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Optimizing Efficiency of Reactivity Controlled Compression Ignition (RCCI) Engine: A Review

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Abstract: *Rising fuel prices and stringent emission mandates have demanded cleaner combustion and increased fuel efficiency from the IC engine. This need for increased efficiency has placed compression ignition (CI) engines in the forefront compared to spark ignition (SI) engines. However, the relatively high emission of oxides of nitrogen (NOx) and particulate matter (PM) emitted by diesel engines increases their cost and raises environmental barriers that have prevented their widespread use in certain markets. The desire to increase IC engine fuel efficiency while simultaneously meeting emissions mandates has thus motivated considerable research. The study showcases development of a single cylinder LD (Low Duty) RCCI (Reactivity Controlled Compressed Ignition) engine. In particular, a dual fuel engine combustion technology called “reactivity controlled compression ignition” (RCCI) is a variant of Homogeneous Charge Compression Ignition (HCCI) as it provides more efficient control over the combustion process and has the capability to lower fuel use and pollutant emissions. RCCI engine technology essentially differs from the HCCI engine in its capability to control the kinetics (reactivity) of the combustion process thereby optimizing the efficiency of the engine and minimizing the emissions. Several experiments were conducted including use of renewable fuels like Biodiesel and Ethanol, observeLP and HP(Low and High Pressure) EGR(Exhaust Gas Recirculation) effects on combustion and performance as well as comparing conventional diesel combustion(CDC) and RCCI (Reactivity Controlled Compressed Ignition) combustion at same operating conditions (CR, boost, IMT(Intake Manifold Temperature), swirl). The comparison between RCCI and conventional diesel showed a reduction in NOx by three orders of magnitude, a reduction in soot by a factor of six, and an increase in gross indicated efficiency of 15 (i.e. 6.5 per cent more of the fuel energy was converted to useful work).*

Keywords: *RCCI, NOx, Particulate Matter, EGR*

1. INTRODUCTION

Researchers all around the globe are looking for development strategies to render maximum thermal efficiency during the the combustion process in an engine and alongside a significant reduction in the emissions [1]. The world emission trends show a steep rise in the amount of emissions in the upcoming decades calling for development and utilization of strategies to reverse emission trends. The world CO_2emissins have risen by 40 percent in the last two decades from 1990 to 2013 [2] and are predicted to go up by 32 percent over the next decade due to increasing awareness and upcoming eco-friendly strategies, but to reverse the trends, radical techniques such as reviewed in the following text needs to be developed and adopted. Also it has been proved that the total emissions and the thermal efficiency bear a direct relationship, thus, the best way to improve upon the emission rates is to optimize the engine efficiency.

Compression ignition engines typically use a 4 stroke cycle like spark ignition engines, with the primary difference being in the way that the combustion event is initiated. Diesel engines inject fuel into the compressed high temperature and pressure air near TDC. The high temperatures and pressures cause the fuel to burn without the need for a spark source. Diesel engines operate with diffusion type of combustion that is highly dependent on mixing rates. Since this type of combustion does not rely on flame propagation to burn the fuel, the fuel air mixture does not have to be near stoichiometric. Therefore, throttling the intake for load control is not necessary with diesel engines because load control can be accomplished by reducing the quantity of the fuel that is injected. Running lean without a throttled intake is an inherent efficiency advantage over SI engines. Since TWC‟s are effective when the air fuel ratio is near stoichiometric, this solution does not work with diesel engines because a TWC is only effective at converting HC and CO emissions at lean conditions and therefore NOx emissions become a problem. High levels of exhaust gas recirculation (EGR) are effective at reducing the NOx produced by the engine with an increase in the soot production [1].Oxides of nitrogen (NOx) include both nitric oxide (NO) and nitrogen dioxide (NO2) grouped together. NO is the primary pollutant produced in cylinder and is formed by the oxidation of atmospheric nitrogen. Nitrogen contained within the fuel can also be oxidized to form NOx, but modern gasoline and diesels tend to have very low nitrogen content and therefore their contributions to overall engine NOx is negligible. The extended Zeldovich mechanism is a widely accepted NO formation mechanism for converting atmospheric nitrogen and oxygen to nitric oxide. The following three reactions constitute this mechanism as shown in equation 1, 2 and 3.

$$O + N_2 \rightarrow NO + N \quad (1)$$

$$N + O_2 \rightarrow NO + O \quad (2)$$

$$N + OH \rightarrow NO + H \quad (3)$$

Equations 1 and 2 are generally referred to as the Zeldovich mechanism and later equation 3 was added and the group of three is referred to as the extended Zeldovich mechanism [1]. NO formation via this mechanism occurs in the high temperature near stoichiometric regions within the cylinder. Since combustion in engines happens at high pressures, the flame reaction zone is very thin (~0.1 mm), and therefore the time available within this region is significantly shorter than the characteristic time required for the completion of reaction 1. NO formation through the above mentioned mechanism is generally insignificant at temperatures below 1800K since the activation energy of the first reaction, Equation 1, is very high (319.05 MJ/kmol) [3]. Due to the thin flame region that exists in diesel engines, the time at elevated temperatures is very short which causes the reaction temperatures to be further elevate to 1900-2000K [5]. Therefore NO production is considered to be decoupled from the flame process [1, 4]. There are three predominant factors that are necessary for NOX production, time, temperature and availability of oxygen. Therefore, one common way of reducing NOX emissions is to increase the EGR and reduce the availability of oxygen [1]. However, adding too much EGR results in increased PM production, loss of combustion stability and eventual misfiring.Particulate matter (PM) is generally defined as any exhaust constituent that can be collected in a filter.

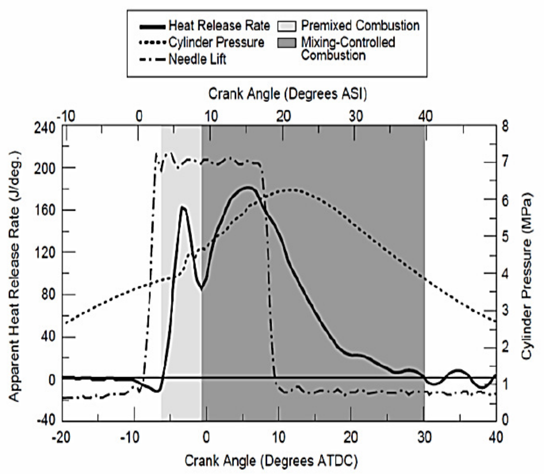

Fig. 1. Heat Release Analysis of Standard Diesel Combustion [7]

The measurements made by Dec [6] in Figure 1clearly show these two combustion regions. The premixed region occurs from about -6 to -1 degrees aTDC and is followed by the mixing controlled combustion event from about -1 to 30dATDC. A few degrees after the start of injection the premixed combustion region occurs and is a consequence of a rapid burn of the premixed fuel air mixture that develops during the ignition delay. The ignition delay is the time delay between the start of injection (SOI) and the start of combustion (SOC) and thus, is a function of in-cylinder conditions and properties of the fuel used.

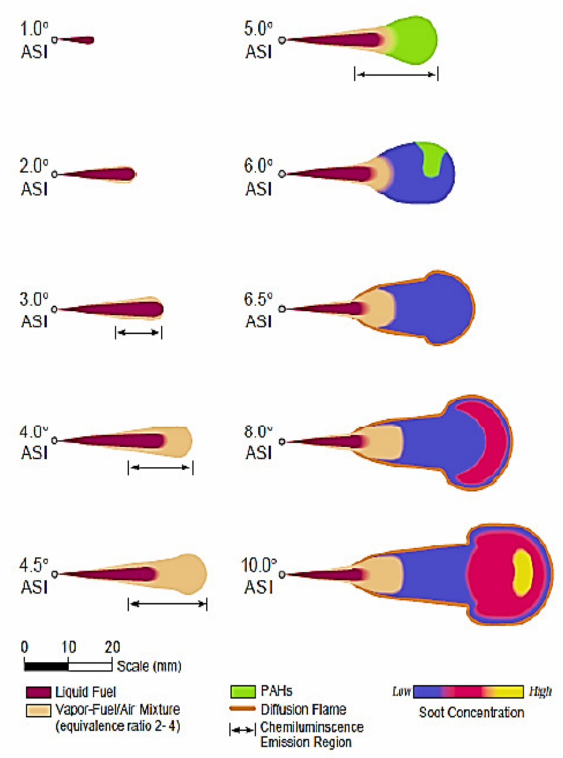

Fig. 2. Temporal Sequence Showing Developmentof Direct Injection Combustion Spray Plumes [7]

In order to further understand direct injection combustion, a conceptual model was developed by Dec [6]. Dec's conceptual model, shown in Figure D, shows steps through the combustion process from SOI to the start of the mixing and controlled burning of the fuel by showing spray plume cross sections at crank angle increments [6]. In this model, the fuel spray jet is shown to have smooth boundaries because it represents the typical jet rather than individual droplets which have irregular boundaries due to small turbulences. The first three images, 1-3° ASI, show the start of the injection process and depict the hot air entrainment and fuel vaporization upto the point where the droplet reaches its maximum size due to enough entrained air to completely vaporize it. The chemiluminscence emissions region begins at 3° ASI and continues until 5° ASI and is caused by large fuel molecules breaking down into smaller fuel fragments according to the work of Flynn et al. [5]. At some point between 3 and 5° ASI, auto-ignition begins and by 4.5° ASI, a head vortex forms and grows in size while by 5° ASI, PAH's form in the head vortex. At 6.5° ASI, a thin film of stoichiometric air fuel ratio develops around the head vortex and it is known as the diffusion flame. Additional heat transfer takes place from the diffusion flame vaporizing some amount of the fuel which in turn shortens the length of the jet by 10-20%. The premixed burn spike that is visible in the heat release rate in Figure C begins from about 4 to 6° ASI and continues until about 7 to 9° ASI. At approximately 9° ASI, the premixed burn is complete and the mixing controlled burn region begins and is very similar to the final image in Figure 2.

The strategy used in HCCI involves compression of a fuel-air mixture that auto-ignites at an appropriate timing, which is determined by the properties of the mixture prior to compression. Several problems arise in the execution of this strategy. Early injection timings result in high levels of spray wall impingement due to low charge densities. Premixed combustion results in rapid heat release rates that can cause engine structural damage at higher loads. Combustion of a homogeneous mixture initiated by auto-ignition lacks consistent control over the start of combustion (SOC) and is highly dependent on intake conditions, which are never consistent outside of laboratory work.

Many concepts have been developed in efforts to reduce the spray wall impingement of advanced injections. These concepts can be lumped into two categories, spray targeting improvement and advanced rail pressure control.The HCCI process essentially involves a completely premixed fuel air charge that is inducted into the cylinder at equivalence ratios that are typically lean. Although HCCI combustion appears thermodynamically attractive, the HCCI concept presents a controllability challenge as it gives up two combustion control aspects that are typically found in conventional engines. First, the timing of ignition is not directly controlled, either by the fuel injection timing, as in a DICI engine, or by the spark timing, as in a spark ignition (SI) engine. Second, the rate of heat release is not directly controlled, either by the rate of fuel injection, as in a DICI engine, or by finite turbulent flame propagation, as in a SI engine. As a result, the near constant volume combustion event can lead to a very rapid rate of heat release, and hence a very rapid rate of pressure rise. This tends to limit the maximum engine load achievable with HCCI combustion.

In PCCI engine, the traditional NOx–soot trade-off that exists with conventional diesel combustion can be defeated with diesel PPC, but required EGR rates in excess of 70%, which is difficult to obtain from an air handling stand point on the engine. The high EGR rate is required because diesel fuel is highly reactive (i.e., high cetane number), meaning that it auto ignites readily, making it difficult to achieve the level of premixing required to avoid NOx and soot formation. In addition, diesel fuel has a relatively high boiling point, making use of early injections with large quantities of fuel a challenge to avoid wetting the cylinder walls. These reasons make diesel fuel not an ideal candidate for PPC operation [7].

RCCI is a dual-fuel partially premixed combustion concept. In this strategy, a low reactivity fuel, such as gasoline, is premixed via port fuel injection (PFI), and a high reactivity fuel, such as diesel fuel, is direct-injected (DI) at multiple times during the compression stroke. This process of in-cylinder fuel blending develops fuel reactivity gradients in the combustion chamber. The stratification of fuel reactivity results in a broad combustion event and reduced pressure rise rates compared to fully premixed HCCI combustion. Using a suite of optical diagnostics, Kokjohn (2012) [8] demonstrated that RCCI is a chemically controlled combustion process, similar to HCCI. The direct injection events are sufficiently early during the compression stroke that the peak equivalence ratio at the start of combustion remains very lean (i.e., equivalence ratio <0.5). This results in sequential auto-ignition events beginning in the regions of highest fuel reactivity and progressing down the reactivity gradient.

2. LITERATURE REVIEW

The engine used by Reitz et al. [9]in the research experiment wasYanmar L70AE Single Cylinder air-cooled DI diesel engine. This engine is designed primarily for the purpose of generating electrical power by being coupled to an alternating current generator. The design parameters of Yanmar L70AE comprise of a geometric compression ratio of 19.5, realised compression ratio of 17, maximum output of 6.7 hp @3600 rpm, SOI -12.5 deg ATDC and DOI 17.1 deg and fuel injection opening pressure of 196 bar.The overhead valves are opened via pushrods and rocker arms, driven by a gear driven camshaft inside the block. This camshaft also has a lobe to operate the mechanical fuel pump. The flywheel provides enough rotational inertia to keep the engine spinning through the compression stroke and also has vanes that pump air through the many air passages in the block, liner and head to cool the engine.

Yanmar L70AE engine has been identified to have a problem with "white smoke" at low load operation which was also found to be consistent with the observations ofYanmar et al [9]. The smoke was a combination of unburned fuel and water, and was caused by improper injection timing at low engine speed and fuel spray impingement on the bowl at light loads throughout the entire range of engine speed. The injection timing was optimized for high engine speed operation, making it too advanced for low engine speeds. This was rectified by the addition of a step plunger in the fuel pump such that the injection timing varied with engine speed.

Several measures were also taken to reduce the fuel spray impingement on the bowl in this engine.The distance between the injector holes and bowl walls was maximized and the compression ratio was increased in order to increase the air temperature and density during the injection event, which has the effect of reducing the spray penetration length. The mechanical fuel system consists of three main components: the fuel pump, the mechanical governor and the fuel injector. The fuel injector has 4 holes with a 150 degree included angle at a 25 degree offset to point the center of the spray cone straight down into the cylinder.The fuel injector is completely mechanical in its actuation. The fuel system consists of a fuel reservoir, a fuel filter, a single positive displacement diaphragm chemical metering pump with adjustable frequency and stroke length. After the fuel leaves the pump it goes into a large volume steel reservoir to help dampen out the pressure waves caused by the pump. The outlet of this reservoir tees and one path is sent to Flowmeter for fuel flow rate measurement and then to the fuel injector, the other path goes to a pressure regulator that maintains fuel pressure and any excess fuel goes through the regulator and through a low pressure return line to the fuel tank.

RCCI combustion was shown to be an effective way of simultaneous NOx and PM reduction. While it maintained high efficiency during its operation, the performance suffered at light load operation due to poor combustion efficiency and lack of optimizationRCCI Hydrocarbon (HC) and Carbon Monoxide (CO) emissions were significantly higher than diesel combustion especially at light load. One possible way to reduce the HC and CO emissions would be to use oxidation catalyst aftertreatment to oxidize the HC and CO. An oxidation catalyst would have virtually zero effect on NOx emissions due to the abundance of oxygen present in the exhaust gas, but NOx emissions from RCCI combustion in this engine were sufficiently low that aftertreatment would not be warranted. Since RCCI is a LTC type of combustion and the HC and CO emissions are a more significant problem at light loads, high enough exhaust gas temperatures (EGT's) for catalyst light-off are of particular concern for this concept. There is definitely potential for reduction of RCCI HC and CO emissions by using an oxidation catalyst at loads slightly above 25% of full load on this engine.

A better way to improve the light load HC and CO emissions would be to improve the combustion efficiency because this would also improve the fuel consumption which suffered due to low combustion efficiencies. Several ways to accomplish this include increasing the equivalence ratio by intake air throttling, increasing intake air temperature, and use of injections optimized for higher background fuel reactivity. Throttling the intake would increase the equivalence ratio and increase the oxidation reaction rates, but this creates additional pumping losses and should only be used if the other methods fail to significantly improve the combustion efficiency. Increased intake air temperature through the use of EGR at low load should increase the oxidation reaction rates and reduce the HC and CO emissions. The HC and CO emission results of the 50% load TIA sweep were fairly insensitive to intake air temperature. It is possible that the highest temperature achieved in this sweep was not high enough to be an efficient method of HC and CO emission reduction. Finally, increasing the background reactivity by taking fuel out of the second direct injection and adding it to the first direct injection will not only increase the background fuel reactivity but also the equivalence ratio as well.

Sreedharaet al. [10] conducted a similar research studying the potential of RCCI technology using oxidized EGR (OEGR).Reduction in BTE is observed with increased LPG percentage. The inductedLPG-air mixture is trapped in crevices during the compressionstroke and increases crevice losses, which in turnreduces BTE. However, BTE loss may be reduced usinglower percentages of LPG. Reduction in PM was observed with increased LPG percentage for each run. Early injection allows better mixing and, hence, reducesthe formation of PM and higher average cylinder temperature, as a result higher CR, enhances oxidation rate of PM.Minor reduction in NOx emissions were found for all runs with lower flow rates of LPG. However, NOx was reduced considerably with higher LPG percentage(*43 % reduction with 40 % LPG).A fraction of LPGairmixture is typically trapped in crevices during thecompression stroke. As a result, higher concentrations of HC were observed with higher amounts of LPG.The operating run results for Optimized RCCI (-15 CAD aTDC injection timing, 18 CR, 25 EGR, 10 LPG) showed 28.58% BTE, 6.07g/kWh CO, 0.42g/kWh HC, 2.63g/kWh NOx, 0.23g/kWh PM while the results for Optimized LTC (-15 CAD aTDC injection timing, 18 CR, 25 EGR, 0 LPG) showed 28.41% BTE, 6.44g/kWh CO, 0.15g/kWh HC, 3.13g/kWh NOx, 0.33g/kWh PM indicating that a considerable reduction in PM (*30 %), NOx (*16 %) and CO (*6%) with an acceptable change in value of HCis achieved with the optimized RCCI run compared to thatfor optimized LTC run.

Leemakers et al. [11] implemented a multi zone model approach to perform the RCCI operation. In this study RCCI combustion was analyzed by a multi-zone model which is developed to perform HCCI/PCCI/RCCI combustion simulations using a wide variety of detailed chemical models.The purpose of this study was to predict the counterintuitiveignition characteristics (earlier injection leads tolater ignition) of the RCCI experiments. During theseexperiments, earlier injection timings caused laterignitions for RCCI combustion measurements, theobjective being to reproduce the measured auto-ignition delay trend using the multi zone model.The ignition characteristics were analysed by using CA50 as the main parameter. For the experiments, a six-cylinder DAF engine, referred toas CYCLOPS, was used of which only Cylinder 1 was considered for observations. This is a dedicated engine test rig, based on a DAF XE 355 C engine. Cylinders 4through 6 of this inline 6 cylinder Heavy Duty DirectInjection (HDDI) engine operate under the stock DAFengine control unit and together with a water-cooled, eddycurrentSchenck W450 dynamometer they are only used tocontrol the crankshaft rotational speed of the test cylinder, i.e. cylinder 1. Apart from the mutual cam- and crankshaft and the lubrication and coolant circuits, the test cylinderoperates autonomously from the propelling cylinders anduses stand-alone air, EGR and fuel circuits for maximumflexibility. The compression ratio is decreased by introducinga cylinder head gasket.A mathematical description of the multi zone model was given which was based upon the first law of thermodynamics.

$$m_z c_v \frac{dT_z}{dt} = -\sum_{I=1}^{N_s} e_I \frac{dm_{z,I}}{dt} - p\frac{dV_z}{dt} + \sum_{I=1}^{N_s} \dot{m}_{z,I}^{in} h_I(T_{in}) + \sum_{I=1}^{N_s} \dot{m}_{z,I}^{out} h_I(T_z)$$

$$+\dot{Q}_z + \dot{Q}_{z,r}^{D} + \sum_{I=1}^{N_s} \dot{m}_{z-1,I}^{D} h_I(T_{z'}) + \sum_{I=1}^{N_s} \dot{m}_{z+1,I}^{D} h_I(T_{z''})$$

The mathematical explanations of the model helped in inferring that initially all zones have the same temperature, mixture composition and volume. The difference between the zones is typically caused by the heat loss to the environment (highest for the outer zone) and the amount of fuel injected per zone (stratification). The zones expand or shrink depending on the zonal conditions. First, the impact of diesel injection timing on RCCI operation was studied. In RCCI, the gasoline washomogeneouslydistributed among all the load zones whilst the diesel injectiontiming was varied. The baseline case consisted of 80% gasolineand 20% diesel fuel. The start of injection was swept from60 degCAbTDCto 90 degCADbTDC.

The ignition characteristics of RCCI combustion were studied with a multi-zone approach including detailed kinetics. The influence of diesel injection timingand different compositions of diesel-gasoline blends was also studied. The main conclusions drawn from the experiments showed that RCCI combustion displayed counter intuitive characteristicsin ignition timings. Earlier injections enable a less stratifiedmixture leading to retarded ignition. This behaviour wasobserved both in the experimental and numerical study.Afterwards the fuel blend was tuned to control ignitiontimings. It was comprehended that the composition of thefuel blend had a crucial role on ignition timing. Increasingthe gasoline ratio clearly extended ignition delay timings.This dependency was also captured accurately by the model. It was concluded that the multi zone model was an effective to predict ignition characteristics of RCCI combustion.

3. CONCLUSIONS

RCCI combustion is potentially the strongest LTC strategy for the simultaneous maximisation of efficiency and reduction of emissions.Gasoline/diesel RCCI provided high thermal efficiency over awide range of engine loads, with a peak gross indicated efficiency of 56% at a 9.3 bar IMEP operating point. Also, while it maintained high efficiency for high engine loads, there was a fall of 2% in BTE with reduction in engine load from 75% to 50%.There was a further fall of 5% in the BTE when the load was reduced to 25% thereby cementing the fact that there RCCI operation had some scope for improvement while operating on low loads. This loss in efficiency could be attributed to the incomplete oxidation of HCs due to lower in-cylinder pressure and temperature. The improved efficiency at high loads has been found to be largely due to reduced heat transfer losses. 16.4% higher gross indicated efficiency has also been achieved using RCCI compared to conventional diesel combustion without EGR.

RCCI combustion has been proved to be an effective way for simultaneous reduction in NOx, PM and CO emissions. The NOx (~3.1 g/kWh), CO (~6 g/kWh) and PM (~0.33 g/kWh) emissions have been consistently low in RCCI operation without EGR which is a reduction of 16%, 6% and 30% in NOx, CO and PM [33, 35] respectively as compared to conventional diesel combustion. Low load RZCCI operation has been found to emit slightly higher NOx and PM due to the advanced injection and combustion thereby reducing the time available for their oxidation. The RCCI operation for multi cylinder engine has also shown similar trends in BTE and emissions over a wide load range. Multi zone model was used to project a single cylinder model from a six cylinder engine which resulted in observations which were concurrent with those for single cylinder DI diesel engines. Thus, RCCI stands as one of the cleanest and most efficient LTC technique due to its high gross efficiency, low emissions and minimum fuel consumption.

4. ACKNOWLEDGEMENT

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