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Experimental Comparison of Different Injection Timings in an HCCI Engine Fueled with N-Heptane

Seyfi Polat[1], H. Serdar Yücesu[2], Kaushik Kannan[3], Ahmet Uyumaz[4], Hamit Solmaz[2], Mahdi Shahbakhti[3]

[1] *Mechatronics Engineering Department, Faculty of Engineering, Hitit University, Çorum, Turkey*
[2] *Automotive Engineering Department, Faculty of Technology, Gazi University, Ankara, Turkey*
[3]*Mechanical Engineering and Engineering Mechanics, Michigan Technological University, Houghton MI, United States*
[4]*Mehmet Akif Ersoy University, High Vocational School of Technical Sciences, Automotive Technology Programme, Burdur, TURKEY*

Abstract

One of the most effective methods to control the combustion phasing of a homogeneous charged compression ignition (HCCI) engine is injection timing. Injection timing affects the homogeneity of the mixture, start of combustion and heat release rate. In this study, the effects of injection timing on in-cylinder pressure, heat release rate, pressure rise rate and combustion duration were investigated in early direct injection HCCI engine as experimentally. The experiments were performed at 6 different injection timings ranging between 20 ◦bTDC and 270 ◦bTDC using n-heptane as the fuel. Test results showed that maximum in-cylinder pressure increased and start of combustion was advanced when the injection timing was advanced. Maximum in-cylinder pressures of 4.7 bar at 2 ◦bTDC and 3.4 bar at -9 ◦bTDC were obtained at injection timings of 270 ◦bTDC and 20 ◦bTDC, respectively. Moreover, single stage HCCI combustion was observed and combustion duration increased when the fuel was injected towards to TDC. An advance in the injection timing resulted in an increase in maximum pressure rise rate (MPRR). MPRR of 1.1 bar/ºCA at 6 ºCA bTDC was obtained at an injection timing of 180 ºCA bTDC. Therefore, combustion phasing in HCCI engines was controlled by changing the injection timing and the knock limit was estimated.

Keywords: HCCI; Combustion; Injection timing; Direct injection

* Corresponding author
Seyfi Polat
seyfipolat@hitit.edu.tr
Adress: Mechatronics Engineering Department, Faculty of Engineering, Hitit University, Çorum, Turkey
Tel:+90364 227 4533
Fax:+90364 227 4535

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1. Introduction

Over the past two decades, research on HCCI engines has been a topic of interest in both academia and industries since it has the advantages of both Spark Ignition (SI) and Compression Ignition (CI) engines air/fuel mixture is delivered into the cylinder with relatively low pumping losses in the throttle valve and auto ignited simultaneously in the combustion chamber thereby resulting in an increase in the combustion efficiency. The heat transfer losses decrease due to the shorter combustion duration. Moreover, there was a substantial improvement in the thermal efficiency since the engine could be operated with higher compression ratios at leaner mixtures. There is a drastic decrease in Nitrogen oxides (NOx) and soot emissions due to these characteristics of HCCI engines [1-3]. Control of combustion phasing and combustion rate in HCCI engines are the current challenges faced which deter its application and implementation in commercial vehicles. Furthermore, chemical reactions govern the combustion process due to fuel properties and thermodynamic properties of the mixture. Therefore, issues of misfire and knock are observed at low and full load conditions, respectively. This limits the operating range of HCCI engines. Parameters such as pre-heating the intake air [4,5], variable compression ratio [6,7], variable valve timing [8,9], different valve lift mechanisms[10], exhaust gas recirculation (EGR) [11-13] and increasing boost pressure [14] are applied in order to control HCCI combustion. Many investigations have been performed on alternative fuels having different octane and cetane numbers [15-17]. However, the operating region of HCCI engines could not be improved, especially at high engine loads, because there is no direct control mechanism of combustion phasing. Injection timing is yet another parameter in order to control the start of combustion and combustion phasing. Injection timing has remarkable influence on obtaining homogeneous charge. Injection timing has a direct impact on the homogeneity of the mixture, vaporization of the fuel and start of auto-ignition [18-20]. Petit et al [21] studied the effect of injection timing on the heterogeneity of the mixture. Tests were performed with two different injection timings: early injection timing with 200 degree before TDC and late injection timing with 80 degree before TDC. Early injection timing produced a reasonably homogeneous mixture while late injection timing produced a stratified mixture. Therefore, the heterogeneity of the mixture could be varied by changing the injection timing. Turkcan et al. [18] investigated the effect of second injection timing on the combustion and emissions characteristics of a direct injection HCCI gasoline engine by using ethanol and methanol blended gasoline fuel. Five different fuels (gasoline, E10, E20, M10 and M20) were studied at the same energy input by them. The test results show that the combustion and emissions characteristics can be directly controlled and HCCI operating range can be extended by the second fuel injection timing. The maximum cylinder gas pressure and rate of heat release significantly decreased and the start of combustion delayed with the retarding of the second fuel injection. Standing et al. [22] investigated the effects of injection timing and negative valve overlap on auto-ignition in a single cylinder direct injection engine. They found that start of combustion was advanced with negative valve overlap at leaner mixtures. Moreover, early fuel injection resulted in a very homogeneous mixture thereby causing the mixture to ignite early and faster burn rates.

In this study, the effects of injection timing on HCCI combustion characteristics were studied in a four stroke, four cylinder gasoline direct injection HCCI engine. Thus, the variations of in-cylinder pressure, heat release rate, normalized cumulative heat release rate, pressure rise rate, maximum pressure rise rate and combustion duration were investigated.

2. Experimental Setup and Procedures

All experiments were conducted at the Advanced Power System Research Center, Michigan Technological University. A 2.0 liter, 4 cylinder, four stroke, direct injection, GM Ecotec gasoline engine was converted to operate in HCCI mode. The test engine specifications are presented in Table 1. An external fuel pump and e-motor were used to provide high pressure fuel (up to 150 bar) for direct fuel injection. An air heater was fitted between throttle body and intake manifold to increase the intake air temperature. The engine load and speed were controlled by a 460 HP GE adjustable speed AC dynamometer. In-cylinder pressures were measured by 115A04 model PCB piezo pressure transducers. The measured pressure data as voltage was amplified using 1104CA model DSP charge amplifier and then processed using ACAP combustion analysis system.

Table 1. Engine Specifications

Engine Specification	Value/Description
Engine model	GM Ecotec LHU Gen I
Bore x Stroke [mm]	86 x 86
Cylinder number	4
Displacement volume [L]	2.0
Compression ratio [-]	9.2:1
Connecting rod length [mm]	145.5
Max power [kW@6000 rpm]	270
Fuel injection system	Gasoline Direct Injection
Valve system	DOHC 4 Valves

An encoder with a resolution of one degree was used to obtain crank angle measurements. The Merriam MDT500 air flow measurement system was used to measure the intake air mass flow rate. Fuel mass flow rate was measured using the 1700 model Micro Motion flow meter. A schematic of the experimental engine setup is shown in Fig.1. HCCI engine was controlled by dSPACE MicroAutoBox and RapidPro units. A MATLAB Simulink model was developed for the engine management system that includes control of injectors, spark plugs, variable valve timing, throttle body, high pressure fuel pump and EGR valve. dSPACE units also measure lambda, crank angle, intake and exhaust cam positions, fuel rail pressure, throttle body position, and EGR valve position.

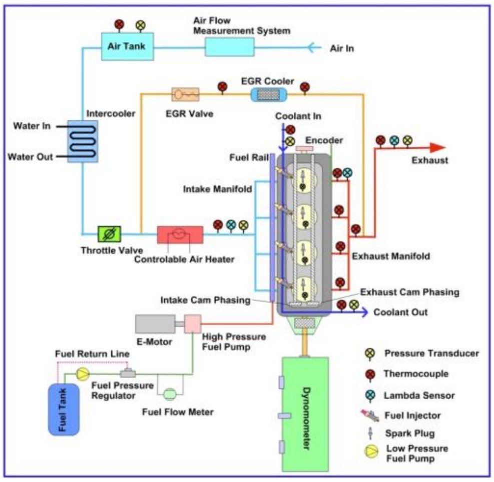

Figure1. Schematic view of the experimental setup

All experiments were performed at six different injection starting angle which are 270, 180, 90, 60, 30 and 20 bTDC crank angle degree using n-heptane as the fuel. All tests were conducted at constant engine speed, intake temperature, injection pressure and full load conditions. In addition, all tests were performed at constant injection duration. Table 2 shows the test conditions.

Table 2. Test conditions

Test Parameters	Value/Description
Engine Speed [rpm]	1000
Injection Pressure [bar]	100
Injection Starting Angle [CA, bTDC]	270, 180, 90, 60, 30, 20
Fuel Type	n-heptane
Intake Valve Open. Angle [CA, bTDC]	25.5
Exhaust. Valve Clos. Angle [CA, bTDC]	22
Throttle Body Position [%]	100
Intake Air Temperature [ºC]	80
Lambda [-]	1.8
Flow mass flow rate [mgr/cycle]	16.18 ±0.18

3. Results and Discussion

Temperature and composition of the charge during the compression stroke has a predominant effect on HCCI combustion. In Low temperature combustion (LTC) regimes such as HCCI, the combustion characteristics are much different from other combustion modes. Control of HCCI combustion is one of the primary challenges. However recent studies have shown that injection timing could be commonly used in order to control HCCI combustion, since it directly impacts the homogeneity of the mixture, start of combustion and combustion process. So, the effects of injection timing on HCCI combustion must be investigated in detail for better understanding of the causalities. Figure 2 shows the variations of in-cylinder pressure at different SOI versus crank angle. Maximum in-cylinder pressure of 4733 kPa at 2°CA bTDC was obtained when the fuel was injected at 270° CA bTDC whereas it reduced to 3368 kPa at 20°CA when the fuel was injected 20°CA bTDC. It was seen that the maximum in-cylinder pressure increased and it was obtained earlier in case of early injection timing. Early fuel injection gives rise to higher homogeneity and better mixing of the charge mixture. Moreover, early injection gives sufficient time for the fuel to vaporize and also improves combustion stability [23,24]. In case of advancing injection timing, the increase of maximum in-cylinder pressure can be explained by the fact that all fuel energy is released at a small interval of crank angle with more homogeneous charge mixture. SOC is retarded and large part of combustion occurs in the expansion stroke when the fuel is injected towards the end of compression stroke. This results in a drop in the maximum in-cylinder pressure.

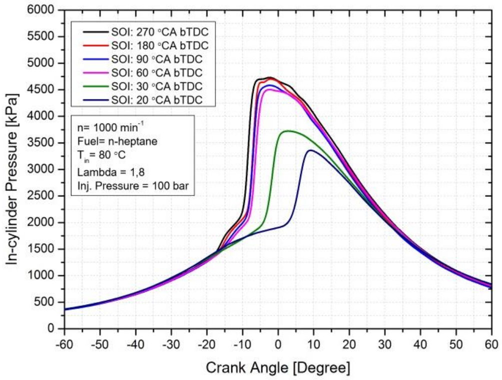

Figure 2. The variations of in-cylinder pressure at different SOI versus crank angle

Figure 3(a) depicts the variations of heat release rate at different SOI versus crank angle. It was depicted from Figure 3(a) that two stage HCCI combustion was seen in case of early injection. If injection retarded towards the end of compression, it results in a single stage combustion. This can be attributed to the fact that low temperature reactions could not occur at late injection timings and charge mixture is not homogeneous enough. As the injection is advanced, maximum heat release rate is obtained earlier at limited range of crank angle. In contrast, maximum heat release rate is determined in expansion stroke at late injection timing. So, maximum heat release rate decreases. Advancing injection timing leads to obtain auto-ignition conditions earlier in combustion chamber. Figure 3(b) shows the variations of normalized cumulative heat release at different SOI versus crank angle. It was seen in Figure 3(b) that early fuel injection leads to earlier start of rising in cumulative heat release curve. For this reason, early fuel injection leads to higher homogeneity and better mixing of air-fuel mixture in the cylinder. Also, the fuel has enough time for vaporization. As the start of injection timing is fixed towards to TDC, cumulative heat release rate gets closer to the TDC. Therefore, the combustion phasing starts at an early crank angle and cumulative heat release curve was advanced. In HCCI engines, the crank angle which corresponds to 50 % of cumulative heat release is very important for thermal efficiency. Especially, it should be nearly after TDC for higher thermal efficiency. If 50 % percentage of cumulative heat release is obtained earlier before TDC, thermal efficiency decreases due to negative work forced on piston. It can be seen in Figure 3(b) that, cumulative heat release decreases in 20-100 crank angle degree bTDC especially at early injection timings. This is because injected fuel into the cylinder at early crank angle vaporizes and absorbs a little amount of heat.

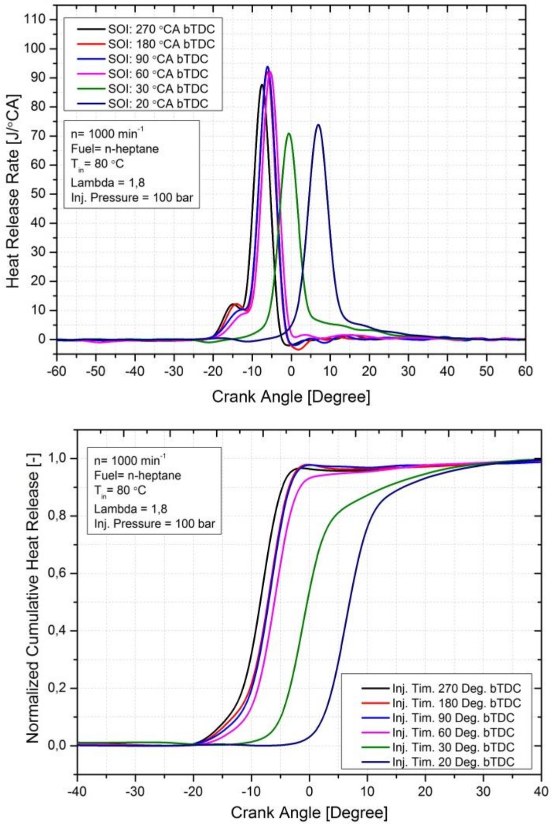

Figure 3 (a) The variations of heat release rate at different SOI versus crank angle (b) The variations of normalized cumulative heat release rate at different SOI versus crank angle.

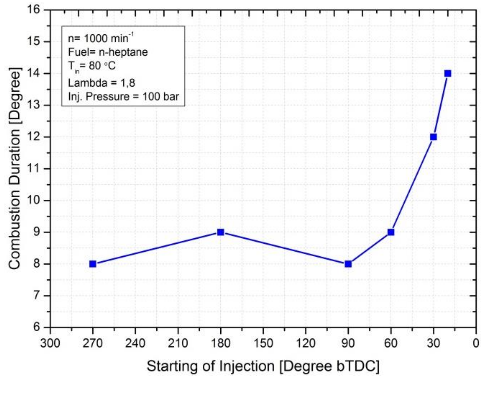

Figure 4 The variations of combustion duration versus SOI.

Figure 4 shows the variations of combustion duration versus SOI. Combustion duration increased when SOI was retarded toward to TDC as seen in Figure 4, because there is no enough time to mix fuel molecules with oxygen molecules resulting in more heterogeneous charge mixture.

So, combustion duration is prolonged at late injection timing values. Short combustion duration was obtained at early injection timing due to the fact that the fuel molecules have enough time to match with oxygen molecules and the mixture has enough homogeneity. Knocking is also impacted by injection timing. Knocking occurs due to the instantaneous release of heat due to fuel energy at smaller range of crank angle. Hence, pressure rise rate increased at higher levels. This undesirable situation causes damage to the engine parts and limits the HCCI operating range.

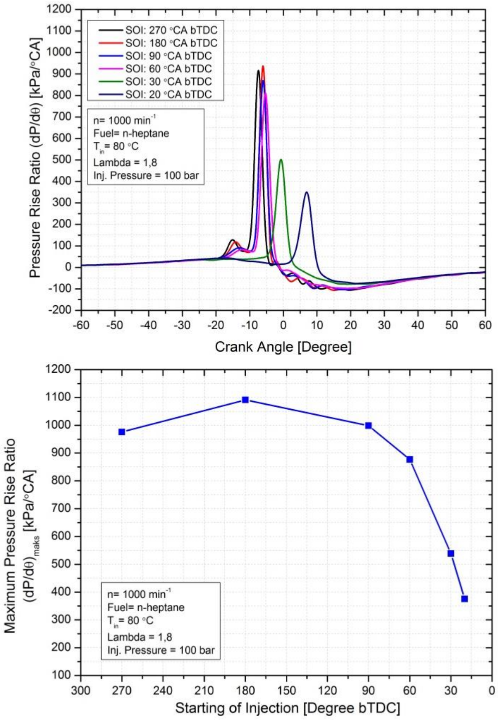

Figure 5 (a) The variations of pressure rise ratio at different SOI versus crank angle (b) The variations of maximum pressure rise ratio versus SOI

Figure 5(a) and 5(b) show the variation of pressure rise rate and maximum pressure rise rate at different injection timing. Maximum pressure rise rate of 1091 kPa/ ºCA at 6 ºCA bTDC was obtained when SOI was fixed at 180 ºCA bTDC. Similarly, maximum pressure rise rate was obtained as 375 kPa/ ºCA at 7ºCA bTDC when SOI was fixed at 20 ºCA bTDC. Maximum pressure rise rate was advanced and increased with the advance of injection timing. In addition, heat is released at smaller range of crank angle and more homogeneous charge mixture is obtained with the advance of injection timing. Pressure oscillations are observed at earlier injection timings as shown in Figure 2. Moreover, the temperature and pressure of mixture are lower with earlier injection timing. It means that the auto-ignition of cooler charge mixture is very difficult. Consequently, all charge mixture tends to participate auto-ignition chemical reactions spontaneously. It results in higher pressure rise ratio.

4. Conclusions

The aim of this study is to investigate the injection timing on combustion characteristics in an early injection HCCI engine fueled with n-heptane. For this purpose, the test engine was run at constant engine speed, injection pressure and lambda at different injection timing including 270, 180, 90, 60, 30, 20 ºCA bTDC. The test results showed that maximum in-cylinder pressure was obtained earlier when injection timing was altered from 20 ºCA to 270 ºCA bTDC. It was also seen that single stage HCCI combustion was observed and combustion duration increased as soon as injection timing is closed to TDC. The test results also showed that maximum pressure rise rate was obtained as 1091 kPa/ºCA at 6 ºCA bTDC when the injection was performed 180 ºCA bTDC. This case shows the knocking tendency at earlier injection timing. It was seen hat HCCI combustion could be controlled via injection timing and stable HCCI combustion occurred. It also causes to extend HCCI operating range at higher engine loads.

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