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Impacts of Intake Throttling on the Combustion Characteristics and Emissions of a Light-Duty Diesel Engine under the Idle Mode

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Abstract: Intake throttling has been verified as an effective approach to increase the exhaust temperature of diesel engines, which could benefit the catalytic efficiency aftertreatment. To better understand the influence of intake throttling on the combustion characteristics and exhaust emissions of light-duty diesel engines operating under idle mode, a light-duty diesel engine was experimentally investigated. This study is a follow-on to previous studies on the effect of throttling on light-duty diesel engine exhaust temperatures and emissions. Tests were conducted at a fixed idle speed of 1100 rpm, and the throttle position and intake manifold air pressure (MAP) were varied. The in-cylinder pressure, pressure rise rate, heat release rate (HRR), in-cylinder temperature, exhaust temperature, and regular gaseous emissions were analyzed. The results indicated that under the influence of intake throttling, the MAP decreased from 101 kPa under wide-open-throttle (WOT) conditions to 52.5 kPa under the heaviest throttling conditions, and the exhaust temperature increased from 100 °C to 200 °C, with a fuel penalty associated with the increase in the pumping indicated mean effective pressure (IMEP). The in-cylinder pressure continuously declined with decreasing MAP, while the HRR generally increased with increasing MAP. Under WOT conditions, the ignition delay decreased, while the combustion duration decreased under heavier throttling conditions. The in-cylinder temperature with throttling was higher than that under WOT conditions, and after post-injection treatment, the in-cylinder temperature exhibited an increasing trend with decreasing MAP. The CO_2, CO, NO_x, and HC emissions increased with increasing throttling amounts.

Keywords: intake throttling; combustion characteristics; exhaust emissions; light-duty diesel engine

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1. Introduction

The continuous and rapid growth in the vehicle population in developing countries, such as China and India, aroused substantial attention regarding energy security and environmental protection. Choosing China as an example, based on vehicle emission data published by the Ministry of Ecology and Environment (MEE) of China, vehicles have remained a major contributor to urban pollution, especially in mega-cities, such as Beijing, where the contribution of vehicles to particulate matter (PM) emissions is 45%. Of the various vehicle fleets, diesel vehicles are the largest contributor to both nitrogen oxides (NO_x) and PM emissions; in particular, more than 70% of NO_x and 90% of PM in vehicular emissions in 2017 could be attributed to diesel vehicles [1]. Countries worldwide have issued increasingly stringent emission laws and regulations to control and manage vehicle emission-related pollution. To meet these strict standards, the exhaust after-treatment system has become an indispensable part of modern diesel vehicles. Most of these exhaust catalytic converters, such as diesel oxidation (DOC), selective catalyst reduction (SCR), and lean NO_x trap (LNT) systems must be heated to temperatures above 200 °C to function effectively [2].

Of the standardized drive cycles, even in the world-harmonized light-duty vehicle test procedure (WLTP), which is more representative of actual on-road vehicle driving conditions than the new European driving cycle (NEDC), the idle mode occupies more than 23% of the total test time [3]. The proportion of the idle mode could be higher during vehicle operation in traffic congestion areas. Note that although some local governments have promoted electric vehicles in public traffic, and diesel vehicles are still used for many municipal services, such as firefighting trucks and emergency ambulances. These vehicles, operated under idle mode, can have exhaust temperatures too low to activate the exhaust catalyst and thus generate high pollutant emissions.

With the continuous tightening of vehicle emission standards and the application of advanced emission control technologies, researchers worldwide have invested increasing effort in the investigation of diesel engine idle behavior characteristics [4–10]. Several methods, techniques, or modified operating conditions, such as intake throttling, post-injection of additional fuel, and cylinder deactivation, could increase the idle exhaust temperatures of diesel engines. The U.S. Environmental Protection Agency (EPA) [11] examined long-duration idling emissions of a diverse group of heavy-duty trucks under various engine speeds, ambient temperatures, and accessory loads. Additionally, emission factors for passenger cars, light-duty trucks, heavy-duty trucks, and motorcycles under idle mode were estimated via a computer model [12]. Additionally, Hardy and Reitz [13] investigated the effect of multiple injection options on pollutant emissions and the combustion noise of a heavy-duty diesel engine. La Rocca et al. [14,15] conducted experiments and employed computational fluid dynamics (CFD) modeling to study the effect of multiple pilot injection options on the mixture preparation characteristics of a light-duty diesel engine. The influence of post-injection technology on soot dynamics was examined in an optical diesel engine under low-temperature combustion conditions [16]. The effect of variable valve timing conditions on the exhaust gas temperature in a low-loaded diesel engine was studied via simulations [17], and the results indicated that the exhaust temperature could be sufficiently increased to exceed 250 °C via the application of an advanced/retarded intake valve closing timing. Huang and Lu [18] compared the effects of various factors on the exhaust temperature of a heavy-duty diesel engine and found that with intake throttling and an increased idle speed, the exhaust temperature could be raised from 131 °C at 850 rpm to 260 °C (well above the activation temperature of the close-coupled DOC system) at 1100 rpm. Note that intake throttling has been widely used for LNT and diesel particulate filter (DPF) regeneration [19–21]. These studies have contributed to a greater understanding of diesel engine idle profiles and have significantly supported the reduction in emissions of light-duty diesel vehicles. From previous studies, we could conclude that intake throttling could increase the exhaust temperature which benefits the efficiency of catalytic after-treatment while having drawbacks regarding engine-out emissions. Meanwhile, there have been few studies focused on the combustion and emission of an intake-throttled diesel engine under idle conditions.

This study is a follow-up to our previous work [22], which investigated methods to increase the exhaust temperature of idling light-duty diesel engines. In this study, the effect of intake throttling on the exhaust temperature, in-cylinder pressure, heat release rate, and emissions of a light-duty diesel engine were evaluated. We also examined the relationship between the exhaust temperature and fuel supply conditions. We aimed to better understand the idle profiles of light-duty engines and promote a reduction in the emissions of light-duty diesel vehicles to meet the requirements of future emission standards.

2. Experimental Setup and Methodology

2.1. Experimental Setup

The experimental setup used in this paper has been mentioned in the literature published by our team [23,24]; hence, only a brief overview is provided. The original engine used in this research was a four-cylinder, common rail, turbocharger, 2.0 L light-duty diesel

engine manufactured by General Motors Corporation. The engine specifications are listed in Table 1. Concerning the working condition in this study, which was the idle mode, in which the intake manifold pressure (MAP) approaches the local atmospheric pressure, the turbocharger was removed from the engine for operational simplicity and to allow more convenient access for engine instrumentation [22]. In our previous study, we analyzed the influence of turbocharger removal and determined a relatively small influence on engine operation under idle conditions.

Table 1. Engine specifications of GM A20DTH.

Item	Characteristics
Type	In-line four-cylinder common rail injection, turbocharged diesel engine
Displacement	1956 mL
Bore	83 mm
Stroke	90.4 mm
Connecting rod length	145 mm
Valve diameter I/E	28.5/25.5 mm
Number of valves/cylinders	4
Compression ratio	16.5:1
Intake valve opening	8 °CA bTDC @ 0.1 mm lift
Intake valve closing	40 °CA aBDC @ 0.1 mm lift
Exhaust valve opening	52 °CA bBDC @ 0.1 mm lift
Exhaust valve closing	10 °CA bTDC @ 0.1 mm lift

2.2. Experimental Process

The engine was matched with an electric dynamometer. However, the dynamometer was only used for the start process of the engine and was deactivated in the experiment. A National Instruments (NI) LabView-based engine control algorithm was developed to control the engine and maintain the desired idle speed using a feedback loop that adjusted the main injection duration [22]. This algorithm was implemented with an eight-slot NI c-RIO system and control modules. An NI c-DAQ system and NI combustion analysis system (CAS) were used for engine data acquisition. A K-type thermocouple measured the exhaust temperature with a precision of 2 °C, installed at the confluence of the four exhaust manifolds. A Continental Model NB1500 NO_x sensor obtained NO_x emission data with a precision of 3%, located downstream of the exhaust manifold. CO_2 and CO were measured using a Horbia MEXA 485L device, and hydrocarbons (HCs) were measured with a Rosemount Analytical Model 400A flame ionization detector (FID) based on C_3 (propane). Figure 1 shows a sketch of the engine bench.

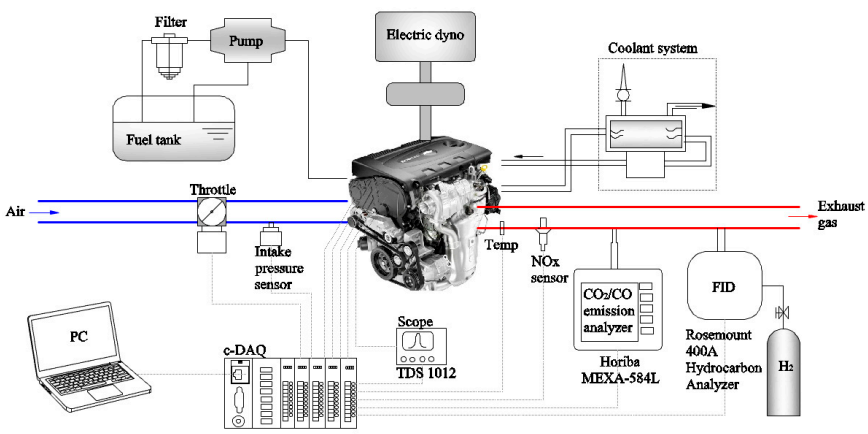


Figure 1. Sketch of the engine bench system.

Before the test, the experimental engine was sufficiently warmed until the coolant temperature reached approximately 80 °C. The laboratory temperature was maintained at 23 ± 1 °C via a central air-conditioning system. The engine speed was fixed at 1100 rpm, which is a typical fast-idle speed during warm-up after cold start. The rail pressure was 500 bar. The heaviest intake throttling level was determined by the engine's ability to maintain the target speed of 1100 ± 5 rpm. The fuel used was #2 ultralow sulfur diesel purchased from a gas station in Texas. Following the optimized injection protocol in our previous study [22,24], four injection steps, including one pre-injection (1st), one main injection (2nd) and two post-injections (3rd and 4th), were used in the present study to examine the influence of intake throttling. The detailed injection timing and injection duration are shown in Figure 2.

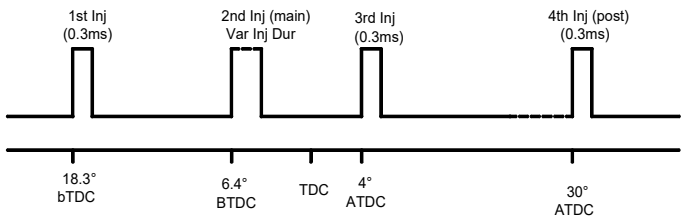


Figure 2. Injection timing diagram.

3. Results and Discussion

In the present study, the ignition delay is defined as the crank angle interval between the 1st injection and ignition, and ignition is identified as the crank angle at which 10% of the fuel mass has been burned, or CA_{10}. The combustion duration is the crank angle interval during which 10–90% of the fuel mass is burned, or $CA_{10–90}$.

3.1. Effects on the Fuel Quality and Exhaust Temperature

Figure 3 shows the total injected fuel mass and exhaust temperature for MAP values ranging from 101 kPa (wide-open throttle, WOT) to 52.5 kPa (maximum throttling point). As mentioned before, the main injection (2nd) is the only one of the four injections for which the injection duration could be adjusted to maintain a steady idle speed; therefore, the difference in total injected fuel mass results from the change in the injection duration of the main injection. The results indicated that both the total injected fuel mass and exhaust temperature generally increased linearly with decreasing MAP. This result is consistent with the findings of a previous study [25,26]. Honardar et al. studied the impacts of throttling on the fuel penalty for a light-duty diesel engine under light load and found a higher fuel consumption penalty. In the present research, only the throttle was adjusted while the boundary conditions, such as the temperature of the intake and coolant fluid, were maintained constant, so we could deduce that the increased fuel consumption was mainly used to offset the energy expenditure due to throttling. Concerning the exhaust temperature, the significant decrease in the air/fuel (A/F) ratio due to the reduction in intake air flow and increase in fuel quantity resulted in a higher adiabatic combustion temperature, thus increasing the exhaust temperature.

3.2. Effects on the In-Cylinder Pressure

Figure 4 shows the in-cylinder pressure versus the volume under the various MAPs. The in-cylinder pressure was significantly influenced by the throttling amount, and with decreasing MAP, the in-cylinder pressure exhibited a downward trend overall, and the peak cylinder pressure decreased from 3397.3 to 1672.1 kPa. The observed reduction in cylinder pressure mainly occurred because the intake airflow under the heavier throttling conditions (lower MAP) decreased, resulting in a lower mass of the fresh charge in the cylinder, thus lowering the in-cylinder pressure. Despite the increase in injected fuel mass, it could not sufficiently compensate for the decrease in intake air mass; moreover, the reduction in intake air mass and increase in fuel reduced the excess air coefficient, thus reducing combustion pressure rise. As shown in Figure 4a,b, both of which are the subplots

of Figure 4, the constant-volume phases of both the work and gas exchange processes increased with decreasing MAP, which could seriously impact the thermal efficiency and pumping losses.

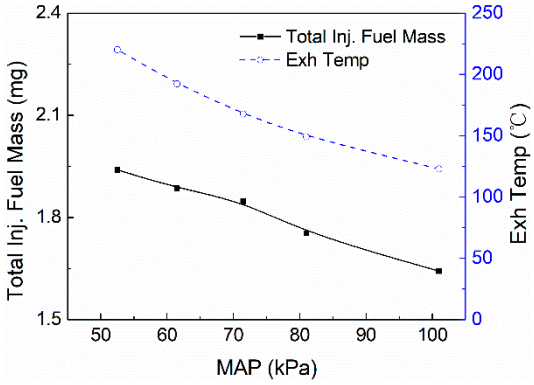
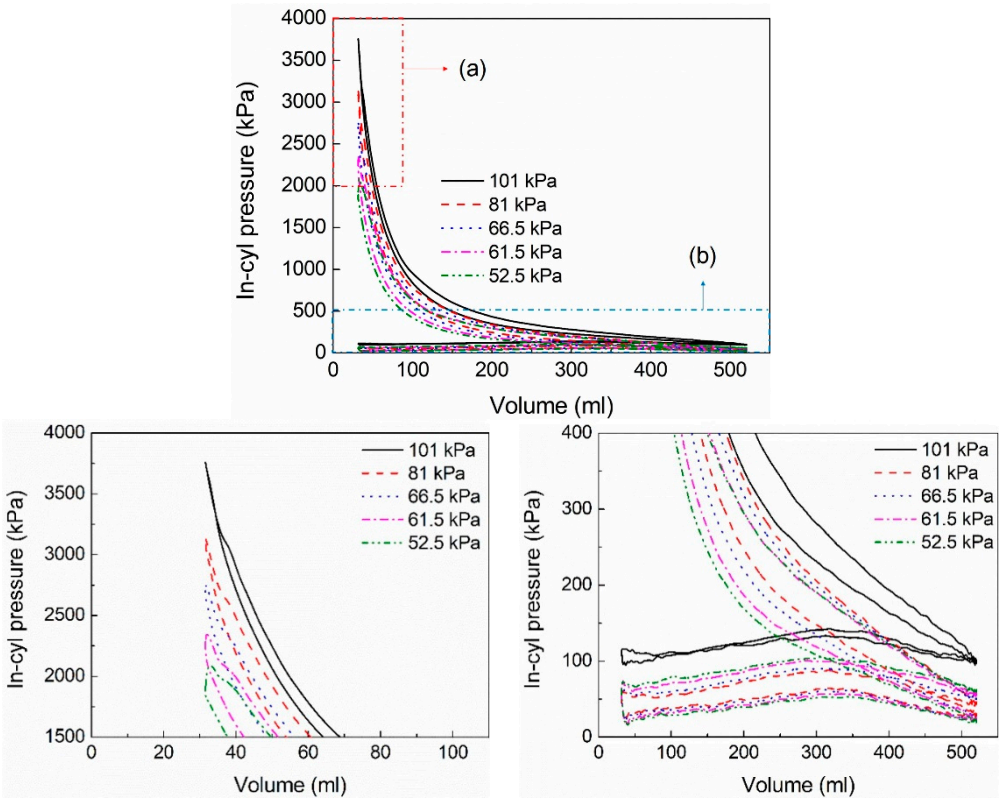


Figure 3. Total injected fuel mass and exhaust temperature under the various MAPs.



(**a**) Peak pressures (**b**) Gas exchange processes

Figure 4. In-cylinder pressure under the various intake manifold air pressures.

Based on the in-cylinder pressure, the gross, net, and pumping indicated mean effective pressures (IMEPs) were calculated. Figure 5 shows the gross, net, and pumping IMEP values under the different MAP levels. Similar to the main injection duration, the gross IMEP first smoothly increased with increasing MAP until the MAP reached 61.5 kPa, after which a sharp increase in the gross IMEP was observed under an MAP of 52.5 kPa; the net IMEP remained relatively constant until an MAP of 62.5 kPa was reached and then began to increase; regarding the pumping IMEP, this quantity exhibited a linearly decreasing

trend with a decreasing MAP. These trends can be captured with the following relationship among the gross, net, and pumping IMEPs (Equation (1)):

$$\text{gross IMEP} = \text{net IMEP} + \text{pumping IMEP} \quad (1)$$

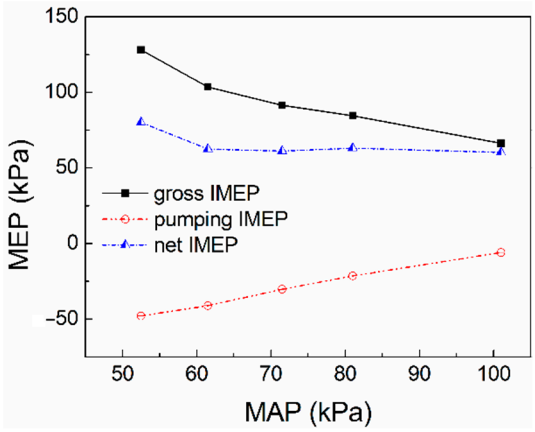


Figure 5. Indicated mean effective pressure under the various MAPs.

Under idling, all work produced by fuel combustion was used to maintain engine operation, without any output. In the present experiment, the throttling amount was varied while the boundary conditions of the test engine, such as the intake temperature and coolant temperature, were kept constant. Therefore, the net IMEP remained almost constant; the linear increase in the pumping IMEP could be attributed to the increased throttling. Regarding the rise in the net IMEP under an MAP of 52.5 kPa, the main reason could be that the reduction in fresh charge and increase in residual gas influenced the fuel combustion process; hence, more fuel was supplied to maintain stable engine operation, which increased the net IMEP, after which the gross IMEP increased.

3.3. Pressure Rise Rate

Figure 6 shows the pressure rise rate under the various MAPs. With a decreasing MAP, the pressure rise rate first decreased, after which it exhibited an increasing trend, approximately from top dead center (TDC). This could be primarily attributed to the reduction in fresh air entering the cylinder. The decrease in the pressure rise rate was also associated with a decline in combustion noise, whereas an increase in intake throttling could increase intake noise. Considering that the main purpose of the present study was not engine noise, the overall operating noise level of the engine was not measured.

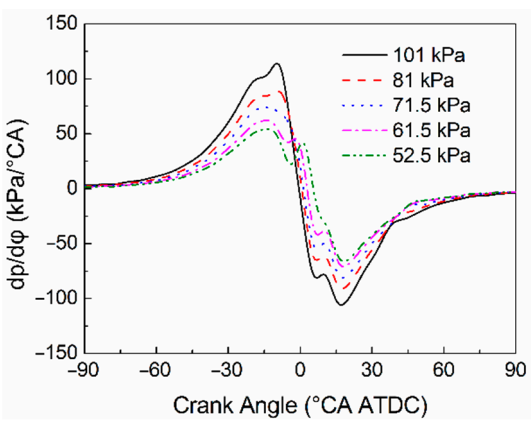


Figure 6. Pressure rise rate under the various MAPs.

3.4. Effects on the Heat Release Rate

To visualize the heat release rate (HRR), the HRR was determined during the main injection and combustion periods. As shown in Figure 7, during the main combustion process, the start of the HRR was retarded with a decreasing MAP, while the peak value of the HRR was enhanced.

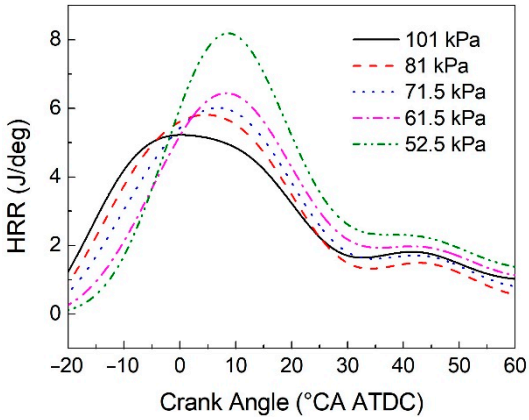


Figure 7. Heat release rate under the various MAPs.

In addition, two peaks emerged in the HRR curves, and the crank angles corresponding to these peak points were slightly retarded with a decreasing MAP. The two peaks could be explained as the evaporation of the fuel injected during the first process (pre-injection), and a trough could be observed after −18.3 °CA aTDC; along with the main injection, the mixture was compressed to ignition, and via compression work, the HHR peaked around TDC. The maximum point then occurred at approximately 10 °CA aTDC, and the fourth injection process (post-injection) yielded the last peak.

The ignition delay and combustion duration under various MAPs are shown in Figure 8. As illustrated, with a decreasing MAP, the ignition delay first decreased and then suddenly increased under an MAP of 52.5 kPa, whereas the combustion duration exhibited the opposite trend. Generally, high pressures and temperatures and low A/F ratios can shorten the ignition delay of a diesel engine. Intake throttling reduced the amount of fresh air entering the cylinder and increased the exchange loss; the scavenging efficiency could also be reduced during the period of valve overlap, which could generate an increase in residual gas. To eliminate the increased pumping loss and maintain stable engine operation, the quantity of injection fuel was increased, and the excess air coefficient was thus reduced. The residual gas could increase the in-cylinder temperature; therefore, as the throttling amount increased from WOT conditions to an MAP of 82.5 kPa, the ignition delay was shortened. Thereafter, the in-cylinder pressure was further reduced with increasing intake throttling and the ratio of residual gas significantly increased, including many triatomic molecules, such as CO_2 and H_2O; this could elevate the average specific heat capacity of the mixture and constrain the in-cylinder temperature increase [27], leading to a delay in the start of ignition, namely the ignition delay increased. In contrast, the reduction in the A/F ratio could benefit the combustion rate and thus shorten the combustion duration.

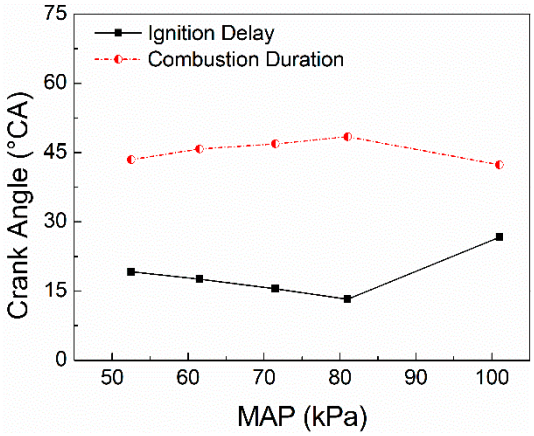


Figure 8. Ignition delay and combustion duration under the various MAPs.

3.5. Effects on the Exhaust Temperature

Figure 9 shows the in-cylinder temperature and exhaust temperature under the various MAPs. With decreasing MAP, the in-cylinder temperature under throttling conditions was generally lower than that under WOT conditions until TDC was reached, after which the in-cylinder temperature generally exhibited an increasing trend; the exhaust temperature revealed a linear increasing trend with higher MAP. The reason for this finding might be that the amount of residual gas, which increased with throttling, enhanced the in-cylinder temperature; in contrast, CO_2 and H_2O in the residual gas constrained the rate of increase in the in-cylinder temperature, leading to a lower in-cylinder temperature during the compression stroke and main combustion process except the one at 71.5 kPa. Regarding the influence of fuel injection mass increase on combustion, the in-cylinder temperature became slightly higher than that under the original conditions and increased with increasing MAP.

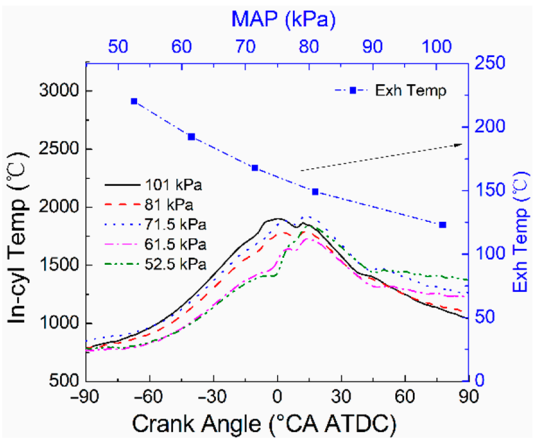


Figure 9. The in-cylinder temperature under various MAPs.

3.6. Effects on Exhaust Emissions

The emissions of CO_2, CO, HC, and NO_x under the various MAPs are shown in Figure 10. The results indicate that all these emissions increased with decreasing MAP. Among these emissions, the CO_2 and NO_x emissions exhibited an approximately linear relationship with decreasing MAP; from WOT conditions to an MAP of 82 kPa, the CO emissions remained almost constant and then linearly increased when the MAP was varied from 82 to 52.5 kPa. The trend in the HC emissions resembled an exponential increase with decreasing MAP. Similar behaviors for the HC and CO emissions in this study were also observed for diesel engines in previous studies [18,25,28]. In these studies, they found that HCs and CO increased with the reduction in MAP.

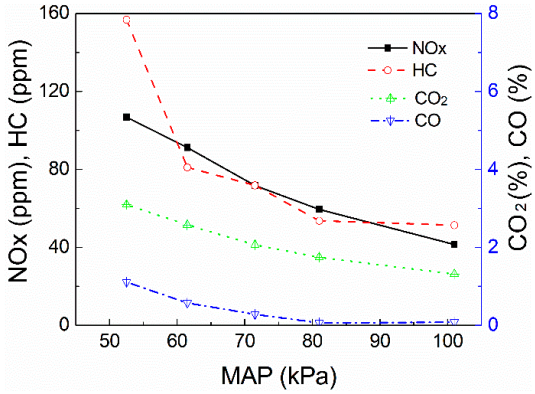


Figure 10. CO_2, CO, NO_x, and HC under the different MAPs.

Specifically, the CO_2, CO, NO_x, and HC concentrations increased from 1.31%, 0.084%, 41.5 ppm, and 51.4 ppm under WOT conditions to 3.1%, 1.1%, 106.9 ppm, and 156.9 ppm, respectively, under heavy throttling, increasing approximately 2.4, 13.2, 2.6, and 3.1 times, respectively.

As mentioned before, from the WOT position to the heaviest throttle position, the MAP decreased from 101 kPa to 52.5 kPa, the duration of the main injection increased from 0.15 to 0.34 ms, and the exhaust temperature increased from 123 °C to 220 °C.

Considering that diesel engines operate under the condition of an A/F ratio higher than 1, CO_2 emissions could be considered a reflection of the fuel injection quantity, even though the injected fuel cannot be completely burned. Based on this theory, the observed increase in CO_2 emissions due to the reduction in the MAP is easy to understand. In the heavier throttling case, the pumping loss increased; to maintain the engine at a stable idle speed, more fuel was injected, thus increasing the CO_2 emissions.

Incomplete combustion due to insufficient oxygen, a sudden decrease in temperature below 1450 K, and CO_2 pyrolysis at a high temperature could generate increased CO formation. In the present study, the increase in CO emissions with decreasing MAP could be mainly attributed to the decline in the A/F ratio, which resulted from a decrease in fresh charges and an increase in fuel mass. A higher in-cylinder temperature could partially generate CO emissions via CO_2 pyrolysis. Furthermore, a decrease in the MAP could result in a decrease in the in-cylinder pressure, which could lead to a lower spray cone angle and longer penetration. Neither a low spray cone angle nor long penetration is beneficial for mixture formation and thus could generate over-rich zones. A large amount of CO was generated in these zones.

Similar to CO, incomplete combustion due to a lack of oxygen was the main reason for HC formation. As described above, over-rich areas occurred in the cylinder due to the reduction in MAP. The A/F mixture in these zones may exceed the combustible limit of fuel, and high HCs were thus formed. To a certain extent, the fuel used to offset the increase in pumping loss could lead to a richer mixture. HC emissions could also be generated by the phenomenon of flame quenching and crevices. Due to the effect of quenching and crevices, a certain amount of HCs could be generated. In addition, certain characteristics under throttling conditions could increase the possibility of HC formation. As shown in Figure 2, the lower in-cylinder pressure resulted in the enhanced evaporation of fuel droplets, which benefited the formation of a richer mixture. As shown in Figure 6, with decreasing MAP, the ignition delay increased, and the combustion duration decreased. A longer ignition delay resulted in a longer fuel droplet evaporation period and the formation of richer mixtures, while a shorter combustion duration resulted in insufficient time for complete combustion.

Regarding NOx emissions, the formation conditions included abundant oxygen, a high in-cylinder temperature, and a long residence time in the reaction area at high temperatures. The NO_x concentration increased with decreasing MAP, approximately 2.5 times between

the WOT and heaviest throttling positions. The result is similar to the findings of a previous study [25,26]. In the case of a lower MAP, a larger amount of fuel was burned during the premixed controlled process and a larger quantity of heat was released, thus drastically increasing the in-cylinder temperature, which was beneficial to NO_x formation.

4. Conclusions

To understand the combustion and emission implications of an intake throttled diesel engine under idle conditions, we investigated the effect of throttling on the combustion characteristics, exhaust temperature and CO_2, CO, HC, and NO_x emissions of a light-duty diesel engine under idling. The experimental investigation results revealed that with the intake air throttling conditions adjusted from the WOT position to the heaviest throttling position, the MAP decreased from 101 to 52.5 kPa, and the exhaust temperature increased from 123.0 °C to 220.3 °C. Additionally, this increased the pumping losses, and thus, injected fuel mass was increased from 1.64 to 1.94 mg/per cycle to maintain stable engine operation. Concerning the combustion characteristics, the in-cylinder pressure continuously declined with decreasing MAP, while the HRR generally exhibited the opposite trend. Except for the WOT case, both the ignition delay and combustion duration decreased with an increasing throttling amount. Generally, the diesel engine produced higher CO_2, CO, NO_x, and HC emissions with increasing throttling amounts. Of these emissions, the CO_2, CO, and NO_x emissions steadily increased with decreasing MAP, while the trend of the HC emissions resembled an exponential increase with decreasing MAP. Although intake air throttling can increase the exhaust temperature and thus activate the catalyst, the relationships among engine-out emissions, exhaust temperature, and fuel penalty should be further considered. This study provides a better understanding of the idle profiles of light-duty engines and promotes the development of ways for cleaner light-duty diesel engines to meet stricter emission standards.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

°CA	Degree Crank Angle
A/F	Air/Fuel
aTDC	After Top Dead Center
bTDC	Before Top Dead Center
C_3	Propane
CA_{10}	The Crank Angle at which 10% of the Fuel mass Has Been Burned
$CA_{10–90}$	The Crank Angle Interval during which 10–90% of the Fuel Mass Is Burned
CAS	Combustion Analysis System
CO	Carbon Monoxide
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter

EPA	Environmental Protection Agency
FID	Flame Ionization Detector
HCs	Hydrocarbons
HRR	Heat Release Rate
IMEP	Indicated Mean Effective Pressure
LNT	Lean NOx Trap
MAP	Manifold Air Pressure
MEE	Ministry of Ecology and Environment
NEDC	New European Driving Cycle
PM	Particulate Matter
SCR	Selective Catalyst Reduction
WLTP	World-Harmonized Light-Duty Vehicle Test Procedure
WOT	Wide-Open Throttle

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