Approaches and solutions to HCCI - a review energy systems: fuel and combustion, injection and atomization

M R Kamesh¹, Dhanush Ashok², Sai Nikhil R², Sanjay Kumar S² and Sanju R²

¹Research Scholar, Department of Mechanical Engineering, DayanandaSagar College of Engineering
² Final Year Mechanical Engineering Student, DayanandaSagar College of Engineering

Corresponding Author: kamesh_mr@yahoo.com

Abstract. SI and CI engines are entities in which conditions of internal combustion was triumphantly implemented. In a gasoline engine both efficiency and emissions are less; on the other hand in a diesel engine both are relatively high. It is hard to achieve a win-win situation where fuel consumption and adverse impact on the environment were diminished. Over the past few decades researchers have assigned themselves to strike a balance in this regard, creating Homogeneous charge compression ignition engine technology, which perfectly amalgamates the principles of Spark Ignition and Compression Ignition engines, making it the holy grail of engines. Homogeneous charge compression ignition engines do not employ spark plug or fuel injector to initiate combustion, the lean homogeneous mixture auto-ignites in multitudinous spots once it is compressed to attain its chemical activation energy. Unlike its contemporaries the combustion is flameless, propelled the fuel efficiency along with an enormous decrease in emissions. This proposed work digs deep into conceptual description of the fundamentals of HCCI engine and various approaches to attain HCCI, along with the challenges encountered related to the same being elaborated. Depending on inferences arrived from the challenges different controlling strategies are proposed in this paper.

Keywords: Homogeneous charge, Mixture formation, Controlling Ignition, Lean Mixture, Injection timing

ABREVATIONS:
CI- Compression Ignition
CO- Carbon monoxide
CO₂- Carbon di Oxide
EGR- Exhaust gas recirculation
HCCI- Homogeneous Charge Compression Ignition
HCLI- Homogeneous charge late injection
HC- Hydro carbons
1. Introduction

An ideal engine is characterized by its efficiency and emission at the opposite extremes. HCCI approached these ideal conditions, making it the panacea of engine technology. Carnot efficiency of a heat engine mainly depends on the source and the sink temperatures. Though HCCI and conventional engines have the same sink temperatures the In-cylinder temperature of HCCI engine is higher than that of a conventional engine. Thus enlarging the gap between the source and sink temperature making HCCI efficiency carnotish.

Dominance of HCCI is attributed mainly to lean air-fuel mixture, this makes an engine to consume less fuel, consequently leading to higher fuel economy. As there is less fuel, the chance of producing un-burnt HC and CO is also less. Lean air-fuel mixture is accompanied by flameless combustion [1,2,3], where the purpose of fuel injector and spark plug is completely abolished. In the absence of fuel injector and spark plug the initiating point for combustion is eliminated, neglecting layer wise combustion of fuel. In a nutshell the entire air fuel mixture ignite simultaneously in a HCCI engine.

In a typical engine there exists a part of fuel trapped in between two layers of combustions, thereby leading to un-burnt HC and substantial wastage of fuel.

Homogeneous air-fuel mixture is utilized in HCCI engines, causing existence of sufficient parts of oxygen in the vicinity for each part of fuel helping to achieve complete combustion. If the operating temperatures of an engine is low, high CO emissions are obtained due to insufficient temperatures. On the other hand for high operating temperatures, higher NOx emissions are obtained due to interaction of nitrogen compounds near the exhaust with oxygen, further hotspots in the cylinder increase NOx emissions. As HCCI engines have intermediate operating temperatures and are free from hotspots they produce least NOx.

HCCI has become one of the best options for utilizing alternate fuels. The former can incorporate any fuel for producing energy with mere change in compression ratio. This characteristic of HCCI permits the usage of blends of several fuels which possess unique properties to achieve optimal outcomes.

2. Principle and Chemistry of HCCI

HCCI technology was conceptualized to eliminate the drawbacks of conventional SI and CI engines. HCCI is said to be the perfect amalgamation of SI and CI engines [4], thus it can be stated that SI and CI engines are the parent engines, which are used to realize HCCI.
HCCI adopts only positive aspects from its parent modes and is free from existing loopholes of conventional engines. HCCI inherits the concept of air-fuel mixture from the gasoline engines and inherits the auto-ignition characteristic from diesel engines. It is important to note that existence of flame front propagation in SI engines and flame diffusion in CI engines act as the root causes for their demerits, whereas in HCCI engines the charge ignites at multiple spots. Hence, HCCI engines are advantageous as they lack these demerit-causing aspects.

After detailed study of HCCI combustion it was concluded that HCCI engine liberates heat in two stages. The two stages are differentiated by prevailing temperatures [1,5], resulting in occurrence of LTR in initial stage and HTR in the later stage. During LTR stage the hydrocarbon molecules in the fuel converted to ketohydroperoxide species and OH radicals.

![Figure 1](image_url)

**Figure. 1.** Heat deliverance curve for HCCI combustion of n-heptane fuel. [6]

There exists a separation period between the two regions called the NTC regime[6] as shown in figure.1, which is characterized by decrease in reactivity and olefins and hydroperoxyl radical formation. Results show that less than 10% of entire is liberated in LTR and remaining heat is released during HTR stage, this is due to oxidation of CO to CO$_2$ in the later stages.

Optical diagnostics were used as a tool in order to assess the chemical kinetics of HCCI. After thorough analysis certain inferences were drawn which showed that a homogeneous weak light occurred throughout the chamber and more strong luminosity was derived during HTR, oxidation of CO being responsible for this strong luminosity [7]. Also, there was no luminosity spotted during NTC period.

External mixture formation, early direct injection and late direct injection are the major methods which can be utilized to accomplish charge homogeneity in HCCI, and these will be elaborated in the forthcoming sections.

### 3. External Mixture Preparation

External mixing is the most effective mechanism to achieve homogeneity as the mixing time is extended before the occurrence of actual combustion. [54] There are several methods such as Port fuel injection, Manifold induction, Fumigation and Wide open throttle carburetion which employ the strategy of external mixing. It was concluded that diffusion is the underlying principle for achieving homogeneity. Diffusion of an atom or a molecule of a gas depends on its concentration gradient, and it is given by the Fick’s law.

Fick’s law states that

$$ \frac{m_i}{A} = -D \frac{dC_i}{dx} $$

where
\( m_N \) = mass of gas per unit time

\[ A = \text{Area through which mass is flowing} \]

\( D = \text{Einstein’s diffusion coefficient} \)

\[ \frac{dx}{dx} = \text{concentration gradient of gas over the length } dx \]

Therefore in order to enhance the diffusion of the gas it is necessary to increase the Einstein’s diffusion coefficient.

Einstein’s diffusion coefficient is given by

\[ D = \frac{RT}{fN_A} \quad (1) \]

where R = gas constant

\[ f = \text{friction factor} \]

\( N_A = \text{Avagadro number} \)

It is inferred that diffusion depends (1) on the existing temperature of gas, thus the former can be increased by preheating the gas. According to the kinetic theory of gas the viscosity of the gas is proportional to square root of its absolute temperature.

Therefore decrement in viscosity of the gas leads to increase in tendency to diffuse. All the above statements are made by considering diffusion of only one gas. To extend the application of the above laws to practical engine it is necessary to study mixture of fluids, this is because during mixture preparation there is involvement of multiple fluids and diffusion characteristics of each fluid must be completely analyzed.

Relative diffusion of one gas within other leads to mixture of two gases. Diffusion of each gas can be propelled by altering the above mentioned factors, consequently allowing rapid mixing of two gases.

Creation of turbulence during or after the mixing of two fluids also results in rapid mixing called Turbulence diffusion. As a result of turbulence heat transfer, evaporation, mixing and combustion rates surge and hence, turbulence has a positive impact. Turbulence is very dominant in decreasing the concentration resulting in quick diffusion.

Turbulence is characterized by formation of large and small eddies, ranging from integral to the kolmogorov scale. Eddies that are smaller than the patch size continually distort, resulting in declivitous concentration gradient which are then equalized by diffusion.

Eddies those are larger than the patch size transport themselves without aiding mixture formation. The mixing process occurs therefore due to the distortion, stretching and convolution of the original patch.

One of the most widely used method for external mixture formation is Port fuel injection which is described below:

3.1. Port Fuel Injection

It is one of the simplest methods to attain charge homogeneity. It incorporates a fuel injector close to the intake manifold which injects fuel into air stream. The implementation of this strategy augments the volumetric efficiency. The turbulence created due to the piston bowl geometry during suction stoke enhances the mixing which results in further improvement in the homogeneity. [11]

This method has been successfully implemented in gasoline and alcohol fuels. Port fuel injection can also be used with diesel fuel but with the help of a vaporizer. The vaporizer facilitates fuel evaporation, reducing the viscosity and improves mixing. [12-14]

This method is cheaper than direct injection as the injector is not exposed to intense heat of the combustion chamber. Since fuel sprayed into air stream rather than inside the combustion chamber, there is copious time for the fuel particles and air to coalesce.
4. EARLY INJECTION HCCI

4.1. Premixed compression ignition combustion (PREDIC)

Contrary to conventional engine operation PREDIC utilizes lean air-fuel mixture. PREDIC makes use of early injection of fuel, promoting mixture formation during occurrence of compression stroke. PREDIC is a strategy where combustion begins near TDC, given that a partly homogeneous mixture is achieved. The latter is obtained when the fuel is injected just before power stroke. It adopts the fuel with a curtail cetane number ranging from 20 to 40 as juxtaposed to conventional diesel fuel in order to refrain the drift towards knocking.

Although PREDIC has the potential to abate Nox and soot dramatically it was unable to maintain the normal air excess ratio \( \lambda = 1.3 \) to 1.5 \[8\], thereby poses problem of generating only half the torque of a traditional diesel engine.

The figure 2. depicts the juxtaposition of injection layout in combustion chamber between PREDIC and conventional diesel. A side injector is brought into play in order to hike the operation range of PREDIC. The side injector maximizes the farness between the injection and the cylinder wall in unlike centre injection, and prevents the wetting of cylinder walls by fuel.

![Figure 2. The comparison of injector layout between PREDIC and conventional diesel. [8]](image)

4.2. Multiple Injection HCCI By Low Cetane Fuel (MULDIC)

Aiming to increase the operation range of the PREDIC systemand to improve torque’s upper limit in PREDIC, a second injection around TDC was introduced. This paved the path for development of multiple stage diesel combustion (MULDIC). Injecting the fuel second time during later part of operation would help to put an end to NOx and smoke. Along with gain in torque output MULDIC is beneficial as it gives out only 40% Nox \[8\]. Fuel economy is picked up to the level of conventional diesel with minimal cetane number. Though initial stage of combustion makes use of premixed lean combustion which lowers NOx emission, the second stage releases heat swiftly generating high temperature and low oxygen condition which germinates enormous un-burnt hydrocarbon and CO emissions

4.3. Narrow Angle Direct Injection (NADI)

Narrow angle direct injection has the ability of paring down the power limitation encountered in HCCI engines. This method focuses on utilizing air and fuel mixture at minor and moderate loads while conventional diesel at maximum loads. Implementation of this would assist in transition between the two modes.
In traditional diesel engines, fuel is admitted towards periphery for igniting the charge, but in NADI the fuel is sprayed at the centre. This prevents the fuel deposition on combustion chamber walls, hence lowering the emissions due to un-burnt particles. Early injection aids in the formation of charge homogeneity, on the other hand if it is too early it results in poor evaporation of fuel and leads to piston bowl spray issues. This ultimately results in early combustion and negative work being done during the compression stroke. [55]

The main objective of NADI is determining the best combustion chamber design suitable for narrow injection and creating a homogeneous mixture. Modifications made in the piston bowl helps in charge homogeneity utilizing the spray velocity. Results indicate that HCCI combustion is favoured with the narrowest spray cone angle [10] as shown in figure.3.

![Figure 3: Differences between conventional and NADI piston bowl geometry](image)

NADI also facilitates multiple stage injection which can be tested and validated. The multiple stage injection leads to a reduction of CO emission by half and noise reduction by 4dB compared to the single injection. HC emission persists which have to be treated in order to meet prescribed standards. The advantage of multiple stage injection is the extension of HCCI range without any compromise in the fuel economy [9].

Distinction between NADI combustion mode compared to conventional diesel combustion include: [8]
- Spray angle is narrow thus it limits the linear impingement
- Piston bowl designed for guiding the fuel
- Reduced compression ratio
- Multiple stage injection

Effects of NADI on engine performance:
NOx emission reduced by 100 times and particulate matter by 10 times in comparison with conventional engine as shown in figure.4 and figure.5. Slight decrease is observed in the emissions; also exhaust gas temperature is quite low. Noise level increased with increase in engine speed. [8]

![Figure 4: CO and HC emission at 1500 rpm](image)
4.4. Uniform Bulky combustion System (UNIBUS)

Innumerable procedures are investigated to intensify novel combustion system for exorbitant reduction of nitrogen oxide and unrefined soot exhausts from diesel engines, while there is substantial increase in fuel economy. An idealized combustion approach is equipped with a premixed compression ignition system, which is found to be the most promising. [8, 15, 16]

This process utilizes shadow graph method and image intensifier as tools to obtain combustion images and weak photic signals. These were used to analyze the gas temperature changing in the engines, which triggers several chemical reactions [8]. The NOx level of about 1/100 that of a conventional direct injection diesel engine was achieved through a range of injection timing. This mechanism had outrageously low NOx. The study disclosed that a novel combustion process could be justified by enhancing fuel scattering prior to ignition.

The concept called Trigger of Ignition was made known in UNIBUS to control ignition through the predominant common rail injection in the manufacturing engines. There would be a chance to build up time period if the mixtures in some parts play as a trigger of ignition, which leads to the mixture attaining Homogeneity [15].

The heat-released rate in the UNIBUS as shown in figure.6 was found to have two-heat release rate peak, while the traditional diesel combustion system provided single heat release peak. The reason for this was found to be, the extent to which the injection timing was fostered, that is, the degree of fuel distribution and the adjacent gas temperature.

![Combustion photograph of UNIBUS system](image)

**Figure 5.** NOx and Particulate matter emission at 1500 rpm [8]

**Figure 6.** Combustion photograph of UNIBUS system [16].
It is challenging to achieve the homogeneous mixture in a higher engine speed operation conditions. The micro-hole nozzle is a reliable solution for the above problem. The increased number of holes and reducing the nozzle hole size showed good proclivity for improving mixture in the engine test. It was verified by the engine test that low pollutant emissions and low noise characteristics were achieved in UNIBUS[16].

4.5. Homogeneous Charge Intelligent Multiple Injection combustion (HIMICS)
For the diminution of NOx and Particulate emission the new abstraction for diesel combustion technology was employed, which utilized numerical simulation, engine experiments and combustion observation. The concept of HIMICS is characterized by pre-mixed compression accompanied with multiple injection[8]. A standard single injection and pilot injection were used as reference for knowing the combustion characteristics of HIMICS. In this concept, pre-mixture is formed by a precursory injection performed from the early stage of the induction stroke to the middle stage of the compression stroke. Engine performances and emissions of each injection method were prognosticated using KIVA-II code modifications [17]. Paradoxically the experimental results were found to be undesirable when compared to that of simulation results. Trade-off relation of HIMICS between NOx emission and fuel consumption, NOx and smoke emission deteriorates when compared with standard injection or pilot injection in the region of regular injection timing[17]. Even though there are certain aspects which are holding back the advancement of HIMICS, it has fuel consumption and smoke emission region where Injection timing is substantially hampered and NOx emission is minuscule. Stupendous HC and CO emissions, lack of homogeneity in the pre-mixture and the premature ignition are observed to be the other obstacles [18].

5. Late Direct Injection
In contrast to early direct injection, late direct injection is a process of delaying the injection just before TDC along the later crank angle, leading to the curtailment in gas temperature and density, which initiates the longer delay for auto-ignition and helps in achieving enhanced mixture formation. Due to which HCCI combustion is ameliorated [8] as shown in figure 7. Integration of high EGR rates with the above process helps in delaying the ignition that is enough to generate the vigorous premixed combustion that diminishes the soot and together narrows down the combustion temperature, which in turn decreases the NOx formation. The variation of HRR due to delay in injection [19] is illustrated. Variation in injection delay in conventional diesel engines will not cause much variation in HRR. But if the SOI is delayed more, then HRR will start to vary. There is a definite increase in premixed burning fraction along with cutback in NOx and soot emissions.
Achieving the maximum load condition with higher efficiency is challenge in this method. The late injection strategies has two major dominance over other methods, firstly they can be easily incorporated in conventional diesel engines and secondly, the combustion phasing is under control by injection timing as there is a coalesce between combustion process and injection.[19] The late direct injection is based on the concepts of (MK) Modulated Kinetics and HPLI[20]. In the MK systems combustion characteristics of HCCI is based on three important parameters: Firstly, In order to depreciate the NOx emission, EGR was implemented so that the inlet air had lower oxygen concentration but this escalated the soot and HC; Secondly, NOx and soot emissions were narrowed down by delaying the start of ignition, which supports for sharpened premixed combustion. But they found HC emissions to be high; and thirdly, further soot emissions were acutely reduced, superior mixture formation was achieved and massive decrement was found in HC emissions. These three parameters play a prominent role in ignition delay, which helps in injecting all the fuel before the combustion starts.

In the current trends the new combustion ideas were introduced and they are HCLI[21] and HPLI. From the figure 8, it is found that the low loads were utilized in HCLI and the medium and high loads were utilized in HPLI in conventional DI diesel engines.

In HCLI, fuel is injected when the piston completes 140 degree from BDC, hence hasty homogeneity is achieved. Compression ratio in HCLI is reduced when juxtaposed with diesel engines in order to prevent over soon auto ignition.

To achieve homogeneity in HPLI the fuel was injected moderately late. In this scenario the period between initiation of injection and end of combustion can be precisely analyzed, thus better mixture formation is achieved. Substantial amount of soot is developed if the injection and combustion lap over, hence at the end of combustion it is very important to maintain marginal increase in temperature.
in order to oxidize the soot. Concurrent decrement of NOx can be accomplished by recirculating 40% of the exhaust gas.[22]

6. Challenges Faced
Any technology cannot be wholly perfect, owing to this statement there are areas in HCCI technology that need to be addressed. Though HCCI has an upper hand over its contemporaries, there are factors that hold back its commercial applications. It is certain that when engineering society overcomes the following barriers the HCCI’s commerciality will definitely surge up.

6.1. Tough to Control Combustion
SI and CI engines utilize fuel injectors and spark plugs to initiate combustion during the end of combustion stroke of every cycle. Unlike the former type, HCCI engine avoids the use of any combustion initiating devices. Absence of sparkplugs and injector in HCCI eliminates flame propagation, but this makes combustion controlling an issue.

Researchers have vehemently tried to attain charge homogeneity. Consequently this intake charge is used as the combustion material in a HCCI engine. As the charge reaches its self-ignition temperature it combusts vigorously and releases heat instantaneously. The point at which the charge burns is dependent on several parameters [23] such as auto ignition temperature, fuel quantity, current engine temperature, and homogeneity of the charge, which are in turn influenced by charge characteristics and bygone temperature of the engine.

Consequently it forces the incorporation of a controlling strategy, which does not disturb the self ignition of the charge, as it is the main purpose of HCCI. If the combustion occurs early it would affect the in-cylinder status and suppose the combustion is delayed there would be promotion of misfire, both outcomes are not intended. Hence, the charge is allowed to auto ignite and controlling of the combustion comes prior to or after the combustion. Anyhow there is a definite delay in controlling which affects the in cylinder condition and other operations. Different combustion controlling strategies will be mentioned in the later part of the paper.

6.2. Unwanted Noise and Pressure Rise
Instantaneous heat release prevails in HCCI as the entire charge auto-ignites simultaneously. Though HCCI is highly efficient it comes with the baggage of sudden and abnormal increase in in-cylinder pressure, leading to engine wear. Further expeditious energy output leads to boisterous operation as compared to conventional engines. Hence to curb down both pressure rise and noise [24] it is necessary to control heat release rate, or else unendurable damage of engine may occur.

6.3. Significant Surge in HC and CO Emissions
Homogeneous entities are always accompanied with parts of intake charge that dodge combustion during compression. Further the temperature after combustion is defiant as the amount fuel used is less. Hence, at low loads this temperature is insufficient to burn the retained charge which renters the cylinder during power stroke. This partially burnt fuel constitutes to the abundant presence of HCs. The existing temperature is unable to speed up the shift over of CO to CO₂ [25], leading to increased CO emissions, due improper oxidation.

It must be noted that if the above mentioned problems are solved there would be further increase in fuel economy.
As most of the regulating bodies are placing stringent conditions regarding emissions that need to be satisfied by any existing or new technology, these two barriers are suppressing the large scale implementation of HCCI.

6.4. Cold Start Incapability
Auto ignition is the commanding characteristic of HCCI engines, which is influenced by intake charge temperature. If the temperature of the ambience is low, a large amount of heat generated is transferred to the cylinder walls and there is significant dwindle in intake charge temperature. Operating the engine in conventional mode helps in procuring sufficient intake temperature. It takes a herculean effort to produce this temperature with sole operation of HCCI and without any transition from conventional modes of combustion. Hence, HCCI condition can be accomplished only after the engine has been operated to reach the desired temperature, limiting the former’s application [26,27,28].

6.5. Limited Operating Range
HCCI engine has a limited operating range; it is susceptible to NOx, HC and CO emissions when it is operated beyond this range. During light load operation engine produces more HC and CO than normal due to low in-cylinder temperature. Further during heavy load operation there is a sudden and steep increase in pressure leading to knocking. Hence most of engines go through conventional mode of operation to warm up and then shift to HCCI mode after required in-cylinder condition is reached. There is a necessity to expand the operating range to make HCCI suitable for applications demanding non-uniform loads [27,28].

6.6. Difficulty in Attaining Homogeneity
Once homogeneous turbulence is achieved HC and CO emissions are defiant, but satisfying the former condition is demanding. HCCI is an amalgamation of CI and SI engines and hence, it incorporates the principle of utilizing air-fuel mixture. Though progressive effort is being put to extract a mixture it would be ideal to attain isentropic homogeneity, which leads to isentropic turbulence of the mixture. In order to make sure that there is sufficient oxygen for fuel to combust it is preferable to lift the level of mixing. The amount of time taken to complete one cycle is diminutive and therefore the available time to for mixture preparation is quite short. It is expected to achieve the best possible mixture in this short interval in order to propel efficiency, but meeting this condition is knotty.

6.7. Developing A Multi-Cylinder Engine
Researchers have mainly concentrated to attain HCCI conditions in a single cylinder engine, but to make HCCI impact the socio-economic life it must satisfy the requisites and this can be done only by building a multi-cylinder engine with maximum power output. Thus, fabricating a four cylinder HCCI engine would boost HCCIs commerciality. To achieve the above condition solutions must be provided to the questions that arise during cylinder-cylinder transition [27,28]. Even when a multi-cylinder engine is developed it would allocate separate cylinders which would only operate in conventional mode.
7. Control Strategies

One of the utmost challenges of HCCI is the devoid of control over ignition timing. Compression ignition of a nearly homogenous mixture of fuel and air takes place when the conditions are right in terms of temperature and pressure for a particular amalgamation of fuel and air. Factors affecting the control of HCCI are EGR or residual rate, fuel properties, compression ratio, air/fuel mixture, inlet charge temperature, or fuel blend, injection timing of a DI engine and coolant temperature [8].

7.1. Variable valve actuation (VVA)

VVA provides a very active mean of affecting the respiration of the engine. For governance of HCCI there are two predominant techniques namely residual gas control and variable compression ratio control. Residual gas is controlled using VVA. VVA can be used to control the initial charge temperature by trapping gas or re-breathing the hot exhaust gas through the exhaust valve. Combustion control by retained residual gas is often called controlled auto ignition.

7.2. Exhaust Gas Recirculation (EGR)

A strategy closely related to residual gas control is the exhausts rebreathe strategy. In which the exhaust valve is reopened during the intake stroke to re-induct part of the exhaust gas into the combustion chamber. The ratio between normal exhaust valve opening and rebreathe opening determine how much hot exhaust is re-inducted. This kind of valve control most likely requires a VVA system. One of the extensive method adopted to run down the NOx emission of diesel engine. Presently, EGR was also employed as a prime bridle to control the ignition timing and burnt rate of HCCI combustion[48, 49, 50]. In EGR the exhaust gas is resent to the combustion chamber along with the charge, in order to control various aspect. The prime role of EGR on HCCI combustion engine had diverse effects on the combustion process and emission. Firstly preheating effect[51] in which it elevated the inlet charge temperature due to the hot EGR mixed with the air-fuel mixture. Secondly, dilution effect the commencement of EGR led to considerable reduction of the oxygen amount in the cylinder. Thirdly, heat capacity effect- the total heat capacity of mixture of EGR, air and fuel would be higher owing to the higher heat capacity of CO$_2$ and water vapour. This would lead to a reduction of gas degree of hotness at the terminal moment of compression stroke. Chemical effect yield of combustion in the EGR pass through the several chemical reaction. In the experimental study, EGR ratio was defined as the ratio of CO$_2$ concentration during inhalation of the gas into the cylinder to that exhalation [52]. It is as shown in figure.9.

EGR Ratio (r) = \( \frac{\text{CO}_2\text{\text{^{in}}}}{\text{CO}_2\text{\text{^{ex}}}} \times 100 \)

**Figure.9.** Effect of EGR on the maximum power output of HCCI-DI combustion. [51]
It was observed that combustion was delayed with increase in EGR and consequently thermal efficiency dropped. The composition of exhaust gas varies during transition of cycles and hence it makes it challenging to assess the response and eventually control. As there is less number of oxygen molecules available for combustion, HC and CO surge [52]. The implementation of higher EGR rates helps in expanding the heat holding capacity of the system due to curtailment of mass flow rate. Further fuel concentration in each cycle of combustion is brought down. Deprivation of engine is prevented as both temperature and pressure decline. Heat generated is absorbed by mixture of air, charge and exhaust, there is a lag in ignition of fuel [53].

Another way to control the charge temperature is by advancing or retarding the intake valve closing. This will reduce the effective compression ratio of the engine. The compression process begins when the piston has already started moving towards TDC. In case of advanced inlet valve controlling (IVC) it is somewhat more complicated. It happens in such a way that IVC occurs during the expansion stroke before the piston has reached the BDC where the combustion chamber volume is maximal. The disadvantage with controlling the effective compression ratio using VVA is that it is also reduces the effective displacement volume.

7.3. Fast Thermal Management

Fast thermal management as shown in figure.10, is an approach that aims to control the mixture temperature right away and thereby combustion phasing.

![Figure 10](image)

**Figure 10** Schematic of a fast thermal management system using heat exchangers and flow-rate control [8].

After the combustion of the mixture in the cylinder, high thermal energy is lost through the heated exhaust gases and coolant. To make use of thermal energy in the exhaust gases and coolant, couple of heat exchanger are utilized to warm up the intake air, as show in figure. One input airflow initially through a coolant air heat exchanger and then through an exhaust gas-air heat exchanger. Another intake air stream bypass the heat exchanger and remains unheated. Both air streams can enter the cylinder. Temperature depends on the mass flow rate of air. The temperature control valve controls the ratio of the two air stream rate. Fast thermal management relies on two temperatures, one heat and one cold, which helps in maintaining the control authority. Intake air is formed as a mixture of air from the cold source and the hot source. Two control valves are used at hot and cold source. By varying the control valves it is possible to achieve and control the temperature of charge.
7.4. Dual Fuel Control (DFC)
Auto ignition proceeds when the charge arrives the ignition temperature of the fuel. Combustion timing can be subjugated with the fuel composition, since the ignition temperature alters notably with the latter. Integration of dual port injection system in an engine decodes the problem of uncontrolled combustion. DFC strategy employs two sets of injectors; one that imparts fuel with low ignition temperature and the other injector set imparts fuel with high ignition temperature. Uncontrolled combustion can be pared down by utilizing DFC strategy where the ratio of fuel injection is varied.

7.5. Variable Compression Ratio (VCR)
Reduction in compression ratio of engine, delays the start of ignition, but if this is over done it leads to decrement in thermal efficiency. In order to obtain maximum brake torque in a HCCI combustion mode, inlet temperature must be devaluated and the compression ratio must be heightened. It was inferred that VCR dominates inlet heating. To expand the flexibility of HCCI engine VCR can be used as a tool, were the compression ratio is proliferated from 10:1 to 28:1 [8].

8. Future Research Direction
HCCI is seen as the holy grail of engine technology, but even this is far from perfection. Existence of incomplete progress opens up ocean of opportunities for the imminent researchers. Even if charge homogeneity is achieved there would be areas where local in-homogeneity prevails. Hence, isentropic turbulence is considered to be the upper limit of homogeneity and thus, it would galvanize future engineers to accomplish the same.

Chemical kinetics governs the operation and effectiveness of HCCI. Therefore it is expected to contemplate about the same in detail in order to aggregate information regarding different set of reactions that occur. Optical diagnosis is emerging as a prominent and reliable technique to decode the nature of reactions.

Several methods are being established and implemented in order to overcome the difficulties faced in HCCI. Though existing control strategies such as EGR are effective they are not satisfying the expectations, hence the onus is now on future controlling techniques possessing impeccable controlling capability. New control strategies such as Ion current sensing, use oxidizing species to control and initiate combustion which are more efficient and effective. Ion current signals are being used to detect the ignition timing in engines. Ionization occurs in two phases, first phase occurs when fuel reacts with oxygen, termed as chemical phase and in the second phase or the thermal phase, fuel which is away from spark plug is burnt due to compression. Voltage applied in cylinder using two electrodes in spark plug to produce current, as ionized gases in cylinder are good conductor. Parameters such as misfire, pre ignition and Trapped residual gas (TRG) levels are measured to determine and control the ignition timing [29].

Another method in order to control combustion is the use of oxidizing species such as peroxide, ozone, etc. which tends to promote combustion [30]. Combustion timing can be controlled by controlling the proportion of pure fuel along with modified fuel in HCCI engine. The use of electromagnetic field is also viewed as one of the controlling methods, the former works by varying the mode and frequency of the microwave which in turn controls the ignition to obtain optimum results. Though above methods seem to be promising their practicality is still being questioned, but researchers believe that there is a silver lining.
It is evident that there are numerous concepts of HCCI which researchers find hard to wrap their brains around, thus paving path for subsequent research.

9. Conclusion
HCCI engines were conceptualized few decades back in order to face the challenges posed by harmful emission from conventional engines. Moreover its ability to limit the harmful emission from engines as well as to retain the efficiency as that of conventional diesel engines is of great importance to the current scenario.

- It mainly operates on lean mixtures consequently eliminating the fuel rich zones that contribute to higher emissions. Performance characteristics such as low specific fuel consumption, lower emission levels as well as high power rating are its forte.
- Another benefit of HCCI engine is the ability to run on alternate fuels which make this concept attractive to many researches. Hence these engines also tackle the problem of depleting fossil fuel resources.
- In spite of these advantages HCCI engines face many limitations such as lack of ignition control, cold starting and low load carrying ability. Paring the limitations and successful commercial implementation has been the main focus of researchers all over the world.
- Though HCCI was a known technique since decades, it has gained prominence and attracted automobile organizations only in the recent past; this is due to lack of supporting electronics and software during the early stages. The concept of HCCI demands the involvement of various aspects such as electronics, software, materials, and hence, development of only one of these aspects is not sufficient for former’s implementation. In order to meet HCCI’s requirements, researchers have brought about tremendous changes in the above-mentioned entities.

Hence the implementation of diesel HCCI engines would subsequently have a satisfactory impact on the economy as well as the environment.

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11. References
[1] M.Furutani, Y. Ohta, K. Komatsu Onset behavior of low-temperature flames caused by piston compression, JSAE Rev, 14 (2) (1993), pp. 12-18
[2] Iida N. 1994 Combustion analysis of methanol-fueled active thermo-atmosphere combustion (ATAC) engine using a spectroscopic observation. SAE paper 940684;
[3] Aoyama T, Hattori Y, Mizuta J, Sato Y. 1996 An experimental study on premixed-charge compression ignition gasoline engine. SAE paper 960081;
[4] SaxenaS, SchneiderS, AcevesS, DibbleR. 2012 Wet ethanol in HCCI engines with exhaust heat recovery to improve the energy balance of ethanol fuels. Applied Energy;98:448–57.
[5] Pucher GR, Gardiner DP, Bardon MF, Battista V. 1996. Alternative combustion systems for piston engines involving homogeneous charge compression ignition concepts – a review of studies using methanol, gasoline and diesel fuel. SAE paper 962063;
[6] J. Kusaka, T. Yamamoto, Y. Daisho, *Simulating the homogeneous charge compression ignition process using a detailed kinetics model for n-heptane mixture*, Int J Engine Res, 1 (3) (2000), pp. 281-289

[7] C. Jin, Z. Zheng, Volume 2015 (2015) *A Review on Homogeneous Charge Compression Ignition and Low Temperature Combustion by Optical Diagnostics*. Journal of Chemistry, Article ID 910348

[8] Hua Zhao, *HCCI and CAI engines for the automotive industry*, Woodhead publishing

[9] T. Colliou, R. Tilagone and B. Martin, (2006) *Adapting the NADI Concept to Heavy Duty Engine, Oil & Gas Science and Technology – Rev. IFP*, Vol. 61, No. 1, pp. 73-84

[10] Alessio DULBECCO 2010 *Modeling of diesel hcci combustion and its impact on pollutant emissions applied to global engine system simulation*, PhD Thesis.

[11] Pravin Kumar, A. Rehman, *Homogeneous Charge Compression Ignition (HCCI) Combustion Engine - A Review*

[12] Panão MRO, Moreira 2007 ALN *Interpreting the influence of fuel spray impact on mixture preparation for HCCI combustion with port-- fuel injection*, Proc Combust Inst; 31:2205–13

[13] Tao Li, Kangyao Deng, Haiyong Peng, Chongmin Wu. 2013 *Effect of partial-heating of the intake port on the mixture preparation and combustion of the first cranking cycle during the cold-start stage of port fuel injection engine*, ExpTherm Fluid Sci; 49:14–21

[14] Srinivas Padala, Minh Khoi Le, Sanghoon Kook, Evatt R. Hawkes. 2013 *Imaging diagnostics of ethanol port fuel injection sprays for automobile engine applications*, ApplThermEng; 52:24–37

[15] Yanagihara, H. et al. 1996 *A simultaneous reduction of NOx and soot in diesel engines under a new combustion system (uniform bulky combustion system UNIBUS)*, 17th. Int. Vienna Motor Symposium.

[16] Yanagihara, H. 2001 *Ignition timing control at TOYOTA ‘UNIBUS’ Combustion System*, IFP International Congress, (Nov.-26–27)

[17] Hashizume T, Miyamoto T, Akagawa H, Tsujimura K. 1998 *Combustion and emission characteristics of multiple stagediesel combustion*, SAE paper no. 980505.

[18] Suzuki T, Kakegawa T, Hikino K, Obata A. 1997 *Development of diesel combustion for commercial vehicles*. SAE paper no. 972685;

[19] Y. Srinivas Padala, M. Khoi Le, S. Kook, E. Hawkes. 2013 *Imaging diagnostics of ethanol port fuel injection sprays for automobile engine applications*. Appl Therm Eng; 52: 24-37

[20] T. Colliou, R. Tilagone, B. Martin. (2006) *Adapting the NADI Concept to Heavy Duty Engine, Oil & Gas Science and Technology – Rev. IFP*, Vol. 61, No. 1, pp. 73-84

[21] T. Colliou, R. Tilagone, B. Martin. (2006) *Adapting the NADI Concept to Heavy Duty Engine, Oil & Gas Science and Technology – Rev. IFP*, Vol. 61, No. 1, pp. 73-84

[22] Y. Srinivas Padala, M. Khoi Le, S. Kook, E. Hawkes. 2013 *Imaging diagnostics of ethanol port fuel injection sprays for automobile engine applications*. Appl Therm Eng; 52: 24-37

[23] T. Colliou, R. Tilagone, B. Martin. (2006) *Adapting the NADI Concept to Heavy Duty Engine, Oil & Gas Science and Technology – Rev. IFP*, Vol. 61, No. 1, pp. 73-84

[24] Y. Srinivas Padala, M. Khoi Le, S. Kook, E. Hawkes. 2013 *Imaging diagnostics of ethanol port fuel injection sprays for automobile engine applications*. Appl Therm Eng; 52: 24-37
[26] Yao M, Zheng Z, Liu H. 2009 Progress and recent trends in homogeneous charge compression ignition HCCI engines. Progress in Energy and Combustion science; 35:398-437.

[27] US Department of Energy. A report to the U.S. Congress : 2001 Homogeneous charge compression ignition (HCCI) technology.;

[28] Lu XC, Chen W, Huang Z. 2005 Study on the ignition, combustion, and emissions of HCCI engines fuelled with primary reference fuels. Society of Automotive Engineers.; SAE2005-01-0155.

[29] Dimitris Panousakis, Andreas Gazis, Jill Patterson and Rui Chen, 2006 Using Ion-current Sensing to Interpret Gasoline HCCI Combustion Processes, Homogeneous Charge Compression Ignition (HCCI) Combustion (SP-2005), SAE TECHNICAL PAPER SERIES 2006-01-0024

[30] THESIS presented by: Jean-Baptiste MASURIER, Experimental study of the HCCI combustion through the use of minor oxidizing chemical species, University of Orléans

[31] M.F. Yao, Z.L. Zheng, 2006 Numerical study on the chemical reaction kinetics of n-heptane for HCCI combustion process Fuel, 85 (17–18), pp. 2605-2615

[32] Easley WL, Agarwal A, Lavoie GA. 2001 Modeling of HCCI combustion and emissions using detailed chemistry. SAE paper no. 2001-01-1029.

[33] S.C. Kong, Y. Ra, R.D. Reitz, 2005 Performance of multi-dimensional models for simulating diesel premixed charge compression ignition engine combustion using low and high-pressure injectors. Int J Engine Res, 6 (5), pp. 475-486

[34] M. Yao, Z. Zheng, H. Liu, 2009 Progress and recent trends in homogeneous charge compression ignition (HCCI) engines. Prog Energy Combust Sci, 35, pp. 398-437

[35] Green RM, Cernansky NP, Pitz WJ, Westbrook CK. 1987 The role of low temperature chemistry in the auto-ignition on n-butane. SAE paper 872108.

[36] Addargarla S, Henig Y, Wilk RD, Miller DL, Cernansky NP. 1989 Effect of fuel-air mixture stressing on pre-ignition heat release in a knock research engine. SAE paper 892082.

[37] Stanglmaier RH, Li J, Matthews RD. 1999 The effect of in-cylinder wall wetting location on the HC emissions from SI engines. SAE paper 1999-01-0502.

[38] Harada A, Shimazaki N, Sator S, Miyamoto T, Akagawa H, Tsujimura K. 1998 The effects of mixture formation on premixed lean diesel combustion. SAE paper 980533.

[39] Onishi S, Jo S, Shoda K, Jo P, Tada T. 1979 Active thermo-atmosphere combustion (ATAC) A new combustion process for internal combustion engines. SAE790501.

[40] Noguchi M, Tanaka Y, Tanaka T, Takeuchi Y. 1979 A study on gasoline engine combustion by observation of intermediate reactive products during combustion. SAE790840.

[41] Kitamura T, Ito T, Senda J, Fujimoto H. 2002 Mechanism of smokeless diesel combustion with oxygenated fuels based on the dependence of the equivalence ratio and temperature on soot particle formation. Int J Engine Res; 3:223-48.

[42] John E. Dec. 2009 Advanced compression-ignition engines understanding of the in-cylinder processes. Proceeding of the Combustion Institute; 32:2727-2742.

[43] Stanglmaier RH, Roberts CE. 1999 Homogeneous charge compression ignition (HCCI): benefits, compromises, and future engine applications. SAE paper 1999-01-3682.

[44] Dec JE. 2002 A computational study of the effects of low fuel loading. SAE paper 2002-01-1309;

[45] Eng J. 2002 Characterization of pressure waves in HCCI combustion. SAE paper 2002-01-2859.

[46] Yao M, Zheng Z, Liu H. 2009 Progress and recent trends in homogeneous charge compression ignition (HCCI) engines. Prog Energy Combust Sci; 35:398–437.

[47] DC John, Magnus S. 2004 Isolating the effects of fuel chemistry on combustion phasing in an HCCI engine SA 2004-01-0557.
[48] Au MY, Girard JW, Dibble, 2001 1.9-Liter four-cylinder HCCI engine operation with exhaust gas recirculation. SAE paper 2001-01-1894.

[49] Oakley A, Zhao H, Lodommatos N. 2001 Experimental Studies on Controlled auto-ignition (CAI) combustion of gasoline in a 4-stroke engine. SAE paper 2001-01-1030.

[50] Lu XC, Chen W, Huang Z. 2005 A fundamental study on the control of the HCCI combustion and emission by fuel design concept combined with controlled EGR. Part 2. Effect of operating conditions and EGR on HCCI combustion. Fuel; 84(9):1084-92.

[51] Wang Ying, He Li, Zhou Longboa, 2009 Study of HCCI-DI combustion and emission in a DME engine. Fuel 88 2255-2261.

[52] Gowthaman S, Sathiyagnanam A P, January-2015 A review of Homogeneous charge compression ignition (HCCI) engine. International journal of Scientific and Engineering Research, Volume 6, Issue.

[53] Thomas Johansson, November 2010 Turbocharged HCCI Engine improving efficiency and operating range. Media-Tryck, Lund.

[54] Pavan Prabhudev, Umesh S, M. R. Kamesh and D. Madhu, MARCH 2016 Attaining HCCI in a CI engine using fuel vaporizer. ARPN Journal of Engineering and Applied Sciences, VOL. 11, NO. 5.

[55] Gowthaman S and Sathiyagnanam A P, A Review on methods of homogeneous charge preparation for hcci mode engine, ISSN 2278 – 0149