Experimental investigations on the cyclic variability of a large bore CNG engine

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Abstract. Experiments were used to explore the cyclic variability of a CNG engine. The experiments were conducted on a large bore (12V190) engine fuelled with pre-mixed natural gas. The influences of the ignition advance angle, the excess air ratio and the ignition energy on the cyclic variability were investigated. At each test condition there were acquired in-cylinder pressure traces of 100 consecutive cycles. Cyclic variability was quantified by the variation of indicated mean effective pressure (IMEP) in this paper. The experimental results showed that the cyclic variation was increased while increasing the dilution levels. And, the cyclic variation was reduced with the increase of the ignition advance angle. Meanwhile, the cyclic variation could not be significantly reduced just by increasing the ignition energy on the specified engine. The reason can be that the most important influence exerted by the ignition energy is the formation of early flame kernel. In order to significantly reduce the cyclic variations, there is also necessary the improvement of the gas mixture's motion state in the cylinder.

1. Introduction

One of the ways of reducing the dependence on raw oil could be moving away from conventional fossil fuel and increasing the usage of alternative energy sources. One such alternative energy is natural gas. Natural gas offers a viable near-term solution to decrease the consumption of crude oil. Natural gas is the least polluted of all fossil fuels. It can improve air pollution by more extensive use of natural gas [1]. Table 1 shows the data comparisons from the Environmental Protection Agency, the combustion of natural gas compared to that of oil and coal produces very little sulfur dioxide and nitrogen oxides, lower levels of carbon monoxide and carbon dioxide, and virtually no particulate matter.

In terms of the combustion advantages of using CNG, the octane level of CNG compared to conventional fuel increases from approximately 90 to 118. By using fuels with better antiknock properties, the engine compression ratios steadily increase, thus improving power and efficiency [2]. By using a fuel with a higher octane rating, the knock margin of the engine can then be increased and a higher efficiency engine calibration strategy can be used. Also by using a fuel with a higher octane number, more spark advance is possible as the risk of pre-ignition is reduced [3]. The key to a reliable combustion is to establish a stable flame kernel in the ignition zone. A number of experimental and production technologies already exist to serve this function.

Table 1. Fossil fuel emission levels [1].

Pollutant	Coal	Oil	Natural Gas
Carbon Dioxide	208,000	164,000	117,000
Nitrogen Oxides	457	448	92
Carbon Monoxide	208	33	40
Particulates	2744	84	7
Sulfur Dioxide	2591	1,122	1
Mercury	0.016	0.007	0.000

*Units: Pounds per Billion Btu of Energy Input

The results of many of these studies, such as [4-7], have shown a reduction in the marginal benefit of dilution (such as lean burn [8]) as the dilution level increases. This reduction in the rate of improvement is primarily due to a decrease in engine stability, which is often brought on by slower burn rates due to dilution. While changes in flow field and other modifications can improve to some degree the dilution tolerance of the engine. The advanced ignition system can improve the dilution tolerance of the engine. This paper presents both experimental data and simulation (AVL FIRE) results to account for the influence of excess air ratio, advance angle of ignition and ignition energy on CNG engine.

2. Experimental setup

A large bore CNG engine (12V190) was used in this research. The cylinder pressure is collected through combustion analyzer (Kistler 2893AK1). A CNG fuelling system and high energy ignition system (Motortech MIC4) are also assembled on the engine. Figure 1 shows the diagram of testing system.

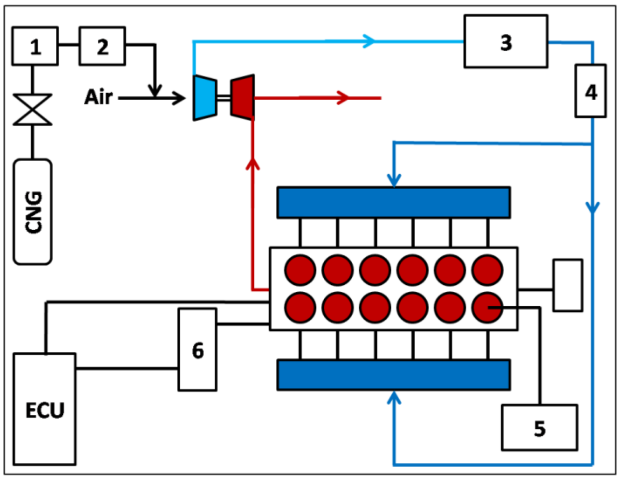


Figure 1. The Diagram of testing system. (1. Flow meter; 2. Reducing valve; 3. Intercooler; 4. Throttle Valve; 5. Combustion analyzer; 6. MIC4)

The devices of the MIC4 series are microprocessor controlled ignition systems, that are comprised of one 32 bit main processor (CPU) and an output board. The ignition controllers of the MIC4 series use information supplied by the pickups to precisely determine the correct timing for the respective outputs. During operation, the ignition controllers continuously monitor the system status of all installed pickups and the correct operation of the primary ignition circuit by checking the information received.

The natural gas is premixed with air flow prior to entering the compressor. Table 2 shows the engine specification. The study focuses on the influences on the combustion when using different air-fuel ratios , advance angle of ignition and ignition energy. By varying the advance angle of ignition and ignition energy, the effects on knock factor (KF), Exhaust temperature and Coefficient of variation in IMEP (COVIMEP) values are obtained. KF reflects the knock severity level defined in reference [9]. The Knock intensity is increasing with the larger value of KF. The summary of the testing criteria can be seen in table 2. There were 5-7 Lambda, 5 advance angles of ignition and 2 different variation of ignition energy used as test points. These test points were all taken under steady-state conditions.

Table 2. Engine specifications.

Base engine	12V190
Compression ratio	11:1
Valves per cylinder	4
Bore x stroke	190mm x 210mm
Fuel system	Premixed
Engine speed	1300 RPM
Ignition energy	150mJ, 300mJ
Advance angle of ignition	26-34 °CA BTDC
Lambda	1.38, 1.41, 1.45, 1.5, 1.55, 1.6, 1.65

All experiments are done by the following test procedure: (1) Warm up the engine with a coolant heater until the coolant temperature reaches 40°C. Air temperature is as the room temperature, which is about 16°C. (2) Start the engine at 1300 RPM. (3) Start combustion analyzer, cylinder pressure recording, and data acquisition if the combustion is stable. These procedures are considered as steady state.

3. Results and discussions

CNG fuel is tested with 2 different values of the ignition energy. The testing results can be analyzed from the aspects of excess air ratio, advance angle of ignition and ignition energy. These three factors are all important controls parameter on the CNG engine. The combustion process in the cylinder and the performance of the CNG engine are directly affected by the values of the excess air ratio and of the advance angle of ignition. With the change of the excess air ratio, of the advance angle of ignition and of the ignition energy, the flame propagation velocity of burning mixture and the combustion stability are varied. Eventually, this can cause significant changes on the engine combustion performance.

3.1. Expand the lean combustion boundary

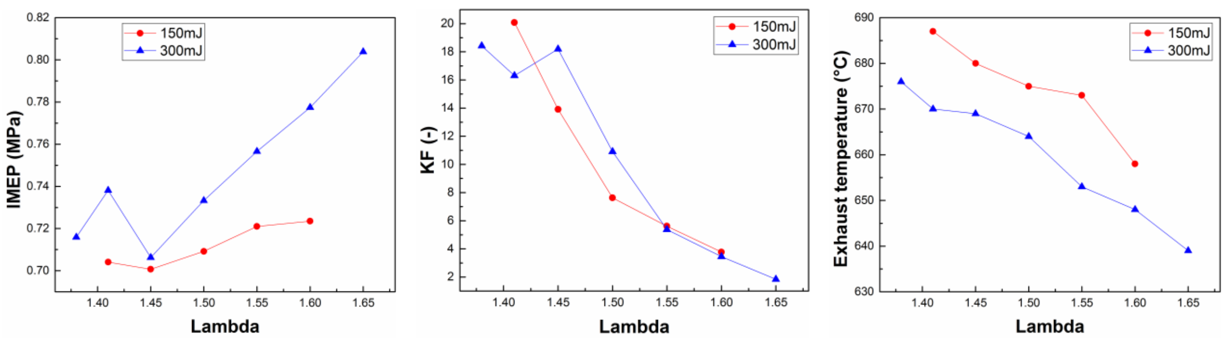
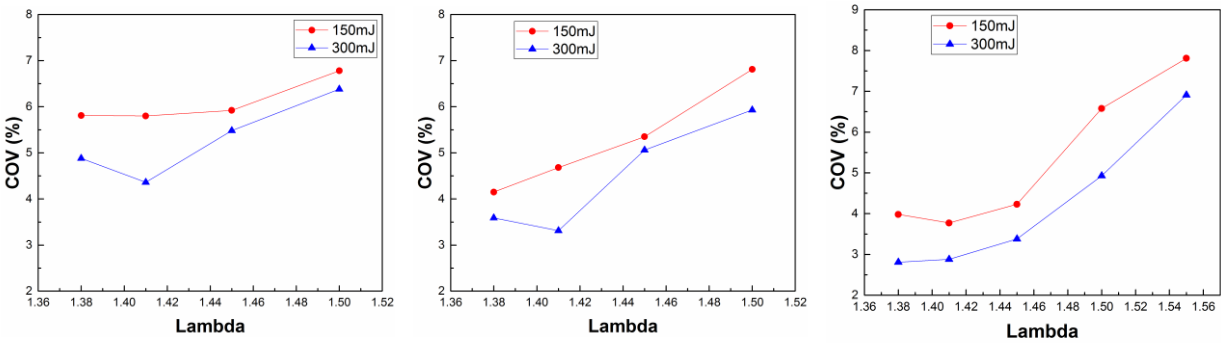


Figure. 2 Data of IMEP, KF and exhaust temperature with two kinds of ignition energy.

Boundary of lean combustion can be extended by high energy ignition technology. Figure 2 shows data of IMEP, KF and exhaust temperature with two kinds of ignition energy. It is observed that the excess air ratio is extended to 1.65 by using 300 mJ ignition energy. While the excess air ratio can only be reached to 1.6 by using 150 mJ ignition energy under the same conditions. It illustrates that the relatively stable flame kernel formed by high energy ignition contribute to the stable operation in the boundary condition of lean combustion.

3.2. COV_{IMEP}

Excess air ratio makes a great influence on cyclic variability of CNG engine. Figure 3 shows he trend of COV_{IMEP} with the change of excess air ratio. It is observed that COV_{IMEP} increases gradually with the increase of excess air ratio. It means the combustion stability is deteriorated. Meanwhile, it can be seen cyclic variability is becoming smaller with the larger advance angle of ignition under the same excess air ratio (eg. 1.5). It is can be seen the larger advance angle of ignition can help to improve the stability of combustion. Whereas the value of COV_{IMEP} tend to be bigger when the excess air ratio increases to 1.55. It illustrates the increase of excess air ratio is a very momentous factor leading to combustion instability of CNG engine.



26°CA BTDC 28°CA BTDC 30°CA BTDC

Figure. 3 Data of COV_{IMEP} with two kinds of ignition energy.

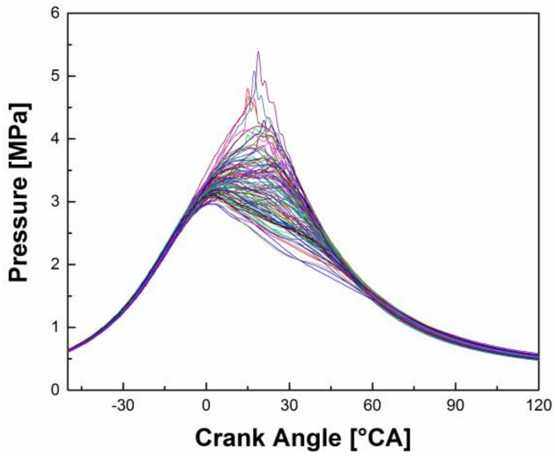


Figure. 4 Variation of cylinder pressure.

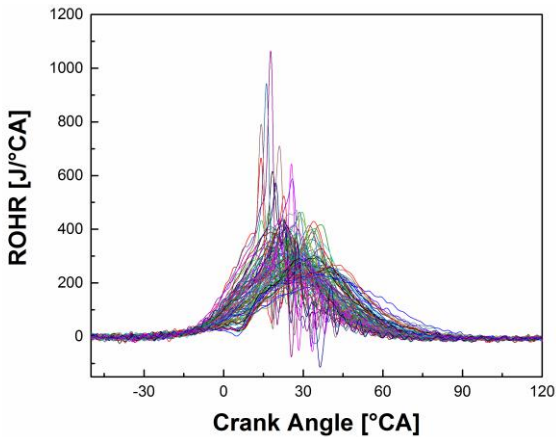


Figure. 5 Variation of ROHR.

3.3. Cylinder pressure and rate of heat release (ROHR)

Figures 4 and 5 show the variations (cycle-by-cycle) of cylinder pressure and ROHR. Pressure and ROHR for 100 successive cycles at 1.5 excess air ratio, 300 mJ ignition energy, 26°CA BTDC advance angle of ignition are shown as a function of crank angle. It can be seen the peak cylinder pressure varies accordingly. And the higher values of ROHR have substantially greater peak cylinder pressure than do the lower ROHR.

3.4. The exhaust temperature

In figure 6, it can be obtained that exhaust temperature decreases as the excess air ratio increases at all advance angles of ignition. This indicates the lean combustion has significant influence on reducing the exhaust temperature. Whereas, in figure 6, it also can be observed the exhaust temperature with 300 mJ ignition energy is not less than 150 mJ at 26, 28 and 34°CA BTDC.

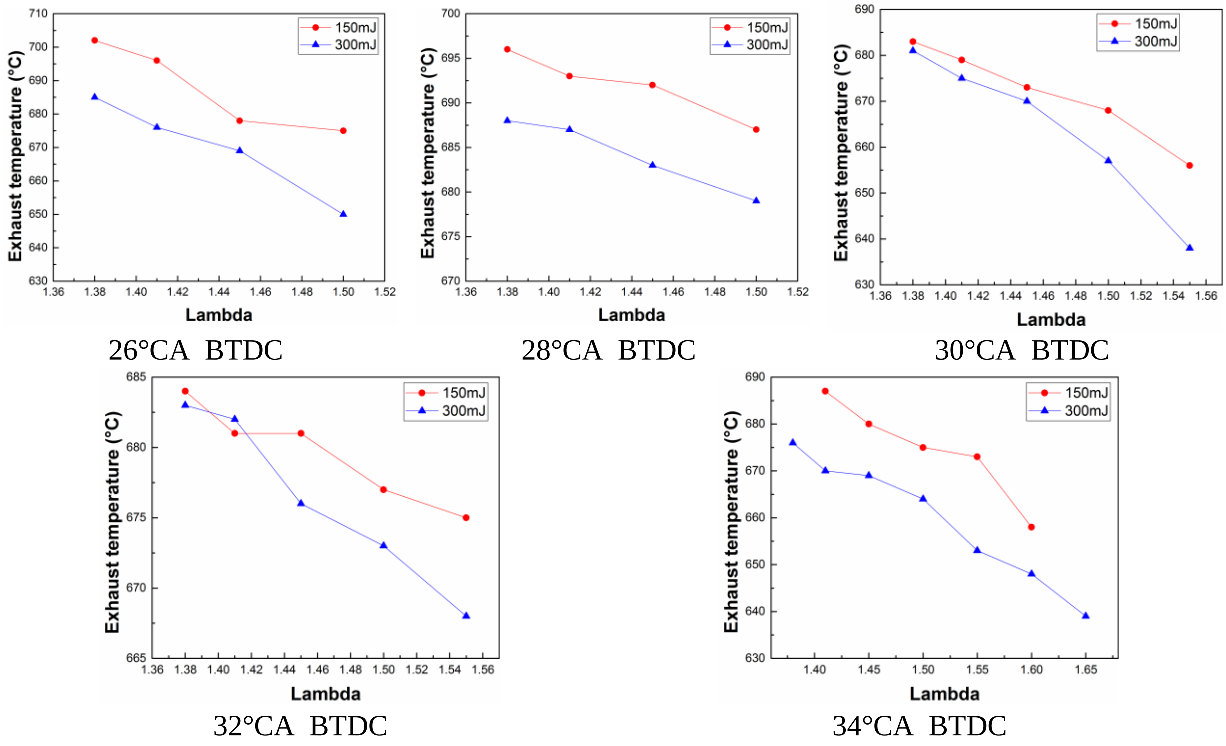


Figure. 6 Data of exhaust temperature at different advance angles of ignition.

3.5. The Mixture flow

A modified intake port with swirling shape have been designed distinguish from the original in this research. The original intake port is 1# (figure 7), and the other one have been marked as 2# (figure 8). The geometric models are built by Computer Aided Design (CAD) software SolidWorks. To import into AVL FIRE, the data should be saved as STL format.

Figure 9 is the comparison curve of mean turbulence kinetic energy (TKE) in cylinder between two different projects. Figure 9 shows the TKE of 2# is obviously higher than 1#. That can be deduced the modified intake port have a significant influence on the TKE in cylinder. The TKE of two projects all reach the peak before TDC. The main reason is that the TKE is at a lower level in the early compression stroke. And the value of TKE in cylinder gets larger in the later period of compression stroke because of the effect of squish flow in cylinder. Then the TKE is declined promptly as the decreasing speed of piston. In terms of the peak of TKE, 1# is 42.8 m^2/s^2; while 2# is 65.8 m^2/s^2 (53.7% higher than 1#). It illustrates that 2# intake port has great influence on promoting the TKE. The change of the TKE in cylinder affects the turbulent flow in cylinder, thereby impacting flame propagation speed in period of rapid combustion.

Figure. 7 The original intake port (1#).

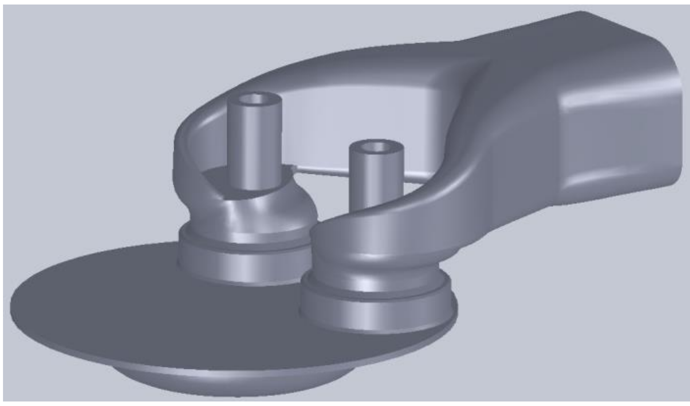


Figure. 8 The modified intake port (2#).

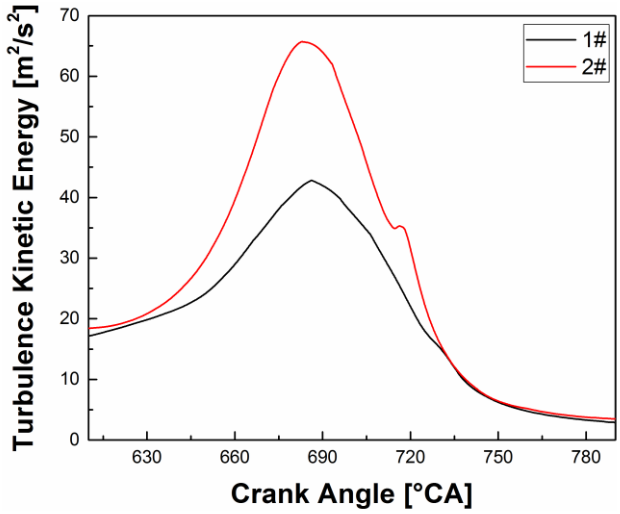


Figure. 9 The curves of the turbulent kinetic energy.

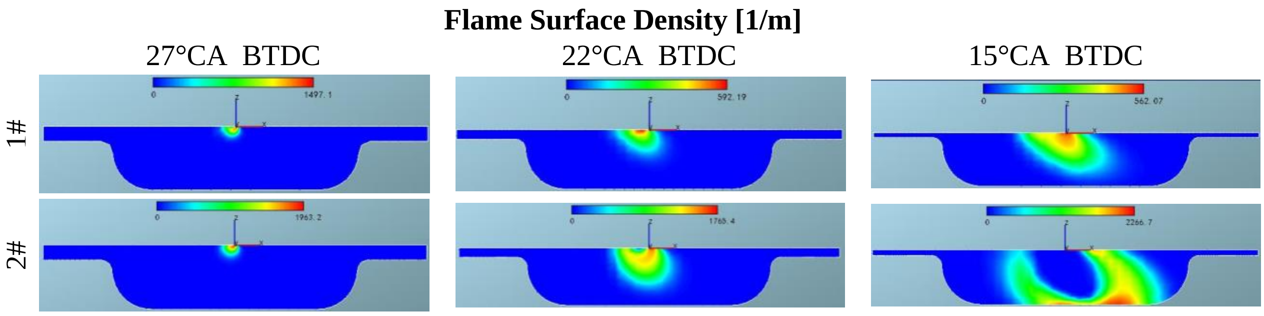


Figure. 10 The distribution of the flame surface density.

The distribution of the flame surface density can reflect the capacity of flame propagation. Figure 10 shows the longitudinal sections of the situation of the flame surface density form 27°CA BTDC to 15°CA BTDC between two different projects. It can be obtained from figure 10 flame propagation velocity in 1# is minimum while which in 2# is larger due to the more active KTE. In figure 10, it also can be obtained that the distributions of flame surface density between two different projects are inconsistent. The flame surface density is maximal for the intake port no. 2# while for the intake port no. 1# it has a minimal value. Also, the flame surface density increases as the flame spreads outward.

This shows that the flame propagation velocity is maximum and the homogeneity of the flame propagation of the intake port no. 2# is better. The main reason is that the discrepancy of the mixture flow caused by the whirling intake port has an important influence on the flame propagation.

4. Conclusions

The present study primarily focuses on the effects of ignition energy on the combustion performance on an engine using CNG. CNG fuel was tested with two levels of ignition energy. The testing results are separated by lambda value and combustion analysis. The results indicate the following conclusions:

- Boundary of lean combustion can be extended by high energy ignition technology. Excess air ratio makes a great influence on cyclic variability of CNG engine.
- Lean combustion can greatly bring down the combustion temperature and avoid the happening of the detonation to the greatest extent.
- The most important influence exerted by ignition energy is the formation of early flame kernel. To reduce the cyclic variations significantly, the improvement of the gas mixture motion state in cylinder is also needed.

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