

Sensitivity Analysis and Modeling Research on Combustion Characteristic Parameters of Diesel LTC

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Abstract. In this paper, first, based on the principle of sensitivity analysis, the key combustion control parameters that influence the combustion characteristics index indicated mean effective pressure (IMEP) and crank angle of 50% heat release (CA50) of diesel low temperature combustion (LTC) are determined by experimental study, which lays a foundation for simplifying the combustion control of diesel LTC. Then, the regulation law of the key combustion control parameters and the influence of that on the combustion characteristics IMEP and CA50 are further analyzed by using the experimental data. Finally, based on the above analysis, the physically-based control-oriented IMEP and CA50 model are developed. The model is validated by using the transient diesel experimental data and the validation result shows that the model can predict not only the dynamic characteristics but also the IMEP and CA50 of diesel engine under LTC conditions, accurately.

Introduction

Reducing emissions is the development trend of internal combustion engines [1]. Therefore, diesel engine LTC technology came into being, and has become a focus direction for diesel engine combustion theory and technology research. [2]. The combustion timing and combustion rate of diesel LTC are difficult to be controlled compared to conventional gasoline and diesel engine, since there is no direct initiator of combustion in diesel LTC [3]. In addition, due to dominated by chemical kinetics, the composition, the intake air temperature and pressure, as well as physicochemical properties of the fuel all affect the diesel LTC., which makes the combustion stability control of diesel LTC more difficult.

All these problems are the bottlenecks that limit the application of diesel LTC in engineering. In order to solve the problem of diesel LTC, internal combustion engine researchers have done a lot of works. The combustion stability of the diesel engine is improved by fixing the CA50 in a narrow crank angle window, through fast, closed-loop feedback control of the combustion process [4]. The combustion efficiency of diesel LTC is improved by the tightened control of the intake oxygen concentration [5]. The combustion mode switching is fast and smooth by using the coordinated control strategy of air and fuel [6]. Most of the methods used in the above researches are the PID closed-loop feedback control. However, PID control has some inherent problems, such as response lag, difficulties of parameter segmentation and so on. Model-based control is another option for diesel LTC control. For model based control of diesel LTC, accurate control oriented model is a necessity.

In this paper, in order to construct a control-oriented combustion model for diesel LTC control, firstly, based on the theory of sensitivity analysis, the key combustion control parameters that influence the combustion characteristics index IMEP and CA50 of diesel LTC were selected by experimental study. Then, the effect of control input (fuel rate, exhaust gas recirculation (EGR) valve opening and variable geometry turbocharger (VGT) nozzle position) on the key combustion control parameters and the combustion characteristics CA50 and IMEP are analyzed. Based on the analysis of the influence, a control-oriented model of IMEP and CA50 of diesel LTC is developed. After then the model was validated by transient experimental data.

Experimental Engine Setup

The test based on a turbocharged diesel engine, which type is four-cylinder common-rail. This engine has a hot high pressure EGR system. To better meet test needs, an EGR intercooler is added in front of EGR valve, further, the turbocharger was replaced by VGT.

Table 1. Experimental engine specifications

Engine type	VMR 425DOHC
Bore × stroke	92 mm × 94 mm
Displacement volume	2.499 L
Compression ratio	17.5:1

Fig.1 showsthe experimental setup. The EGR rate, which is determined by O₂.

$$\% EGR_V = \frac{O_{2air} - O_{2int}}{O_{2air} - O_{2exh}} \times 100 \quad (1)$$

Formula (1) is an expression of EGR rate. Where, O_{2air} ; O_{2int} and O_{2exh} are the oxygen concentrations of air, intake and exhaust.

Sensitivity Analysis

In this paper, based on the principle of sensitivity analysis[7], the key combustion control parameters that affect the combustion of diesel LTC were determined by experimental study, which lays a foundation for simplifying the combustion control of diesel LTC.

In this paper, the single factor analysis method was used. The influence of individual combustion control parameters on diesel LTC is studied by adjusting the individual combustion control parameters while ensuring the other combustion control parameters are constant at a certain operating condition. The sensitivity coefficient can be calculated by the following equation:

$$S(a_i) = \frac{|\Delta Y_i|/Y_i}{|\Delta a_i|/a_i} \quad (2)$$

Where, $a_i(i=1,2,\dots,n)$ are the influence parameter, respectively; Δa_i is variation of each influence parameter; Y_i is the reference value of the performance index; ΔY_i is the change of the performance index.

For diesel LTC control, the combustion phase characterization parameter CA50 control and the load characterization parameters IMEP control are the focus and difficulty of the diesel LTC control. During the process of combustion, CA50 and IMEP will change with the change of the intake parameters and fuel injection parameters, and different parameters have different effect on CA50 and IMEP. In order to compare the effects of different combustion control parameters on CA50 and IMEP, the sensitivity coefficients of each parameter need to be calculated. Therefore, the values of CA50 and IMEP are selected as the combustion performance index Y of diesel LTC, and the intake parameters (intake oxygen concentration F_{Oim} , intake pressure P_{im} and intake temperature T_{im}) and fuel injection parameters(injection pressure P_{inj} and injection timing t_{inj}) are selected as influence parameters $a_i(i=1,2,3,4,5)$

In the single factor sensitivity analysis, the number of values for each parameter is called the number of levels of the parameter. In this paper, the five levels of sensitivity analysis of performance characters of diesel LTC are selected for each influence parameter, that is, the deviation of each influence parameter relative to the reference value is -10%, -5%, 0, 5%, 10%. The reference value and the setting values for each parameter are shown in Table 2.

Table 2. Setting values of each combustion control parameters of diesel LTC

	-10%	-5%	0	5%	10%
Intake oxygen concentration $F_{Oim}(\%)$	17.1	18.05	19	19.95	20.9
Intake pressure $P_{im}(\text{bar})$	1.08	1.14	1.2	1.26	1.32
Intake temperature $T_{im}(\text{°C})$	45	47.5	50	52.5	55
Injection pressure $P_{inj}(\text{MPa})$	90	95	100	105	110
Injection timing $t_{inj}(\text{°CA ATDC})$	-9	-9.5	-10	-10.5	-11

Fig 2 show the sensitivity analysis results of combustion characteristic parameter CA50 and IMEP of diesel LTC to each combustion control parameters, respectively. It can be seen that the influence degree of combustion control parameters on diesel LTC combustion characteristic parameter CA50 is sorted as: $t_{inj} > F_{Oim} > P_{im} > P_{inj} > T_{im}$. Injection timing is the most direct control parameter for CA50. Related studies have shown that, CA50 can be kept in an appropriate phase by selecting the appropriate injection timing, which is important for improving the combustion efficiency and combustion stability of diesel LTC [5]. The influence of intake oxygen concentration on CA50 is second only to the injection timing. The intake oxygen concentration changes the combustion timing by changing the length of the delay period, and further affects the combustion phase CA50. The influence degree of combustion control parameters on diesel LTC combustion characteristic parameter IMEP is sorted as: $F_{Oim} > P_{im} > t_{inj} > T_{im} > P_{inj}$. The intake oxygen concentration and intake pressure are two main control parameters that affect IMEP, which is mainly due to the load of diesel LTC is determined by the amount of fuel and gas into the cylinder. The sensitivity analysis shows that the intake temperature and injection pressure have less impacts on CA50 and IMEP. In order to simplify the control strategy, these two combustion control parameters can be neglected while developing the control-oriented model of CA50 and IMEP.

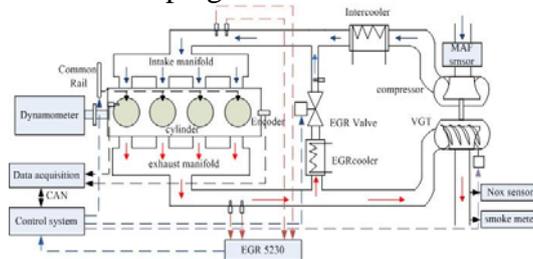


Figure 1. Four-cylinder VM common-rail testbench schematic

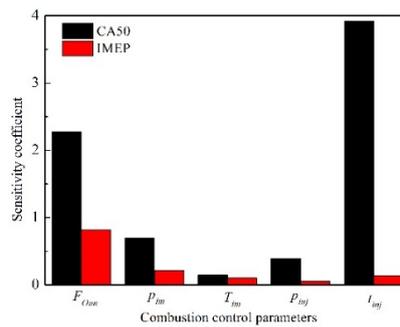


Figure 2. Sensitivity analysis of CA50 and IMEP to control parameters

Regulation Analysis of Combustion Control Parameters

Through the above sensitivity analysis, the intake oxygen concentration, intake pressure and injection timing have great influence on CA50 and IMEP. They are regarded as the key state variables for regulating the combustion phase and load of diesel LTC. Which are also affected by the various input variables (EGR opening, VGT opening, fuel rate) and engine speed during the operation of diesel LTC. Based on experimental data, the regulation and coupling rules of these key state variables are analyzed in this section, and the influence of these rules on the combustion characteristic CA50 and IMEP of diesel LTC are further studied, which lays a foundation for the

construction of control-oriented model of CA50 and IMEP.

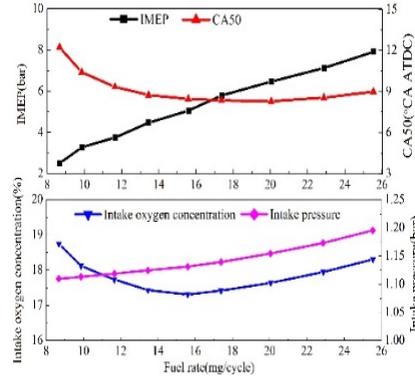


Figure 3. The effect of fuel rate on the state variable and combustion characteristic parameters

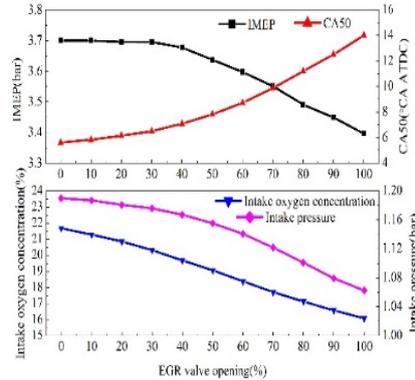


Figure 4. The effect of EGR valve opening on the state variable and combustion characteristic parameters

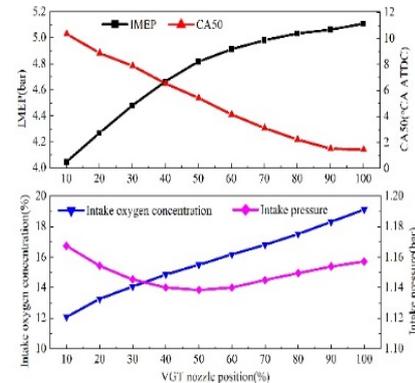


Figure 5. Effects of VGT opening on the state variable and combustion characteristic parameters

The effect of fuel rate can be seen in Fig. 3 with the fuel rate increases from 8.2 mg/cycle to 25.8 mg/cycle, 1500r/min, EGR valve closed, 70% VGT opening. It can be seen from the figure that the intake oxygen concentration of the diesel decreases presents a similar variation of the inverted parabola with the increase of fuel rate. In contrast, the intake pressure increases gently with the increase of fuel rate. With the combined effects of the intake oxygen concentration and the intake pressure, the combustion controlled output CA50 of diesel LTC presents a similar variation of the inverted parabola while the controlled output IMEP shows an approximately linear increase with the increase of fuel rate. Which indicated that the regulation ability of the fuel rate to IMEP is strong, and the fuel rate can be used as the main control input parameter of IMEP.

Fig. 4 shows that the variation of the key state parameters and the combustion controlled output CA50 and IMEP with the EGR valve form closed to fully open, at 1500r/min engine speed, 30% load, the fuel rate remains constant, 60% VGT opening. as the EGR valve opening's increase, the intake oxygen concentration and intake pressure decrease simultaneously. With the combined effects of intake oxygen concentration and intake pressure, the IMEP decreases slowly while the CA50 postponed gradually. In addition, the effect of EGR valve opening on intake oxygen

concentration, intake pressure, CA50 presents highly linear. That indicates that the EGR valve opening can be used as the main control input parameter for CA50.

Fig. 5 indicates the variation of the key state parameters and the combustion controlled output CA50 and IMEP with the VGT opening from 10% to 100%, 1500r/min engine speed, fixed fuel rate and EGR valve opening. As the VGT opening decreases gradually, the intake oxygen concentration has the same trend. The reason is that the increase of the pressure difference between the pressure before the turbine and the pressure after the compressor with the decrease of the VGT opening. The intake pressure shows a variation of decrease first followed by a slow increase. The trajectory is similarly as parabola, which is mainly due to the coupling effect of the EGR and VGT. With the decrease of VGT opening, the IMEP decreases gradually while the CA50 is far away from the TDC. The VGT opening has a highly linear effect on CA50, which suggests that the VGT opening can be used as the another control input variable for CA50.

Control-oriented Modeling and Validation of CA50 and IMEP

Based on the above analysis, the key combustion control parameters of diesel LTC and the regulation rules of these control parameters are determined, which lays the foundation for the control-oriented modeling of combustion phase and load. In this section, model of the combustion characteristic parameters CA50 and IMEP are developed and validated. Using oxygen fuel ratio in-cylinder $F_{O_{cyl}}$ substitute the fuel equivalence ratio.

$$SOC = \theta_{ivc} + a_1 N_e F_{O_{cyl}}^{a_2} X_{egr}^{a_3} \exp\left(\frac{-E_a}{RT_{mix}}\right) \quad (3)$$

Formula (4) is an expression of diesel LTC start crank angle of combustion (SOC)'s combustion starting point. Where, θ_{ivc} is the crank angle at intake valve close (IVC) moment, θ_{soc} is the crank angle at SOC moment, N_e is the engine speed, $F_{O_{cyl}}$ is the oxygen fuel ratio in-cylinder, X_{egr} is the EGR rate in cylinder, E_a is the fuel activation energy, R is the gas constant of mixture in cylinder, T_{mix} is the temperature of mixture in cylinder, a_1 , a_2 and a_3 are the tuning parameters. The tuning parameters a_i are determined by solving a linear least-squares problem that minimizes $(SOC - SOC_{meas})^2$ with the tuning parameters as the optimization variables.

According to the above analysis, it shows that the intake oxygen concentration and intake pressure are key control parameters of CA50. Therefore, the correction of the intake oxygen concentration and intake pressure are added, CA50 can be calculated by the following fitted correlation:

$$CA_{50} = (b_1 F_{O_{im}} + b_2)(b_3 p_{im} + b_4) CA_{10} + b_5 \quad (4)$$

Where, $b_i (i=1,2,3,4,5)$ are the tuning parameters. The tuning parameters b_i are determined by solving a linear least-squares problem that minimizes $(CA_{50} - CA_{50_{meas}})^2$ with the tuning parameters as the optimization variables.

IMEP is another important combustion index of diesel LTC. Which can be obtained by the following equation:

$$IMEP = m_f LHV_f \left(1 - \frac{V_{ivc}}{V_{TDC}}\right) \cdot (c_1 F_{O_{im}}^2 + c_2 F_{O_{im}} + c_3) \cdot (c_4 p_{im} + c_5) \quad (5)$$

Where, m_f is the fuel rate, LHV_f is the low heat value of the fuel, V_{ivc} is the cylinder volume at the IVC moment, V_{tdc} is the cylinder volume at the TDC moment, $c_i (i=1,2,3,4,5)$ are the tuning parameters. The tuning parameters c_i are determined by solving a linear least-squares problem that minimizes $(IMEP - IMEP_{meas})^2$ with the tuning parameters as the optimization variables.

Based on this gas system models and combustion models [9], the model of CA50 and IMEP developed in this paper can be calculated. The Experimental validation has been finished in our previous study [10]. The verification results are shown in the figure 6~9.

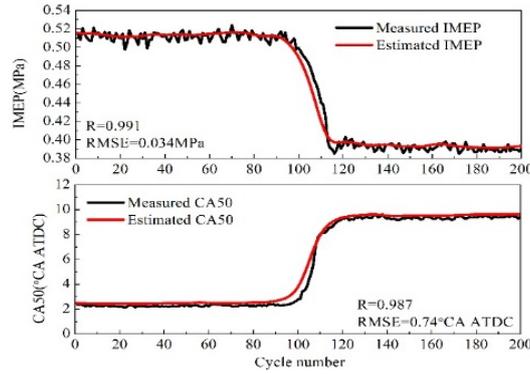


Figure 6. Intake oxygen concentration step: comparison between estimated and measured of IMEP and CA50 (1500r/min)

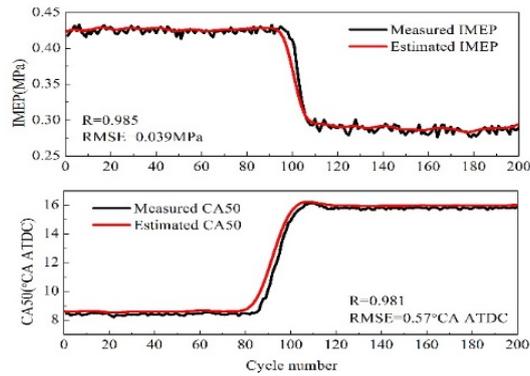


Figure 7. Intake oxygen concentration step: comparison between estimated and measured of IMEP and CA50 (2000r/min)

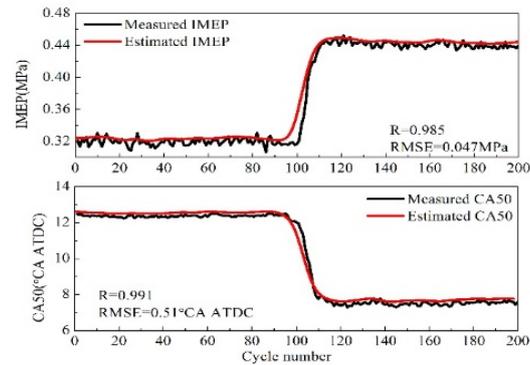


Figure 8. Fuel rate step: comparison between estimated and measured of IMEP and CA50 (1500r/min)

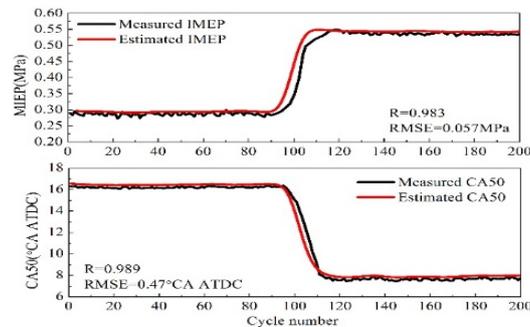


Figure 9. Fuel rate step: comparison between estimated and measured of IMEP and CA50 (2000r/min)

From the Fig. 6, the engine working at 1500r/min, 24mg/cycle fuel rate, 0.12MPa intake pressure. The intake oxygen concentration's transient response from 21.6% to 16.1%. During the intake oxygen concentration steps, the CA50 and IMEP from predicted model has a good conformity with experimental.

From the Fig. 7, the engine working at 2000r/min, 18mg/cycle fuel rate, 0.12MPa intake pressure.

When the intake oxygen concentration step from 21.6% to 14.3%, it compares the transient response between the estimated model and the experiment. The figure shows the model can capture the overall dynamic trend of the variations and predict IMEP and CA50.

Fig. 8 presents a comparison of the model's prediction of IMEP and CA50 versus the experimental IMEP and CA50 data when the fuel rate steps from 8mg/cycle to 17mg/cycle, with the diesel engine working at 1500r/min, 0.13MPa intake pressure, 21.6% intake oxygen concentration. The result shows the model well describes the combustion characteristics parameters CA50 and IMEP when the fuel rate steps.

Fig. 9 illustrates the transient response during the fuel rate step change from 6mg/cycle to 21mg/cycle, with the diesel engine working at 2000r/min, 1.2MPa intake pressure. It can be seen from the figure that the model performed well over the fuel rate step. The estimated data and measured data of IMEP and CA50 have a good agreement with each other.

The result shows that the model can predict not only the dynamic characteristics but also the IMEP and CA50 of diesel engine under LTC conditions, accurately.

Conclusions

(1) According the sensitivity analysis, the intake oxygen concentration, intake pressure and injection timing are the key control parameters that affect IMEP and CA50 of diesel LTC in all the intake parameters and injection parameters. (2) In three control inputs (fuel rate, EGR valve opening, VGT nozzle position), fuel rate can be used as the main control input parameter for IMEP control while EGR valve opening and VGT nozzle position can be used as the two control input parameters for CA50 control. (3) A physically-based control-oriented model that can accurately describe the dynamics of the combustion characteristics IMEP and CA50 were developed. The validation results show that the model can capture the dynamic characteristics and predict IMEP and CA50 under different transient conditions within satisfactory ranges.

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