EXPERIMENTAL INVESTIGATION OF THE EFFECT OF ALTITUDE ON EFFICIENCY AND EMISSIONS OF A DIESEL ENGINE

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The diesel engine is expected to be available for operation at high altitude. However, power loss and emission deterioration have been plaguing highland diesel engines. Therefore, this study aimed to investigate the impact of altitude on the performance and combustion characteristics of diesel engines that is limited discussed in existing studies. The research was conducted by varying the altitude from 0-4,500m using a research diesel engine and analyzing the combustion characteristics at different combustion phases with the help of triple Wiebe function. The results indicated a noticeable drop in power output with increasing altitude, and the deterioration of performance and emissions became significant when the altitude exceeded 3,000m. Specifically, the indicated specific CO, unburnt hydrocarbon, and soot emissions increased while nitrogen oxides showed a reverse trend. Additionally, it was found that the lower cylinder pressure at high altitude extended the ignition delay and caused a higher heat release rate in the premixed combustion stage. Moreover, the high altitude condition shortened the duration of combustion and reduced the energy release fraction in the diffusion phase. Furthermore, the late combustion phase occurred earlier and lasted longer at high altitude, which consequently reduced the combustion and thermal efficiency. The most important finding is that the engine performance, especially the combustion efficiency, shows an abrupt degradation with altitudes above 3000 meters. As a result, engines operating at extremely high altitudes require multi-stage turbocharging to compensate for combustion deterioration.

Key words: *Diesel engine, Plateau environment, Combustion process, Wiebe function, emission*

1. Introduction

For decades the diesel engine serves as the main power source of transportation including automobiles, trucks, marine and off-road power-generation [1]. The economy performance of diesel engine are primary concerns for consumers, while the emissions level is also considered as important factor because of stricter emission regulations [2]. Thus, the diesel engine is desired to operate with less fuel consumption rate and emissions at different regions, including plains, plateaus, mountains and hills, etc. Among the various terrains, the engine performance on plateaus is a noteworthy area of concern due to the vast area at high altitude and the significant deterioration in engine performance [3]. Plateaus, along with enclosed basins, cover about 45% of the Earth's land area and are widely distributed throughout the world [4]. These areas are densely populated, with unignorable vehicular traffic, making it crucial to focus on measures for energy conservation and emission reduction. The altitude of plateaus ranges from 1,000 to 5,000 meters, accompanied by a significant decrease in atmospheric pressure. As diesel engines draw in air only during the intake stroke, the lower ambient pressure directly reduces the volume efficiency [5]. Under low-temperature and low-pressure operating conditions, the amount of fuel/air mismatch would occur, leading to degraded engine performance. Therefore, it is essential to investigate the overall changes in diesel engine performance under deteriorated conditions, rather than optimal conditions, particularly with regard to intake temperature and pressure. However, the current situation is such that most diesel engines are designed to operate at altitudes below 3,000 meters [6]. High altitude application scenarios require diesel engines that can operate at 4,500 meters without unacceptable performance deterioration. Additionally, the performance degradation at elevated altitudes, as mentioned above, has been reported by many researchers. Several studies have investigated the impact of high altitude on diesel engine performance and reliability. Li et al. [7] observed severe piston wear in a diesel engine operating at plateau areas. Similarly, Gan et al. [8] reported various engine failures in highland diesel engines, including piston overheating, cylinder bore scratches, and small holes on the cylinder head. In terms of engine efficiency, both Zhang et al. [5] and Benjumea et al. [9] found that as altitude increases, thermal efficiency significantly decreases. Furthermore, Liu et al. [10] suggested that high altitude may increase heat losses, leading to a further increase in fuel consumption rates. These studies highlighted the importance of considering the impact of high altitude on diesel engine design and operation to ensure reliability and efficiency. Wang et al. [11] found dropped thermal efficiency with raising of altitude, especially at low speed and low load condition. The delayed ignition timing, lower specific heat ratio and deteriorate spray, enhanced heat transfer that caused by high altitude condition is considered as the reasons for brake thermal efficiency deterioration.

Previous research has shown that diesel engines experience power degradation and emission deterioration as altitude increases. However, previous studies have mainly focused on altitudes below 3000m, with limited research on higher altitudes. This is understandable because engine benches in the plains, when simulating high altitude environments, have lower intake pressures than ambient pressures, resulting in additional pressure differentials on the intake pipeline. To prevent damage to experimental equipment, simulated altitudes are limited. Thus, in most studies conducted on the plain, the altitude was limited to below 3000m. The novelty of this study was that the experimental setup was located at an altitude of 2,000 meters, enabling investigations at higher altitudes, up to 4,500 meters. In addition, the study employed the triple

Wiebe function to analyze the combustion process of diesel engines at different altitudes, providing a deeper understanding of the effect of altitude on combustion events, which is lacking in previous studies. Although CFD simulations can provide information on the physical and chemical fields in the cylinder, it cannot perform a segmental analysis of the combustion stages. Therefore, there is a lack of quantitative and detailed studies on the effect of altitude on the premixing and diffusion combustion stages of diesel engines at different altitudes. The findings of this study are expected to provide guidance for the design of diesel engines at high altitudes and help avoid possible problems with engine combustion at plateau.

2. Experiment apparatus

A 4-stroke direct injection (DI) compression ignition engine was utilized in the conducted experimental study. The experimental setup and schematic are presented in Figure 1. The engine was connected to a hydraulic dynamometer (Model SCHENCK D2600) to maintain a constant engine speed at different loads, with an error below 0.1%. The fuel injection timing and needle valve lift were measured using Hall-effect proximity sensors. The cylinder pressure was deemed to be the dominant indicator for inferring the combustion process in the cylinder, which was tracked by a piezoelectric pressure sensor with an accuracy of ±0.05%. Meanwhile, a high-frequency data acquisition system captured the cylinder pressure curve as well as the needle lift through a shaft encoder mounted on the crankshaft, from which data was recorded every 0.1 crank angle degrees. In each condition, the pressure data collected from hundreds of cycles were averaged to feed the analysis and Wiebe function modeling. The temperature of the intake, exhaust, coolant, oil, and others was measured using K-type thermocouples with an error of less than 2 K. The fuel consumption rate was recorded by a fuel consumption meter (Model AVL TGS1760, with $\leqslant$0.1% accuracy). The CO, NOx, and UHC emissions were measured by a Fourier-Transform InfraRed (FTIR) Model AVL FTIR i60 with an error of 1.2, 1.5, and 20 ppm for these emissions, respectively. Furthermore, an opacimeter model AVL SPC 439 was employed to measure the emitted soot concentrations.

As discussed in the previous section, atmospheric environments at different altitudes were simulated using the corresponding ambient pressures. To achieve the adjustable intake pressure, a plateau simulation system was installed to researched engine. Specifically, this system consisted of a centrifugal air unit, an inlet air regulating valve and an inlet air pressure stabilization tank. The ambient pressure at intake and exhaust ports was controlled through feedback regulation, which was capable to simulate altitude effects with an error of less than 1 kPa. The intake temperature was maintained constant in the present study, as it is widely agreed by previous research that the temperature has limited impacts on engine performance at altitudes below 4,500m. Zhang et al. [5], for instance, conducted investigations on engine performance at various altitudes by varying intake pressure while keeping the intake temperature constant. The engine speed was maintained at a constant value of 1,500 rpm, while the ambient pressure was varied from that of sea level up to an altitude of 4,500 meters, specifically 0, 1,500, 3,000, and 4,500 meters. In this altitude-simulation engine experiment, only changes in ambient pressure were considered, while all other environmental conditions were kept constant. This was done as the ambient pressure was considered the primary factor affecting engine performance at different altitudes. As the primary cause of engine performance degradation at different altitudes was the mismatch between fuel and air quantity, the fuel flow rate was kept constant at the level used at sea level, rather than adjusting it to an optimal level. Similarly, in this study, the start of injection (SOI) was kept constant. As the peak pressure location was almost identical for the same SOI, suggesting the negligible phasing lose. A comprehensive list of the detailed engine operating conditions is provided in Table 1.

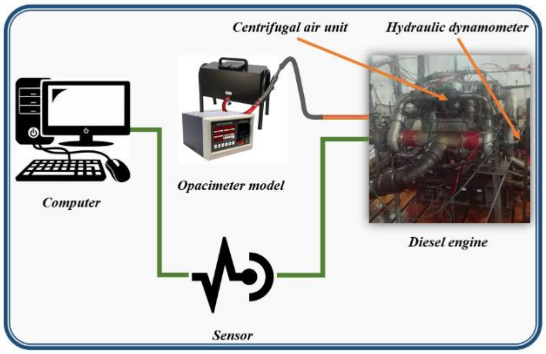

Figure 1. Experimental apparatus

Table 1. engine operating conditions

Altitude	0, 1,500, 3,000, 4,500 meters
Ambient pressure	1.01, 0.84, 0.67, 0.50 bar
Ambient temperature	298K
Boost pressure	1.0 bar
Injected fuel mass/cycle	270 mg
Engine speed	1500 rpm

3. Engine combustion modelling

The heat release rate (HRR) is considered as the key indicator for engine combustion analysis, because HRR curve directly reflects the in-cylinder combustion characteristics along with crank angle [12]. Typically, HRR can be calculated from pressure curve through single-zone zero-dimensional model [13] shown in Eq(1), which is deduced from the first law of thermodynamics.

$$\frac{\partial Q}{\partial \theta} = \left(\frac{k}{k-1}\right) P \frac{dV}{d\theta} + \left(\frac{1}{k-1}\right) V \frac{dP}{d\theta} \tag{1}$$

Where, $\partial Q/\partial \theta$ is the heat release rate, P is the cylinder pressure, V is the cylinder volume, k is the polytropic index, and θ is the crank angle degree. It is notable to point out that this single-zone 0D model assumes a closed homogenous system and an isentropic thermal path. In this way the apparent HRR can be inferred from cylinder pressure trace to further investigate the engine combustion.

A triple Wiebe function is utilized in this study to model the engine combustion at different altitude. Wiebe function combustion model is a zero-dimensional (0D) modeling approach based on the rules of chemical kinetics and chain reactions [14], which is recognized as a reliable combustion model to trace the engine in-cylinder heat release [15,16]. In this study, the combustion events were investigated using the triple Wiebe function. Diesel combustion is usually characterized by a premixed combustion event followed by a mixing-controlled combustion event, and the dual-Wiebe function is a good choice to describe it. The triple Wiebe function was used here due to the prominent role of late oxidation process at high altitude conditions, which may not be as prominent in the case of cleaner combustion. In other words, the combustion deterioration at high altitudes made it necessary to use another Wiebe function to describe the late oxidation stage. It is also important to mention that the triple Wiebe function modeling is also employed in commercial software GT-Power when describing diesel engine combustion [17]. Specifically, the combustion process in a compression ignition engine can be divided into three distinguishable stages: (1) the first phase is characterized by high but short HRR ; (2) the second phase refers to the duration around second, lower HRR peak; (3) the third phase refers to the long tail of the HRR curve. In other words, these phases correspond to premixed, diffusion and tail combustion (i.e. late oxidation process), respectively. For high-altitude diesel engines, a longer ignition delay, indicating a higher HRR peak value at first phase has been reported by Ref [9,12]. Meanwhile, the late combustion process in the third stage of a plateau diesel engine cannot be neglected. Again, this is the reason why the triple Wiebe function was adopted in this study to capture the combustion characteristics of a highland diesel engine. The mathematical expression of the triple-Wiebe function is shown in Eq(2) and Eq(3).

$$x_{ER}(\theta) = \sum_{i=1}^{3} \lambda_i \left\{1 - exp\left[-a_i \left(\frac{\theta - \theta_i}{\Delta\theta_i}\right)^{m_i+1}\right]\right\} \tag{2}$$

$$\sum_{i=1}^{3} \lambda_i = 1 \tag{3}$$

Where, $x_{ER}(\theta)$ is the energy release (ER) fraction at specific crank angle θ. λ_i is the total energy released fraction at various phases ($i = 1, 2, or\ 3$). m_i and a_i are the form factor and efficiency parameter, which determine the shape of the energy release curve and the combustion duration for each stage. θ_i and $\Delta\theta_i$ are the start angle and the duration of the corresponding combustion stage. In addition, the start of premixed combustion (θ_1) is advanced compared to θ_2 and θ_3.

It can be inferred from the equation presented that the energy release fraction is controlled by both parameters a_i and $\Delta\theta_i$. When a specific value of a_i is given, theta refers to the duration during which a_i corresponding percentage of energy is released. In other words, they can be combining a_i and $\Delta\theta_i$ and into one factor α_i [14], as seen in Eq. (4).

$$x_i(\theta) = \lambda\left\{1 - \exp\left[-\left(\frac{\theta-\theta_0}{\alpha_i}\right)^{m_1+1}\right]\right\} \tag{4}$$

where α_i is the combined factor that determines the combustion duration. This implies that different combinations of the two parameters can result in the same energy release profile. To determine the combination of a_i and $\Delta\theta_i$, it is recommended to assume the a_i value to be constant, corresponding to an energy release fraction of 95%. Otherwise when the a_i is changed, the definition of $\Delta\theta_i$ would also change, leading to unmatched parameter combination. Consequently, the corresponding a_i value can be determined using Eq. (5, 6).

$$95\% = 1 - exp(-a_i) \tag{5}$$

$$a_i = -\ln(1 - 0.95) \approx 3 \tag{6}$$

During the calibration of the model parameters, the value of m_i was adjusted to match the experimental data. Typically, the value of m_i for each combustion phase remains constant regardless of altitude. These parameters were obtained through a fitting method. The calibration is based on the comparison between the mass fraction burned (MFB) curves predicted by model and that of experimental data. The HRR predicted by the Wiebe function is the derivative of the cumulative energy release per crank angle, as shown in Eq(7).

$$\frac{dQ_n}{d\theta} = \frac{dx_{ER}(\theta)}{d\theta} \cdot m_{fuel} \cdot LHV_{fuel} \cdot \eta_{comb} \tag{7}$$

Where, $dQ_n/d\theta$ is the apparent HRR, m_{fuel} is the injected fuel mass per cycle, LHV_{fuel} is the lower heating value of diesel. In addition, η_{comb} is the combustion efficiency, which can be calculated from the incomplete combustion emission concentrations.

From the Wiebe function model prediction result, i.e., apparent heat release rate, cylinder pressure can be inferred by the single-zone heat release model mentioned above, shown in Eq(8)

$$\frac{dP}{d\theta} = \frac{\gamma - 1}{V} \cdot \frac{dQ_n}{d\theta} - \gamma \cdot \frac{P}{V} \cdot \frac{dV}{d\theta} \tag{8}$$

Where γ is the heat capacity ratio.

4. Results and discussion

This section aims to investigate the performance of the engine in terms of power, economy, and emissions, using the analysis of IMEP, ISFC, and emissions of CO, NOx, UHC, and soot. Furthermore, the study employs the single zone 0D heat release model and triple Wiebe function to reveal the engine in-cylinder combustion characteristics at different altitudes, including cylinder pressure, HRR, and combustion phases.

Typically, engine power output is a critical specification of interest to both manufacturers and consumers. Therefore, this section initially focuses on the power loss of the diesel engine at high altitudes. The indicated mean effective pressure (IMEP) and indicative specific fuel consumption (ISFC) are displayed in Figure 2 to assess the power performance. IMEP is a widely used metric in internal combustion engine research to measure the efficient work output capacity, regardless of engine displacement. As shown in Figure 2, the trend of decreasing IMEP with higher altitude is evident. To be precise, when the altitude is below 3000m, every increase in elevation of 1,500m results in a power loss of approximately 6.34%. This finding is consistent with other studies that have reported a power degradation of about 3.6% per 1000 meters elevation [18]. However, it is noteworthy that a significant decline in IMEP is observed when the altitude exceeds 3,000m, which exhibits a distinct trend compared to the range of 0-3,000m altitude. Indicative specific fuel consumption (ISFC), defined as the mass of fuel burned per kWh indicated work, are plotted in figure 2 to evaluate the effect of altitude on engine economy performance. Figure 2 displays an upward trend in ISFC with increasing altitude, with a sharp rise observed at an altitude of 4,500m. This trend is in opposite to that of IMEP, which would be expected to decrease in the presence of incomplete combustion and a deficient air charge. It is reasonable to anticipate an increase in specific consumption under these conditions, assuming the same fuel/cycle is being applied. Since the ISFC is determined by in-cylinder combustion analysis, it can be inferred from this tendency that the higher elevation reduces the combustion and thermal efficiency, which will be discussed in detail below.

Apart from engine power output, emissions levels are also a significant concern when diesel engines operate due to increasingly stringent regulations. Therefore, Figures 3 and 4 depict the emitted indicated specific CO, UHC, NOx, and soot at various altitudes to assess the variation in their respective emission levels. As depicted in Figure 3, the concentration of CO emitted from the engine increased sharply when the altitude exceeded 3,000m. Moreover, the steep increase in UHC and soot emissions indicated an almost-failure of the incomplete combustion production oxidation process when the altitude further reached 4,500m. This signifies an aggravation of incomplete combustion. At high altitudes, reduced ambient pressure leads to lower air excess coefficients, which may exacerbate the level of incomplete combustion. This can explain the increment of CO and UHC, as also reported by previous studies [19,20]. Further investigations on combustion efficiency will assist in confirming this explanation.

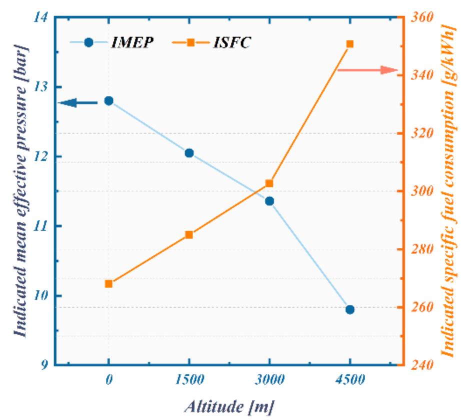

Figure 2. Effect of altitude on IMEP and indicated specific fuel consumption

In Figure 4, the indicated specific NOx is plotted at various altitudes, exhibiting a continually decreasing trend. Based on the thermal NOx production theory [21], the NOx formation process favors high temperature, oxygen enrichment, and adequate reaction time. A plausible explanation for the observed trend is that higher altitudes tend to reduce the excessive air coefficient and degrade the combustion. In other words, the oxygen concentration is leaner, and the burnt gas temperature is lower, which suppresses NOx formation.

It is also crucial to evaluate the indicated specific soot emission of diesel engines at plateaus. Figure 4 illustrates a continually increasing trend in soot emissions with higher altitude.

Since soot formation favors a fuel-rich environment, the higher equivalence ratio caused by high elevation is likely the primary reason for the increment in soot emissions. Generally, soot is partly oxidized in the expansion stroke. However, the low amount of oxygen inhaled at lower atmospheric pressure tends to hinder the further oxidation of soot, exacerbating the already high levels of soot emissions. Also the soot at altitude above 3,000m shows rapid raising tendency.

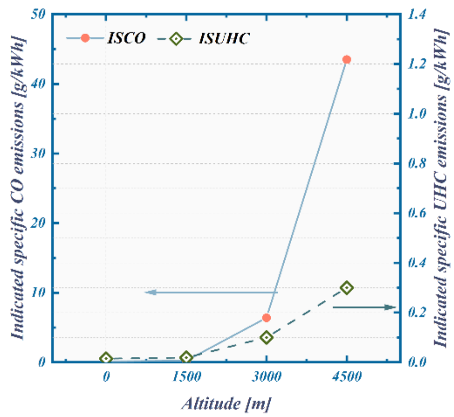

Figure 3. Effect of altitude on indicated specific CO and UHC

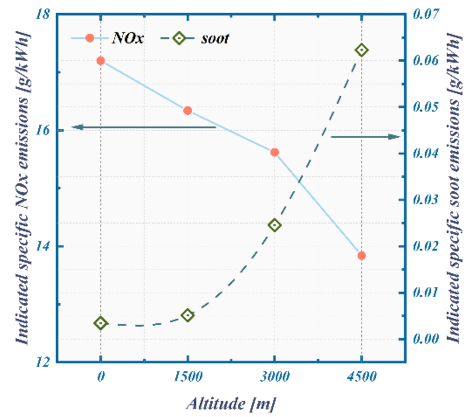

Figure 4. Effect of altitude on indicated specific NOx and soot

After analyzing the engine's output power, fuel consumption rate, and various harmful emissions at different altitudes, the next step is to focus on the engine's in-cylinder combustion characteristics at each stage. The discussion regarding the engine's combustion characteristics is based on the results obtained using the single-zone 0D heat release model and triple Wiebe function. The parameters of Wiebe function is obtained by fitting method.

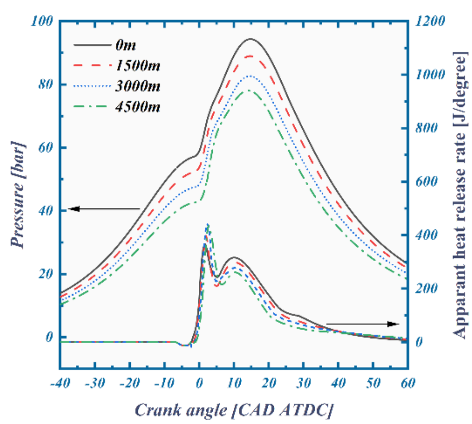

Figure 5. Effect of altitude on cylinder pressure and apparent heat release rate

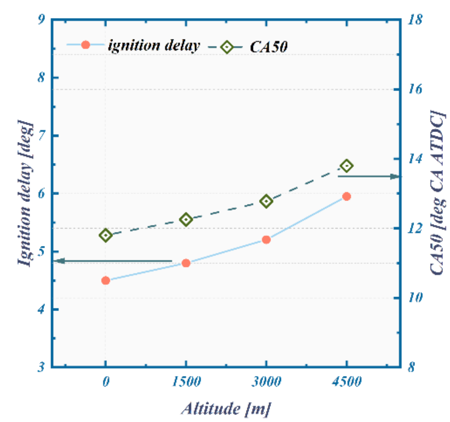

Figure 6. Effect of altitude on ignition delay and CA50

The cylinder pressure and corresponding apparent heat release rate (AHRR) are essential indicators for investigating the engine combustion process. As depicted in Figure 5, the different intake pressure at various altitudes has maintained the magnitude relationship for all the processes from intake valve close to exhaust valve open, as expected according to classical thermal theory. The impact of higher altitudes on the engine combustion process is significant, as it leads to lower peak pressure and a delayed location, which are detrimental to thermal efficiency [22], when compared to sea level. Even with a high-pressure rise rate, the gap cannot be bridged. The heat release rates shown in Figure 5 indicate that higher altitude operation delays the start of combustion, resulting in a larger maximum heat release rate, which signifies a rougher combustion process. Furthermore, increasing altitude also increases the proportion of premixed combustion and reduces the proportion of mixture-controlled combustion, as evidenced by the smaller peak heat release rate during diffusion combustion. These results highlight the complex nature of the combustion process in diesel engines operating at high altitudes and demonstrate the importance of accurately characterizing the combustion behavior for optimizing engine performance in such conditions.

Figure 6 presents the altitude effects on engine phasing, as calculated from the heat release curve. The figure shows that operating at higher altitudes prolonged the ignition delay. The ignition delay is determined by the difference between injection timing and start of combustion. To investigate the reason for extension of ignition delay at high altitude, the in-cylinder temperature and pressure at injection timing is calculated. Assuming that the compression process is a polytropic process, thermodynamic theory can be used to calculate the cylinder temperature and pressure at the time of fuel injection. For altitudes ranging from 0-4,500m, the pressures are calculated to be 53, 48, 44, and 39 bar respectively, with a corresponding temperature of 669, 700, 732 and 763K. This finding provides an explanation for the longer ignition delay and rougher premixed combustion observed at high altitudes. Specifically, the pressure reduction that occurs at higher altitudes was found to increase the ignition delay, whereas the temperature increase could potentially shorten the ignition delay. In the conditions investigated in this study, it was found that the effect of pressure decrease dominated in the elevated altitude condition, resulting in a longer ignition delay [10]. A short delay is typically necessary to keep the maximum cylinder gas pressure below the engine’s maximum tolerable limit. Therefore, when operating in plateau areas, mechanical failures of engine heads and pistons may occur [23]. The combustion phasing information presented in Figure 6 demonstrated a slight lag in the CA50 values during higher altitude operations, indicating a delay in the combustion event. This delay led to the combustion event occurring under less optimal conditions, which ultimately contributed to combustion degradation at altitude. These findings provide valuable insights for improving engine performance and efficiency under high altitude conditions.

Therefore the effect of altitude at each combustion stage will be analyzed respectively with triple Wiebe function. The start of combustion (SOC) for the premixed combustion phase is defined as the crank angle at which the apparent heat release rate first exceeds zero after fuel evaporation. The SOC for second and third combustion phases were determined by fitting approach. Assessing the prediction accuracy of the calibrated triple Wiebe function is crucial to validate the results obtained in this study. Figure 7 depicts the comparison between the predicted and measured cylinder energy release fraction and apparent heat release rate. The energy release fraction trace predicted by the Wiebe function agrees well with the experimental data at each altitude. Although slight differences are observed, the Wiebe function accurately captures the overall energy release fraction trace. As shown in Figure 7(b), the apparent HRR provided by the Wiebe function also agrees well with the experimental results. Although the peak of the first stage predicted with the Wiebe function is lower than the experimental value, this is understandable because spontaneous combustion dominates the premixed combustion stage, leading to an extremely rapid increase in HRR, which is challenging to model with the Wiebe function. In summary, the triple Wiebe function successfully captures the primary features of the apparent HRR curves at different altitudes, particularly the start of combustion. The comparison between the predicted and measured energy release fraction and apparent heat release rate confirms the accuracy of the triple Wiebe function in investigating the combustion characteristics at each phase. Therefore, the triple Wiebe function is a reliable tool for analyzing and predicting the combustion behavior of diesel engines under deteriorated conditions. The detailed parameters used in triple Wiebe function is shown in Table 2.

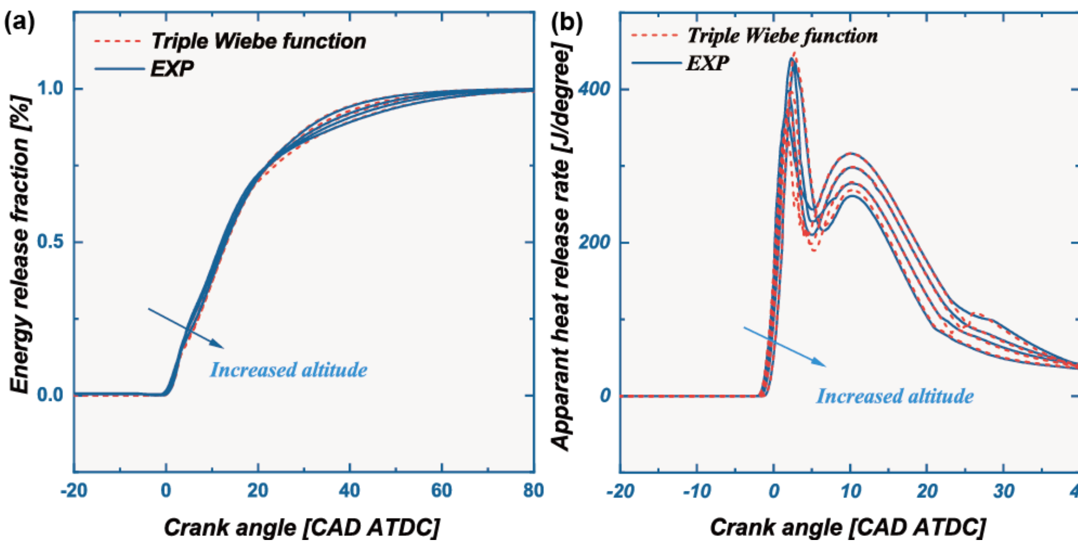

Figure 7. Comparison of energy release fraction (a) and apparent heat release rete (b) predicted by Wiebe function and measured from experiment at different altitude (MFB)

Table 2. Triple Wiebe function parameters

Altitude [m]	0	1500	3000	4500
	0.14	0.17	0.20	0.25
λ	0.74	0.68	0.62	0.53
	0.12	0.15	0.18	0.22
	-2.1	-1.95	-1.70	-1.30
θ	2.8	3.53	4.05	4.82
	25.7	25.0	23.40	22.01
	5.8	6.16	6.3	6.7
$\Delta\theta$	26.88	24.93	22.9	20.26
	38.22	42.06	46.46	53.21
a	3	3	3	3
	3	3	3	3

	3	3	3	3
	2.4	2.4	2.4	2.4
m	0.6	0.6	0.6	0.6
	0.3	0.3	0.3	0.3

Figure 8 depicts the respective apparent HRR and energy release fraction of each combustion phases, which is determined by the corresponding Wiebe function. The duration of combustion (DOC) for each combustion stage is also shown in Figure 9, and the value is shown as a relative ratio to sea level for display convenience. In Figure 8(a, b), the impact of altitude on the premixed combustion phase, as predicted by the Wiebe function model, is presented. As shown in Figure 8(a), the premixed phase demonstrates a rapid and narrow bulge shape caused by auto-ignition of fuel-gas mixture. As the altitude increases, the ignition time is delayed and the HRR is higher, the prolonged ignition delay at high altitude caused more fuel fraction to be burned at this stage, as evidenced by the larger energy release fraction shown in Figure 8(b). A possible explanation is that the lower ambient pressure on the plateau results in lower cylinder pressure during injection, which inhibits auto-ignition of the injected fuel. Additionally, Figure 8(a) demonstrates that the peak heat release rate also increased with altitude, resulting in a larger value for the pressure rise rate and adversely affecting the health of engine components. Such a trend could help explain the failure of the engine head and piston at 4,500 meters reported in Ref.[4], considering that the rate of pressure rise increased sharply with altitude above 3,000 m. Regardless of the various shapes of the AHRR, it can be concluded from Figure 9 that the combustion duration is observed to increase with increasing altitude, which is likely due to the requirement of more fuel to be burned during this stage. Overall, these findings suggest that the effect of high altitude on the premixed combustion phase is negative.

Typically, the diffusion combustion phase dominates the diesel engine combustion, characterized by the second and lower HRR peak. This phase involves various processes, including atomization of liquid fuel, vaporization, mixing of fuel vapor with air, and pre-flame chemical reactions. The rate of combustion during this stage is primarily controlled by the mixing process of fuel vapor with air. The effect of altitude on the diffusion combustion phase is displayed in Figure 8(c, d). Similarly, the diffusion combustion phase is also retarded at higher elevations, but the end of the phase remains approximately constant, possibly limited by spray penetration. This phenomenon is also reflected in Figure 9, where the DOC of diffusion combustion shortens with increasing altitude. In addition, the HRR values and energy release fractions exhibit a decreasing trend with altitude, in contrast to the case of premixed combustion. Considering the competition for burnt fuel in both phases, more fuel consumption in the first phase weakens the energy release from diffusion combustion. Hence, the plateau operating condition can deteriorate the diffusion combustion process.

In Figure 8(e, f), the impact of altitude on the AHRR and energy release fraction of the late combustion phase, estimated by the Wiebe function, is presented. This phase is characterized by the slow oxidization of residual fuel and incompletely combusted products, including CO, UHC, and soot. The late combustion phase in diesel engines is known for continuing heat release at a lower rate into the expansion stroke, owing to various factors such as incomplete combustion, presence of soot and fuel-rich combustion products, mixing for complete combustion, and slower kinetics of the final burnout process. However, late combustion is not desirable, as it adversely affects combustion efficiency and increases emissions. The results presented in Figure 8(e, f) indicate that the increase in altitude has a negative impact on the late combustion phase, leading to an increase in energy release and a decrease in combustion efficiency.

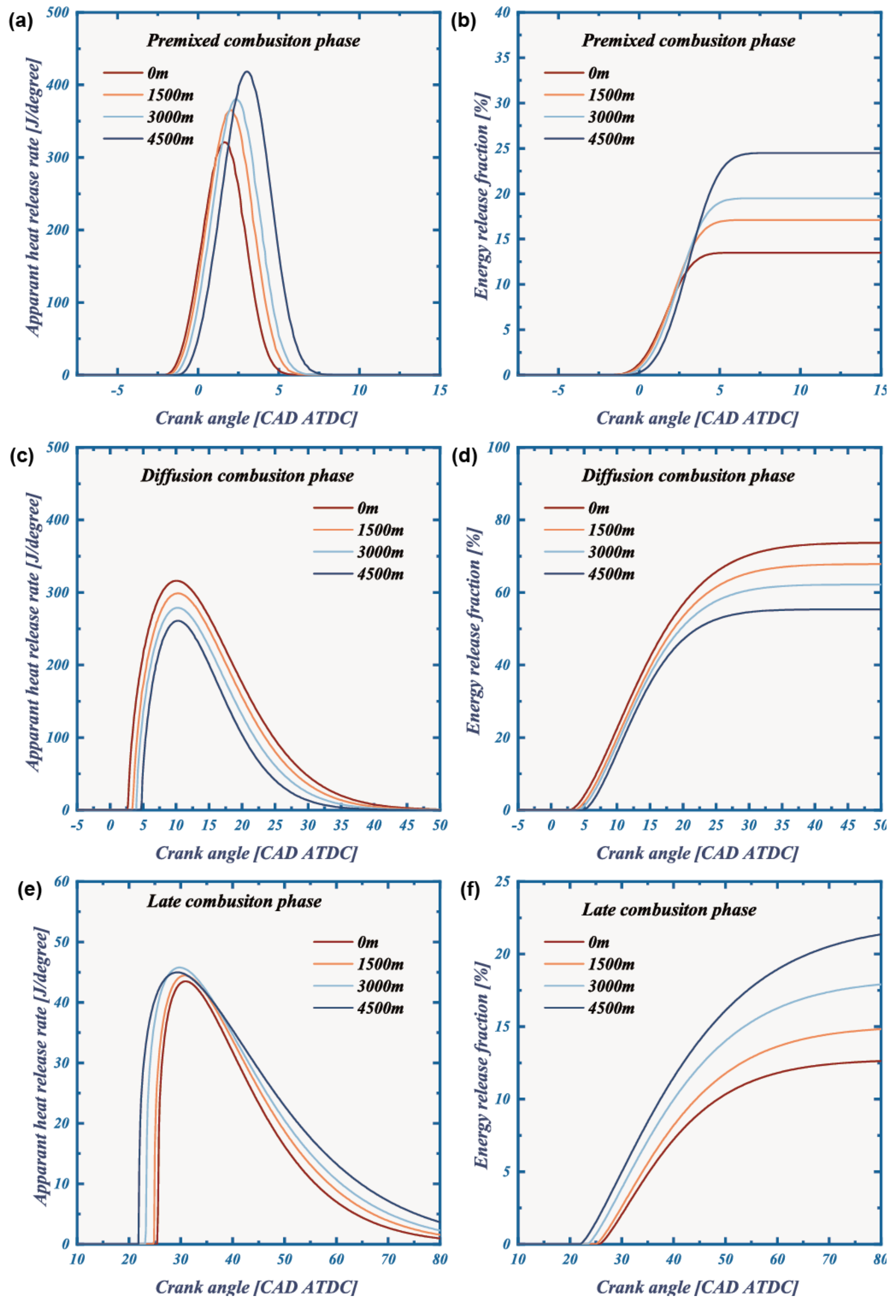

Figure 8. Apparent heat release rate (a, c, e) and energy release fraction (b, d, f) at different combustion phases and different altitude

It is noteworthy that the magnitude of the HRR of late oxidation at an altitude of 4,500 m is not significantly increased. This observation suggests that the later oxidation process at altitudes above 3,000 m is also degraded. This degradation may explain the sharp increase in CO and soot emissions, as presented in Figure 3 and Figure 4. Additionally, Figure 9 illustrates that the combustion duration at high altitudes is prolonged due to an earlier combustion initiation angle and a delayed combustion end angle, leading to a further reduction in combustion efficiency and an increase in incomplete combustion levels. The prolongation of the late oxidation process under such unfavorable conditions exacerbates incomplete combustion levels. Overall, these findings suggest that the impact of high altitude on the late combustion phase is detrimental to the combustion efficiency of diesel engines. In summary, the analysis based on the Wiebe function model showed that operating at higher altitudes prolonged the ignition delay, delayed the end of combustion, and extended the combustion time of the diesel cycle. The increased altitude also raised the heat release rate during the premixed combustion phase, reduced the fuel fraction burned during the main mixing-controlled combustion phase, and led to more intense late combustion, all of which negatively affected combustion efficiency.

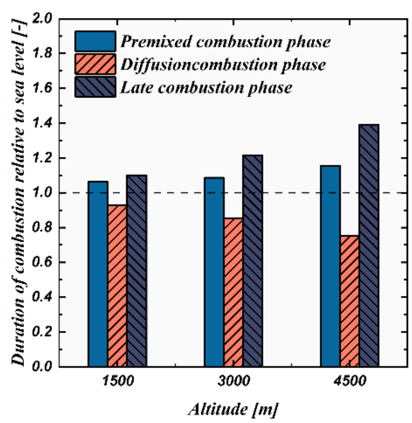

Figure 9. Duration of combustion of premixed, diffusion and late combustion relative to sea level at different altitude

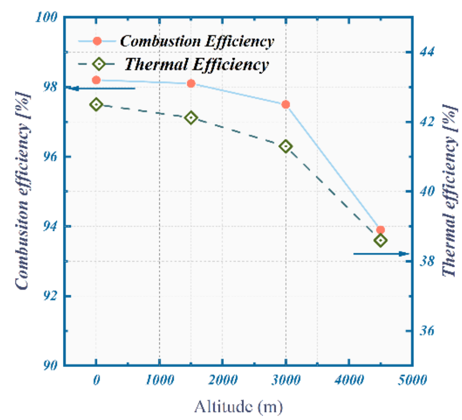

Figure 10. Effect of altitude on combustion efficiency and thermal efficiency

Figure 10 presents a comparison of thermal and combustion efficiency at different elevations. The combustion efficiency is calculated as the ratio of chemical heat released to the total injected fuel chemical energy. As depicted in Figure 10, the combustion efficiency decreased as the altitude increased, which is consistent with the observed increase in incomplete combustion products such as CO and UHC. This trend could be attributed to the intensified premixed combustion, worsened diffusion phase, and deteriorated tail combustion. In addition to combustion efficiency, thermal efficiency, which represents the ratio of chemical energy conversion to mechanical energy of the fuel, is also of interest to consumers. Figure 10 shows a decreasing trend of thermal efficiency with increasing altitude, which could be explained by the combustion phases discussed above. Typically, a CA50 between 5 and 11 CAD ATDC, as well as a narrower DOC, are favorable for obtaining maximum thermal efficiency. Thus, a delayed combustion phase and a longer DOC are responsible for the deterioration of thermal efficiency.

5. Summary and Conclusions

This study investigated the effect of altitude on engine combustion, power output performance and emission levels through the analysis of experimental data of an altitude simulated diesel engine. The experiments were operated at different ambient pressure corresponding to different altitude, but constant engine speed and fuel injection strategy. Furthermore, the single-zone 0D heat release model together with a triple Wiebe function was applied to investigate the in-cylinder combustion characteristics. The results showed that the increase in altitude during diesel engine operation can lead to various negative effects on the combustion process. One significant effect is the delay in the start of premixed combustion due to the reduction in cylinder pressure caused by the lower ambient pressure. This reduction resulted in a longer ignition delay. Additionally, the increase in altitude caused more fuel to be burned in a shorter time, increasing the heat release rate during the premixed combustion phase and elevating the risk of engine component failure. The end of the premixed flame was also delayed due to the high altitude, resulting in a longer duration for this phase. The quality of mixing-controlled combustion was degraded at higher altitudes, with the beginning of combustion being delayed but completion being advanced. Furthermore, the altitude increase resulted in a decrease in the amount of diesel fuel burned during the diffusion combustion phase, leading to a lower heat release rate. Late combustion was also more significant at higher altitudes, with a longer heat release tail indicating that late oxidation was not fully completed before the reactions frozen. As a result, the combustion efficiency was reduced. When the altitude exceeded 3,000 m, the engine emissions degraded sharply. This steep deterioration was caused by a dramatic decline in combustion efficiency. The increased elevation resulted in enhanced penetration of the fuel injection spray. In addition, high altitude conditions reduced the spatial distribution of spray, exaggerated soot formation, and reduced soot oxidation capacity due to restricted air entrainment. To make matters worse, engine operation at high altitudes contributed to the formation of fuel-rich mixtures in smaller areas of the combustion chamber, which reduced air utilization and thus led to degradation of combustion. In other words, fuel–air mismatch due to high altitude environment was the root cause of engine performance degradation. These insights can serve as a guide for future research and development efforts aimed at improving the performance and efficiency of diesel engines at high altitudes.

6. Nomenclature

UHC	unburnt hydrocarbon	NOx	nitrogen oxides
ISFC	indicated specfic fuel consumption	HRR	heat release rate
IMEP	indicated mean effective pressure	CAD	crankangle degree
CFD	computational fluid dynamics	DOC	duration of combustion

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