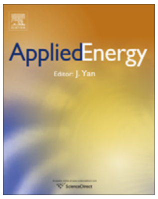
Applied Energy 88 (2011) 3712–3725

Contents lists available at ScienceDirect

Applied Energy

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



Numerical analysis of two-stroke free piston engine operating on HCCI combustion

Shuaiqing Xu *, Yang Wang, Tao Zhu, Tao Xu, Chengjun Tao

State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 23 December 2010
Received in revised form 21 April 2011
Accepted 2 May 2011
Available online 12 June 2011

Keywords:
Free piston
HCCI
Combustion phasing
Ringing intensity
Scavenging efficiency

ABSTRACT

An opposed-piston hydraulic free piston engine operating with homogenous charge compression ignition (HCCI) combustion, has been proposed by State Key Laboratory of Engines as a means of significantly improving the IC engine's cycle thermal efficiency and lowering exhaust emissions. Single and multi-zone Chemkin model with detailed chemical kinetics, and unique piston dynamics extracted from one dimensional gas dynamic model, have been used to analyze the combustion characteristics and engine performance. Intake heating, variable compression ratio and internal EGR are utilized to control the combustion phasing and duration in the cycle simulations, revealing the critical factors and possible limits of performance improvement relative to conventional crank engines. Furthermore, real engine effects such as heat transfer with air swirl, residual mass fraction, thermal stratification, and heat loss fraction between zones are considered in the sequential CFD/multi-zone method to approach the realistic engine performance at an acceptable knock level.

1. Introduction

Free piston engine concept can be traced to original gasifiers for single stage turbines as well as gas compression engines in the mid-20th century [1]. From then on, more novel applications such as hydraulic pumps and linear generators have been studied. Free piston engines are linear, 'crankless' engines, in which output power is extracted by a linear load device directly coupled to the moving piston. The absence of the crank mechanism allows the compression ratio to be varied. Compared to conventional engines, the free piston engine has potential advantages of simplicity of the units, giving a compact engine with low frictional losses, and the operational flexibility through the variable compression ratio, potentially offering extensive multi-fuel and operation optimization possibilities [2,3]. Because of its advantages, in recent years, the free piston engine concept attracts more attention among research engineers.

The homogenous charge combustion ignition (HCCI), as an alternative to spark-ignition and compression–ignition combustion in internal combustion engines, has the advantages of high efficiency and low emissions [4,5]. Mikalsen and Roskilly [6] presented the free piston engine is well suited for HCCI operation, since the piston motion is not controlled by a crankshaft, making it have low ignition timing control requirements. Recent studies of HCCI combustion on a free piston engine using a rapid compression expansion machine have shown that very rapid combustion is possible with certain fuels, and that ideal Otto cycle performance can be closely approached, while low NO_X emissions are possible (<10 PPM) [7]. A zero dimensional, thermodynamic model with detailed chemical kinetics, empirical scavenging, heat transfer, and friction component models has been used to analyze the steady state operating characteristics of this engine using hydrogen as the fuel [8]. The successful HCCI combustion process employed by the free piston engine is demonstrated by Sandia National Laboratories [7], operating at high compression ratio (∼30:1) and low fuel/air equivalence ratio (∼0.35).

Free piston engine combustion was studied in the mid-20th century and differences when compared to conventional engines were reported by a number of authors. Golovitchev et al. [9] presented numerical results of combustion process simulations in a two-stroke, uniflow scavenging dual free piston engine designed for electricity generation. Wherein two fuels, diesel oil and dimethyl ether (DME), were studied in order to achieve HCCI-like combustion. Li et al. [10] investigated the performance of a two-stroke free piston engine under HCCI combustion for electrical power generation, using Matlab/Simulink, Chemkin, as well as the finite element method (FEM). Mikalsen and Roskilly [11] investigated the in-cylinder gas motion, combustion process and nitrogen oxide formation in a free piston diesel engine and compared the results to those of a conventional engine, using a computational fluid dynamics engine model.

Most of the HCCI studies to date for free piston engine, however, have concentrated on achieving improved thermal efficiency by very rapid combustion speed, and only single-zone model is used to simulate the thermodynamic processes. The limiting factors

---

* Corresponding author. Address: State Key Laboratory of Engines, Tianjin University, No.92 Weijin Road, Nankai District, Tianjin 300072, China. Tel./fax: +86 22 27406842 8017.

E-mail address: xushuaiqing@tju.edu.cn (S. Xu).

0306-2619/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2011.05.002

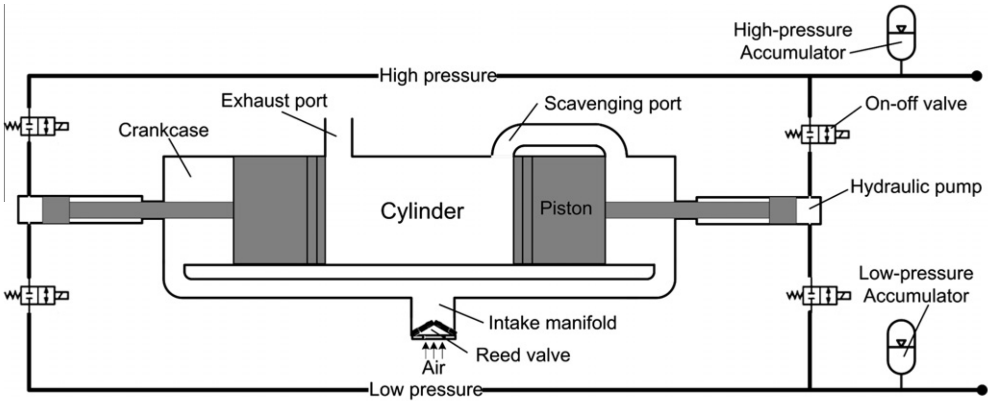


Fig. 1. Opposed-piston hydraulic free piston engine configuration.

Table 1
Free piston engine specifications.

Parameter	Value	Unit
Bore	95	mm
Stroke	95	mm
Nominal compression ratio	20[a]	
Displacement (single cylinder)	0.673	L
Dead volume of crankcase	2.019	L
Pump rod diameter	20	mm
Piston mass	1–5	kg
Exhaust valve close (ATDC)	79	mm
Intake value close (ATDC)	85	mm
Exhaust port circumference ratio	2/3	
Scavenging port circumference ratio	2/3	
Scavenging port tangential angle	20	

[a] Trapped compression ratio is 16.8.

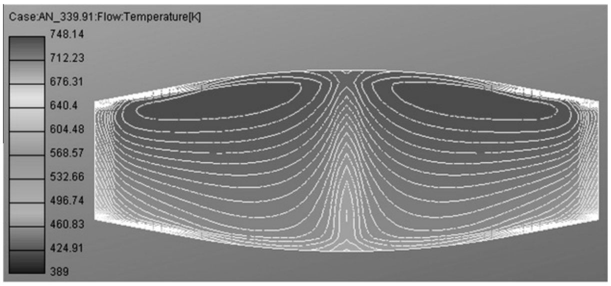


Fig. 2. Temperature field at an average temperature of 718 K.

Table 2
Temperature, mass and heat loss fractions at an average temperature of 700 K.

Zone	Temperature	Mass fraction	Heat faction
1	717.1	10.5	19
2	677.5	11	10
3	687.7	18	8.2
4	690.1	0.5	0.6
5	685.1	3.1	5
6	661.2	3.3	4
7	720.4	17.1	25.2
8	710.7	17.3	17
9	698.4	19.2	11

such as knock and charge stratification on combustion are not considered. Moreover, reaching higher loads is one important issue that must be addressed to practical application of HCCI. Up to now there are some fundamental aspects left for the free piston engine with HCCI combustion mode under the unique piston dynamics relative to the crank engine, for example, the compression heating required for auto ignition, over-compression, retardation of combustion phasing and the control of the combustion duration.

An opposed-piston hydraulic free piston engine (OPFP), is being developed by State Key Laboratory of Engines (SKLE), due to its potential as a low-cost and high-efficiency prime mover for engine-pump combination and hybrid power. Our approach utilizes two free pistons in an opposed-piston cylinder. Combustion occurs in the middle of the cylinder and two pistons move synchronously, with intake and exhaust processes accomplished through a two-stroke cycle. Two hydraulic pumps are mounted in each side of the cylinder, serving to both generate useful hydraulic power and control the compression ratio by varying the compression pressure.

Zhu et al. [12] at SKLE has adequately analyzed the engine performance, characteristic of gas flow and thermodynamic process of the new engine prototype, using a computational fluid dynamics engine model. Simulations have shown that a peak hydraulic efficiency of 39% is achievable under continuous operation with the piston mass of 5 kg and compression ignition. Besides, exceptional repeatability and precise control of compression ratio for the free piston engine were also demonstrated. The HCCI combustion process, for its very rapid combustion, is being employed by this free piston engine to reduce emissions and improve thermal efficiency, and its capability has been investigated with isooctane as the substitute of gasoline. Intake heating, variable compression ratio and internal EGR are utilized to control the combustion phasing and duration in the cycle simulations.

2. Engineering configuration of the OPFP

The OPFP being designed by SKLE is illustrated in Fig. 1. In this configuration, there is low pressure line to provide the compression pressure during the compression stroke, and high pressure line, serving to output the hydraulic power during the expansion stroke. High-speed on–off valves are used to regulate the input and output hydraulic flow. At a defined compression ratio, the hydraulic control system set a fixed compression pressure. When the piston reverses the direction, the on–off valves close the intake flow and output high pressure hydraulic power instantaneously. That is to say, the compression pressure acts on the whole compression stroke, and similarly the output pressure on the whole expansion stroke. As a result, the desired compression ratio can be achieved through modification of the operating parameters, as