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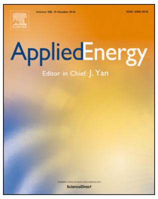

Influence of single injection and two-stagnation injection strategy on thermodynamic process and performance of a turbocharged direct-injection spark-ignition engine fuelled with ethanol and gasoline blend

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HIGHLIGHTS

- This study demonstrated the ability of two-stagnation injection strategy control on thermodynamic process and performance.
- The combustion efficiency can be improved and optimized by two-stagnation injection strategy.
- The mean gas temperature in cylinder declined with two-stagnation injection strategy.
- NOx emissions significantly decreased with changing SI mode into various TSIS modes.

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ABSTRACT

A comparative investigation was conducted on a turbocharged direct-injection spark-ignition engine fuelled with gasoline and ethanol blend. Influences of single injection (SI) and two-stagnation injection strategy (TSIS) on thermodynamic process and performance of the engine operated on part-load condition were discussed and compared in this paper. The results indicated that 50% combustion position was slightly shifted to TDC and 10–90% combustion duration was shortened by using TSIS modes as compared with SI mode. However, the coefficient of variation in the indicated mean effective pressure was significantly increased with the second injection fuel mass repartition. In addition, the brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) were increase by adopting the TSIS modes, but the increase amplitude of BTE and BSFC was decreased, and even deteriorated in TSIS 6 mode. In comparison with SI mode, Hydrocarbon and carbon monoxide were declined with advanced second injection timing while both of them increased with increasing second injection fuel mass repartition. Moreover, NOx emissions were dramatically reduced by utilizing TSIS modes. Eventually, CO2 emission was mainly related to the carbon atom content, combustion efficiency and heat-work conversion in-cylinder.

1. Introduction

With the escalating degrees in the depletion of traditional fossil fuels and the deterioration of environment issues, more stringent emission norms and fuel consumption regulations have been implemented on internal combustion engines (ICEs) [1–3]. Thus, the optimization of performance and reduction of exhaust gas emissions of ICEs are important priorities. The adoption of the gasoline direct injection (GDI) also known as direct-injection spark-ignition (DISI) engine entered the car market in the late 1990s [4,5], and now DISI engine is considered indispensable and became the mainstream technology for the car makers throughout the world due to its higher thermal efficiency, better fuel economy, more precise air-fuel ration ratio and faster cold start or transient response [6], which can be coupled with downsizing and turbo-charging to achieve the future carbon dioxide (CO_2) [7,8] target emission. In contrast with port fuel injection (PFI) engine, DISI engine dramatically decreases the pumping loss at part-load operations and fuel injection events are decoupled from valve actuation [9]. Moreover, DISI engine is more efficient for charged cooling due to fuel evaporating in cylinder, resulting in improving the volumetric

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Nomenclature

P_e	brake power (kW)
$LHV_{gasoline}$	lower heating value of gasoline (kJ/kg)
$LHV_{ethanol}$	lower heating value of ethanol (kJ/kg)
$\dot{v}_{gasoline}$	volumetric flow rate of gasoline (m^3/h)
$\dot{v}_{ethanol}$	volumetric flow rate of ethanol (m^3/h)
$\rho_{gasoline}$	density of gasoline (kg/m^3)
$\rho_{ethanol}$	density of ethanol (kg/m^3)
V_d	cylinder displacement (m^3)
dV	differential of cylinder volume (–)
p	instantaneous in-cylinder pressure (MPa)
b_e	brake specific fuel consumption (g/KW·h)
B	mass flow of the blend fuel (kg/h)
$\eta_{combustion}$	combustion efficiency (–)
h_{CO}	enthalpy of CO (kJ/kmol)
h_{THC}	enthalpy of THC (kJ/kmol)
$\dot{m}_{CO}$	mass flow of CO (kg/h)
$\dot{m}_{THC}$	mass flow of THC (kg/h)

Abbreviation

ICEs	internal combustion engines
GDI	gasoline direct injection
DISI	direct-injection spark-ignition
CO_2	carbon dioxide
PFI	port fuel injection
TWC	three-way-catalyst
PM	particulate matter
CCV	cycle-to-cycle variation
VVT	variable valve timing
VCR	variable compression ratio
EGR	exhaust gas recirculation
PCCI	premixed charge compression ignition
CR	compression ratio
CI	compression ignition
IMEP	indicated mean effective pressure
COV_{IMEP}	coefficient of variation of IMEP
CO	carbon monoxide
HC	hydrocarbon
ECU	electric control unit
NOx	nitrogen of oxides
EDI	ethanol direct injection
GPI	gasoline port injection
BDC	bottom dead center
NEDC	New European Driving Cycle
TSIS	two-stagnation injection strategy
HRR	heat release rate
SI	single injection
TDC	top dead center
SOC	start of combustion
CA50	50% mass fraction burned
BTE	brake thermal efficiency
BSFC	brake specific fuel consumption
LTC	low temperature combustion

efficiency of the engine. The DISI engine can even operate with overall lean mixture by fuel stratified injection, namely by forming a stoichiometric air-fuel ratio around the spark plug and lean mixture close to the in-cylinder wall. Most GDI engines are operated on the stoichiometric combustion mode for the three-way-catalyst (TWC) working with a high efficiency.

However, since the gasoline fuel is injected directly into the cylinder, the formation time of the fresh air and fuel mixture is shorter than that in PFI engine. Hence, the homogeneousness of the mixture in the cylinder is nonuniform because of the flow field varying with engine operating conditions, and there are some locality rich mixture regions at the ignition timing. These locality rich mixture regions have been unveiled as one of the major sources of particulate matter (PM) formation and uncompleted combustion [9,10]. At the same time, high cycle-to-cycle variation (CCV), which is one of the drawbacks of spark ignition (SI) engines, can limit the performance of ICEs. Variation in gas motion during the intake process, compression and combustion, variation in the amount of fuel per cycle, fresh air and residual gas, and variation in the mixture composition near the spark plug affect the CCV and emissions characteristics in SI engines [11–13]. Thus, several techniques such as variable valve timing (VVT) [14], variable compression ratio (VCR) [15,16], fuel injection strategies and variable injection pressure [17,18], intake air temperature control [19], and exhaust gas recirculation (EGR) [20–22] have been widely used in order to address these disadvantages. Hunicz et al. [23] investigated the influence of fuel injection strategies in controlled auto-ignition gasoline engine, and results reported that application of split injection showed benefits versus the single injection and examination of various fuel mass split ratios and variable second injection timing resulted in further optimization of mixture formation. In addition, at equal share of the fuel mass injected in the first injection during negative valve overlap and in the second injection at the beginning of compression, the lowest emission level and cyclic variability improvement were observed. Sementa et al. [24] performed ultraviolet-visible imaging measurements on a GDI engine, operating in homogeneous and stratified charge mixture conditions fueled with gasoline and bio-ethanol, and results revealed that gasoline spray was more sensible to air motion and in-cylinder pressure than ethanol was. Apart from that, the stratified flame front for both fuels was about 40% faster compared with homogeneous in the first phase due to the A/F ratio local distribution, resulting in better performance in terms of stability and maximum pressure. Morcinkowski et al. [25] investigated cycle-to-cycle fluctuations of a gasoline auto ignition engine by conducting numerical simulation and experiments. Due to the high amount of residual gas in the cylinder, the preceding cycle and its combustion have strong influences on the next cycle by directly affecting the thermodynamic state of the in-cylinder charge. The simulation reported a nearly exact agreement to the measured mean pressure curve. Also the cycle-to-cycle fluctuations were resolved. Thus, the model can be described by fluctuations in fuel mixture, residual gas and temperature stratification.

Other strategies, which blend with various alternative fuels (for instance, hydrogen, methanol, and ethanol) and different mixing ratios, were widely implemented on DISI engine to attain lower emission [26–30]. Among them, ethanol is a promising alternative fuel addition to gasoline, such as E10 (10% v/v of ethanol in gasoline) [31,32], E30 [33,34], and even E90, E100 [35], which were widely used in a series of engines without great modification to controlling and operating parameters of the electric control unit (ECU) [36]. Alcohol has a higher octane number which indicates a relative high antiknock value, good property and quality at high compression ratio, avoiding end-gas region self-ignition [37]. Furthermore, its greater latent heat of vaporization in the cylinder provides a higher charge density; its faster laminar flame speed and oxygenated fuel enable the engine to operate at leaner or stratified conditions and more diluted air–fuel mixtures [38]. Meanwhile, it decreases pollutant emissions compared with pure gasoline. Baêta et al. [38] explored the limits of a down-sized ethanol direct injection spark ignited engine and enhanced the combustion behavior of a 1.4 L down-sized engine, and reduction of HC emissions (18%) and NOx emission (12%) was obtained due to the improved in-cylinder mixture distribution and the cooled EGR. Huang et al. [39] studied the