Simulation on plateau power recovery of turbocharged diesel engine matched with electronic unit pump

Yupo Ma¹, Yu Feng, Zengbin Wu, Changcheng Wang, Tongzhou Liao, Zhanyu Zhan, Zhenyu Zuo, Guoning Shi
China North Vehicle Research Institute, Beijing, 100072, China
¹Corresponding author’s e-mail: mayupo2015@163.com

Abstract. Aiming at the problem of power reduction of supercharged diesel engine equipped with electronic unit pump in plateau operation, a simulation model is established by using one-dimensional software BOOST. Under the condition that the maximum combustion pressure and exhaust temperature are basically unchanged, the variation of maximum power, optimal injection advance angle and excessive air coefficient with inlet absolute pressure at typical speed is analyzed, which has important guiding significance for the control strategy of diesel engine in plateau operation.

1. Introduction
Diesel engines are widely used in industries, agriculture and transportation. In plain areas, turbocharged diesel engines have excellent performance on the aspects of power, efficiency and fuel consumption [1, 2]. However, when it works in plateau areas, many serious problems will arise. These problems can cause deterioration of performance and increase of harmful emissions [3, 4].

The main characteristics of plateau climate environment are low atmospheric pressure, air density, air oxygen concentration and average air temperature, as shown in Table 1. When the supercharged diesel engine works in plateau area, the intake pressure decreases, and the air quality in the cylinder decreases. When the speed and fuel supply are constant, the excess air coefficient decreases, so the exhaust temperature and specific fuel consumption will increase significantly, while the maximum power and maximum combustion pressure will decrease greatly. The more obvious the deterioration of diesel engine performance occurs with the higher altitude [5].

Table 1. Parameters of atmosphere at different altitudes.

| Height (m) | Atmosphere Pressure (kPa) | Atmosphere Temperature (K) | Air density (kg.m⁻³) | Oxygen density (kg.m⁻³) |
|-----------|---------------------------|----------------------------|----------------------|-------------------------|
| 0         | 101.3                     | 288                        | 1.1981               | 0.251                   |
| 1000      | 90                        | 282                        | 1.1117               | 0.226                   |
| 2000      | 81                        | 275                        | 0.9733               | 0.204                   |
| 3000      | 70.1                      | 268                        | 0.8919               | 0.187                   |
| 4000      | 61.6                      | 261.5                      | 0.8063               | 0.169                   |

For highly intensified supercharged diesel engines, the maximum explosion pressure and exhaust temperature are the two most important limiting parameters [6]. Excessive maximum explosion pressure will increase the mechanical load of the cylinder head, while excessive exhaust temperature
will increase the thermal load of the exhaust system. In the working process of the engine, they need to be strictly controlled and cannot exceed the prescribed limits for a long time. In this study, under the condition that the maximum combustion pressure and exhaust temperature are basically unchanged, the variation laws of parameters such as maximum power, optimal injection advance angle and optimal excess air coefficient with supercharging pressure at the maximum engine speed are analyzed by one-dimensional BOOST simulation software, which has important guiding significance for the control strategy of diesel engines working at plateau areas.

2. Establishment and calibration of simulation model

2.1. Main parameters of original diesel engine

In this study, a V-type eight-cylinder supercharged diesel engine is taken as the research object, as shown in Table 2, the maximum displacement is 16L, the compression ratio is 14:1, the maximum power is 650kW (engine speed is 2500r/min), and the maximum torque is 2780N.m (engine speed is 1800r/min). The combustion chamber of the engine adopts the double swirl combustion chamber developed by Beijing Institute of Technology [7, 8], which improves the combustion speed and shortens the combustion duration to a certain extent. Delphi electronic unit pump oil supply system is adopted in the oil supply system, in which the plunger diameter is 11mm, and the oil supply cam adopts the deceleration cam profile designed by Beijing Institute of Technology, which improves the injection pressure and basically realizes the ideal constant pressure oil supply characteristics [9-11].

Table 2. The original diesel engine main parameters.

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Bore diameter & Stroke (mm)      | 132&145                |
| Compression ratio                | 14:1                   |
| Combustion chamber               | double swirl           |
| Ignition sequence                | 1-8-4-5-7-3-6-2        |
| Start injection pressure (MPa)   | 20                     |
| Nozzle number                    | 8                      |
| Nozzle diameter (mm)             | 0.27                   |
| Max torque (N.m)                 | 2780@1800r/min         |
| Max power (kW)                   | 650@2500r/min          |

2.2. Simulation model

There is no supercharger model in the model, but the inlet pressure to be simulated is directly input at the inlet of the intake manifold, and a 200mm pipe is added to the exhaust pipe to simulate different exhaust backpressure by changing its diameter. As shown in Figure 1:
2.3. The calibration of simulation model

When the ambient pressure is 101 kPa, the above simulation model is calibrated according to the experimental data of the typical working point of the engine, which mainly includes parameters such as cylinder pressure curve, power, fuel consumption, excessive air coefficient, injection advance angle and exhaust temperature, as shown in Figure 2 and Table 3: It can be found that the simulation model has been calibrated very well and can be used to conduct the simulation research for this diesel engine.

Table 3. Comparison between experimental and simulation results of different performance parameters.

| Performance parameters | Experiment results | Simulation results | Performance parameters | Experiment results | Simulation results |
|------------------------|--------------------|--------------------|------------------------|--------------------|-------------------|
| Power (kW)             | 651.4              | 651.7              | Specific fuel consumption (g/kW.h) | 232.2              | 232.0             |
| Excessive air coefficient | 1.53              | 1.53               | Inlet temperature (°C) | 82.5              | 82.7             |
| Maximum combustion pressure (bar) | 174               | 173.7              | Inlet pressure (bar) | 3.37              | 3.37             |
| Exhaust temperature (°C) | 748.5             | 748                | Exhaust pressure (bar) | 3.42              | 3.45             |
3. Simulation analysis of diesel engine plateau performance

By changing the intake pressure, simulate on the plateau working performance of diesel engine have been conducted. Firstly, the simulation was carried out without optimization matching, and the main problems to be solved were found out. Then, according to the limitation of maximum combustion pressure and exhaust temperature, the system optimization matching simulation analysis of all injection parameters is carried out, and the optimal injection advance angle and injection quantity under different intake pressures are determined.

3.1. Simulation analysis on plateau performance of diesel before systematical optimization

In order to directly reflect the influence of altitude on the performance of diesel engine, based on the experimental data when the engine is in plain, the diesel engine is simulated by changing the intake pressure independently while keeping the intake manifold temperature, injection advance angle and cycle fuel supply unchanged. Figures 3-7 showed the simulation results of power, specific fuel consumption, excessive air coefficient, maximum combustion pressure and exhaust temperature before turbocharger.

From the above figures, it can be seen that when the intake pressure decreases from 3.4 bar to 2.4 bar, the power decreases by 55 kW, the specific fuel consumption increases by 22 g/(kW.h), the excessive air coefficient decreases by 0.48, the maximum combustion pressure decreases by 37 bar, and the exhaust temperature before turbocharger increases by 160 °C. This is because when the injection advance angle and circulating fuel supply are unchanged, the decrease of intake pressure will cause the decrease of intake air volume. As a consequence, longer combustion duration, lower combustion efficiency and more post combustion happens.

Figure 3. Simulation of power before optimization.

Figure 4. Simulation of SFC before optimization.

Figure 5. Simulation of EAC before optimization.

Figure 6. Simulation of MCP before optimization.
Figure 7. Simulation of ET before optimization.

It should be pointed out that with the decrease of intake pressure, the exhaust temperature before vortex rises obviously, which will greatly reduce the mechanical strength of exhaust pipe and turbocharger. In some severe cases, it will directly damage the exhaust system, resulting in huge faults and losses. Therefore, when the intake pressure decreases, the control parameters of the engine need to be adjusted accordingly to ensure its normal and safe operation. In addition, the highest combustion pressure also has a great influence on the reliability of the engine, which needs to be strictly controlled during the adjustment process of the engine.

3.2. Simulation analysis on plateau performance of diesel with systematical optimization

To sum up, when the intake pressure decreases, the performance and reliability of the engine are seriously deteriorated, so it is necessary to take corresponding measures to optimize the control of the engine. The principle of optimization in this study is to obtain the maximum power under the condition that the maximum combustion pressure and exhaust temperature before vortex do not exceed the results of plain operation. According to the experimental results in Table 3, the constraint conditions are given: maximum combustion pressure less than 175 bar, exhaust temperature before turbocharger less than 750°C.

For diesel engine with electronic unit pump oil supply system, injection advance angle and fuel supply per cycle are two flexible control parameters, which can be adjusted in a wide range by adjusting the position of start-up current and the length of injection pulse width. Theoretically, the greater the injection advance angle, the greater the proportion of premixed combustion, so the higher the maximum combustion pressure and the lower the exhaust temperature. When the injection advance angle is constant, the larger the fuel supply per cycle is, the longer the combustion duration is, so the exhaust temperature increases correspondingly, but the maximum combustion pressure is basically unchanged. This is because the maximum combustion pressure is basically only related to the premixed combustion process, so the combustion pressure quickly reaches the maximum at the initial stage of the combustion process, which has nothing to do with the length of injection pulse width.

In the process of optimization, for a certain intake pressure, the relationship between the highest combustion pressure and the injection advance angle can be obtained by changing the injection advance angle, and the best injection advance angle under the intake pressure can be determined according to the constraint condition of the highest combustion pressure. Then, by changing the fuel supply per cycle, the relationship between exhaust temperature and it can be obtained.
Figure 8. The variation of MCP with IAA.

Figure 8 shows the variation of the maximum combustion pressure with the injection advance angle under different intake pressures. According to the constraint value of the highest combustion pressure, the best injection advance angle under different intake air pressures can be determined. In addition, it can be found that under different intake pressures, the maximum combustion pressure basically increases linearly with the injection advance angle, but its slope changes. When the intake pressure is 3.2 bar and 2.4 bar respectively, the maximum combustion pressure increases by about 5 bar and 3.5 bar for every 1°CA increase of the injection advance angle. Therefore, the higher intake pressure, the faster the maximum combustion pressure increases with the injection advance angle.

After the optimal injection advance angle being determined, the exhaust temperature before turbocharger and its variation law can be obtained by adjusting the fuel supply per cycle, as shown in Figure 9. According to the constraint value of exhaust temperature before turbocharger, the best fuel supply per cycle can be obtained. In addition, it can be found that under different intake pressures, the exhaust temperature before turbocharger basically increases linearly with the increase of fuel supply per cycle, and the slope is basically unchanged, that is, for every 1mg increase of fuel supply per cycle, the exhaust temperature before turbocharger increases by about 2 °C.

Figures 10-12 show the relationship between the optimal injection advance angle, the optimal fuel supply per cycle and the optimal excessive air coefficient with the intake pressure. In the process of optimization, the variation intervals of fuel supply per cycle and injection advance angle are 1mg and 0.5°CA, respectively. As shown in Figure 10, with the decrease of intake pressure, the optimal injection advance angle increases parabolically, that is, the lower the intake pressure, the faster the optimal injection advance angle increases. As shown in Figure 11 and Figure 12, with the decrease of intake pressure, the optimal fuel supply per cycle and the optimal excessive air coefficient decreases linearly. When the intake pressure decreases by 0.1 bar, the fuel supply per cycle and the optimal excessive air coefficient decreases by 5.8mg and 0.015 respectively.

Figure 13 shows the relationship between optimized diesel engine performance and intake pressure. It can be found that the optimized maximum power decreases linearly with the decrease of intake pressure, and it decreases about 17kW for every 0.1 bar decrease of intake pressure. The minimum specific fuel consumption is basically unchanged at first, and then increases significantly. In addition, when the intake pressure increases, the minimum specific fuel consumption tends to increase, because the injection advance angle is small at this time, which deviates from the most economical injection position.
4. Conclusions
Aiming at the problem that the performance of diesel engine deteriorates significantly due to the drop of intake pressure when working in plateau environment, a simulation model of a V-type eight-cylinder supercharged diesel engine is established by using one-dimensional calculation software BOOST. The simulation model is calibrated according to the experimental data of the typical point of the engine in plain area. Firstly, the simulation calculation is carried out by changing the intake pressure alone, and then the influence of injection advance angle on the maximum combustion pressure and the influence of fuel supply per cycle on the exhaust temperature before turbocharger are analyzed respectively. Finally, under the condition that the maximum combustion pressure and exhaust temperature before turbocharger do not exceed the plain experimental results, the engine is optimally controlled, and the optimal injection advance angle, fuel supply per cycle, excessive air coefficient, the maximum power and the lowest specific fuel consumption under different intake pressures are obtained. The main conclusions are as follows:

(1) Before optimization, when the intake pressure is reduced alone, the engine performance such as power and specific fuel consumption obviously deteriorates, among which the exhaust temperature before turbocharger deteriorates most seriously, and it increases by about 16 °C for every 0.1 bar decrease of intake pressure, which has a serious impact on the reliability of the engine.

(2) Under different intake pressures, the maximum combustion pressure increases linearly with the increase of injection advance angle, and the higher the intake pressure, the faster the maximum combustion pressure increases with injection advance angle.
(3) Under different intake pressures, with the increase of fuel supply per cycle, the exhaust temperature before turbocharger increases linearly, and its slope is basically independent of intake pressure.

(4) With the decrease of intake pressure, the optimal fuel supply per cycle, excessive air coefficient and the maximum power all decrease linearly. The optimum injection advance angle basically increases parabolically. When the intake pressure is greater than 3 bar, the minimum specific fuel consumption remains basically unchanged.

References
[1] Yan J, Chou S K, Desideri U, Xia X 2014 Innovative and sustainable solutions of clean energy technologies and policies (Part I). Appl Energy 130: 447-79
[2] Chou S K, Chua K J, Ho J C, Ooi C L 2004 On the study of an energy – efficient greenhouse for heating, cooling and dehumidification applications. Appl Energy 77: 355-73
[3] Shi X, Li W X 2011 Simulation on Plateau Performance of Diesel Engine Matched with Two-stage Sequential Turbocharging System. Acta Armamentarii 32(4): 397-399
[4] Zhang L F, Liu S, Zhang H Y et al 2017 Study on Fuel-Air Synergistic Control of Regulable Two-Stage TurbochargedDiesel Engine Working at High Altitude. Diesel Engine, 39(3): 1-3
[5] Li H L, Shi L, Deng K Y, et al. 2015 Calculation Research on Variable Altitude Adaptability of Regulated Two-Stage Turbocharging System. Chinese Internal Combustion Engine Engineering, 36(3):1-5
[6] Shang H K, Dong C L, He J F, et al 2017 Research on Compression Ratio and Fuel Injection Advance Angle Optimization of Two-stage Turbocharged Diesel Engine. Acta Armamentarii (36): 20-25
[7] Shang Y, Liu F S, Li X R, Wu J 2012 Research on Parametric Design Method of Combustion Chamber on Diesel Engine. Advanced Material Research. p.383-390
[8] Li X R, Sun Z Y, Du W 2010 Research and Development of Double Swirl Combustion System for a DI Diesel Engine. Combustion Science and Technology: 1029-1049
[9] Qiu T, Liu X H, Liu F S, Yu L 2008 The Study for Cam Profile Design of EUP. Transactions of CSICE, 26(5): 476-478
[10] Zhang Z 2017 Methodology to parametric design of cam profile for electronic unit pump. Energy, 139: 170-172
[11] Wang P, Liu F S, Li X R 2012 Driving characteristics for electronic control unit pump fuel injection system. In: 2012 International conference on computer distributed control and intelligent environmental monitoring. IEEE. p.264-7