

Combustion and Emission Characteristics of a Heavy-Duty Diesel Engine at Idle at Various Altitudes

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ABSTRACT

This present paper described an experimental study on the combustion and emission characteristics of a diesel engine at idle at different altitudes. Five altitudes ranging from 550m to up to 4500m were investigated. Combustion parameters including in-cylinder pressure and temperature, heat release, fuel mass burning and so forth, together with emission factors including CO, HC, NO_x and PM were tested and analyzed. The result of on-board measurement manifested that in-cylinder pressure descended consistently with the rising of altitude, while both the maximum in-cylinder temperature and exhaust temperature ascended with the altitude. It was found that ignition delay was lengthened at higher altitude, but the combustion duration became shorter. The crank angle towards 90% fuel burnt has hardly changed with the variation of altitude. As for heat release, the difference of slopes observed at different altitudes was quite slight. However, the peak heat release increased with altitude in the cases where altitude is lower than 3300m, and shrinkage appeared at 4500m. The curvature of pressure rise has duplicated the tendency of heat release. Further study on each emission factor yielded that an increase in altitude correlated to a continuous increase in CO and PM emissions. Generally, HC emissions had a positive correlation with altitude despite the slight fluctuation at mid-altitudes. Similar to heat release, a consistent increase in NO_x emissions corresponded to an increase in altitude till the final drop observed at 4500m.

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INTRODUCTION

In China, more than 6 million vehicles are operating in the regions where altitude is higher than 1000m. Due to the lean ambient air in high altitude regions, charge motion of the internal combustion engines becomes much undesired, and a series of combustion and emission problems would be aroused. It is well known that vehicles operating at such an altitude could encounter serious power de-rating and produce more particulate emissions. But, the current scenario is that the study on high altitude emission are still not sufficient or detailed enough for us all to take effective measures. Considerable prior researches were conducted in the laboratories instead of real-world practice and they were conducted several years ago. This situation is very unfavorable for the governmental departments, who are in charge of the civil ambient air quality and vehicular emission control. A shortage of references embarrasses the effective policymaking process and makes the countries and cities suffer from the polluted atmosphere, especially for some developing countries like China.

The issue of high altitude emission was first recognized by Environmental Protection Agency (EPA) in the late 1980s. By cooperating with Southwest Research Institute (SwRI), they simulated the ambient air condition at 6000 feet and conducted a series of experiments to compare the emission characteristics at high altitude and near sea level [1]. After that, California Air Resource Board (CARB) carried out a comparative study on the smoke opacity of heavy-duty diesel trucks at 125 feet and 5800 feet [2]. Being different with the study of EPA and SwRI, over 80 testing objects in this study were picked up randomly on the road, which included a variety of models, years and healthy conditions of sample vehicles. Comparing with a study in the lab, this method could better reflect the factual situation. A following research was done by SwRI on a turbocharged after-cooled diesel engine; both gaseous and particulate emission factors were examined [3]. With the help of high altitude simulation, they mimicked two altitudes and compared them with local results. Besides, Gary et al conducted a long-term in-use heavy-duty test by adopting remote sensing measurements [4]. Currently, He et al reported their results on the emission characteristics of a heavy-duty diesel engine at simulated

high altitudes [5]. Although there were great discrepancies in the methodology, object and conduction in the previous works mentioned above, all the studies have confirmed the serious deterioration in vehicular emission in high altitude regions.

Except for emission characteristics, some researchers also devoted to the combustion characteristics at high altitude. Representative works were done by Shen et al [6]. Both natural aspirated and turbocharged diesel engines were introduced in this article. Three altitudes were simulated by using micro-computer controlled atmosphere-simulating devices. Pedro et al published a novel research on the performance and combustion characteristics of a diesel engine fuelled with diesel and biodiesel at 500m and 2400m [7]. Coincided conclusions like higher in-cylinder temperature and exhaust temperature, and postponed ignition delay at high altitude were made.

Although over twenty years has passed since the issue of high altitude emission was first aroused, many limitations remains in the treatment and management of high altitude vehicular pollution in China. Gaps existing between the realistic circumstances in China and in the U.S cannot be neglect. For instance, the highest altitude has been studied is still too low for China. The lab with highest altitude in the U.S is in Denver, where the altitude is around 2600m, but in the west of China, vehicles often operate where altitude is more than 3000m. Similar difficulties may also trouble some other countries, like Nepal and India. Hence, experimental study in a wider range of altitude should be executed.

As a significant operating condition in urban driving, idle is responsible for a large portion of civil ambient air pollution and getting public and researchers' attention. In order to further promote the civil air quality, some euro countries are projecting to introduce new type-approval test cycle, in which the percentage of idle test is greatly increased. For example, in the current test cycle, idle only occupies about 6% in the entire process, while this percentage has been raised to 17% in the future WHTC cycle. Due to the fact that turbocharger does not work at idle, the engine may encounter severe inadequate fresh charge at high altitude, which makes the problem of idle emission even more serious.

In this present paper, an experimental study on the combustion and emission characteristics of a heavy-duty diesel engine at various altitudes is reported, aiming at benefiting the vehicular emission management and control in the high altitude regions in China and other countries.

APPARATUS AND METHODOLOGY

Fig.1 illustrated a sketch of the on-board engine bench system, which integrated engine combustion analysis with emission measurement in a mobile platform. This setup could provide great convenience to the experiment location choosing; thereby the experiments with satisfied accuracy and credibility could be carried out at any expected altitude. A heavy-duty turbocharged diesel engine (Type

CA6DF3-20E3) manufactured by FAW Co, Ltd was introduced as the testing engine, of which the specifications were listed in Tab.1. The eddy current engine dynamometer introduced in this present paper was a product of CAMA, type CW440D, the minimum step of engine speed control was 1 r/min of this device.

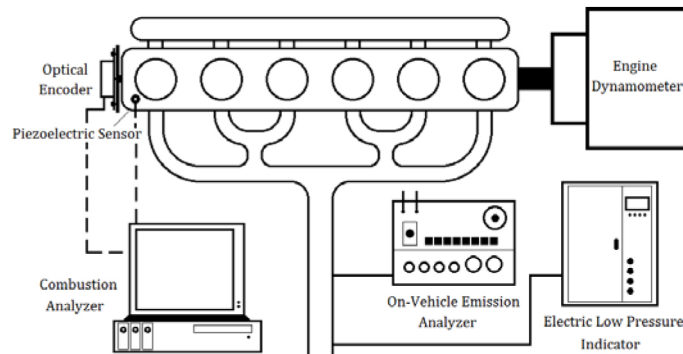


Figure 1. Sketch of the on-board engine bench system

Table 1. Specifications of the testing engine

Displaced volume	6.7 L
Stroke	125 mm
Bore	107 mm
Compression ratio	18.2:1
Maximum power	147 kW @ 2300 r/min
Maximum torque	760 Nm @ 1400 r/min
Emission target	EURO III

In-cylinder combustion analysis subsystem was mainly made up of a cylinder pressure sensor, optical encoder and combustion analyzer. Piezoelectric crystal sensor type 6052C made by Kistler was used to collect the instantaneous in-cylinder pressure, which was affixed in the cylinder head of the first cylinder. The measurement of crankshaft position was accomplished by an optical encoder type Kistler 2613, the precision of this apparatus was 0.2 degree crank angle. Dewetron 5000 series combustion analyzer was adopted to monitor the real-time condition of the engine and to record the data including crank angle, in-cylinder pressure, working displacement and temperature. Based on these data, gross heat release and fuel mass burning rate were calculated by self-made programs. In the calculation programs, the estimate of in-cylinder specific heat ratio followed the recommendation of Heywood in his book [8]. And Taylor's assumption of heat transfer item was introduced when calculating the gross heat release. Having finished the calculation of these two parameters, adjacent smoothing was applied to each output figures due to the undesired fluctuations found in the curves.

Both regulated gaseous emissions and particulate matters were measured in the emission test subsystem. On-vehicle emission analyzer SEMTECH-DS was in charge of measurement of regulated gaseous emissions, including CO, CO₂, HC and NO_x. The principle of carbon oxides test was NDIR method, while it was NDUV method in the measurement of nitric oxides. A heated FID device was used to measure the total hydrocarbon components in the exhaust stream. The resolution for CO, CO₂, HC and NO_x test was 10ppm, 0.01%, 1.0ppmC and 1ppm, respectively. Resolution time of this device was 1ms. Besides, real-time location, altitude and speed data was tested by a GPS device integrated in SEMTECH-DS.

DEKATI electrical low pressure indicator was responsible for the measurement of particulate matters. Based on that a particle would deflect in an electric field, it classified the particles contained in the exhaust flow into 12 levels by their aerosol diameters. The average diameter in each level was 0.021, 0.039, 0.072, 0.121, 0.203, 0.317, 0.486, 0.766, 1.234, 1.960, 3.102, 6.317 μ m, respectively. The aerosol diameter series designed in this device could exactly cover the range of PM_{2.5} and PM₁₀.

In each experiment, both the engine and the measurement devices were fully warmed, and both the coolant temperature and the lubricant oil temperature were in the appropriate range. At the beginning of combustion and emission test, the apparatus were first zeroed and stabilized to ensure the credibility of the results.

RESULTS AND DISCUSSION

Combustion Characteristics at Various Altitudes

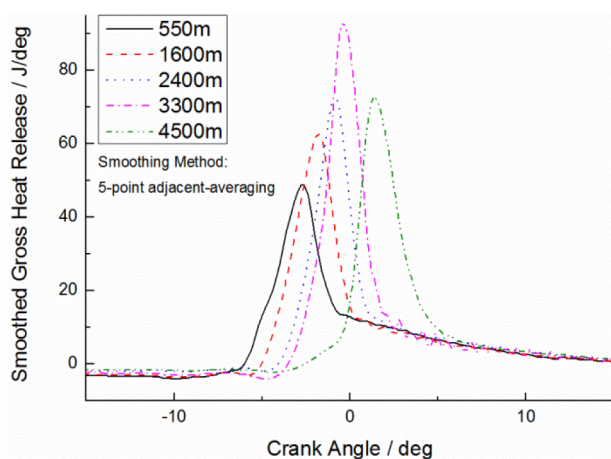


Figure 2. Smoothed gross heat release at various altitudes

In this section, combustion characteristics at various altitudes were discussed. Gross heat release was illustrated in Fig.2. As illustrated, the start of heat release was seriously

postponed with the rising of altitude. In another word, ignition delay became lengthened with the increase of altitude. This phenomenon was extremely obvious in the case where altitude was 4500m. Due to the fact that the atmospheric pressure at higher altitude was lower than that at lower altitude, when operating at high altitude, the intake mass flow became smaller. Hence, at higher altitude, the charge in-cylinder needed even longer compression to reach the self-ignition temperature of diesel, which led to a longer ignition delay at higher altitude.

Unlike gross heat release, there was a plateau appeared at 3300m in the correlation between the peak heat release and altitude. Regardless of the differences in the start and peak of heat release at various altitudes, the slopes of the heat release curves were very similar to each other; multi-ignition effect in a diesel engine and limited combustion reaction rate might contribute to this phenomenon.

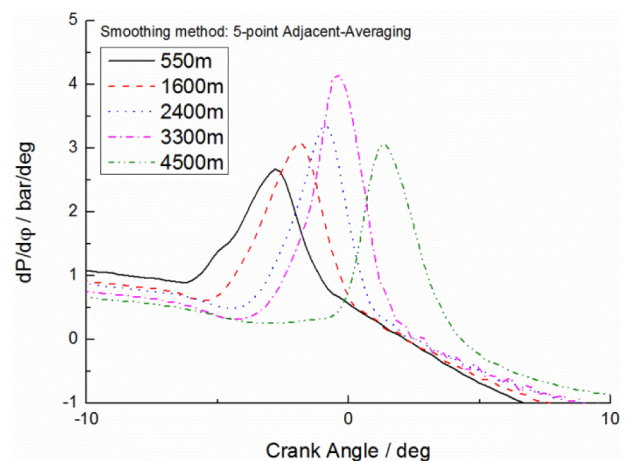


Figure 3. Smoothed pressure rise at various altitudes

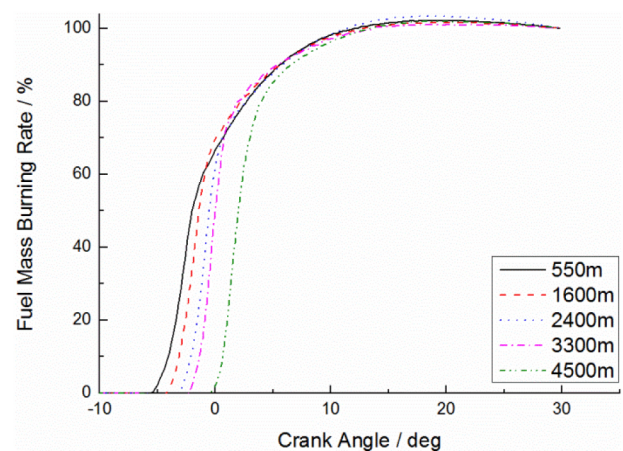


Figure 4. Fuel mass burning rate at various altitudes