Energy Conversion and Management 123 (2016) 185–199

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Effect of asynchronous valve timing on combustion characteristic and performance of a high speed SI marine engine with five valves

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ARTICLE INFO

Article history:
Received 31 March 2016
Received in revised form 12 June 2016
Accepted 13 June 2016
Available online 20 June 2016

Keywords:
SI engine
Asynchronous valves timing
Combustion
Turbulence kinetic energy
Engine performance
Emissions

ABSTRACT

Based on a high-speed spark ignition (SI) gasoline engine with five valves, a novel concept of asynchronous valves timing (AVT) and synchronous valves timing (SVT) systems has been proposed. In order to demonstrate the effect of AVT and SVT on gas exchange process, combustion process, engine performance, fuel economy and emissions, a comparative study between AVT and SVT systems are conducted by using computational fluid dynamics (CFD) simulation and experiment. Considering the disadvantages of original cam profile, the intake and exhaust cam profile are redesigned. The valve train would be able to work more steadily and reliably under the high speed movement condition after optimized. Followed experiments for the AVT and SVT schemes were performed under full load to measure engine performance and operating parameters. Finally, in order to study the in-cylinder working process, a numerical calculation was conducted by using the CFD code AVL-FIRE. Additionally, a GT-Power simulation model was set up and calibrated by experimental data to study the impact of AVT and SVT on gas exchange process and secure accurate boundary conditions for the CFD calculation. The simulation results show that AVT scheme can strengthen in-cylinder gas rotational flow, increase gas turbulence kinetic energy (TKE) at the ignition timing, which is beneficial to increase the flame propagation speed. The IVC timing can significantly affect the in-cylinder pressure and heat release rate. With late IVC, both the mass flow rate and the peak in-cylinder pressure of retarding 20 °CA opening are decreased. The experimental results show that the engine torque, BSFC, CO and HC emissions of advancing 20 °CA opening are better than those under retarding 20 °CA opening and SVT at full load. However, NOx and CO_2 emissions are worse than those of the other two schemes.

1. Introduction

At present, due to the draining energy sources and increasingly serious environmental problems, especially the petrol shortages and air pollution, more attention has been paid to the energy saving and environmental protection [1–5]. Automobile is the main consumer of fossil oil and one of the main sources of air pollutants, and it becomes the primary object for energy conservation and emission reduction [6,7]. As the main power source for automobiles, internal combustion (IC) engine has attracted more and more attention from both scientists and engineers on its thermal efficiency [8,9].

Recently, the high speed SI gasoline engine is widely used on the marine yachts for the advantages of smaller size, higher power and lower emissions. However, higher speed technology can make the combustion duration shorter than traditional vehicle gasoline engine, and easily cause the insufficient combustion in cylinder [10]. Under the circumstances, better organization of intake rotating flow and improvement of in-cylinder combustion process are the two major research directions for the high speed SI gasoline engine [11,12]. According to the existing research, several approaches and technologies were proposed to achieve this goal, e.g., multi-valves technology, tumbling stratification of fresh charge, variable valve actuation (VVA).

The multi-valves (more than two valves) technology is used in gasoline engine for increasing inlet flow area, reducing the flowing losses and enhancing the volumetric coefficient [13]. For instance, FEV company conducted a performance comparison between a four-valve engine and a two-valve engine. They found that,

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http://dx.doi.org/10.1016/j.enconman.2016.06.042
0196-8904/

Nomenclature

SI	spark ignition
IC	internal combustion
VVA	variable valve actuation
VVT	variable valve timing
VVO	variable valve overlap
BMEP	brake mean effective pressure
GVSTD	guide vane swirl and tumble device
CFD	computational fluid dynamics
AVT	asynchronous valves timing
SVT	synchronous valves timing
BSFC	brake specific fuel consumption
OHC	overhead camshaft mechanism
ECU	Electronic Control Unit
IVO	intake valve opening
IVC	intake valve closure
EVO	exhaust valve opening
EVC	exhaust valve closure
BTDC	before top dead center
ATDC	after top dead center
RANS	Reynolds average Navier Stokes
ECFM	extended coherent flame model
RGF	residual gas fraction
TDC	top dead center
CO	carbon monoxide
HC	unburned hydrocarbon
NOx	nitrogen oxides
CO_2	carbon dioxide
NO	nitric oxide
CA	crankshaft angle

compared with the two-valve engine, the volumetric efficiency of four-valve engine increased by 15%, while the brake mean effective pressure (BMEP) increased by 25%. Furthermore, after the compression ratio is improved, the engine power per liter increased to 65 kW/L and the fuel consumption decreased to 245 g/(kW h) [14]. Lee et al. [15] pointed out that the five-valve engines had larger valve opening area, larger intake mass flow rate and higher tumble ratio than that of four-valve engines. Although the five valves would not only increase the complexity of the engine but also weaken the strength of the cylinder head, there are two main advantages for this technology. On the one hand, increasing the valve number makes the individual valve lightweight and miniaturization. The smaller inertia of the valves allows them to open and close faster, so the time area of the intake valves will increase. It is also beneficial to increase the rotational speed of IC engine. On the other hand, since the spark plug can be arranged at the center of the combustion chamber in these multi-valves engines, the distance of the flame propagation is shortened. Furthermore, the high heat release rate is guaranteed and the possibility of detonation is reduced [16].

The stratification of fresh charge has been attempted on four valve gasoline engine in recent years [17]. It can be achieved if the in-cylinder tumble and swirl are better organized. By changing intake valve timing or cam profile, the valve lift would be staggered from each other. This is done to strengthen swirl intensity on the basis of keeping intake tumble during the intake process. Due to the longer duration and less dissipation in radial direction during the compression process, it is easy for swirl to achieve in-cylinder stratified charge technique. In addition, adopting advanced intake system and keeping a large scale tumble motion in the compression process can also achieve fuel stratification [18,19]. A larger cyclic variation might be caused using this approach, but if the air flow motion can be well organized to make the tumble broken into small scale of turbulence before ignition, the combustion process can be promoted instead [20]. Compared to four-valve engine, the intake valves arrangement of five-valve engine is triangle, the in-cylinder rotational flow can be strengthened not only by changing the left or right valve timing, but also by regulating the middle intake valve timing.

VVA has been widely used on gasoline engines for improving volumetric efficiency, reducing the pumping losses and reducing harmful emissions. To achieving those benefits, early/late intake valve closure (IVC), early/late intake valve opening (IVO), variable valve overlap (VVO) can be implemented [21]. Fontana G and Galloni E [22] studied a numerical approach to evaluate the engine performance when load is controlled by the variable valve timing (VVT) system, and deeply investigated the influence on in-cylinder phenomena of the valve timing variation. It was found that the VVT system was an effective tool in reducing the pumping losses and the specific fuel consumption, at partial load. Dalla Nora and Zhao [23] performed a valve timing optimization study using a fully flexible valve train unit, where the intake and exhaust valve timings were advanced and retarded independently at several speeds and loads. The authors also investigated the effects of valve timing and boost pressure in this two-stroke poppet valve engine by a detailed analysis of the gas exchange process and combustion heat release.

With the previous studies discussed above, the intake airflow motion and in-cylinder combustion efficiency could be improved significantly if these technologies are made good use of. Furthermore, the engine performance and emissions would be strongly influenced [24–26]. As is well known, swirl and tumble are the two main rotating flows in premixed SI engines. Swirl is the rotational motion around an axis parallel to the axis of the cylinder, and tumble is the rotational motion around an axis perpendicular to the cylinder axis [11]. Due to the symmetric port geometry, it is difficult to generate swirl in four-valve engines with pent-roof combustion chambers. However, the alternative large-scale motion, tumble, has been considered to be favorable. The reason is that tumble can be effectively generated with a straight and symmetrical dual intake port with negligible adverse effect on the flow coefficient [27]. The tumble has been studied by many scientists and investigators. Bari et al. [28] proposed that a Guide Vane Swirl and Tumble Device (GVSTD) be installed in front of the intake port to develop an organized turbulence to assist in the breakup of fuel molecules for improved mixing with air. Haworth et al. [29] reported that tumble motion was found to be more effective than swirl motion both in extracting energy from the piston and in transferring kinetic energy of the mean motion into turbulence during compression. The development of tumbling vortex flow structure in cylinder depends on inlet port design, valve lift, and manifold absolute pressure. Although the intake port design, take the GVSTD for example, has a good effect on improving swirl and tumbling, it also makes the engine intake system more complicated. As one of the most promising strategies for strengthening the tumble flows, adjustable valve timing system attracts increasing attentions recently because of its effectiveness and convenience. It should be noted that lots of researches has been conducted in the field of four-valve engine, and many approaches have been proposed to improve the intake airflow motion and in-cylinder combustion. However, few researches are studied on five-valve technology because of the special valve distribution.