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ANALYSIS OF ADVANCED TECHNOLOGY FOR COMBUSTION OF HOMOGENEOUS FUEL MIXTURE

Summary. The most serious problems to overcome for a successful operation of the HCCI engine are control of the combustion phase, limited operational range, cold start of engine and high noise level during engine operation. This study aims at describing the engine power output characteristics and emission characteristics of HCCI engines under different testing conditions and the various challenges associated with these engines. Furthermore, this study holds a potential guide for overcoming these challenges and improvement of the engine power output as well as the emission characteristics. Thus, it is possible to say, concerning the performed investigation work, that HCCI combustion can be applied in existing conventional engines after their modifications. The most significant result of the HCCI process application is the reduction of NOx emissions and soot emissions, keeping almost the same engine power output as the conventional combustion process.
Keywords: analysis, advanced technology, combustion, fuel mixture

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1. INTRODUCTION

Currently, there is an important modification of a trend, which is presented in the form of pressure, to reduce engine emissions significantly. However, this task requires long-term, sustainable, and effective solutions, such as the advanced combustion technology known as Homogeneous Charge Compression Ignition (HCCI). The HCCI technology is a combination of the gasoline engine with spark ignition and the diesel engine with compression ignition, using the best characteristic feature of both ignition systems. There is applied gasoline as a fuel, however, with a higher efficiency, which is typical for the diesel engine. Combustion of the homogenous charge runs simultaneously in the whole piston combustion area, that is, the charge is combusted almost completely, without a rest. Exploration of gasoline using HCCI technology is very efficient, as it offers a significant reduction in fuel consumption and exhaust gas emissions, whereas NOx emissions are almost negligible. However, the application of HCCI technology is connected with some basic problems; for example, there is a high level of pressure values during compression, thermal loading during combustion and complicated control of the self-ignition process. It is necessary and purposeful to inform the professional community about recent significant advances reached in the area of HCCI combustion technology. This article is focused on the power output characteristics and emission characteristics of HCCI engines compared to conventional engines. Both categories of engines are discussed in detail in different sections. Finally, the results obtained from the individual investigations are summarized in tabular form to present their comparison understandably. In addition, appropriate solutions were proposed for specific challenges concerning HCCI engines.

2. ENGINE POWER OUTPUT

The power output of an engine is a relevant parameter that is important for the acceptability of the engine. The engine power output is significantly influenced by the following factors: fuel properties, fuel injection pressure, valve timing, fuel-air mixture, injected amount of fuel, etc. This part of the article provides a practical comparison of performance between HCCI engines and conventional engines that use different kinds of fuel, taking into consideration the cylinder pressures, Heat Release Rate (HRR), Specific Fuel Consumption (SFC), thermal efficiency, exhaust gas temperatures, and ignition delay. The comparative results of each investigation, relating to the performance characteristics of HCCI engines (using different fuels) and conventional engines, are summarized in Table 1.

Tab. 1

The comparative results

Type of testing engine	Conditions and fuel	Increasing parameters	Decreasing parameters
4-stroke,1-cylinder, air-cooled, compression ignition, direct-injection, compression ratio: 17.5:1, power: 4.4 kW, speed: 1500 rpm	Constant speed, different load, Diesel	HC, CO, NOx, Smoke	Thermal efficiency, Cylinder pressure
4-stroke,1-cylinder, naturally aspirated, compression ignition,	Constant speed,	HC, CO, Soot,	Thermal efficiency, NOx

direct-injection, compression ratio: 18.5:1, speed: 1800 rpm	different load, Diesel	Cylinder pressure, HRR	
4-stroke,1-cylinder, water-cooled, naturally aspirated, compression ignition, compression ratio: 14.8:1	Variable speed, different percentages of EGR, Diesel	HC, CO	Cylinder pressure, SFC, NOx, Smoke
4-stroke,1-cylinder, compression ignition, compression ratio: 19:1, power: 11 kW, speed: 3000 rpm	Variable speed, different loads, Diesel	SFC, HC, CO	NOx, Smoke
4-stroke, 2-cylinder, air-cooled, compression ignition, direct-injection, compression ratio: 16.5:1, power: 5.85 kW, speed: 1500 rpm	Constant speed, different loads, different percentages of EGR, Biodiesel–diesel blend	Cylinder pressure, HC, CO, Smoke	Thermal efficiency, SFC, HRR, NOx
4-stroke,4-cylinder, compression ignition, direct-injection, compression ratio: 16.5:1	Constant speed, different loads, Biodiesel–diesel blend	SFC, Thermal efficiency, CO	NOx, HC
4-stroke,1-cylinder, compression ignition, direct-injection, compression ratio: 17.5:1, power: 4.4 kW, speed: 1500 rpm	Constant speed, different loads, different percentages of EGR, Biodiesel–diesel blend	Cylinder pressure, HC, CO	HRR, NOx, Smoke
4-stroke,1-cylinder, naturally aspirated, compression ignition, direct-injection, compression ratio: 16.1:1, power: 62 kW, speed: 1800 rpm	Variable speed, different loads, Gasoline	SFC, Thermal efficiency, Cylinder pressure, HRR, HC, CO	NOx
4-stroke,1-cylinder, water-cooled, naturally aspirated, compression ignition, direct-injection, compression ratio: 17:1	Variable speed, different loads, Gasoline-Alcohol	SFC, HRR, HC, CO	Cylinder pressure, NOx

2.1. Pressure in engine cylinder

Many researchers reported higher or lower cylinder pressures in HCCI engines in comparison to conventional engines [1-12]. For example, there were investigations on the experimental characteristics of combustion, power output and emissions for HCCI engines using different fuel mixtures and the obtained results were compared with conventional engines. A two-cylinder, four-stroke and air-cooled diesel engine was modified for the HCCI operation, applying different percentages of the Exhaust Gas Recirculation (EGR), namely the values 0, 15 and 30%. It was monitored that the cylinder pressure was higher in the HCCI engines than in the conventional engines. Several research works mentioned herein have also used hydrogen as fuel to investigate the combustion characteristics of the HCCI engine. Higher pressure values were recorded in the engine cylinder, and using CO_2 as an additive, kept the pressure in the cylinder at an adequate level. Several researchers, using different techniques, have found that the values of cylinder pressures in HCCI engines are lower than in conventional engines. There were also realized experiments to apply the technology of internal and external exhaust gas recirculation for reduction of the cylinder pressure. The recirculation of cooled exhaust gases was very helpful in this case.

2.2. Heat release rate (HRR)

It is possible to state for the HCCI engine regime that HRR during this kind of combustion is completely different from CI and SI combustion [8, 9]. Most of the analyses align with the works [2-12], which found that HRR is higher in HCCI engines than in conventional engines.

Formation of a proper fuel-air mixture and suitable self-ignition chemistry are critical factors for the reduction of HRR in HCCI engines [4]. In addition, HRR in HCCI engines is also influenced by the equivalence ratio of the fuel-air mixture and the engine speed [13-15]. Careful control of the HCCI process can ensure a suitable HRR in HCCI engines.

3. PROBLEMS OF HCCI COMBUSTION

3.1. Control of combustion phase

Although HCCI engines have many advantages compared to conventional engines in terms of thermal efficiency and NOx emissions, they still have some serious disadvantages. One of which is the problem with the timing of ignition, which is a significant challenge, as it eventually affects engine power output and efficiency. Unlike SI and CI engines, HCCI engines do not have any direct mechanism for control of the combustion beginning. Therefore, the HCCI process fully depends on the self-ignition of the fuel-air mixture. According to [16, 17], this self-ignition is influenced by several factors. The most important of them are: the chemical and thermodynamic properties of the fuel self-ignition, burning time, temperature of the cylinder walls, concentration of reactants, degree of fuel mixture homogeneity, suction temperature, compression ratio, amount of EGR, engine speed, convective heat transfer to the engine and others. Higher values of suction temperatures and suction pressures cause the time advance of ignition moment due to faster chemical kinetics [18-20]. A lower specific heat due to higher equivalence ratios leads to ignition temperature, assuming higher compression heating. However, in real operation and for both types of applied fuels, higher equivalence ratios increase the residual temperatures on the cylinder walls, influencing combustion timing

[20]. Utilization of EGR has different effects on combustion timing in dependence on the EGR application technique. Application of EGR with cooling causes a delay in the ignition timing, after which the residual gases remain circulating as non-reactive diluents in the fuel mixture inside the cylinder [5-7]. Internal EGR using, for example, the Negative Valve Overlap (NVO), can achieve an earlier ignition timing given the fact that the temperature of residual gases is much higher [2]. Most researchers opine that the HCCI process is governed by chemical kinetics [7]. Failure in the control of combustion timing can also cause high levels of HC and CO emissions because these emissions depend on ignition timing [6].

3.2. High level of engine noise

Another serious challenge for HCCI engines is the high noise level of their operations, which is caused by the rapid increase of pressure in the engine cylinder at high operational loads. During the compression stroke, instantaneous heat is released by the self-ignition of the homogeneous fuel-air mixture, creating high pressure values [7]. Failure in the control of this rapid heat release, which is the main source of high pressure, can damage the engine [8]. A higher value of the heat release rate means not only a higher value of pressure increase, which can lead to mechanical damage but also a higher temperature of the cylinder wall and piston surface. These temperatures are high enough to cause physical damage to the material. Also, high local pressure peaks can damage the engine and the cylinder head gasket due to high pressure. Pressure fluctuations can result in serious damage for two reasons. The first reason is that the rate of pressure increase in each oscillation cycle can physically damage the engine. And the second reason is that pressure fluctuations may occur at the resonance frequency of the engine cylinder. These excitations due to oscillating fluctuations can also lead to physical damage of the engine. The acceptable increase of the pressure limit for the noise is ≈ 8 bar / CA [9].

3.3. Engine operational range

Another obstacle to the successful commercialization of HCCI engines and their establishment on the market is their limited operational range. It is imperative to extend this range for maximization of the benefits HCCI engines offer. However, it is necessary to control the ignition timing in the extended operational area [9]. The self-ignition properties of the fuel and geometry of the engine significantly influence the engine's operational range [2]. It is difficult to achieve self-ignition for extremely low engine load, so there is a lower load limit for the HCCI operation. In addition, the HCCI operation is also limited for higher engine load [5] due to the knocking phenomenon. HCCI engines have remarkably low levels of NOx and PM emissions; however, on the other hand, the emissions values of CO and unburned hydrocarbon are increased because the engine operational area is limited.

3.4. Cold start of engine

In connection with the above-mentioned problems, the conditions required for a cold start of the HCCI engine can cause serious complications. During the cold start of the engine, the temperature of the compressed gas in the HCCl engine is low, as the mixture is not pre-heated in the intake pipe, and the compressed mixture is cooled rapidly due to the transfer of heat to the walls of the cold combustion chamber. The low levels of temperatures of the low-pressure mixture complicate the cold start of the HCCI engine if some compensation mechanism is not applied. A stable HCCI operation often primarily relies on stable (and preferably high) suction temperatures. Therefore, the cold start is quite challenging [7], and the initial ignition is extraordinarily demanding without the help of thermal inertia. Possibility of a reliable cold start is vital for the high and low operational load of the HCCI engines to utilize all their benefits.

3.5. Preparation of homogeneous mixture

Efficient preparation of the fuel-air mixture is central to reducing HC and PM emissions and achieving high fuel efficiency [2]. The fuel condensed on the surface of the combustion chamber is a negative phenomenon regarding HC emissions, even for fuels with moderate evaporability, such as petrol [2]. For fuels with low evaporability, such as diesel fuel, it is very difficult to prepare a homogeneous fuel-air mixture. The available time to prepare a homogeneous fuel-air mixture in the combustion chamber is small due to the short time interval of the thermodynamic cycle [1].

4. PROPOSED SOLUTIONS TO PROBLEMS

4.1. Control of engine noise

One of the many suitable solutions for controlling ignition timing is changing the mixture temperature. The change in the fuel-air mixture temperature can be achieved in several ways. The main possibilities are: Variable Valve Timing (VVT) method, Variable Compression Ratio (VCR) method [6-9], method of variable EGR [5], capturing of the residual exhaust gases [3-5], control of the injection timing [10, 17], modulation of the suction temperature [5], water injection [6], and changing of the coolant temperature [7]. Another possible solution to ignition timing proposed by many researchers is the control of the ignition timing using a change in the mixture reactivity. Also, this can be achieved in many ways, for example, by the modulation of two or more fuels, fuel stratification [4], the use of fuel additives and regulation [9].

4.2. Engine operational range

There were performed several measurements aimed at enlarging the engine's operational range at high and low engine loads. A possible solution for the extension of the high load area can be increasing the air intake amount [11] using the residual gas capture method with cooled EGR [1] or by employing the two-stroke operation in the engine equipped with a possibility to switch between the two-stroke and four-stroke operational regime [20]. The low load area can be extended using the spark or the reduced coolant temperature.

4.3. Cold start of engine

Various mechanisms were proposed to overcome the problem with the cold start of the engine. The most suggested solution is to start the engine in the conventional mode and then switch the engine into the HCCI mode after a short warm-up. Other proposed solutions are: the application of glow-plugs, application of other kinds of fuel or fuel additive, increase of the compression ratio based on the Variable Compression Ratio (VVR) method, utilization of the VVT and also use of the Spark Assisted Compression Ignition (SACI) [6]. Although the proposed solutions seem suitable and feasible, it is necessary to perform another extensive research and development focused on verifying these concepts and preparing them for the production of engines [7].

4.4. Preparation of homogeneous mixture

Several successful strategies were developed and determined as the solution to the problem of creating a homogeneous fuel-air mixture. Low Temperature Combustion (LTC) was already applied in various combustion aggregates, for example, in internal combustion engines and gas turbines, mainly to reduce NOx emissions. Classification of LTC relating to strategies focused on the preparation of homogeneous mixture is presented in Figure 1 [2]. Other suitable steps intended for the solution of the given task are: fuel injection at high-turbulent intake of air, application of highly evaporative fuels [8, 9] and early fuel injection into the engine cylinder using sophisticated fuel injectors [13].

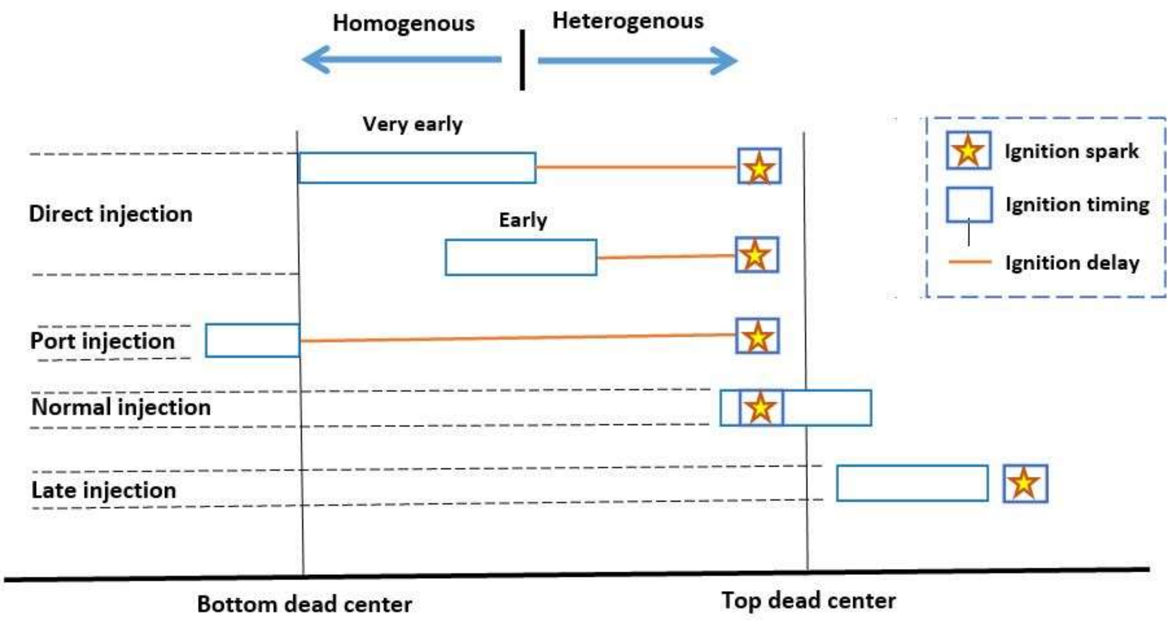

Fig. 1. Low temperature combustion

5. CONCLUSION

Although there are always certain inconsistent trends concerning the combustion characteristics of HCCI engines (for example, different engine power outputs and emissions for different tested engines, operational conditions, driving cycles, applied fuels, measuring techniques and instruments), it is, however, possible to formulate the following conclusions:

- Chemical kinetics plays a dominant role in the HCCI combustion process.
- The internal combustion engine, working with the HCCI combustion process, has a real potential to reach higher thermal efficiency than the conventional engine.
- For HCCI combustion, the amount of NOx and PM emissions is negligible; this is similar to the trend of HC and CO emissions compared to the conventional combustion process.

- A successful operation of the HCCI engine requires overcoming the difficulties associated with the HCCI combustion, including the problems relating to the combustion phase, the extension of the operational range, engine cold start and preparation of the homogeneous fuel-air mixture.

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References

1. Duan Xiongbo, et al. 2019. "Experimental Study the Effects of Various Compression Ratios and Spark Timing on Performance and Emission of a Lean-Burn Heavy-Duty Spark Ignition Engine Fueled with Methane Gas and Hydrogen Blends." *Energy* 169: 558-571. DOI: https://doi.org/10.1016/j.energy.2018.12.0295571.571.
2. Duan Xiongbo, et al. "Influence of Single Injection and Two-Stagnation Injection Strategy on Thermodynamic Process and Performance of a Turbocharged Direct-Injection Spark-Ignition Engine Fuelled with Ethanol and Gasoline Blend." *Applied Energy* 228: 942-953. DOI: https://doi.org/10.1016/j.apenergy.2018.06.090.
3. Duan Xiongbo, et al. 2020. "Quantitative Investigation the Influences of the Injection Timing under Single and Double Injection Strategies on Performance, Combustion and Emissions Characteristics of a GDI SI Engine Fueled with Gasoline/Ethanol Blend." *Fuel* 260: 116363. DOI: https://doi.org/10.1016/j.fuel.2019.116363.
4. Gracanin Danijela, et al. 2014. "Using Cost-Time Profile for Value Stream Optimization." *Procedia Engineering* 69: 1225-1231. DOI: https://doi.org/10.1016/j.proeng.2014.03.113.
5. He Bang-Quan, et al. 2015. "Comparison of Combustion Characteristics of n-Butanol/Ethanol-Gasoline Blends in a HCCI Engine." *Energy Conversion and Management* 95: 101-109. DOI: https://doi.org/10.1016/j.enconman.2015.02.019.
6. Kester Johannes, et al. 2018. "Policy Mechanisms to Accelerate Electric Vehicle Adoption: A Qualitative Review from the Nordic Region." *Renewable and Sustainable Energy Reviews* 94: 719-731. DOI: https://doi.org/10.1016/j.rser.2018.05.067.
7. Kučera Pavel, Václav Píštek. 2014. "Virtual prototype of a heavy duty off-road truck driveline in Simulink software". *Proceeding of International Conference Transport Means. "Transport Means"*. K. Donelaičio st. 73, LT-44029 Kaunas: Kaunas University of Technology. P. 5-8. ISSN: 1822-296X.
8. Chríbik Andrej, Marián Polóni, Matej Minárik, Radivoje Mitrovic, Zarko Miskovic. 2019. "The Effect of Inert Gas in the Mixture with Natural Gas on the Parameters of the Combustion Engine." *Computational and Experimental Approaches in Materials Science and Engineering*: 410-426. DOI: https://doi.org/10.1007/978-3-030-30853-7_24.

9. Czech Piotr. 2011. „Diagnosing of disturbances in the ignition system by vibroacoustic signals and radial basis function - preliminary research.” *Communications in Computer and Information Science* 239: 110-117. DOI: https://doi.org/10.1007/978-3-642-24660-9_13. Springer, Berlin, Heidelberg. ISBN: 978-3-642-24659-3. ISSN: 1865-0929. In: Mikulski Jerzy (eds), Modern transport telematics, 11th International Conference on Transport Systems Telematics, Katowice Ustron, Poland, October 19-22, 2011.
10. Czech Piotr, Jerzy Mikulski. 2014. „Classifier and Entropy of Vibration Signals to Diagnose Damage of Head Gasket in Internal Combustion Engine of a Car.” *Communications in Computer and Information Science* 471: 225-232. DOI: https://doi.org/10.1007/978-3-662-45317-9_24. Springer, Berlin, Heidelberg. ISBN: 978-3-662-45316-2; 978-3-662-45317-9. ISSN: 1865-0929. In: Mikulski Jerzy (eds), Telematics – support for transport, 14th International Conference on Transport Systems Telematics, Katowice Ustron, Poland, October 22-25, 2014.
11. Czech Piotr. 2012. „Determination of the Course of Pressure in an Internal Combustion Engine Cylinder with the Use of Vibration Effects and Radial Basis Function - Preliminary Research.” *Communications in Computer and Information Science* 329: 175-182. DOI: https://doi.org/10.1007/978-3-642-34050-5_21. Springer, Berlin, Heidelberg. ISBN: 978-3-642-34049-9; 978-3-642-34050-5. ISSN: 1865-0929. In: Mikulski Jerzy (eds), Telematics in the transport environment, 12th International Conference on Transport Systems Telematics, Katowice Ustron, Poland, October 10-13, 2012.
12. Czech Piotr. 2013. „Intelligent Approach to Valve Clearance Diagnostic in Cars.” *Communications in Computer and Information Science* 395: 384-391. DOI: https://doi.org/10.1007/978-3-642-41647-7_47. Springer, Berlin, Heidelberg. ISBN: 978-3-642-41646-0; 978-3-642-41647-7. ISSN: 1865-0929. In: Mikulski Jerzy (eds), Activities of transport telematics, 13th International Conference on Transport Systems Telematics, Katowice Ustron, Poland, October 23-26, 2013.
13. Pavlenko Ivan, Milan Saga, Ivan Kuric, Alexey Kotliar, Yevheniia Basova, Justyna Trojanowska, Vitalii Ivanov. 2020. “Parameter Identification of Cutting Forces in Crankshaft Grinding Using Artificial Neural Networks.” *Materials* 13(23): 5357. DOI: https://doi.org/10.3390/ma13235357.
14. Sága Milan, Vladimír Bulej, Nadežda Čuboňova, Ivan Kuric, Ivan Virgala, Manfred Eberth. 2020. “Case Study: Performance Analysis and Development of Robotized Screwing Application with Integrated Vision Sensing System for Automotive Industry.” *International Journal of Advanced Robotic Systems* 17(3): 172988142092399. DOI: https://doi.org/10.1177/1729881420923997.
15. Brezocnik Miran, et al. 2011. “Evolutionary Algorithm Approaches to Modeling of Flow Stress.” *Materials and Manufacturing Processes* 26(3): 501-507. DOI: https://doi.org/10.1080/10426914.2010.523914.
16. Kuric Ivan, et al. 2021. “Analysis of Diagnostic Methods and Energy of Production Systems Drives.” *Processes* 9(5): 843. DOI: https://doi.org/10.3390/pr9050843.
17. Liu Jingping, et al. 2017. “Experimental Study on the Performance, Combustion and Emission Characteristics of a High Compression Ratio Heavy-Duty Spark-Ignition Engine Fuelled with Liquefied Methane Gas and Hydrogen Blend.” *Applied Thermal Engineering* 124: 585-594. DOI: https://doi.org/10.1016/j.applthermaleng.2017.06.067.
18. Liu Jinlong, Cosmin E. Dumitrescu. 2018. “3D CFD Simulation of a CI Engine Converted to Si Natural Gas Operation Using the G-Equation.” *Fuel* 232: 833-844. DOI: https://doi.org/10.1016/j.fuel.2018.05.159.

19. Lu Q., T. Tettamanti. 2021. "Impacts of Connected and Automated Vehicles on Freeway with Increased Speed Limit." *International Journal of Simulation Modelling* 20(3): 453-464. DOI: https://doi.org/10.2507/ijsimm20-3-556.
20. Ojstersek Robert, et al. 2020. "Simulation Study of a Flexible Manufacturing System Regarding Sustainability." *International Journal of Simulation Modelling* 19(1): 65-76. DOI: https://doi.org/10.2507/ijsimm19-1-502.

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