Huge Potential of HCCI Engine in Rarefied Air Environments

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Abstract. Homogeneous Charge Compression Ignition (HCCI) engines represent a significant technological advancement over the traditional Spark Ignition (SI) and Compression Ignition (CI) engines by offering prospects for improving thermal efficiency and emission reduction. This study explores the advantages of HCCI engines in thin air environments specifically, and it delves into latent design considerations such as the square bowl piston, two-stroke engine-inspired type piston, Superchargers and Turbochargers, methanal injections and other considerations. While the HCCI cycle holds substantial potential in the realm of engine technology, inherent challenges are confronted in controlling combustion phasing and maintaining consistent reliability. These pivotal concerns require dedicated attention to be addressed in future studies. In short, with the increasing need for efficient combustion mechanisms, the insights offered herein underscore the importance of improving the HCCI engine's operational range and reliability without compromising its inherent benefits. With continued research and design innovations, HCCI may become the optimal engine of choice for a thin-air environment.

Keywords: HCCI; vehicle; thin air; thermal efficiency; emission reduction.

1. Introduction

Homogeneous charge compression ignition, often referred to as the HCCI cycle, is an engine technology with great potential but is still in its infancy. In an HCCI cycle, the homogeneous mixture of air and fuel is compressed to the point of ignition without the use of a spark plug in the SI engine or a fuel injector in the CI engine. By doing so, the HCCI cycle combines the advantages of both Otto and Diesel cycles while avoiding their drawbacks, such as the low compression ratio and slow combustion spread of Otto engines, as well as NOx formation and Soot accumulation in Diesel engines [1]. Essentially, HCCI not only achieves higher thermal efficiency but also possesses the advantage of eco-friendly emission.

These appealing features, unfortunately, came with significant drawbacks that prevented the HCCI engine from massive commercialization. One of them is the challenge of incontrollable combustion phasing, in other words, an unpredictable ignition timing [1]. This profound consequence of instability is mainly the result of the compression ignition applied to the Air-fuel mixture: the premixed ratio could significantly affect the chemical reaction rate, even leading to a circumstance of multiple combustion stages [2]. Traditionally, on the Otto cycle, the spark plug is used for the ignition process, providing a convenient and tractable way of combustion phasing. One of the malfunctions of the Otto cycle, called engine knocks or detonation, refers to the accidental compression ignition in the combustion chamber that happened before the spark plug functions. The Knock potentially damages the engine as not only does it create higher stress than the engine is designed for, but it also disturbs the ignition timing. HCCI, however, utilizes this detonation to ignite the fuel. This allows for a higher compression ratio since an Otto cycle would purposefully reduce its compression ratio to avoid detonation. But simultaneously, the unwanted part of detonation is also present in the HCCI engine: it is innately difficult to control the ignition timing, as the dynamic of compressing premixed air and fuel is more than complicated [2]. And it brings a series of objective issues, including narrow operation range, poor light-load performance, difficulties in cold start, and many other aspects [1].

When working in the thin air environment, it is believed that a few characteristics, such as high compression ratio, on the HCCI engine would potentially allow for better performance compared with the traditional Otto or Diesel cycle [3]. This paper provides insight into numerous design considerations that could be employed when optimizing thin-air performance for HCCI engines.

2. Theory of HCCI Engine Compared with SI and CI Engine

Compared with traditional SI engines, HCCI possesses a major advantage of not having a spark plug. Essentially, if you zoom into a microscopic view of the combustion chamber with a spark plug, it would be clear that the combustion started from the top of the chamber, where the plug set the flame. It takes time for the flame to spread all the way to the bottom of the chamber, where the piston is; such a phenomenon is regarded as unwanted because it slows down the combustion rate during the combustion stage. A potential defect of slow combustion rate is if the piston reaches the bottom while the combustion is still happening, the still-burning fuel will be wasted if they aren't already doing negative work on the piston. Apart from that, the spark plug itself also experiences the effect of carbon deposition, which, despite not significantly affecting the engine's overall performance and reliability, does contain a risk of malfunction.

HCCI, comparingly, provides a faster combustion rate due to the feature of compression ignition. The CI process takes place with the fuel preinjected into the combustion chamber so that whenever the pressure reaches the ignition point, ideally, all the fuel inside the combustion chamber will start to burn. Therefore, the HCCI combustion stage does not experience the slow spread of ignition as inside of a regular SI engine. However, the rapid combustion rate also brings the problem of high stress. In this case, HCCI engines are usually subjected to higher stress during the combustion stage compared with SI engines. The compression ignition features also made HCCI innately unreliable, as it lacks a method to control the ignition timing effectively [4]. For the Otto cycle, the ignition is triggered by the spark plug, and for the diesel cycle, the mechanism is achieved by direct fuel injection. On the HCCI engine, since the air-fuel mixture is presented in the cylinder since the beginning of the combustion stage, the ignition timing would be mainly correlated with temperature and pressure inside of the chamber, which is difficult to control directly [1]. In this case, the reliability of the HCCI engine is not excellent, especially for situations under high load or severe environments.

HCCI allows for a higher compression ratio, even up to 14 and higher [4]. Such characteristic allows the HCCI engine for more efficient combustion of the air-fuel mixture compared with most of the other engine types. However, the higher compression ratio also takes a longer time to achieve in every cycle, resulting in a slower cycle rate due to the extra time spent on compression. Therefore, the overall power rating of an HCCI engine might not be as competitive as that of a high rpm configured Otto engine. On the other hand, the high compression ratio also resulted in higher requirements for engine construction, as the stress asserted to the mechanical parts would be higher than that of low compression ratio configurations. When regarding the performance under a thin-air environment, the air-based cooling is particularly weakened due to the reduced mass flow rate of air, which further negatively influences the reliability of the HCCI engine. Air intake is also limited under environments with rarified air, such as high-altitude plateaus, which also limits the amount of air intake for engines. In this case, the effect of compression ratio due to ambient air pressure needs to be analyzed and addressed.

3. Related Design Considerations

3.1. Square Bowl Piston

Square Bowl Piston is a viable design approach to improve HCCI engine performance under a thin-air environment, as shown in Fig. 1. The bowl-type piston refers to the design feature such that the top of the piston head is concaved inwards, creating the shape of a bowl. A Square Bowl Piston is when the concaveness is designed as a square shape in specific.

Fig. 1 Example of square bowl-type piston [2]

The square groove on the piston head directly influenced the rate of heat release of the HCCI engine. The geometry of the chamber generates small eddies on the corners of the square during combustion, which improves the air-fuel mixing process. Such characteristic offers improved high-load capability with acceptable pressure increase, improved thermal efficiency, and reduced fuel consumption [2].

Additionally, there is a tendency towards longer burn duration due to the thicker boundary layer, which further results in a broader temperature distribution. Such a tendency might be bad for SI engine, which desires faster burning speed, but it could be beneficial for HCCI engines, which already possess a rapid burning rate and could potentially reduce stress by decelerating it [2]. Bowl-type pistons, not exclusive to square bowl type, also possess the advantage of increasing cycle rate, which is necessary for HCCI engines since they usually have slower cycle rates [2].

3.2. Two Stroke Piston

Design principles based on two-stroke engines are also preferable for HCCI engines. For example, two-stroke pistons are usually lightweight, compact, and contain higher clearance volume in the cylinder; these features improve the intake and exhaust process, which are helpful for improving functionality and reliability under strong mechanical loads. When using these pistons on the HCCI engine, the fuel would need to be specified as the compression ratio could be dropped to 9:1 or even lower [2,5].

3.3. Supercharger and Turbocharger

The addition of a supercharger or turbocharger might not be viable. Usually, superchargers and turbochargers are priority options when trying to increase compression ratio. However, for HCCI engines, since they tend to present a feature of fast combustion in lean mixtures within a high compression ratio, the use of compression boosters would be particularly risky, as they increase the risk of causing detonation [2]. The detonation is when combustion happens at an unwanted time, causing a significant and rapid increase of pressure and temperature in the combustion chamber and eventually damaging engine parts. Knock is particularly common on HCCI engines under high loads since, as mentioned previously in the introduction, they essentially operate in the form of a controlled detonation [2,6]. Some studies, on the other hand, intended to show that turbochargers could be used on HCCI engines. The rational utilization of turbochargers on HCCI engines greatly enhances performance [2].

3.4. Systems with Variable Compression Ratios

Features such as the Millar system and VCR (Variable Compression Ratio)-turbo engine that is capable of providing alterable compression ratio would be beneficial for HCCI engines to operate under thin air environment by providing an extra method to control the combustion phasing [7]. An example of Millar cycle design feature is to adjust the valve closing timing in order to release the air-fuel mixture inside the combustion chamber and achieve the purpose of reducing the compression ratio [7].

Alternatively, a VCR mechanism, usually equipped with a specially designed piston crank consisting of a multi-bar linkage system, could achieve a range of distinct compression ratios. The alliance research of Renault and Nissan has been developing this technology and implementing the system onto their M9R 2I diesel engine, achieving an improvement upon the pollutant emission (Fig. 2) [8]. However, the mechanical reliability and reparability of complicated linkage cranks still need to be fully studied. The effective control over the compression ratio could account for HCCI's undesirable small operating range, as well as enhance the environmental adaptation capability, including that of thin air environments [1].

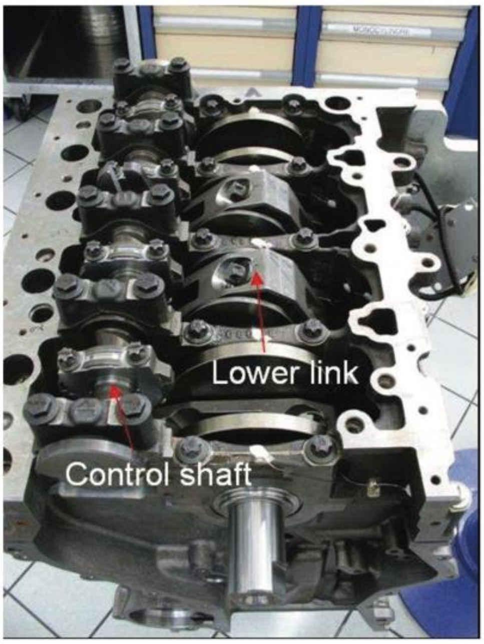

Fig. 2 M9R 2I engine by alliance research of Renault and Nissan [8]

3.5. Methanol Injection

The addition of methanol injection improves the engine's efficiency and reduces emissions of CO, NOx, and unburned hydrocarbons [9]. Methanol possesses a higher octane rating and lower ignition delay than natural gas, which leads to faster and more complete combustion [10]. It also contains less carbon content compared with natural gas and fossil fuels, proving its eco-friendliness. Regarding performance, the injection of methanal compounds improves the lean-burn stability and power output, which is ideal for the use of a thin-air environment [9]. However, the reduction of unburned methane emissions is important for reducing the greenhouse effect, as methane has a higher global warming potential than carbon dioxide [9].

4. Conclusion

To sum up, the pros and cons of each design consideration are concluded and recorded in Table 1. These design considerations are judiciously selected from recent research. While this paper posits that these features could be applied in thin air environment, the actual utility and efficacy are merely speculative. Further analysis would be imperative to verify the feasibility of these features. For example, the VCR feature in diesel engines employing the HCCI cycle was initially conceptualized to increase specific power while limiting maximum cylinder pressure. The technology, however, also manifests latent capability in maintaining the necessary compression ratio under a thin-air environment.

Table 1. Pros and cons of each design consideration

Feature	Advantages	Disadvantages
Square bowl piston	Improved air-fuel mixture process that increases cycle rate and extends burning duration.	No obvious shortcomings
2-stroke piston inspirations	Improved intake and exhaust process that enhances functionality and reliability	Low compression ratio tends to require special fuel or super-/turbo-chargers to reach necessary compression ignition pressure.
Supercharger and turbocharger	Achieved higher compression ratio	Reduce reliability
variable compression ratios	Allow the HCCI engine for better environmental adaption	Complicated structure that might be unreliable
Methanol injection	Better power and efficiency	Unburned methane is harmful to the environment

In the future, the key objective of developing HCCI in thin air is to improve the operation range and reliability without sacrificing too much on the innate advantages, such as optimal thermal efficiency. It is necessary to conduct further research on pressure and temperature sensing inside the combustion chamber, which not only provides valuable data on combustion phasing but also lays the foundation for advanced features such as variable compression ratio.

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