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# Investigation to charge cooling effect and combustion characteristics of ethanol direct injection in a gasoline port injection engine

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## HIGHLIGHTS

- Charge cooling became more effective with increase of ethanol ratio within 0–58%.
- Greater ethanol ratio (>58%) led to local overcooling, wall wetting and lean mixture.
- Combustion performance was improved with increase of ethanol ratio up to 58%.
- NO emission decreased and CO and HC emissions increased with the increase of ethanol ratio.
- Performance of an EDI + GPI engine can be optimised at ethanol ratio of 40–60%.

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## ABSTRACT

Ethanol direct injection has the potentials to increase the engine compression ratio and thermal efficiency by taking advantages of ethanol fuel such as the high octane number and latent heat. In this study, CFD modelling and experiments were carried out to investigate the charge cooling effect and combustion characteristics of ethanol direct injection in a gasoline port injection (EDI + GPI) engine. Experiments were conducted on a single-cylinder spark ignition engine equipped with EDI + GPI over a full range of ethanol ratio from 0% (GPI only) to 100% (EDI only). Multidimensional CFD simulations to the partially premixed dual-fuel spray combustion were performed to understand the experimental results. The simulations were verified by comparing with the experimental results. Simulation results showed that the overall cooling effect of EDI was enhanced with the increase of ethanol ratio from 0% to 58%, but was not enhanced with further increase of ethanol ratio. When the ethanol ratio was greater than 58%, a large number of liquid ethanol droplets were left in the combustion chamber during combustion and fuel impingement on the cylinder wall became significant, leading to local overcooling in the near-wall region and over-lean mixture at the spark plug gap. As a consequence, the CO and HC emissions increased due to incomplete combustion. Compared with GPI only, the faster flame speed of ethanol fuel contributed to the greater peak cylinder pressure of EDI + GPI condition, which resulted in higher power output and thermal efficiency. Meanwhile, the mixture became leaner with the increase of ethanol ratio. As a result, the IMEP was increased, combustion initiation duration and major combustion duration were decreased when ethanol ratio was in 0–58%. The combustion performance was deteriorated when ethanol ratio was greater than 58%. Experimental and numerical results showed that the IMEP, thermal efficiency and emissions of this EDI + GPI engine can be optimised in the range of ethanol ratio of 40–60%.


## 1. Introduction

Engine downsizing is a promising technology to achieve the future $CO_2$ reduction target of spark ignition (SI) engines [1–4]. However one major issue associated with the downsized engines is the increased knock propensity [1,4]. Recently ethanol direct injection (EDI) has emerged as a potential technology to fully implement the engine downsizing. The engine knock propensity can be reduced by the higher octane number of ethanol fuel, and supplemented by the cooling effect enhanced by direct injection and ethanol's greater latent heat.

Compared with port injection (PI), direct injection (DI) is more effective for charge cooling due to fuel evaporation inside the combustion chamber. Moreover, cooling effect of DI can be further enhanced by the fuel with greater latent heat of vaporisation, such

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**Nomenclature**

| | | | |
|---|---|---|---|
| ASOI | after the start of injection | MFB | mass fraction burnt |
| BTDC | before top dead centre | PDF | probability density function |
| CAD | crank angle degrees | PI | port injection |
| CFD | computational fluid dynamics | RON | research octane number |
| DI | direct injection | SI | spark ignition |
| ECFM | Extended Coherent Flame Model | $\Phi$ | equivalence ratio |
| EDI | ethanol direct injection | CA0–10% | combustion initiation duration |
| GPI | gasoline port injection | CA10–90% | major combustion duration |
| EDI + GPI | ethanol direct injection plus gasoline port injection | E′X′ | X% ethanol by volume. e.g. E46 is 46% ethanol via DI + 54% gasoline via PI |
| IMEP | indicated mean effective pressure | | |

as ethanol fuel. Cooling effect of DI has been measured in different ways. The most effective way may be to measure the in-cylinder temperature directly. Kar et al. [5] and Price et al. [6] used a cold wire resistance thermometer to measure the in-cylinder temperature in PI and DI engines. However this method requires fast response of the temperature sensor and protection for the fragile sensor. So the measurements were only performed in non-firing conditions [5,6]. The Planar Laser Induced Fluorescence (PLIF) thermometry technique was used to measure the cylinder temperature of DI engines [7]. Up to date, the experimental methods to quantify the charge cooling used the parameters linked to the charge cooling directly or indirectly, such as in-cylinder pressure, volumetric efficiency, and anti-knock ability. Ahn et al. [8] used in-cylinder pressure to evaluate the cooling effect of ethanol fuel. Wyszynski et al. [9] measured the volumetric efficiency of different fuels on a DI SI engine fitted with both port and direct fuel injection systems. However, using intake air flow rate to quantify the amount of charge cooling only captured part of the cooling effect that took place during the intake stroke. Fuel evaporation process may continue after the intake valves are closed, and even in the combustion process [10]. To evaluate the cooling effect on a special aim, knock onset was used to measure the charge cooling effect in a turbocharged SI engine equipped with both PI and DI of blended ethanol/gasoline fuels [10,11]. Similar investigation was carried out in an attempt to identify the thermal and chemical benefits of DI and PI [12]. They reached the same conclusion that the ethanol's cooling effect enhancement to the engine performance was comparable to that of its higher octane number [11,12]. To quantify the thermal and chemical benefits of ethanol fuel, it is reported that a 2–8 kJ/kg increase of "cooling power" of the mixture had the same impact as one-point increase of research octane number (RON) [1]. Or 10% of ethanol addition to gasoline results in five-point increase of RON [13].

Meanwhile, numerical simulations have also been applied to investigate the cooling effect. 0-D simulations (involving no engine geometry) were performed to calculate the theoretical improvement in volumetric efficiency of DI over PI [9]. 1-D gas dynamics and thermodynamics engine simulations were carried out to investigate the anti-knock effect of direct injection with ethanol/gasoline blends [11]. As the 0-D and 1-D simulations were developed for special purposes, the information obtained in the results was limited. Kasseris and Heywood [10] used 3-D numerical modelling to investigate the effect of intake air temperature on the amount of realised charge cooling. The simulation results showed that almost all the theoretical charge cooling was realised when the intake air temperature was increased to 120 °C. However the simulated evaporation rate of ethanol fuel in low temperature conditions (naturally aspirated engines) was much lower than gasoline's [14,15]. This limited the cooling effect of ethanol fuel.

Since ethanol has high latent heat and low evaporation rate, EDI is not appropriate to be used on SI engines alone in cold conditions (e.g. cold start problem) [14]. One alternative way is to use it with gasoline port injection (GPI). Studies have investigated the dual-injection concept. The dual-injection concept for knock mitigation with E85 DI plus gasoline PI was tested [16]. The combustion characteristics of three different dual-injection strategies, including gasoline PI plus gasoline DI, gasoline PI plus E85 DI, and E85 PI plus gasoline DI, were investigated [17]. The dual-injection concept of gasoline PI and ethanol or DMF DI was studied as a flexible way to use bio-fuels [18]. The knock mitigation ability [19] and combustion characteristics [20] of dual-injection strategy were examined. The leveraging effect and knock mitigation of EDI in a GPI SI engine (EDI + GPI) were investigated recently [21,22].

The above reviewed experimental studies have shown advantages of EDI + GPI over the conventional PI engines. The thermal efficiency was improved [16–18,21] and knock propensity was reduced [16,19,22], whilst some reported the increase of HC, CO [21,22] or NO emissions [19] when EDI was applied. Although experimental investigations are reliable and essential in the development of EDI + GPI engine, they are costly and difficult to understand the in-cylinder mixture formation and combustion mechanisms of this new combustion system. Nowadays, multi-dimensional computational fluid dynamics (CFD) modelling has been proven a useful tool to exploit the detailed and visualised information about the in-cylinder flows. The dual-fuel combustion of in-cylinder fuel blending by gasoline port injection and early diesel direct injection was modelled with a 60° sector mesh of the combustion chamber [23]. The combustion and emission characteristics of a dual-fuel injection system with gasoline port injection and diesel direct injection were numerically investigated with a 45° sector mesh [24]. However, since the computational meshes used in Refs. [23,24] did not include the intake manifold, the gasoline port injection spray was not modelled. The dual-fuel combustion with diesel direct injection and natural gas premixed with air in the intake manifold was simulated [25]. CFD modelling was conducted to investigate the spray, mixture preparation and combustion processes in a spray-guided DI SI engine [26]. CFD models coupled with detailed chemical reaction mechanisms were applied to simulate the multi-component fuel spray combustion [27,28]. However, coupling the chemistry with the CFD solver is very time consuming and incompatible for complex industrial configurations [29,30]. Instead, Extended Coherent Flame Model (ECFM) was adopted to simulate the combustion process of SI engines [29,31,32]. To accommodate the increasingly complex chemical kinetics, realistic turbulence/chemistry interaction and multiple combustion regimes in three-dimensional time-dependent device-scale CFD modelling is a difficult task in turbulent combustion [33]. A hybrid approach of probability density function (PDF) method and laminar flamelet model was applied to address the