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Experimental Research of Ignition System for Lean Burn CNG Engine

Jing Haiguo, Yang Liping and Ma Xiuzhen
Institute of Power and Energy Engineering, Harbin Engineering University, Harbin, 150001, China

Abstract: For the sake of reducing lean burn Compressed Natural Gas (CNG) engine cyclic variation, a dual-coil discharge ignition system was designed in this study. The change rule of secondary voltage was studied in constant temperature and pressure atmosphere and the impact of ignition system on combustion stability was studied on the engine test bench. Experimental results of secondary voltage show that compared with single-coil ignition, the new ignition system can increase secondary voltage, extend spark duration and achieve multiple discharges under apposite charging time. Bench test shows that, in suitable discharging mode, this system can reduce the cyclic variation coefficient of CNG engine; consequently it improves the combustion stability of lean burn CNG engine.

Key words: Cyclic variation, dual-coil ignition system, secondary voltage, cyclic variation coefficient

INTRODUCTION

Natural gas is using as alternative fuel in power machinery which can solve the problem of environment pollution and energy shortage to a large extent. Lean burn technology can bring further improvement on fuel economy and emission. However, the burning rate of natural gas is slower, so it is easy to produce combustion cyclic variation and this phenomenon is more obvious to lean burn natural gas engine which restricts the development of this engine (Cho and He, 2007). Ozdor *et al*. (1994) pointed out that the factors affecting cyclic variation was divided into four categories, among them ignition characteristic parameter was an important factor influencing combustion cyclic variation. The mechanism of flame kernel formation and quenching is different under different working conditions. In cold start condition, temperature of combustion chamber is low, so high-energy and multiple times ignition is needed to generate initial flame and reduce misfire probability, thereby reduce emissions (Zhang *et al*., 2010; Zhou *et al*., 2012; Ma *et al*., 2012). In theoretical AF (amplitude-frequency) ratio condition, smaller ignition energy will be able to meet the requirements of stable ignition (Guo *et al*., 2006). In lean burn condition, combination gas is thin, combustion speed slows down, so long spark and high-energy ignition makes for increasing the flame volume and enhancing the operation stability (Qu *et al*., 2011). Moreover, multiple discharge is helpful to reduce misfire rate (Takashima *et al*., 2012). With the purpose of improving performance of inductive ignition system (Qiao *et al*., 2004; Gao *et al*., 2005), a dual-coil discharge ignition system was designed. The change rule of secondary voltage was studied in constant temperature and pressure atmosphere and the impact of ignition system on combustion cyclic variation was studied on the engine test bench.

DESING OF DUAI-COIL IGNITION SYSTEM

According to the category of energy storage, it can be divided into two kinds of coil discharge ignition, one is inductive ignition system, shown in Fig. 1; the other is capacitive ignition system, shown in Fig. 2. To inductive ignition system, ignition coil starts charge when controller connects, energy is stored in primary coil, according to

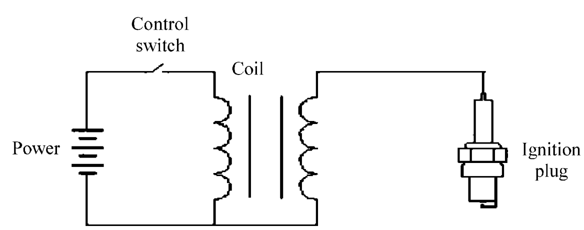

Fig. 1: Inductive ignition system

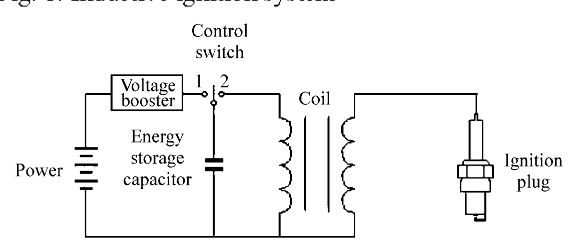

Fig. 2: Capacitive ignition system

Corresponding Author: Jing Haiguo, Institute of Power and Energy Engineering, Harbin Engineering University, Harbin, 150001, China

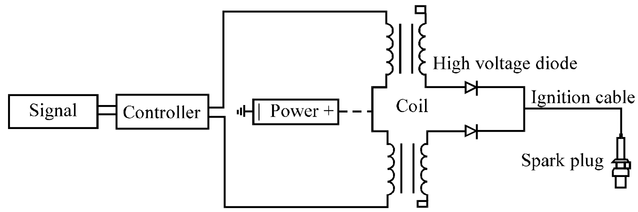

Fig. 3: Dual coil discharge ignition system

Table 1: Components of ignition system

Name	Type	Manufacturer
Coil	7J12	Delphi
Plug	IXU22	DENSO
Power	BT-12M14AC	Saite
Controller	Self made	HEU
High voltage diode	HV600S12	Gete

electromagnetic induction principle, when controller shuts, induced voltage is produced, spark plug is breakdown, ignition spark is created. As to capacitive ignition system, when switch connects to joint 1, it starts to charge, the energy is stored in capacitance; when switch is shifted from joint 1-2 m sec^{-1}, ignition happens.

Inductive ignition has the advantage of longer spark duration (1-2 m sec^{-1}), hoverer it needs longer charging time, so it is difficult to achieve multiple discharge during one engine cycle; To capacitive ignition, spark duration is about 5-50 μ sec, it is difficult to form initial ignition flame in lean burn condition, in theory superposition discharge can be achieved, but influencing factors are different to control. In order to combine the advantages of capacitive ignition and inductive ignition, according to energy superposition principle, a dual-coil ignition system was developed by using two ignition coils. The discharge laws were controllable by changing the discharge time interval of the two coils. The ignition system components is shown in Fig. 3. The system is composed of ignition control module, 12 V DC power supply, ignition coil, high-voltage diode, ignition cable and spark plug. The ignition control module is used to control charging time and discharge time interval of the two coils. For the sake of eliminating the interference between the two coils, two high-voltage diodes are used in secondary circuit. The type components are shown in Table 1. The dual-coil discharge ignition system can adjust discharging features by controller.

PARAMETER MEASUREMENT AND EXPERIMENTAL CONDITION

Parameter measurement: Two parts are included in parameter measurement, one is secondary voltage measurement of the new ignition and the other is Indicated Mean Effective Pressure (IMEP) measurement in bench test. Many messages are contained in secondary voltage, such as the maximum voltage, voltage rise rate, spark duration and so on, so secondary voltage can be taken as the index to evaluate the dual-coil ignition system. Evaluation index of combustion cyclic variation includes IMEP, the maximum explosion pressure, the time of maximum pressure and so on. IMEP is calculated according to crank angle, considering the effect of crank angle on combustion process, coefficient of variation of IMEP is used to evaluate cyclic variation:

$$COV_{IMEP}\ (\%) = \frac{SD(IMEP)}{\overline{IMPE}} \times 100 \qquad (1)$$

Where:

SD(IMEP) = The standard deviation of IMEP sample

$\overline{IMPE}$ = Mean value of IMEP sample:

$$SD(IMEP) = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}(IMEP(j) - \overline{IMEP})} \qquad (2)$$

Where:

N = The number of IMEP sample

IMEP (j) = The j value of IMEP sample

Experimental condition

Secondary voltage experimental condition: Secondary voltage of ignition system is strongly influenced by discharge conditions, temperature and pressure of combustion chamber change a lot when engine is working, so secondary voltage was measured when plug was placed in atmosphere, where temperature and pressure were constant. In the experimental process, charging time of both coils was 2.6 m sec^{-1}, the changing laws of secondary voltage were studied in single-coil discharge mode, in dual-coil discharge mode with no time interval and in dual-coil discharge mode with some time interval. TeKtronix P5100A high-voltage probe was used directly to measure secondary voltage and the results were stored in oscilloscope.

Table 2: Engine specifications

Engine type	Before refitting	2135G diesel
	After refitting	CNG engine
Compression ratio	Before refitting	17
	After refitting	13
Ignition type	Dual-coil ignition system	
Spark advance angle	Single coil, dual-coil simultaneously discharge mode	20 BTDC
	Dual-coil multiple discharge mode	20 and 15 BTDC
Inject mode	Manifold multi-point injection	

Table 3: Experimental apparatus

Name	Type	Manufacturer
Dynamometer	CW-260	NAN-FENG
Cylinder pressure sensor	GU21C	AVL
Combustion analyzer	DS9100	ONO SOKKI
λ apparatus	LA4-4.9	ETAS
Water temperature controller	FC2420D	Xiangyi

Test bench condition: The bench test was carried out in a multiple injection CNG engine which was refitted by a 2135 G diesel engine. Electric eddy current dynamometer was used to load, in order to research engine nonlinear characteristics; feedback controls except for speed closed-loop control were abolished. The acquisition system of cylinder pressure consists of piezoelectric cylinder pressure sensor, charge amplifier,combustion analyzer and computer. In order to eliminate the influence of cooling water temperature to combustion cyclic variation, a cooling water temperature adjusting device is installed, the temperature of cooling water was fixed at 80°C during bench test. At the speed of 1000 r min^{-1}, air throttle is fully open and the air-fuel ratio λ, respectively is 1 (theoretical air-fuel ratio), 1.31 (medium lean burn) and 1.53 (lean burn limit), cylinder pressure time series reacquired. The engine parameters and bench test instruments, respectively shown in Table 1-3.

EXPERIMENTAL RESULTS

Experimental results of secondary voltage: Figure 4-8, respectively experimental wave of secondary voltage in single-coil mode, in dual-coil mode with no time interval, in dual-coil mode with 0.4 m sec^{-1} interval, in dual-coil mode with 0.8 m sec^{-1} interval and in dual-coil mode with 1.1 m sec^{-1} interval.

Figure 4 shows that secondary voltage increases to 700 V rapidly in single-coil discharge mode when ignition happens, voltage between two end of the spark plug is keep at about 500 V until the discharge ends, spark duration is about 1.15 m sec^{-1}. Figure 4 shows that compared with single-coil mode and the spark duration changes little in the dual-coil mode with no time interval, the breakdown voltage is increased from 700-1100 V; Fig. 6 and 7 demonstrate that in the dual-coil mode with 0.4 and 0.8 m sec interval superimposed

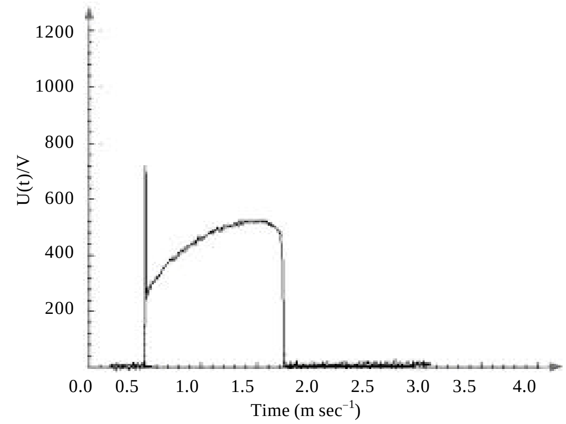

Fig. 4: Experimental wave of secondary voltage in single-coil mode

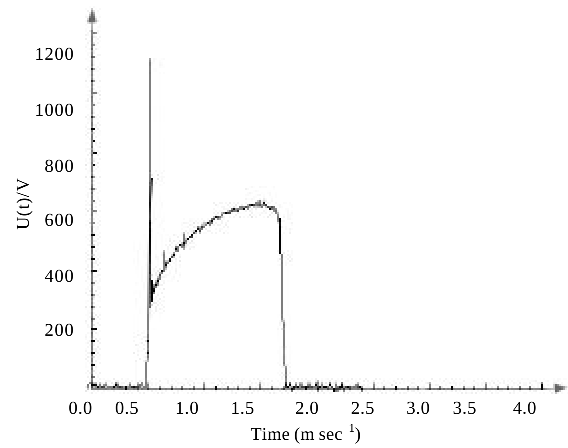

Fig. 5: Experimental wave of secondary voltage in dual-coil mode with no time interval

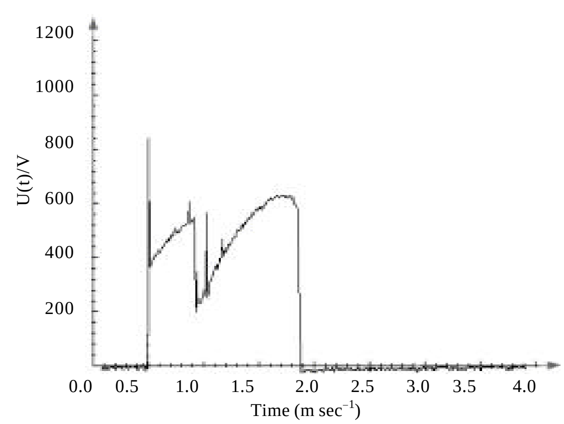

Fig. 6: Experimental wave of secondary voltage in dual-coil mode with 0.4 m sec^{-1} interval

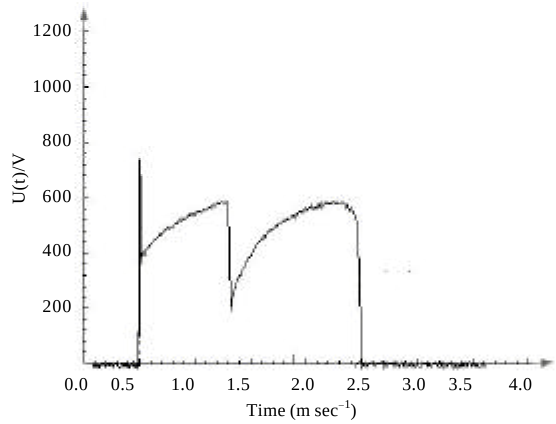

Fig. 7: Experimental wave of secondary voltage in dual-coil mode with 0.8 m sec^{-1} interval

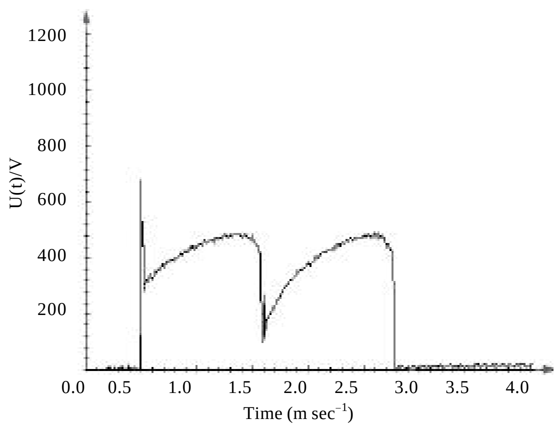

Fig. 8: Experimental wave of secondary voltage in dual-coil mode with 1.1 m sec^{-1} interval

waveform appears in discharge process, the incremental time is 0.4 and 0.8 m sec^{-1} in proper order; Fig. 7 explain that in dual-coil mode with 1.1 m sec^{-1} interval the second coil starts to discharge when the secondary voltage drops below 200 V, the spark goes out then, the entire discharge process is equivalent to double ignition.

Results of bench test: In theoretical air-fuel ratio conditions (λ = 1) and medium lean burn conditions (λ = 1.31), 1000 cyclic pressure data were acquired and 100 circulation data were listed in figure; in lean burn limit condition (λ = 1.53), 2000 cyclic pressure data were acquired and 200 circulation data were listed in figure.

Theoretical air-fuel ratio condition: Figure 9 is IMEP time series in different discharge mode under theoretical air-fuel ratio condition, Fig. 10 is the cyclic variation coefficient calculated by IMEP time series.

Figure 9 shows in theoretical air-fuel ratio condition, fluctuation of IMEP is small; the maximum fluctuating value is 0.051 MP. Figure 10 shows in theoretical air-fuel ratio condition, in single-coil mode, dual-coil simultaneously discharge mode, dual-coil continuously discharge mode and dual-coil multiple discharge mode, COVIMEP are 1.06, 0.88, 0.89 and 1.09% in order. Compared with single-coil mode, COVIMEP decreases a little in dual-coil simultaneously discharge mode and dual-coil continuously discharge mode, the reduction is 0.18 and 0.17% in order, the effect is not obvious; in dual-coil multiple discharge mode, COVIMEP improves little.

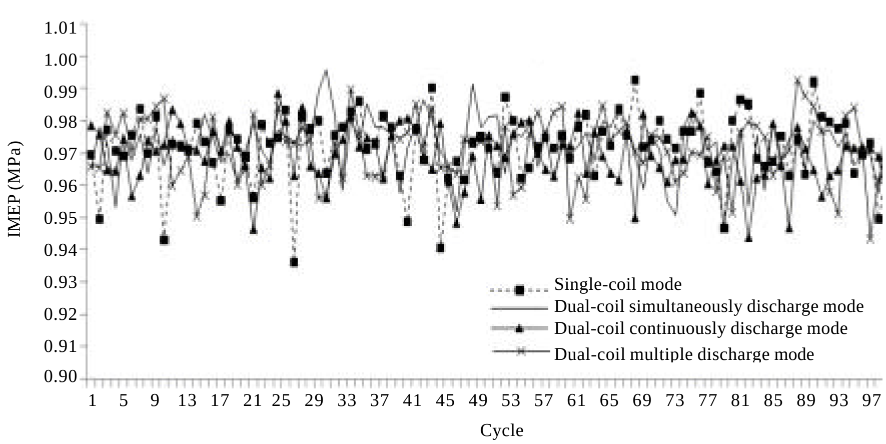

Fig. 9: IMEP time series in different discharge mode under theoretical air-fuel ratio condition

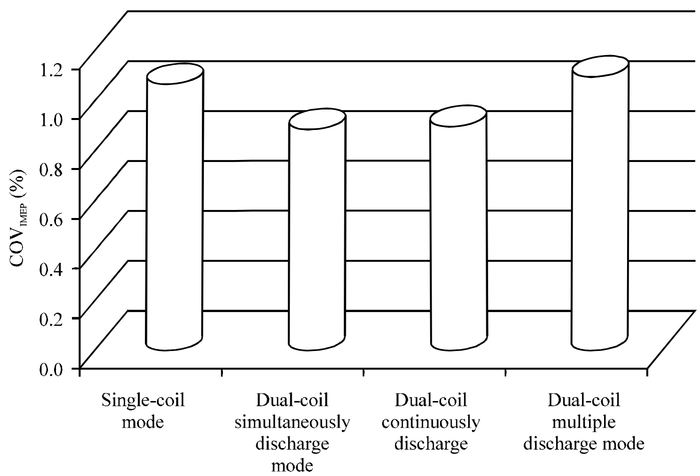

Fig. 10: Cyclic variation coefficient in different discharge mode under theoretical air-fuel ratio condition

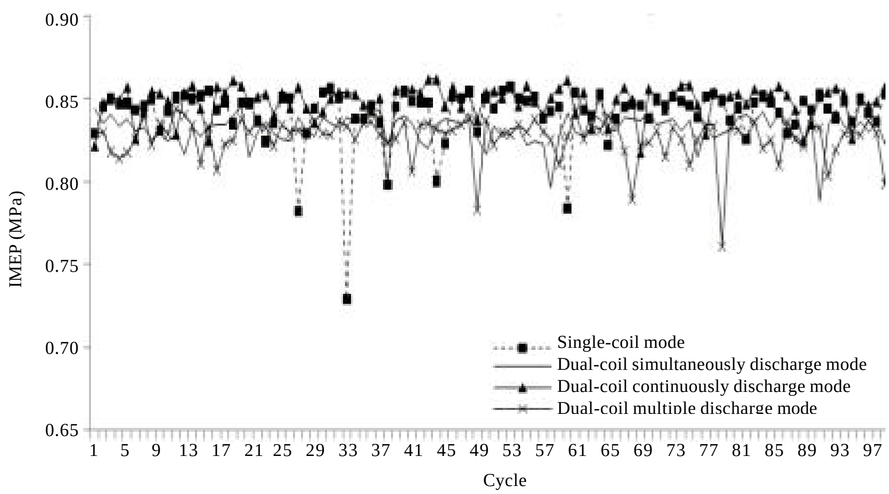

Fig. 11: IMEP time series in different discharge mode under lean burn condition

Medium lean burn condition: Figure 11 is IMEP time series in different discharge mode under medium lean burn condition. Figure 12 is the cyclic variation coefficient calculated by IMEP time series.

Compared with Fig. 9, 11 shows that fluctuation of IMEP is more obvious in single-coil mode, fluctuating value changes from 0.051 MP to 0.115 MPa, COVIMEP increases from 1.06% to 1.62. Under medium lean burn condition in dual-coil simultaneously discharge mode, dual-coil continuously discharge mode and dual-coil multiple discharge mode, COVIMEP are 1.11, 1.21 and 1.39% in order, compared with single-coil mode, COVIMEP can be decreased in any dual-coil discharge mode. It has the most obvious effect in dual-coil simultaneously discharge mode, followed by continuously discharge mode, finally dual-coil multiple discharge mode. COVIMEP decreases by 0.51, 0.41 and 0.23% in order.

It can be known that initial kernel has a great influence on combustion cyclic variation, so it is benefit for forming initial kernel in dual-coil continuously discharge mode and in dual-coil continuously discharge mode. As for dual-coil multiple discharge mode, it has little influence on initial kernel, but it is still contribute to the development of combustion flame.

Lean burn limit condition: Figure 13 is IMEP time series in different discharge mode under lean burn limit condition. Figure 14 is the cyclic variation coefficient calculated by IMEP time series.

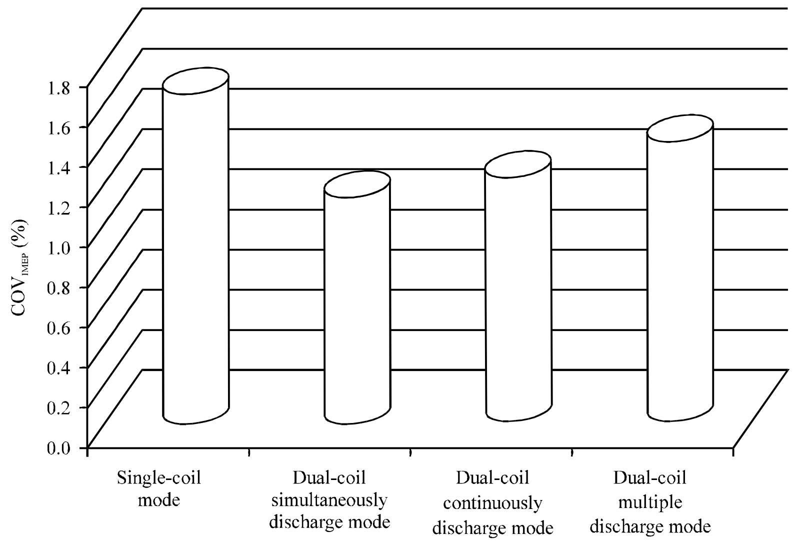

Fig. 12: Cyclic variation coefficient in different discharge mode under lean burn condition

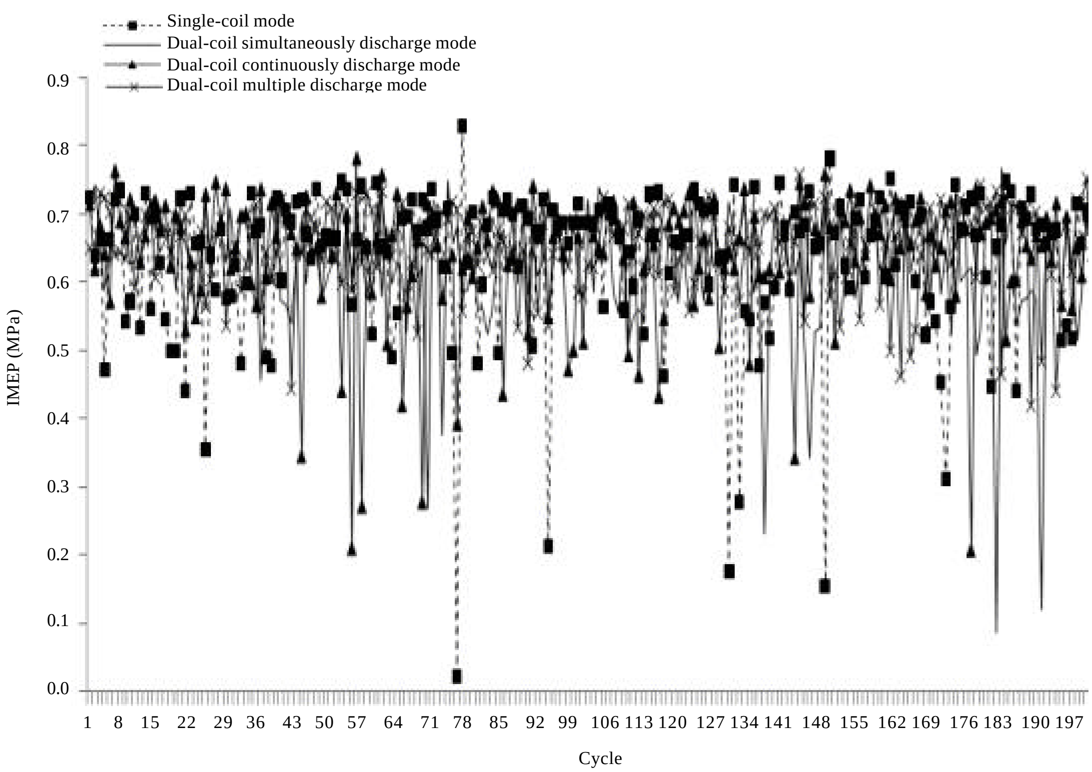

Fig. 13: IMEP time series in different discharge mode under lean burn limit condition

Figure 13 shows that it has a large fluctuation in single-coil mode under lean burn limit condition, IMEP changes from 0.02-0.81 MPa, as to dual-coil discharge mode, fluctuating value has a obvious decrease. Figure 14 shows under lean burn limit condition, in single-coil mode, COVIMEP is 11.38%, combustion is very unstable; in dual-coil simultaneously discharge mode, dual-coil continuously discharge mode and dual-coil multiple

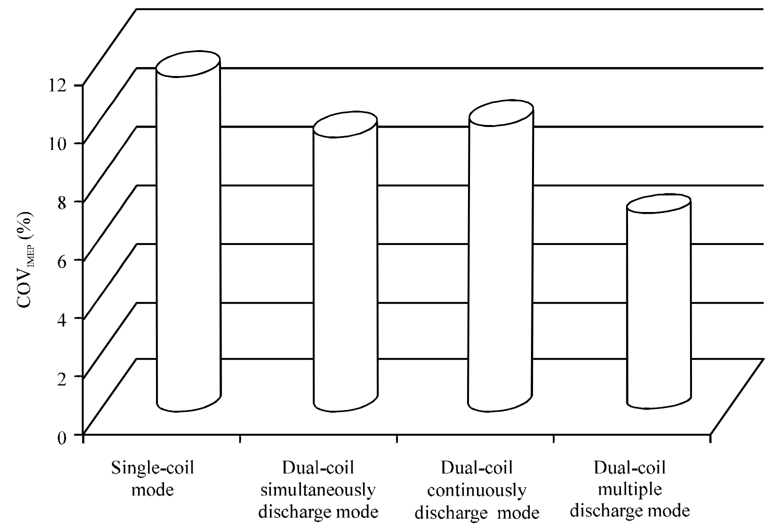

Fig. 14: Cyclic variation coefficient in different discharge mode under lean burn condition

discharge mode, COVIMEP are 9.33, 9.72 and 6.51% in order, successively decreases by 2.05, 1.66% and 4.87. It is the dual-coil multiple discharge mode.

CONCLUSION

- Contrast to single-coil mode, ignition energy can be double in any dual-coil mode, secondary voltage can be increased by 30% in dual-coil continuously discharge mode, spark duration can be extended in dual-coil continuously discharge mode, the incremental time is equal to time interval and multiple discharge can be achieved if time interval is longer than spark duration
- Dual-coil discharge mode has an effect on cyclic variation, the effect is not obvious in theoretical air-fuel ratio condition and dual-coil simultaneously discharge mode has the most obvious effect in medium lean burn condition and dual-coil multiple discharge mode has the most obvious effect in lean burn limit condition

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