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Comparative study on thermodynamics, combustion and emissions of turbocharged gasoline direct injection (GDI) engine under NEDC and steady-state conditions

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ABSTRACT

For a vehicle engine, it usually operates under transient conditions, and the transient behaviors represent its actual performance. In order to improve the actual performance of GDI engine during vehicle driving cycles, the vehicle test was conducted under new European driving cycle (NEDC), and the thermodynamics, combustion and emission characteristics were tested. Then, the transient performance of GDI engine was compared with the steady-state behaviors. In this way, the differences in various performance parameters under NEDC and steady-state conditions were demonstrated, and the reasons were revealed. Results show that, the spark timing, start of combustion (SOC), ignition delay, 50% combustion location and 10–90% combustion duration of GDI engine under NEDC deviate from their steady-state values seriously especially at low load, resulting in the large combustion instability. The consistency of pumping mean effective pressure (PMEP) under NEDC and steady-state conditions is satisfactory, while the indicated thermal efficiency has a large fluctuation during NEDC, and in most cases it is lower than the steady-state values. Both the transient HC and CO emissions are larger than the steady-state values especially at low load, while the transient NOx emission during NEDC is less than the steady-state values. All those not only demonstrated the change rules of combustion and emission characteristics of GDI engine under NEDC, but also provided guidance for improving the actual performance of vehicle engine.

1. Introduction

With the rapid development of economy and the increase of population, the global energy and environment crisis arose and is becoming more and more serious, which has aroused great attention of people. As the largest developing country in the world, the energy and environmental problems in China are particularly severe [1–3]. Due to the shortage of petroleum resources and increasing petroleum demand, China has become the world's largest petroleum importer and consumer in recent years, and its net petroleum import presents an upward trend [4]. The statistics suggested that internal combustion (IC) engine consumes approximately two-thirds of the total consumption of crude petroleum and meanwhile discharges about one-third of the total harmful gas emissions in China [5,6]. For this reason, the energy saving and emission reduction for IC engine are of great significance.

As it is known to all, the performance development, optimization and calibration of operating parameters for IC engines are usually accomplished by numerical simulation or bench test under steady-state conditions at present [7,8]. However, the actual operating conditions of vehicular engines are mostly transient, which causes the deviations between the steady-state behaviors under bench test and the actual operating performance under driving conditions. Due to the lack of online detection method and technology for IC engine operating and performance parameters under transient conditions in the past, the actual performance for IC engine equipped in the vehicle was usually unknown [9]. The differences between transient and steady-state tested results and the influence factors were not explained clearly. The quality of parameters calibrated under the steady-state conditions is often confused under transient conditions. Because of these, the actual performance of vehicle engine deviates from the bench tested results to some extent [10,11].

Recognized the importance of transient performance, many scientists and engineers have paid lots of attention on the IC engine transient performance from several aspects [12–17]. Xu et al. [18] compared the in-cylinder combustion and heat-work conversion processes of vehicle engine under transient and steady-state conditions, and found that

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Nomenclature

X_ϕ	mass fraction burned [–]
$\frac{dQ_E}{d\varphi}$	instantaneous heat release rate [J/°CA]
m_{fuel}	fuel mass [kg]
H_u	low heating value [kJ/kg]
p	pressure [Pa]
V_h	displacement [L]
η_i	indicated thermal efficiency [–]
η_τ	percent of ignition delay [%]
τ_{SA-SOC}	ignition delay [°CA]

Abbreviations

AFR	air–fuel ratio
BTE	brake thermal efficiency
CA	crank angle
GDI	gasoline direct injection
HDDI	heavy-duty direct injection
HRR	heat release rate
IC	internal combustion
IMEP	indicated mean effective pressure
LNT	lean NOx trap
LPG	liquefied petroleum gas
MFB	mass fraction burned
NEDC	new European driving cycle
PFI	port fuel injection
PID	percent of ignition delay
PM	particulate matter
PMEP	pumping mean effective pressure
PN	particulate number
RGF	residual gas fraction
RON	research octane number
SI	spark ignition
SOC	start of combustion
TDC	top dead center
TWC	three way catalyst
UDC	urban driving cycle
VGT	variable geometry turbocharger
VVT	variable valve timing
WLTC	world-wide harmonized light duty test cycle
WLTP	world-wide harmonized light duty test procedure

there is a satisfactory consistency of IC engine performance under load-step and steady-state conditions. However, the operating and control parameters gravely deviate from the steady-state values under vehicle driving conditions. Zhang et al. [19] experimentally analyzed the combustion deterioration of an automotive diesel engine under transient operation and optimized the transient combustion process by adjusting the fuel injection parameters. For the purpose of reducing fuel cost and CO_2 emissions, Emiliano [20] studied the spark ignition feedback control by means of combustion phase indicators under steady and transient operations. Through the research, the combustion phase indicators proved to be suitable for proportional-integral feedback spark advance control, allowing fast and reliable control even in transient operations.

Tziourtzioumis et al. [21] compared the results of steady-state and transient engine bench tests of a common-rail passenger car diesel engine fuelled by B70 biodiesel blend with the corresponding results of baseline tests with standard EN 590 diesel fuel. The results indicate significant differences in fuel system dynamics and transient engine operation with the B70 blend at high fuel flow rates. Wu et al. [22] investigated the influence of Miller cycle and variable geometry turbocharger (VGT) on combustion and emissions under steady and transient operations of a heavy-duty diesel engine. The results revealed that Miller cycle decreased soot and NOx emissions and increased brake thermal efficiency (BTE) under certain circumstance, and in the transient process VGT strategy can achieve good torque response and emissions. Gao et al. [23] proposed an on-line combustion phase optimization and control approach, and then validated it at steady-state and mild transient-state operating conditions. By using this approach, the combustion phase can be optimized to keep maximum indicated fuel conversion efficiency. Rakopoulos et al. [24] evaluated the impact of properties of vegetable oil, bio-diesel, ethanol and n-butanol on the combustion and emissions of turbocharged heavy-duty direct injection (HDDI) diesel engine operating under steady-state and transient conditions, and analyzed the fuel injection, combustion chamber pressure and heat release rate (HRR) diagrams to reveal interesting features of the combustion mechanisms.

In terms of IC engine emission performance under transient conditions, there is also lots of previous work. Chen et al. [25] studied the characterizing particulate matter emissions from GDI and port fuel injection (PFI) vehicles under transient and cold start conditions, and concluded that acceleration has great impact on the particulate matter (PM) emissions under warm-up conditions, whilst torque has a significant impact on the PFI vehicle PM emissions under cold start conditions. Pavlovic et al. [26] tested the CO_2 emissions and energy demands of vehicles under the NEDC and the new WLTP conditions, and then claimed that diesel vehicles are more impacted than gasoline from NEDC to WLTP transition. Liu et al. [27] experimentally investigated the cold start characteristics at low temperatures based on the first firing cycle in a liquefied petroleum gas (LPG) engine. 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. [28] compared the effects of various technologies on light-duty vehicle CO_2 emissions over NEDC and WLTP. The study showed that the effects of each technology on CO_2 emissions are different between NEDC and WLTP, owing to different characteristics of each cycle. Ko et al. [29] investigated the NOx emission characteristics from a Euro 6-compliant diesel passenger car over the NEDC and WLTC at various ambient temperatures, and found more lean NOx trap (LNT) regeneration events of 2.5 times in the WLTC than NEDC mode. Myung et al. [30] comparatively studied the engine control strategies for particulate emissions from direct injection light-duty vehicle fueled with gasoline and liquid phase LPG. The experimental results showed that significant particulate number (PN) emissions were produced during the cold start and the transient warm-up operations of GDI vehicle, due to application of split injection and catalyst heating function. Iodice et al. [31] studied the effect of ethanol–gasoline blends on CO and HC emissions in last generation spark ignition (SI) engines within the cold-start transient, and the results indicated that CO and HC cold start emissions decrease compared to the use of commercial gasoline, with the 20% ethanol blend achieving the highest emission reduction. Kim et al. [32] experimentally evaluated engine control strategy on the time resolved THC and nano-particle emission characteristics of liquid phase LPG direct injection (LPG-DI) engine during the cold start, and the experimental results showed that the retarded spark timing after the top dead center (TDC) and lean operation have advantage to improve the time resolved THC and combustion characteristics in the cold start condition. Tsokolis et al. [33] assessed the effect of WLTP introduction on the reported CO_2 emissions from passenger cars presently measured under the NEDC and the corresponding test protocol, and found the average cold start effect on CO_2 emissions over WLTP 6.102 g/km, while for NEDC it was found 12.302 g/km. Dardiotis et al. [34] studied the low-temperature cold-start gaseous emissions of late technology passenger cars, and the test results showed that CO and total HC emissions of gasoline vehicles increased from 2.3 to 11.3 times at 617 °C