Research on the Control Mode of Homogeneous Charge Compression Ignition Combustion Working Process and Its Technical Prospect

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Abstract. The homogeneous charge compression ignition (HCCI) engine is considered an advanced technique, a form of internal combustion in which well-mixed fuel and oxidizer (typically air) are compressed to the point of auto-ignition. HCCI engines have higher thermal efficiency and lower emissions than Spark Ignition (SI) and Compression Ignition (CI) engines. The emissions of NOx can be neglected compared to the CI engine. In addition, a wide variety of fuels, combinations of fuels and alternative fuels can be used in this type of internal combustion engine. Moreover, when investigating the heat release rate of a HCCI engine for both single- and two-stage ignition fuels, the results show that for both fuel types, the cycle changes in the ignition and combustion phases increase with the delay of the combustion phase. Also, the cycle change of iso-octane (the single-stage ignition fuel) is higher than that of PRF80 (the two-stage ignition fuel). This paper will first introduce the control mode of the HCCI engine and then review its current status from the perspective of combustion, emissions, and consumption. After presenting the current status, the authors present suggestions about the prospect of further development with respect to the timing of ignition, the expansion of the engine operating range, and the choice of fuel mixture in this new mode of technology.

1. Introduction
Long since the first Industrial Revolution, vehicles driven by heat engines have gradually become indispensable to people [1]. Due to highly developed traffic and severely polluted environment, the pursuit of higher efficiency and lower emissions for engines has only become more urgent, regarding compression-ignition (CI) engines and spark-ignition (SI) engines as two popular options. On the one hand, CI engines vents polluting by-products due to incomplete combustion, in exchange for the highest thermal efficiency among all internal combustions [2]. Operating with premixed fuels such as gasoline and autogas (LPG), on the other hand, SI engines diminish potential burning residue but have a limited compression ratio and, therefore, lower efficiency. In the hope of an applicable alternative of both SI
and CI, Homogenous Charge Compression Ignition (HCCI) later came into being. Combining features from SI and CI, HCCI can produce satisfactory efficiency and limit its emission at a low level [3]. It has not gone through a long enough period of time. However, HCCI is still limited by several technical difficulties such as cold start, autoignition timing, operation range, etc.

Homogeneous charge compression ignition (HCCI, homogeneous charge compression ignition) is the combustion method adopted by the next generation of piston internal combustion engines [4]. The thermal efficiency of this type of internal combustion engine is comparable to that of a compression-ignition direct-injection diesel engine, and the NOx and PM emissions are very low [5]. The HCCI internal combustion engine uses diluted pre-mixed gas [6]. When the mixed gas is compressed and ignited by the piston, the mixed gas in the cylinder is combusted in a volumetric manner. There is no flame propagation process, allowing the combustion to occur at a lower temperature. The HCCI internal combustion engine is innovatively designed based on homogeneous charge spark ignition gasoline engine and stratified charge compression ignition diesel engine, combining the advantages of the two. After the homogeneous charge is compressed, its pressure and temperature increase [7]. When it reaches the spontaneous ignition point, it ignites at several points almost at the same time. The combustion process is rapid, close to the ideal Otto Cycle (Otto Cycle), with high thermal efficiency and no throttling. Loss, full combustion, the low maximum temperature is conducive to control emissions [8].

This article analyzes the control mode of the HCCI internal combustion engine working process and summarizes its current status from the aspects of combustion, emission and fuel consumption. Finally, the future development of the HCCI internal combustion engine has been prospected.

2. Control mode

The HCCI engine's control mode can be highly efficient because it emits a limited amount of carbon dioxide, NOx, and particulate matter [9]. Thus, the usage of the HCCI engine is critical in cutting down on pollution. The limited amount of greenhouse gases emitted by the HCCI engine implies that the engine will potentially lower the rate of climate change. The reduction of the rate of climate change suggests that the engine will uphold the requirements of society concerning the mechanisms that can be adapted to maintain the quality of life. The greenhouse gases display to cause global warming that causes climate change. Climate change, in turn, triggers hazards that lead to the loss of biodiversity. Therefore, using HCCI engines will enhance the protection of biodiversity through the limitation of greenhouse gases emitted.

The HCCI control mode engine faces operations difficulties, especially when running the engine at high loads. Running the HCCI engine at high loads triggers the cold start aspect that makes the engine running idle. Besides, the attempts made to facilitate the control of the engine in the entire period of its operation limit the efficacy of its practical application. The reduction of the efficacy associated with applying the HCCI engine induces the limitation of usage quality. The solution to the problem of cold start in the HCCI engine can be realized by integrating the hybrid model. In the hybrid model, the engine operates at cruising, medium, and low loads, and while operating at high loads, idle, and cold start, the engine switches to a spark ignition mechanism [10]. Using spark ignition eliminates the need for advancement of monitoring of the engine throughout the cause of its operation.

In the process of advancing the operation of the HCCI engine in the hybrid model, effective transitions in its operations SI and HCCI and SI modes are required [11]. The shifts are mandatory due to the changes in the speed of the engine and the load. The effectiveness correlated with the changes displayed to promote the engine's operations' quality and thus uphold its performance. The changes also require the HCCI engine to be fitted with appropriate combustion parameters in excellent ranges. The proper integration of the combustion parameters manifests the transition strategy and thus integrates the fueling rate's efficiency. The switch in the control approaches of the HCCI engine is mandatory because it depends on pressure, composition, and charge temperature. Thus, using the direct control approach like the SI combustion is not applicable for the HCCI engine.

Moreover, to uphold the efficacy of the performance of the HCCI engine, adequate capacities of transition between the SI to HCCI to SI are required [12]. The integration of exhaust gas circulation
(EGC) portrays a smooth and faster transition between the SI – HCCI – SI. Enhancing the smooth and more rapid transition provides the engine with relevant aspects of operation, thus enhancing HCCI combustion quality. The increased efficacy of combustion implies that the objectives of operation of the HCCI engine will be attained. Additionally, the effective control of the HCCI engine portrays to limit the greenhouse emission and thus curbing the plight of global warming.

3. Current status

3.1. Combustion
HCCI uses a fuel-air mixture in a cylinder through the compression process, reaching the spontaneous combustion temperature to ignite everything. There is no spark plug and not allowed to inject fuel to control ignition timing. The combustion simply bases on the temperature inside the cylinder. The fuel injection and combustion conditions of HCCI will be described in the following.

HCCI usually uses port fuel injection (PFI) or early direct injection (DI) to make a relatively uniform fuel-air mixture [1]. Partial fuel stratification (PFS), an example of using a combination of PFI and DI, has been shown to prevent excessive ringing from allowing higher load from HCCI engines. This allows most of the fuels to mix well, with local regions of higher equivalence ratio exist.

When it comes to how to make combustion happen, although it depends on internal temperature, it can be implemented by high compression ratios, high intake temperatures, high intake pressure and highly reactive fuels through Samveg Saxena's article [13].

Here is an example of the heat release rate from an HCCI of different fuels. For different fuels of HCCI engine, the occurrence of single- or two-stage ignition is a way of characterizing the specific fuel. In general, low-octane fuels such as n-heptane, diesel, PRF80, and dimethyl ether (DME) are shown for two-stage ignition, while high-octane fuels such as ethanol or isooctane are shown for single-stage ignition [14]. Figure 1 illustrates the difference in the performance of single-stage and two-stage ignition fuels in HCCI engine combustion.

![Heat Release Rate](image)

Figure 1. Heat release rate from an HCCI engine using two different fuels, PRF80 which exhibits two-stage ignition, and iso-octane which exhibits single-stage ignition [15]

3.2. Emissions and fuel consumption
HCCI typically has low nitrogen oxides, soot, and particulate matter emissions and higher emissions of unburned hydrocarbons and carbon monoxide [16]. The two aspects, unburned hydrocarbons and carbon monoxide and nitrogen oxides, and soot, will be described in the following.

The in-cylinder temperature is a key factor in determining unburned HC and CO [17]. Lower temperatures usually result in higher emissions of unburned HCs and CO. However, there is a temperature range for HC emissions when CO is reduced. Figure 2 and Figure 3 show a series of equivalent ratios and combustion timing for unburned HC and CO emissions. From Figure 4., the trend in both numbers shows that HC and CO emissions generally increase with lower equivalence ratios and delayed combustion times because these factors lead to lower cylinder temperatures. The hot spot fire
and auxiliary co-oxidation threshold temperature are important considerations for HC and CO emission characteristics.

Figure 2. Experimental results of unburned hydrocarbon emissions for emissions different equivalence ratios and combustion timings at Pin¼ 1.8 bar combustion timings and 1800 RPM [18]

Figure 3. Experimental results of carbon monoxide for different equivalence ratios and at Pin¼ 1.8 bar and 1800 RPM [18]

Figure 4. Experimental results of mass averaged peak in-cylinder temperature for different equivalence ratios and combustion timings at Pin¼ 1.8 bar and 1800 RPM[18]

Then NOx and soot are put together because they are both low in the HCCI engine. Nitrogen oxide emissions, NO and NO₂, are formed mainly through the Zeldovich chemical pathway by breaking strong triple bonds between nitrogen atoms in N₂ [19]. Given that the peak cylinder temperature of HCCI is still too low compared to diesel or spark-ignited engines to reach the activation temperature needed for the chemical reaction of NO and NO₂ to occur [20]. As a result, HCCI engines can achieve high power output with very low NOx emissions.
Soot is a major concern for diesel engines. When the fuel breakdown begins, it forms in the concentrated fuel spray area of the fuel spray, and there is insufficient oxygen. Given that the fuel is fully mixed before ignition of the HCCI engine, negligible levels of soot emissions occur.

In diesel engines, the high radiation of NOx and soot requires the use of an expensive post-treatment system [21], such as particulate filters and oxidation catalysts [22], which are as expensive as the diesel engine itself. Thus, an obvious advantage of HCCI is that it can achieve the same level of efficiency with low CO2 comparable to diesel engines [23] without the need for expensive NOx and soot removal post-treatment systems.

4. Technology prospects

4.1. Timing for ignition
HCCI engines operate with autoignition, in which a clear control mechanism is absent. Several factors of this autoignition are fuel chemistry, burning duration, surrounding and intake temperature, compression ratio, and other parameters related to the engine. Earlier ignition can be caused by high intake temperature and pressure due to rapid chemical reactions. It is worth noting that either prematurity or delay on combustion phases may cause higher CO emissions, residues of incomplete combustion.

4.2. The expansion of the engine operating range
Certain reasons prevent the enlargement of the HCCI operation range, such as knocking, cold start, ignition timing, high pressure rate, and burning noise.

While the increasing frequency of knocking bounds the higher load limit, the lower limit is defined by the difficulty of autoignition at excessively low loads. Cold start, though it reduces emission, contradicts stable HCCI operation that prefers higher intake temperature. While ignition timing is arduous to control, the absence of preheating process may even forbid the firing due to unexpected heat loss. Furthermore, since autoignition inevitably produces high internal pressure, rapid heat release and pressure oscillation that follows may produce a high level of noise and damage engine components.

5. Conclusion
Review of present performance of HCCI engines remains crucial to anticipate and accomplish their future progress. That is, only after existing issues are settled or bypassed can engines be thoroughly utilized. Major conclusions are as follows:

(1) Though the ignition timing of HCCI seems to remain a critical obstacle, various proposed solutions have been put into use, which focuses on the timing of valves, compression ratio, injection timing, or fuel mixture. In the future, researchers may want to test the combinations of more factors in certain values, seeking better control of timing.

(2) Difficulty in cold start might be solved by adding more features from traditional engines. Existing methods are starting the engine in conventional modes, retrofitting a glow plug, or utilizing different fuels. At best, HCCI may someday achieve a stable cold start all by itself, without the assistance of the methods above. To realize it, fuels that burn at a relatively lower temperature may be the breaking point, requiring more advanced research.

(3) Efforts regarding restraining noise concentrate on its production or propagation. Although noise itself could not break the engine, it implies acute transmissions of heat and pressure and may cause accumulated damage to human hearing. Assuming that huge internal pressure is unavoidable during combustion, noise propagation must be intensively suppressed, which may be done by exploiting sound insulation materials in engine manufacturing.

(4) That draft animal was replaced by engine and steam engine was gradually substituted with internal-combustion one [24] indicates even HCCI might not be the ultimate resolution of transportation. Considering HCCI to be a promising choice presently, though, the use of technologies in it from wider various fields can be valued in the future. Such mixture may identity components that can either be added or removed from HCCI, promoting its perfection and even evolution.
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