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Numerical Study of the Effects of Lambda and Injection Timing on RCCI Combustion Mode

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Abstract

Reactivity Controlled Compression Ignition (RCCI), which is a low temperature combustion mode based on the principle of working with dual fuel, has attracted the attention of researchers in recent years due to its advantages such as high thermal efficiency, low NO_x and soot emissions, and controllability of combustion. In this study, the effects of injection timing and lambda on RCCI combustion mode were investigated numerically by validating the experimental data with Converge CFD software. A four-cylinder, four-stroke gasoline direct-injection engine with a compression ratio of 9.2 was used in RCCI combustion mode at an engine speed of 1000 rpm. The maximum cylinder pressure also increased and RCCI combustion was advanced while the injection timing was advanced. The highest peak pressure was obtained at SOI=-50°CA aTDC, and the lowest peak pressure was obtained at SOI=-25°CA aTDC. Similarly, the highest peak HRR value was acquired as 213 J/°CA at SOI=-50°CA aTDC. It has been observed that as the lambda decreases, the maximum cylinder pressure increases, and combustion advances. In addition, the heat release rises with a decrease in lambda value. The maximum heat release rate was acquired as 77.91 J/°CA at λ=1.2. The results show that injection timing and lambda have a great influence on RCCI combustion mode and the combustion phase can be controlled with these parameters.

Keywords: Combustion; Computational fluid dynamics (CFD); Injection timing (SOI); Lambda; Reactivity controlled compression ignition (RCCI)

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1. Introduction

Considering the environmental standards on exhaust emissions and the increase in price of petroleum products, the need to increase the efficiency of internal combustion engines arises [1]. Researchers have developed low-temperature combustion (LTC) strategies to meet these requirements. Reactivity controlled compression ignition (RCCI) mode is the most recently developed and can be considered the most effective combustion mode [2-4]. In RCCI combustion mode, two different reactivity fuels are used. Low reactivity fuel (LRF) is delivered into the cylinder through the intake port, and high reactivity fuel (HRF) is injected directly into the cylinder [5-7]. The combustion phase is controlled by injection timing using these different reactivity fuels. In addition, NO_x and soot emissions are significantly reduced in this way [8]. The thermal efficiency is higher in RCCI combustion mode compared to other combustion modes [4,9]. RCCI combustion characteristics are affected by specific parameters such as injection timing, air-fuel ratio, reactivity of fuels, intake air temperature, intake manifold pressure. Some studies clearly show this situation. Uyumaz and Solmaz stated that the maximum cylinder pressure and heat dissipation increased as the lambda decreased in a gasoline engine operated in RCCI mode at different lambda values. In addition, it was observed that the maximum indicated thermal efficiency was 42.47% at 80°CA and at lambda value of λ=2.2, considering the injections at different crank angles [8]. In another study, the thermal efficiency and combustion characteristics of the RCCI engine were investigated at different engine speeds and loads. It has been determined that there is an increase of up to 5% in brake thermal efficiency and a 92% decrease in NO_x emissions compared to diesel combustion [1]. In a study in which a part of the RCCI combustion process was investigated experimentally and numerically, first the diesel fuel and then the gasoline and air mixture were self-ignited. Subsequently, it was observed that the increase in temperature and pressure at many points throughout the combustion chamber caused flame development throughout the low temperature region [10]. Ma et al. experimentally investigated the effects of early and late injection of diesel fuel (high reactivity fuel) on RCCI combustion mode. The reactivity of the fuel mixture is very important to improve thermal efficiency. The more homogeneous mixture obtained by early diesel injection is sufficient to create the ideal reactivity for high thermal efficiency. It was stated that HC and CO emissions can be reduced by controlling the injection timing as combustion efficiency increases [11]. In a study conducted in a single injection strategy, it was observed that a significant increase in NO_x emission occurred as the injection timing advanced from 80°CA aTDC, while a delay in the injection timing caused a significant increase in HC and CO emissions [12]. Tong et al. conducted a study in which the effects of injection timing and lambda on RCCI combustion mode were investigated experimentally. In experiments with four different lambda values, it was stated that a stable and controllable RCCI combustion was achieved by using gasoline and polyoxymethylene dimethyl ether fuels. In addition, it has been observed that RCCI combustion occurs at stoichiometric ratios when the engine is operated at high loads [13]. Uyumaz et al. [14] examined the effect of the lambda on RCCI combustion mode. The tests were carried out at 40% premixed ratio, while isooctane and n-heptane reference fuels were used in the study. It was stated that the start of combustion was delayed as the amount of fuel injected into the cylinder increased. It has been stated that this situation is due to the decreasing of the cylinder temperature as a result of the evaporation of more fuel. In addition, as lambda value increased, the fuel consumption decreased and thermal efficiency increased. It was found that the cyclic differences increased rapidly to over 10% in leaner mixtures with a lambda value of 2.65 and cyclic differences of 5.91%. Mohammadian et al. [15] determined an ideal injection strategy to minimize the amount of fuel injected by direct injection in an RCCI engine using isobutanol and isobutanol+20% di-tert-butyl peroxide (DTBP) fuels. The effects of some injection parameters were investigated numerically by validating the experimental data with the CONVERGE CFD software, which includes combustion and spray models. The results showed that the RCCI engine could have better performance at the start of injection (SOI) of 88°CA after top dead center (aTDC), the injection pressure of 1400 bar, and the spray cone angle of 45°.

A direct-injection gasoline engine was operated in RCCI combustion mode at a constant engine speed of 1000 rpm, intake air temperature of 80°C, a compression ratio of 9.2, and experimental results were obtained. In this study, it is aimed to investigate numerically the effects of injection timing and lambda on RCCI combustion characteristics were investigated numerically by validating the experimental data with Converge CFD software.

2. Material and Method

2.1 Experimental setup

The experiments were carried out in a GM Ecotec gasoline engine with a four-cylinder direct injection system. The technical specifications of the test engine used in the tests performed in the Advanced Power System Research Center at Michigan Technological University are shown in Table 1. The starting of the test engine was provided by an AC dynamometer with 460 HP power.

Table 1. Technical specifications of test engine [16]

Test Engine	GM Ecotec GDI Gasoline Engine
Cylinder number	4
Compression ratio	9,2:1
Stroke (mm) x Bore (mm)	86 x 86
Cylinder volume (cc)	1998
Max. Power (kW@5300 rpm)	164
Max. Torque (Nm@2400 rpm)	353
IVC (°CA aTDC)	-147
EVO (°CA aTDC)	135

The control of the RCCI engine was achieved using MicroAutoBox, dSPACE and RapidPro. The parameters affecting engine management such as ignition system, premix ratio, fuel rail pressure, EGR valve position, cam positions, throttle body position, intake air temperature and pressure were controlled using dSPACE with the MATLAB Simulink model embedded on the processor. The intake air temperature was changed using an electrical heater controlled by dSPACE. The amount of fuel injected from both port fuel injection (PFI) and direct injection (DI) injectors was measured with a Coriolis type Micro Motion 1700 mass fuel flow meter with an accuracy of 0.1%. Equations were defined to Simulink model using the obtained measurements. In this way, the opening time of the injectors were determined by MicroAutobox, depending on the amount of fuel and premix ratio defined in dSPACE. Halis et al. [18] shared the details of this engine's injector control and adjustment of fuel amount in a study. In-cylinder pressure was measured by using 115A04 model PCB pressure sensor. The voltage signals of the obtained in-cylinder pressures were amplified with the DSP 1104CA charge amplifier and processed into the combustion analysis system using an encoder with 1°CA measurement accuracy.

Experiments using isooctane and n-heptane fuels were carried out at 80°C, lambda values and different injection timings. The properties of these fuels are given in Table 2. N-heptane and iso-octane fuels show similar physical properties and have different reactivity. The high reactivity fuel (n-heptane) was injected directly into the cylinder with direct fuel injectors, while the low reactivity fuel (isooctane) was injected into the intake manifold from the port-type fuel injectors of the engine operated in RCCI mode. The n-heptane fuel with high reactivity is preferred to control the rate of chemical reactions and is also used to release fewer nitrogen oxides and soot. In addition, using n-heptane with an octane number of 0 and iso-octane with an octane number of 100 provides convenience in terms of obtaining the desired premix ratio. The fuel mixture used in the experiments consisted of 20% isooctane injected into the manifold and 80% n-heptane injected directly into the cylinder. This premixed fuel ratio (PR20) was kept constant in all experiments. The experimental setup is shown in Figure 1.

Table 2. The properties of fuels [17-18]

Properties / Fuels	n-heptane	iso-octane
Chemical Formula	C_7H_{16}	C_8H_{18}
Research octane number	0	100
Higher heating value [MJ/kg]	48.07	47.77
Lower heating value [MJ/kg]	44.56	44.30
Density [kg/m^3]	686.6	693.8
H/C ratio	2.29	2.25

Maximum in-cylinder pressure and temperature, Specific fuel consumption (SFC), heat release rate (HRR), indicated mean effective pressure (IMEP), integrated heat release rate (IHRR), thermal efficiency, combustion efficiency, volumetric efficiency, CA50, coefficient of variation of IMEP (COV_{IMEP}), and maximum pressure rise rate (MPRR) were calculated with a developed MATLAB code using the experimental data obtained.

The amount of heat released per crank angle was calculated with Eq. (1) by considering the first law of thermodynamics.

$$\frac{dQ}{d\theta}=\frac{n_c}{n_c-1}P\frac{dV}{d\theta}+\frac{1}{n_c-1}V\frac{dP}{d\theta}+\frac{dQ_{heat}}{d\theta} \qquad (1)$$

The heat transfer from cylinder wall was calculated by using Eq. (2). In this equation, coefficient of heat transfer was calculated with modified Woschni heat transfer model [19].

$$\frac{dQ_{heat}}{d\theta}=\frac{1}{6n}h_g A\left(T_g-T_w\right) \qquad (2)$$

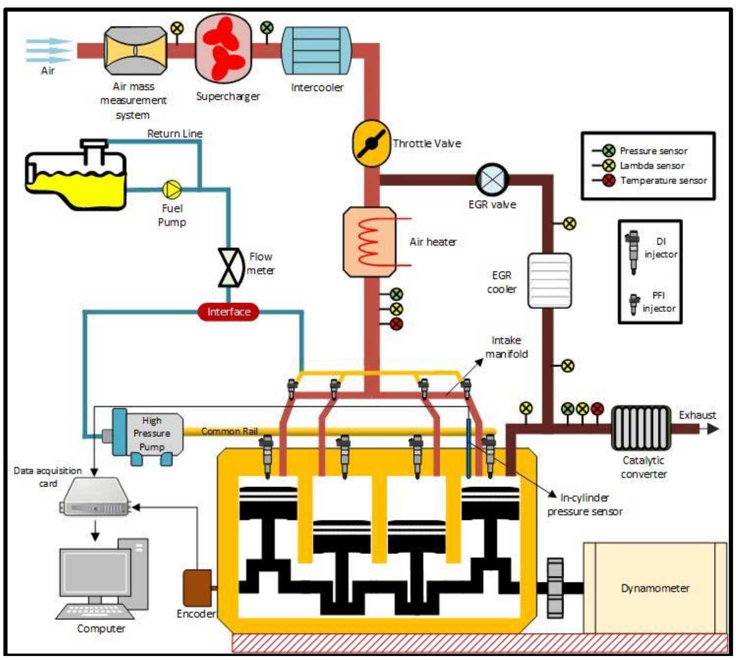

Fig. 1. The diagram of experimental setup

2.1 Numerical model and validation

The computational fluid dynamics (CFD) model in Converge software was used to simulate experimental data obtained in RCCI engine. The geometry of GM Ecotec GDI Turbo engine was modeled with SOLIDWORKS. The auto-mesh refinement module defined in the Converge software was used in modeling. A mesh technology called "adaptive mesh refinement (AMR)" that provides more sensitive mesh structure in regions such as nozzle, spray zone and combustion chamber, automatically regulates the grid at each time-step in Converge. The model of engine geometry and mesh structure are seen in Figure 2.

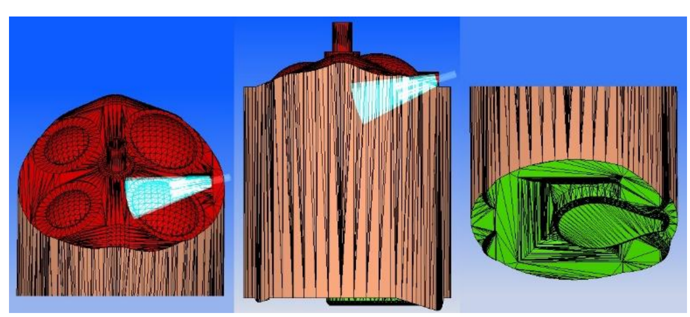
Fig. 2. Model of engine geometry and mesh structure

The numerical analyzes were performed by using closed-cycle assumptions from IVC to EVO. In this test engine, two injectors (PFI and DI) with different functions were used. The low reactivity fuel (isooctane) and the high reactivity fuel (n-heptane) were injected with PFI and DI injectors, respectively. The direct injection process was simulated by using the Discrete Droplet Model (DDM) [20]. The Kelvin-Helmholtz (KH)/Rayleigh-Taylor (RT) model was selected as spray atomization model. The primary breakup is modeled by applying KH model; RT model is used for the secondary breakup [21]. The Renormalized Group (RNG) k-ε/Reynolds Averaged Navier-Stokes (RANS) was used for calculation of turbulence model [22]. The discrete equations are solved by using PISO iterations in Converge. Momentum equations are used for determining of velocity field [23]. The combustion process was modeled with the SAGE detailed chemical kinetic solver [24]. The detailed chemical kinetic mechanism developed by Luong et al. [25], which contains 171 species and 861 reactions, was used to represent chemical structure of isooctane and n-heptane.

The validation was carried out with numerical model and experimental results. The case setup of validation process is given Table 3. The validation of the numerical model has been successfully achieved when compared with the experimental results. In Figure 3, the alteration of in-cylinder pressure and HRR on the changing of crank angle is shown. It has been seen that the process of RCCI combustion used isooctane and n-heptane fuels were analyzed well when the numerical and experimental results were compared. Accordingly, it can be said that the numerical model and validation process were applied correctly. When the experimental and numerical results compared for validation are examined, there is a very small difference in the in-cylinder pressure, while there is a difference of 1.74% for the maximum HRR value.

Table 1. The case setup of validation at initial conditions

Direct injection fuel	n-heptane (80%)
Port injection fuel	iso-octane (20%)
Intake air temperature	80°C
Engine speed	1000 rpm
Intake manifold pressure	103 kPa
Engine load	Full
Injection pressure	100 bar
Start of direct injection (SOI)	-25 °CA aTDC
Lambda	1.2
Total fuel mass	22 mg/cycle
Mesh size	1 mm
AMR level	3
Min. time step	1e-08 s
Max. time step	1e-04 s

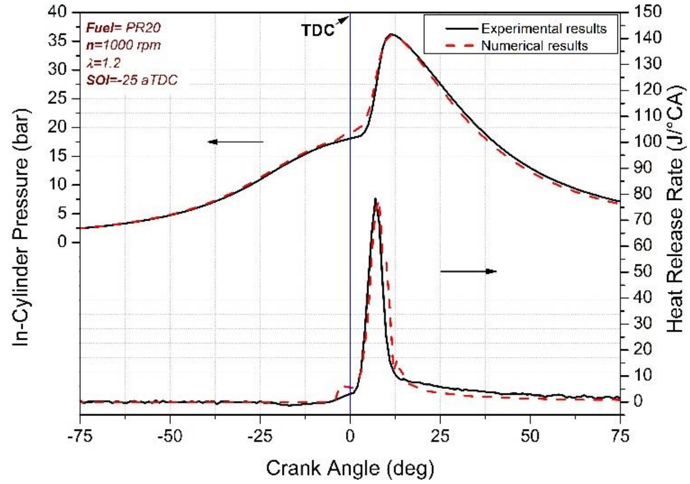

Fig. 3. Experimental and numerical results of in-cylinder pressure and heat release rate

3. Results and Discussion

The validation process includes numerical modeling of the data obtained from the experiments performed under the conditions in Table 3. It has been examined the effects of injection timing and lambda on RCCI combustion mode with this numerical study.

3.1 Effects of injection timing

The combustion phase changes with the start of injection in the RCCI engines. Figure 4 shows the effects of injection timing on in-cylinder pressure and heat release in RCCI combustion mode. The analyzes were performed at λ=1.2, an engine speed of 1000 rpm and five different injection timings for examining this situation. It is possible to say that as the injection timing is advanced, the maximum in-cylinder pressure increases and the combustion is advanced. It is seen that the highest peak pressure is obtained at SOI=-50° aTDC and the lowest peak pressure is obtained at SOI=-25° aTDC. This may be due to the increased time for mixing n-heptane with the isooctane-air mixture homogeneously as SOI advances. However, delaying the SOI timing does not significantly affect the cylinder peak pressure. In a study, Nazemi and Shahbakhti [26] stated that after a point, this delay may be more effective on emissions. The homogeneous mixture cannot be obtained with late injection, combustion quality and net work are reduced. Accordingly, the injection timing directly changes the course of RCCI combustion. Similar to the in-cylinder pressure results, the highest peak HRR value is 213 J/°CA at SOI=-50° and the lowest peak HRR value is 77.91 J/°CA at SOI=-25° aTDC. Thus, it can be concluded that the cylinder gas temperature is highest at SOI =-50 aTDC and auto-ignition points of n-heptane fuel can ignite more isooctane fuel compared to other SOI timings.

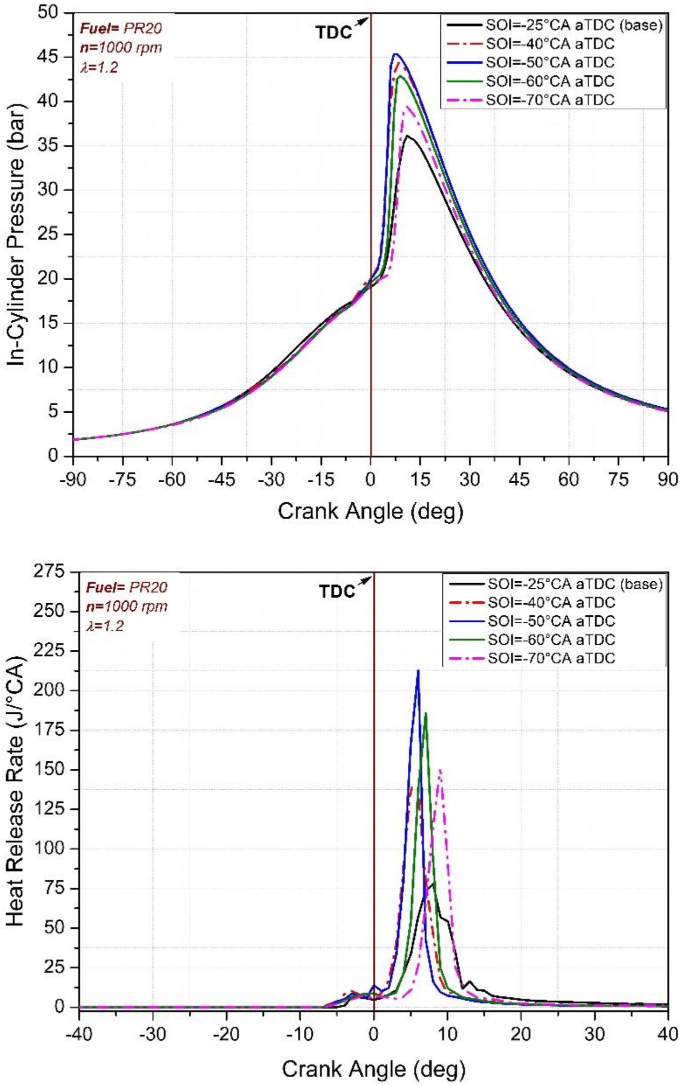

Fig. 4. The effects of injection timing on in-cylinder pressure and heat release rate in RCCI combustion mode

3.2 Effects of lambda

The lambda value, which is directly related to the fuel mixture in the cylinder, significantly affects RCCI combustion. The effects of lambda value on in-cylinder pressure and HRR in RCCI combustion mode is seen in Figure 5. The analyzes were carried out at SOI=-25°CA aTDC, an engine speed of 1000 rpm and five different lambda values. The fuel energy increases and higher in-cylinder pressure is obtained with the richer mixture taken into the cylinder. However, it is seen that the maximum in-cylinder pressure decreases with the lean fuel mixture. As the lambda value decreases, the maximum in-cylinder pressure increases. The increase of fuel energy in the combustion chamber causes the maximum in-cylinder pressure to be achieved and the heat release increased [8]. In a study, it was stated that a more homogeneous mixture was obtained with an increase in the amount of low-reactivity fuel in RCCI combustion. It was also observed that as the LRF ratio increased, the in-cylinder pressure also rised [27]. When the effect of the change of lambda on the heat release was examined, the maximum heat release was obtained at λ=1.2. It is seen that the combustion is delayed as the mixture becomes leaner. As the stoichiometric mixture ratios approach, the heat release in the combustion chamber goes up with the increase in the amount of fuel included in the combustion. The oxygen and fuel molecules can react more easily in the combustion chamber at richer mixing ratios. Therefore, the heat release rate in the cylinder and the temperature increase, and it is possible to say that there is a stable combustion throughout the combustion chamber [28].

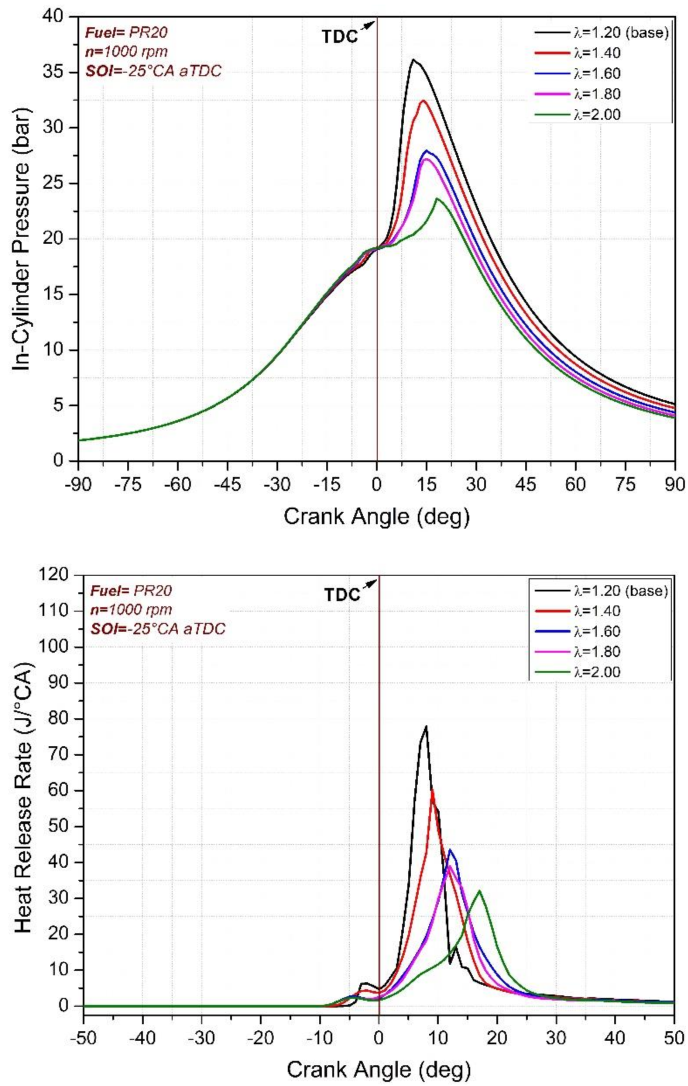

Fig. 5. The effects of lambda on in-cylinder pressure and heat release rate in RCCI combustion mode

4. Conclusions

In this study, the effects of injection timing and lambda on RCCI combustion were investigated numerically by validating the experimental data with Converge CFD software. When the results obtained from the analyzes with the established numerical model are compared with the experimental data, it can be said that the validation process is at a satisfactory level. It has been observed that the injection timing significantly affects the combustion phase in the RCCI combustion mode. As the injection timing was advanced, the maximum cylinder pressure also increased and RCCI combustion was advanced. The highest peak pressure was obtained at SOI=-50°CA aTDC, and the lowest peak pressure was obtained at SOI=-25°CA aTDC. Similarly, the highest peak HRR value was acquired as 213 J/°CA at SOI=-50° and the lowest peak HRR value was acquired as 77.91 J/°CA at SOI=-25° aTDC. It has been observed that as the lambda decreases, the maximum cylinder pressure increases and combustion occurs earlier. Moreover, the heat release rate increases with declining in lambda value. The maximum heat release rate was acquired as 77.91 J/°CA at λ=1.2. The results show that injection timing and lambda have a great influence on RCCI combustion and the combustion phase can be controlled with these parameters.

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Nomenclature

AMR : Adaptive Mesh Refinement
aTDC : After Top Dead Center
CA : Crank Angle
CA50 : Crank Angle Corresponding to 50% of the Total Heat Release
CFD : Computational Fluid Dynamics
CI : Compression Ignition
CO : Carbon Monoxides
COV_{IMEP} : Coefficient of Variation of IMEP
DDM : Discrete Droplet Model
EGR : Exhaust Gas Recirculation
EVO : Exhaust Valve Opening
GDI : Gasoline Direct Injection
HC : Hydrocarbon
HCCI : Homogeneous Charged Compression Ignition
HRF : High Reactivity Fuel
HRR : Heat Release Rate
IHRR : Integrated Heat Release Rate
IMEP : Indicated Mean Effective Pressure
IVC : Intake Valve Closing
LRF : Low Reactivity Fuel
MPRR : Maximum Pressure Rise Rate
NO_x : Nitrogen Oxides
PCCI : Premixed Charge Compression Ignition
RANS : Reynolds Averaged Navier-Stokes
RCCI : Reactivity Controlled Compression Ignition
SFC : Specific Fuel Consumption
SI : Spark Ignition
SOI : Start of Injection

CRediT Author Statement

Serdar Halis: Conceptualization, Writing-original draft, Visualization, Data curation, Validation.
Hamit Solmaz: Conceptualization, Funding acquisition, Data curation, Supervision.
Seyfi Polat: Conceptualization, Methodology, Supervision.
H. Serdar Yücesu: Conceptualization, Writing-review and editing, Supervision.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

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