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# 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

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# 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.

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### 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

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http://dx.doi.org/10.1016/j.apenergy.2016.07.051 0306-2619/© 2016 Elsevier Ltd. All rights reserved. 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







#### Nomenclature

BDC CVBottom Dead Center $p_1$ pressure of cylinder when the combustion starts, Pa CVCV COEfficients of Variations $p_H$ pressure of high pressure rail, MPaCU EL EL EL PEFFrequency Control Valve $\Delta p_V$ pressure difference of the hydraulic valve, Pa $\Delta p_{Ox}$ pressure of root pump, PaPFE Free Piston Engine HPIDHydraulic Free-Piston Engine $q_{H1}$ volume flow of high pressure rail, m <sup>3</sup> /sPID PMP Pulse Pause Modulation C2 C $q_{V}$ volume flow of low of root pump, m <sup>3</sup> /s $q_{VRX}$ exhaust gas mass flow, kg/sSymbols C2 C2 C4 C4 C4 C4 C4 C4 C4Te velocity coefficient of gas in cylinder $Q_{RR}$ exhaust specific heat at constant pressure, J $T_1$ cylinder temperature when the combustion starts, K $Q_{IIII}$ released energy of diesel combustion starts, K $Q_{IIIII}$ released energy of diesel combustion starts, K $Q_{IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII$	Abbreviation		$p_0$	pressure of cylinder in motoring condition, Pa
$CoV$ Coefficients of Variations $p_{I}$ pressure of high pressure rail, MPaECUElectronic Control Unit $p_{I}$ pressure of high pressure rail, MPaECUElectronic Control Valve $\Delta p_{V}$ pressure difference of the hydraulic valve, PaPFEFree Piston Engine $\Delta p_{V}$ pressure difference of the pump clearance, PaPFEGFree Piston Engine Generator $p_{Ri}$ intake pressure of root pump, PaHEUIHydraulic Electronic Unit Injector $p_{Ro}$ outlet pressure of root pump, PaHEPEHydraulic Free-Piston Engine $q_{H}$ volume flow of low pressure rail, $m^3/s$ PPMPulse Pause Modulation $q_V$ volume flow of low pressure rail, $m^3/s$ PDProportion Integration Differentiation $q_{V}$ volume flow of low of root pump, PaIDCTop Dead Center $q_{WR}$ exhaust gas mass flow, $kg/s$ SymbolsQHTenergy loss of heat transfer, JC1velocity coefficient of gas in cylinderQasreleased energy of diesel combustion, JC2combustion chamber shape coefficientSvainTtemperature, KDpower piston bore, mToToatmosfer at ansfer at ansfer at an featDpower piston diameter, mToatmosfer atmosfer at ansfer at ansfer at ansfer at ansfer at ansfer at an featElevatorthe hydraulic load, MPaToxexhaust gas takes away, JElevatorthe hydraulic energy absorbed, JtrytryElevatorenergy consumed by root pump, Jtow <td>BDC</td> <td>Bottom Dead Center</td> <td><math>p_1</math></td> <td>pressure of cylinder when the combustion starts, Pa</td>	BDC	Bottom Dead Center	$p_1$	pressure of cylinder when the combustion starts, Pa
ECUElectronic Control Unit $p_i$ pressure of the low pressure rail, MPaFCVFrequency Control Valve $Ap_{V}$ pressure difference of the hydraulic valve, PaPFEFree Piston Engine $Ap_{Ok}$ pressure difference of the hydraulic valve, PaPFEGFree Piston Engine Generator $P_{Bi}$ intake pressure of root pump, PaHUIHydraulic Erec-Piston Engine $q_H$ volume flow of high pressure rail, $m^3/s$ PMDProportion Integration Differentiation $q_i$ volume flow of valve, $m^3/s$ PMDPulse Pause Modulation $q_V$ volume flow of valve, $m^3/s$ Symbols $Q_{WR}$ intake volume flow of root pump, $n^3/s$ $Q_{WR}$ exhaust gas mass flow, kg/sSymbols $Q_{WR}$ entransfer, JC1velocity coefficient of gas in cylinder $Q_{kR}$ C2combustion chamber shape coefficient $T_{in}$ C4the viscous damping coefficient $T_{in}$ C5power piston bore, m $T_0$ D1hydraulic load, MPa $T_{kx}$ D2power piston bore, m $T_0$ D4hydraulic load, MPa $T_{kx}$ EHFINDUthe volupt Hydraulic load, MPa $T_{kx}$ EHFINDUthe hydraulic energy absorbed, JtraveEHFINDUthe hydraulic energy absorbed, JtraveEHFINDUthe hydraulic energy absorbed, JtraveEHFINDUthe hydraulic energy of HFPE, J $Q_{ki}$ EHFINDUthe hydraulic energy of HFPE, J $Q_{ki}$ EHF	CoV	Coefficients of Variations	$p_H$	pressure of high pressure rail, MPa
FCVFrequency Control Valve $\Delta p_{V}$ pressure difference of the hydraulic valve, PaFPEFree Piston Engine Generator $P_{Ri}$ intake pressure of root pump, PaHEUIHydraulic Electronic Unit Injector $P_{Ro}$ outlet pressure of root pump, PaHEUIHydraulic Free-Piston Engine $q_{H}$ volume flow of low pressure rail, $m^3/s$ PIDProportion Integration Differentiation $q_{L}$ volume flow of low pressure rail, $m^3/s$ PIDProportion Integration Differentiation $q_{V}$ volume flow of low of root pump, $m^3/s$ PMDPulse Pause Modulation $q_{V}$ volume flow of root pump, $m^3/s$ PMDDebad Center $q_{WRI}$ intake volume flow of root pump, $m^3/s$ SymbolsQarrreleased energy of diesel combustion, JC1velocity coefficient of gas in cylinder $Q_{RRI}$ released energy of diesel combustion, JC2combustion chamber shape coefficient $T_1$ cylinder temperature, KCptxexhaust specific heat at constant pressure, J $T_1$ cylinder temperature, KDpower piston bore, m $T_0$ atmospheric temperature, KDhydraulic load, MPaTexexhaust gas temperature, K $E_{HIPOHPH}$ theydraulic energy.Jtcwc $E_{RL}$ hydraulic energy.Jtcwc $E_{RL$	ECU	Electronic Control Unit	$p_I$	pressure of the low pressure rail, MPa
FPE Free Piston Engine $\Delta p_{0k}$ Pistpressure difference of the pump clearance, PaFPEG Free Piston Engine Generator $p_{Ri}$ intake pressure of root pump, PaHEUL Hydraulic Electronic Unit Injector $p_{Ri}$ outlet pressure of root pump, PaHFPE Hydraulic Free-Piston Engine $q_{H}$ volume flow of high pressure rail, m <sup>3</sup> /sPID Proportion Integration Differentiation $q_{L}$ volume flow of low pressure rail, m <sup>3</sup> /sPID Proportion Integration Differentiation $q_{L}$ volume flow of volve, m <sup>3</sup> /sPID CTop Dead Center $q_{VRi}$ intake volume flow of root pump, m <sup>3</sup> /s $q_{VRi}$ intake volume flow of root pump, m <sup>3</sup> /s $q_{VRi}$ $c_1$ velocity coefficient of gas in cylinder $Q_{RE}$ released energy of diesel combustion, J $C_2$ combustion chamber shape coefficient $T_{VR}$ released energy of diesel combustion starts, K $C_p$ velocity coefficient of gas in cylinder $S_{VRI}$ energy loss of heat transfer val. $D_p$ power piston bore, m $T_0$ atmospheric temperature, K $D_p$ mydraulic load, MPa $T_{EX}$ exhaust gas temperature, K $d_k$ piston diameter, m $T_{VRI}$ temperature of heat transfer val. $E_{FINPWH}$ the hydraulic energy, Jtztume $E_{FINPWH}$ the hydraulic energy of HFPE, J $L_{SSNC}$ BDC timing in compression stroke $E_{FIN}$ energy that the exhaust gas takes away, Jtstransfer val. $E_{FIN}$ the engry loss from the frict	FCV	Frequency Control Valve	$\Delta p_{\rm V}$	pressure difference of the hydraulic valve, Pa
FPEGFree Piston Engine Generator $p_{Ri}$ intake pressure of root pump, $Pa$ HEUIHydraulic Electronic Unit Injector $p_{Ro}$ outlet pressure of root pump, $Pa$ HEUIHydraulic Electronic Unit Injector $p_{Ro}$ outlet pressure of root pump, $Pa$ HPEHydraulic Tecer-Piston Engine $q_{H}$ volume flow of high pressure rail, $m^3/s$ PIDProportion Integration Differentiation $q_L$ volume flow of low pressure rail, $m^3/s$ PPMPulse Pause Modulation $q_V$ volume flow of root pump, $Pa$ TDCTop Dead Center $q_{WL}$ intake volume flow of root pump, $n^3/s$ SymbolsQirrenergy loss of heat transferJC1velocity coefficient of gas in cylinderQirrreleased energy of diesel combustion, JC2combustion chamber shape coefficientTtemperature of gas in cylinder, KCptxexhaust specific heat at constant pressure, JT1cylinder temperature of gas in cylinder, KDpower piston bore, mTokTokatmospheric temperature, KD1hydraulic load, MPaTexexhaust valve close timingEHrimputthe output hydraulic energy, JttimeEHrimputthe hydraulic energy of HFPE, JttimeEHrimputthe energy loss from the friction force and the viscoustimeEHrimputthe hydraulic energy of HFPE, J $\Delta U_i$ Output hydraulic energy of HFPE, J $V_1$ cylinder volume handersEritinput energy, JVintake p	FPE	Free Piston Engine	$\Delta p_{0k}$	pressure difference of the pump clearance, Pa
HEUI HUP Hydraulic Electronic Unit Injector $p_{Ro}^{T}$ $q_{H}$ outluet pressure of root pump, Pa $q_{H}$ HFPE HVD Proportion Integration Differentiation $q_{L}$ volume flow of low pressure rail, $m^{3}/s$ PPM PUD Poportion Integration Differentiation $q_{L}$ volume flow of low pressure rail, $m^{3}/s$ PPM PUS PostPulse Pause Modulation $q_{L}$ volume flow of valve, $m^{3}/s$ TDCTop Dead Center $q_{WRi}$ (intake volume flow of root pump, $m^{3}/s$ $q_{WRi}$ Symbols C1velocity coefficient of gas in cylinder $Q_{RE}$ (combustion chamber shape coefficientC2 Cpxcombustion chamber shape coefficient $S_{wall}$ (heat transfer area, $m^{2}$ Cf Cpxvelocity coefficient of pas in cylinder $T_{L}$ (combustion chamber shape coefficientD D power piston bore, mT T (comperative) constant pressure, JT (comperative) constant pressure, J T (comperative) constant pressure, JD L hydraulic load, MPaTex temperature of past transfer wall, K temperature, KD L Hydraulic cenergy absorbed, Jtevc tex tex the hydraulic cenergy absorbed, JEHouput EH Huput the hydraulic cenergy, Jtot temperature, KEH EWenergy that the exhaust gas takes away, JEH EWtenergy that the exhaust gas takes away, JE ER the hydraulic leakage energy, Jtot tessorE Huput thydraulic energy of HFPE, J $U_{H}$ toyAE Huput thydraulic energy of HFPE, J $U_{H}$ toyAE <b< td=""><td>FPEG</td><td>Free Piston Engine Generator</td><td><math>p_{Ri}</math></td><td>intake pressure of root pump, Pa</td></b<>	FPEG	Free Piston Engine Generator	$p_{Ri}$	intake pressure of root pump, Pa
HFPEHydraulic Free-Piston Engine $q_{H}$ volume flow of high pressure rail, $m^3/s$ PIDProportion Integration Differentiation $q_{L}$ volume flow of low pressure rail, $m^3/s$ PIDPulse Pause Modulation $q_{V}$ volume flow of volve, $m^3/s$ TDCTop Dead Center $q_{VRi}$ intake volume flow of root pump, $m^3/s$ Symbols $Q_{RE}$ energy loss of heat transfer, JC1velocity coefficient of gas in cylinder $Q_{RE}$ released energy of diesel combustion, JC2combustion chamber shape coefficient $T_{u}$ temperature of gas in cylinder, KCpExexhaust specific heat at constant pressure, J $T_1$ cylinder temperature, KDpower piston bore, m $T_0$ atmospheric temperature, KDpower gas borbed, Jtrawtransfer value, KEHHoutputthe output hydraulic energy. JttEHHoutputthe output hydraulic energy. JttERthe hydraulic date work, JttmeerERthe energy loss from the friction force and the viscousBDC timing in compression strokeERenergy of output hydraulic energy. J $V_1$ output value of controller in current sampling $E_1$ load energy, J $V_2$ vicinder volume, misERinput energy. J $V_1$ output value of controller in current sampling $F_1$ load energy. J $V_2$ vicinder volume, mis $F_1$ load energy. J $V_2$ vicinder volume, mis $F_1$ load	HEUI	Hydraulic Electronic Unit Injector	$p_{Ro}$	outlet pressure of root pump, Pa
PID PID POP Pulse Pause Modulation $q_L$ $q_V$ volume flow of low pressure rail, $m^3/s$ $q_V$ volume flow of valve, $m^3/s$ $q_V$ volume flow of valve, $m^3/s$ $q_V$ intake volume flow of root pump, $m^3/s$ $q_V$ $q_V$ intake volume flow of root pump, $m^3/s$ $q_V$ $q_W$ <	HFPE	Hydraulic Free-Piston Engine	$q_{\rm H}$	volume flow of high pressure rail, m <sup>3</sup> /s
PPMPulse Pause Modulation $q_V$ volume flow of valve, m³/sTDCTop Dead Center $q_{VRI}$ intake volume flow of root pump, m³/sSymbols $q_{VRI}$ intake volume flow of root pump, m³/sSymbols $Q_{HTL}$ energy loss of heat transfer, JC1velocity coefficient of gas in cylinder $Q_{EE}$ released energy of diesel combustion, JC2combustion chamber shape coefficient $S_{wall}$ heat transfer area, m²C4the viscous damping coefficientTtemperature of gas in cylinder, KC5power piston bore, mToatmospheric temperature, kD1hydraulic load, MPaTEXexhaust gas temperature, KD4hydraulic load, MPaTeXexhaust valve close timingEHIPDUPUtthe voltput hydraulic energy, JttimeEHIPDUPUtthe output hydraulic energy, JttimeEExenergy loss from the friction force and the viscoustcBDC timing in compression strokeEFLin energy, Jtticcintake port opent timingEFLload energy, JVviption voluce(v, m/sEFLinput energy, JVviption voluce(v, m/sEFLinput energy, JVviption voluce(v, m/sEFLinput energy, JVviption voluce(v, m/sEFLthe viscue gas takes away, JtessocBDC timing in expansion strokeEFLthe hydraulic energy of HFPE, J $\Delta u_i$ output value of controller in current samplingEFL<	PID	Proportion Integration Differentiation	$q_{\rm L}$	volume flow of low pressure rail, m <sup>3</sup> /s
TDCTop Dead Center $q_{VRi}$ intake volume flow of root pump, m³/sSymbols $q_{MEX}$ exhaust gas mass flow, kg/sSymbols $Q_{HTL}$ energy loss of heat transfer, JC1velocity coefficient of gas in cylinder $Q_{RE}$ released energy of disel combustion, JC2combustion chamber shape coefficient $S_{wall}$ heat transfer area, m²Cfthe viscous damping coefficientTtemperature of gas in cylinder, KCpExexhaust specific heat at constant pressure, JT1cylinder temperature, KDpower piston bore, mT0atmospheric temperature, KDLhydraulic load, MPaTExexhaust gas temperature, KEHPinputthe hydraulic energy absorbed, Jtrevcexhaust valve close timingEHPuinputthe hydraulic energy, JttimeEHEWeffective indicated work, JtcsmocBDC timing in compression strokeEELthe energy lost from the friction force and the viscousticintake port close timingdamping force, JV1cylinder volume when the combustion starts, m³EALload energy, JV1cylinder volume when the combustion starts, m³Eq.energy tot the current samplingV1cylinder volume, m³EALoutput hydraulic energy of HFPE, J $\Delta u_i$ output value of controller in current samplingEALload energy, JV2cylinder volume, m³Eq.energy consumed by root pump, JV2cylinder volume, m³Eq.iput ener	PPM	Pulse Pause Modulation	$q_{\rm V}$	volume flow of valve, m <sup>3</sup> /s
Symbols $q_{MEX}$ exhaust gas mass flow, kg/sSymbols $Q_{TE}$ energy loss of heat transfer, J $C_1$ velocity coefficient of gas in cylinder $Q_{RE}$ released energy of diesel combustion, J $C_2$ combustion chamber shape coefficient $T$ temperature of gas in cylinder, K $C_{pt}$ the viscous damping coefficient $T$ temperature of gas in cylinder, K $C_{ptx}$ exhaust specific heat at constant pressure, J $T_1$ cylinder temperature when the combustion starts, K $D$ power piston bore, m $T_0$ atmospheric temperature, K $D_L$ hydraulic load, MPa $T_{EX}$ exhaust gas temperature, K $d_k$ piston diameter, m $T_{wall}$ temperature of heat transfer wall, K $E_{HPoutput}$ the hydraulic energy, J $t_{EV}$ exhaust valve close timing $E_{HPoutput}$ the dydraulic leakage energy, J $t_{EV}$ exhaust valve open timing $E_{EW}$ effective indicated work, J $t_{CSBDC}$ BDC timing in compression stroke $E_{ER}$ the hydraulic leakage energy of HFPE, J $\Delta u_i$ output value open timing $d_{energy}, J$ $V_1$ cylinder volume when the combustion starts, m <sup>3</sup> $E_{FL}$ input energy loss from the friction force and the viscous $t_{IC}$ $d_{energy}$ output hydraulic energy of HFPE, J $\Delta u_i$ $d_{energy}, J$ $V_1$ cylinder volume when the combustion starts, m <sup>3</sup> $E_{FL}$ load energy, J $V_1$ cylinder volume, m <sup>3</sup> $E_{ent}$ input energy, J <td>TDC</td> <td>Top Dead Center</td> <td><math>q_{\rm VRi}</math></td> <td>intake volume flow of root pump, m<sup>3</sup>/s</td>	TDC	Top Dead Center	$q_{\rm VRi}$	intake volume flow of root pump, m <sup>3</sup> /s
Symbols $Q_{HTL}$ energy loss of heat transfer, J $C_1$ velocity coefficient of gas in cylinder $Q_{RE}$ released energy of diesel combustion, J $C_2$ combustion chamber shape coefficient $T$ temperature of gas in cylinder, K $C_F$ the viscous damping coefficient $T$ temperature of gas in cylinder, K $D_p$ power piston bore, m $T_0$ atmospheric temperature, K $D_L$ hydraulic load, MPa $T_{EX}$ exhaust gas temperature, K $d_k$ piston diameter, m $T_{wall}$ temperature of heat transfer wall, K $E_HPinput$ the output hydraulic energy, Jttime $E_HW$ effective indicated work, JtcssocBDC timing in compression stroke $E_{HV}$ energy that the exhaust gas takes away, JtcssocBDC timing in compression stroke $E_{HL}$ the hydraulic energy of HFPE, J $\Delta U_i$ output hydraulic energy of HFPE, J $\Delta U_i$ $AE_H$ output hydraulic energy of HFPE, J $\Delta U_i$ output value of controller in current sampling $E_i$ input energy, J $V_1$ cylinder volume when the combustion starts, m <sup>3</sup> $E_i$ load energy, J $V_1$ cylinder volume, m <sup>3</sup> $E_i$ niput energy, C $V_1$ cylinder volume, m <sup>3</sup> $E_i$ input energy, J $V_1$ cylinder volume, m <sup>3</sup> $E_i$ input energy, J $V_1$ cylinder volume, m <sup>3</sup> $E_i$ input energy, J $V_1$ cylinder volume, m <sup>3</sup> $E_i$ input energy, J $V_1$ cylinder vo			$q_{\rm MEX}$	exhaust gas mass flow, kg/s
Drivevelocity coefficient of gas in cylinder $Q_{RE}$ released energy of diesel combustion, J $C_1$ combustion chamber shape coefficient $S_{wall}$ heat transfer area, $m^2$ $C_f$ the viscous damping coefficientTtemperature of gas in cylinder, K $C_{PEX}$ exhaust specific heat at constant pressure, J $T_1$ cylinder temperature when the combustion starts, K $D_1$ hydraulic load, MPa $T_{EX}$ exhaust gas temperature, K $d_k$ piston diameter, m $T_{wall}$ temperature of heat transfer wall, K $HPinput$ the output hydraulic energy, Jttime $EHPinput$ the output hydraulic energy, Jttime $E_{FL}$ the hydraulic leakage energy, Jt_ESDCBDC timing in compression stroke $E_{EX}$ energy that the exhaust gas takes away, Jt_ESDCBDC timing in expansion stroke $E_{FL}$ the energy loss from the friction force and the viscous $t_{IC}$ intake port close timing $d_{H}$ output hydraulic energy of HFPE, J $\Delta u_i$ output value of controller in current sampling $E_I$ input energy, J $V_1$ cylinder volume, m <sup>3</sup> $E_I$ input energy, J $V_2$ cylinder volume, m <sup>3</sup> $E_I$ input energy, J $V_2$ cylinder volume, m <sup>3</sup> $E_I$ input energy, J $V_1$ cylinder volume when the combustion starts, m <sup>3</sup> $E_K$ energy consumed by root pump, J $V_2$ cylinder volume, m <sup>3</sup> $E_I$ input energy, J $V_2$ cylinder volume, m <sup>3</sup>	Symbols		Q <sub>HTL</sub>	energy loss of heat transfer, J
$C_2$ combustion chamber shape coefficient $S_{wall}$ heat transfer area, $m^2$ $C_f$ the viscous damping coefficientTtemperature of gas in cylinder, K $C_{pEX}$ exhaust specific heat at constant pressure, JT1cylinder temperature when the combustion starts, K $D_p$ power piston bore, mTexexhaust gas temperature, K $D_L$ hydraulic load, MPaTexexhaust gas temperature, K $d_k$ piston diameter, mTwalltemperature of heat transfer wall, K $E_{HPinput}$ the output hydraulic energy, Jttimethe output hydraulic leakage energy, Jttime $E_{EL}$ the hydraulic leakage energy, JtcsBDCBDC timing in compression stroke $E_{EL}$ the energy loss from the friction force and the viscousticintake port close timing $d_{kH}$ output hydraulic energy of HFPE, J $\Delta u_i$ output value of controller in current sampling $\Delta E_H$ output hydraulic leakage vot pump, J $V_P$ cylinder volume when the combustion starts, m <sup>3</sup> $E_i$ input energy, J $V_P$ cylinder volume when the combustion starts, m <sup>3</sup> $E_i$ input energy, J $V_P$ cylinder volume, m <sup>3</sup> $E_i$ input energy, J $V_P$ displacement of hydraulic pump in one cycle, mm <sup>3</sup> $e_i$ error value in current sampling $X_i$ mean value of parameters $e_i$ friction coefficient $X_{BDC}$ displacement of hydraulic pump in one cycle, mm <sup>3</sup> $h_k$ hight of clearance in radius deraction, m <td>C1</td> <td>velocity coefficient of gas in cylinder</td> <td><math>Q_{RE}</math></td> <td>released energy of diesel combustion, J</td>	C1	velocity coefficient of gas in cylinder	$Q_{RE}$	released energy of diesel combustion, J
$c_f$ the viscous damping coefficientTtemperature of gas in cylinder, K $C_{pEX}$ exhaust specific heat at constant pressure, J $T_1$ cylinder temperature when the combustion starts, K $D$ power piston bore, m $T_0$ atmospheric temperature, K $D_L$ hydraulic load, MPa $T_{EX}$ exhaust gas temperature, K $D_k$ piston diameter, m $T_{wall}$ temperature of heat transfer wall, K $E_{HPinput}$ the hydraulic energy absorbed, J $t_{EVC}$ exhaust valve close timing $E_{HPinput}$ the output hydraulic energy, Jtt $E_{HPinput}$ the output hydraulic energy, Jtt $E_{HPinput}$ the hydraulic leakage energy, JttcsBDC $BDC$ timing in compression stroketime $E_{EL}$ energy that the exhaust gas takes away, JtessBDCBDC timing in expansion stroke $E_{EL}$ energy loss from the friction force and the viscousticintake port close timing $damping force, J$ $\Delta u_i$ output value of controller in current sampling $E_1$ load energy, J $V_2$ vpiston velocity, m/s $E_1$ load energy, J $V_2$ cylinder volume when the combustion starts, m <sup>3</sup> $E_1$ load energy, J $V_2$ visiton velocity, m/s $E_1$ load energy, J	$C_2$	combustion chamber shape coefficient	Swall	heat transfer area, m <sup>2</sup>
$C_{PEX}$ exhaust specific heat at constant pressure, J $T_1$ cylinder temperature when the combustion starts, K $D$ power piston bore, m $T_0$ atmospheric temperature, K $D_L$ hydraulic load, MPa $T_{EX}$ exhaust gas temperature, K $d_k$ piston diameter, m $T_{wall}$ temperature of heat transfer wall, K $EHPinputthe hydraulic energy absorbed, Jt_{EVC}exhaust valve close timingEHPinputthe output hydraulic energy, JttimeE_{EW}effective indicated work, Jt_{CSBDC}BDC timing in compression strokeE_{EW}energy that the exhaust gas takes away, Jt_{ESBDC}BDC timing in expansion strokeE_{EL}the hydraulic energy of HFPE, J\Delta u_ioutput hydraulic energy of HFPE, J\Delta u_idamping force, JV_1cylinder volume when the combustion starts, m3E_{FL}input energy, JV_1cylinder toutput null call on the combustion starts, m3E_{FL}input energy, JV_2cylinder volume when the combustion starts, m3E_{FL}input energy, JV_2cylinder volume, m3E_1input energy, JV_2cylinder volume, m3E_1input energy of pump, JV_2cylinder volume, m3E_1input energy, JV_2cylinder volume, m3E_1input energy input energy of pump, JV_2cylinder volume, m3E_1input energy of pump, JV_2cylinder volume, m3E_1<$	Cf	the viscous damping coefficient	Т	temperature of gas in cylinder, K
Dpower piston bore, m $T_0$ atmospheric temperature, K $D_L$ hydraulic load, MPa $T_{Ex}$ exhaust gas temperature, K $d_k$ piston diameter, m $T_{wall}$ temperature of heat transfer wall, K $E_{HPinput}$ the hydraulic energy absorbed, J $t_{EVC}$ exhaust valve close timing $t_{HPinput}$ the output hydraulic energy, Jttime $E_{HPoutput}$ effective indicated work, J $t_{CSBDC}$ BDC timing in compression stroke $E_{EW}$ effective indicated work, J $t_{CSBDC}$ BDC timing in expansion stroke $E_{EL}$ the hydraulic leakage energy, J $t_{EvO}$ exhaust valve open timing $E_{EL}$ energy that the exhaust gas takes away, J $t_{ESDC}$ BDC timing in expansion stroke $E_{EL}$ the energy loss from the friction force and the viscous $t_{IC}$ intake port close timing $damping$ force, J $u_i$ output value of controller in current sampling $AE_H$ output hydraulic energy of HFPE, J $u_i$ output value of controller in current sampling $E_i$ input energy, J $V_1$ cylinder volume when the combustion starts, m <sup>3</sup> $E_{SC}$ energy consumed by root pump, J $V_P$ displacement of hydraulic pump in one cycle, mm <sup>3</sup> $e_i$ error value in current sampling $\overline{X}$ mean value of parameters $e_{i-1}, e_{i-2}$ error value before current sampling $\overline{X}$ mean value of parameters $f$ friction coefficient $x_{iming}$ injection timing $h_k$ hight of	CDEX	exhaust specific heat at constant pressure. I	$T_1$	cylinder temperature when the combustion starts, K
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$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$d_{\nu}$	piston diameter, m	$T_{wall}$	temperature of heat transfer wall, K
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$\begin{array}{llllllllllllllllllllllllllllllllllll$		damping force, J	t <sub>IO</sub>	Intake port open timing
$E_i$ load energy, J $v$ piston velocity, m/s $E_i$ input energy, J $V_1$ cylinder volume when the combustion starts, m³ $E_{SC}$ energy consumed by root pump, J $V_c$ cylinder volume, m³ $E_{VTL}$ hydraulic valve throttling loss, J $V_P$ displacement of hydraulic pump in one cycle, mm³ $e_i$ error value in current sampling $\overline{X}$ mean value of parameters $e_{i-1}, e_{i-2}$ error value before current sampling $X(i)$ measured variablesffriction coefficient $x_{timing}$ injection timing $h_k$ hight of clearance in radius deraction, m $x_{BDC}$ real BDC position $H_u$ low calorific value of fuel, J/kg $x_{BDC}$ real BDC position	$\Delta E_H$	output hydraulic energy of HFPE, J	$\Delta u_i$	output value of controller in current sampling
$E_i$ input energy, J $V_1$ cylinder volume when the combustion starts, m³ $E_{SC}$ energy consumed by root pump, J $V_c$ cylinder volume, m³ $E_{VTL}$ hydraulic valve throttling loss, J $V_P$ displacement of hydraulic pump in one cycle, mm³ $e_i$ error value in current sampling $\overline{X}$ mean value of parameters $e_{i-1}, e_{i-2}$ error value before current sampling $X(i)$ measured variablesffriction coefficient $x_{timing}$ injection timing $h_k$ hight of clearance in radius deraction, m $x_{BDC}$ real BDC position $H_u$ low calorific value of fuel, J/kg $x_{BDC}^*$ designed BDC position	$E_l$	load energy, J	v	piston velocity, m/s
$E_{SC}$ energy consumed by root pump, J $V_c$ cylinder volume, m³ $E_{VTL}$ hydraulic valve throttling loss, J $V_P$ displacement of hydraulic pump in one cycle, mm³ $e_i$ error value in current sampling $\overline{X}$ mean value of parameters $e_{i-1}, e_{i-2}$ error value before current sampling $X(i)$ measured variables $f$ friction coefficient $x_{timing}$ injection timing $h_k$ hight of clearance in radius deraction, m $x_{BDC}$ real BDC position $H_u$ low calorific value of fuel, J/kg $x_{BDC}^*$ designed BDC position	Ei	input energy, J	$V_1$	cylinder volume when the combustion starts, m <sup>3</sup>
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$H_{\rm u}$ low calorific value of fuel, J/kg $\chi^*_{\rm BDC}$ designed BDC position $K_{\rm L}$ load coefficient	$h_k$	hight of clearance in radius deraction, m	$x_{BDC}$	real BDC position
K <sub>L</sub> load coefficient	$H_{\rm u}$	low calorific value of fuel, J/kg	$x_{BDC}^*$	designed BDC position
I longth of clearance in avial deraction m Creake	KL	load coefficient		
$L_k$ religin of clearance in axial defaction, in Greeks	$L_k$	length of clearance in axial deraction, m	Greeks	
$m_{\rm f}$ cycle fuel injection quantity, kg $\eta_{\rm u}$ combustion efficiency	m <sub>f</sub>	cycle fuel injection quantity, kg	$\eta_{\mathrm{u}}$	combustion efficiency
<i>N</i> cycles $\eta_i$ indicated thermal efficiency	Ν	cycles	$\eta_{ m i}$	indicated thermal efficiency
<i>n</i> polytropic exponent $\mu_{Ok}$ the oil dynamic viscosity, Pa s	п	polytropic exponent	$\mu_{Ok}$	the oil dynamic viscosity, Pa s
p pressure of gas in cylinder, Pa $\sigma_X$ standard deviation of parameters	р	pressure of gas in cylinder, Pa	$\sigma_X$	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

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