INFLUENCE OF HYDROGEN ON COMBUSTION PROCESS AND ON EMISSION PARAMETERS IN THE RCCI ENGINE

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Thanks to its carbon-free nature, it is possible to say that hydrogen is a potential fuel for future automotive systems. Its main favourable properties include high burning rate, wide range of flammability and low ignition energy. In combination with hybrid electric technology, the hydrogen combustion engine has the potential for further development with the goal of maximum efficiency in energy conversion. For more efficient hydrogen combustion, a dual fuel injection hybrid system is designed, where one injector is designed for direct hydrogen injection into the engine cylinder and the other injector is supply fuel to the engine's intake pipe. The greatest challenge is development of a control algorithm intended for management of the combustion process in hydrogen engine and optimization of fuel injection divided into individual doses.

KEYWORDS

hydrogen, combustion process, emission, RCCI

1 INTRODUCTION

Recently, the European Parliament voted to approve a new law banning the sale of gasoline and diesel motorcars from 2035. The legislation requires automotive producers to reduce carbon emissions origin from the new vehicles by 100 %. In practice, this means that from 2035, no new conventional vehicles driven by fossil fuel can be sold. However, some countries are resisting this change and forming an alliance to oppose the given changes and delay the decision. For example, Germany reached an agreement with the European Commission to continue selling vehicles driven by carbon-neutral synthetic fuels. In addition to climate-neutral e-fuels, the solution for internal combustion engines can also be hydrogen, whose direct combustion in the internal combustion engines will probably play an important role, especially for sectors, in which the use of battery electric drives is inefficient. For the future of the automotive industry in the EU, the acceptance of the exemption for climate-neutral fuels is therefore very good news, because a significant alternative to battery electric cars will emerge in the form of combustion engines using e-fuels or hydrogen for vehicle driving system.

For example, the company Toyota is experimenting with hydrogen fuel, which also uses it in motorsport. The automotive companies Yamaha, Honda, Kawasaki and Suzuki have received approval from Japan's Ministry of Economy, Trade and Industry to establish a technology research association called HySE (Hydrogen Small mobility & Engine technology) to develop hydrogen engines for small mobility. Small mobile vehicles include motorcycles, small vehicles, small marine vessels, mobile building equipment, etc.

The partners said that realizing of a decarbonized society requires a multi-level strategy to address various issues in the mobility sector rather than focusing on a single energy source. In this context, research and development aimed at the commercialization of mobility with hydrogen-powered engines is gaining momentum. However, the use of hydrogen presents technical problems, including high flame speed and large ignition area, which often lead to unstable combustion and limited fuel tank capacity when used in small mobile vehicles. To address these challenges, the HySE members are committed to fundamental research, leveraging their wealth of expertise and technology in gasoline engine development, and aim to work together on the common mission of creating a design standard for small vehicle hydrogen engines. Various scientific organizations, but also the private sector, are experimenting with the possibility of combining different fuels such as diesel and hydrogen. In Australia, a project for mixing different fuels with hydrogen was supported and co-financed by the Australian Government in the amount 2.59 million of Australian dollars and with a total cost 8.61 million of Australian dollars. The result of the study was, among other things, obtaining of knowledge about the possibilities of mixing hydrogen into diesel, while due to the influence of diesel in the combustion chamber, there was a significant elimination of the problems that arise during the direct combustion of pure hydrogen. The research also included the development of an H2DDI type engine, without the pre-ignition and knocking limitations typical of a purely hydrogen fuel-injected engine. The development was based on an automobile diesel engine with a common-rail injection system when an additional high-pressure hydrogen injector was mounted in the engine cylinder head. The result of the research was an engine using a 50% mixture of hydrogen and diesel, which achieved relatively high indicated efficiency and low emissions.

Hydrogen has the highest energy content per unit of mass among all chemical substances. The hydrogen heat of combustion (142 $MJ \cdot kg^{-1}$) is 2.5 times higher than the methane heat of combustion (55.55 $MJ \cdot kg^{-1}$). These properties of hydrogen combustion process are very important for future development of internal combustion engines. To achieve better ignition of the fuel mixture, it is possible to replace nitrogen by the rare gases with a higher specific heat ratio during the compression process. Therefore, it will be necessary to investigate the influence of burning hydrogen and various rare gases on distribution and transfer of heat as well as on the limitation of possible detonations. Based on current knowledge, helium or argon could potentially be the most suitable gases for combustion control and for heat distribution. However, these conclusions will require more detailed research to achieve the desired results applicable in a real engine.

In order to create a possible compromise between the fuel consumption and combustion stability, it is necessary to find a way how to realise the stable combustion process. The suitable innovative technology is called the LTC technology, i.e. the Low Temperature Combustion in the engines. This technology was primarily developed as a solution determined to reduce the NO_X emissions [Ascanio 2008, Brennan 2008].

According to Fig.1, it is evident that generation of NO_X can mostly be prevented by keeping the local temperature below the level approximately 2200 K. This condition can be fulfilled by combustion of an extremely lean fuel mixture. At the same time, the LTC conception can be also applied to simultaneous reduction of particulate matter, depending on the fuel-air equivalence ratio. LTC integrates the best characteristic features of diesel and spark combustion, namely high efficiency and low emissions. The main conceptual idea is to create a very lean mixture, homogeneous as possible, potentially capable of self-ignition at one moment and in the whole combustion volume. The complex solution of this task is considerably complicated.

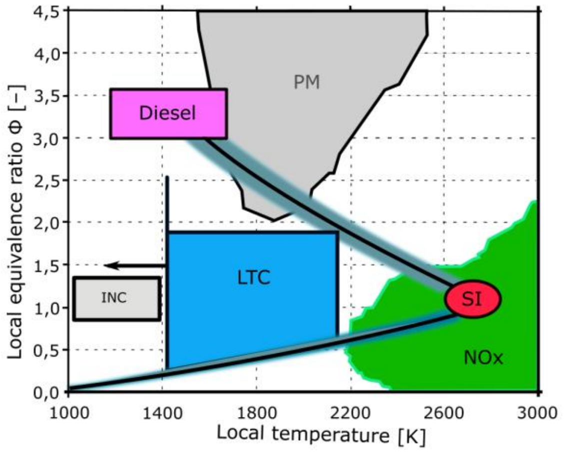

Figure 1. Low temperature combustion in engines - LTC

The LTC combustion includes several combustion technologies that are subjects of continual development with the aim to achieve a long-term reliability. These individual LTC combustion technologies differ mainly in the procedure required for preparing of the fuel mixture and in the ignition concept. However, homogeneous lean mixture, which reduces the NO_X and PM emissions at the same time, means a problem during ignition. The solution is to create fuel-rich zones inside the combustion chamber, for example by means of partial stratification, which may aid ignition of the mixture, but on the other hand it may increase pollutant emissions [Dresler 2018].

Several motor-car companies are investing in development of the LTC technologies, for example the companies General Motors (GM), Mazda, Mercedes Benz or Hyundai and it is possible to say that the current emission challenges confirm correctness of this step. Especially, the company Mazda sees the LTC engine concept as a right way towards a better electric future in 10, 25 or many years: "We think, it is essential that we strive for the ideal internal combustion engine," said the head of research and development in the Mazda company, Mr. Kiyoshi Fujiwara. "Electrification is necessary, but the internal combustion engine should be first."

The relevant LTC technologies, with a significant, promising potential of future practical development and application, are as follows:

- HCCI (Homogeneous Charge Compression Ignition),
- PCCI (Premixed Charge Compression Ignition),
- SCCI (Stratified Charge Compression Ignition),
- RCCI (Reactivity Controlled Compression Ignition),
- SACI (Spark Assisted Compression Ignition).

2 COMBINATION OF HYDROGEN AND DIESEL FUEL

Hydrogen is generally a clean, energy-rich and environmentally friendly alternative fuel. Currently, research focused on hydrogen enrichment with biodiesel is running very intensive due to its special perspective on helping the environment. It is important to mention a fact that the self-ignition temperature of hydrogen is relatively low, and this ignition point causes problematic combustion in diesel engines. On the other hand, combination of hydrogen with other fuels is a feasible method to achieve increased engine power output and to improve combustion while reducing emission characteristics in diesel engines. Therefore, biodiesel is used as a fuel suitable for mixing with hydrogen. Fig. 2 presents the advantages of diesel fuel with hydrogen combination and Fig. 3 summarizes the advantages of biodiesel with hydrogen combination. Since viscosity plays a major role in combustion, the application of biodiesel was classified as high viscosity fuel and low viscosity fuel for investigation with hydrogen as fuel in CI engine.

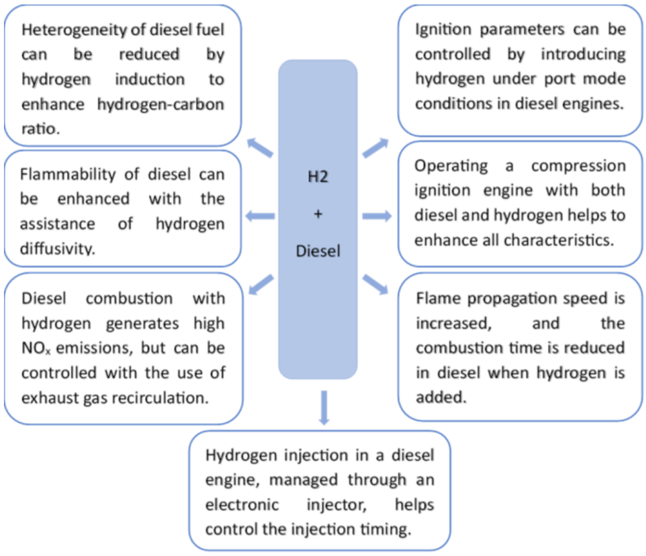

Figure 2. Advantages of diesel-hydrogen combination

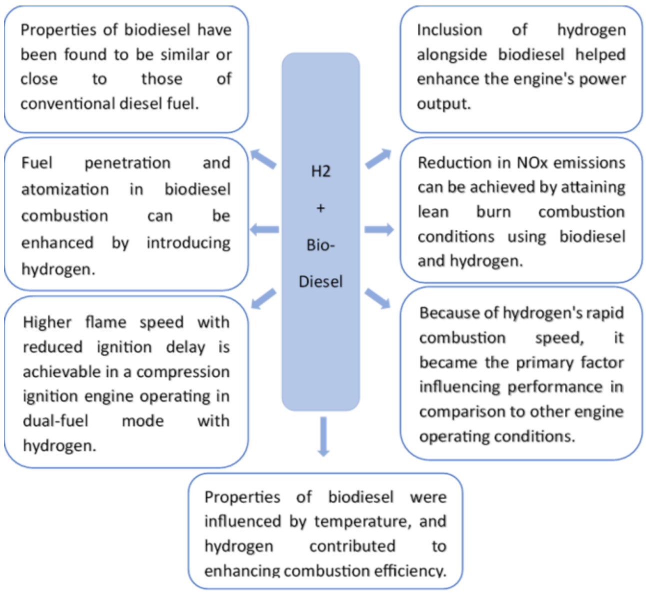

Figure 3. Advantages of biodiesel-hydrogen combination

3 APPLICATION OF HYDROGEN IN RCCI

The RCCI engines utilize the low-reactivity fuels, i.e. the fuels with high-octane number and also the high-reactivity fuels, i.e. the fuels with high-cetane number. The low-reactivity fuel uses the system of Port Fuel Injection (PFI), in which the fuel is premixed with air during the suction stroke. The high-reactivity fuel is injected into the engine cylinder by the Direct Injection (DI). Thus, the high-reactivity fuel is used to control self-ignition and combustion of a lean premixed fuel-air mixture, which is composed of low-reactivity fuel mixed with air and, possibly, with a moderate amount of exhaust gases (Fig. 4). In this way, the reliable combustion is ensured.

Low-reactivity fuel can be injected by several early direct injections or by a single intake manifold injection. Direct injection of high-reactivity fuel can be implemented one or more times to optimize phasing and according to duration and extent of the combustion process.

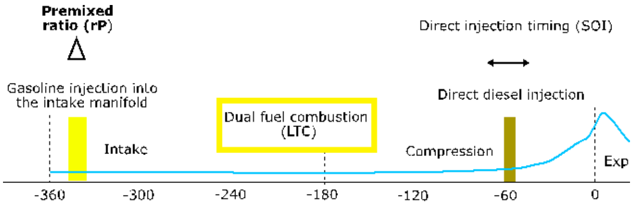

Figure 4. Timing of fuel injection in RCCI

Gasoline and diesel, ethanol (methanol or butanol) and diesel or gasoline as well as gasoline with different octane numbers can be used as fuels [Tucki 2021]. Since it is a dual-fuel system, a double Wiebe function is proposed to calculate the mass fraction of the burned fuel to the total fuel mass, which is based on the following relation [Famfulik 2021]:

$$x_b = \alpha\left\{1 - exp\left[-a_1\left(\frac{\theta-\theta_{01}}{\Delta\theta_1}\right)^{m_1+1}\right]\right\} + (1-\alpha)\left\{1 - exp\left[-a_2\left(\frac{\theta-\theta_{02}}{\Delta\theta_2}\right)^{m_2+1}\right]\right\},$$

where x_b is the mass fraction of the burned fuel. Variables 1 and 2 indicate combustion of the fuel 1 and 2, and θ_{01} and θ_{02} represent beginning of combustion for the first and for the second fuel (Fig. 34). In addition, α is the fuel mass fraction burned during combustion of the fuel 1, what is the mass fraction of the burned fuel at θ_{02}. The burning time of the first fuel is $\Delta_{\theta 1} = \theta_{02} - \theta_{01}$.

The rate of burned fuel in combination with dual-fuel combustion can be expressed as:

$$\frac{dx_b}{d\theta} = \alpha\left(\frac{dx_{b1}}{d\theta}\right) + (1-\alpha)\left(\frac{dx_{b2}}{d\theta}\right),$$

where x_{b1} and x_{b2} are the mass fractions of the fuel burned in each stage of combustion:

$$\frac{dx_{b1}}{d\theta} = a_1\left(\frac{m_1+1}{\Delta\theta_1}\right)\left(\frac{\theta-\theta_{01}}{\Delta\theta_1}\right)^{m_1} exp\left[-a_1\left(\frac{\theta-\theta_{01}}{\Delta\theta_1}\right)^{m_1+1}\right],$$

$$\frac{dx_{b2}}{d\theta} = a_2\left(\frac{m_2+1}{\Delta\theta_2}\right)\left(\frac{\theta-\theta_{02}}{\Delta\theta_2}\right)^{m_2} exp\left[-a_2\left(\frac{\theta-\theta_{02}}{\Delta\theta_2}\right)^{m_2+1}\right].$$

Combustion using a reactive dual-fuel strategy results in relatively higher thermal efficiency compared to combustion with other LTC derivatives, while maintaining lower NO_X and PM emissions than at diffuse diesel combustion, without the need of post-treatment by means of other methods. Therefore, it is considered to be one of the most promising technologies [Puskar 2021]. By using of compression heat, the high-reactive fuel ignites, which subsequently leads to self-ignition and to burning of fuel with low reactivity. There was performed a design solution of the engine based on RCCI. A four-cylinder supercharged internal combustion engine was chosen for the technical-constructional solution, which is illustrated on Fig. 5 in a modified version.

Numerical simulation of the RCCI engine was performed with hydrogen, diesel and dimethyl ether by means of a simulation software tool and using Reynolds averaging of conditions in the Navier-Stokes equations [Puskar 2022]. Compared to the one-dimensional simulation, an increase of pressure during combustion and also increase of heat release rate was recorded at this simulation [Rodriguez 2023]. Analysis of the model discovered that it shows a similar trend of flow and turbulence in combustion of hydrogen and dimethyl ether compared to the HCCI combustion phenomenon. A three-dimensional model of the developed system was also found to cause a higher pressure and higher heat release rate [Rodriguez 2022]. There was performed a numerical analysis of an RCCI engine with a compression ratio of 17.2:1 at the engine speed 800 rpm. The content of hydrogen was from 0% to 50% (Table 1), together with the application of diesel and dimethyl ester as a second fuel.

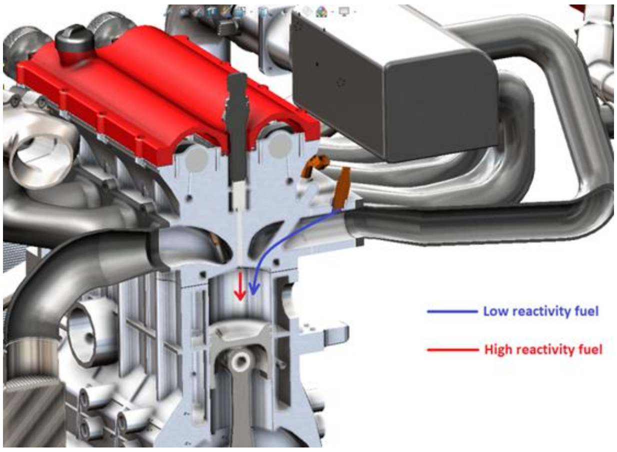

Figure 5. Proposed design of engine

The analysis of the obtained results shows that the pressure in the combustion chamber increased, as well as the rate of heat release. There was also recorded reduction of the HC and CO emissions, but at the same time the NO emissions increased. Furthermore, a numerical simulation of the RCCI engine using hydrogen and at the same compression ratio was performed, with the hydrogen ratio from 0 to 30% and with the IMEP values from 3.20 to 3.40. Diesel was used as the second fuel. The heat release rate and the pressure values also increased. In the case of emissions, the same results were recorded, i.e. an increase of the NO emissions and a decrease of the HC and CO emissions.

A decreasing trend in the mass fraction of CO and an increasing trend in the mass fraction of NO were observed due to the increase in temperature. A decreasing trend in CO and HC emissions was recorded with the increase in compression ratio. It was found that NO_x emissions are higher when using hydrogen and the opposite trend is in soot emissions with increasing hydrogen feed level and with increasing compression ratio parameters in the engine.

In the next experiment, the same compression ratio was used, but the amount of the added hydrogen was only at the level from 0 to 9%. Simulations were performed at high IMEP (Tab.1). The second applied fuel was dimethyl ether. There was recorded an increase in the operational pressure and in the rate of heat release as well as at the same time a decrease in all the monitored emission parameters NO, HC, CO.

It was found that the addition of hydrogen into the RCCI engine improves the combustion pressure with a decrease of the mass fractions of CH_2O and CH_3. However, it was also observed that the heat release rate in the system increases due to support of combustion by the injected hydrogen. There were also performed experiments with the aim to study transformation process from a hydrogen diesel dual-fuel engine to the RCCI engine. Divided diesel injection was used with two different injection times and with two various injected fuel amounts. Hydrogen RCCI improved engine power output and significantly reduced emissions. The final experiment was realised using reduced compression ratio value 16.1:1 and with hydrogen amount from 0% to 70%. The speed range was from 1200 to 1300 rpm. Hydrogen was applied as the second fuel. Again, it is possible to observe an increase in pressure and in heat release rate, and there was a reduction in all the regulated emission parameters according to the EURO standard (Table 1). It can be stated that compared to the traditional diesel engines, the RCCI engine had high efficiency and lower concentration of particulate matter and NOx emissions.

Table 1. Results of numerical simulations

Type of study (RCCI)	CR	Condition	Fuels	Combustion	Emission
Numeric	17.2:1	H_2:0,10,20,30, 40 and 50% Speed 800rpm	Diesel, Di-methyl ether	ICP:↑ HRR: ↑(15.9%)	CO: ↓(1.2g/kWh) HC: ↓(0.1g/kWH) NO: ↑((0.426 g/kWh)
Numeric	17.2:1	H_2: 0, 10, 20, and 30% IMEP:3.20- 3.40	Diesel	ICP:↑ HRR: ↑(5.01%)	HC: ↓(29.8%) CO: ↓(35.5%) NO:↑(23.1%)
Numeric	17.2:1	H_2 : 0 - 9 % IMEP: 9 bar	Dimethyl ether	ICP:↑ HRR: ↑	NO: ↓ CO: ↓ HC: ↓
Numeric	16.1:1	H_2: 0 to 70% Speed 1200 and 1300 rpm	Diesel	ICP:↑ HRR: ↑	NO_x : ↓ Soot: ↓ CO: ↓ HC: ↓

In fact, the relevant engine operational parameters, such as injection timing, compression ratio, fuel ratio, speed of EGR and combustion chamber geometry were optimized. This inclusive review emphasizes an important fact that an effort was made to achieve the improved thermal efficiency of the RCCI engines using hydrogen fuel. Similarly, biodiesel also presents a usage potential when combined with hydrogen fuel.

4 CONCLUSION

Utilisation of the renewable fuels can lead to reduction of engine gaseous emissions, and in this way to reduction of negative consequences caused by climatic change and environmental problems [Brezinova 2018, Chausov 2019]. Among the available fuels, the properties of hydrogen as a fuel and its constant availability make it a prominent alternative fuel. Although the use of pure hydrogen alone as a fuel for internal combustion engines was almost impossible, this article analyses the possible integrated combustion of hydrogen together with diesel. The combined effect of high flame velocity, better diffusivity and wide flammability range of hydrogen improve the combustion parameters, what was indicated by increasing of thermal efficiency and by high pressure rise rate. Diesel fuels contributed to improvement of combustion thanks to their excess of oxygen and higher cetane number of them. Using hydrogen-enriched diesel, more complete combustion was improved, and higher engine cylinder temperatures were achieved, what caused excessive NO_x generation [Toman 2017].

In diesel engines, high concentrations of smoke and NOx emissions were observed at high temperatures and rich fuel part of sprayed pattern. Therefore, change of the injection profile was considered as method to achieve reduction of NOx and smoke emissions. At high engine load, the RCCI engine can operate using technology of exhaust gas recirculation (EGR).

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