HCCI technology using hydrogen energy and artificial intelligence

Yinlong Fu[1, †], Erhan Hu[2, †] and Zongxian Xia[3, †, 4]

[1] Kunming No.8 High School, Kunming, 650000, China
[2] Chongqing Nankai Secondary School, Chongqing, 400000, China
[3] Nanjing University of Aeronautics and Astronautics, 210016, China
[†] *These authors contributed equally.*

[4] 182110118@nuaa.edu.cn

Abstract. The principle of a HCCI engine is to inject a mixture of fuel and air into the cylinder and allow it to self-ignite under a high compression ratio. Unlike traditional gasoline and diesel engines, the mixture in the HCCI engine is homogeneous and does not require an ignition system to ignite it. The air-fuel mixture in the cylinder is burned completely by compressing. It makes effective use of fuel. The structure is simpler than a conventional internal combustion engine. HCCI engine has a huge application prospect in many fields. Among them, the automobile is one of the biggest parts. However, some applications have not been widely used. Although the HCCI engine has so many advantages, as this study has discussed, many of its drawbacks are still serious, such as the difficulty in controlling the parameters in the combustion and work process, resulting in the theoretical process being difficult to realize fully. The stringent environmental constraints of HCCI engines, the scarcity of suitable fuels and the significantly lower lifetime of HCCI engines than conventional engines pose significant obstacles to their practical use. This study presents the idea of using artificial intelligence system-assisted control system to accurately control HCCI engines in real time, which has shown great potential in HCCI engine misfire detection and HCCI engine initial burn time prediction.

Keywords: HCCI technology, hydrogen energy, artificial intelligence, sustainability.

1. Introduction

A spray field is a traditional diesel engine composed of liquid fuel, oil droplets, liquid column, oil vapor and air mixed field. The spray field is a very heterogeneous and sensitive thermodynamic system. Conventional diesel engines spontaneously combust through piston compression of the above-mentioned spray field, causing its temperature to rise. Incomplete and uneven diesel combustion produces NO_x and PM emissions, and this is the problem with conventional diesel engines, where fuel and air in the spray field mix neither quickly nor evenly [1]. NO_x is produced in the high-temperature flame zone, and PM is produced in the high-temperature overconcentration zone.

Traditional gasoline engines ignite gas through a spark plug, and it is premixed quasi-homogeneous combustion; there is no combustion to produce a lot of harmful gas problems [1]. But at the same time, gasoline engines can only use a small compression ratio to do work, which makes them inefficient. And this efficiency limit is difficult for conventional engines to overcome. Homogeneous charge compression ignition (HCCI) combines the advantages of both spontaneous and homogeneous combustion compression [1]. HCCI engines avoid locally uneven combustion by igniting a thin, uniform mixture and then distributing the combustion [1]. This method greatly reduces the production and emission of pollutants, such as NO_x and PM, while maintaining the engine's efficiency. Therefore, the HCCI engine has great research potential and a broad market. From the fuel point of view, HCCI internal combustion engine can choose more kinds of fuel, and the engine flexibility and adaptability are better; From the perspective of pollutant emission, the emission of HCCI is low, resulting in less environmental pollution and lower environmental governance costs, which is in line with the overall background of the development of green economy in the world [2]. At the same time, HCCI internal combustion engine requires far less precious metal than gasoline and diesel engines, which can greatly reduce costs and has a strong economy [2]. The HCCI internal combustion engine is superior to the traditional internal combustion engine in technology and more in line with sustainable development and ecological protection in the new era, which is worthy of our exploration [2]. In this study, the advantages of the HCCI engine compared with traditional engines are introduced, and the problems encountered in its development are explained, as well as the feasible solutions.

2. The working principle of HCCI engines

The principle of an HCCI engine is to inject a mixture of fuel and air into it to self-ignite under a high compression ratio. Unlike traditional gasoline and diesel engines, the mixture in the HCCI engine is homogeneous and does not require an ignition system to ignite it. Instead, the self-ignition of the mixture is achieved by generating enough temperature and pressure through a high compression ratio. Specifically, during the working process of the HCCI engine, both the intake and exhaust valves are closed, and the mixture is compressed, increasing its temperature and pressure until it reaches the self-ignition point. Then, the mixture begins to self-ignite, producing high-temperature and high-pressure combustion gas, which pushes the piston down to generate power. Since the combustion is self-ignited, there is no need for spark plugs or injectors to ignite or spray fuel, reducing engine components and costs and improving fuel efficiency.

To ensure that the mixture self-ignites appropriately, it is necessary to control parameters such as intake temperature and pressure to control the self-ignition point precisely. At the same time, to avoid premature or delayed self-ignition, the mixture ratio, compression ratio, and intake temperature need to be adjusted. The control and adjustment of these parameters require advanced electronic control systems to ensure engine stability and reliability. In summary, the principle of the HCCI engine is to achieve the combustion process through self-ignition, without the need for an ignition system or fuel injection system, which can achieve higher fuel efficiency and lower exhaust emissions.

3. Unique advantages of HCCI engines in automobile

3.1. Complete burning of the air-fuel mixture by compression

Recent research reveals that the combustion method of the HCCI engine has a significant characteristic: the homogenization of mixed gases in the turbine and their exhaustion in low temperatures. Its combusting procedure relies on chemical reactions' highlights in the mixed gases. Based on the graph, there are two distinguished subdivisions. One is called low-temperature heat release, another is called high-temperature heat release, and the latter subdivision occupies most of the total heat consumed. But one thing to notice: for the critical point lies on the boundary of both subdivisions, its vertical coordinate could directly influence the heat-releasing disciplinarian. On the other hand, the matching turning corner on the curved axis of 50% of total heat released during the high-temperature heat release process is an essential factor in controlling the HCCI combustion process. To be more specific, "explosive combustion" is a typical signal of incomplete combustion, as to prevent it from happening, a stabilized HCCI engine must situate its combustion control's crank angle in a range of (0,6) [3].

Thus, the reason why HCCI engines possess a higher thermal efficiency is figured out in the following two aspects: Through a low-temperature negative-entropy-induced reaction, the pressure and

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temperature of gases increase, it not only optimizes the combustion conditions of mixture gases but also decreases the fraction of dissipation of work conducting ability. Burning tenuously pushes to complete combustion and shifts up the multilateral index. By the way, to harness the engine properly, engineers suggest users regulate the peak combustion temperature beneath 1800 K to minimize the production of NO_x. This culprit resists high efficiency and contaminates the environment but exceeds 1500 K to unlock the automatic igniting point.

3.2. Different types of fuels

Mazda is the pioneer in applying the HCCI engine on an automobile. In 2007, the CEO of Mazda published a creative technology called SPCCI (spark-controlled compression ignition), which could thoroughly realize super-subtle combustions in its ordinary loading range and lower oil consumption rate. Since the HCCI engine would spark simultaneously in different locations, the throttling loss is eliminated, and the subtle mixing gases can adopt a relatively high compression ratio. When the ideal isochoric combustion gets access, the engine will provide a high thermal efficiency; meanwhile, another course for achieving higher thermal efficiency is due to a low climax of combustion temperature, minimizing the amount of heat transferred from the sparking locations to air cylinder wall surface even in the case that the thermal conductivity is unchangeable. With more heat transfer, HCCI can fit many fuels, including gasoline, diesel oil, natural gas, alcohol, and dimethyl ether (DME). The principle is that as the fuel could vaporize and effectively react to air before the spark appears, it is classified as qualified.

3.3. Simpler structure and easier manipulation for HCCI

Distinguished from traditional car engines, the HCCI engine does not require an air damper because it can automatically control the amount of fuel injection. For traditional engines, its burning process is called sparking ignition. Combustion of SI requires the local flame (the burning gas) to be mixed with the unburned gas, allowing the local unburned gas temperature to rise above the spontaneous ignition temperature before combustion. Therefore, the rate of combustion depends on the rate of local gas mixing, which is relatively slow.

But the situation is not so in HCCI. In the HCCI engine, the gas temperature in the cylinder is around 1100 K; some gas temperature is higher, and some gas temperature is lower. The hottest gas burns first and gives off some heat, and at this point, the colder gas is above 1,100 K, so it starts burning. The process is very fast: for example, if the gas temperature in the tank is exactly 1,100 K, then suddenly, all of the gas will spontaneously ignite and burn. And then it would look exactly like an ideal Otto cycle. But in reality, since the cylinder wall is cold, the gas will have different temperatures. Thus, the ignition time is slightly later because the cold gas only needs to be hotter to burn. In certainty, the HCCI will still burn much faster than the SI. Here is a picture of the temperature distribution of the gas in an optical engine cylinder, where hot and cold are randomly distributed. When the hot spot burns up, the little bit around it burns up quickly rather than spreading outward from the center, like SI. In this case, its strong control of temperature in each part reflects the fact that valves are not necessary to be installed, resulting in an easier manipulation restriction for the staff, who only needs to notice the variation of the multilateral index, gas exhaustion rate, compression ratio and degree of NO_x emission.

4. Practical application of HCCI engine

HCCI engine has a huge application prospect in many fields. Among them, the automobile is one of the biggest parts. However, some applications have not been widely used.

4.1. GM OPEL vectra and GM saturn aura

They both used 2.2L L4 gasoline engines with HCCI technology. Due to the HCCI technology, their oil consumption is only 4.3 L/100 km, more than 15% lower than that of conventional vehicles. Unfortunately, due to the temporary unsophistication of combustion moment control technology, the HCCI engines cannot always work properly. On the other hand, the cold start of these engines is extremely hard because the air-fuel mixture`s initial temperature is too low to burn by compressing, and it becomes even worse in a frozen environment. These two factors determined the effect of these vehicles have not carried out volume production, which had made their names rarely known by people.

4.2. 2007 mercedes F700

Its Diesel Otto 1.8T straight 4 CGI direct injection engine adopts HCCI technology, the output power reaches 238 horsepower, and the maximum torque reaches 400N.m, which can be compared to a 3.5 L V6 engine's performance. The rare thing is that its fuel consumption is only 6 L/100 km, and the carbon dioxide emission is only 127 g/100 km. Due to the market and manufacturing costs, Mercedes-Benz has a very mature traditional internal combustion engine manufacturing technology, making this car a dazzling concept car.

4.3. Mazda oncella 3

Theoretically, the HCCI engine does not need a spark plug, but HCCI engines cannot perform well and reach high thermal efficiency in low-temperature environments. This also led to another problem: more pollution in this process was produced. HCCI is prevalent with diesel-powered engines, but gasoline has been a tough cookie to crack since the initial temperature is the one factor that must be present for the air-fuel mix to combust. If the engine is too hot, engine knock and unpredictable timing is present; if it is too cold, ignition problems ensue. So, Mazda looked to the past and found a solution: use a spark plug. Like a traditional gas engine, Mazda's HCCI engine uses a spark plug to ignite the air and fuel mixture should ambient temperatures be too low, if the engine is subject to a cold start and during high-rpm driving situations. For example, when the car constantly cruises on the highway or during low-load situations around town. According to Mazda's official data, Mazda has said its HCCI engine, known as Skyactiv-X, will be 20 to 30 percent more efficient than its current crop of powertrains.

5. Challenges and development prospects of HCCI diesel engine commercialization

5.1. Strict environmental *conditional restrictions*

5.1.1. Threshold of temperature. The ignition threshold temperature for a cold starting state, referring to a relatively hard sparking induction, is approximately 1000 K. Being ignited in an unprepared situation, the temperature of combustor walls is low, which does not enable heat absorption from the gas intake turbine and does not have accessible hot, exhausted gases. Such a condition is hard to provide additional heat from the last circulation. Likewise, without temperature compensation, igniting the HCCI engine to reach the threshold temperature during the cold starting stage is nearly a miracle.

5.1.2. Picky for loading degree. If encountering underloads, the working condition for the engine belongs to subtle combustion. Since the number of components and their molecular concentrations of the mixing gaseous fuel are few, it is easier to be on fire when igniting. On the other hand, if encountering overloads, the engine would burn rapidly; under such a situation, the mixture of gases is excessively dense, resulting in a horrible explosion. In fact, according to a claim made by the CEO of Mazda, the most comfortable degree of loading for the engine’s combustion is the mid-low one.

5.1.3. Pollution. There is an engineering chain: the pollution index, a standard statistic to measure the degree of contamination, depends on nitrogen oxidization emission. At the same time, the level emission of nitrogen oxidations is largely decided by the air-fuel ratio, and the ternary catalytic converting technology aimed to improve this ratio effectively constrains the pollution index. For the strata of air-fuel ratio, when promising its value to surpass 16, which signals the upper bound of NO_x emission, with a marginal increase of air-fuel ratio, there is no supplement of NO_x gases, and they have been substituted by pure inhaling air. Although the absolute value of noxious exhaustion gases remains constant, more units of kinetic energy could present for a steady amount of NO_x, which implicitly controls their emission. By the way, the essence of tackling key problems of the scanty air-fuel ratio is important: it is equivalent to controlling the ejection of combusting oils. The ECU system is based on real working conditions to ensure the correction factor and nominal fuel ejection rate. There are three ways to control: a. Feedback-proved air-fuel ratio control; b. Physical model-based air-fuel ratio control with the self-correcting regulator; c. Combusting pressure control. However, none of the above technologies have been studied thoroughly.

5.2. *Rarity of ideal kinds of fuel*

Since the ternary catalyst requires the reduction reaction for NO_x with assistance from HC or CO from the exhausted gases, with incremental air-fuel ratio, the decreased temperature after the combustion of mixed gases causes depression on the production of HC and CO, impeding the reduction reaction trend of NO_x. In this way, the engine usually needs an additional NO_x -absorbing catalytic converter in subtle combustion. But a new difficulty emerges. This converter reveals intensive repulsion of manganese and sulfur, implying that it cannot be applied to stick their venomous compounds when filtering. If these venomous elements sediment in the converter, they could damage the original functions of catalyzing. Take sulfur as an example; to obliterate it, engineers can either adopt low-sulfur oils or increase the combustion temperature to 650 degrees [4]. Objectively scrutinizing, the low sulfur oil mentioned in the former solution cannot be found in common stores, and economically, no authorized brands are formed, reflecting the hardship of its manipulation.

5.3. Shorter lifespan

The working pattern of an advanced HCCI engine still experiences 4 stages when being observed, and the discoverer would conclude that all of them contain difficulties of the small piston. Besides, a spring was installed and tangled on the moving piston to alleviate the explosive vibrating effect when homogeneous combustion occurred to prolong the engine's lifespan. The consequence is inconceivable without the installment. Otherwise, compared to traditional engines, the HCCI engine possesses a higher pressure if gasoline explodes because of a larger displacement of the dragged piston. A long-run overload accelerates its despoiling process [5].

6. Artificial intelligence for HCCI

6.1. Emission and operation characteristics of HCCI engines

The factors in HCCI engine operation, such as intake temperature, intake pressure, fuel type, EGR rate, load, speed and so on, strongly correlate with the engine's output parameters [6]. However, this correlation is not a simple linear but sensitive nonlinear relationship [6]. Over the years, several researchers have explored ways to solve this problem. Javad et al. used fuel mixing ratio and excess air coefficient as input parameters to construct a radial basis neural network and feed-forward neural network, respectively, to predict the output parameters of the HCCI engine [6]. Finally, experimental data verification found that the average error of parameter prediction of the two models was lower than 4% [6]. Harisankar et al. also designed a hybrid model of generalized regression neural network and particle swarm optimization and used an optimization algorithm to optimize the intake temperature, EGR rate and load of HCCI engines [6]. Artificial neural networks are also nonlinear systems, so it is possible to design AI suitable for the operation and control of HCCIs. The previous example is a good example of this.

6.2. Artificial intelligence and HCCI engine real-time control

Exhaust gas recirculation, variable valve timing, intake heating and controllable oil supply system are necessary auxiliary control systems to ensure the stable operation of the HCCI engine in the actual working process. HCCI engines must carry many of the above auxiliary control systems, which greatly increases the complexity of the HCCI engine and the cost of HCCI engine control. Previous studies mainly focused on using experimental data to train the neural network to predict the running parameters

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of the HCCI engine in an off-line state. However, this requires a large amount of experimental data, requiring high computer processing power and calculation cost. On the other hand, different engines have different optimum operating conditions, which makes it difficult for some neural networks with good training effects to be applied to other engines [6]. At the same time, the HCCI engine will generate much data that needs attention, but the subtle changes in the engine will significantly impact the control process. This puts forward the requirement of fast operation and fast update iteration for the prediction model of artificial intelligence. To solve the above problems, Vijay et al. developed a stable online learning algorithm (SG-ELM) based on a stochastic gradient extreme learning machine combined with the characteristics of online real-time control of the HCCI engine, which can carry out online regression learning of an HCCI engine and detect the dynamic operating boundary of the engine [6]. Although there are still many problems that cannot be solved for the time being, the SG-ELM algorithm guarantees the stability of learning and reduces the amount of computation, which is likely to be applied to the real-time control of the HCCI engine in the future.

6.3. HCCI engine misfire detection

Misfire is an important factor restricting the expansion of the HCCI engine to low load. SI/HCCI composite engines need to switch combustion modes, and the accuracy of misfire detection will directly affect the safety and speed of this process. HCCI engine fire is mainly caused by unstable combustion. Once the engine fire causes unburned fuel into the tail gas post-treatment system to cool the catalyst, when the activity of the catalyst is reduced, it will significantly increase the emissions of HC and CO, the addition of these combustible gas components, and aggravate the instability of combustion. Therefore, misfire detection of HCCI engines is very important, which is an important link to ensure the safety and availability of HCCI engines [6]. Experiments have verified that the accuracy of predicting engine misfires can reach 100% using neural network input. Bahram B et al. found the in-cylinder pressure at 5, 10, 15 and 20 °C. A top dead center was the key factor determining engine misfires [7].

6.4. Initial combustion time prediction of HCCI engine

HCCI engine belongs to homogeneous compression combustion, and chemical reaction dynamics control the initial combustion moment. Intake temperature, pressure and fuel characteristics will affect the initial combustion moment. The initial combustion time plays a leading role in the combustion process of the internal combustion engine [6]. The spark plug ignition controls the initial combustion time of the ignition engine, while the pressure combustion engine indirectly controls the initial combustion time by the injection time [8]. Taghavi et al. compared engine speed, intake temperature, pressure, equivalent ratio, octane number and EGR Rate as the input, the neural network was constructed to predict the initial combustion time, and the genetic algorithm was used to optimize the structural parameters of the neural network, which not only improved the prediction accuracy but also reduced the calculation cost [9]. Choi et al. established a new prediction model of the initial combustion time by coupling the semi-empirical model of the initial combustion time with the artificial neural network, and the average CPU calculation time of this prediction model is 20-30 ms [10]. Therefore, it has the potential to be applied to the real-time dynamic control of HCCI engine combustion.

7. Conclusions

According to the study, adding a spark plug into HCCI engines lets its cold start easier and brings in fuel economy. The stable operation of the HCCI engine is affected by many factors, so it is more difficult to predict the output parameters of the HCCI engine. The trained artificial neural network can achieve higher prediction accuracy than other prediction models. At the same time, the artificial intelligence prediction model does not need to monitor the complex in-cylinder combustion process in real time and can complete the prediction through the initial parameters, and the prediction speed is extremely fast. In the future, this technology will be applied to the HCCI engine on a large scale. With the needs of national and social development, there will certainly be more research on the HCCI engine in the future, and the difficulties the HCCI engine is facing will be solved, and it will shine brightly in the practical field.

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