulic electronic
Free piston engine
Control
Injection
Energy flow

ABSTRACT

The fuel injection system in two stroke engine is very important, therefore the hydraulic electronic unit injector system is developed and the injection characteristics of hydraulic electronic unit injector are investigated. Firstly the HFPE and the hydraulic electronic unit injector working principle are analyzed, and then PID control strategy is built by engine demand. In order to validate the feasibility of hydraulic electronic unit injector, the prototype test bench is established. The specific measurement principle is presented. Further the injection characteristics, such as the effect of injection pressure on injection delay and the effect of engine frequency on injection delay, are analyzed. In order to optimize the engine stability performance, the BDC control based on fuel injection control is investigated. The load control based on fuel injection is also discussed and the BDC feedforward control with the load variation is investigated. Experiment results of stead engine operation shows that the hydraulic electronic unit injector system based on PID control can be satisfied with the engine operation demand. In addition, cycle fuel injection quantity is tested online and off-line engine operation. It is obvious that the fuel injection quantity is affected by the hydraulic pressure. The fuel injection quantity variation can be improved with decreasing the fluctuation of drive pressure or adopting more suitable oil common rail instead of connected with exhaust valve hydraulic drive oil-way. The energy flow in HFPE is analyzed and the hydraulic output energy can be optimized by selecting suitable hydraulic valves parameters. The fuel injection quantity should be designed by the energy balance and the stable operation requirement in spite of the higher thermal efficiency.

1. Introduction

The free-piston engine (FPE) concept has been developed for nearly one century. Many researchers have done efforts on it and various engines were manufactured by many auto companies such as GM, Ford, and Renault [1,2]. Free piston engines can be designed as various kinds of engines such as free piston gasifiers [1,3], hydraulic free-piston engine (HFPE) [4–8] and free piston engine generator (FPEG) [9,10]. HFPE is a combination of combustion engine and a hydraulic linear pump. It is a rigid connection between the combustion piston and the pump plunger. The combustion energy is directly converted to hydraulic energy. There is no connecting rod and crank shaft in the HFPE which results in less mechanical structure. Therefore the free piston engine has advantages of simple construction and the variable compression ratio compared to the crank-shaft engines, which can improve the engine performance by adopting various fuels in required conditions.

This high energy efficient conversion system is consisted of combustion part and the hydraulic pump part. For the hydraulic part, researchers have proposed proper methods for controlling

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http://dx.doi.org/10.1016/j.apenergy.2016.07.051

Nomenclature

Abbreviation

BDC	Bottom Dead Center
CoV	Coefficients of Variations
ECU	Electronic Control Unit
FCV	Frequency Control Valve
FPE	Free Piston Engine
FPEG	Free Piston Engine Generator
HEUI	Hydraulic Electronic Unit Injector
HFPE	Hydraulic Free-Piston Engine
PID	Proportion Integration Differentiation
PPM	Pulse Pause Modulation
TDC	Top Dead Center

Symbols

C_1	velocity coefficient of gas in cylinder
C_2	combustion chamber shape coefficient
c_{f}	the viscous damping coefficient
c_{pEX}	exhaust specific heat at constant pressure, J
D	power piston bore, m
D_{L}	hydraulic load, MPa
d_k	piston diameter, m
E_{HPinput}	the hydraulic energy absorbed, J
E_{HPoutput}	the output hydraulic energy, J
E_{EIW}	effective indicated work, J
E_{EL}	the hydraulic leakage energy, J
E_{EX}	energy that the exhaust gas takes away, J
E_{FL}	the energy loss from the friction force and the viscous damping force, J
ΔE_H	output hydraulic energy of HFPE, J
E_l	load energy, J
E_i	input energy, J
E_{SC}	energy consumed by root pump, J
E_{VTL}	hydraulic valve throttling loss, J
e_i	error value in current sampling
e_{i-1}, e_{i-2}	error value before current sampling
f	friction coefficient
h_k	hight of clearance in radius deraction, m
H_{u}	low calorific value of fuel, J/kg
K_{L}	load coefficient
L_k	length of clearance in axial deraction, m
$\mathrm{m_f}$	cycle fuel injection quantity, kg
N	cycles
n	polytropic exponent
p	pressure of gas in cylinder, Pa
p_0	pressure of cylinder in motoring condition, Pa
p_1	pressure of cylinder when the combustion starts, Pa
p_H	pressure of high pressure rail, MPa
p_L	pressure of the low pressure rail, MPa
Δp_{V}	pressure difference of the hydraulic valve, Pa
$\Delta p_{\mathrm{O}k}$	pressure difference of the pump clearance, Pa
p_{Ri}	intake pressure of root pump, Pa
p_{Ro}	outlet pressure of root pump, Pa
q_{H}	volume flow of high pressure rail, $\mathrm{m^3/s}$
q_{L}	volume flow of low pressure rail, $\mathrm{m^3/s}$
q_{V}	volume flow of valve, $\mathrm{m^3/s}$
q_{VRi}	intake volume flow of root pump, $\mathrm{m^3/s}$
q_{MEX}	exhaust gas mass flow, kg/s
Q_{HTL}	energy loss of heat transfer, J
Q_{RE}	released energy of diesel combustion, J
S_{wall}	heat transfer area, $\mathrm{m^2}$
T	temperature of gas in cylinder, K
T_1	cylinder temperature when the combustion starts, K
T_0	atmospheric temperature, K
T_{EX}	exhaust gas temperature, K
T_{wall}	temperature of heat transfer wall, K
t_{EVC}	exhaust valve close timing
t	time
t_{CSBDC}	BDC timing in compression stroke
t_{EVO}	exhaust valve open timing
t_{ESBDC}	BDC timing in expansion stroke
t_{IC}	intake port close timing
t_{IO}	Intake port open timing
Δu_i	output value of controller in current sampling
v	piston velocity, m/s
V_1	cylinder volume when the combustion starts, $\mathrm{m^3}$
V_{C}	cylinder volume, $\mathrm{m^3}$
V_P	displacement of hydraulic pump in one cycle, $\mathrm{mm^3}$
$\overline{X}$	mean value of parameters
$X(i)$	measured variables
x_{timing}	injection timing
x_{BDC}	real BDC position
x^*_{BDC}	designed BDC position

Greeks

η_{u}	combustion efficiency
η_{i}	indicated thermal efficiency
$\mu_{\mathrm{O}k}$	the oil dynamic viscosity, Pa s
σ_X	standard deviation of parameters

hydraulic energy [11]. On the other hand, the combustion engine part, including the fuel injection system and the scavenging system. The injection system must be one of the most important systems of the engines. As there is no crank-shaft in the HFPE and it is inconvenient to supply the fuel by high pressure pump. Many researches involved the fuel injection process of two stroke engines in the FPE field. Jia et al. adopted the PFI system with integrated electric fuel pump in a FPEG. The pump conveys the required amount of fuel from the tank to the injectors at a constant pressure. The fuel is injected into the intake manifold to form a stoichiometric air/fuel mixture [12]. Similarly, the researchers also utilized the electronically controlled common-rail fuel injection system for better fuel atomization. The system accurately controls the fuel injection timing and mass flow [13]. For the diesel free piston engine, the fuel injection pressure reaches 100–200 MPa as the diesel fuel should be atomized as much as possible. Literature [14] utilized the HEUI injection system and developed the electronic control system. The hydraulic actuation of the fuel injector is directly realized by means of the hydraulic pump part. However the specific characteristics of HEUI are not mentioned. Actually, the injection system of diesel engine is complex as the high pressure of fuel should be obtained by fuel pump. In the HFPE case, there is no crank shaft and the fuel pump is inconvenient. The HEUI system may be more suitable for the HFPE.

For the specific HEUI system, many researchers focused on the development and performance validation of HEUI system in conventional combustion engine. Wang et al. concluded that common-rail pressure and length of the injection rate-shaping pipe determine the injection pressure in HEUI system, while the pressure rising rate and injection duration determines the peak injection pressure [15]. Posey et al. used time-averaged rate analysis and the control system specifies discrete voltage pulses to conform the HEUI's injection rate to reference input based on fuel consumption requirements [16]. Hardy and Reitz utilized the advantage that a very wide range of crankshaft timings (from approximately 90° BTDC to 90° after TDC) to realize the premixed charge compression