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Experimental study on combustion and emission characteristics of turbocharged gasoline direct injection (GDI) engine under cold start new European driving cycle (NEDC)

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A R T I C L E I N F O

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A B S T R A C T

In this study, the combustion and emission characteristics of a turbocharged GDI engine under cold start NEDC were investigated based on chassis dynamometer test. The operating states, combustion and emission performance of GDI engine were measured continuously during vehicle driving cycles. Then, the combustion and emission characteristics of GDI engine under cold start NEDC were obtained and the influence factors were revealed by synchronous analysis of various operating parameters. The results show that, the combustion duration from start of combustion (SOC) to 50% combustion location changes a little under cold start NEDC. At most time, the 10–90% combustion duration usually changes in the range of 20–40 °CA, which turns longer under idling conditions but shorter under acceleration conditions. Since the sparking timing is severely retarded in the beginning stages of NEDC, the effect of cold start on hydrocarbon (HC) emission is very limited. HC emission increases sharply under deceleration conditions, due to the decrease of engine indicated mean effective pressure (IMEP). Carbon monoxide (CO) emission does not seem to have relevance to the cold start condition, and it is very sensitive to excess air coefficient while the effects of other parameters are very little. Nitrogen oxide (NOx) emission increases under acceleration conditions but decreases under deceleration conditions, which is mainly influenced by the IMEP, then followed by engine speed. All those not only demonstrated the change rules of combustion and emission characteristics of turbocharged GDI engine under cold start NEDC, but also provided the guidance for improving the vehicle emission performance.

1. Introduction

Recently, energy shortage and environmental pollution have become two major global issues [1–4]. As one of the most widely used source powers for automotive propulsion, internal combustion (IC) engine not only consumes a great deal of fuel but also produces a number of harmful pollution emissions [5,6]. Taking China as an example, IC engine consumes approximately two-thirds of the total consumption of crude oil, and meanwhile discharges about one-third of the total harmful gas emissions in China [7]. Hence, it is a very effective way to increase the fuel efficiency and reduce the harmful gas emissions of IC engine for the energy conservation and emission reduction of transportation. As such, in recent years the emission and fuel consumption regulations for vehicle are increasingly stringent all over the world. In order to meet those regulations, lots of advanced technologies are adopted in modern engines, including GDI [8–10], turbocharging [11,12], variable valve timing (VVT) [13,14], exhaust gas recirculation (EGR) [15,16], etc. Although the previous studies showed that IC engine fuel efficiency and emission performance can be effectively improved by adopting these advanced technologies, it is difficult to ensure the improvement of actual vehicle performance [17]. This is because in most cases the vehicle operates under transient conditions rather than

Abbreviations: ATDC, after top dead center; BTDC, before top dead center; CADC, common artemis driving cycle; CO, carbon monoxide; DCG, double clutch gearbox; EGR, exhaust gas recirculation; EUDC, extra urban driving cycle; GDI, gasoline direct injection; HC, hydrocarbon; IC, internal combustion; IMEP, indicated mean effective pressure; LPG, liquefied petroleum gas; NEDC, new European driving cycle; NOx, nitrogen oxide; PFI, port fuel injection; PM, particulate matter; RGF, residual gas fraction; RON, research octane number; SI, spark ignition; SOC, start of combustion; TDC, top dead center; TWC, three way catalysts; UDC, urban driving cycle; VVT, variable valve timing; WLTC, world-wide harmonized light duty test cycle; WLTP, world-wide harmonized light duty test procedure

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steady-state conditions, and the transient behaviors of IC engine under vehicle driving conditions are usually worse than its steady-state level. In other words, the steady-state performance of IC engine tested on bench cannot represent the actual performance of IC engine under vehicle driving conditions. Therefore, only by improving the combustion and emission characteristics of IC engine under transient conditions, can it ensure the satisfactory fuel efficiency and emission performance of vehicle [18]. On the other hand, in recent years, GDI and turbocharging are regarded as the two mainstream technologies for modern gasoline engine, thus the emission reduction potential of turbocharged GDI engine becomes a research hotspot in the field.

For the purpose of improving vehicle emission performance, scientists and engineers have made unremitting efforts for decades [19–23]. Chen et al. [24] investigated the characterizing particulate matter (PM) emissions from GDI and port fuel injection (PFI) vehicles under transient and cold start conditions, and stated that acceleration has a great impact on the PM emissions under warm conditions, whilst the torque has a significant impact on those of the PFI vehicle under cold conditions. Pavlovic et al. [25] carried out detailed experimental investigation on the differences of CO_2 emissions and vehicle energy demands under NEDC and worldwide light-duty test procedure (WLTP), and found that the WLTP worst-case scenario produces on average 11% higher CO_2 emissions and 44% higher energy demands than NEDC. Liu et al. [26] studied the cold start characteristics of liquefied petroleum gas (LPG) engine at low temperatures based on the first firing cycle. The results showed that combustion reliability, crankshaft speed and HC emission are significantly affected by the excess air coefficient during cold start. Dimaratos et al. [27] compared the effect of various technologies on light-duty vehicle CO_2 emissions over NEDC and WLTP, and found the effect of each technology on CO_2 emissions is different between NEDC and WLTP, owing to the different characteristics of each cycle. Sileghem et al. [28] studied emission results of a test programme of six vehicles on the test cycles worldwide light-duty test cycle (WLTC), NEDC and common artemis driving cycle (CADC). The analysis showed that the first trip of the test cycle could have an important contribution to the total emissions depending on the length of the trip. Myung et al. [29] studied the engine control strategies for particulate emissions from direct injection light-duty vehicle fueled with gasoline and liquid phase LPG, and found that significant particulate emissions were produced during the cold start and the transient warm-up operations of the GDI vehicle. Iodice et al. [30] investigated the effect of ethanol–gasoline blends on CO and HC emissions in last generation spark ignition (SI) engines within the cold-start transient conditions, and indicated that CO and HC cold start emissions decrease compared to the use of commercial gasoline. Kim et al. [31] evaluated engine control strategy on the time resolved HC and nano-particle emission characteristics of liquid phase LPG direct injection engine during the cold start. The experimental results showed that the retarded spark timing after the top dead center (TDC) and lean operation have an advantage to improve the time resolved HC, light-off temperature, and combustion characteristics in the cold start condition. Tsokolis et al. [32] investigated the fuel consumption and CO_2 emissions of passenger cars over the new worldwide harmonized test protocol, and quantified the CO_2 between WLTP-H and NEDC for a small gasoline and a medium diesel vehicle. Dardiotis et al. [33] tested the low-temperature cold-start gaseous emissions of late technology passenger cars, and claimed that CO and HC emissions of gasoline vehicles increased from 2.3 to 11.3 times at -7°C over the urban driving cycle (UDC), however remaining below the current legislative limits by 45% and 65% respectively. To provide recommendations for the new cycle, Demuynck et al. [34] analyzed the noxious emission results of a test programme of seven vehicles on the test cycles NEDC and CADC, and found the zones with the highest emissions of modern vehicles differ from vehicle to vehicle.

Although lots of research has been carried out on the IC engine emissions under vehicle driving conditions, the previous work is neither systematic nor complete. As mentioned above, lots of studies were focused on one or two kinds of emissions under vehicle driving cycles, while little attention was paid to the all kinds of vehicle emissions. At the same time, most of the previous research was focused on the change rules of vehicle emissions, without the in-cylinder combustion process of engine discussed. Thus, it is difficult to reveal the influence mechanisms or key control factors for engine emissions under vehicle driving cycles. To the authors' knowledge, the previous work on the completed emissions analysis of turbocharged GDI engine under vehicle driving cycles is few, and the authors failed to find the similar work about coupling analysis on combustion and emissions of turbocharged GDI engine under cold start NEDC. Therefore, the actual effects of vehicle operating states on the combustion and emission characteristics of turbocharged GDI engine are still not clear, and thus there is lack of theoretical basis to improve the actual emission performance of vehicle. For this reason, further studies on these issues are still necessary.

To solve these issues mentioned above, in this study the combustion and emission characteristics of a turbocharged GDI engine under cold start NEDC were studied based on chassis dynamometer test. In this paper, the complete descriptions of vehicle test rigs and measuring systems were reported, and the test programs of vehicle chassis dynamometer test were introduced. Through the research of this paper, the change rules of combustion and emission characteristics of turbocharged GDI engine under cold start NEDC were investigated. In this way, the influence mechanisms of combustion and emission characteristics of turbocharged GDI engine under vehicle driving conditions were revealed, and the suggestions were proposed for the purpose of improving the actual performance of vehicle. All these not only have provided basic data and optimization direction for improving vehicle emission performance, but also have greatly extended the research field of IC engine transient performance.

2. Experimental setup and vehicle test

2.1. Experimental setup

In order to investigate the combustion and emission characteristics of gasoline engine under vehicle driving cycles, both the engine emission performance and the parameters related to in-cylinder combustion of engine should be continuously tested firstly. In this study, the vehicle test was conducted on the chassis dynamometer, and the schematic diagram of test rig layout is shown in Fig. 1. As it can be seen, the vehicle test was processed in a closed system called as climatic chamber. The vehicle was fixed on the chassis dynamometer so as to simulate the actual operation under driving cycles [5]. The test rig control system consists of various subsystems, including central air-conditioning control system, fuel consumption meter, data acquisition and control system, monitoring system and fan control system, all of which were controlled by the main control system of test rig. A passenger vehicle was taken as the object of this study, which is powered by a four-cylinder, four-stroke, 1.4 L, turbocharged GDI engine. The main technical parameters of the turbocharged GDI engine are listed in Table 1. Since the content of this research was under vehicle driving conditions, the specifications of the tested passenger vehicle are also given, as shown in Table 2.

To test the combustion and emission performance of GDI engine under vehicle driving conditions, the corresponding test instruments and sensors were employed for vehicle test, and the technical parameters of test instruments are presented in Table 3. It should be noted that the accuracy value in Table 3 was obtained according to the calibration data or the technical documentation of test instruments. The measuring range and accuracy of test instruments were carefully selected and then accurately calibrated so as to ensure the accuracy and reliability of tested data. More specifically, the range and accuracy of cylinder pressure sensor, temperature sensor and Lambda analyzer were selected according to the test standard. Before the vehicle test, the temperature sensor was calibrated from room temperature to high