Energy Conversion and Management 123 (2016) 104–115

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Numerical simulation coupling with experimental study on the non-uniform of each cylinder gas exchange and working processes of a multi-cylinder gasoline engine under transient conditions

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A R T I C L E I N F O

Article history:
Received 23 April 2016
Received in revised form 9 June 2016
Accepted 11 June 2016
Available online 18 June 2016

Keywords:
Gasoline engine
Transient conditions
Cylinder-to-cylinder variation
Residual gas fraction
Non-uniform

A B S T R A C T

Cylinder-to-cylinder variation is unavoidable in multi-cylinder engine and has a severe impact on engine performance. To explore the cylinder-to-cylinder variation of engine under transient conditions, a hybrid method of dynamic signal measurement coupling with gas dynamics and thermodynamics processes simulation is presented to detect the parameters of engine. Then, this method is applied to an automobile engine under road test conditions, and the continuous state and performance parameters of each cylinder were obtained from cycle to cycle. On this basis, the range and influence factors of non-uniform of engine performance parameters were analyzed. The results show that, under transient conditions, the relative deviation of excess air coefficient in each cylinder is within ±5%, which is mainly affected by intake average pressure in low to medium speed operating regions but influenced by exhaust pressure wave and residual gas fraction in high-speed and high-load operating regions. There appears a symmetry relation between the non-uniform of RGF and excess air coefficient. The relative deviation of indicated mean effective pressure in each cylinder depends largely on the gas exchange performance, including excess air coefficient and residual gas fraction, and the maximum is larger than ±30%.

1. Introduction

With the increasingly serious energy crisis and environmental pollution, countries around the world have made more stringent regulations in the fuel consumption and emissions [1–4]. New regulation standards demand a continuous reduction in emissions from automobile while fuel consumption is a matter of concern for all engine users as well as for environment protection due to its relation to the production of green house gas CO_2 [5]. According to the previous studies [6–10], the in-cylinder combustion and heat-work conversion performance of internal combustion (IC) engine depend largely on the state and operating parameters, including air fuel ratio (AFR), residual gas fraction (RGF), and trapped fresh charge. Due to the irregular structure of engine intake and exhaust systems, the pressure fluctuation of intake and exhaust gas, the λ closed loop control which can only reflect the average of excess air coefficient of each cylinder, etc., the in-cylinder trapped fresh charge, AFR, RGF and other parameters of each cylinder in multi-cylinder engine inevitably differ from each other even under steady-state conditions [11,12]. When the engine operates under transient conditions, the random change of operating conditions exacerbates the pressure fluctuation in intake and exhaust systems and aggravates the non-uniform of state and performance parameters in each cylinder, thus the engine overall performance and working stability are affected more seriously [13,14]. As the fuel-injection quantity of each cylinder is the same, the unevenness of intake performance directly leads to the difference of AFR in each cylinder, and then the in-cylinder combustion process as well as the heat-work conversion process is influenced. At the same time, the non-uniform of exhaust performance results in the difference of RGF in each cylinder, which influences the engine intake and combustion processes in the next cycle. Due to the non-uniform distribution of AFR and RGF as well as other parameters, it is very difficult for the multi-cylinder engine to realize clean and efficient combustion in all cylinders. Therefore, the uniformity of each cylinder's performance is an important indicator to evaluate the combination property of multi-cylinder engine, and decreasing the cylinder-to-cylinder variation (CTCV) has been the goal of the scientific researchers for many years.

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http://dx.doi.org/10.1016/j.enconman.2016.06.028
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Nomenclature

p	pressure (Pa)
T	temperature (K)(°C)
u	flow velocity (m/s)
ρ	density (kg/m^3)
D	diameter (m)
F	area (m^2)
R	gas constant (J/(K mol))
γ	specific heat ratio (–)
x	space scale (–)
t	time scale (–)
$\Delta\phi$	time step (–)
λ	excess air coefficient
ε	relative deviation (–)
m	mass (kg)
H_u	low heating value (MJ/kg)
V_h	cylinder displacement (m^3)
η_{HP}	high-pressure cycle efficiency (–)

Abbreviation

IC	internal combustion
AFR	air fuel ratio
RGF	residual gas fraction
IMEP	indicated mean effective pressure
NMEP	net mean effective pressure
VVT	variable valve timing
TDC	top dead center
CTCV	cylinder-to-cylinder variation
EGR	exhaust gas recirculation
GDI	gasoline direct injection
HCCI	homogeneous charge compression ignition
ECU	electronic control unit
TDC	top dead center
CoV	coefficient of variation
IVC	intake valve closing

Aimed at the research field of non-uniformity of multi-cylinder engine, many scholars have made unremitting efforts [15–18], and their research work can be summarized in the following three aspects. The first is the characteristic of CTCV of various engine parameters as well as their influence factors. For example, Czarnigowski [19] found the relationship between the air-fuel mixture and CTCV through analyzing the CTCV of individual cylinders and observing the differences in the non-uniform standard deviation of indicated mean effective pressure (IMEP). Misztal et al. [5] provided the most important parameters causing CTCV and presented a discussion with some parameters on a gasoline direct injection (GDI) and homogeneous charge compression ignition (HCCI) engine under steady conditions. Baratta et al. [20] quantified the cycle-to-cycle and the cylinder-to-cylinder combustion variation and revealed the reason for the CoV_IMEP of cylinders. Cui and Pan [21] studied the CTCV of losses in intake regions of IC engine and indicated the physical mechanisms for CTCV. The second is how the CTCV influences the performance parameters of multi-cylinder engine. Maiboom et al. [22] discovered the effects of CTCV in intake gas composition and temperature on the emissions increase of high-speed direct injection diesel engine with exhaust gas recirculation (EGR). Persson and Pfeiffer [23] investigated how cycle-to-cycle and cylinder-to-cylinder deviations limit the operating region of HCCI engine and revealed the effects of spark assistance on the operating region. Luján et al. [24] used the method of experimental tests combined with both one-dimensional and three-dimensional fluid dynamic models to study the effect of EGR distribution between cylinders on engine behavior. The last is how to decrease the CTCV of multi-cylinder engine. Hyvönen et al. [25] tested different strategies to balance the cylinders in variable compression ratio engine. Through their research, they found the best engine performance regarding fuel consumption, combustion stability and emissions with cylinder individual combustion phasing control using inlet air temperature. Bittle et al. [26] attempted to decrease the CTCV through changing combination of exhaust gas recirculation and fuel distribution in a low-temperature combustion mode, but the results show that the emissions levels are actually not affected under less CTCV. Yun et al. [27] developed a cylinder balancing control strategy to address high CTCV and combustion noise was significantly reduced at high load while combustion stability was improved at low load.

Although lots of investigations about IC engine CTCV have been carried out, there are still some lacks in this research field. Firstly, the existing research mainly focused on IC engine steady-state conditions, and little attention was paid to transient conditions. Secondly, there have been few comprehensive studies tracking the CTCV in the whole gas exchange and working processes of engine, especially the RGF. The reasons for the above two issues are listed as follows. For one thing, even though the intake mass flow rate and excess air coefficient can be tested since modern engines are equipped with advanced air flow sensor and oxygen sensor, there is still no mature technology to detect in-cylinder RGF and actual AFR especially under transient conditions. The backflow from cylinder to intake system and from exhaust system to cylinder makes it more difficult to confirm the in-cylinder gas composition as well as combustion process. As a matter of fact, the test results of intake mass flow rate and excess air coefficient are not accurate enough, due to the effects of intake and exhaust gas pressure wave especially under transient conditions. For another, both the frequency response and precision of current air flow sensor and oxygen sensor do not meet the requirement for accurate detecting or controlling intake and exhaust parameters from cycle to cycle. In a word, there is lack of method or tool to detect the gas exchange process and in-cylinder working process under transient conditions, thus it is difficult to investigate the CTCV in multi-cylinder engine under transient conditions.

In light of the condition, in this paper a method of dynamic signal measurement coupling with numerical simulation is presented to continuously detect each cylinder parameters and working process under engine transient conditions. By using the proposed method, the whole gas exchange and working processes of a four-cylinder engine were detected under road test conditions. On this basis, the comprehensive studies of the CTCV in gas exchange and working processes of this engine were carried out. Accordingly, the work presented in this paper was split into two main parts. Firstly, the working principle of the proposed method to detect the CTCV of multi-cylinder engine and the testing process on a four-cylinder automobile engine were introduced. Secondly, a detailed discussion with respect to the detected results of CTCV on the four-cylinder automobile engine including the change rules and influencing mechanism of CTCV was conducted.

2. Workflow and principles of the proposed detection method

2.1. Workflow of the proposed detection method

The workflow and principles of the method for detecting engine gas exchange and working processes under transient conditions