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# Quantitative investigation the influences of the injection timing under single and double injection strategies on performance, combustion and emissions characteristics of a GDI SI engine fueled with gasoline/ethanol blend

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ABSTRACT

An experimental investigation of the single injection strategy and double injection strategy on the combustion phasing, performance and emissions characteristics in the GDI engine fueled with E10 was conducted. The effective expansion ratio (EER), effective expansion efficiency (EEE) and residual gas fraction (RGF) characteristics were further investigated under single injection strategy and double injection strategy. The result indicated that under the single injection strategy, the change trends of the EER and EEE were the same as the gasoline effective brake thermal efficiency (GEBTE). The maximum value of the EER and EEE were 7.86 and 0.513, and the maximum decrease magnitude of EER and EEE was 8.86% and 3.63%, respectively. However, the change trend of RGF was opposite to BTE, and its maximum increase magnitude of RGF was 4.72%. In addition, with the increase of the second end of injection timing, the peak combustion pressure (PCP), maximum heat release rate (HRR) and mean in-cylinder temperature gradually increased. The position of the maximum PCP and maximum HRR closed to the TDC. The CA50 combustion location advanced and the combustion duration shortened, and thereby increasing the EER, EEE and GEBTE. Finally, comparing the single injection strategy with the double injection strategy, the GEBTE decreased by 5.09%, while the NOx and HC emissions sharply decreased by 54.46%, 31.81%, respectively.

## 1. Introduction

Currently, the automobile industry still plays an irreplaceable and important role in the development of the world economy, science, and technology. However, it also brings about the energy crisis and environmental pollution caused by the internal combustion engine (ICE) fueled with traditional gasoline or diesel [1–4]. With the limitation of the air pollution and more stringent emission requirements (China-6 or Euro-6), decreasing the fuel consumption and emissions from the ICE have become the major issues for the sake of achieving the sustainable development of society and economy in the world, particularly in China. For example, compared with the China-5 emission standard, the amount of HC, CO and NOx emissions are sharply reduced by half, and both particle mass (PM) and particle number (PN) measurement requirements are introduced in China-6 emission standard [5]. Although new energy vehicles (NEVs) can alleviate the problem of reducing emissions and fuel consumption to a certain extent, the key system (lithium batteries or fuel cells) is difficult to make substantial technological breakthroughs in the short term [6]. Therefore, the ICE would be the main power source in the transportation industry in next decades in the traditional vehicle and hybrid vehicle, particularly in heavy transport applications. In addition, a series of advanced technologies

*Abbreviations:* ICE, internal combustion engine; CO, carbon monoxide; HC, hydrocarbon; NOx, nitrogen oxide; NO, nitric oxide; PM, particle mass; PN, particle number; NEVs, new energy vehicles; EGR, exhaust gas recirculation; VVL, variable valve lift; VVT, variable valve timing; HCCI, homogeneous charge compression ignition; GDI, gasoline direct injection; SG-SIDI, spray-guided spark-ignited direct-injection; IMEP, indicated mean effective pressure; BTE, brake thermal efficiency; TDC, top dead center; bTDC, before top dead center; CNG, compressed natural gas; BSFC, brake specific fuel consumption; PCP, peak combustion pressure; EER, effective expansion ratio; EEE, effective expansion efficiency; RGF, residual gas fraction; CR, compression ratio; ECU, electronic control unit; ROHR, rate of heat release; SOC, start of combustion; EOC, end of combustion; $COV_{IMEP}$, coefficient of variation in the IMEP; GEBTE, gasoline effective brake thermal efficiency; GEITE, gasoline effective indicated thermal efficiency; HRR, heat release rate

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such as exhaust gas recirculation (EGR) [7,8], variable valve lift (VVL) [9,10], variable valve timing (VVT) [11,12], homogeneous charge compression ignition (HCCI) [13,14] and spray-guided spark-ignited direct-injection (SG-SIDI) [15,16] have been widely applied to reduce emissions and fuel consumption. In terms of GDI engine, since the fuel is directly injected in the cylinder, the injection strategies, which consist of the number of injections and injection timing, exerted great influences on the quality of the in-cylinder mixture, combustion and emissions. Therefore, many researchers have engaged in researching on the injection strategies for many years, and further studied the effects of single injection strategy and multi-injection strategy on performance, combustion and emissions characteristics of a GDI engines.

As for the single injection strategy, Oh et al. [17] studied the effects of injection timing on the spray and combustion characteristics in a SD-SIDI engine. The results presented that, with the increase of injection timing, both the combustion stability and combustion efficiency first improved and then decreased, and generated many incomplete combustion products when injection timing was earlier or later because of over or insufficient mixing. In addition, the soot increased with the delay of the injection timing, and the NOx emissions decreased with the increase of indicated mean effective pressure (IMEP) and the delay of the injection timing. Jiang et al. [18] investigated the effects of different injection pressures and injection timings in a GDI engine on the combustion and emissions of the surrogate fuels. The results showed that the brake thermal efficiency (BTE) first increased and then decreased with the increase of the injection pressure and the injection timing. Besides, when the injection timing was set at before top dead center (bTDC) 330 °CA, the BTE reached the highest and the CO and HC reached the lowest. Wang et al. [19] studied the effect of injection pressure and fuel types on particle mass (PM) and particle number (PN) on a single cylinder GDI engine. The results reported that compared with gasoline, the combustion of ethanol produced more PM and less PN. Furthermore, the injection pressure had little effect of the production of PM for ethanol, but the higher injection pressure produced more PM for gasoline.

As for the multi-injection strategy, Schmidt's research work [20] showed that multi-injection strategy resulted in improving combustion stability compared with the single injection strategy in SI-SIDI engine. Park's research [21] showed that compared with single injection strategy, multiple injection strategy extended the misfire limit, and double injection with a slight delay could effectively ensure the combustion stability of lean combustion but increase the soot emissions due to the shortening of the mixing time. In addition, multi-injection strategy could reduce NOx emissions, but there was a trade-off between the reduction of NOx emissions and the improvement of fuel economy. Oh et al. [22] studied the effects of multi-injection strategy on combustion characteristics in a GDI engine. The split ratio of each multi-injection strategy was 1:1 for double injection and 1:1:1 for the triple injection. The results showed that compared with single injection strategy, both the IMEP and combustion efficiency increased, but the cycle-to-cycle variations of IMEP sharply decreased for double and triple injection strategy. In addition, both the HC and CO emissions sharply decreased, but the NOx emissions increased at the double injection strategy. Song et al. [23] studied the effects of multiple injection strategy on the mixture quality and the combustion characteristics in a GDI engine. The results presented that for the single injection, both combustion rate and in-cylinder pressure increased with the increase of injection timing due to the higher turbulence intensity. In addition, compared with the single injection strategy, the double injection strategy could improve the BTE and engine power by utilizing the additional turbulence induced by the spray motion.

Apart from those advanced technologies were applied in the GDI engines, many researchers have engaged in researching on the alternative fuels for many years, and studied the effects of alternative fuels blended with the gasoline on performance, combustion and emissions characteristics of a GDI engines, such as compressed natural gas (CNG), hydrogen, methanol, and ethanol [24–27]. Among those alternative fuels, ethanol is considered as the one of the most promising alternative fuels for GDI engines because of its advantages [28]. First of all, the latent heat of vaporization of ethanol is larger than that gasoline, which is beneficial to improve the volumetric efficiency by reducing the intake air temperature, decrease brake specific fuel consumption (BSFC) by improving the combustion process of the engine, and reduce the NOx and soot emissions through reducing in-cylinder temperature. Secondly, compared with pure gasoline, the ethanol/air has the higher laminar flame speed, and those advantages are conducive to operating at leaner and more diluted mixture [29]. Lastly, the ethanol has the higher octane number and shows good anti-knocking performance, which can improve the compression ratio of gasoline engine and enhance the indicated thermal efficiency. Iodice et al. [30] studied the effects of different percentages of ethanol mixed in gasoline fuel blends (10%, 20% and 30% volume of ethanol in gasoline) on emissions and energy consumption characteristics of SI engine. The results showed that the SI engine fueled with optimal blend could get the lowest CO, NOx and HC emissions. In our previous works [31,32], injection strategies were investigated on thermodynamic process and performance characteristics of GDI engines fueled with E10 (10% ethanol content). The results showed that compared with single injection strategy, 50% combustion position was slightly shifted to TDC and 10–90% combustion duration was shortened in double injection strategy, and the cycle-by-cycle variations of IMEP was significantly increased with the second injection fuel mass repartition. In our latest work [33], an experimental study on the combustion phasing, performance and emissions characteristics was conducted on DISI engines fueled with E10. And the results showed that for single injection strategy, both peak combustion pressure (PCP) and maximum in-cylinder temperature first increased and then decreased with the increase of injection timing and the optimal injection timing was set at 300 °CA BTDC. In addition, for double injection strategy, with the increase of the percentage of first fuel injection distribution, the HC emission increased but the NOx emissions decreased. Besides, the coefficient of variations in the IMEP was remarkably affected by the percentage of first fuel injection distribution.

Based on the above literature, the control parameters (fuel composition, injection pressure, injection timing, and the first fuel injection distribution under double injection) comprehensively investigated in previous works. However, few studies have combined gasoline/ethanol blend and two-stage injection strategy (sweeping the end of the second injection timing) to investigate the combustion process, performance and emissions characteristics on a GDI engine. Thus, in this paper, the effect of injection timing under single injection strategy was further investigated on the effective expansion ratio (EER), effective expansion efficiency (EEE) and residual gas fraction (RGF) characteristics in the GDI engine fueled with E10. Then the effects of the end of the second injection timing under double injection strategy were also study by analyzing the thermodynamic process (including EER, EEE, RGF and combustion phasing), performance, emissions characteristics. From this viewpoint, this study is quite different from the previous works, including the control strategy and performance parameters analysis.

## 2. Experimental setup

### 2.1. Test engine and bench

In order to analyze the effects of injection strategies on the thermodynamic progress, performance, emissions characteristics of a GDI engine fueled with E10, some preparations were done before starting the experiments, such as building the engine test bench, installing and calibrating the experimental equipments and sensors. First, the tested GDI engine in this paper was a turbocharged, intercooler, double VVT, inline 4-cylinder engine with a displacement of 2.0 L and a geometric compression ratio (CR) of 10. And the main features of the test engine were listed in Table 1. The properties of gasoline, ethanol, and E10