Development of control strategy for fast idling condition of diesel engine based on target torque

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Abstract
This article puts forward the concept of fast idling condition. The comparative experiments of idling and fast idling warming up engine show that: during cold start, the warm-up of fast idling condition whose maximum speed is 1350 r/min is the most fuel-efficient, fuel-saving about 4.5%, time-saving about 32.5%; at normal temperature, warming up engine of fast idling condition does not save fuel. The warm-up experiments of fast idling condition that accelerations are different in the descent phase show that when the engine is cold, the smaller the acceleration in the descent phase of fast idling condition is, the more time and fuel are saved; at normal temperature, the bigger the acceleration in the descent phase of fast idling condition is, the better the fuel economy is. Therefore, it is inferred that the engine should be warmed up under fast idling condition when the engine is cold and idling condition is used to warm up engine at normal temperature. To sum up, when the engine is cold, the engine should be warmed up under the fast idling condition whose maximum speed is 1350 r/min; at normal temperature, it should be warmed up in idling condition to save fuel.

Keywords
Diesel engine, warm-up, idling condition, fast idling condition, cumulative fuel consumption, GT-Power, GT-Cool, simulink

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Introduction
Due to its high thermal efficiency, wide power coverage, reliable operation, and durability, the diesel engine is widely used in the fields of motor vehicles, and has an irreplaceable position in the field of agricultural machinery due to its good economy.\textsuperscript{1} The increasing of diesel engine sales and the expansion of its application ranges have also brought about serious environmental pollution. There are hundreds of different compounds in diesel exhaust, which not only smell strange, but also make people dizzy and nauseous and affect people’s health.\textsuperscript{2} The average temperature in January is below 0°C in most provinces to the north of Qinling Mountains-Huaihe River Line.\textsuperscript{3} Three Northeastern Provinces of China, Inner Mongolia, and Xinjiang have a long winter, which can last for 4 months, and the monthly minimum temperature in winter can even reach minus 20°C.\textsuperscript{4} When the engine warms up in idling condition, the coolant temperature rises slowly, the engine does not output power, the fuel and air mix are unevenly, and the accumulated fuel injection quality

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and accumulated air pollutant emissions are large.\(^5\) Starting and idling conditions have become the main working conditions of engine HC and CO emissions.\(^6\) How to warm up the engine quickly has become a research hot issue. There are contradictions among fuel quantity of starting, cold starting emissions, and starting reliability.\(^7\) When the engine does not misfire, the fuel injection quantity in the first cycle should be reduced as far as possible to reduce HC emission; in the case of low ambient temperature, the reliability of starting can be improved by increasing the coolant temperature, and HC emissions can be reduced to a certain extent.\(^8\) When the engine temperature is low, in order to maintain the stable operation of the engine, the low idling speed should not be set. On the contrary, when the engine temperature is high, the thermal loads of the engine body increase. If the idling speed is set too high, the engine will overheat, the thermal loads of the engine body increase. If the idling speed increases, the outlet temperature of engine coolant increases, which is conducive to the improving for system temperature of post-treatment. The friction loss pressure is greatly affected by the coolant temperature. When the engine is warmed up, the coolant temperature increases fast, and the energy of friction loss decreases.\(^12\) However, the rising speed of lubricating oil temperature is slower than that of coolant temperature, which is not conducive to the increasing of engine speed for idling condition.\(^13\) When the engine is warmed up in idling condition, the ratio of heat absorbed by coolant from cylinder head to engine block is basically kept at 2:1.\(^14\) When the ambient temperature is low, the stability of idling speed can be improved by pre-injection; with the increasing of idling speed, the outlet temperature of engine coolant increases, which is conducive to the improving for system temperature of post-treatment. The exhaust advance angle can realize the emission reduction of pollutants such as NOx and micro particles when the idling speed increases.\(^15,16\) To sum up, the increase of idling speed is conducive to the improving of warm-up speed; there is an optimal warm-up mode which makes the fuel consumption and HC emission of the diesel engine lower during the warm-up period.\(^17\) Therefore, on the basis of previous studies, this article intends to develop the control strategy of fuel injection quality when the engine warms up.

**Establishment of the engine thermal management simulation model**

The GT-Power model of the prototype is firstly established in this paper, and verifies the GT-Power model by comparing the effective torque of the simulation output with that of the output of the prototype. The GT-Cool model is established, and then the GT-Power model and the GT-Cool model are coupled. The coupled model is called engine thermal management model. Finally, the engine thermal management model is verified by comparing the experimental value of engine coolant outlet temperature with the simulation value of that.

**Building the GT-Power model**

The prototype used in this experiment is the Great Wall 2.8tc turbocharged engine. The GT-Power model is shown in Figure 1. The model consists of external environment modules, intake modules, four injector modules, four cylinder modules, a crankshaft module, exhaust pipe module, exhaust turbocharger module, EGR + intercooler module. After treatment is not considered, the engine exhaust gas is directly discharged into the atmospheric environment. The opening of VNT and EGR is constant.

When verifying the GT-Power model, the engine speed is 1000, 1600, 2000, 2600, 3000, 3600 r/min respectively, and the engine pedal opening is 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100% respectively. The initial temperature of the coolant is 353 K during the simulation, the error between the effective torque output from the GT-Power model and that provided by the original engine manufacturer is within 5%. It shows that the performances of the GT-Power model meet the requirements, and the specific data are shown in Figure 2.

**Establishment of the GT-Cool model**

The cooling system of the prototype consists of a radiator, a thermostat, a water pump, a compensation bucket, a cooling fan, etc. The cooling system model is shown in Figure 3. The water pump and fan are connected to the crankshaft by a belt. The engine radiator is actually a heat exchanger, which is simulated by “HxMaster” and “HxSlave” component in GT-Cool. Because it is not necessary to study the temperature distribution of the radiator and high frequency pressure wave of fluid, the central heat exchanger is used.

**Coupling of the GT-Power model and the GT-Cool model**

In order to directly couple the GT-Power and the GT-Cool model, it is necessary to establish a cylinder block model. The finite element module of cylinder is used to define the geometric dimensions and the heat transfer coefficients of cylinder head, cylinder liner, intake, and exhaust valves. The cylinder model is shown in Figure 4.
The GT-Power and GT-Cool models can be directly integrated according to the following steps:

1. The crankshaft module in GT-Power is connected with the water pump module and fan module in GT-Cool through shaft module and gear module.

2. The cylinder structure of finite element in GT-Cool is connected with the cylinder module in GT-Power model. This is because the cylinder...
The finite element module specifies the specific dimensions of the cylinder head, cylinder liner, and other structures, as well as the heat transfer coefficients between the cylinder head, cylinder liner, and other structures of the engine. This connection is very important. It provides boundary conditions for combustion simulation in GT-Power and coolant temperature calculation in GT-Cool.

(3) The crankshaft module in GT-Power and the finite element module of each cylinder in GT-Cool are connected by the “ThermalCompConn” component. Through this connection, the friction heat calculated of the cylinder module in GT-Power can be transferred to the cylinder finite element module in GT-Cool. The model of direct integration of GT-Power and GT-Cool is shown in Figure 5.
Verification of the thermal management model

Because this article mainly studies the changing of coolant temperature during the engine warm-up, this article needs to compare the simulation results of engine coolant outlet temperature with the test results of that. The initial coolant temperature is kept at 334.75 K and the ambient temperature is 300 K. The working condition of the engine is idling. The comparison chart of coolant temperature is shown in Figure 6.

It can be seen from the Figure 6 that the coolant temperature measured by the experiment shows a ladder shape, which is caused by the accuracy of the temperature sensor. The coolant temperature obtained by simulation reflects the change trend of the actual coolant temperature, and the error is less than 5%. Therefore, the thermal management model of engine can meet the needs of warm-up experiment.

Fuel injection control based on target torque

For control algorithm of single cylinder injection quantity based on torque, the target indicated torque is regarded as the “link” of fuel injection quantity of per cycle. When an accessory is added, we only needs to calibrate the target indicated torque of the accessory, which is convenient for the integration and expansion of the engine. It has been widely used in the control system of diesel engine. This article puts forward the concept of fast idling condition that the engine speed rises from the starting speed to the setting speed and then drops to the idling speed, and the setting speed is called the maximum speed of fast idling in this paper.

Because this paper needs to carry out the contrast experiments of fast idling and idling warm-up, therefore this article needs to establish the injection control strategy of fast idling condition, also needs to establish the injection control strategies of the starting condition and the idling condition.

Determination of target indicated torque of fast idling condition

The calculation of fuel injection quantity is divided into two parts, one is the calculation of the target indicated torque, the other is the determination of conversion coefficient between the target indicated torque and the fuel injection quantity of single cylinder. The calculation of target indicated torque of fast idling condition is divided into two parts: one is the calculation of target indicated torque that engine speed is from starting speed to the highest speed of fast idling condition that is, fast idling rising stage; the other is the calculation of target indicated torque that engine speed is from the maximum speed of fast idling to idling speed, that is fast idling down phase.

Determination of target indicated torque in the rising phase of fast idling condition.

In this paper, the control chart of target indicated torque in fast idling rising stage is built, as shown in Figure 7.

In Figure 7, the target indicated torque $T_{rqi}$ consists of three parts: the drag torque $T_{rd}$, the acceleration resistance torque $T_{ra}$, and the compensation torque $T_{rc}$. Since the rising phase of fast idling condition is an unsteady condition, the power generated by the engine not only needs to overcome the friction loss of the engine, but also needs to overcome the acceleration resistance torque (inertia resistance torque) when the engine accelerates.

The drag torque used in this article is obtained through the motored test. The higher the speed is and the lower the coolant temperature is, the larger the engine drag torque is.

Acceleration resistance torque. The acceleration resistance torque is related to the changing of engine speed with time. We assume that the law of the changing of speed with time in the rising phase for fast idling satisfies the parabolic equation, as shown in Figure 8.

The change law of speed $n$ with time $t$ is a parabola which is symmetric about $x = t_0$ and its opening is downward. The parabolic equation is shown below.

$$n = \frac{n_{\infty}}{t_0^2} t^2 + 2 \frac{n_{\infty}}{t_0^3} t + \frac{n_{\infty}}{t_0^4}$$

Where $n_{\infty}$ is the maximum speed of fast idling. The relationship between torque and acceleration is:

$$T_{rqi} = 2\pi T \frac{dn}{dt} \frac{1}{60}$$
According to equations (1) and (2), the inertia resistance torque of the prototype for the rising phase of fast idling is obtained as following:

\[
\text{Trq}_I/C_0 = \frac{p}{C_0} \frac{I_n}{C_0} t/C_0 \left(1 - \frac{t}{t_{\text{c}}}ight) \left(1 - \frac{n}{n_{\text{c}}}ight) \quad (3)
\]

Where \( I \) is the moment of inertia of the engine; \( t/C_0 \) is the expected time of fast idling rising phase, \( \text{Trq}_I/C_0 \) is the inertia resistance torque.

As can be seen from equation (1), \( t/C_0 \) is a function of \( t_{\text{c}}/C_0, n_{\text{c}}/C_0, \) and \( C_{\text{c}} \), and considering the actual control of the engine, we should simplify equation (3). It can be seen from equation (3) that when \( t \) approaches \( t_{\text{c}}/C_0 \), that is, when the speed \( n \) approaches speed \( n_{\text{c}}/C_0 \), the inertia resistance moment \( \text{Trq}_I \) approaches 0. This law should be followed when simplifying the equation. Therefore, we obtain equation (4)

\[
\text{Trq}_I/C_0 = \frac{p}{C_0} \frac{I_n}{C_0} t/C_0 \left(1 - \frac{n}{n_{\text{c}}/C_0}ight) \quad (4)
\]

Since the moment of inertia is an estimated value, and there are errors in the measurement of the drag torque by using the motored test, so we use acceleration cut-off speed of fast idling \( n_{\text{a}} \) to calculate the drag torque.

\[
\text{Trq}_I/C_0 = \frac{p}{C_0} \frac{I_n}{C_0} t/C_0 \left(1 - \frac{n}{n_{\text{a}}/C_0}ight) \quad (5)
\]

Where the unit of moment of inertia \( I \) is kg m\(^2\), the unit of time \( t/C_0 \) is s, and the unit of rotational speed \( n \) is r/min.

**Compensation torque.** The compensation torque is used to ensure that the engine can start normally at low temperature.\(^{19}\) The compensation torque is calculated by acceleration. The compensation torque is calculated as following:

\[
a_n^* = \frac{\text{Trq}_I/C_0}{2\pi I} \quad (6)
\]

Where \( a_n^* \) is the target acceleration

\[
a_n = \frac{(n - n_{\text{last}})/60}{i} = \frac{i}{4} \left( \frac{n - n_{\text{last}}}{(n + n_{\text{last}})/60} \right) \quad (7)
\]

Where \( a_n \) represents the actual acceleration, \( n_{\text{last}} \) represents the last sampling crankshaft speed, and \( i \)
represents the number of engine cylinders. The compensation torque can be obtained by formula (8)

\[ \text{Trq}_{\text{comp}} = K_{\text{comp}} \times \text{Trq}_{1} \frac{a_n^2 - a_n}{a_n} \]

\[ = K_{\text{comp}} \times \left( \frac{\pi}{15r_o} (n_{-a} - n) - \frac{\pi}{1800} \left( \frac{n - n_{-\text{last}}(n + n_{-\text{last}})}{15r_o} \right) \right) \]  

Where, \( K_{\text{comp}} \) represents compensation coefficient, the value is 1.

By changing the maximum speed of fast idling condition into the successful speed of starting, the control strategy of speed rising phase of fast idling condition can be transformed into the control strategy of starting condition, and the workload can be reduced. Fuel injection control strategy of the starting condition no longer describes here.

\[ n = \left( \frac{t - t_o}{t_e - t_o} \right) (n_{\text{idle}} - n_{-o}) + n_{-o} \]  

\( n_{-o} \) represents the maximum speed of fast idling, \( n_{\text{idle}} \) represents idling speed.

\[ \text{Trq}_{1} = 2\pi I_1 \frac{dn}{dt} - \pi I_1 \left( \frac{n_{\text{idle}} - n_{-o}}{1800} \right) \]

Where the unit of speed is \( r / \text{min} \), and \( t_e \) represents the end time of fast idling.

The drag torque \( \text{Trq}_{d} \) uses the same map as the drag torque \( \text{Trq}_{\text{d}} \) of fast idling acceleration phase.

Idling closed loop control based on target indicated torque

Because this article needs to carry out comparative experiments to determine whether to use the idling condition or the fast idling condition to warm up the engine under different external conditions, so this article needs to build the idling closed-loop control strategy. In this article, the closed-loop control of idling condition only uses PI controller. The specific calculation formula is as follows:

\[ \Delta M = kp(n_{-\text{last}} - n) + ki(n_{\text{idle}} - n) \]

Where, \( \Delta M \) represents adjusting quantity of PI controller.

In this paper, the PI control logic diagram is built, as shown in Figure 11.

It can be seen from Figure 9 that the target indicated torque \( \text{Trq}_i \) consists of the drag torque \( \text{Trq}_{d} \) and the acceleration resistance torque \( \text{Trq}_{I} \). \( \text{Trq}_i = \text{Trq}_{d} + \text{Trq}_{I} \). The acceleration resistance torque \( \text{Trq}_{I} \) is related to the changing law of speed with time. In this article, for the convenience of control, it is assumed that the curve of speed changing with time in the descent phase of fast idling condition is linear. The changing rule of fast idling speed with time is shown in Figure 10.

The relationship between the speed and time in the descending stage of fast idling follows equation (9).

\[ \text{Trq}_{\text{I}} = \frac{2\pi I_{15}}{1800} = \frac{\pi I_1}{30(t_e - t_0)} \]  

Where, \( n_{-o} \) represents the maximum speed of fast idling, \( n_{\text{idle}} \) represents idling speed.

The inertia resistance moment in the falling stage of fast idling speed is:

\[ \text{Trq}_{\text{I}} = \frac{2\pi I_{15}}{1800} = \frac{\pi I_1}{30(t_e - t_0)} \]  

Where, \( n_{-o} \) represents the maximum speed of fast idling, \( n_{\text{idle}} \) represents idling speed.
static error; when \( kp = 0.01 \) is very small, although the speed can fluctuate near the idling speed, it takes about 7 s to stabilize around the idling speed, and the adjustment speed is slow. When \( kp = 0.03 \), it only takes 4.5 s to stabilize the speed near the idling speed, so \( kp \) is selected as 0.03.

After \( kp = 0.03 \), we study the influence of \( ki \) on idling speed stability, as shown in Figure 13.

It can be seen from Figure 13 that when \( ki = 0.05 \), the adjustment is slightly delayed, and the speed is stable after about 6 s, and the speed fluctuates between 770 and 815 r/min, and the fluctuation is relatively large; when \( ki = 0.15 \), the speed fluctuation is 765–815 r/min, and the static difference is large; when \( ki = 0.1 \), the speed fluctuates between 785 and 825 r/min, and the adjustment speed is fast, so \( ki \) is 0.1. In conclusion, when the ambient temperature is 300 K, \( kp = 0.03 \), \( ki = 0.1 \). When the ambient temperature is different, the parameters of \( kp \) and \( ki \) can be adjusted appropriately.

### Switching of control strategies for different target indicated torques

From the above, it can be seen that the control strategies of target indicated torque in the rising phase and in the descending phase of fast idling condition are different, and the control strategies of target indicated torque in the descending phase of fast idling condition and the target indicated torque in idling condition are
also different. Therefore, it is necessary to formulate the conversion methods for control strategies of different target indicated torque. In this paper, the Stateflow is used to realize the conversion of control strategies. The Stateflow software is a graphic tool, and its simulation principle is the theory of finite state machine.\(^2\)

The state machine established in this experiment is shown in Figure 14.

The purpose of establishing the state machine as shown in Figure 14 is to realize the following functions: judging according to the input speed, when the speed reaches the maximum speed of fast idling, the output value of model is 1, and then the engine cuts into the control strategy of descending phase of fast idling; when the speed reaches the idling speed, the output model value is 2, and the control strategy of target indicated torque for idling condition is activated. Similarly, the state machine can be used to set up control strategy of starting condition cutting into idling condition, which is not repeated here.

### Determination of conversion coefficient between target indicated torque and single cylinder injection quantity

The injection quantity per cycle (mg/cycle) of a single cylinder can be obtained by formula (12)

\[
V_{\text{cyc}} = \frac{B \times 10^6}{2 \times n + 60} \tag{12}
\]

Where, \(B\) is fuel consumption (kg/h) and \(n\) is engine speed (r/min).

\[
b_{-i} = \frac{B}{P_i} \times 10^3 \tag{13}
\]

\[
b_{-i} = \frac{3.6 \times 10^6}{\eta_{-i} H_u} \tag{14}
\]

From the above equations (15) and (16), equation (17) is obtained.
\[ B = \frac{3.6 \times 10^3}{\eta_{.i} \cdot H_u} \cdot p_i \]  

Where, \( B \) represents hourly fuel consumption, its unit is kg/h, \( p_i \) represents indicated power, its unit is kW, \( H_u \) represents low calorific value of fuel, kg/kJ, \( \eta_{.i} \) represents indicated thermal efficiency, \( b_{.i} \) represents indicated fuel consumption rate, its unit g/(kW h).

\[ p_i = F \cdot V \cdot 10^{-3} = \left( \frac{Trq}{r} \right) \cdot \left( \frac{2\pi r \cdot \frac{n}{60}}{r} \right) \cdot 10^{-3} \]  

Where, \( F \) represents force, its unit is N, \( V \) represents speed, its unit is m/s, \( r \) represents arm of force, its unit is m.

Equation (17) is obtained from equations (12), (15), and (16).

\[ V_{cyc} = \frac{B \cdot 10^6}{2 \cdot n \cdot 60} = \frac{10^6}{2 \cdot n \cdot 60} \cdot \frac{3.6 \times 10^3}{\eta_{.i} \cdot H_u} \cdot p_i \]  

Research on control strategy for fast idling warming engine

This article studies the economy of warming up the engine. When the engine can be loaded, the coolant temperature is defined as the end temperature of diesel engine warm-up. The end temperature of diesel engine warm-up is set at about 335 K.

Establishment of engine thermal management model and simulink joint simulation platform

Combined with GT-Power, GT-Cool and the control strategy in simulink, we build the engine thermal management model, as shown in Figure 16. The engine thermal management model is used for the following idling and fast idling warm-up experiments.

In Figure 16 above, the output quantities from GT-SUITE include engine crankshaft speed \( n \), coolant temperature \( T_{coolant} \), last sampling crankshaft speed \( n_{.last} \), and indicated thermal efficiency \( \eta_{.i} \), while the input into GT-SUITE is injection quantity of single cylinder. The control strategy of fuel injection quantity is packaged into the subsystem when the engine warms...
up in idling condition or fast idling condition. Because the speed of the first cycle is 220 rpm under fast idling condition, the simulation can not be started directly from the idling speed (800 r/min) when the engine is warmed up in idling condition, but the simulation is started from starting condition that the starting speed is 220 r/min. At this time, the engine cuts into the starting condition, and when the speed reaches the acceleration cut-off speed $n_{a}$, it cuts into the idling condition.

In this article, the following simulation experiments will be carried out through the joint simulation model:

1. Determination the time for the rising phase of fast idling
2. Determination the maximum speed for fast idling condition
3. Determination the acceleration for the descending phase of fast idling

**Analysis of fast idling rising phase**

In order to study the influence of fast idling rising phase on engine warm-up process, comparative experiments between fast idling rising phase and starting condition is carried out. The relationships between speed and fuel injection quantity with time are shown in Figures 17 and 18. The initial coolant temperature is 300 K.

It can be seen from Figure 17 that the speed curves of the rising phase of the fast idling condition (rise time 3.5 s, rise time 2.5 s) and the starting condition basically coincide before 0.5 s, because all initial fuel injection quantity are 30 mg. After 0.5 s, the shorter the rise time is, the bigger the fast idling speed is. After the speed reaches 1000 r/min, speed of fast idling conditions rises slowly, so when switching to the descent phase of fast idling condition, the transition is gentle and there will be no sudden change in fuel injection quantity. After about 3.5 s, the change curves of speed with time of the fast idling conditions with different rising time coincide. For starting condition, the speed rises slowly after reaching 700 r/min, which is conducive to the transition to idling condition. It can be seen from Figure 18 that the shorter rising time of fast idling condition is, the bigger the fuel injection quantity is. However, with the increasing of engine speed, the difference of fuel injection tends to decrease under the fast idling conditions whose rise time is different. After the rising phase of fast idling is finished, the curves of fuel injection
quantity with time basically coincide. The fuel injection quantity of starting condition is smaller than that of rising phase of the fast idling condition which shows that the starting safety under the fast idling condition is higher than that under the starting condition, but the fuel injection quantity fluctuates greatly when the speed is close to the idling speed. Under the fast idle conditions with different rise time, the coolant temperature hardly changes after 3.5 s, and the curves of speed and fuel injection quantity with time coincide which shows that this time, combustion conditions have tended to be consistent in the cylinder, therefore, it can be inferred that the curves of fuel injection quantity and speed with time in the descent stage of fast idling condition coincide. So it can be inferred that the rising phase of fast idling has little effect on the increasing of coolant temperature during the whole warm-up process when the time of fast idling rising phase is between 2.5 and 3.5 s.

The same conclusions can be obtained when the initial coolant temperature and the maximum speed of fast idling are different. In this paper, the time of fast idling rising phase is between 2.5 and 3.5 s.

Determination of the maximum speed for fast idling condition

In this section we determine the appropriate maximum speed of fast idling condition by comparing the accumulative fuel consumption of the warming up engine in fast idling condition with that in idling condition.

At normal temperature, comparing of economy for warming up engine between fast idling condition and idling condition. When the maximum speed of the fast idling is 1200, 1350, 1500 r/min respectively, and the idling speed is 800 r/min, the changing relationships of speed and coolant temperature with time are shown in Figures 19 and 20. The initial temperature of the coolant is 300 K.

At the end of the fast idling condition whose maximum speed is 1200 r/min, the whole process of fast idling takes about 170 s, and the coolant temperature rises to 330.4 K, with the accumulated fuel consumption of 55.4 g, therefore the fuel consumption is 1.173 kg/h. When the coolant temperature rises to 330.4 K, the idling condition takes 213 s and consumes 53.9 g fuel,
therefore the fuel consumption is 0.911 kg/h. So when the coolant temperature reaches 330.4 K, the accumulative fuel consumption during the warm-up process of fast idling is 102.8% of that under idling condition, and the time consumption is 80% of that under idling condition. The details are shown in Table 1.

At the end of fast idling condition whose maximum speed is 1350 r/min, the whole process of fast idling takes about 160 s, and the coolant temperature rises to 333.3 K, with the accumulated fuel consumption of 59.6 g, therefore the fuel consumption is 1.341 kg/h. When the coolant temperature rises to 333.3 K, the idling condition takes 231 s and consumes 58 g fuel, therefore, the fuel consumption is 0.904 kg/h. So when the coolant temperature reaches 333.3 K, the accumulative fuel consumed in the warm-up process of fast idling is 102.7% of that in the idling condition and the time consumed is 69.3% of that in the idling condition. The details are shown in Table 2.

At the end of the fast idling process whose maximum speed is 1500 r/min, the whole process of fast idling warm-up takes about 170 s, and the coolant temperature rises to 338 K, with the accumulated fuel consumption of 67.1 g, that is, the fuel consumption is 1.421 kg/h. When the coolant temperature rises to 338 K, the idling condition takes 260.5 s and consumes 64.7 g fuel, that is, the fuel consumption is 0.903 kg/h. Therefore, when the coolant temperature reaches 338 K, the accumulative fuel consumed in the warm-up process of fast idling condition is 103.4% of that in the idling condition and the time consumed is 65.3% of that in the idling condition. The details are shown in Table 3.

To sum up, when the initial temperature of the coolant is 300 K, using the fast idling condition to warm up the engine does not save fuel. If at the expense of economy, you can use the fast idling condition whose maximum speed is 1350 r/min to warm up the engine.

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Table 1. Comparison of total fuel consumption of warm-up under idling condition and fast idling condition whose maximum speed is 1200 rpm.

| Fuel consumption (g) | Work conditions | Time (s) |
|----------------------|-----------------|----------|
| Idling condition     | Fast idling condition |
| 213                  | 53.9            | 55.4     |
| 170                  |                 |          |

Table 2. Comparison of total fuel consumption of warm-up under idling and fast idling whose maximum speed is 1350 rpm.

| Fuel consumption (g) | Work conditions | Time (s) |
|----------------------|-----------------|----------|
| Idling condition     | Fast idling condition |
| 231                  | 58              |          |
| 160                  | 59.6            |          |

Table 3. Comparison of total fuel consumption of warm-up under idling and fast idling whose maximum speed is 1500 rpm.

| Fuel consumption (g) | Work conditions | Time (s) |
|----------------------|-----------------|----------|
| Idling condition     | Fast idling condition |
| 260.5                | 64.7            |          |
| 170                  | 67.1            |          |
During cold engine, comparing of economy for warming up engine between fast idling condition and idling condition. The relationships of speed, fuel injection, and coolant temperature with time are shown in Figures 21 and 22, when the engine is warmed up under the fast idling conditions whose maximum speed is 1200, 1350, and 1500 r/min separately and in idling condition. The initial coolant temperature is 253 K.

At the end of the fast idling condition whose maximum speed is 1200 r/min, it takes about 650 s, the accumulated fuel consumption is 240.6 g, that is, the fuel consumption is 1.333 kg/h and the coolant temperature rises to 322.8 K. When the coolant rises to the same temperature in idling condition, it takes about 830 s and 241.9 g fuel is consumed, therefore the fuel consumption is 1.049 kg/h. The accumulated fuel consumed in fast idling condition is 99.4% of that in idling condition. The details are shown in Table 4.

At the end of the fast idling condition whose maximum speed is 1350 r/min, it takes about 600 s, the accumulated fuel consumption is 244.3 g, therefore the fuel consumption is 1.466 kg/h. When the coolant temperature rises to 325.6 K under idling condition, it takes about 891 s and the accumulated fuel consumption is 255.7 g, therefore the fuel consumption is 1.033 kg/h. The accumulated fuel consumption in fast idling condition is 95.5% of that in idling condition. The details are shown in Table 5.

At the end of the fast idling condition whose maximum speed is 1500 r/min, it takes about 550 s, the accumulated fuel consumption is 236.2 g, therefore the fuel consumption is 1.466 kg/h. When the coolant temperature rises to 329.2 K under idling condition, it takes about 830 s and the accumulated fuel consumption is 245.8 g, therefore the fuel consumption is 1.049 kg/h. The accumulated fuel consumption in fast idling condition is 93.3% of that in idling condition. The details are shown in Table 6.

Table 4. Comparison of total fuel consumption of warm-up under idling and fast idling whose maximum speed is 1200 rpm.

| Time (s) | Idling condition | Fast idling condition |
|---------|------------------|-----------------------|
| 830     | 241.9            | 240.6                 |
| 650     |                  |                       |

Figure 21. Comparison of speed variation with time.

Figure 22. Comparison of coolant temperature variation with time.
consumption is 1.546 kg/h and the coolant temperature rises to 323.7 K. When the coolant reaches the same temperature in the idling condition, it takes 842 s and consumes 244.7 g of fuel, therefore, the fuel consumption is 1.046 kg/h. The accumulated fuel consumption in fast idling condition is 96.5% of that in idling condition. The details are shown in Table 6.

Therefore, by comparing the cumulative fuel consumption during warming up engine under fast idling condition whose maximum speed is different with that under idling condition, we come to the conclusion that the maximum speed of fast idling should be 1350 r/min when the ambient temperature is 253 K.

### Determination of acceleration in the descent phase of fast idling condition

According to formula (9), when the maximum speed of fast idling condition, speed of idling condition, and rising time of fast idling condition are determined, the acceleration can be adjusted by adjusting time of fast idling condition during fast idling down phase. When the warm-up time of fast idling is short, and the whole warm-up process includes fast idling and idling conditions. In order to study the influence of fast idling down phase on the economy and rapidity in the whole warm-up process, the external environment of the simulation experiments are selected as cold engine (253 K) and normal temperature (300 K), and the maximum speed of fast idling is 1200, 1350, and 1500 r/min respectively.

| Fuel consumption (g) | Work conditions | Fast idling condition
|----------------------|-----------------|------------------------|
| Time (s)             | Idling condition| Fast idling condition |
| 842                  | 244.7           | 236.2                  |
| 650                  |                 |                        |
Figure 23. Comparison chart of speed changing with time.

Figure 24. Comparison chart of single cylinder injection quantity changing with time.

Figure 25. Comparison of coolant temperature changing over time.

Table 7. The comparison of the total fuel consumption for the warming up engine when the accelerations are different in the descent phase of fast idling whose maximum speed is 1200 r/min.

| Warm-up time of fast idling (s) | Total warm-up time (s) | Accumulated fuel consumption (g) |
|-------------------------------|------------------------|---------------------------------|
| 580                           | 680                    | 239.3                           |
| 360                           | 755                    | 242.6                           |

Table 8. The comparison of the total fuel consumption for warming up engine when the accelerations are different in the descent phase of fast idling whose maximum speed is 1350 r/min.

| Warm-up time of fast idling (s) | Total warm-up time (s) | Accumulated fuel consumption (g) |
|-------------------------------|------------------------|---------------------------------|
| 580                           | 600                    | 243                             |
| 420                           | 676                    | 244.5                           |
results of speed, fuel injection quantity, and coolant temperature with time are shown in Figures 26 to 28.

At the end of warm-up work condition that fast idling takes 120 s, the coolant temperature rises to 325 K, and the accumulated fuel consumption in this process is 47.8 g, the fuel consumption is 1.117 kg/h; under warm-up work condition that fast idling takes 80 s, when the coolant temperature rises to 325 K, it takes 168 s, and the accumulated fuel consumption is 47.6 g, the fuel consumption is 1.02 kg/h. The details are shown in Table 10.

**Table 9.** The comparison of the total fuel consumption for the warm-up when the accelerations are different in the descent phase of fast idling whose maximum speed is 1500 r/min.

| Warm-up time of fast idling (s) | Total warm-up time (s) |
|--------------------------------|------------------------|
| 600                            | 682                    |
| 530                            | 240.5                  |
| 390                            | 242.7                  |

**Table 10.** The comparison of the total fuel consumption when the accelerations in the descent phase of fast idling whose the maximum speed is 1200 r/min are different.

| Warm-up time of fast idling (s) | Total warm-up time (s) |
|--------------------------------|------------------------|
| 154                            | 168                    |
| 120                            | 47.8                   |
| 80                             | 47.6                   |

When the initial coolant temperature is 300 K, the shorter time of fast idling condition whose maximum speed is 1200 r/min is, that is, the bigger the acceleration in the descent phase of fast idling, the better the fuel economy is.

When the initial coolant temperature is 300 K and the maximum speed of fast idling is 1350 or 1500 r/min, the same conclusion can be obtained. This article does not repeat them, but only give the comparison table for total fuel consumption of warming up engine. The details are shown in Tables 11 and 12.

In conclusion, at normal temperature, the bigger the acceleration is, the less the cumulative fuel consumption is. It can be inferred that when the initial coolant
temperature is 300 K, the engine warming up under the idling condition is more economical than warming up in fast idling condition.

Conclusion

In this article, the concept of fast idling condition is proposed in view of the fact that when the engine is warm-up in idling condition, the coolant temperature rises slowly, and the accumulated fuel injection quantity and accumulated air pollutant emissions are large. The co-simulation platform of the engine thermal management model and simulink is used to develop the fuel injection control strategy of warming up engine. In order to make the results representative, the coolant temperature is selected as normal temperature (300 K), cold engine (253 K), and the maximum speed of fast idling condition is selected as 1200, 1350, and 1500 r/min respectively. The specific conclusions are as follows:

The conversion coefficient between the target indicated torque and the fuel injection quantity is deduced, and the conversion coefficient between the target indicated torque and the fuel quantity is inversely proportional to the indicated thermal efficiency.

The contrast experiments of fast idling rising phase and starting condition are carried out. The experimental results show that the rising phase of fast idling condition takes a short time and has little effect on the increasing of coolant temperature during the whole warm-up process when the time of fast idling rising phase is between 2.5 and 3.5 s.

The maximum speed of fast idling is determined by comparing accumulated fuel consumption between warming up engine in fast idling and warming up engine in idling. The experimental results show that when cold starting (initial temperature of coolant is 253 K), warming up the engine in the fast idling condition whose maximum speed is 1350 r/min is the most fuel-efficient, about 4.5%. At normal temperature, warming up the engine under fast idling condition does not save fuel, but it saves time.

The warm-up experiment is carried out to determine the acceleration in the descent phase of fast idling condition. The experimental results show that when the engine is cold (the ambient temperature is 253 K), the smaller the acceleration in the descent phase of fast idling condition is, the more the fuel are saved; at normal temperature (the ambient temperature is 300 K), the bigger acceleration is and the better the fuel economy is. During warm-up process, the smaller temperature is 300 K, the engine warming up under the idling condition is more economical than warming up in fast idling condition.

| Warm-up time of fast idling (s) | Total warm-up time (s) |
|-------------------------------|------------------------|
| 55                            | 215 170                |
| 125                           | 58.1 59.2              |

| Warm-up time of fast idling (s) | Total warm-up time (s) |
|-------------------------------|------------------------|
| 100                           | 212 180                |
| 155                           | 66.3 67                |

Table 11. The comparison of the total fuel consumption when the accelerations in the descent phase of fast idling whose the maximum speed is 1350 r/min are different.

Table 12. The comparison of the total fuel consumption when the accelerations in the descent phase of fast idling whose maximum speed is 1500 r/min are different.

Figure 28. Comparison of the injection quantity changing with time in warm-up process that fast idling time is different.
acceleration in fast idling descent phase is, and the longer time occupied by fast idling condition is, whereas, the larger acceleration in fast idling descent phase is, and the longer time occupied by idling condition is. Therefore, it is deduced that when the engine is cold, it should be warmed up under the fast idling condition to save fuel, and at normal temperature, the engine should be warmed up in idling condition to save fuel.

Finally, the following conclusions are obtained: when the engine is cold, the fast idling condition of the maximum speed 1350 r/min is used to warm up the engine, which can save fuel by 4.5%; at normal temperature, the engine is warmed up in idling condition to save fuel.

**Author contributions**

Jiesong Jian improved the experimental ideas, carried out theoretical analysis and, experimental simulation, and wrote this paper; Yingchao Zhang improved the experimental ideas, analyzed the experimental results; Xuedong Lin put forward ideas and provided theoretical guidance; Yuanchun Ren provided a lot of Simulink technical support; Chun Shen and Chengchun Zhang carefully reviewed this article and gave many suggestions for modification of the article, such as the modification of pictures and tables. All authors have read and agreed to the published version of the manuscript.

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**Appendix**

**Notations**

| Symbol | Unit       | Meaning                                             |
|--------|------------|-----------------------------------------------------|
| Trq, ṭ | N·m        | Target indicated torque                            |
| Trq, d | N·m        | Drag torque                                         |
| Trq, I | N·m        | Acceleration resistance torque                      |
| Trq, comp | N·m | Compensation torque                                |
| n₀     | r/min      | Maximum speed of fast idling                        |
| t₀     | s          | Expected time of fast idling rising phase           |
| t      | s          | Engine working time                                 |
| n      | r/min      | Engine speed                                        |
| l      | kg·m²      | The moment of inertia of the engine                 |
| nₐ     | r/min      | Acceleration cut-off speed of fast idling           |
| nₗast  | r/min      | Last sampling crankshaft speed                      |
| K_comp | dimensionless | Compensation coefficient                        |
| n_idle | r/min      | Idling speed                                        |
| tₑ     | s          | The end time of fast idling                         |
| kp     | dimensionless | Proportional coefficient                     |
| ki     | dimensionless | Integral coefficient                          |
| B      | kg/h       | Fuel consumption                                    |
| Vcyc   | mg/cycle   | Injection quantity per cycle                        |
| pᵢ     | kW         | Power                                               |
| Hu     | kg/kj      | Low calorific value of fuel                         |
| ηᵢ     | dimensionless | Indicated thermal efficiency                      |
| bᵢ     | g/(kWh)    | Indicated fuel consumption rate                     |
| F      | N          | Force                                               |
| r      | m          | Arm of force                                        |
| T_coolant | K  | Coolant temperature                               |