INFLUENCE OF CO-COMBUSTION RATIO ON PERFORMANCE OF A DIESEL ENGINE MODIFIED TO FUELED NATURAL GAS/DIESEL DUAL-FUEL

Jiantong SONG[1], Jiangyi LV [2]

The co-combustion ratio(CCR) as an important operating parameters effects prominently combustion and emissions of a NG/diesel dual-fuel(DF) engine. In order to investigates the effects of CCR on performance of a NG/diesel DF engine, the cycle-by-cycle variation in peak cylinder pressure, brake specific fuel consumption and emissions of a NG/diesel DF engine under the CCR of 0% to 91% were analyzed. The experimental results show that with increasing CCR, the distributions of peak cylinder pressure distinctly scatters, the distribution of crankshaft angle corresponding to peak cylinder pressure scatters under low CCRs while does not variate obviously under high CCRs, the BSFC and CO emission increase first and then decrease, the HC and NO_x emissions increase while the CO_2 and soot emissions decrease sharply.

Keywords: common rail diesel engine; natural gas/diesel dual-fuel; co-combustion ratio; cycle-by-cycle variation; performance; exhaust emissions

1. Introduction

The diesel engines have been widely used in different kinds of vehicles with excellent thermal efficiency and reliability[1]. For a long time in future, they will continue to be the primary power machinery in the industry. With the increasingly strict emission regulations and the serious shortage of petroleum resources in various countries in the world, it is imperative to develop a more excellent performance clean fuel to replace diesel to further improve the emissions and relieve the petroleum crisis[2, 3]. Natural gas(NG) as one clean alternative fuel for various vehicles has attracted more and more attention due to the advantages of abundant resources, lower price, higher octane number and H/C ratio[4, 5].

It is difficult for NG to be run as the sole fuel in a compression ignition engine due to its higher auto-ignition temperature[6]. Under NG/diesel dual-fuel(DF) mode, a small pilot diesel is injected into the cylinder in order to ignite the NG-air mixture, the NG is the primary fuel, and the pilot diesel is only ignition source[7]. In general, the NG/diesel DF engine is modified from a diesel engine by

[1] Prof., College of Automotive Engineering, Beijing Polytechnic, China, e-mail: songjiantong@bpi.edu.cn
[2] Prof., College of Automotive Engineering, Beijing Polytechnic, China, e-mail: lvjiangyi@bpi.edu.cn

adding the NG supply system and electronic control system[4]. The NG/diesel DF engine uses the original diesel injection system to injected directly pilot diesel into the cylinder at the end of the compression stroke, a NG mixer installing on the intake pipe is used to mix NG with air generally or uses port fuel injectors to inject the NG into the intake manifolds[8, 9].

A number of parameters influence significantly on the combustion and emission of the NG/diesel DF engine, such as pilot diesel quantity[10], pilot diesel injection timing (*PDIT*)[11], injection pressure, engine speed, exhaust gas recirculation, equivalence ratio, substitution rate[12, 13], hydrogen addition[14], piston-top shape, and compression ratio[15]. Zhu and Li et al investigated the effect of natural gas energy fraction (*NGEF*) on performance, and the emission characteristics of natural gas/diesel dual-fuel engines. The results revealed that increasing the *NGEF* retarded the start of combustion, decreased the peak pressure, significantly affected the distribution of the ignition kernel. The lower soot volume fraction and unburned hydrocarbon emissions could be obtained by increasing the *NGEF* from 0% to 70%, whereas further increasing the NGEF to 85% deteriorated combustion[16].

The co-combustion ratio (*CCR*) as an important operating parameter effect prominently the combustion and emissions of a NG/diesel DF engine. This study investigates the effects of *CCR* from 0% to 91% on cycle-by-cycle variation in peak cylinder pressure and performance of a NG/diesel DF engine with a high-pressure common rail diesel injection system at the maximum torque speed of 1600 r/min under the brake power of 72.9kW (50% load).

2. Experimental apparatus and procedure

2.1 NG/diesel DF engine

The NG/diesel DF engine for the experiment is modified from a six-cylinder common rail diesel engine, whose specific parameters are shown in Table 1. The experimental bench of DF engine and primary test equipment is shown in Fig.1. The liquefied natural gas(LNG) is preserved in a double-layer LNG vessel, which is made of stainless steel. The LNG is reserved below -162 °C and between 0.5-1.4 MPa. When the pressure of LNG is lower than 0.8 MPa, the power of DF engine will decrease, meanwhile it will maybe fail to start. The LNG absorbs heat and gasifies into gaseous NG when it goes through the vaporizer connected in series in the cooling system of the original diesel engine. The NG mixes with air in the NG mixer after going through NG solenoid valve, filter, pressure regulator and rail, and then enters into the engine when the intake valves open. The *CCR* has a significant impact on the maximum torque pilot diesel injection timing of DF engine. When the *CCR*s are 18%, 56% and 91%, the *PDIT*s are respectively set as 17°CA BTDC, 20°CA BTDC, 42°CA BTDC, which are the maximum torque *PDIT*s. We also found that *CCR* had a lower effect on the maximum torque *PDIT* when it is less than 75%. So the *PDIT*s are set as 17°CA BTDC and 20°CA BTDC under the *CCR*s of 39% and 75%.

Table 1

The original diesel engine specifications

Items	Parameters
Rated power	199 kW@2200r/min
Maximum torque	1080 Nm@1200-1700r/min
Compression ratio	17.5
Displacement	7.8 L
Bore×Stoke	112×132 mm

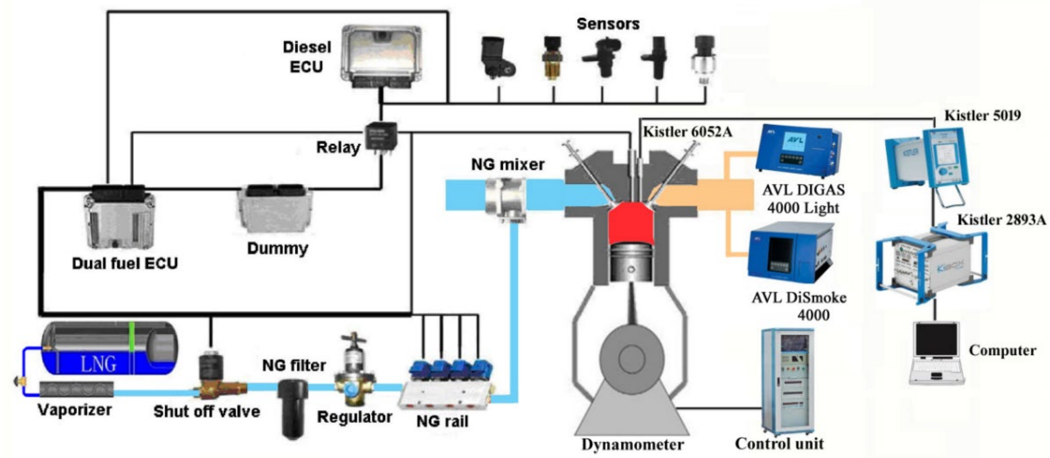

Fig. 1. The experimental bench of the DF engine

2.2 Data processing

2.2.1 Brake specific fuel consumption

BSFC refers to the fuel consumption by the unit of effective work output of the engine. According to equivalent calorific value replacement, the consumption of NG is converted to the consumption of diesel.

$$BSFC = \frac{m_{diesel} + \frac{LHV_{NG}}{LHV_{diesel}} \times m_{NG}}{Pe} \times 10^3 \qquad (1)$$

Where m_{NG} represents the mass flow rate of NG(kg/h), m_{diesel} represents that of diesel(kg/h), LHV_{NG} represents the low heating value of NG, LHV_{diesel} represents that of diesel, *Pe* represents the brake power(kW). The LHV_{NG} and LHV_{diesel} are 49.54 MJ/kg and 42.5 MJ/kg in this study, respectively.

2.2.2 Co-combustion ratio

CCR of DF refers to the percentage of energy released by NG combustion in the total energy released by NG and diesel combustion. The mass fractions of NG in DF are listed in Table 2.

$$CCR = \frac{m_{NG} \times LHV_{NG}}{m_{diesel} \times LHV_{diesel} + m_{NG} \times LHV_{NG}} \times 100\% \quad (2)$$

CCR=0 represents diesel mode.

Table 2

The mass fractions of NG in DF

CCR	18%	39%	56%	75%	91%
$m_{NG}/(m_{NG+}\ m_{diesel})$	16 %	35 %	52 %	72 %	90 %

3. Results and discussion

3.1 Cycle-by-cycle variation in peak cylinder pressure

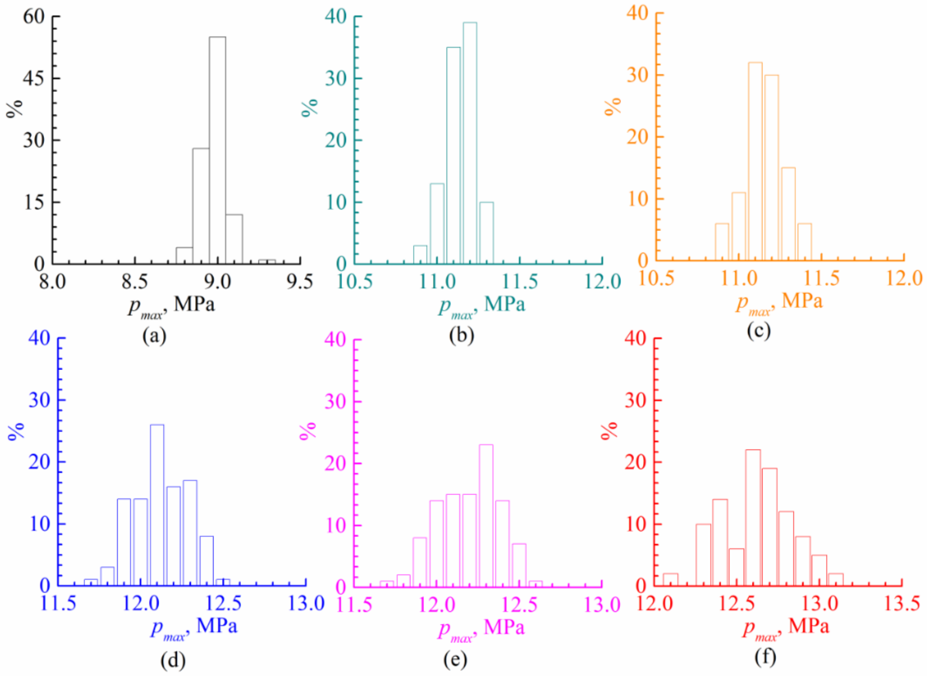

Fig. 2. Variation in percentage distribution of p_{max} for the NG/diesel DF and diesel engines: (a) *CCR*=0%, (b) *CCR*=18%, (c) *CCR*=39%, (d) *CCR*=56%, (e) *CCR*=75%, (f) *CCR*=91%

Under different *CCR*s, variation in percentage distribution of the peak cylinder pressure (p_{max}) for DF and diesel engines is shown in Fig. 2. The percentage of p_{max} of 9.0 MPa is maximum and up to 55% under diesel mode. Compared to diesel, the maximum percentage of p_{max} of DF decreases significantly. Under the *CCR*s of 18%, 39%, 56%, 75% and 91%, the maximum percentage of p_{max} of DF are 39%, 32%, 26%, 23% and 22%, respectively. With increasing *CCR*, the maximum percentage of p_{max} of DF decreases obviously, and the distribution of p_{max} distinctly scatters. Under different *CCR*s, the mean value of p_{max} ($\bar{p}_{max}$) and standard deviation of p_{max} (σ_{pmax}) for DF and diesel engines are shown in Fig. 3. With increasing *CCR*s, there is an increasing tendency for the $\bar{p}_{max}$ and σ_{pmax} of the dual-fuel engine. Zhongshu Wang et al. found that both the σ_{pmax} and the coefficient of variation in p_{max} showed a uniform upward trend with the increase of *CCR*[12]. At the same *PDIT*, with increasing *CCR*, the $\bar{p}_{max}$ of the dual-fuel engine does not change obviously, but the σ_{pmax} decreases.

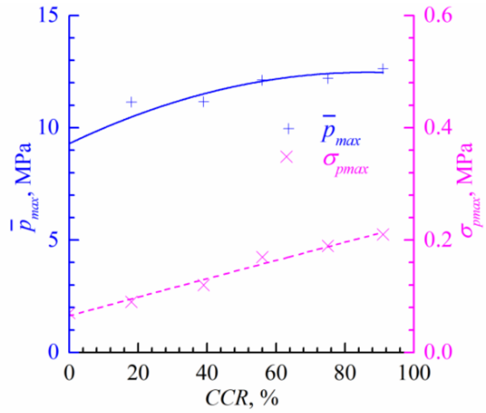

Fig. 3 Variation in $\bar{p}_{max}$ and σ_{pmax} with *CCR* for the NG/diesel DF and diesel engines

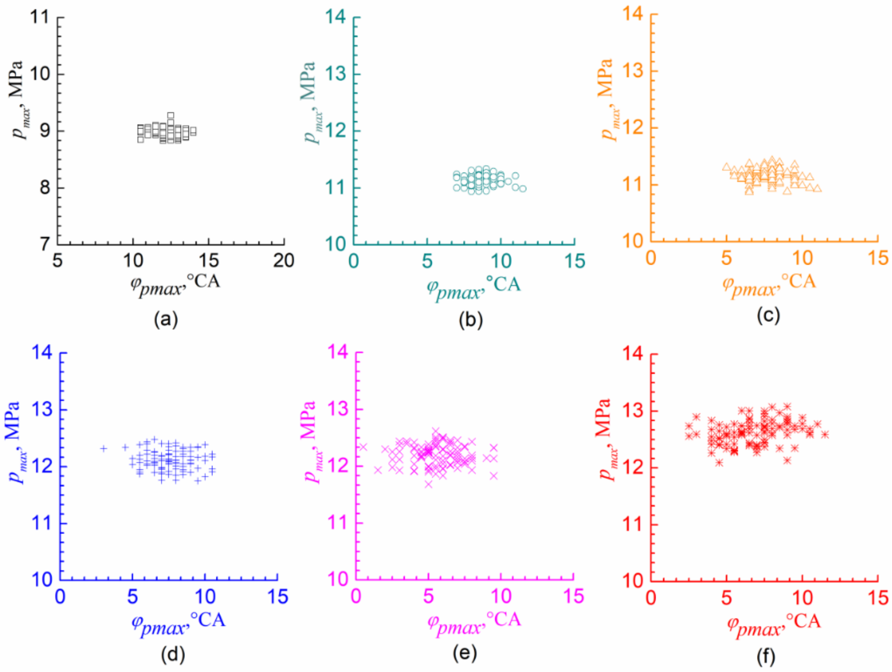

Fig. 4. The interdependence between p_{max} and φ_{pmax} for the NG/diesel DF and diesel engines: (a) *CCR*=0%, (b) *CCR*=18%, (c) *CCR*=39%, (d) *CCR*=56%, (e) *CCR*=75%, (f) *CCR*=91%

Under different *CCR*s, the interdependence between p_{max} and crankshaft angle corresponding to $p_{max}(\varphi_{pmax})$ for DF and diesel engines is shown in Fig. 4.

Compared to the diesel engine, the concentrated distribution range of φ_{pmax} of the DF engine reduces slightly under the *CCR* of 18%, but that increases under the *CCR*s of 39% to 91%. With increasing *CCR*, the distribution of φ_{pmax} scatters under low *CCR*s of 18% to 56%, while the distribution of φ_{pmax} do not variate obviously under high *CCR*s of 56% to 91%. The interdependence between p_{max} and φ_{pmax} for the NG/diesel DF and diesel engines is not evident. At the same *PDIT*, with increasing *CCR*, the p_{max} moves up to the top dead center, the maximum percentage of φ_{pmax} of DF engine under the *CCR* of 39% is distinctly lower than that under the *CCR* of 18%. Zhongshu Wang et al. found that the φ_{pmax} was concentrated under lower *CCR*s, while the φ_{pmax} was scattered when the *CCR* was more than 70%[12].

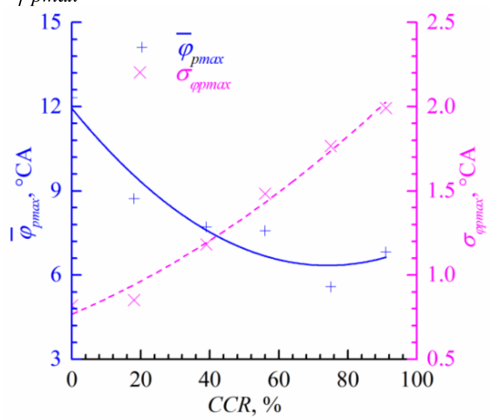

Fig. 5. Variation in $\bar{\varphi}_{max}$ and $\sigma_{\varphi pmax}$ with *CCR* for the NG/diesel DF and diesel engines

Under different *CCR*s, the mean value of φ_{pmax}($\bar{\varphi}_{max}$) and standard deviation of φ_{pmax}($\sigma_{\varphi pmax}$) of the DF and diesel engines are shown in Fig. 5. With increasing *CCR*, the $\bar{\varphi}_{max}$ of the DF engine decreases while the $\sigma_{\varphi pmax}$ increases.

3.2 Performance analysis

3.2.1 λ and *BSFC*

The λ and *BSFC* for DF and diesel engines with different *CCR*s are shown in Fig. 6. With increasing *CCR*, the λ of the DF engine decreases slightly. This is mainly because NG in gaseous state enters the cylinder, taking up a part of the cylinder volume, the air entering cylinder reduces, leading to the slight decrease of λ.

With increasing *CCR*, the *BSFC* of the DF engine increases first and then decreases. The *BSFC* of DF engine reaches its maximum value under the *CCR* of 39%; it is lower only under the *CCR* of 91% than that of the original diesel engine. This is mainly because when the *CCR* is less than 39%, the NG-air mixture is so lean that can not combust completely. In addition, as increasing *CCR*, the *PDQ* decreases, the energy and quantity of the ignition point of natural gas decrease, resulting in the further incomplete combustion of NG. When the *CCR* is more than 39%, as the increase of *CCR*, the NG-air mixture becomes richer, the combustion condition is improved, with multipoint ignition, the constant volume combustion and thermal efficiency increase. So under the *CCR* more than 39%, the *BSFC* of the DF engine decreases with increasing *CCR*, and the *BSFC* reaches its maximum value under the *CCR* of 39%.

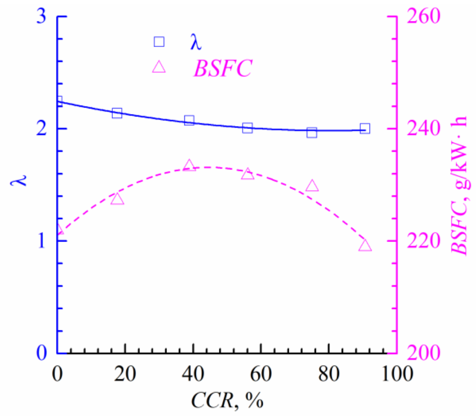

Fig. 6. Variation in λ and *BSFC* with *CCR* for the NG/diesel DF and diesel engines

3.2.2 CO, HC and CO_2 emissions

The CO, HC and CO_2 emissions for DF and diesel engines with different *CCR*s are shown in Fig. 7. With increasing *CCR*, the CO emission of the DF engine raises first and then reduces, which reaches the maximum under the *CCR* of 56%. The λ of the DF engine is more than two under the test point, so the CO produced by lack of oxidants is very little. When the *CCR* is less than 56%, the NG-air mixture is so lean that the CO emission produced by misfire increases with increasing *CCR*. When the *CCR* is more than 56%, the NG-air mixture becomes richer, and the CO emissions decreases with increasing *CCR*.

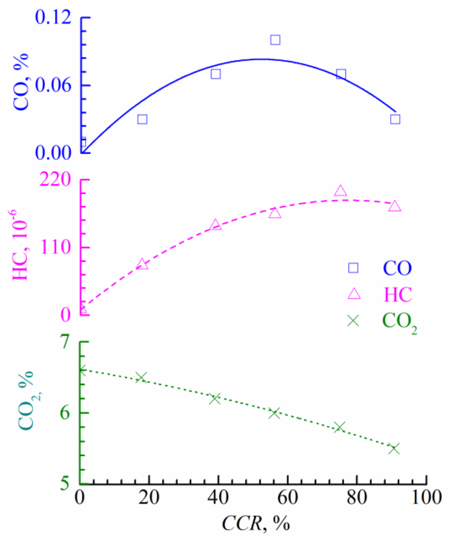

Fig. 7. Variation in CO, HC and CO_2 emissions with *CCR* for the NG/diesel DF and diesel engines

With increasing *CCR*, the HC emission of the DF engine increases significantly. This is mainly because NG enters the cylinder in a gaseous form and premixes with air, the NG-air mixture is very homogeneous, but it is so lean that easy to misfire, so the HC emissions increased, especially under low *CCR*s. In addition, the lean NG-air mixture with a high spontaneous ignition temperature, the HC emissions produced by extinguishment due to encountering cooler cylinder wall increases. Thirdly, there is a strong possibility for DF engine that the premixed NG-air mixture scavenges from exhaust valve during the intake stroke because the valve overlap angle of the experimental engine is 25°CA, the NG-air mixture becomes richer with increasing *CCR*, so the HC emission increases. Finally, with increasing *CCR*, the NG compressed into the narrow gap between the piston and cylinder wall during compression stroke increases, they can not burn and lead to the further increase of HC emission.

With increasing *CCR*, the CO_2 emission of the DF engine decreases sharply. This is mainly because the methane as main component of NG has the highest H/C ratio in hydrocarbon fuels, the combustion of NG produces the lowest CO_2 emission with releasing the same energy.

3.2.3 NO_x and soot emissions

The NO_x and soot emissions for DF and diesel engines with different *CCR*s are shown in Fig. 8. Comparing to diesel engine, the NO_x emissions of the DF engine reduce only under *CCR* of 18%. With increasing *CCR*, the NO_x emissions of the DF engine increase slightly. The NO_x emissions of the internal combustion engine are significantly effected by the temperature and duration of combustion and the oxygen content of mixture. Firstly, the λ of the DF engine decreases slightly with increasing in CCR as shown in Fig.6, so the oxygen content decreases. In addition, with increasing *CCR*, the NG-air mixture becomes richer, the combustion rate of DF increases with multipoint simultaneous ignition, so the duration of combustion becomes shorter as listed in table 3. Therefore, despite the p_{max} of DF increases sharply compared with diesel, the NO_x emissions of DF raise slightly under the combined effect of the three factors.

Table 3

The combustion duration of DF and diesel

CCR	0%	18%	39%	56%	75%	91%
Combustion duration	19.5°CA	16.5°CA	16°CA	15.5°CA	14.5°CA	16°CA

With increasing *CCR*, the soot emission of the DF engine reduces significantly, reducing to 0 under the *CCR* of 91%. The soot emission of the diesel engine is mainly produced by the local high-temperature combustion of the fuel with lack of oxygen. However, the NG in gaseous state premixes with air, the NG-air mixture is very uniform and the λ of DF is more than 2. Moreover, the C/H ratio of NG is lowest in hydrocarbon fuels, and there are no C-C bonds. Finally, in a NG/diesel dual-fuel engine, the soot generated by the combustion of pilot diesel continues to burn during the combustion of NG. Therefore, the soot emission reduces significantly with increasing *CCR* under DF mode.

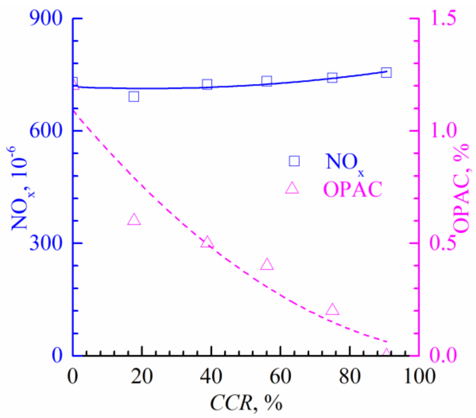

Fig. 8. Variation in NO_x and soot emissions with *CCR* for the NG/diesel DF and diesel engines

4. Conclusions

The effects of *CCR* from 0% to 91% on combustion and performance of a NG/diesel DF engine under 50% load at the maximum torque speed of 1600 r/min are investigated. With increasing *CCR*, the following main conclusions are listed:

(1) The maximum percentage of p_{max} decreases obviously, and the distribution of p_{max} distinctly scatters, the $\bar{p}_{max}$ and σ_{pmax} keep an increasing tendency, there is no obvious difference in the $\bar{p}_{max}$, but the σ_{pmax} decreases at the same *PDIT*.

(2) The distribution of φ_{pmax} scatters under low *CCR*s of 18% to 56%, while it does not variate obviously under high *CCR*s of 56% to 91%. The interdependence between p_{max} and φ_{pmax} for the NG/diesel DF and diesel engines is not evident. The $\bar{\varphi}_{max}$ decreases while the $\sigma_{\varphi pmax}$ increases. At the same *PDIT*, the p_{max} moves up to the top dead center

(3) The *BSFC* and CO emission increase first and then decrease, the HC and NO_x emissions increase while the CO_2 and soot emissions decrease sharply.

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R E F E R E N C E S

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