

Article

Effects of Diesel Hydrocarbon Components on Cetane Number and Engine Combustion and Emission Characteristics

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Abstract: Commercial diesel consists of hundreds of hydrocarbons such as alkanes, cycloalkanes, and aromatics. The components of the fuel's composition are what determine its physical and ignition properties, and their variations affect engine performance. In this study, n-heptane, n-dodecane, tetralin, and decalin were chosen as typical additives to blend with commercial diesel according to the China VI standard (Heavy Duty Diesel Vehicle Pollutant Emission Limits and Measurement Methods) in 20% and 50% volume fractions, respectively. The physical properties of the fuel blends, such as viscosity, density, cetane number (CN), and distillation range, were measured first. Then, the commercial diesel's lower heat value was measured, and blended fuels were calculated accordingly. The CN of the blended fuel is tested by an Ignition Quality Tester (IQT), which is known as the derived cetane number (DCN). The results show that adding n-dodecane increases the value of DCN, while tetralin reduces the DCN, and n-heptane and decalin have negative effects. This study uses a type of WP12 diesel engine made by Weichai that meets China's emission regulation 6. During the tests, the fuel injection strategy was kept as a pure diesel operation without any modifications. Compared with pure diesel operation, the bench test results show the following characteristics: the maximum torque output increased with increased decalin, followed by tetralin and n-dodecane, while n-heptane has a side effect compared to pure diesel operation. The addition of n-dodecane and n-heptane can reduce fuel consumption, while tetralin will increase it, and decalin has no obvious effect on fuel consumption. It was found that n-heptane increases HC and NO_x emissions significantly. Furthermore, n-dodecane slightly increases CO, HC and NO_x emissions. Decalin increases CO and HC emissions when mixed in a large proportion. In addition, tetralin causes a substantial increase in HC, CO and NO_x emissions at medium and high loads.

Keywords: diesel hydrocarbon components; derived cetane number; combustion characteristics; emission characteristics



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1. Introduction

Diesel fuel is a traditional fossil fuel, and it consists of hundreds of hydrocarbons, including 50–60% alkanes, 20–30% cycloalkanes and 7–30% aromatics, according to fuel regulations [1]. The hydrocarbons are required by the engine combustion to some extent, and on the other hand, they are subjected to the petroleum-refining process. Therefore, changing the component hydrocarbons in the fuel on the basis of the China VI standards is of great significance for improving the combustion and emission performance of the engine. The hydrocarbon content in diesel directly affects the combustion and emission characteristics of the engine, as well as the engine power and fuel economy. For instance, as is known to all, the straight-chain alkanes have a significant effect on fuel cetane number (CN), which affects the ignition delay of the combustion process within the cylinder [2].

Poly-aromatics can lead to higher particulate matter (PM) emissions and therefore are limited to below 7% in most current fuel regulations. A higher aromatics fraction has been proven to have negative effects on fuel CN. Different petroleum products and their related refining processes output fuel products with different hydrocarbon constitution and cost input, and so on. Thus, the investigation of diesel hydrocarbon constitution has significance for engine combustion and emission control, which means engine operating costs of fuel and urea and control strategy [3].

Ge et al. have studied reducing volatile organic compound emissions from diesel engines using canola oil biodiesel, palm oil biodiesel, and ethanol blends [4–7]. Balamurugan et al. [8] added 4% and 8%_{vol.} n-pentane into diesel fuel and studied the emission characteristics of the engine. Results showed that CO emissions increased slightly, and NO_x emissions were reduced. Meanwhile, the in-cylinder temperature decreased at full load conditions. Qian [9] et al. prepared toluene/diesel, n-butylbenzene/diesel, tetralin/diesel and 1-methylnaphthalene/diesel blended fuels in a ratio of 30% and found that soot emissions decreased and the peak value of heat release rate increased. The importance of decalin and tetralin as bicyclic hydrocarbon components in diesel has been studied for their high thermal stability [10]. According to these studies, n-heptane, n-dodecane, decalin and tetralin were chosen as the additives to diesel in this study.

Our pre-tests showed that the blended fuels in the ratio of 10% of the four hydrocarbons have no significant effect on engine performance. Since there is not much difference in lower heating value (LHV), changing the hydrocarbon content has little influence on combustion and engine power but results in a significant improvement in emissions. Furthermore, engine emissions are more restricted in the Heavy Duty Diesel Vehicle Pollutant Emission Limits and Measurement Methods (China VI standard), which is basically equivalent to Euro VI (European exhaust emission regulations) and California Air Resources Board Low Emission Vehicles III (CARB LEV III). Additionally, the technologies and combustion strategies of modern diesel engines are quite different from the conventional ones in order to meet China/EU VI standards, e.g., higher pressure and split injection and higher cylinder temperature and pressure. Currently, limited investigations have been reported on China/EU VI standard engines to study the effects of diesel hydrocarbon constitution on its performance. Hence, four fuel blends that blend the four hydrocarbons with China VI diesel in the fractions of 20% and 50%_{vol.} were studied on a six-cylinder China VI diesel engine.

The addition of hydrocarbons affects the fuel properties, including density, lower heat value, and cetane number (CN). Among these, CN is the most important property for combustion. As a macroscopic feature of fuel chemical kinetic behavior, CN can be directly related to ignition quality, and its estimation is of practical significance [11]. The Cooperative Fuel Research (CFR) engine is a piece of authorized equipment to measure CN. However, the CFR method requires specialized engine and operational expertise, which means higher costs [12], and its reliability is only guaranteed within a specific CN range [13]. The Ignition Quality Tester (IQT) method was alternately suggested [14]. In this method, a standardized constant volume combustion chamber is utilized to detect the ignition delay of the test fuel under a given pressure and temperature condition. A derived cetane number (DCN) is obtained by evaluating the ignition delay of the test fuel based on the standard fuels with different CN. This method requires lower costs and fewer samples compared with the CFR engine [15], and it ensures the reproducibility of experiments in different experimental environments [16]. It has been adopted as the measurement of fuel CN in the American Standard of Testing Material (ASTM D6751) and the European Standard (EN 14214) due to its convenience [16]. This method was widely used to study the fuel properties of combustion. Dahmen et al. [13] and Baghban et al. [15] utilized the IQT method to predict the derived cetane number (DCN) of oxygenated hydrocarbons and proved that this method is quite suitable for various fuel components. Hence, before engine tests, the blended fuel CN is measured by an IQT.

In addition, the density, viscosity, LHV and distillation range of the eight blended fuels were measured in this work.

2. Test Fuels and Properties

2.1. Test Fuel and Additives

The basic fuel used in this work was China VI standard commercial 0# diesel bought from a gas station. The n-heptane, n-dodecane, tetralin and decalin were of analytical grade. Figure 1 gives the structure of these molecules, and the main physicochemical properties of the test fuels are listed in Table 1.

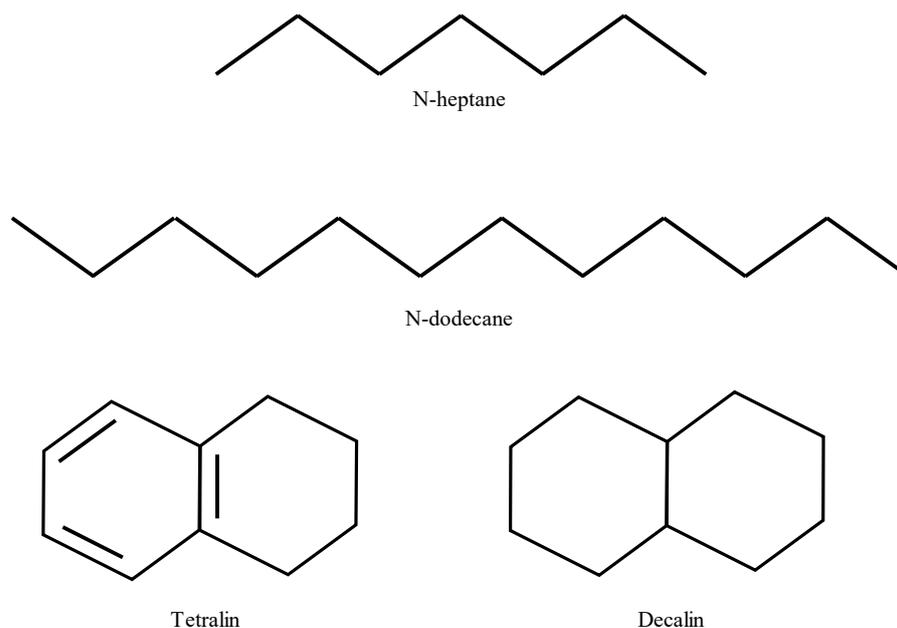


Figure 1. The molecular structure of n-heptane, n-dodecane, tetralin, and decalin molecules.

Table 1. Properties of the test fuels.

Properties	Diesel	n-Heptane	n-Dodecane	Tetralin	Decalin
Molecular formula	C ₁₀ ~C ₂₂	n-C ₇ H ₁₆	n-C ₁₂ H ₂₆	C ₁₀ H ₁₂	C ₁₀ H ₁₈
Molar mass (g/mol)	-	100.21	170.34	132.2	138.25
Density (g/cm ³)	0.817	0.684	0.75	0.97	0.896
Viscosity (40 °C) (mm ² /s)	2.675	0.485	1.414	1.06	1.667
Boiling point (°C)	205	98.5	215	207.6	195.8
Ignition temperature (°C)	220	247	216	385	262
CN	51.6	56	82.5	8.9	46.5
LHV (MJ/kg)	42.52	44.57	44.11	40.53	42.5

The four hydrocarbons were blended with the commercial diesel in the 20% and 50% volume fractions and they are labeled as HE20 (HE = heptane), HE50, DO20 (DO = dodecane), DO50, TE20 (TE = tetralin), TE50, DE20 (DE = decalin), and DE50, respectively. D100 denotes diesel.

First, the density of the test fuels was measured with a petroleum density meter following the method of “GB/T 1884-2000”, and the results are shown in Table 2. As shown in Figure 2, the density of the blended fuels is nearly linear to the volume fractions of diesel and hydrocarbons. This shows that they are well soluble, and there is no volume shrinkage that occurred within the test range.

Table 2. Main properties of test fuels.

Fuels	Components	Density g/cm^3	Viscosity mm^2/s	LHV MJ/kg	Distillation Range/ $^{\circ}C$		
					T10	T50	T90
D100	Diesel	0.817	2.675	42.52	205	258	331
HE20	n-Heptane 20% Diesel 80%	0.786	1.493	42.87	116	233	301
HE50	n-Heptane 50% Diesel 50%	0.756	0.982	43.45	102	129	280
DO20	n-Dodecane 20% Diesel 80%	0.792	2.032	42.82	195	230	318
DO50	n-Decocane 50% Diesel 50%	0.771	1.787	43.28	198	220	303
TE20	Tetralin 20% Diesel 80%	0.848	1.985	42.06	199	229	330
TE50	Tetralin 50% Diesel 50%	0.863	1.856	41.44	202	211	296
DE20	Decalin 20% Diesel 80%	0.824	2.489	42.53	195	239	332
DE50	Decalin 50% Diesel 50%	0.844	2.105	42.55	188	203	306

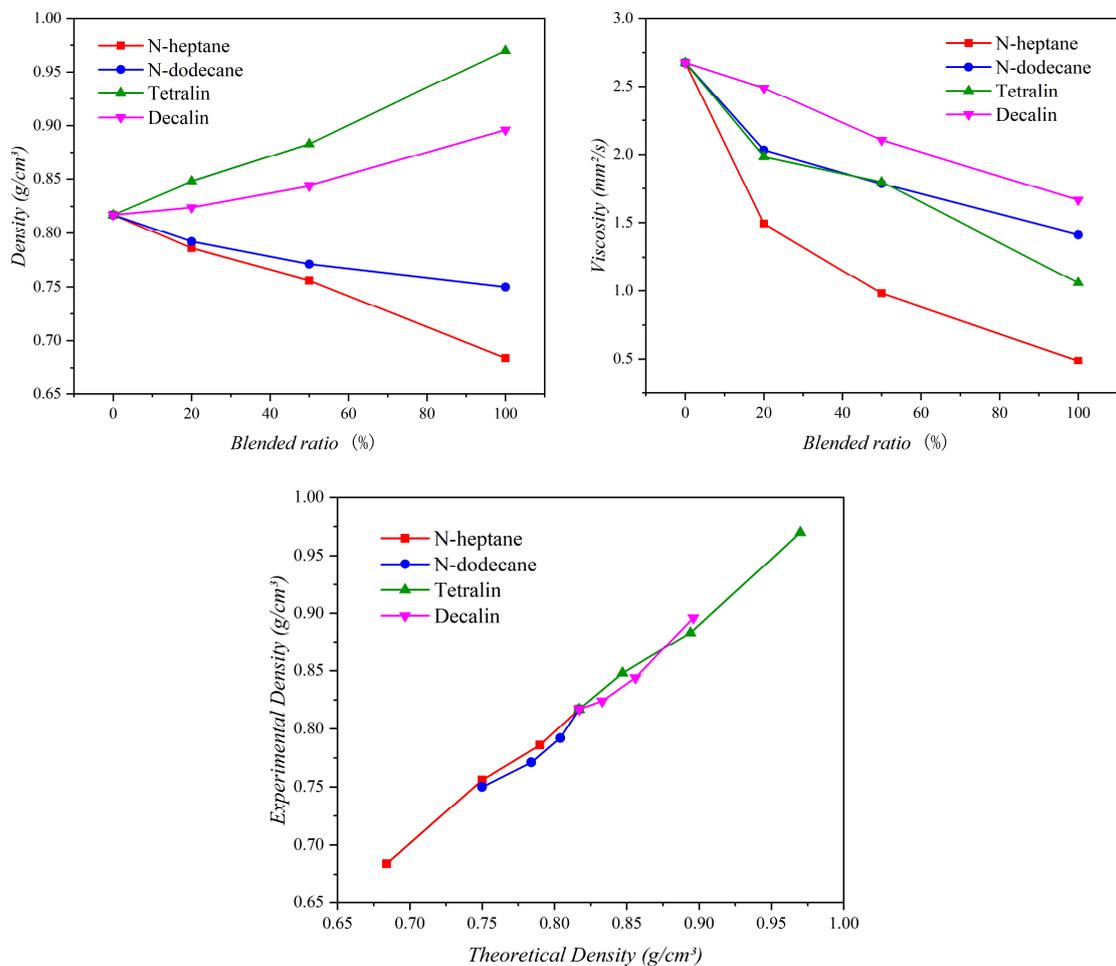


Figure 2. The experimental fuels' density and viscosity.

The kinematic viscosity of the fuels is related to fuel delivery and spray atomization. It was measured by a Pinker viscometer following the method of “GB/T 265”. The tests were kept at a constant temperature of 40 °C [17]. In addition, molar mass and ignition temperature were provided by the manufacturer. The experimental value and the comparison of the theoretical and experimental values on density are shown in Figure 2, and details are listed in Table 2. It can be seen that the addition of the hydrocarbons results in reduced viscosity. Except for the pure diesel, the blended fuels’ viscosities are more linear to their fractions. As a result, the viscosity reduction caused by the addition of small molecular hydrocarbons to diesel should be taken into account.

The boiling temperatures of hydrocarbons are constant and lower; therefore, the addition of hydrocarbons will lead to a change in the distillation temperatures. The distillation tests were done with a distillation gauge. For the test, 100 mL sample fuel was added into the test tube after it was warmed up to 50 °C. The average speed of condensation was kept at 4–5 mL/min by adjusting the heating power. Table 2 lists the temperatures of the distillation ranges of 10%, 50% and 90%. T10 represents the volatility of the light components in the fuel, T50 indicates the average volatility of the fuel, and T90 represents the volatility of the heavy components in the fuel. The addition of hydrocarbons brings down the distillation characteristic temperatures of the blended fuels. More distillation information can be seen in Figure 3. The boiling point of heptane is 98.5 °C, so it has a significant effect on the distillation process. The addition of low-boiling-point n-heptane increases volatility, which causes a great reduction of T10. The boiling points of the remaining hydrocarbons are similar to the T10 of diesel (205 °C), so their effects are shown in higher-fraction blending cases.

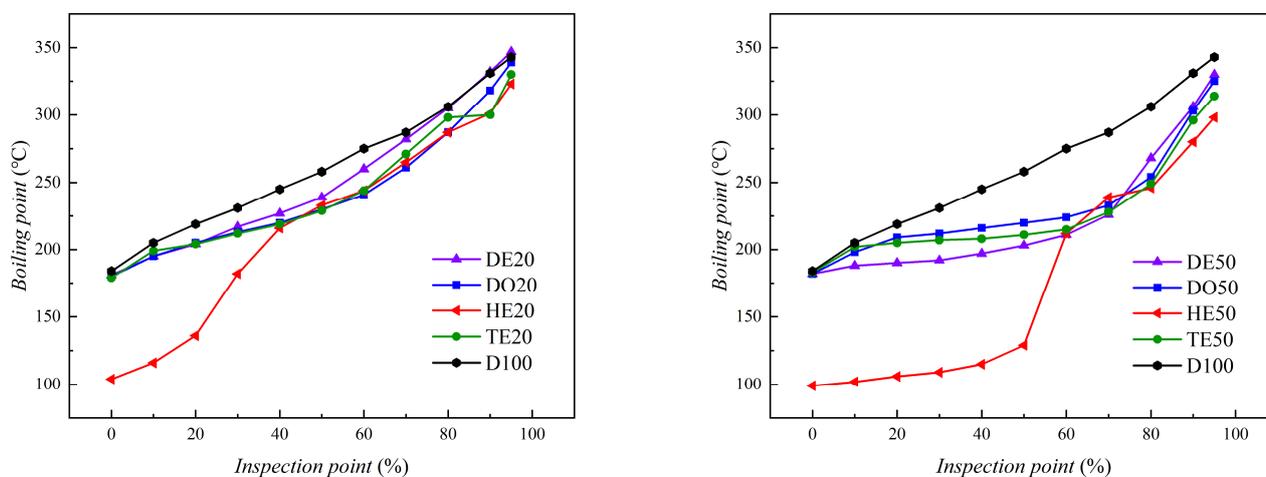


Figure 3. The distillation range curves of test fuels.

The LHV of diesel was measured by the calorimeter, and the four components were known. Through measurement, the volume of the blended components and diesel after mixing is consistent with the sum of the respective volumes. Therefore, the LHV of the blended fuels can be calculated according to the following formula [18]:

$$H_u = \frac{(1 - \varphi) \cdot H_D \cdot \rho_D + \varphi \cdot H_B \cdot \rho_B}{(1 - \varphi) \cdot \rho_D + \varphi \cdot \rho_B} \quad (1)$$

where H_u , H_D and H_B denote the LHV of blended fuels (MJ/kg), diesel, and hydrocarbon components, respectively; ρ_D and ρ_B are the density of diesel and hydrocarbon components (kg/m^3), respectively, and φ denotes the blended volume fraction (%).

The calculated LHVs in mass are shown in Table 2, as well as the volumetric lower heating value. Though heptane has the highest LHV, the LHV of the heptane blended fuels is lower for its density. On the contrary, tetralin has the lowest LHV, but its blended fuels

have the highest volumetric LHV. Nevertheless, the difference is within 5% compared to diesel fuel.

2.2. DCN of Test Fuels

The DCN was tested by an IQT. The IQT utilizes a constant-volume combustion bomb to determine the ignition delay (*ID*). First, the primary fuel was tested, and its CN is known. The test results are listed in Table 3. Accordingly, the formula can be fitted as Equation (2):

$$DCN = 4.460 + 186.6/ID \quad (2)$$

where *DCN* denotes the derived cetane number, and *ID* denotes the ignition delay (ms).

Table 3. The measured DCN of test fuels.

Fuels	D100	HE20	HE50	DO20	DO50	TE20	TE50	DE20	DE50
ID (ms)	3.958	3.836	3.860	3.531	3.052	4.829	7.278	4.247	4.266
DCN	51.6	53.1	52.8	57.3	65.6	43.1	30.1	48.4	48.2

Then, the ignition delay of the blended fuels was tested. Their *ID* data and the calculated *DCNs* are shown in Table 3. Based on the data, when diesel is mixed with hydrocarbons in any fraction, its *DCN* can be estimated by Equation (3):

$$CN_P = CN_D \cdot (1 - \varphi) + CN_B \cdot \varphi \quad (3)$$

where *P*, *D* and *B* denote the predicted, diesel and additive hydrocarbons, respectively. φ is the volume fraction (%) of blended hydrocarbons.

There is an obvious effect on *DCN* when diesel is mixed with hydrocarbons. Since n-dodecane has the highest *CN* of 82.5, its addition will increase the dodecane/diesel blended fuels' *CN*. Since tetralin's *CN* is 8.9, the blending of tetralin with diesel will sharply reduce the *CN* of the mixture.

3. Test Engine and Equipment

3.1. Test Engine and Apparatus

The test engine is a four-stroke six-cylinder in-line diesel engine with an intercooling and turbocharging system. It is equipped with a Bosch common rail high-pressure injection system to achieve a pre- and main dual injection strategy to meet the China VI emission regulation. The main technical specifications of the engine are shown in Table 4. In this study, the engine adopted the same electronic control unit (WP EDC7); that is, the engine was controlled by the same strategy as pure diesel operation.

Table 4. Engine specifications.

Item	Specification
Engine type	Turbocharged, inter-cooling, six-cylinder in-line
Bore × stroke (mm)	126/155
Displacement (L)	11.6
Compression ratio	17
Maximum power (kW)	338
Maximum speed (r/min)	1900
Emission standard	China VI

The kinematic viscosity was obtained by a petroleum product kinematic viscosity tester, and the service temperature was required to be above 30 °C. The distillation range was conducted using a petroleum product distillation tester. LHV was measured by a microcomputer oxygen bomb calorimeter [17,19]. The IQT was utilized to obtain the DCN.

The detailed schematic diagram of the experimental setup is shown in Figure 4. The engine speed and torque were controlled by an eddy current dynamometer. A Kistler 6052C cylinder pressure sensor was utilized to measure the cylinder pressure. A KiBox was used to process the signal of cylinder pressure and crank angle, and thus, the combustion process was analyzed. The regular emissions of hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxides (NO_x) were measured by a Horiba 7100DEGR.

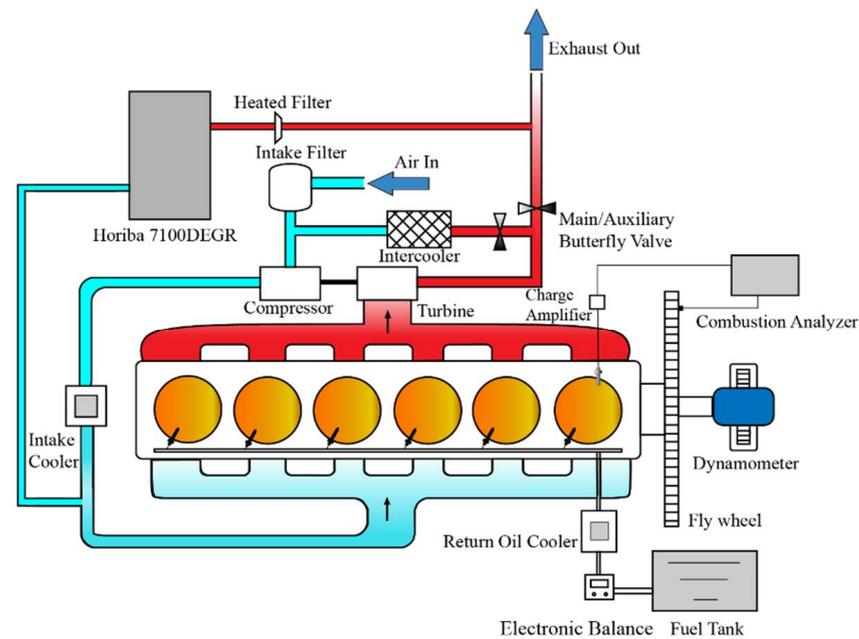


Figure 4. Schematic diagram of the experimental setup.

3.2. Engine Test Conditions

The engine tests were carried out under speeds of 1700, 1800 and 1900 r/min and loads of 25%, 50%, 75% and 100% according to the off-road engine test standard, and the corresponding torques are shown in Table 5. During the tests, the cooling water temperature was set at 85 ± 1 °C, and the oil temperature stabilized at 100 ± 2 °C. At each condition, the combustion pressure data were sampled and averaged over 100 continuous engine cycles to eliminate the effects of cycle-to-cycle variation [20].

Table 5. Engine conditions.

Engine Load	25%	50%	75%	100%
Torque (N·m) @1700 rpm	476	952	1428	1904
Torque (N·m) @1800 rpm	448	896	1344	1790
Torque (N·m) @1900 rpm	428	856	1284	1712

4. Engine Test Results and Discussions

4.1. Fuel Effects on Engine Performance

At full load conditions, the brake torque (T_{tq}) and brake specific fuel consumption (BSFC, b_e) are shown in Figure 5 when the engine runs on the 9 fuels. Decalin-blended fuels give the best power performance, and heptane gives the best BSFC. Tetralin-blended fuel has the highest volumetric energy but the worst BSFC, though its power performance is still high.

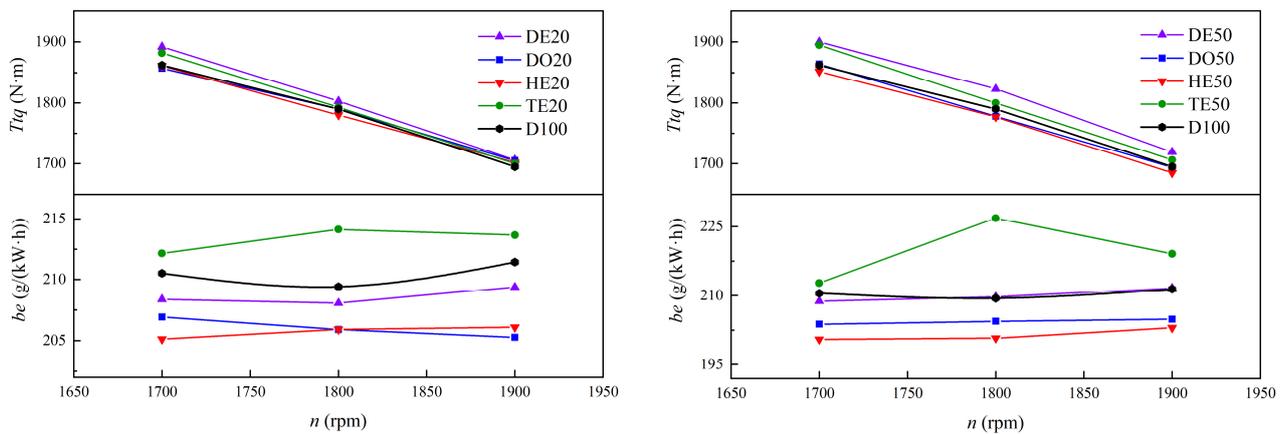


Figure 5. The power and economy performance at 100% load.

Except for the minor effect of fuel viscosity, the cyclic fuel injection quantity by volume can be considered the same at full load conditions. The volumetric LHV from high to low are tetralin, decalin, diesel, dodecane and heptane, so the addition of tetralin and decalin will increase engine output torque. As shown in Figure 5, when burning TE50 and DE50 at 1900 r/min, the engine torques increase by 33 N·m and 41 N·m, respectively. Additionally, the lower the engine speed, the more the torque.

At the most interesting speed (rated speed) condition of 1900 r/min, the effect of the addition of hydrocarbons on BSFC is shown in Figure 6. The same trend exists in that the addition of straight-chain hydrocarbons, including heptane and dodecane, improve the fuel economy, while tetralin, representing aromatics, increases the engine's fuel consumption.

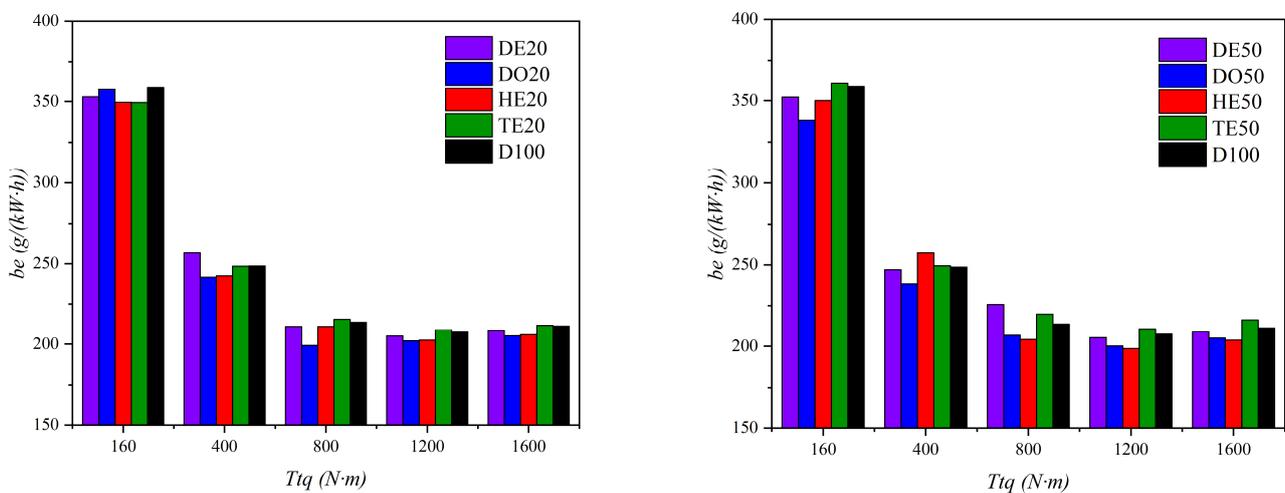


Figure 6. Effective specific fuel consumption at 1900 r/min.

As is shown in Figure 7, BSFC can be decreased by adding heptane and dodecane. Since the AI50 of n-heptane and n-dodecane is lower, the combustion phase is advanced, which, in turn, causes the reduction of BSFC. The lower viscosity and boiling temperature can also promote spray atomization, mixing with air and thus accelerating the combustion process [8,21]. The addition of tetralin is the worst, as the combustion analyses show that the peak cylinder pressures are lower, while the peak heat release rates are high. This indicates that the decrease in CN delays the combustion process, which can be proved by the curves of the calculated cumulative heat release in Figures 8–11 in the next section.

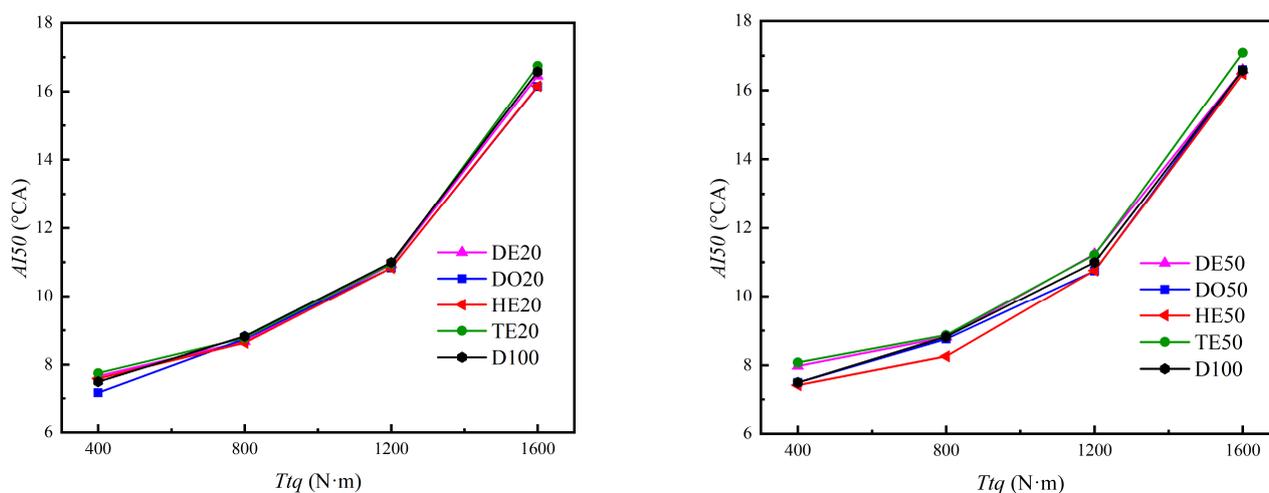


Figure 7. AI50 at 1900 r/min.

4.2. Engine Combustion Characteristics

There are three important aspects of the diesel engine CI combustion process: ignition delay, premixed combustion and diffusion combustion. To study the effect of the addition of hydrocarbons to diesel on engine combustion, the cylinder pressures were sampled, and the combustion heat release rates were analyzed. Figures 8–11 display the measured cylinder pressures, the peak cylinder pressure, and the calculated heat release rates (HRR), the peak HRR and cumulative HRR at the speed of 1900 r/min, respectively.

4.2.1. Effects on the Combustion of the Pre-Injected Fuel

It is known that the ignition delay of fuel is related to its cetane number. A higher CN of fuel means a lower autoignition temperature or a shorter time of ignition delay at the same temperature. In this study, n-heptane and n-dodecane have higher CN values of 56 and 82.5; their mixtures also have higher CN. On the contrary, tetralin and decalin have lower CN values of 8.9 and 46.5, which reduces the CN of mixtures compared with diesel.

The sampled injection strategy of the engine is shown when it runs on diesel in Table 6. In the experiments, the fuel injection strategy consisted of pre-injection and main injection. Under the full load conditions, all the fuels utilize the same injection strategy, that is, the same timing and duration, while under the partial load conditions, there are few adjustments according to the opening of the peddle to achieve the same power/torque due to the difference of the blended fuels. Of course, the injection timings and the duration of the split injection will change a little, accordingly.

From Figure 8, it can be seen that the starts of the combustion of the preinjected fuels generally follow the CN rule; that is, the higher the fuels' CN, the earlier the start of the combustion. With increased engine load, it becomes irregular, but the differences are within 2–3 °CA.

The combustion process of the pre-injected fuels cannot be simply divided into premixed and diffusion, either. There is no typical dual peak heat release rate. Due to the relatively longer ignition delay, the higher injection pressure, and the higher temperature of the air in the cylinder, the combustion of the pre-injected fuels is all premixed combustion.

The preinjected fuel combustion on the cylinder pressure shows a weak influence. For an injection duration of about 0.2 ms, there is some nonlinearity affecting the injected fuel quantity, and the total quantity is rather small.

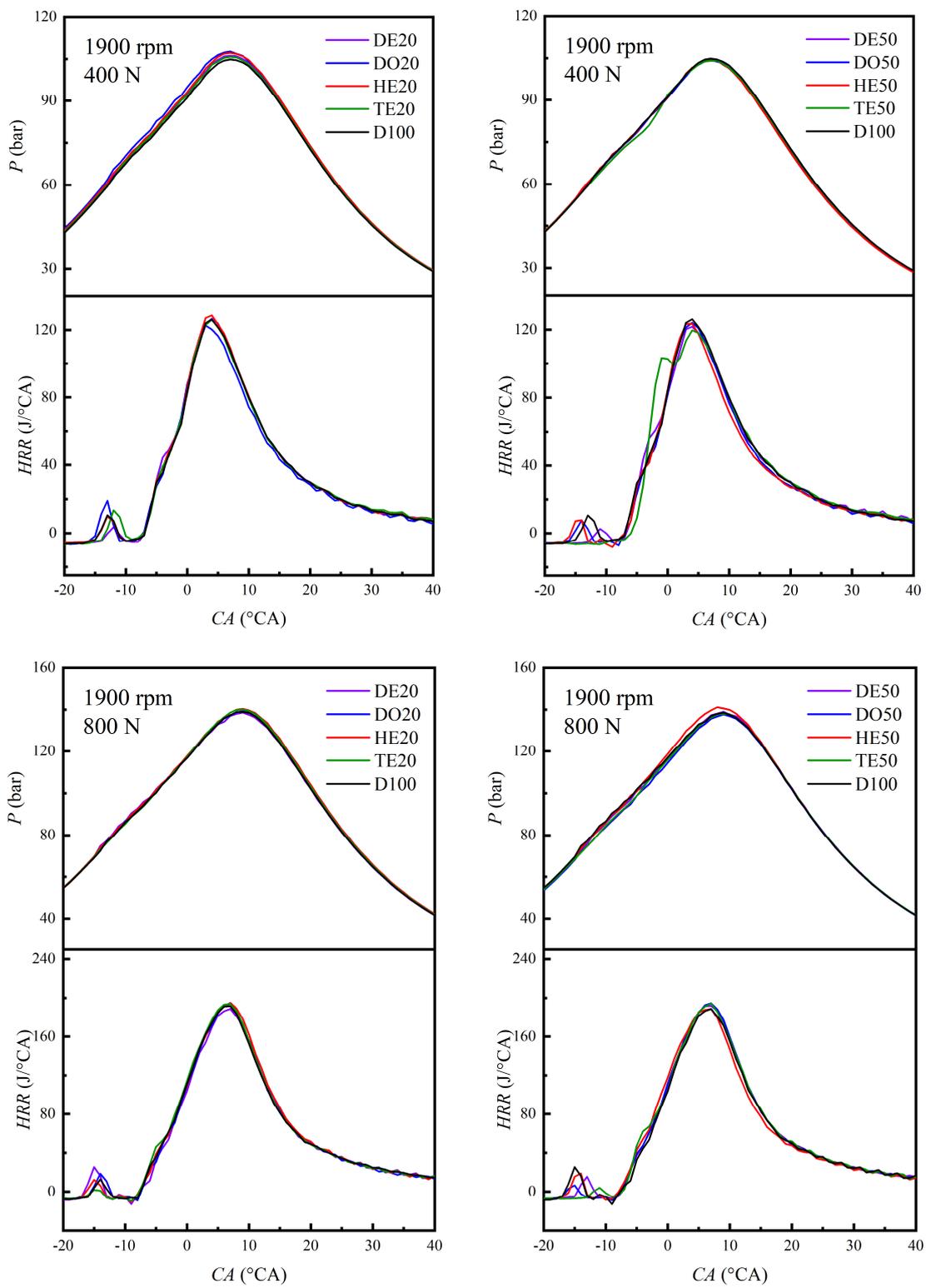


Figure 8. Cont.

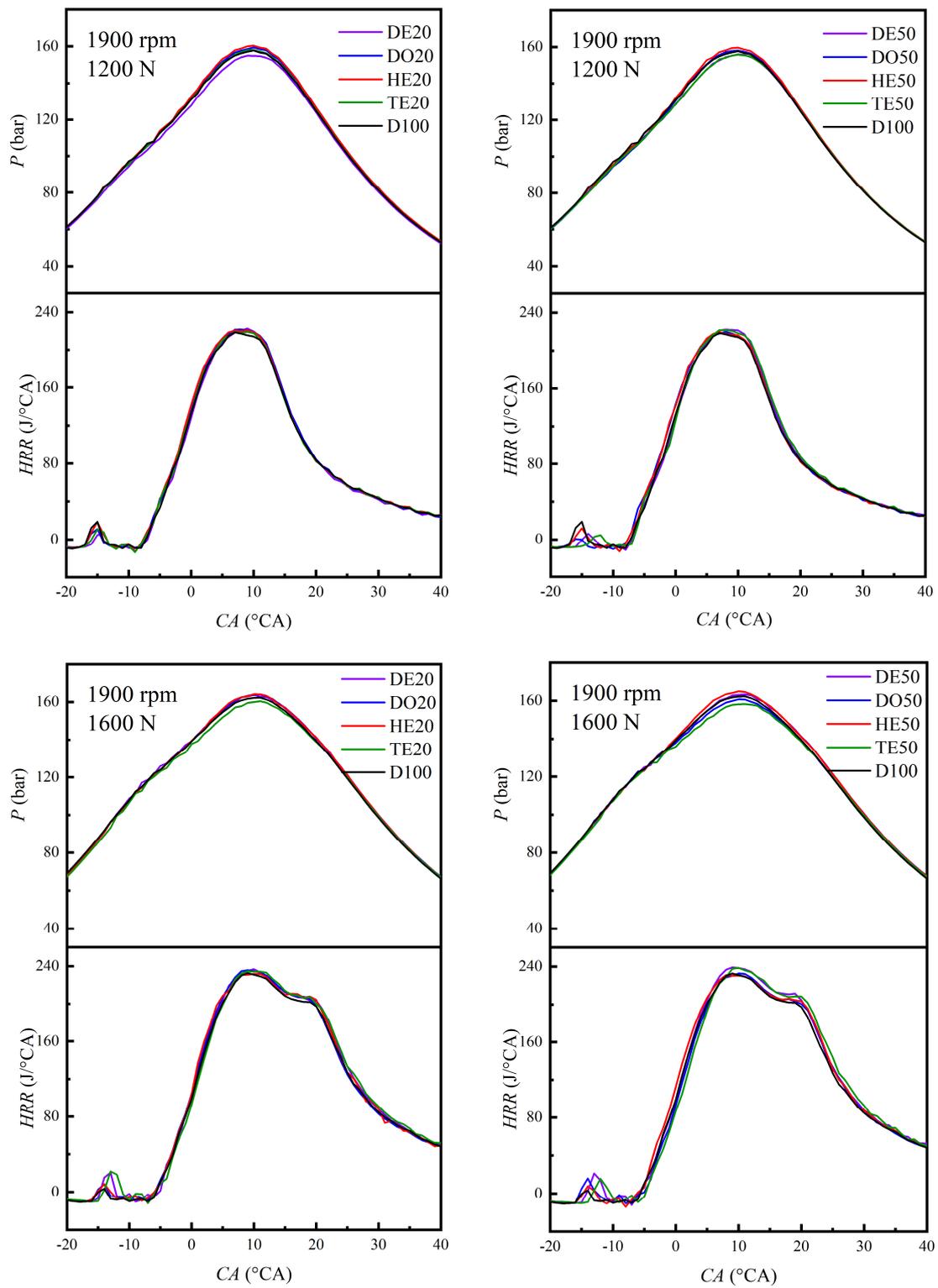


Figure 8. The curves of in-cylinder and HRR at 1900 rpm.

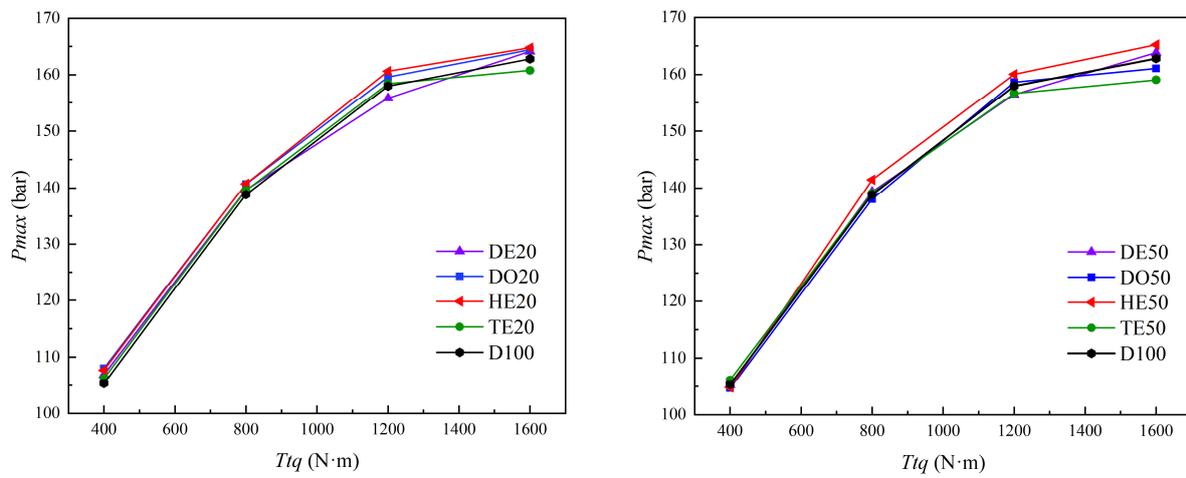


Figure 9. The peak values of in-cylinder pressure versus engine loads.

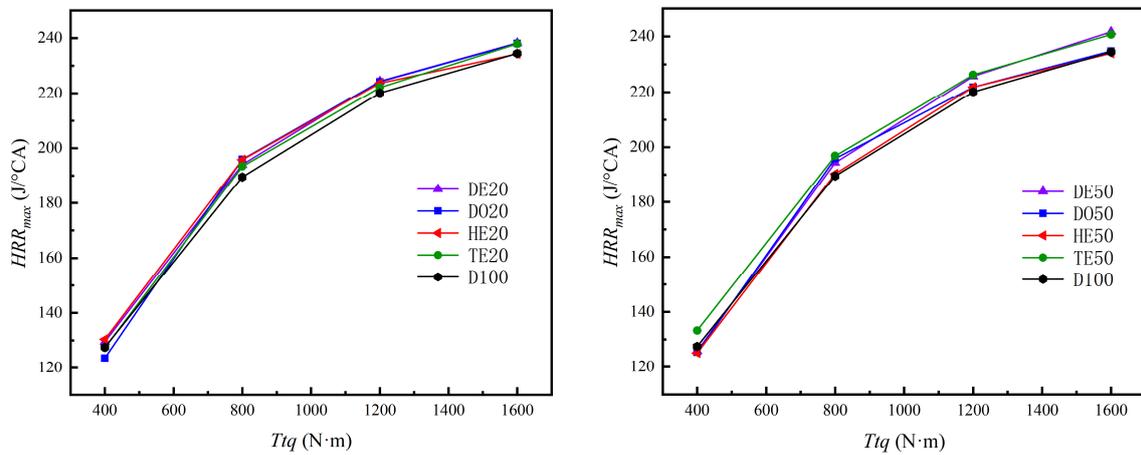


Figure 10. The peak values of HRR versus engine loads.

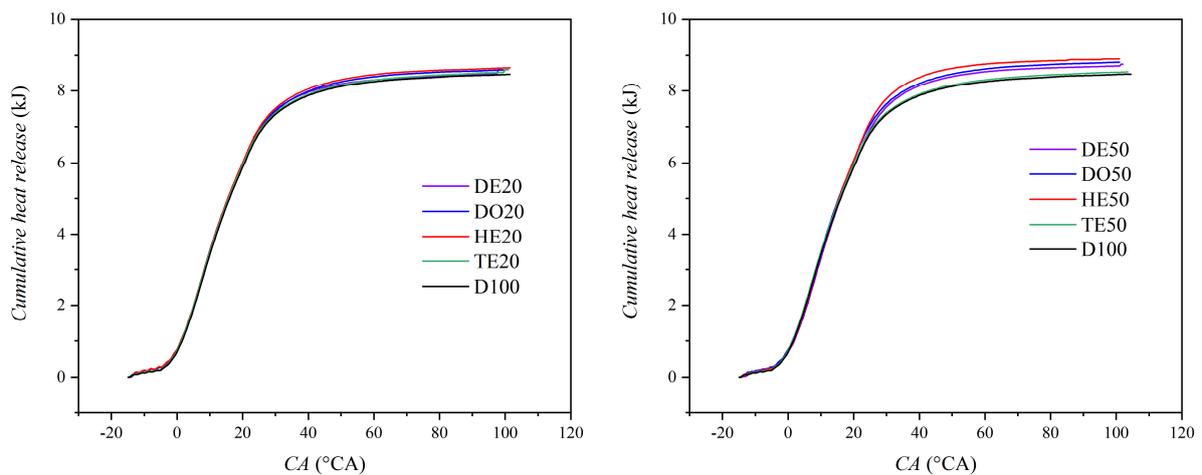


Figure 11. The cumulative heat release versus crank angles at 1900 rpm.

Table 6. Injection strategy at 1900 r/min.

Torque (N·m)	Start of Pre-Injection (°CA BTDC)	Duration of Pre-Injection (°CA)	Start of Main Injection (°CA BTDC)	Duration of Main Injection (Diesel) (°CA)
400	26.2	3.1	14.6	9.8
800	25.7	2.7	14.5	12.6
1200	24.4	2.5	13.6	16.7
1600	21.7	2.4	11.3	22.5

4.2.2. Effects on the Combustion of the Main Injected Fuel

The combustion processes of the main injected fuel shown in the figures are quite similar when the engine is running on different fuels at different loads. There are no significant differences in ignition delay or the shape of the HRR. The autoignition and combustion processes are affected mainly by the cylinder temperature and elevated further by the combustion of the preinjected fuel, while the fuel properties like CN and viscosity play a minor factor [22].

Tables 6 and 7 list the main injection timing, injection pressure, and other conditions at different loads. It can be seen that most fuel injection is completed very early, and there is little difference between the ignition delay and the start of the combustion of the main injected fuel. By comparing the HRR curves in Figure 8, it is clear that most fuel is burned in the premixed form only under full load conditions, i.e., above 1600 Nm, the combustion typically shows premixed and diffusion characteristics.

Table 7. Other conditions in experiments.

Torque (N·m)	Injection Pressure (MPa)	Cooling Water Temperature (°C)	Oil Temperature (°C)
400	107	83	101
800	139	85	102
1200	158	85	100
1600	169	87	103

Nevertheless, it is clear that the addition of heptane can improve the main combustion process in middle- and high-load cases. With additions of both 20% and 50%, the engine has a higher cylinder pressure and HRR, as shown in Figures 8–10. The low viscosity has positive effects on atomization and the mixing process of air fuels [23], resulting in the higher peak values of in-cylinder pressure for HE20 and HE50. Moreover, the low cetane number of tetralin affects the combustion duration [21,24], which causes the lowest peak values of in-cylinder pressure of TE20 and TE50.

4.3. Engine Emission Characteristics

4.3.1. Fuel Effects on NO_x Emissions

Nitric oxide (NO) and nitrogen dioxide (NO₂) are usually called nitrous oxides (NO_x) together. NO plays a predominant role. The mechanism of thermal NO can be applied to analyze its formation in diesel engines. It can be simply ascribed to the following three factors: the concentration of oxygen (O₂), the highest temperature, and the retaining time of the nonuniform burned gas. This mechanism mainly occurs during the diffusion combustion phase and in regions behind the front of the flame, where the temperature is rather higher than the calculated average temperature of the bulk gas within the cylinder [25].

From the minor difference in Figures 8 and 12, heptane- and tetralin-blended fuels have the highest cylinder pressure and burned zone temperature in most cases, which indicates that they improve the combustion and result in higher NO_x emissions. Figure 13 displays the NO_x emissions under different loads at the speed of 1900 r/min. Generally, with increased load, NO_x increases and then decreases when the load exceeds a higher value.

In the ascending range, the increased combustion temperature plays a dominating role. After the inflection load, the concentration of oxygen dominates NOx formation. However, the addition of the four hydrocarbons almost all increase NOx emissions, especially the addition of tetralin. The addition of heptane and tetralin increases NOx emissions, so this shows that NOx emissions do not follow the change of cetane number of the blended fuels, nor does the change of distillation range. There is an exceptional case of the addition of 20% dodecane on NOx emissions, but the effect of heavy paraffin needs further study. From the constitution of diesel hydrocarbons, the addition of tetralin and heptane addition are obviously deteriorated the engine-out NOx emissions.

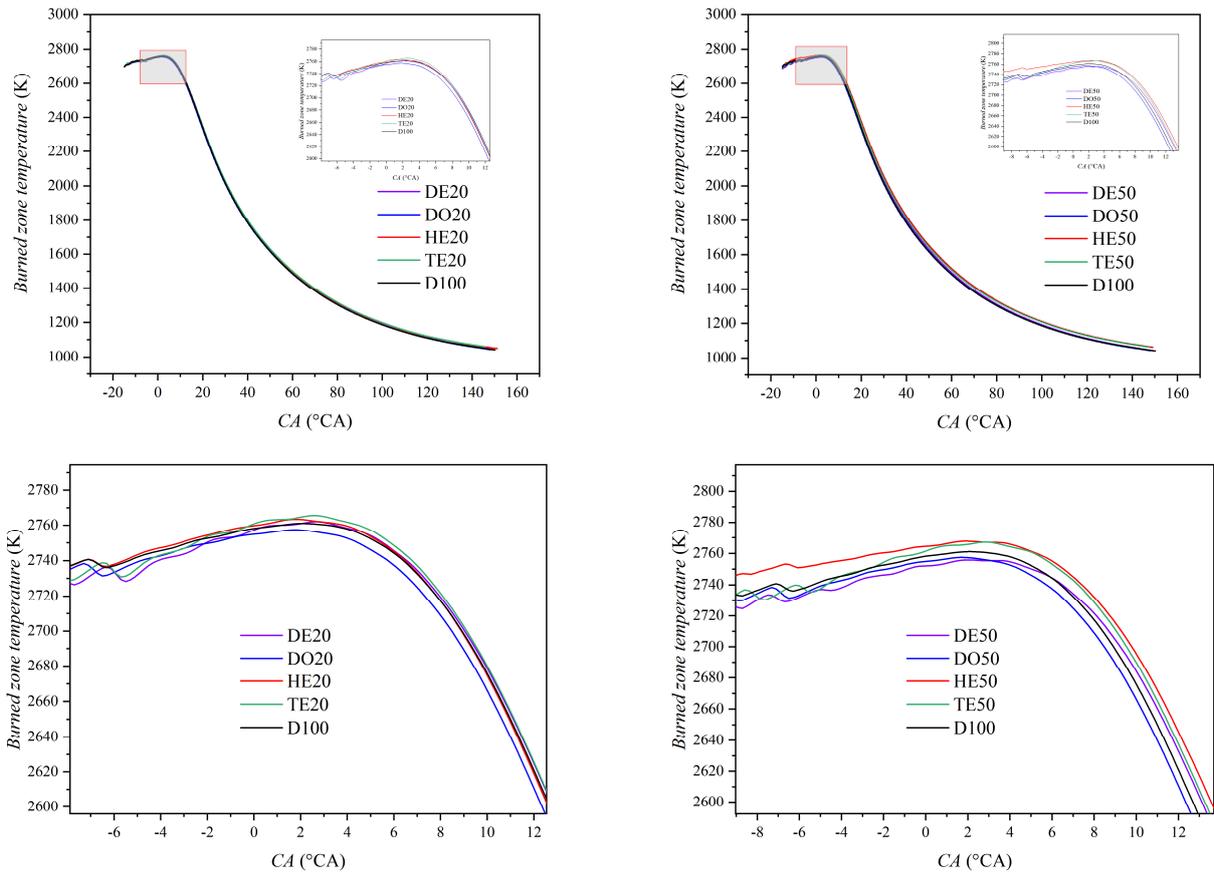


Figure 12. The burned zone temperature versus crank angles at 1900 rpm.

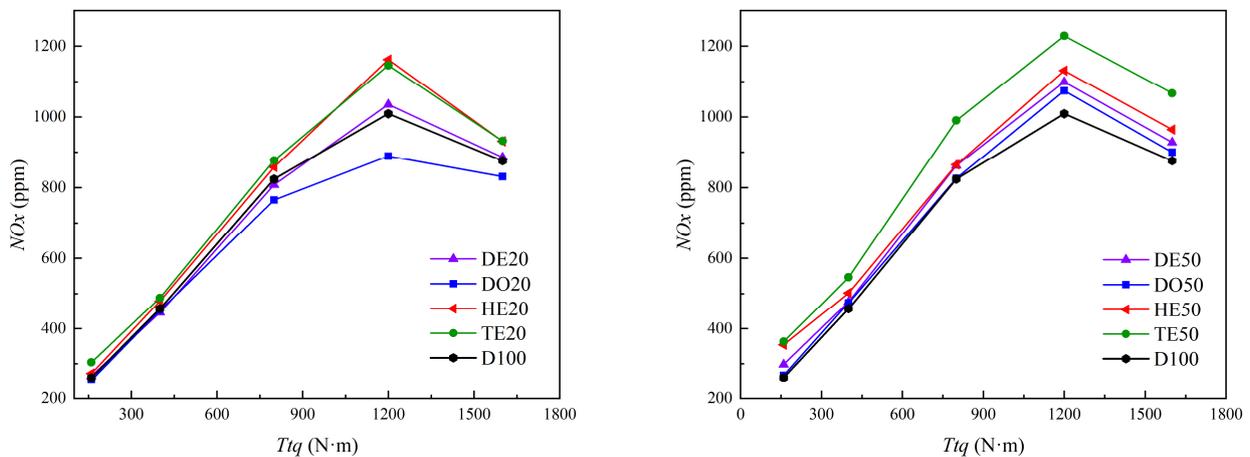


Figure 13. NOx emissions versus engine loads at 1900 rpm.

4.3.2. Fuel Effects on HC and CO Emissions

HC and CO emissions are from unburned fuel. They are lower but must be considered in China VI diesel engine technology. The effects of hydrocarbons on engine HC and CO emissions are shown in Figures 14 and 15.

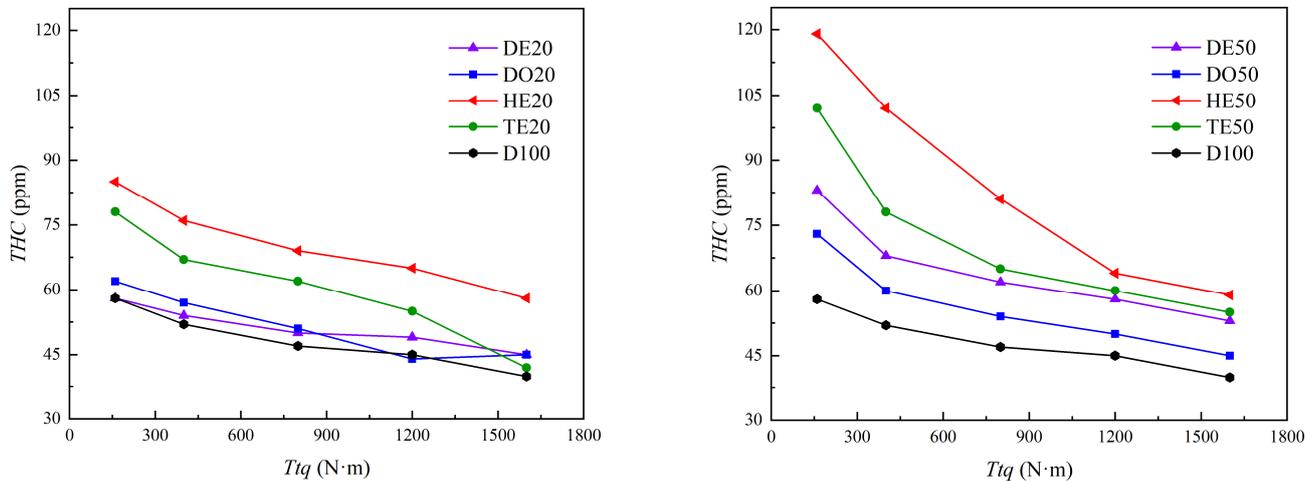


Figure 14. THC emissions versus engine loads at 1900 rpm.

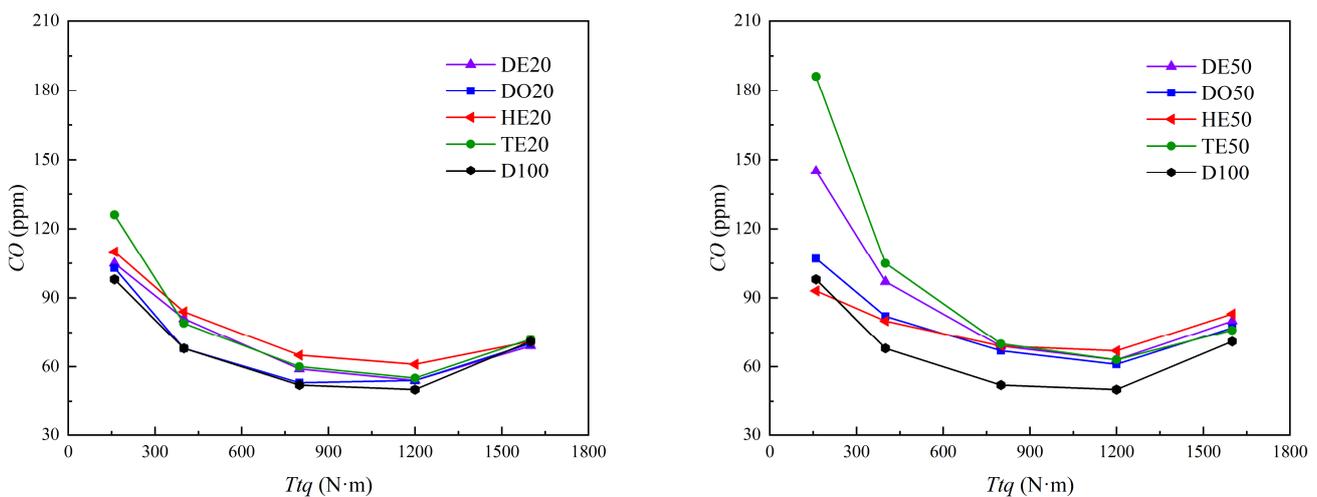


Figure 15. CO emissions versus engine loads at 1900 rpm.

In Figure 14, the addition of hydrocarbons results in increased HC emissions. Diesel fuel always emits lower HC than blended fuels. Additionally, the greater the addition, the more HCs. The low boiling temperature and 10% distillation temperature are the reason for high HC emission, which can be seen in Tables 2 and 3. Among them, n-heptane is the lowest, which leads to the highest HC emission [26]. Dodecane and decalin follow the rule, but tetralin is an exception due to its stable molecular structure. Figure 15 shows the CO emissions. The highest CO under low load conditions is unrelated to its addition ratios of 20% and 50%. The carbon-carbon bond in tetralin is harder to break, which causes higher CO formation at low load conditions [27]. At higher load conditions, CO emissions follow the distillation temperature rule, similar to HC emissions. Diesel operation has the lowest CO emissions.

Therefore, HC and CO emissions can be attributed to the fuel distillation temperature. The addition of the hydrocarbons reduces the distillation temperature and thus results in increased HC and CO emissions. Secondly, the molecular structure of the hydrocarbon has particular effects on CO emission.

5. Conclusions

In this paper, n-heptane, n-dodecane, tetralin and decalin are blended with diesel in the volume ratios of 20% and 50% to study the effects of hydrocarbon components on China VI diesel engine power, fuel economy, combustion and emission characteristics. The main conclusions are summarized as follows.

- (1) The blending of hydrocarbons into diesel linearly changes the fuel's density, viscosity, LHV and CN in the range of blending rates, but there is a significant change in distillation temperatures which changes the engine combustion and emission characteristics deeply;
- (2) Due to the lower boiling temperature, the addition of heptane will improve spray atomization and thus enhance the combustion process. The hydrocarbons of heptane and dodecane with higher CN can reduce fuel consumption. The addition of decalin will promote engine power because of its higher energy. Polyaromatic hydrocarbons like tetralin have a weak effect on power but worsen fuel economy to some extent;
- (3) For the China VI heavy-duty diesel test engine with two-stage injection, the addition of hydrocarbons has confused effects on the combustion of pre-injected fuel but limited effects on the main injection and combustion. The differences in in-cylinder pressure and HRR of the different fuels are less than 2% under the same conditions, which indicates that the fuel hydrocarbons are not so sensitive to the main combustion phase;
- (4) The addition of heptane and tetralin will increase the emissions of HC, CO and NO_x, because of the higher volatility of heptane and the molecular specialty of tetralin.

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