Effect of Engine Operating Conditions and Injection Strategy on Performance and Exhaust Characteristics of Biodiesel Engines - A review

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Abstract

As the main fuel for modern transportation, navigation, and industrial and agricultural production processes, excessive use of diesel fuel has caused the depletion of fossil fuels, rising fuel prices, and environmental pollution, in order to solve these problems, more scholars have devoted themselves to the research of alternative fuels.Biodiesel is one of the most commonly alternative fuels used for alternative energy, it has the advantages of environmental protection, non-toxic, renewable and without changing the engine structure for using.Under different engine operating conditions and injection strategies, improve engine performance and reduce exhaust emissions.Therefore, this paper summarized the effects of physicochemical properties (such as cetane number, kinematic viscosity, calorific value, density, oxygen content, etc.) of some common biodiesels on engine performance (such as cylinder pressure, heat release rate, BTEand EGT, etc.) and exhaust emissions (such as CO, HC, NO_x, CO_2, smokeandPM, etc.); And the effects of engine performance (such as BSFC, BTE, EGT, etc.) and exhaust emissions under different engine operating conditions (such as engine load, engine speed, compression ratio, EGR system, etc.) and different injection strategies (such as injection time, injection pressure, injection angle, etc.).

***Keywords*:** Biodiesel; Operating conditions; Injection strategies; Exhaust emissions; Engine performance

1. Introduction

According to the statistics of the transportation department, due to the excessive use for industrialization and modernization, the average fuel consumption of diesel increases rapidly at the rate of 1.1% per year, resulting in a significant reduction in the existing fossil fuel reserves.In addition, harmful emissions from diesel engines include hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and smoke, causedglobal environmental warming problem[1].Biodiesel as an alternativeclean fuel, has attracted extensive attention, it can be directly used in existing engines in the form of pure fuel (B100) or mixed with diesel in a certain proportion, due to its high viscosity, high density and low calorific value, it will lead to ignition delay, incomplete combustion, reduce engine performance and increase exhaust emission.So, many scholars have found that the different engine operating conditions and injection strategies can effectively promote combustion, improve engine performance and reduce exhaust emissions.

T. Ganapartyet al [2]. measured the effects of injection time and engine speed on the engine performance, combustion and emission characteristics when Jatropha biodiesel used on a single-cylinderfour-strokeair-cooledverticaldiesel engine, when the injection timing at 340CAD, BSFC, CO, HC and smoke would be reduced, and BTE, Pmax, HRRmax and NO_x emissions would be increased; when the injection time at 350CAD, the least NO_x emissions would be found.MohdHafizil Mat Yasin et al [3]. used KOH and methanol as catalysts to produced palm biodiesel by transesterification, they acted on a four-strokefour-cylindernaturally aspirated diesel engine with EGR system, when the engine at the constant speed(2500rpm) and full load, the influence of EGR system on engine performance and exhaust emission had been analyzed. The results showed that BSFC and NO_x increased significantly, and the emissions of others decreased slightly; After using EGR system, NO_x emissions and EGT were significantly reduced, and CO, CO_2 and HC emissions were increased. G. R. Kannan et al [4]. collected waste cooking oil to produce biodiesel through transesterification reaction with KOH as catalyst, the experiment was carried out at a constant speed of 1500 rpm under a single-cylinderfour-strokedirect injectiondiesel engine, the effects of injection pressure and injection time on engine performance and emission characteristics were studied, that BTE, Pmax and HRRmax increased were be found at an injection pressure of 280bar and an injection time of 25.5 ° bTDC,shortened ignition delay, reduced NO_x and smoke emissions, and improved the engine performance, combustion and emission characteristics. Özer can et al [5]. used soybean biodiesel made an experiment in a single-cylinderdirect injectionfour-strokediesel engine at constant speed (2200rpm), different loads and EGR conditions, the results showed that under all loads, the premixed combustion fraction generally increased and the diffusion combustion fraction correspondingly decreased; With the increase of EGR, BSFC, Pmax and HRRmax increased, NO_x and smoke emissions decreased, in addition, with the increase of load, BSFC decreased, BTE, CO, HC, CO_2, NO_x and smoke increased.

Although most scholars have made great contributions to the researched of engine operating conditions and injection strategies on engine combustion and emission, they were single parts, in order to better reduce exhaust emissions and improve engine performance, more comprehensive consideration will be needed. Therefore, in order to further study the effects of different operating conditions and different injection strategies on engine performance and emission characteristics, the structure of this paper will be shown as follows:

The first part summarized the influence of physical and chemical properties of common biodiesel (such as Jatropha biodiesel, soybean oil biodiesel, palm oil biodiesel, waste cooking oil biodiesel) on engine; The second part analyzed the effects of biodiesel on engine performance and combustion characteristics under different injection strategies and engine operating conditions; The third section introduced the effects of biodiesel on exhaust emission characteristics under different operating conditions and different injection strategies.

2. Characteristics of diesel and biodiesel

Different biodiesels have different physicochemical properties, the physicochemical properties of common biodiesel are shown in Table 1.

Table 1. Properties of Biodiesel and Diesel [1,2,4,5,9,13]

Biodiesel Properties	Diesel	Jatropha Biodiesel	Soybean oil Biodiesel	Palm oil Biodiesel	Waste cooking oil Biodiesel
Kinematic Viscosity (mm^2/s)	2.049	3.7–5.8	4.08	4.6	4.027
Cetane Number	48	46–70	40–53	58	66
Calorific Value (MJ/l)	42	38.5–42	39.76	39	38.034
Cloud Point (°C)	-1	-11 - 16	-2	10	13
Fire Point (°C)	83	178–197	/	194	190
Flash Point (°C)	68	170–191	69	180	170
Density (kg/l)	0.85	0.855	0.855-0.89	0.8858	0.866
Pour point (°C)	-8	-15 to 13	-3.8	6	9
C (wt%)	85.74	/	77.03	/	76.26
H (wt%)	13.72	/	11.9	/	13.308
O (wt%)	0	11	10.95	/	9.816
N (wt%)	0.483	/	/	/	0.616

Compare with diesel, biodiesel has lower calorific value, under the same working condition, the engine needs to consume more fuels to achieve the same power [6]. Moreover, biodiesel contains oxygen molecules, the release of oxygen molecules during combustion duration helps to promote complete combustion, improve cylinder pressure, BTE and EGT, and reduce the generation of HC, CO and smoke. It can be foundthe biodiesel properties from table 1 that biodiesel has greater advantages in safety, the flash point of biodiesel is higher than that of diesel, which can be better transport and store. The cetane number of biodieselis higher than or close to that of diesel, so the ignition performance is improved, the ignition delay is shortened, the combustion duration is longed, promote combustion, improve the engine performance and reduce exhaust emission. In addition, compare with diesel, biodiesel has a higher viscosity and density, which can cause poor fuel atomization, weaken the mixing effect with air, and cause incomplete combustion, resulting in higher BSFC and more HC, CO and smoke emissions[7].

3. Combustion Characteristics

3.1 In-Cylinder pressure

Figure 1 shown the effect of compression ratio on the combustion of palm biodiesel engine, with the increased of compression ratio, the premixed combustion stage was improved, the fuel atomization effect was bettered, promoted the combustion of fuel, increased the cylinder temperature and the cylinder pressure [1].As shown in Figure 2, G.R. Kannan et al[4]. studied the effect of injection pressure and injection timing on cylinder pressure, with the advanced of injection timing and the increased of injection pressure, advanced the combustion start time, shortened the fuel ignition delay, and increased the maximum cylinder pressure, which occurred at the earlier crank angle.Vineet Kumar et al [8]. found that when the ignition delay was recorded by crank angle, the ignition delay increased with the increased of engine speed, and the corresponding crank angle at the same time increased, resulted in the delay of combustion start and two peak cylinder pressures during the expansion stroke.Figure 3 shown that increased the cylinder pressure with the increased of injection pressure and loads.Under high load, the combustion temperature would be increased with the increased of pressure, and the evaporation rate also would be increased, which promoted the complete combustion of fuel and increased the cylinder pressure [9].Özer can et al [5]. studied the effect of EGR on soybean oil biodiesel engine and found that with the increase of EGR, the available oxygen atom content decreased, decreased the cylinder combustion and the cylinder pressure.

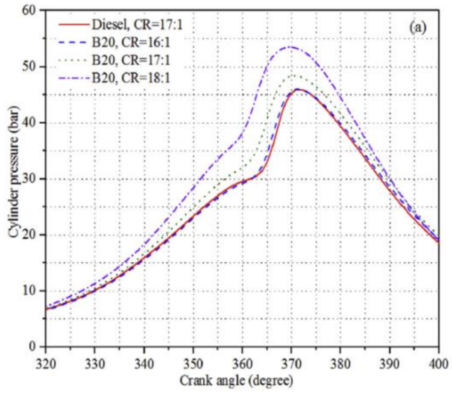


Fig.1 Variation of In-cylinder pressure at different CRs[1].

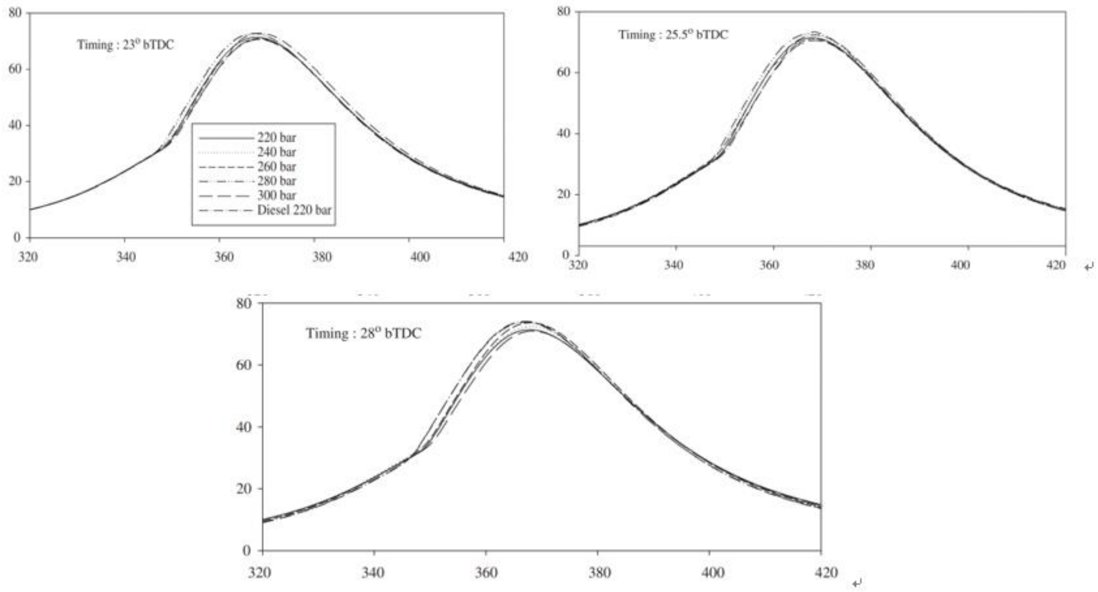


Fig.2 Variation of In-cylinder pressure at different injection pressures and timings [4].

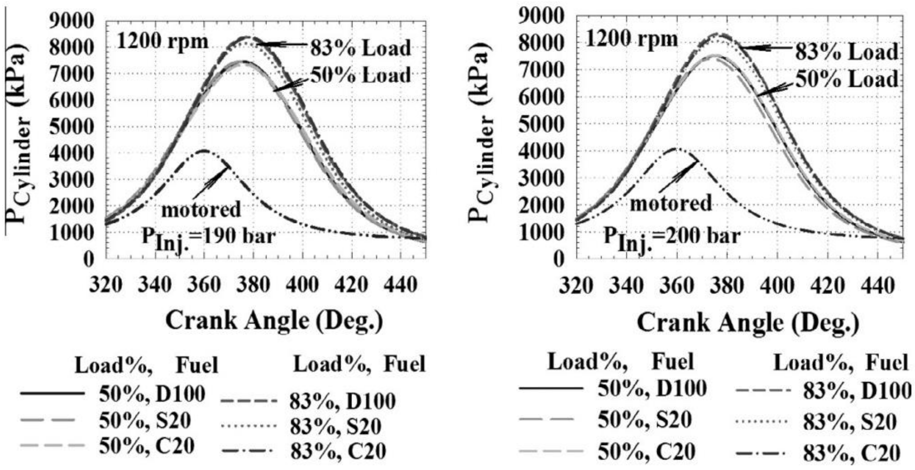
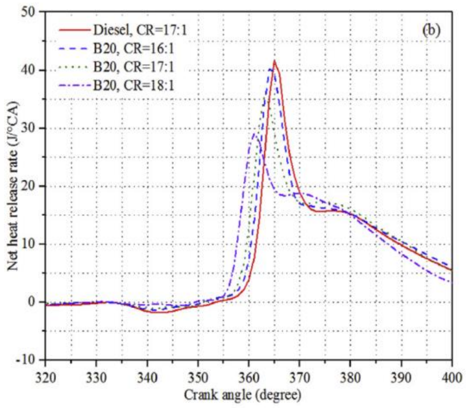


Fig.3Cylinder pressure at 1200 RPM for different injection pressures and loads[9].

3.2Heat release rate (HRR)

Pali rosha et al [1]. studied the effect of compression ratio on the heat release rate of palm biodiesel and its mixed fuel with diesel, as shown in Figure 4.Compared with biodiesel-diesel dual fuel, diesel had low cetane number, prolonged ignition delay, increased fuel air premixing time,promoted complete combustion, and higher peak heat release rateduring the diffusion combustion stage; With the increased of compression ratio, higher cylinder pressure and temperature improved fuel atomization, reduced fuel viscosity, promoted the mixing air and fuel, reduced ignition delay, increased combustion cycle and reduced heat release rate.Figure 5 shown the effect of EGR system on heat release rate, with the increase of EGR, the air-fuel mixing rate decreased, resulted in incomplete combustion, lower combustion temperature and lower heat release rate [10].G. R. Kannan et al [4]. studied the effects of injection timing and injection pressure on the heat release rate of diesel mixed with waste cooking oil biodiesel, it was found that when the injection timing was advanced from 25.5 degrees before TDC to 28 degrees before TDC, increased the ignition delay, the fuel accumulation was increased, resulting in incomplete combustion and reduced the heat release rate; With the increase of injection pressure, the fuel atomization effect was increased, promoted complete combustion and reduced the heat release rate.



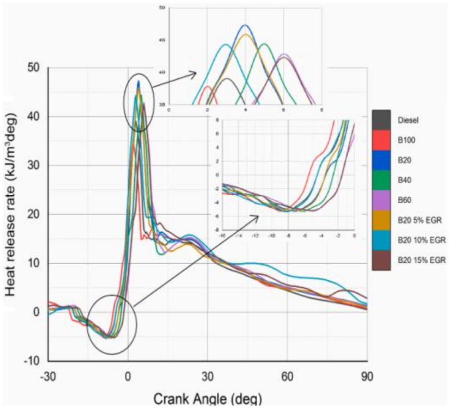


Fig.4 Variation of Heat release rate at different CRs[1].Fig.5 Variation of Heat release rate at different EGR[10].

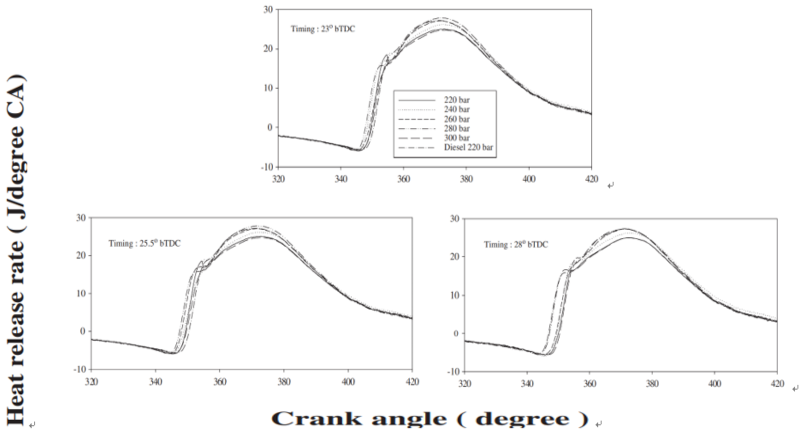


Fig.6 Variation of Heat release rate at different injection pressures and timings [4].

3.3Brake Specific Fuel Consumption (BSFC)

Rajesh et al [11]. studied the effect of load and EGR system on Jatropha biodiesel engine, as shown in Figure 7, at low load, the combustion temperature was low and the mixing of fuel and air was poor, resulted in incomplete combustion and higher brake specific fuel consumption; With the increase of load, at medium and high load, the higher temperature and atomization minimized the negative effects of mixed fuel, improved the combustion effect, increased the engine power output and reduced the braking fuel consumption rate.With the increase of EGR, the oxygen content in combustion would be decreased and decreased the engine power, resulted in incomplete combustion and increased brake specific fuel consumption.Figure 8 shown the effect of injection pressure and engine speed on brake specific fuel consumption, with the increase of engine speed and injection pressure, the fuel atomization effect was strengthened, the fuel mixing speed was accelerated, and the brake specific fuel consumption was reduced [12].Vineet Kumar et al [8]. found that different injection timing and speed have different effects on the brake specific fuel consumption of Jatropha biodiesel engine.At a certain speed, with the advance of injection timing, the full combustion of fuel in diffusion combustion stage was promoted, and increased the brake specific fuel consumption.Pali rosha et al [1]. studied the effect of compression ratio on the brake specific fuel consumption of palm biodiesel engine, with the increase of compression ratio, improved the combustion characteristics and the thermal efficiency, reduced the brake specific fuel consumption, as shown in Figure 9.

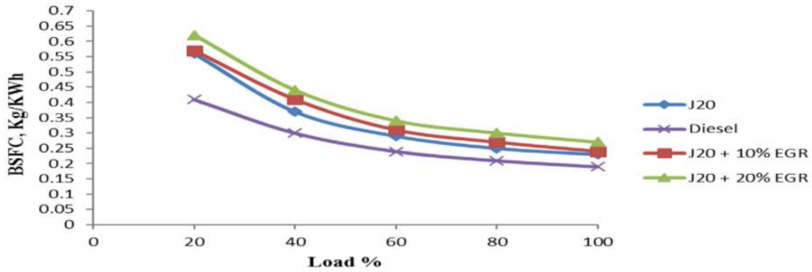


Fig.7 Variation ofBSFC at different EGRs and loads [11].

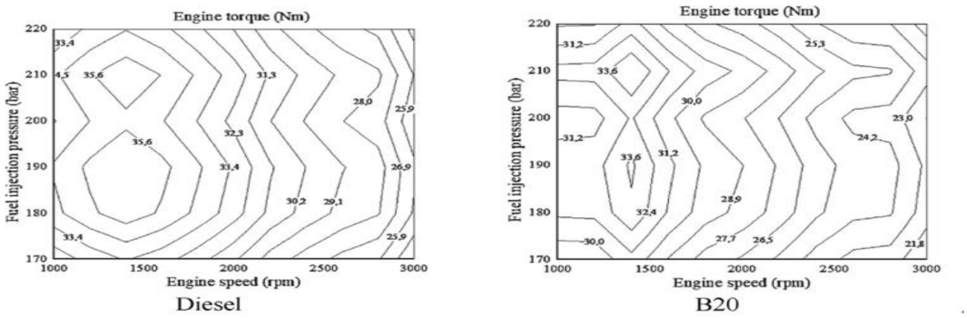


Fig.8 Variation ofBSFC at different injection pressuresand speeds [12].

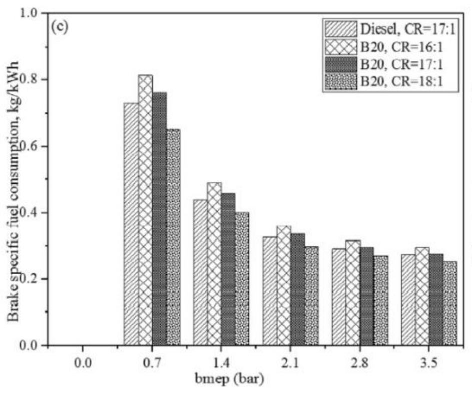


Fig.9 Variation ofBSFC at different CRs [1].

3.4 Brake thermal efficiency (BTE)

Sivakumar sivalingam et al [13]. studied the effect of EGR on the braking thermal efficiency of Jatropha biodiesel engine,it can be seen from Figure 10 that with the increase of EGR percentage, decreased the oxidation degree of air and fuel, and reduced the thermal efficiency; The readings were taken only up 75% EGR at 50% load operation because the engine goes off mode due to insufficient oxygen in the cylinder.G. R. Kannan et al [4]. studied the effects of injection pressure and injection timing on the braking thermal efficiency of biodiesel,on the one hand, with the increase of injection pressure, promoted fuel atomization and complete combustion, on the other hand, with the delay of injection timing, the engine ignition delay increased and the mixing in premixing stage was improved, which promoted better combustion in diffusion combustion stage, increased the braking thermal efficiency, as shown in Figure 11.Jatinder kataria et al [14]. studied the effect of compression ratio on the braking thermal efficiency of waste cooking oil biodiesel, as shown in Figure 12, with the increase of compression ratio, promoted fuel atomization, the mixing of fuel and air was accelerated, the fuel was completely burned, and increased the braking thermal efficiency.Vineet Kumar et al [8]. studied the effects of load and speed on Jatropha biodiesel engine, at low load and speed, the combustion temperature was low and the fuel air mixing was incomplete, resulted in incomplete combustion and low braking thermal efficiency; With the increase of load and speed, increased the combustion temperature, which promoted complete combustion and increased the braking thermal efficiency.

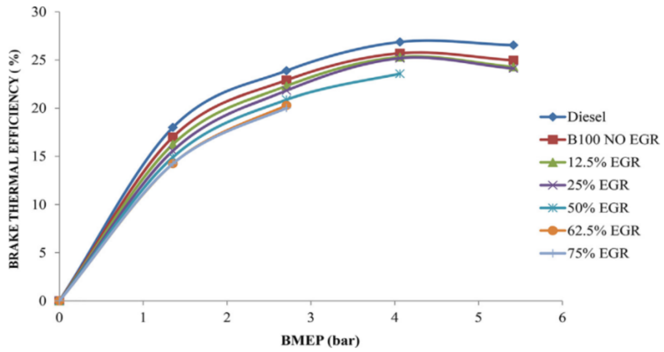


Fig.10 Variation of BTE at different EGRs [13].

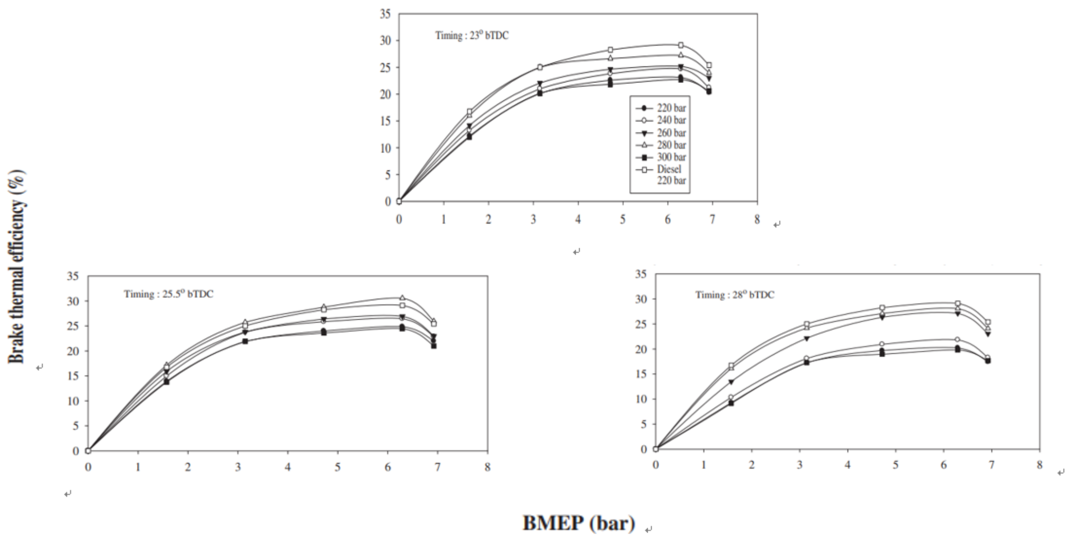


Fig.11 Variation of BTE at different injection pressures and timings [4].

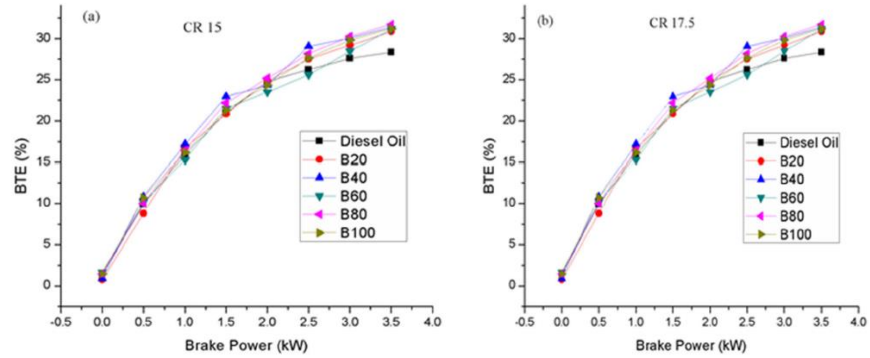


Fig.12 Variation of BTE at different CRs [14].

3.5 Exhaust gas temperature

Murat Kadir yesilyurt et al [12]. studied the effect of different engine speed and injection pressure on exhaust gas temperature, with the increase of engine speed and injection pressure, promoted fuel atomization effect, promoted complete combustion and increased exhaust gas temperature, as shown in Figure 13.Figure 14 shown the effect of engine load and speed on exhaust gas temperature when using soybean oil biodiesel, with the increase of load, more fuels were injected into the cylinder and more heat was released by combustion; Under a certain load, the turbulence intensity increased with the increase of engine speed, and the fuel and air were mixedbetter, resulted in complete combustion and increased exhaust gas temperature [9].Mohdhafizil mat Yasin et al [3]. measured the effect of EGR on exhaust gas temperature, it can be found from Figure 15 that with the increase of EGR percentage, more exhaust gases participated in cylinder combustion, and the decreased of intake oxygen content in the air lead to the reduced of power and torque of test fuel, resulted in low combustion efficiency and incomplete combustion of fuel, reduced exhaust gas temperature.In addition, the change of compression ratio willeffect on the exhaust gas temperature, with the increase of compression ratio, the cylinder pressure and combustion chamber temperature generated by compressionincreasing, promoted atomization, improved the mixingof fuel and air, and increased the exhaust gas temperature.

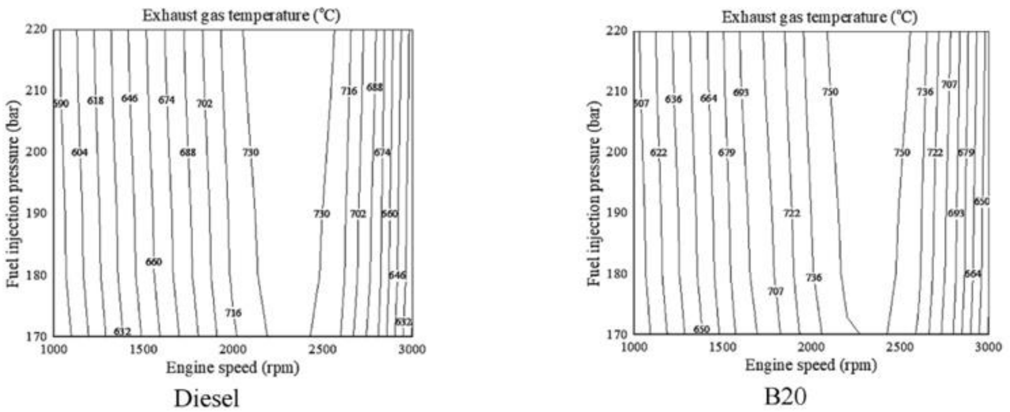
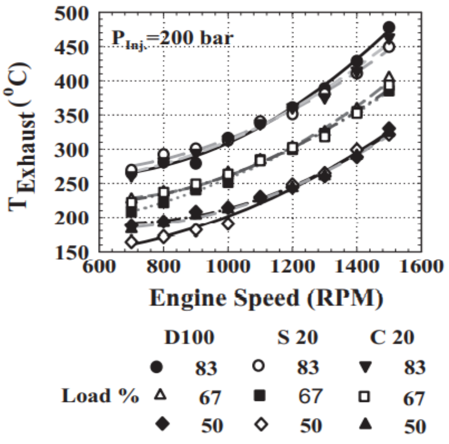


Fig.13 Variation of EGT at different speeds andinjection pressures[12].



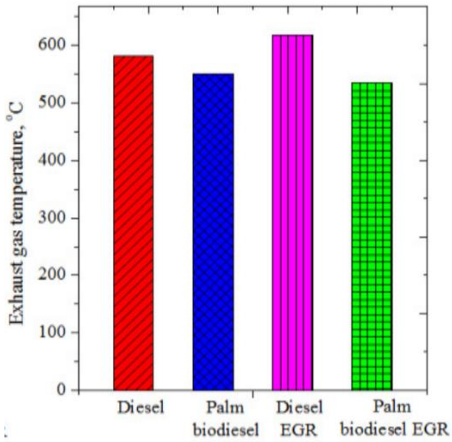


Fig.14 Variation of EGT at different speeds andloads[9].Fig.15 Variation of EGT at EGRs[3].

4. Exhaust gas emissions

4.1 CO emission

Carbon monoxide is the product of incomplete combustion of engine, the main reasons affecting the increase of CO emission are low combustion temperature and insufficient oxygen.Joonsik Hwang et al [15]. studied the effect of different injection pressure and injection timing on CO emission under different engine loads, as shown in Figure 16, under most conditions, oxygen molecules in biodiesel improved combustion and reduced CO emission. Under high load conditions, with the increased of injection pressure, fuel-air mixing better, promoted complete combustion.Under low load conditions, delayed injection timing, promoted fuel-air mixing in premixed combustion stage, increased fuel combustion in diffusion combustion stage, and easy to produce rich combustion zone, resulted in incomplete combustion in cylinder and increased CO emission; However, at high load, increased the combustion temperature, with the delay of injection timing,which improved the oxidation process of carbon and oxygen atoms, and the CO emission was decreased first and then increased.Figure 17 shown the effect of compression ratio on CO emission of waste cooking oil biodiesel engine, with the increase of compression ratio, increased the combustion temperature in cylinder, and promoted fuel combustion in diffusion combustion stage and reduced CO emission [14].With the increase of engine speed, improved air-fuel mixing, promoted complete fuel combustion and reduced CO emission [16].Mohdhafizil mat Yasin et al [17]. studied the effect of EGR percentage on CO emission of palm biodiesel-diesel mixed fuels, with the increase of EGR percentage, more exhaust gases were participated in combustion duration and diluted the fuel air mixture ratio, resulted in lower oxygen content, worse combustion and increased CO emission.

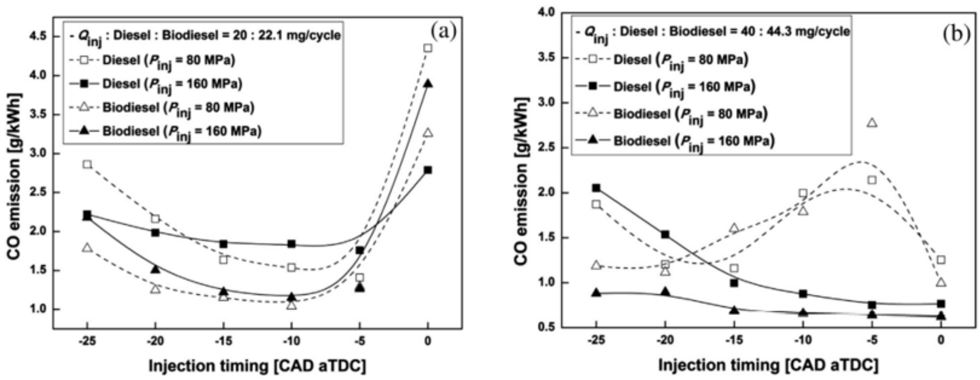


Fig.16 Variation of CO at different loads,injection pressures and injection timings [15].

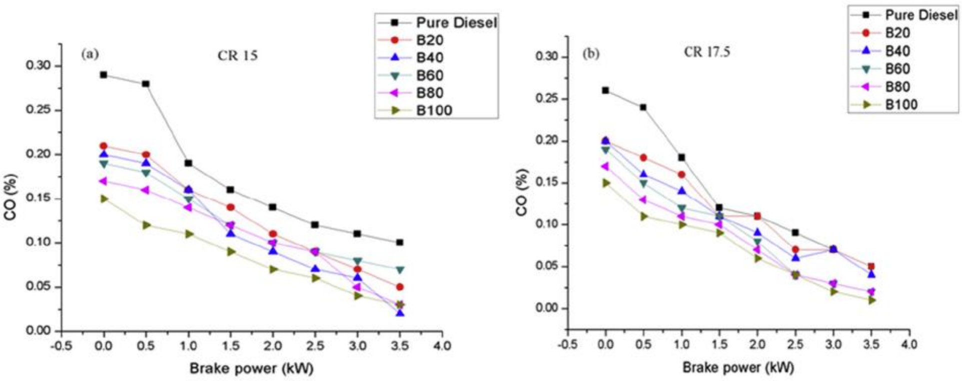


Fig.17 Variation of CO at different CRs [14].

4.2 HC emission

The cause of HC is similar to that of CO, which is mainly due to incomplete fuel combustion caused by hypoxia, resulting in the reaction of a large number of carbon atoms with hydrogen atoms to produce HC.Figure 18 shown the change of HC emission of waste cooking oil biodiesel with engine load, at low load, HC emission was low, with the increase of load, more fuels participated in combustion, resulted in local rich fuel area and local hypoxia, resulted in incomplete combustion and increased HC emission [18].With the increase of engine speed, improved air-fuel mixing and promoted complete fuel combustion [16].Joonsik Hwang et al [15]. studied the effects of different injection pressure and injection timing on HC emission of biodiesel-diesel mixed fuels, biodiesel had high viscosity and lead to poor atomization at low injection pressure, with the increase of injection pressure, fuel air mixing in the combustion chamber was improved, complete combustion was promoted and HC emission was reduced; In addition, HC was greatly affected by fuel air mixing, so at low load, HC emission was almost unchanged in injection timing, as shown in Figure 19.Vineet Kumar et al [8]. studied the effect of injection timing on HC emission of Jatropha biodiesel engine and found the same results, however, at high load, with the advance of injection timing, increased the ignition delay, improved the fuel air mixing degree and reduced the HC emission.Pali rosha et al [1]. found that with the increase of compression ratio, higher compression ratio provided higher in cylinder temperature and pressure, improved fuel combustion and reduced HC emission.As shown in Figure 20, dhineshbalasubramanian et al [10]. studied the effect of EGR on HC emission of biodiesel-diesel mixed fuels, with the increase of EGR percentage, more exhaust gases were participated in the combustion process, decreased the oxygen content, and a larger flame extinction zone was generated in the diffusion combustion stage, resulted in an increases in HC emission.

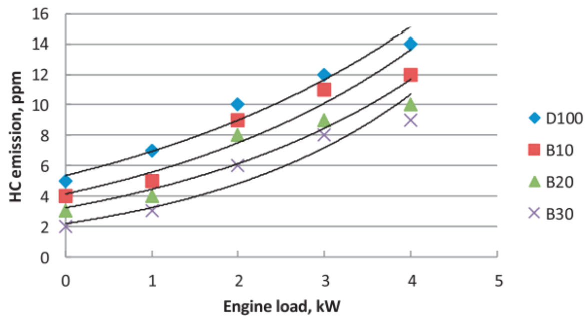


Fig.18 Variation of HC at different loads[18].

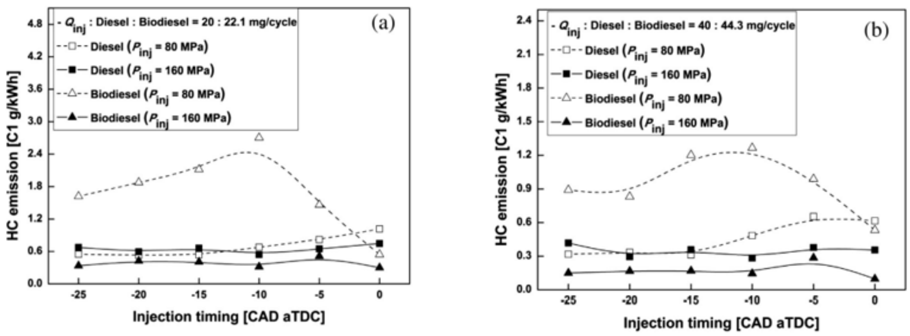


Fig.19 Variation of HC at different injection pressures and timings [15].

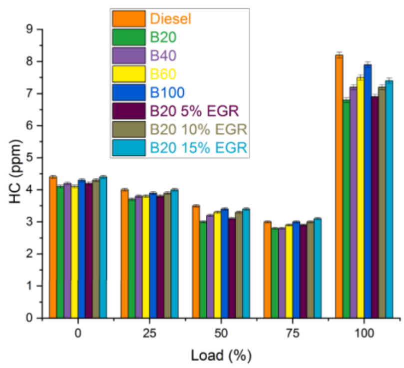


Fig.20 Variation of HC at different EGRs [10].

4.3 NO_x emission

NO_x is the product of complete combustion, which is mainly affected by oxygen concentration and reaction temperature. The higher the combustion temperature, the greater the NO_x emission.Lijiang Wei et al [19]. studied the effect of load and speed on NO_x emission of waste cooking oil biodiesel-diesel mixed fuels, with the increase of engine load and speed, improved fuel air mixing, promoted complete combustion, increased cylinder temperature and NO_x

emission, as shown in Figure 21.Figure 22 shown the effect of injection pressure on NO_x emission of palm biodiesel engine, with the increase of injection pressure, increased fuel atomization effect, completed combustion, increased flame temperature and NO_x generation rate [20].In addition, with the advance of injection timing, increased the engine ignition delay, and promoted better mixing of fuel and air, speeds up the combustion rate, increased the combustion temperature in the cylinder and increased the NO_x emission [21].Shweta Tripathi et al [22]. studied the effects of engine speed and EGR percentage on NO_x emission of palm biodiesel-diesel mixed fuels under a certain compression ratio, with the increase of EGR percentage, the content of exhaust gas was involved in combustion increased and the air content decreased, therefore, the oxygen content was involved in combustion in the combustion chamber decreased, resulted in incomplete combustion of fuel and lower combustion temperature, NO_x emission was reduced.As shown in Figure 23, Pali rosha et al [1]. studied the effect of compression ratio on NO_x emission of palm biodiesel engine, with the increase of compression ratio, promoted the increase of cylinder pressure and combustion chamber temperature, improved fuel atomization, promoted fuel air mixing, improved combustion process, increased combustion temperature in cylinder and increased NO_x emission.

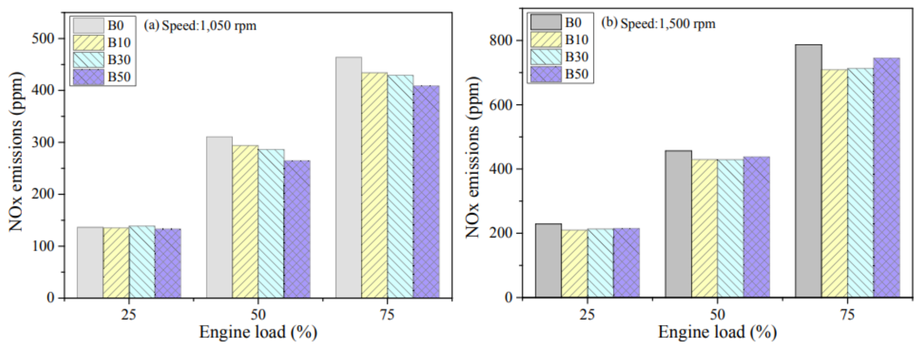
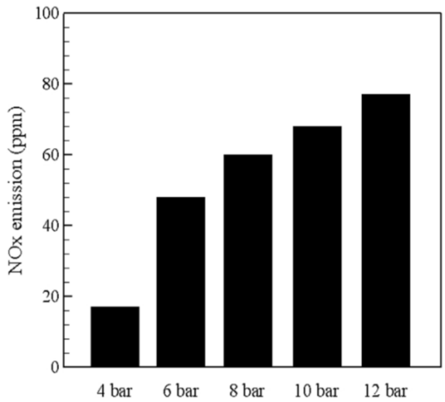


Fig.21 Variation of NO_x at different loads and speeds [19].



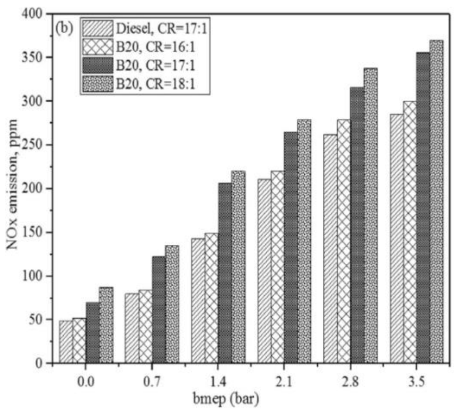


Fig.22 Variation of NO_x at different injection pressures[20].Fig.23 Variation of NO_x at different EGRs [1].

4.4 CO_2 emission

CO_2 is the product of complete combustion in the engine cylinder.Figure 24 shown the variation trend of various experimental fuels with engine load and speed, the results shown that CO_2 increased with the increase of engine load and speed,lead to increase in fuel consumption, increase in cylinder temperature, and improve in the combustion process, promote the complete combustion of fuel and increase CO_2 emissions [6,18].In addition, the injection timing and compression ratio had a great impact on CO_2 emission, with the advance of injection timing, increased the ignition delay and promoted the degree of fuel air mixing; The increased of compression ratio increased cylinder pressure and combustion temperature, improved fuel atomization, promoted complete combustion and increased CO_2 emission.Nidal h. Abu hamdeh et al [20]. studied the effect of injection pressure on CO_2 emission of palm biodiesel-diesel mixed fuels, the results showed that the increase of injection pressure improved the degree of fuel atomization, promoted fuel air mixing, produced complete combustion and increased CO_2 emission.Mohdhafizil mat Yasin et al [17]. studied the effect of EGR system on CO_2 emission of biodiesel-diesel mixed fuels, as shown in Figure 25, with the increase of EGR percentage, decrease the oxygen in intake air and increased the CO_2 content in exhaust gas.

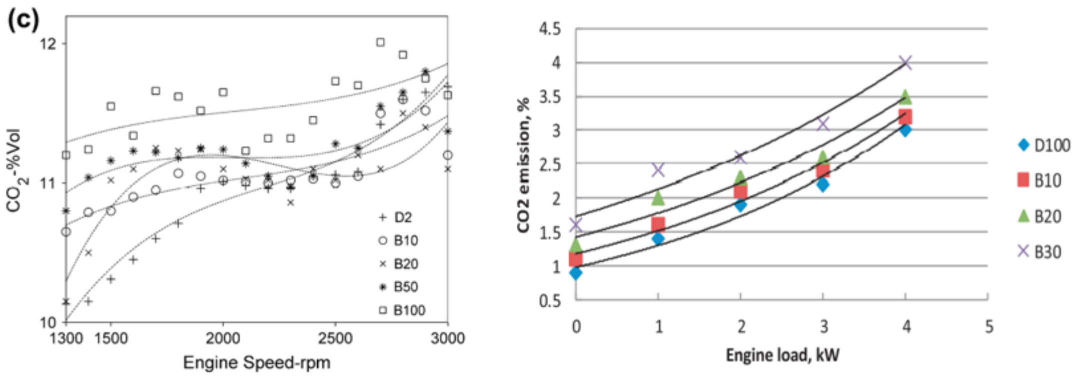


Fig.24 Variation of CO_2 at different loads and speeds [6,18].

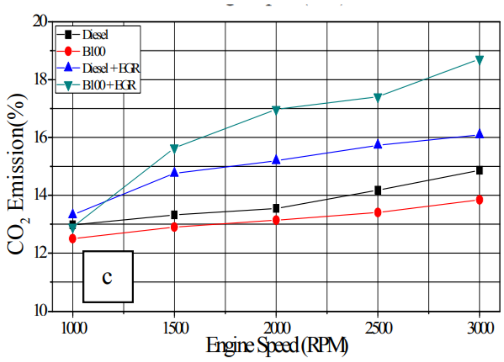


Fig.25 Variation of CO_2 at different EGRs [17].

4.5 Smoke emission

Smoke is the product of incomplete combustion of engine, by improving the mixing degree of air and fuel, improving fuel atomization and providing sufficient oxygen, combustion can be improved and smoke emission can be reduced.Figure 26 shown the effects of injection pressure and injection timing on smoke emission of waste cooking oil biodiesel-diesel mixed fuels, with the increase of injection pressure, promoted better fuel atomization, fuel particles become smaller, improved combustion process and reduced smoke emission; With the advance of injection timing, the oxidation time of smoke particles during the expansion stroke was increased, improved the combustion chamber temperature, promoted complete combustion and reduced smoke emission [4].Dhineshbalasubramanian et al [10]. studied the effects of load and EGR percentage on the smoke emission of biodiesel engine, the results shown that the smoke emission increases with the increase of load. At low load, the air-fuel mixture was rich, the fuel viscosity increased and the atomization range was poor; With the increase of load, more fuel was injected into the cylinder, increased fuel consumption, decreased air-fuel equivalence ratio, local rich fuel area was formed, and increased smoke emission; In addition, as the EGR percentage increased, more exhaust gas mixing reduced oxygen availability, resulted in incomplete combustion and increased smoke emissions.As shown in Figure 27, the compression ratio had a great impact on smoke emission, with the increase of compression ratio, increased the cylinder combustion temperature, improved the combustion process, promoted complete combustion and reduced smoke emission [1].T. Ganaparty et al [2]. studied the effect of engine speed on the smoke emission of Jatropha biodiesel, with the increase of engine speed, the fuel-air mixing was improved, improved the combustion process, increased the combustion temperature and reduced the smoke emission.

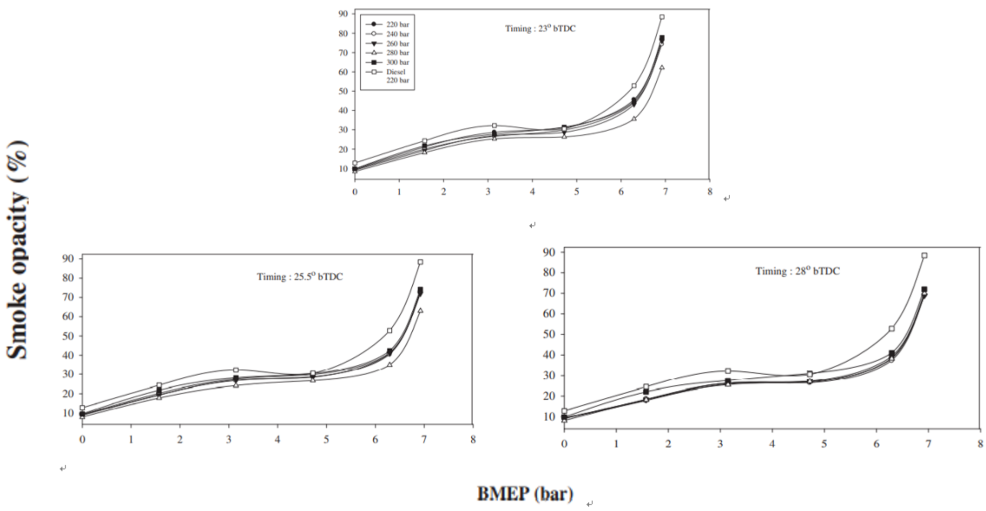


Fig.26 Variation of smoke at different injection pressures and timings [4].

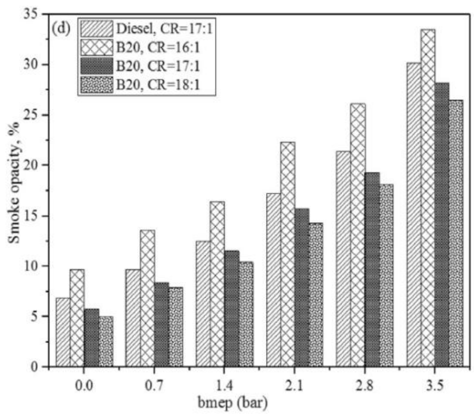


Fig.27 Variation of smoke at different CRs [1].

5. Conclusions

Biodiesel is a renewable and clean energy, when used as a substitute fuel for diesel engine, it can reduce emissions and effectively reduce the damage to the environment, moreover, by changing the engine operating conditions and injection strategy, it can effectively improve the engine performance and reduce exhaust emissions.

1. Biodiesel has similar physical and chemical properties to traditional diesel fuel, and can be used directly without changing the structure of existing diesel engine.
2. With the increase of compression ratio and injection pressure, improved fuel atomization and improved combustion, increased cylinder pressure, BTE, EGT, NO_x and CO_2, while HRR, BSFC, CO, HC and smoke emissions would be shown a downward trend.
3. With the advance of injection timing, increased the ignition delay, increased the air-fuel mixing degree in the premixing stage, increased the cylinder pressure, BSFC, BTE, EGT, NO_x and CO_2 emissions, and decreased the emissions of HRR, CO and HC.
4. With the increase of engine speed and load, increased cylinder pressure, HRR, BTE and EGT, while decreased BSFC.For exhaust emission, with the increase of rotating speed, CO, HC and smoke were shown a downward trend, while NO_x and CO_2 emissions were increased; With the increase of load, increased CO, HC and NO_x emissions, decreased CO_2 and smoke emissions.With the increase of load and speed, from two sides to analyzed, one side, the fuel injection volume increases, resulting in local rich combustion zone and incomplete combustion, increased HC and CO emissions, decreased NO_x emissions; On the other hand, the increase of cylinder pressure and combustion temperature enhances the combustion effect and produces complete combustion, decreased HC and CO emissios, increased NO_x emission.
5. When EGR is applied to diesel engine, with the increase of EGR percentage, the exhaust gas was involved in combustion increased, decreased the cylinder pressure, HRR, BTE and EGT, and increased the emissions of BSFC, CO, HC, CO_2 and smoke. However, due to the low oxygen content in exhaust gas and the reduction of combustion temperature, decreased the NO_x emission.

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Conflicts of interest

The authors have no conflicts of interest to declare.

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