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Homogeneous charge compression ignition combustion: Advantages over compression ignition combustion, challenges and solutions

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A B S T R A C T

The homogeneous charge compression ignition (HCCI) engine uses a relatively new mode of combustion technology. In principle, there is no spark plug or injector to assist the combustion, and the combustion auto-ignites in multiple spots once the mixture has reached its chemical activation energy. It is noticeably faster than either compression ignition (CI) or spark ignition combustion (SI). The HCCI combustion mode provides better thermal efficiency and maintains low emission by modifying CI as well as SI engines. A wide variety of fuels, combinations of fuels and alternative fuels can be used in this technology. However, some challenges including combustion phase control, limited operating range, cold start, a high level of noise and homogeneous charge preparation need to be overcome for successful operation of HCCI engines. The objective of this study is to illustrate the engine performance and emission characteristics of HCCI engines at different test conditions and various challenges associated with these engines. Also introduced is a potential guideline to overcome these challenges and improve engine performance and emission characteristics. From the review, it can be concluded that HCCI combustion can be applied in existing CI engines with modifications and the most significant result of applying this combustion is the lower NO_x and soot emissions with almost the same performance as with CI combustion.

Contents

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1. Introduction

Internal combustion engines have become very popular for various purposes, but the emissions produced by these engines are not at a satisfactory level. In order to reduce the emission levels, researchers are searching for a new mode of combustion. In this regard, the homogeneous charge compression ignition combustion mode has potential. HCCI combustion is defined as a process by which a homogeneous mixture of air and fuel is compressed until auto-ignition occurs near the end of the compression stroke. It is noticeably faster than either compression ignition or spark ignition combustion [1]. A comparison of different parameters influencing the combustion processes in SI, CI, and HCCI is given in Table 1 [2]. HCCI combustion can improve the thermal efficiency and maintain low emissions and can also be implemented by modifying either SI or CI engines [3–5]. A wide variety of fuels, combinations of fuels and alternative fuels can be used. Usually, a lean air–fuel mixture is used in HCCI engines. It ignites automatically in several locations and is then burned volumetrically without visible flame propagation [6]. Once ignited combustion occurs very quickly and it is fully controlled by chemical kinetics rather than spark or ignition timing [7]. It is very difficult to control the auto-ignition of the mixture, the heat release rate at high load operations, the extent to which emissions standards are met, or engine knock [8].

The advantages of HCCI technology are: i) HCCI engines are fuel-lean and can operate at diesel-like compression ratios (>15), thus achieving higher efficiencies than conventional SI gasoline engines [9,10]; ii) it can operate on a wide range of fuels [10,11]; iii) it can produce a cleaner combustion and lower emissions and especially NO_x levels are almost negligible [12]. Alternatively, HCCI technology has some disadvantages such as high levels of unburned hydrocarbons (UHC) and carbon monoxide (CO) as well as knocking under certain operating conditions [13]. In terms of emissions, diesel engines produce higher NO_x and particulate matter (PM) or soot, which require proper control strategies because of having negative health and environmental effects, which can be solved by using HCCI combustion engines [14]. As HCCI operates on lean mixtures, the peak temperatures are much lower than SI and CI. The low peak temperatures reduce the formation of NO_x. However, the low peak temperatures also lead to incomplete burning of fuel, especially near combustion chamber walls. This leads to high carbon monoxide and hydrocarbon emissions. An oxidizing catalyst can remove the regulated species, because the exhaust is still oxygen-rich.

There is a need to report the recent advances in HCCI combustion due to the significant development of the technology. In this study, peer-reviewed articles of highly rated journals on HCCI engines have been reviewed. This report focuses on the engine performance and emission characteristics of HCCI engines and compares the data with CI engines. Each of them is discussed in detail in different sections. Finally, different research results are presented in tabular form for ease of comparison. In addition, because there remain some challenges, suitable solutions to these challenges are proposed. The report consists of seven sections, where Section 2 presents the basics of HCCI diesel combustion. Sections 3 and 4 compare the performance and emission characteristics between HCCI and conventional CI engines, Section 5 depicts recent challenges associated with HCCI engines and Section 6 contains proposed solutions to these challenges, concluding with Section 7.

Table 1
Comparison of parameters influencing SI, CI, and HCCI combustion engines [2].

Engine type	SI	HCCI	CI
Ignition method	Spark ignition	Auto-ignition	Compression ignition
Charge	Premixed homogeneous before ignition	Premixed homogeneous before ignition	In-cylinder heterogeneous
Ignition point	Single	Multiple	Single
Throttle loss	Yes	No	–
Compression ratio	Low	High	–
Speed	High	–	-
Combustion flame	Flame propagation	Multi-point auto-ignition	Diffusive flame
Fuel economy	Good	Best	Better
Max. efficiency	30%	$>40\%$	40%
Major emissions	HC, CO and NO_x	HC and CO	NO_x, PM and HC
Injection type	Port injection	Port and direct injection	Direct injection
Equivalence ratio	1	<1	–

2. Fundamentals of HCCI combustion

2.1. Chemistry of HCCI diesel combustion

HCCI diesel combustion is characterized by a set of several hundreds of species and complex reactions. This process consists of a two-stage heat release. The first stage of heat release occurs due to low temperature reactions (LTR) and during this stage a small portion of total energy (7–10%) is released, while the second stage of heat release occurs due to high temperature reactions [15] and during this stage a huge amount of energy (approximately 90% of the total energy) is released [16]. During LTR, fuel is consumed through an initial breakdown of hydrocarbon (HC) fuel molecules, which leads to the formation of hydrocarbon radicals. These radicals react with oxygen to form alkylperoxy radicals. The alkylperoxy radicals are then changed into hydroperoxy alkyl radicals through an isomerization process. After that, a second oxygen molecule addition reaction occurs, where