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# Effect of Intake Air Temperature and Premixed Ratio on Combustion and Exhaust Emissions in a Partial HCCI-DI Diesel Engine

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**Abstract:** Homogeneous charge compression ignition (HCCI) is considered an advanced combustion method for internal combustion engines that offers simultaneous reductions in oxides of nitrogen ($NO_x$) emissions and increased fuel efficiency. The present study examines the influence of intake air temperature (IAT) and premixed diesel fuel on fuel self-ignition characteristics in a light-duty compression ignition engine. Partial HCCI was achieved by port injection of the diesel fuel through air-assisted injection while sustaining direct diesel fuel injection into the cylinder for initiating combustion. The self-ignition of diesel fuel under such a set-up was studied with variations in premixed ratios (0–0.60) and inlet temperatures (40–100 °C) under a constant 1600 rpm engine speed with 20 Nm load. Variations in performance, emissions and combustion characteristics with premixed fuel and inlet air heating were analysed in comparison with those recorded without. Heat release rate profiles determined from recorded in-cylinder pressure depicted evident multiple-stage ignitions (up to three-stage ignition in several cases) in this study. Compared with the premixed ratio, the inlet air temperature had a greater effect on low-temperature reaction and HCCI combustion timing. Nonetheless, an increase in the premixed ratio was found to be influential in reducing nitric oxides emissions.

**Keywords:** sustainable environment; HCCI; self-ignition; renewable fuels; low-temperature reaction; emissions and combustion

## 1. Introduction

The internal combustion engine was invented over a century ago as a replacement for the steam engine. Due to their superior weight to power ratio which grants them higher mobility, they have assumed the lead role in powering transportation. Put simply, two major types of internal combustion engines are spark ignition (SI) and compression ignition (CI) engines. SI engines generally have lower thermal efficiency than CI engines, which are more favourable in heavy duty uses. However, the former emit less nitrogen oxides ($NO_x$) and particulate matter (PM) into the environment. Over the past few years, global greenhouse gas emissions have continued to grow despite efforts to mitigate climate change. Besides this, among emissions that are commonly found in internal combustion engines are $NO_x$, carbon monoxide (CO), smoke and PM. Unburnt hydrocarbon (HC) also makes up part of internal combustion engine exhaust due to the use of carbon-rich fossil fuels. The release of those gases due to the combustion of fuel in engines has become a public concern since they threaten not only the environment but are also detrimental to human well-being.

Recently enforced emissions regulations that emphasize a reduction in greenhouse gas emission and improvement in fuel economy have pushed automakers to develop cleaner technologies to meet the stringent requirements. The automotive sector is poised to be a main source of emissions in the year 2030. The Kyoto protocol aims at a more sustainable imminent future by decreasing pollution secreting energy sources [1]. As a result, improvements in SI and CI engine combustion aspects such as optimised fuel injection (FI) timing, altered combustion chamber shape and FI with higher pressure have been introduced over the last decades to make internal combustion engines cleaner and more efficient. Nevertheless, these techniques were not able to substantially resolve SI and CI engines' emission problems. In search of better solutions, attempts to improve contemporary combustion strategies, including low-temperature combustion (LTC), that combine the benefits of both fewer emissions and greater thermal efficiency with a lower combustion temperature have been initiated [2]. Homogeneous charge compression ignition (HCCI) is one of the LTC strategies introduced by Onishi et al. [3] as an attempt to improve combustion stability in gasoline-fuelled engines. It utilises the auto-ignition of well-premixed fuel–air mixture channelled into engine cylinders by piston intake stroke to achieve combustion near the top dead centre (TDC) when the mixture is being compressed and detonated. Since then, many researchers had adapted HCCI combustion in engines operating with various fuels such as alcohols, diesel and biofuels and reported its potential to revolutionise the automobile sector [4–7].

Generally, HCCI combustion offers reductions in $NO_x$ and smoke emissions, defying the well-known $NO_x$–smoke trade-off with superior fuel flexibility [8–10]. Due to fuel ignitions at multiple spots spontaneously in HCCI combustion, the formation of a localized high-temperature zone that favours thermal $NO_x$ formation through the Zeldovich mechanism can be prevented [8]. Furthermore, the combustion of homogeneous premixed mixture gives rise to the absence of a fuel-rich zone to assist soot formation. Several researchers have also reported comparable or even higher efficiency with the use of HCCI combustion than conventional SI and CI modes [9,11,12]. With its merits, the HCCI strategy has caught the attention of researchers and manufacturers as a promising alternative especially to overcome high $NO_x$ emissions from diesel engines. However, the use of HCCI combustion in engines is also associated with difficulties, particularly in its combustion phase control, cold start, limited operating range and premixed mixture preparation. Engine knocking at high load conditions and misfiring due to late auto-ignition when employing HCCI take a toll on engine performance and may contribute to engine wear and damage [13,14]. Unfortunately, higher emissions of unburnt HC and CO also were found with HCCI combustion [15–17]. To overcome the pitfalls of HCCI, combustion modes extended from HCCI such as premixed charge compression ignition (PCCI), homogeneous charge diesel combustion (HCDC) and stratified charge compression ignition (SCCI) were proposed. Besides this, control strategies and systems to achieve designed ignition timing and the start of combustion (SOC) of the fuel mixture have been studied by many researchers [18–21].

One of the extended combustion strategies is premixed/direct injection HCCI combustion or HCCI-DI that employs the preparation of a homogeneous fuel–air mixture upstream of the cylinder intake manifold and directly injected fuel to trigger combustion near TDC. HCCI-DI has been claimed to provide a wider operating range for the engine with greater thermal efficiency than engines running with pure HCCI combustion [22]. Furthermore, this combustion strategy also exhibits advantages over its predecessor with relatively lower