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REVIEW ON COMBUSTION AND PERFORMANCE ANALYSIS OF REACTIVITY CONTROLLED COMPRESSION IGNITION (RCCI) ENGINE

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Abstract—*This paper describes recent progress to improve the fuel efficiency of diesel or CI engines through advanced combustion and fuel research. A dual-fuel Reactivity Controlled Compression Ignition (RCCI) combustion strategy will address these issues due to the existence of precise means for controlling the heat release rate and combustion phasing. In the RCCI strategy two fuels with different reactivity (auto-ignition characteristics, e.g., gasoline and diesel) are blended inside the combustion chamber. Combustion phasing is controlled by the relative ratios of these two fuels and the combustion duration is controlled by the local equivalence ratio gradient between the two fuels. This review focuses on development of RCCI engine combustion model and understanding the effects of key parameters controlling RCCI engine combustion.*

Key words- *emission; combustion; performance; ignition; engine*

I. INTRODUCTION

Diesel engines are widely used for power-generation and transportation applications because of their high fuel efficiency. However, diesel engines can cause environmental pollution owing to their high NO_x and soot emissions. Considerable effort has thus been devoted toward reducing these pollutant emissions as these have adverse effects on the environment and human health [11]. Recent technologies developed to reduce both NOx and soot generation are difficult to implement and control and many still require expensive after-treatment measures. As a result, a significant need is felt for engines that provide the efficiency of a diesel engine while meeting or exceeding current emissions standards. Developing engine technologies to achieve these targets while meeting emission mandates will require substantial research progress, even beyond that made so far.

Accordingly, reduction of NO_x and soot in-cylinder has been investigated by many researchers. Most of the current strategies can be placed in the category of premixed Low Temperature Combustion (LTC). Due to the high activation energy of the NO formation reactions Lower combustion temperatures result in NO_x reduction [10]. Additionally, utilizing long ignition delay times allows sufficient time for mixing prior to the start of combustion; during that time, rich regions in the combustion chamber will be reduced and soot formation is inhibited.

1.1 HCCI Combustion

The homogeneous charge compression ignition (HCCI) of IC engine study has been the topic of much research and development work. This system uses a fully premixed charge of air and fuel that is compressed up to reaches auto-ignition, where the charge undergoes a volumetric combustion process. In this combustion system, the fuel is injected through port fuel injector system.By using this strategy, the homogeneous charge compression ignition combustion both NO_X and soot emission can be avoided theoretically as shown in Figure 1. They successfully elaborated the lean flammability limit of their engine's operating regime, and observed that fuel oxidation kinetics could be competently controlled in a way the engine could operate in homogeneous compression charge ignition combustion mode.

The homogeneous compression charge ignition combustion strategy has difficulty with the rate of heat release and control of the ignition timing due to not having definite means of control actuation such as spark plug in spark ignition engines or compression ignition injection timing in the CI engines. In the spark ignition engine the rate of heat release is controlled by finite turbulent flame propagation while in the compression ignition engines the rate of heat release is controlled by the rate of fuel injection. Because homogeneous compression charge ignition combustion depends on a premixed mixture of air and fuel, the fuel injection(s) is/are typically very early in the compression stroke. Hence there is enough time for the intake air and fuel to mix each other.

Early fuel injection in the cycle results in a long ignition delay period (i.e; the time between initiation of combustion and the end of injection). Therefore, the combustion process and the injection stage are not linked. Accordingly, the homogeneous compression charge ignition combustion strategy depends on chemical kinetics to initiate auto-ignition of the mixture.

By changing the ratio between the low and high reactivity fuels (e.g., ethanol/n-heptane and iso-octane/n-heptane), it was achieved that more control over the combustion process is possible.

However, the experiments were limited in load due to losses imposed by the turbocharger. Exhaust gas temperatures in homogeneous compression charge ignition are significantly lower in comparison to other combustion strategies, so high levels of boost were unreachable. However, efficient low-load operation is still a big challenge for homogeneous compression charge ignition and homogeneous compression charge ignition like combustion strategies.

In an effort to increase controllability of the homogeneous compression charge ignition engine over the rate of heat release and ignition timing, and Premixed Charge Compression Ignition (PCCI) is another combustion strategy which has been proposed that utilizes early direct injection of fuel in the compression stroke.

1.1 PPCI and PCCI Combustion

In partially premixed compression ignition (PPCI) and premixed charge compression ignition (PCCI) combustion strategies, a direct fuel injection system is takes place. Depending on the level of homogeneity of the air-fuel mixture, premixed charge compression ignition combustion strategy uses early direct injection while partially premixed compression ignition applies late direct injection of fuel to prepare partially premixed mixture of air and fuel. Single or dual fuel can be used in PPCI and PCCI combustion strategies. It was observed that the NO_X and soot emission compromise which is typical in Conventional Diesel Combustion (CDC) can be avoided in this PPCI combustion strategy, but at the cost of a decrease in combustion efficiency.

By using high levels of exhaust gas recirculation (EGR) the NO_x emission is become near zero and the soot emission values decrease dramatically. Both load conditions showed gross indicated thermal efficiency values of 50% and low NO_x emissions. However, while peak pressure rise rate (PPRR) and low soot emission were achieved at medium load, achieving peak pressure rise rate and low soot emission was challenging at high load conditions. Although partially premixed compression ignition combustion method result in low emissions values and high thermal efficiency, maintaining low peak pressure rise rate values is a big challenge, particularly at high load condition.

1.2 Reactivity Controlled Compression Ignition RCCI Combustion

Based on studies of, Reitz et al. [10] a clean and highly efficient dual fuel combustion strategy in a heavy duty single cylinder engine using diesel and gasoline fuels was developed. It was found that early diesel injection timings cause the high pressure rise rates to decrease dramatically, which allowed the development of a new in-cylinder fuel blending strategy called Reactivity Controlled Compression Ignition (RCCI) [12]. In this approach, gasoline is injected through the port fuel injection system, creating a homogeneous air-fuel charge during compression stroke.

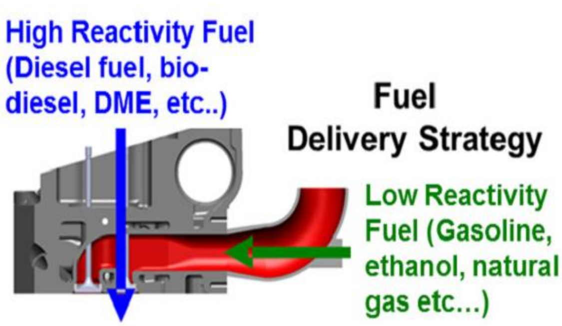

Figure 1. RCCI Combustion using direct injection (DI) of a high reactivity fuel (e.g diesel fuel) and port fuel injection (PFI) of a low reactivity fuel (e.g gasoline), (Rolf Reitz 2013)

Next, fuel is injected through the direct injection system to introduce a stratification of reactivity zones within the cylinder. A dual-fuel RCCI concept improves other modes of LTC engines such as HCCI or PCCI by offering precise means for controlling the heat release rate and combustion phasing. In the RCCI strategy two fuels with different reactivity (auto-ignition characteristics) are blended inside the combustion chamber. RCCI results by Kokjohn and Reitz et al. [10] showed high thermal efficiency as well as very low NO_x and soot emissions over a wide engine load range from 4 bars IMEP to 14.5 bar IMEP using gasoline and diesel fuels in the RCCI combustion strategy.

By using EGR at the high load operating conditions, NO_x emission and combustion noise values were kept as low as possible. Combustion phasing is controlled by the relative ratios of these two fuels and the combustion duration is controlled by spatial stratification between the two fuels.

In RCCI Combustion Heat release occurs in three stages

- Cool flame reaction results from n-heptane (diesel) injection
- First energy release occurs where both fuels are mixed
- Final energy release occurs where lower reactivity fuel is located

Changing fuel ratio changes the magnitudes of stages and fueling ratio provides "next cycle" CA50 transient control
RCCI engine is quite different from conventional in case of temperature difference during combustion

- ✓ High temperature in conventional diesel next to piston bowl surface
- ✓ Highest temperature for RCCI in center of chamber (adiabatic core)
- ✓ Region near liner has similar temperatures
- ✓ Heat transfer differences are at piston bowl surface

1.2.1 Advantages and disadvantages of RCCI engine

I. Advantages of Reactivity Controlled Compression Ignition (RCCI) engine

- Minimize NO_X and soot emissions
- Reduces heat transfer losses
- Increases fuel efficiency
- Increases thermal efficiency
- Eliminates need for costly after treatment systems
- RCCI can be used with alternative fuels, including hydrated "wet" ethanol
- Complies with EPA 2010 emissions guidelines without exhaust after treatment
- Eliminates carburetor and spark plug cost

II. Disadvantages of Reactivity Controlled Compression Ignition (RCCI) engine

- Increase HC and CO comparison to conventional diesel combustion
- Implementation challenges
- Control challenges
- It provides separately port fuel injector, a reservoir, fuel filter, fuel meter, electrically driven pump and heat exchanger.

II. LITERATURE REVIEW

To understand what conditions yield NO_x and soot emissions, a plot of "local" equivalence ratio (f) versus "local" temperature is shown in Figure 3.1

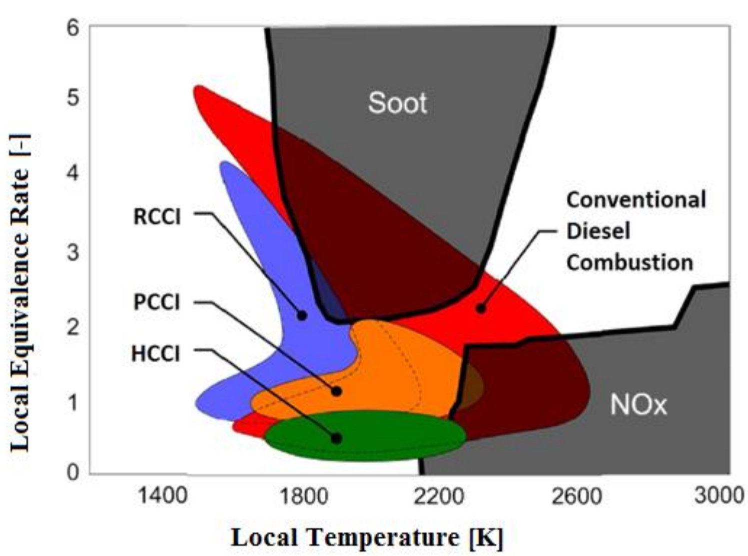

Figure 2. Soot and NO_x regions in f -T space Adapted from, (MR Nazemi Msc thesis 2015)

It can be observed that there are two distinct zones for soot and NO_x emissions formation: at stoichiometric mixture condition (f=1), there is a diffusion flame (i.e., mixing-controlled burning) that results in high NO_x formation rates, while 2 < f < 3 with T = 2000 K, results in unacceptably high soot formation rates [5]. In an effort to simultaneously reduce NO_x and soot emissions, many advanced combustion strategies have been proposed.

The goal of these strategies is to develop a combustion process that avoids high temperatures (i.e., the NO_x production regime) as well as rich mixture (i.e., the soot production regime) conditions. The strategies presented here typically consider all or most of the fuel to be premixed to remove locally rich regions in the combustion chamber.

The premixed fuel can be achieved by injecting through port fuel or direct injections early in the intake and compression strokes and/or several injection events containing small amounts of fuel. Overall, spray angle is found as the dominant parameter affecting RCCI combustion and engine performance, while injection pressure has less effect on RCCI combustion and performance for the operating conditions studied in this thesis.

Rolf D. Reitz et al. [11] this article covers key and representative developments in the area of high efficiency and cleans internal combustion engines. The main objective is to highlight recent efforts to improve (IC) engine fuel efficiency and combustion.

This paper describes recent progress to improve the fuel efficiency of diesel or CI engines through advanced combustion and fuels research. In particular, a dual fuel engine combustion technology called “reactivity controlled compression ignition” (RCCI), which is a variant of Homogeneous Charge Compression Ignition (HCCI), is highlighted, since it provides more efficient control over the combustion process and has the capability to lower fuel use and pollutant emissions.

M. Nazemi and M. Shahbakhti et al. [10] in this study, a detailed 3D/Computational Fluid Dynamics (CFD) combustion model in CONVERGE CFD code is developed and validated against experimental data at different engine operating conditions.

Next, the effects of fuel injection parameters on the performance and emissions characteristics of an RCCI engine are analyzed. The fuel injection parameters include spray angle, injection pressure, Start of Injection (SOI) timing, and Premixed Ratio (PR). The baseline simulation results show that a proper selection of spray angle can cause significant reduction in HC and CO emissions, while improving combustion and gross indicated efficiencies. Furthermore, decreasing injection pressure and PR along with advancing SOI timing can improve the RCCI engine’s HC and CO emissions productions. The developed CFD model is then used in an extensive computational study to determine optimum fuel injection parameters for the best RCCI engine performance.

While improving gross indicated and combustion efficiencies $\eta_c = 94.8\%, \eta_{ind-g} = 42.8\%$, HC = 41.4 g/kg-fuel, CO = 25.4 g/kg-fuel, soot = 0.006 g/kg-fuel, NOx = 0. 14 g/kg-fuel, RI = 2.57MW/m2). It is also observed that choosing spray angle 45^o, the highest injection pressure (i.e., 580 bar), SOI $=-63^0$aTDC and PR = 0.76 provides the second most optimum RCCI engine performance. In addition, it is seen that a combination of the widest spray angle (i.e.74^0), the lowest injection pressure (i.e., 380 bar), SOI = -53^0aTDC and PR = 0.76 improves engine performance in comparison to the baseline condition. Proper selection of spray angle and SOI timing is critical for the engine performance since they specify the location of impingement of diesel fuel parcels in the combustion chamber. As a result, strong auto-ignition points initiate from the piston bowl which results in strong combustion. Meanwhile some of the diesel fuel parcels auto-ignite near the liner and squish regions which causes gasoline fuel to burn on those regions and therefore HC emission decreases. Finally, a proper combination of PR and spray angle will be critical to obtain proper combustion phasing (CA50 = $5 - 8^0$ aTDC) in order to reach highest η_{ind-g}, while avoiding an unacceptable RI level.

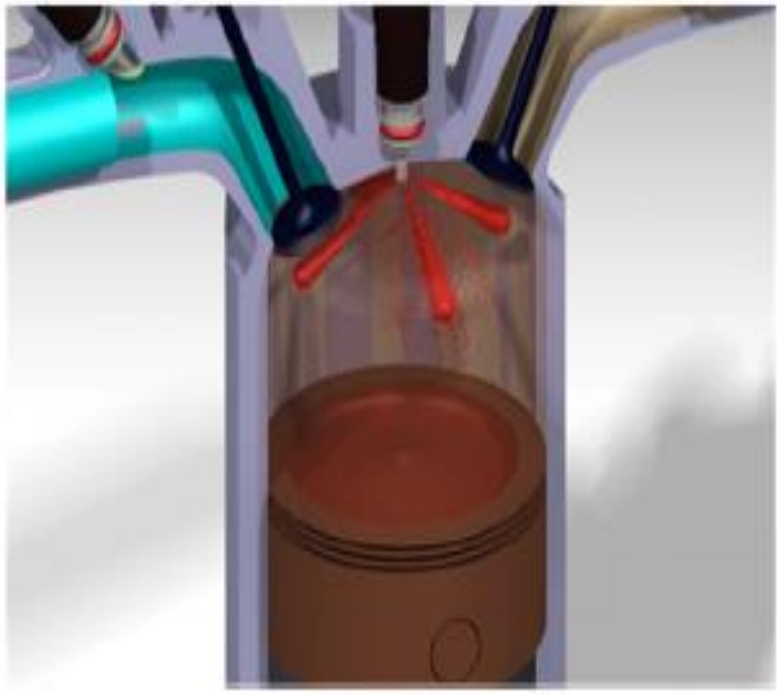

Figure 3. Schematic of RCCI engine's combustion chamber, (M. Nazemi from applied energy journal 2015)

The optimization results show that spray angle 55^0, SOI $=-53^0$aTDC, 580 bar injection pressure, and PR = 0.76 provide the best combination of four major fuel injection parameters for the speed and load conditions studied. By choosing this set of parameters, HC and CO emissions decrease by 23% and 39% from the baseline condition while a notable improvement is observed in gross indicated and combustion efficiencies.

Mohammadreza Nazemi et al. [9] this paper focuses on development of RCCI engine combustion model and understanding the effects of key parameters controlling RCCI engine combustion.

In the RCCI strategy two fuels with different reactivity (auto-ignition characteristics, e.g., gasoline and diesel) are blended inside the combustion chamber. Combustion phasing is controlled by the relative ratios of these two fuels and the combustion duration is controlled by the local equivalence ratio gradient between the two fuels. The effects of PR, injection pressure, SOI timing and spray angle on the combustion and performance of the RCCI engine were studied. It was observed that by increasing PR, peak in-cylinder pressure and HRR decrease and combustion phasing is retarded.

Additionally, increasing premixed ratio causes unburned hydrocarbon and carbon monoxide emissions to increase. Focusing on all performance parameters and emissions, premixed ratio (PR) =0.76 was found the optimal value for the operating condition studied where HC and CO emissions decrease by 6 and 25 g/kg-fuel, respectively, and combustion efficiency improves by 1.5% compared to the base point with PR= 0.815. For this reactivity controlled compression ignition engine with existing injection system, decreasing injection pressure from the base case 480 bar by 100 bar result in carbon monoxide and unburned hydrocarbon will decrease 20g/kg-fuel and 10g/kg-fuel respectively and slightly improve the combustion efficiency by about 1%. And also it was observed that advancing start of injection timing is important for the engine due to increase in mixing time of diesel fuel with premixed air and gasoline where combustion and gross indicated efficiency improve by about 1%, load Indicated Mean Effective Pressure (IMEP) increases by 0.17 bar and carbon monoxide and hydrocarbon emissions decrease 18 and 9 g/kg-fuel, respectively. Decreasing spray angle from 74^o to 55^o causes carbon monoxide and hydrocarbon emissions to decrease 11 and 8 g/kg-fuel, respectively. And also, gross indicated efficiency and combustion will improve by around 0.7%.

Yaopeng Li et al. [13] this study investigates the effects of methanol mass fraction, SOI and initial temperature on combustion and emission characteristic in a methanol/diesel RCCI engine. The results indicate that the methanol addition and SOI have a significant effect on the fuel reactivity and equivalence ratio distributions. With increased methanol, the lower CN of methanol results in longer ignition delay and lower combustion rate at initial combustion stage, which decreases the peak of HRR and ringing intensity.

The equivalence ratio distribution is more homogeneous with the increment of premixed methanol, and it leads to larger area of high combustion temperature which is beneficial for reduction of HC and CO emissions. Moreover, retarded ignition timing is helpful for decreasing the residence time of mixture in the high ambient temperature, and consequently inhibits the NOx formation.

Sage L. Kokjohn et al. [3] in this study, Reactivity controlled compression ignition combustion has been indicated to grant improved performance over compression ignition engine (CI) in terms of emissions and efficiency at mid load conditions.

However, operation under low load and high load conditions is a major challenge with reactivity controlled compression ignition combustion. This indicates that the optimum compression ratio could be different when both loads are taken into consideration.

Additionally, the bowl geometry, optimal injector configuration, and air handling could all be very different considering the large difference in fuel mass associated with the low and high load operating conditions. In consequence, the current analysis discusses the results from a computational optimization study that was conducted considering the performance at high load-low speed (20 bar, 1300 rev/min) and low load-high speed (2 bar, 1800 rev/min) operating conditions simultaneously.

This study was performed using detailed computation fluid dynamics modeling in combination by considering the performance at high load-low speed (20 bar, 1300 rev/min) and low load-high speed (2 bar, 1800 rev/min) operating conditions, simultaneously. The optimization study resulted in an optimum compression ratio (CR) of 13.1 with a stepped piston bowl geometry that had two distinctive regions when both conditions were equally weighted. The results also indicated that a narrow spray angle for diesel fuel and a wide spray angle for gasoline would be necessary to target the two regions of the bowl.

The optimal fueling strategy had a diesel low temperature combustion strategy at low load with a low gasoline percentage (15% of the total fuel mass) and very little premixed fuel. At high load, the optimum strategy was a mixed mode combustion strategy with 92% of the fuel being gasoline and the majority of it being premixed.

Kamran Poorghasemi et al. [7] this paper studies**,** the effects of direct injection strategies on the combustion and emission characteristics of an improved light duty reactivity controlled compression ignition engine, fueled with natural gas and diesel were numerically investigated. Natural gas with higher octane number (ON) is mixed with air through intake port, whereas diesel fuel with lower octane number is directly injected into the combustion chamber throughout compression stroke by means of split injection strategy. During this approach, Converge CFD code using a detail chemical kinetics mechanism was used for 3D simulation of combustion process and emissions estimate.

The impact of some parameters, including the injection pressure, premixed ratio (PR) of natural gas, diesel fuel fraction in first and second injection pulses, the spray angle and first and second start of injection timing (SOI1 and SOI2) on the engine performance and emission characteristics are investigated. The lower reactivity of natural gas causes lower combustion rate and longer ignition delay by increasing premixed ratio.

Chaitanya Kavuri et al. [2] this paper describes gasoline compression ignition (GCI) and reactivity controlled compression ignition (RCCI) combustion are promising approaches to improve efficiency and reduce pollutant emissions. However, the benefits have generally been confined to mid-load operating conditions. In this section, the performance and emissions of Reactivity Controlled Compression Ignition and conventional diesel combustion engines are compared. Reactivity Controlled Compression Ignition and gasoline compression ignition combustion strategies were compared at a high load, low speed condition of 20 bar IMEP and 1300 rev/min.

Further analysis was done to study the effect of input and operating condition variation on combustion control, performance, and combustion constancy. The results indicated that both the combustion system have related combustion characteristics with a near TDC injection initiating and controlling the combustion phasing for both the approaches. However, the RCCI strategy was found to have more control over combustion phasing than the GCI strategy. The increased control is due to the shorter ignition delay of diesel fuel than gasoline.

Jesus Benajes, et al. [6] this experimental work investigates the effects of piston bowl geometry on RCCI performance and emissions at low, medium and high engine loads. For this purpose three different piston bowl geometries with compression ratio 14.4:1 have been evaluated using single and double injection strategies.

The experiments were conducted in a HD single-cylinder engine adapted for dual fuel operation. All the tests were carried out at 1200 rev/min. From result the author suggest that piston geometry has great impact on combustion development at low load conditions, more so when single injection strategies are used. It terms of emissions, it was proved that the three geometries enables ultra-low NOx and soot emissions at low and medium load when using double injection strategies. By contrast, unacceptable emissions were measured at high load taking into account EURO VI limitations. In the present experimental work, three different piston bowl geometries has been tested at the same engine operating points using single and double injection strategies, providing a direct comparison in terms of RCCI performance and emissions from low to high load.

The results at low load, in which the greatest differences in combustion pattern between pistons were observed, showed that the more pronounced bowl of the stock piston enhanced the mixing process providing earlier SOC than bathtub and stepped geometries. In spite of these differences, all pistons allowed ultra-low NOx and soot emissions whatever the injection strategy used. Also, the new geometries resulted in slightly increased CO and HC levels due to the smoother combustion process. By contrast, at medium load, the reduced heat transfer losses due to the remarkable lower area to volume ratio of bathtub piston promoted higher combustion temperature peaks, which contributed to reduce combustion losses and fuel consumption while maintaining NOx and soot emissions under EURO VI levels. Finally, a single injection pattern was required to reach low NOx and soot emissions with moderate pressure rise rates at high load.

Santiago Molina et al. [7] this work investigates the effect of low reactivity fuel characteristics and blending ratio on low load reactivity controlled compression ignition (RCCI) performance and emissions using four different low reactivity fuels: E85, E20-95, E10-98 and E10-95 (port fuel injected, PFI) by keeping constant the same high reactivity fuel: diesel B7 (direct injected, DI). The experiments were takes place using a HD single cylinder research diesel engine adapted for dual fuel operation.

All tests were carried out at 1200 rev/min and constant CA50 of 5 CAD ATDC. For this case, the premixed energy was equal for the different blends and the EGR (exhaust gas recirculation) rate was modified as required, keeping constant the rest of engine settings.

From this study it was observed that these parameters (i.e. premixed ratio, injection pressure, start of injection and spray angle) have major effects on the light duty reactivity controlled compression ignition engine performance and pollutant gas emissions. And also, it was revealed that by decreasing the first injection pressure from 450 to 300 bar, the gross indicated efficiency increases by 5% and CA50 is retarded by 4 CAD. Moreover, the CA50 is advanced by 6 CAD and gross indicated efficiency decreases by 4% when the spray angle reduced from 144^0 to 100^0.

The results indicated that reduction in NOx emission is feasible, whereas managing unburned hydrocarbon and carbon monoxide emissions, in case of increasing the natural gas fraction, advancing the SOI1, increasing the fuel fraction in first direct injection with lower injection pressure and using a wider injector spray angle.

Investigation on the effects of the first injection timing (SOI1) was completed by sweeping SOI1 from 85 degree to 45 degree bTDC while keeping SOI2 timing constant. SOI2 timing was at 20 degree bTDC for case b. For this case, 70% of the total diesel fuel was injected at the first pulse and 30% at the second pulse.

Amir Hasan et al. [1] under this article, a numerical study is accomplished to investigate the emission and combustion characteristics of RCCI combustion mode in a single cylinder, heavy-duty diesel engine with diesel and gasoline fuels.
At the beginning, a comparison is performed between RCCI and CDC, performance and emissions to indicate the superior features of reactivity controlled compression ignition combustion. Then, the impact of diesel fuel mass fraction in SOI1 on combustion and emission of reactivity controlled compression ignition engine is studied. It is verified that by increasing the diesel mass fraction in SOI1, combustion event happens earlier and peak pressure rise rate is slightly higher. However this parameter has an insignificant influence compared to primary reference fuel range and start of injection timing.

The numerical study of the reactivity controlled compression ignition combustion mode discovered that the reactivity controlled compression ignition combustion mode offers higher gross indicated efficiency and lower NOx emissions compared to traditional diesel combustion. However, its ringing intensity is significantly higher, but it is still below the allowable limit. As the peak pressure is nearer to the TDC, gross indicated efficiency and ringing intensity are higher.

III. CONCLUSION

Understanding of reactivity controlled compression ignition combustion is very important to optimize engine operation and to achieve maximum efficiency. Under this condition, experiments and simulation models are plays a great role to provide insight into reactivity controlled compression ignition combustion. For thermo-kinetic modeling of reactivity controlled compression ignition engine simulation models with different dimensions have been proposed. In summary, a lot of researcher's experiments conducted using the reactivity controlled compression ignition (RCCI) strategy on the high duty and low duty diesel engines revealed the following achievements,

- ✓ The studies indicate that reactivity controlled compression ignition is a promising plan to meet current and future emissions controlling without using after-treatment.
- ✓ Gasoline/diesel reactivity controlled compression ignition provided high thermal efficiency on the variation of engine loads, with a peak gross indicated efficiency and at specified indicated mean effective pressure (IMEP) operating point on a light load, mid high-load and high load engine.
- ✓ The heavy duty engine experiments also clearly explained the reasons for the improved performance of reactivity controlled compression ignition combustion over conventional diesel combustion.
- ✓ The improved efficiency was found to be largely due to reduced heat transfer losses.
- ✓ In agreement with the different research experiments, it was found that at identical operating points, NOx was reduced, soot was reduced, and gross indicated efficiency was improved.
- ✓ Natural gas/diesel reactivity controlled compression ignition operation on high duty engine yielded clean, quiet, and efficient combustion throughout the tested load and speed range.
- ✓ The use of natural gas as the low reactivity fuel allowed extending the load limit and the combustion process, and emissions results were found to be sensitive to the injection mass split.

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