Effect of altitude on thermal balance of a heavy-duty diesel engine

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Abstract. Diesel engines working at high altitudes are prone to thermal failure. In this paper, a series of experiments and simulations were conducted to analyze the thermal balance, in-cylinder heat transfer, and performance of diesel engines at various altitudes. A six-cylinder four-stroke diesel engine was used to conduct the thermal balance tests at altitudes from 0 m to 4500 m. The experiment results show that the engine thermal efficiency declines from 37.8% to 33.9% at the rated speed as altitude rises. The heat loss through cooling water has no significant change in trend and remains about 22%-24% in most conditions. The heat loss through exhaust decreases as altitude rises and accounts for 26.7%-39.8% of total energy. The unaccounted losses increase greatly as altitude rises but it makes up no more than 12.1% of total energy at all altitudes. To acquire more detailed in-cylinder heat transfer parameters, a one-dimensional in-cylinder simulation was conducted. The simulation results show that the in-cylinder heat transfer coefficient and heat fluxes increase first and then decrease as altitude rises. In addition, with the increase of altitude, the in-cylinder average gas temperature substantially increases. This study has practical significance for reducing thermal load of the engines working at high altitudes.

1. Introduction

On the plateau, the inlet air pressure drops linearly with the increase of altitude. Therefore, diesel engines working at high altitudes are prone to problems such as power loss, fuel economy deterioration, emission increase and thermal failure in the combustion chamber [1]. The experimental study of thermal balance shows the potential to optimize the diesel engine [2]. Therefore, it’s meaningful to investigate the thermal balance and performance of the diesel engine operated at high altitudes.

Many researchers studied the performance of diesel engines working on the plateau [3,4]. They find that as altitude rises, power and torque of diesel engines both decrease, especially at altitude above 2000m. The increase of altitude results in more fuel consumption and narrower fuel economic region, particularly at low engine speeds. In addition, some scholars conducted researches about the effects of high altitude on diesel engine emissions characteristics [5,6]. The results show that average emissions of HC (Hydrocarbon), CO (Carbonic Oxide) and PM (Particulate Matter) at high altitudes are two to four times as much as at low altitude conditions. Moreover, some studies of the energy balance of diesel engines also have been conducted [7,8]. These studies analyzed the thermal balance or energy distributions on low heat rejection diesel engine and the diesel engine operating on hydrogen.
or other alternative fuels. However, these studies did not investigate the effect of altitude on the thermal balance.

All in all, the kinds of literature focused on how to improve the performance of diesel engines working at high altitudes and the thermal balance of diesel engines working on the plain both can be found easily, while the researches about thermal balance of diesel engine at high altitudes is less. Therefore, the aim of this paper is to analyze the thermal balance, performance and in-cylinder heat transfer of diesel engines operated at various altitudes by experimental and emulation methods. Firstly, the bench tests of diesel engines working at various altitudes were conducted in order to obtain the parameters required for the calculation of thermal balance. Secondly, the one-dimensional simulation model was established to investigate the in-cylinder heat transfer coefficient, heat fluxes and gas temperature at various altitudes. Finally, by analyzing the relationship between thermal balance and in-cylinder heat transfer parameters at various altitudes, this paper found the reasons why the thermal balance changed as the altitude increase, which could also explain why the performance of diesel engines become terrible on the plateau.

2. Experiments

Experiments were conducted on a V-type six-cylinder four-stroke water-cooled supercharged diesel engine. The experiments were carried out at altitudes of 0 m, 1000 m, 2000 m, 3000 m, 3700 m, 4500 m at the 100% load engine speed characteristic curve. The fuel injection system of the diesel engine was electronically controlled high-pressure common rail fuel injection system with an ECU (Electronic Control Unit). The fuel injection strategy for ECU was that the throttle position was fully opened and maintained at 100%, and the fuel injection amounts were equal at all altitudes and engine speeds. The fuel injection timings were set at 28°CA (Crank Angle) before TDC (Top Dead Center) all the time. In addition, in order to exclude the effects of ECU strategies on the test results, the fuel injection control strategies were the same at all altitudes and working conditions.

The three typical operating engine speed conditions of rated speed 2200 r/min, intermediate speed 1900 r/min and maximum torque speed 1500 r/min were selected to conduct the research. The operating parameters of the engine at different altitudes conditions were measured, including engine speed, output torque, fuel consumption, in-cylinder gas pressure, engine oil temperature, turbocharged air temperature and pressure, ambient air temperature and pressure, cooling water flow rate and temperature, etc.

Figure 1 shows the schematic layout of the setup of the test bench. Limited by the actual situation, the experiments were carried out on the plain. However, the atmospheric pressure decreases from 101 kPa to 56.7 kPa while the altitude increases from 0 m to 4500 m. Therefore, in order to simulate the low-pressure environment at high altitudes, two vacuum pumps were used to create low pressure before the inlet and after the exhaust passage as shown in figure 1. When the test condition was at 0 m above sea level, the vacuum pump didn’t work, so the intake air could directly enter the engine from ambient. When the test condition was at altitudes higher than 0 m, the vacuum pump would create a low atmospheric pressure condition. At altitudes from 1000 m to 4500 m, the negative pressure output by the vacuum pump was 89.7 kPa, 79.2 kPa, 69.3 kPa, 63.4 kPa, 57.6 kPa respectively. The surge tank was used to store the low atmospheric pressure air and connected to the intake pipes. Other temperature sensors were used to measure the temperature of inlet cooling water, outlet cooling water, and engine oil as shown in figure 1. In the exhaust port, the throttle valve controlled exhaust gas flow at low pressure in the same way as in the intake port. The in-cylinder gas pressure and fuel consumption were also measured during tests. To get the accurate heat loss terms of the engine at various operating conditions, the engine run for at least half an hour and the test parameters were recorded after the temperature of cooling water reached steady for minutes at each test condition.
3. In-cylinder heat transfer simulation

To acquire more detailed heat transfer parameters and further explore the connection of thermal balance and in-cylinder heat transfer of diesel engines at various altitudes, the one-dimensional in-cylinder heat transfer simulation model was established. Therefore, the in-cylinder heat transfer parameters could be obtained from the calculation results. The Woschni formula shown below was used to calculate the in-cylinder heat transfer coefficient \([9]\).

\[
h = 130 D^{-0.2} p^{0.8} T^{-0.53} \left[ C_i C_m + C_2 V_H T_1 \left( \frac{p}{p_i} - 1 \right) \right]^{0.8}
\]  

(1)

where \(D\) is the cylinder diameter, \(C_i = 2.28 + 0.308 C_u / C_m, C_m\) is mean piston velocity, \(C_u\) is inlet swirl velocity. \(C_2 = 0.00324\). \(T_1\) and \(p_i\) are the in-cylinder temperature and pressure at the intake valve close time respectively. \(p_0\) is the in-cylinder pressure at the engine start time.

The in-cylinder combustion heat release model chose the Vibe model. The simulation model needed to be calibrated to ensure calculation accuracy. By adjusting the system parameters based on the experimental results, these operating parameters such as pipe gas pressure, compressor airflow, in-cylinder gas pressure, power, and torque were all predicted in a reliable range. After calibration of the diesel engine model, the errors between calculated in-cylinder pressure values and measured values were less than 10% as shown in figure 2.

Figure 1. Schematic diagram of test bench setup.

Figure 2. The calculated in-cylinder pressure values and measured values at various altitudes.
4. Results and discussion

4.1. Thermal balance test analysis

The energy items of thermal balance are composed of engine brake power, heat loss through cooling water, heat loss through the exhaust and the unaccounted losses. Figure 3 shows the proportion of each energy item to total energy as altitude rises from 0 m to 4500 m at three different engine speeds.

It can be seen from those figures that as the altitude rises, the ratio of energy used for useful work namely brake power obviously decreases at all engine speeds. At 1500 r/min, the thermal efficiency shows the same change trend and decreases from 37.8% to 31.8% as altitude rises. The engine thermal efficiency declines from 39.6% to 34.9% at 1900 r/min as altitude rises. At rated speed, the thermal efficiency decreases from 37.8% to 33.9% gradually from 0 m to 4500 m. The reason is that the intake air mass decreases as ambient pressure decreases and this leads to the decrease of engine performance and efficiency. The ratio of heat loss through cooling water seems that it has a slight rise trend as altitude rises at 1500 r/min except at 1000 m point. In addition, the ratio remains at about 17.1%-24.5% at 1900 r/min and 2200 r/min as altitude changes. At an altitude of 1000 m, the ratio of heat loss through cooling water at all engine speeds decreases significantly. The reason is that the deteriorative combustion in the cylinder causes a lot of heat to be removed by exhaust gas. The ratio of heat loss through the exhaust gas decreases as altitude increases essentially at all engine speeds except that the maximum value appears at 1000 m rather than 0 m. The ratio of the unaccounted losses increases with the increase of altitude at all engine speeds and makes up no more than 12.1% of total energy at all altitudes. The experiment results from figure 2 show that the altitude has a remarkable influence on the thermal balance of diesel engines. In general, the proportion of brake power declines sharply at high altitudes. The proportion of exhaust energy descends at high altitudes. The proportion of unaccounted losses augments at high altitudes. At the three test engine speeds, the change trends of the ratio of energy items to thermal balance are the same from altitude of 0 m to 4500 m.

![Figure 3. Thermal balance of the engine operating at various altitudes.](image-url)
Figure 4 and Figure 5 show the turbocharger pressure ratio and equivalent air-fuel ratio at various altitudes respectively. From these figures, we can explain why high altitudes affect the thermal balance and performance of diesel engines. The turbocharger pressure ratio rises as altitude increases, and the engine equivalent air-fuel ratio declines as altitude increases. It means that the high-pressure ratio is still not enough to compensate for the decline of ambient pressure as altitude rises. The decrease of the equivalent air-fuel ratio is the main reason why the variation of thermal efficiency and performance of the engine at various altitudes. The engine can not get enough air for combustion at higher altitudes, so the fuel energy can not fully released. The decrease of equivalent air-fuel ratio can also explain why the ratio of heat loss through the exhaust gases decreases as altitude increases. The intake air mass decreases sharply as altitude rises, so the exhaust energy decreases as well. The total mass flow rate declines sharply, thus exhaust energy decreases as altitude increases through exhaust temperature increases to some extent. The decrease of intake air mass directly leads to the decrease of the ratio of heat loss through the exhaust gases in the thermal balance of the engine. The ratio of heat loss through cooling water is not quite different at various altitudes. This is because the flow rate and temperature of cooling water remain near the same at various altitudes. The unaccounted heat loss increases with the increase of altitude because fuel energy is not fully released and flowed away with exhaust gases. In addition, the decrease of equivalent air-fuel ratio at high altitudes leads to combustion lag, so the energy loss of the unburned fuel increases.

4.2. Simulation analysis

Figure 6 and Figure 7 show the engine in-cylinder heat transfer coefficients and heat fluxes at various altitudes respectively. The curves in figure 6 shows that at all engine speeds, the in-cylinder maximum heat transfer coefficient reaches the maximum at 1000 m. At the altitude above 2000 m, the heat transfer coefficient decreases as altitude increases. Especially at 4500 m, the heat transfer coefficient drops about one quarter compared to it at 3000 m. The curves in figure 7 shows that at all engine speeds, the engine in-cylinder maximum heat fluxes drop as altitude increases broadly from 0 m to 4500 m. At altitudes above 3000 m, the downward trend is significantly speeding up as altitude rises. The maximum heat fluxes at altitudes from 1000 m to 3700 m change a little. The curves of heat transfer coefficients and heat fluxes show that they have the same change trend and drop apparently at high altitudes especially above 3000 m. Therefore, the change of in-cylinder heat transfer parameters can partly explain how altitude affects the thermal balance of diesel engines.
Figure 7. The engine in-cylinder heat fluxes at various altitudes.

Figure 8 and Figure 9 show the in-cylinder average gas temperature and cycle maximum gas temperature at various altitudes respectively. The in-cylinder average gas temperature increases near linearly with the increase of altitude from 0 m to 4500 m. The maximum gas temperature increases first as altitude rises from 0 m to 3700 m and then drops a little at 4500 m. The thermal balance tests have found that the ratio of heat loss through the exhaust gases decreases as altitude increases. It’s because the equivalent air-fuel ratio decreases greatly as the altitude rises and the rise of average gas temperature can’t make up for it. At high altitudes, the engine works worse than on the plain because of insufficient air and worse cooling. The higher in-cylinder gas temperature at high altitudes leads to the rise of the ratio of unaccounted heat loss because of insufficient air and unburned fuel. The average gas temperature increases and maximum gas temperature change obviously as altitude rises, that’s the reason why thermal efficiency drops and heat losses increase. Altitude has a significant influence on the in-cylinder heat transfer and thermal balance of the diesel engine. At high altitudes above 3000 m the effects are especially more significant. To relieve in-cylinder thermal load, it’s vital to reduce heat loss to exhaust and control the exhaust gas temperature.
5. Conclusions

The experiment tests were conducted to study the thermal balance of a V-type six-cylinder turbocharged heavy-duty diesel engine working at various altitudes ranging from 0 m to 4500 m. To acquire detailed in-cylinder heat transfer parameters and better explain the thermal balance and energy distributions of the engine, one-dimensional in-cylinder heat transfer simulation was finished. From the results of the research, the following conclusions can be drawn.

(1) Altitude has a significant influence on the thermal balance of the engine, especially at high altitudes above 3000 m because of the oxygen content in the air gradually decreases.

(2) In general, the engine thermal efficiency decreases as altitude rises, and its maximum arises at 1900 r/min. The ratio of heat loss through exhaust gases decreases as altitude increases except at 1000 m. The ratio of heat loss through cooling water slightly increases at 1500 r/min but changes a little at other engine speeds. The ratio of unaccounted heat losses shows an obviously upward trend at all engine speeds as altitude increases.

(3) The simulation results show that the in-cylinder heat transfer coefficients and heat fluxes increase first and then decrease as altitude rises, and they both reach the maximum at 1000 m. The engine in-cylinder average gas temperature and maximum gas temperature substantially increase as altitude increases.

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