Energy 102 (2016) 650–659

Contents lists available at ScienceDirect

Energy

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

Thermodynamic and energy saving benefits of hydraulic free-piston engines

Zhenfeng Zhao*, Shan Wang, Shuanlu Zhang, Fujun Zhang

School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China

ARTICLE INFO

Article history:
Received 27 May 2015
Received in revised form
5 January 2016
Accepted 4 February 2016

Keywords:
Hydraulic free-piston engine
Thermodynamic benefits
Energy saving benefits
Experimental

ABSTRACT

The hydraulic free-piston engine integrates the internal combustion engine with a hydraulic pump. The piston of an HFPE is not connected to the crankshaft and the piston movement is determined by the forces that act upon it. These features optimize combustion and make higher power density and efficiency increase. In this paper, a detailed thermodynamic and energy saving analysis is performed to demonstrate the fundamental efficiency advantage of an HFPE. The thermodynamic results show that the combustion process can be optimized to an ideal engine cycle. The experimental results show that the HFPE combustion process is a nearly constant-volume process; the efficiency is approximately 50%; the piston displacement and velocity curves for a cycle are the same at any frequency, even at a 1.25 Hz. The maximum velocities are of the same value at high or low frequencies. Similarly, pump output flow is not influenced by frequency. The independent cyclic characteristics of HFPE determine that it should work in higher frequencies when the vehicle runs in Japanese 10–15 road conditions. It indicates that a higher working frequency will lead to the starting frequency of HFPE, and a lower frequency will decrease the pressurized pressure of the hydraulic accumulator.

1. Introduction

Due to increasing energy demands and environmental problems, environmental protection and energy issues have emerged as serious problems. Internal combustion engines have become the focus of research for investigating fossil fuel consumption and emission. Engines can be made more energy efficient and environmentally friendly either by improving the thermal efficiency of conventional engines or by developing new types of high-efficiency engines. Among the many new concepts for high-efficiency engines, the HFPE (hydraulic free-piston engine) has attracted considerable attention from researchers. The HFPE is an unconventional engine in which the piston is not restricted by a crankshaft as in a conventional crankshaft engine. The HFPE structure integrates an internal combustion engine with a hydraulic pump.

In an HFPE, the energy of the combustion process is almost directly converted into hydraulic energy. The form of the power output is hydraulic energy, which is non-rigid transmission. The flow output is controlled via PPM (Pulse Pause Modulation) of the piston frequency [1,2]. This promising approach has potential advantages over conventional engines, such as a variable compression ratio, control of the combustion process by adjusting the operating parameters, a shorter energy transmission chain, and control of the output power by adjusting the frequency, and flexible power transmission [3,4]. Theoretically, these characteristics result in low emissions and high thermal efficiencies, which make HFPE as engine for vehicles. Therefore, this type of engine has attracted the interest of many research institutes and researchers.

Since the concept of the free-piston engine was proposed in 1928 [5], various prototypes of this type of engine had been presented, including the hydraulic free piston engine, free-piston generator, free-piston gas generator, etc. [6–10]. Unfortunately, the development of this type of engine was stopped due to the limitations of the technical and research means available at that time.

In recent years, due to the advancements in electronic control technologies, fast-responding actuator technology and internal combustion engine technology, investigations into free-piston engines are being enthusiastically carried out by researchers.

Looking back in the history of HFPE, many researchers have tried to explore the potential advantages of this type of engine using theoretical analysis and experimental research. Roskilly et al.

* Corresponding author. Tel.: +86 1068912295; fax: +86 1068912514.
E-mail address: zhzhf@bit.edu.cn (Z. Zhao).

http://dx.doi.org/10.1016/j.energy.2016.02.018
0360-5442/

Nomenclature

Abbreviation

BDC	Bottom Dead Center
CE	Conventional Engine
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
HEUI	Hydraulic-Electronic Unit Injector
HFPE	Hydraulic Free-Piston Engine
HCCI	Homogeneous Charge Compression Ignition
SOC	State of Charge
TDC	Top Dead Center

Greeks

α	T_d/T_a
ε	Compression Ratio
η	Engine Thermal Efficiency
λ	Presssure Ratio
θ	V_c/V_a
ρ	Cutoff Ratio

Symbols

c_v	Specific heat at constant volume, kJ/(kg.K)
k	Heal capacity ratio
m	Mixture gas mass, kg
T	Temperature, K
V	Cylinder volume, m^3
W_p	Power of the cycle, W
W_d	Power density, W/m^3
W_p	Efficient power, W

investigated the advantages of dual-piston free-piston engine combustion and emission through theoretical analysis and simulation. The results showed that the free-piston engine has potential advantages over conventional technology in terms of fuel efficiency as a result of the mechanical simplicity and faster power stroke expansion [11]. A higher heat release rate from the premixed combustion phase due to an increased ignition delay was also found, along with potential reductions in the emission of nitrogen oxides [12]. It was concluded that the main advantage of this technology lied in the simplicity and flexibility of the concept [13]. Achten et al. investigated the advantages of a single-piston hydraulic free-piston engine. A very high part of load efficiency was achieved via PPM control of the piston frequency [4]. The dynamic piston characteristics were reported, such as high piston acceleration around TDC (top dead center) and a faster expansion stroke than in a conventional engine. The results showed that the engine could achieve efficiencies greater than 50% and a fuel consumption advantage of 20% compared to a conventional engine and hydraulic pump unit [2,4]. Somhorst et al. investigated the combustion process of the free piston engine in early experiments. The research results showed that, at maximum efficiency, the engine had an indicated efficiency of 51%, an NO_x emission of 6 gr/kWh and a soot emission corresponding to a Bosch Filter Number of less than 0.5 [14]. Kleemann et al. analyzed the free-piston engine prototype used in a series of hybrid vehicles to reach high efficiency level combined with low emissions based on 3D CFD (Computational Fluid Dynamics) simulations. An indicated efficiency greater than 50% was demonstrated, and low emission levels for soot and NO_x could be ensured via high compression ratios, elevated EGR (Exhaust Gas Recirculation) rates and HCCI (Homogeneous Charge Compression Ignition)combustion using direct injection and early injection timing [15]. Hibi and Ito presented test results from a hydraulic free-piston internal combustion engine pump. The hydraulic thermal efficiency, namely the ratio of hydraulic energy produced to the fuel energy consumed, was measured. The measured value of the hydraulic thermal efficiency was 31%. The hydraulic thermal efficiency was constant even if the hydraulic power output was very small [16,17]. However, some researchers showed that the free-piston engine did not give noticeable performance advantages over conventional engines [13]. Misfiring may represent a problem in the free-piston engine, since it does not have energy storage capable of driving the engine for several revolutions like the flywheel in a conventional engine. Others problems in free-piston engines are the mechanical wear and damage, mainly due to high temperatures and pressures. Recently advances in free-piston engine research are mainly focused on efficiency enhancement and emissions reduction and it attracts a lot of researchers.

In this paper, a detailed thermodynamic and energy saving analysis is performed to demonstrate the fundamental efficiency advantages of an HFPE over a conventional engine through the theoretical analysis and experimental test. The approach of combustion optimization was obtained by adjusting the injection timing and compression ratio. The high efficiency area of HFPE was given as a function of injection timing and compression pressure. The potential advantages of the HFPE will be determined by analyzing the detailed thermodynamic characteristics and the engine technical parameters. The energy saving benefits by adjusting the operating frequency in Japanese 10–15 road condition was investigated. The results showed that the HFPE had better performance at low speeds and low loads, which were harsh conditions for conventional engines. The experimental results showed that the combustion process could be optimized to a nearly constant-volume cycle by adjusting the injection timing and compression ratio. The efficiency was approximately 50%. The piston displacement and velocity curves for a cycle were the same at any frequency, even at a 1.25 Hz operating frequency.

2. Principle and characteristics of the HFPE

The HFPE is an unconventional engine that does not employ the crankshaft arrangement. In the HFPE, the diesel engine and hydraulic pump are integrated into one component by leaving out the connecting rod, crankshaft, pump axle and swash plate. The piston and the hydraulic plunger are directly connected. A schematic diagram of an HFPE is shown in Fig. 1. The result is a small and mechanically simple device. The power piston works in the cylinder as a two-stroke diesel engine, and the pump piston works in the plunger sleeve as a reciprocating plunger pump. Normally, the compression piston and the accumulator are necessary because the piston is not connected to any mechanism, which provides the energy for the compression stroke [18].

The working principle of the HFPE is explained with the help of the illustration in Fig. 1. When the engine is started, the piston is at rest in the BDC (Bottom Dead Center). Then, the frequency control valve is opened. High-pressure oil from the accumulator is introduced to the compression chamber through the frequency control valve. The compression piston is pushed towards TDC. During the