HCCI Engine: Advancements in Combustion Control and Potential Innovation in Power Configuration for Vehicles

Zhenxi He[1], Xiaohui Yang[2] and Pengsen Zhang[3, *]

[1]Beijing National Day School, Beijing,100039, China

[2]Department of Power and Energy Engineering, Harbin Engineering University, Harbin, 150001, China

[3]Department of Physics, University of California Santa Barbara, California, 93106, United States

*Corresponding author: pengsen_zhang@ucsb.edu

Abstract. Due to the increasingly severe problem of environmental pollution, homogeneous charge compression ignition (HCCI) engines are highly encouraged to be used in lots of countries. HCCI engines aim to reduce load operation and increase efficiency. The potential environmental impact is also discussed and highlights the effect of the HCCI engine on sustainability. Nowadays, hybrid vehicles are becoming increasingly widespread as a possible alternative other than electric vehicles (EV). There are many individuals and companies on the market seeking a much cleaner and more efficient technology for vehicles. This essay will discuss and summarize the positive effect of HCCI engines on combustion control strategies, hybrid powertrain configuration, and the challenge and offer some possible solutions. By examining the cooperativity between HCCI engines and electric motors, there is an overall improvement in fuel efficiency and performance. In addition, some exploration of the real-life examples of car industries that use the HCCI engine or its variant will be demonstrated. The study concludes by stating that the HCCI engine will be a revolutionary step in the future landscape of hybrid vehicles.

Keywords: Combustion control; HCCI engine; power configuration; vehicle.

1. Introduction

With the direction of global car industries moving toward more sustainable and much more efficient technologies [1]. Homogeneous charge compression ignition (HCCI) stands out of the pack as a crucial innovation. This technology is aimed to reduce the emission of harmful gas and improve overall fuel efficiency compared to traditional internal combustion engines (IC). Although some will say the efficiency of diesel engines is remarkable, there are many strategies to reduce the pollutants produced by gasoline engines. The approach of the HCCI engine is much more direct, and all the technologies are already possessed in the car industry. It will be possible to reduce operational costs and be more reliable than current people.

HCCI engine has unique working mechanics compared to traditional gasoline engines; it utilizes a compression process similar to diesel engines to ignite the air-fuel mixture. However, due to its characteristic of homogeneous ignition compared to diesel engines, it can drastically reduce nitrogen oxide (NOx) and particles, such as PM 2.5, emissions. Therefore, it harnesses the vantage of both gasoline engines and diesel engines and provides a completive alternative compared to traditional and electric powertrains. Besides, the HCCI engine also has demonstrated the property of improving fuel economy, thereby satisfying the pressing need for cost-effective vehicles [2,3].

This paper aims to discuss the detailed advancements in combustion control strategies for HCCI engines to the potential implication of HCCI engines on hybrid powertrains. From how to resolve the drawbacks of the HCCI engine, from its limited range of effective power output to different types of integration between HCCI and hybrid powertrains. This review will provide an extensive discussion on how the HCCI engine and its potential implication will be a game changer in the current automotive industry.

While recognizing the above advantages, there is also a need to discuss the limitations of current combustion technologies. HCCI is needed to resolve the problem will low thermal efficiency and high emission level. It not only provides an opportunity for cleaner and more sustainable development for the future but also possibly indicates the coming of a new era of high efficiency and innovation for automotive engineering. Therefore, emphasizing the urgency of utilizing technologies such as HCCI and its alternatives is not just pragmatic but indispensable for leading future development in automotive, improving efficiency and achieving a sustainable future.

2. Fundamentals and Distinctive Advantages of HCCI Engine

HCCI combined the most advantageous characteristics of both gasoline engines and diesel engines. From the initial debut of this concept until now, the HCCI technology has demonstrated some undeniable strength in the automotive industry [2]. Similar to its counterpart, such as spark ignition (SI) and compression ignition (CI), it also uses a four-stroke cycle engine with carefully ratioed air-fuel mixture injected into the cylinder before ignition. However, unlike its counterpart, the HCCI engine does not need a spark plug [3]. It compresses the fuel similar to a diesel engine but generates a multifocal ignition throughout the cylinder volume.

Due to the HCCI engine's characteristics, It can be a solution to bridge the difference between gasoline and diesel engines. Compared to diesel engines, gasoline engines often suffer from low thermal efficiency resulting from their low compression ratio. However, diesel engines will produce more pollutants due to heterogeneous combustion in the fuel mixture [4]. With its ability to compress and ignite the charge similarly to a diesel engine while combusting the thin air-fuel combination at a low temperature, the HCCI engine combines the benefits of both gasoline and diesel engines. Therefore, resulted in a much higher thermal efficiency and more complete combustion. As a result, reduces the gap between efficiency in the two types of engines. The HCCI engine also performs exceptionally well in reducing toxic pollutants, such as nitrogen oxides (NOx) and particulate matter (PM). This is because HCCI engines promote a more complete combustion for air-fuel mixture and thereby reduce the emission of these pollutants.

Besides emission, HCCI also transcends traditional SI and CI engines in efficiency and fuel economy. Compared with traditional engines, HCCI engines have an increase in efficiency of around 20% and lowered brake-specific fuel consumption (BSFC). Therefore, it allows HCCI engines to use less fuel to achieve similar work output than traditional ones. This not only proves to increase fuel efficiency but also lowers the operational cost, which many automotive companies emphasize [3]. Furthermore, when using natural gas as a fuel, HCCI engines demonstrate a further increase in thermal and combustion efficiency, outperforming diesel by 9-10% and petrol by 5-10%. This characteristic makes natural gas an ideal fuel alternative and also supports the prevailing view of using natural gas as an alternative for vehicles. All these vantages present by the HCCI engine provide a promising future for pursuing higher performance while remaining sustainable and highly efficient for energy utilization [3].

3. Combustion Control Strategies

Due to their potential to lower harmful gas and particulate emissions, several combustion management methods utilized in HCCI engines have gained much interest recently, as well as improving combustion efficiency. Systematic research into the potential of diesel-fueled HCCI engines for automotive applications did not start until the mid-1990s. Controlling the combustion phasing and reducing the emissions of NOx, unburned hydrocarbon, and carbon monoxide has always been the main goal for scientists. Common combustion control strategies are Exhaust Gas Recirculation (EGR), Variable Valve Timing (VVT), advanced control algorithms, Charge Stratification, Fuel injection control and so on [4,5]. This section will cover some detailed understandings of EGR, VVT and advanced control algorithms.

3.1. EGR

EGR is the process of recirculating some of the exhaust gases back into the combustion chamber. The introduction of EGR in HCCI engines has several advantages for combustion efficiency: EGR reduces the oxygen concentration in the combustion chamber by diluting the new air charge, and this decreases the peak combustion temperatures, which in turn lessens the risk of knocking and decreases nitrogen oxides (NOx) generation. This decreases energy lost to the cooling system and consequently improves overall thermal efficiency. Improved stability lengthens the ignition delay and thus reinforces combustion process stability. This results in the fuel-air mixture having more time to mix, creating a more evenly distributed mixture prior to combustion. The improved stability decreases cycle-to-cycle variation, which in turn enhances combustion efficiency.

3.2. VVT

The major target for manufacturing an engine is minimizing fuel consumption and reducing emissions. One strategy for solving this problem is to separate the inlet and exhaust valves (working independently in the position of the piston) and give up the camshaft (a part that regulates the closing and opening of the engine’s inlet and exhaust valves). VVT strategy is very flexible because there are various intake and exhaust philosophies, such as Late/Early intake or exhaust valve opening/closing referred to the possible combinations. These can regulate and enhance the effectiveness of the compression ratio, mixture temperature, and trapped residuals by modifying the intake and exhaust valve timings. Internal EGR, which can cut NOx emissions, can be obtained by the manipulation of VVT. Reducing pumping losses and increasing efficiency is feasible by integrating the intake and exhaust valve schemes [6].

3.3. Advanced Control Algorithms

The performance of HCCI engines is optimized by advanced control algorithms that harness feedback from sensors to adjust combustion parameters regularly. These algorithms comprise model-based predictive control, cylinder pressure-based control, or advanced combustion phasing algorithms. These algorithms can spot and compensate for variations, adjusting injection timing or other parameters and resulting in more consistent combustion from cycle to cycle.

It is important to employ a combination of strategies to attain optimal combustion control in HCCI engines. Through the use of VVT, EGR, and advanced control algorithms, engine designers can enhance the combustion process, leading to a reduction in emissions, improved efficiency and superior performance.

4. Combining HCCI Engines with Hybrid Powertrains

It’s the strategy that optimizes the efficiency of combining HCCI and hybrid electric vehicles (HEV) technologies. The simulation conducted by Benjamin et al. thoroughly went over the integration between the HCCI engine and parallel Hybrid configuration. HCCI engines improved the fuel frequency significantly, and hybridization was also pursued to reduce low load. Thus, what the outcome would be if the two technologies are overlapping? The combined hybrid powertrain configurations have the advantages of both series and parallel hybrid powertrains. In addition, it's suitable for various working conditions and has the best performance of systems and fuel efficiency.

4.1. Parallel Hybrid Configuration

The parallel configuration here means the engine is working together with the electric motor, directly providing power to the wheels. Two parallel hybrids with various levels of electrification are used in this setup. The goal of the research conducted by Benjamin Lawler is to reduce the mode between the HCCI and SI engines and increase the HCCI engine's efficiency. Their approach is named e-HCCI, a power configuration harnessing the combined advantage of a hybrid powertrain and a HCCI engine. The engine is dual-mode, and the data have shown the effect of HCCI in reducing fuel combustion. Due to its approach of increasing the time spent in the HCCI working zone and avoiding mode transition, e-HCCI shows superior performance and higher efficiency in the simulation. The result is also promising; compared to traditional engines, the fuel efficiency of e-HCCI has increased by 20%. The researchers put it in a "mild" HEV configuration, which is a power configuration of a 2.5-liter Four-cylinder Dual mode SI-HCCI engine with 6-speed transmission and 5 kilo-Watt Electric motor with 0.5 kilo Watt per hour Batteries, the fuel efficiency has increased up to 35%. If electric motors and Batteries are switched to 10 kilo-watt and 1 kilo-watt per hour, the fuel efficiency will increase by almost 40 percent. This integration not only emphasizes the potential of the HCCI engine in Hybrid configuration but also highlights the improvements in increased fuel efficiency and lowered emissions [7,8].

4.2. Series Hybrid Configuration

There are another two researchers who explored the integration of the HCCI engine in a series hybrid configuration. In contrast to parallel hybrid powertrain, the engine in the series powertrain only acts as a generator. The motor provides the power, and the engine serves as an auxiliary power source. It will not deliver power to the axis of the vehicle. The series hybrid configuration is most used in extended-range HEVs. The research presented by Ali Solouk and Mahdi Shahbakhti in 2014 and 2017 demonstrated that the fuel economy could have a remarkable enhancement if the HCCI engine is combined in series with a HEV powertrain [7,8]. One of their research projects emphasizes that series HEV with HCCI engine can increase the fuel economy in the general driving cycle in Northern America up to 12.6%. The mechanical energy generated by the engine is converted into electric energy due to the function of a certain generator which is in charge of driving the motor. Another research shows that the integration of HCCI and HEV in a series configuration can increase the fuel economy by up to 18.9 percent compared to modern SI engines in the Urban Dynamometer Driving Schedule (UDDS) published by the Environmental Protection Agency [9]. This combination also allows the operating point in the HCCI engine to increase further.

5. Challenges and Solutions

5.1. Combustion Control

Controlling ignition timing, achieving combustion stability and managing transitions between modes are major challenges in HCCI combustion control. After the subject research, some reasonable solutions are found to solve these problems. These algorithms continually track several parameters, including cylinder pressure, temperature, and chemical species concentrations, using real-time data from sensors. The algorithms can improve ignition timing and ensure stable combustion by modifying fuel injection time and valve timing depending on this feedback. Achieving combustion stability is a key challenge in HCCI engines due to the lack of direct spark or flame initiation. The HCCI combustion process is more susceptible to changes in operating circumstances and fuel characteristics, which makes it more likely to misfire or knock.

EGR is another strategy to improve combustion stability. By recirculating a portion of the exhaust gases, EGR reduces the likelihood of knocking and helps dampen combustion pressure fluctuations. The dilution effect of EGR promotes a slower and cooler combustion process, resulting in improved stability [5]. Advanced control algorithms enable seamless transitions between modes by monitoring key combustion parameters and adjusting fuel injection timing, spark timing and valve timing. These algorithms ensure smooth mode transitions by optimizing the combustion process and minimizing performance gaps or emission spikes during the transition.

5.2. Hybridization with HCCI

HCCI engines provide enhanced fuel efficiency, and achieving homogeneous fuel-air mixture combustion can further improve the thermal efficiency of IC. If combined with a hybrid system, the

HCCI engine can operate at its most efficient operating point, leading to an even greater reduction in fuel consumption [10].

Although challenges still exist, HCCI technology holds a promising future in the automotive industry. With stricter regulations surrounding emissions and the drive to improve fuel efficiency and other innovative solutions, HCCI is poised to have a considerable impact in achieving these targets. The potential of HCCI is further elevated when integrated with hybrid powertrains. With research advancing and technology developing, HCCI engines may become more widespread in the automotive market, bringing with them a balance of fuel efficiency, reduced emissions and performance [10,11].

6. Conclusion

It is now the pivotal moment for the rapid development of HCCI technology. It merges both the benefit of gasoline and diesel engine and pave a path for improving efficiency and reducing emission. By punctilious control over the combustion dynamics, utilizing VVT, EGR and advancing control algorithms, a future of promising thermal efficiency and diminishing pollutant emission has been shaped by the HCCI engine.

There is also a revolutionary change regarding fuel economy on HCCI technologies with both parallel and series hybrid powertrain configurations. The significant enhancements in E-HCCI configuration and the research on the integration of HCCI engines and HEV have also proved this point. Furthermore, the Skyactiv-X series from Mazda has proved the fact that the potential for HCCI is remarkable.

However, there are challenges presented in the pioneer realm of automotive industries. HCCI engine requires a complex control strategy and is also limited by emission regulations. There is an urgent need for technological development on controlling and perhaps a reexamining of current combustion patterns. However, there is a significant improvement in controlling units and alternative fuel options, demonstrating the commitment industries have made to overcome these challenges in order to maintain performance while protecting the environment.

With the push propelled by HCCI technologies, the automotive industries are currently standing on the edge of stepping into a new era of automotive engineering. With an increasing number of technological breakthroughs in this technology, automotive industries are forging a future that is not only sustainable and highly efficient but also adapted to the needs of our society. The HCCI engine is a possible beacon that can lead us towards a path to a cleaner, more efficient, more sustainable future for automobiles.

Author Contribution

All the authors contributed equally, and their names were listed in alphabetical order.

References

[1] Lawler Benjamin, Ortiz-Soto Elliott, Gupta Rohit, et al. Hybrid electric vehicle powertrain and control strategy optimization to maximize the synergy with a gasoline HCCI engine. SAE International Journal of Engines, 2011, 4(1): 1115-1126.

[2] Mulane Shamla A. and Limaye S. D. Homogeneous charge compression ignition (HCCI) engine technology-a review. International Journal of Current Engineering and Technology, 2016, 4: 160-163.

[3] Verma Sanjeev Kumar, Gaur Subhashish, Akram Tabish, et al. Performance characteristic of HCCI engine for different fuels. Materials Today: Proceedings, 2021, 47: 6030-6034.

[4] Yin Pengbo. Current status and prospect of homogeneous charge compression ignition (HCCI) technology application of transportation. Highlights in Science, Engineering and Technology, 2022, 18: 76-80.

[5] Fontana G. and Galloni E. Variable valve timing for fuel economy improvement in a small spark-ignition engine. Applied Energy, 2009, 86(1): 96-105.

[6] Hong H., Parvate-Patil G. B. and Gordon B. Review and analysis of variable valve timing strategies-eight ways to approach. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2004, 218(10): 1179-1200.

[7] Solouk Ali, Shahbakhti Mahdi and Mahjoob Mohammad J. Energy management and control of a hybrid electric vehicle with an integrated low temperature combustion (LTC) engine. In Dynamic Systems and Control Conference, 2014, 46193: V002T20A005.

[8] Solouk A., Tripp J., Shakiba-Herfeh M., et al. Fuel consumption assessment of a multi-mode low temperature combustion engine as range extender for an electric vehicle. Energy Conversion and Management, 2017, 148: 1478-1496.

[9] Solouk Ali and Shahbakhti Mahdi. Modelling and energy management of an HCCI-based powertrain for series hybrid and extended range electric vehicles. International Journal of Powertrains, 2017, 6(3): 226-258.

[10] Wang Yue, Biswas Atriya, Rodriguez Romina, et al. Hybrid electric vehicle specific engines: State-of-the-art review. Energy Reports, 2022, 8: 832-851.

[11] Pandey Shyam, Diwan Parag, Sahoo Pradeepta Kumar, et al. A review of combustion control strategies in diesel HCCI engines. Biofuels, 2018, 9(1): 61-74.