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Innovative Approaches to Charge Preparation in HCCI Engines: A Detailed Review

Hemant A. Kinikar[1], Avinash P. Kaldate[2], Amarsingh B. Kanase-Patil[3]
Chetan. V. Papade[4]

1,2,3Department of Mechanical Engineering, Sinhgad College of Engineering,

Savitribai Phule Pune University, Pune-411041, India

[4]Department of Mechanical Engineering,

Nages Karajagi Orchid College of Engineering and Technology Solapur,

Dr. Babasaheb Ambedkar Technological University, Raigad, Maharashtra- 402103

[1]hakinikar@rediffmail.com *[2]er.avinashkaldate@gmail.com* *[3]amarbkanase@yahoo.co.in*
4cvpapade@gmail.com

[2]ORCID: 0000-0002-4836-5151 *[3]ORCID: 0000-0002-4836-3965* *[4]ORCID:0000-0003-2606-7353*

Abstract:- Homogeneous charge compression ignition (HCCI) engines are known for their low levels of harmful particles and gases, which reduce fuel consumption. These benefits are achieved due to the homogeneous mixture of air and fuel in the engine, which ensures efficient combustion of the fuel and produces fewer pollutants. However, to achieve this homogeneous mixture, it is necessary to implement new and at the same time accurate fuel-air mixture preparation methods. The efficiency and emission benefits of HCCI engines depend on how well the mixing technique is performed. Therefore, they need to be studied and improved. This article provides a detailed summary and analysis of the various methods of fuel-air mixture preparation used in different types of HCCI engines. These techniques include: injecting fuel before or after a certain time, mixing different types of fuel, reusing a portion of the exhaust gas to control combustion, and injecting fuel into the intake port. These types of strategies have been studied in detail, examining how evenly the fuel-air mixture is distributed, how consistent the combustion process is, what pollutants are produced and in what quantities, and how well the engine performs overall. When the fuel starts to burn and how quickly energy is released during the combustion process are also central to the study. How these methods affect key performance indicators, particularly the types and amounts of pollutants produced, is also examined. This review provides important insights into the progress, challenges, and ways to improve fuel mixture preparation methods for HCCI engines. The discussion also highlights new and creative solutions to address the problems of older methods. A roadmap is also suggested to enhance the fuel economy and pollution reduction capabilities of future HCCI engines. This insightful information contributes to efforts to ensure that these engine types become as efficient as possible for environmentally friendly and cost-effective energy use.

***Keywords**: Homogeneous charge compression ignition engine, Homogeneous charge preparation methods, Charge mixture homogeneity, Combustion mixture preparation*

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1 Introduction

After-treatment technologies such as catalytic converters and particulate filters have long been used to reduce emissions from engines. However, these technologies are expensive and add complexity to engine systems. To reduce or completely avoid dependence on such devices, improvements to the combustion process itself are needed. HCCI has emerged as a promising method that maintains or improves engine performance while achieving low emissions. The HCCI combustion process uniquely combines the advantages of com- pression ignition (CI) and spark ignition (SI) systems, providing a new approach to clean and efficient combustion [1].

HCCI combustion is based on the chemical process (chemical kinetics) and temper- ature development in the combustion chamber. One of its unique features is the rich fuel-air mixture, which produces soot-containing components. However, the beneficial mechanism is more capable of emitting incompletely burned hydrocarbons (HC) and car- bon monoxide (CO), which poses a problem for taking full advantage of HCI technology. Effective propellant—that is, the process of creating a homogeneous fuel-air mixture—is essential to overcome these and to maximize the efficiency of HCCI. Researchers have studied various propellant techniques. These include tractive direct injection, near-direct injection, multiple injections, and port fuel injection. Each of these techniques requires precise control of the fuel charge timing, pressure, and nozzle position signal parameters, which affect the mixture utilization and combustion properties [2].

Fuel properties, such as viscosity, latent heat of vaporization, and cetane number, sig- nificantly influence the charge preparation process. Fuels with high viscosity are generally more challenging to vaporize, affecting mixture uniformity and combustion efficiency. Re- search by Starck et al. (2010) [2] highlights that fuels with low cetane numbers and high volatility are particularly well-suited for HCCI operation, as they enhance evaporation and mixture formation. These fuel properties extend the operating range of HCCI engines by up to 30% without compromising performance compared to conventional CI engines. Understanding the interplay between fuel properties and charge preparation techniques is essential for developing fuels specifically tailored for HCCI applications [3]. Recent studies have further explored the use of various fuel blends, such as isopropanol-gasoline blends [4] and tamanu methyl ester [5], demonstrating their impact on HCCI combustion performance and emissions.

Recent advancements in charge preparation for HCCI engines focus on combining innovative techniques and advanced control strategies. For instance, advanced fuel in- jection systems with high-pressure capabilities enable better atomization and mixing of fuel. Additionally, variable valve timing (VVT) systems allow precise control of intake and exhaust flows, optimizing in-cylinder conditions for HCCI combustion. Exhaust gas recirculation (EGR) is

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another technique widely used in HCCI engines. By recirculating a portion of the exhaust gases back into the combustion chamber, EGR reduces combustion temperatures and NOx emissions while promoting mixture homogeneity. Researchers have also explored the use of alternative fuels, such as biofuels [6] and synthetic fuels, to enhance HCCI performance. These fuels often have properties that are more conducive to HCCI combustion, such as lower cetane numbers and higher volatility [7].

Despite its advantages, HCCI technology faces several challenges that need to be addressed to achieve widespread adoption. One of the primary challenges is controlling the combustion process, which is highly sensitive to operating conditions. Factors such as intake air temperature, fuel properties, and engine load significantly affect combustion timing and stability. Developing robust control strategies to manage these variables is critical for reliable HCCI operation. Additionally, while HCCI engines produce low NOx and soot emissions, HC and CO emissions remain relatively high. Advanced after- treatment systems still required to address these emissions, although their complexity and cost offset the benefits of HCCI technology. The discussion in this paper includes an evaluation of different injection methods, the role of fuel properties, and the impact of advanced control strategies on emissions and performance. These insights contribute to the ongoing efforts to optimize HCCI engine technology for sustainable and efficient energy solutions.

2 HCCI Engine Principle

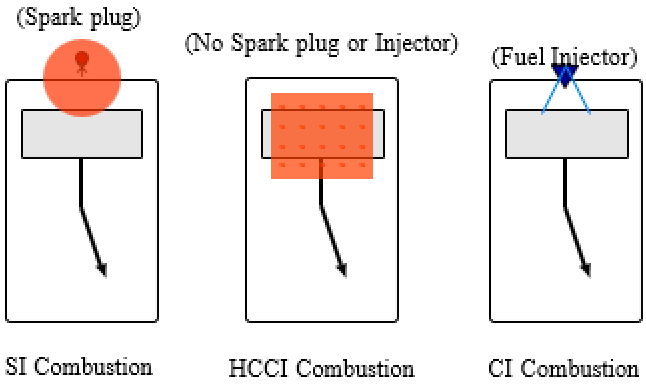

Figure 1: Differences in combustion between SI, HCCI, and CI

Fig. 1 shows the combustion chamber arrangements used for Spark Ignition (SI), Compression Ignition (CI), and HCCI engines. Unlike SI and CI engines, HCCI combustion operates without conventional control systems — such as spark ignition in SI engines or fuel injection timing in CI engines [8]. This unique process of HCCI combustion pro- vides an effective way to increase efficiency and reduce emissions in internal combustion engines,

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making it a promising alternative to conventional designs. Mathematical mod- els are essential for understanding and optimizing HCCI combustion. HCCI engines are successful in significantly reducing soot and nitrogen oxides (NOx) emissions, which are common problems in direct injection (DI) engines. This is possible by maintaining a homogeneous and lean air-fuel mixture, which makes combustion more uniform. Chemical kinetics models, such as the extended Zeldovich mechanism, are used to predict NOx formation. Also, hydrocarbon oxidation models are used to predict HC and CO emissions [9]. These models help researchers identify key factors influencing emissions and optimize engine parameters to balance efficiency and environmental compliance. Numerical investigations have also been conducted to study the combustion and performance indices of hydrogen driven HCCI engines [10].

The high thermal efficiency of HCCI engines is based on their ability to achieve high compression ratios and near constant volume combustion. Heat Release Rate (HRR) is a very important parameter, which is analyzed using zero-dimensional single-zone models. Despite these advantages, the implementation of HCCI technology poses several major challenges. The absence of direct ignition mechanisms makes combustion control more complex, requiring advanced control strategies such as Model Predictive Control (MPC). In MPC, timing and stability are optimized using real-time combustion data and predictive mathematical models. In addition, the Livengood-Wu integral is used to analyze ignition delays and understand their impact on combustion stability [1].

HCCI combustion is an innovative approach that balances high thermal efficiency and low emissions in internal combustion engine design. Mathematical model integration with thermodynamic models, chemical kinetics models, and control models is required to solve technical problems and improve engine performance. Ongoing research into effective thermal management in advanced charge preparation techniques and advanced after-treatment systems will be crucial to exploiting the full potential of HCCI technology. With the proper use of these tools, HCCI engines play a significant role in sustainable and energy-efficient transportation solutions [8]. HCCI engines face major challenges because they do not have a combustion control system (such as a spark plug or fuel injector), which is commonly used in spark ignition (SI) engines. The lack of such adirect control mechanism makes it very difficult to control the combustion phase in HCCI engines. Therefore, proper management and optimization of the combustion process becomes a major challenge in HCCI operations. In addition, the operational range of HCCI engines is also limited by certain phenomena e.g., knocking at high loads and misfiring at low loads. Under low-load conditions, a too lean mixture leads to misfiring, while under high-load conditions, the rapid heat release rate leads to knocking, which is a characteristic of the compression ignition process in HCCI combustion. These limitations prevent HCCI engines from operating effectively under a wide range of operating conditions and therefore their full potential cannot be utilized [11]. Natural gas-fueled HCCI engines have

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been analyzed and compared with SI and spark-assisted operations to understand their performance and emissions characteristics [12]. Advantages of HCCI Engines In a wider operational range, researchers have focused on increasing the limits of HCCI operations. Several innovative solutions have been proposed, including greater control of the air-fuel mixture, increasing combustion stability, and expanding the workable load range. In applications where high-engine output is required, high-performance SI and CI engines typically improve engine power by increasing the intake air pressure. Similar techniques are being applied to HCCI engines, addressing current operational constraints and bringing the full potential of HCCI combustion to bear [8].

3 Homogeneous Charge Preparation Strategies

The main challenge in HCCI combustion is to produce a homogeneous air-fuel mixture that self-ignites on compression and does not require a spark plug. The formulation of diesel fuel for such a mixture is inherently difficult due to its low volatility and high cetane number. For HCCI engine performance, it is necessary to achieve an optimal air fuel mixture that ensures smooth and stable combustion, while reducing pollutants such as NOx and soot. To overcome these challenges, it is necessary to use various innovative charge preparation techniques. These techniques can be broadly classified into two types those used inside the combustion chamber or those used outside [13].

Parameter	**Spark-Ignited (SI) [7], [14]**	**Diesel (CI) [7], [15]**	**Homogeneous Charge Compression Ignition (HCCI) [16]–[18]**
Fuel/Air Mixture Type	Premixed (Mathematical model: Stoichiometric ratio) $AFR_{stoich} = 1/\lambda$	Non-premixed (Mathematical model: Fuel-air mixing time) $\tau_{mixing} = L_{fuel}/u_{mixing}$	Premixed (Mathematical model: Lean mixture ratio) $\lambda_{HCCI} = Air_{mass}/Fuel_{mass}$
Ignition Type	Spark-Ignited (Model: Ignition delay time) $\tau_{ignition} = k_{ignition} \cdot T^{-1.5}$	Compression Ignited (Model: Compression ratio) $\tau_{ignition} = k_{ignition} \cdot CR \cdot T_{in}^{-1.3}$	Compression Ignited (Model: Compression ratio and temperature distribution) $\tau_{ignition} = k_{ignition} \cdot CR \cdot T_{in}^{-1.3}$

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Power Output Control	Airflow control with stoichiometric air-fuel ratio (Model: Air-fuel ratio variation) $P = \eta \cdot m_{air} \cdot (h_{exhaust} - h_{intake})$	Fuel flow control with lean air-fuel ratio (Model: Air-fuel ratio dynamics) $\lambda_t = m_{air(t)} / m_{fuel(t)}$	Fuel flow control with lean air-fuel ratio (Model: Fuel rate adjustment and combustion efficiency) $\lambda_t = m_{fuel(t)} / m_{air(t)}$
Mechanism Controlling Fuel Burning Rate	Flame propagation speed (Model: Combustion front velocity) $v_{flame} = S_f \cdot T_{intake} / T_{exhaust}$	Time for fuel vaporization and mixing (Model: Evaporation rate and mixing rate) $R_{vap} = D_{vapor} / L_{fuel} \cdot P/T$	Chemical kinetics (Model: Chemical reaction rates and energy release) $r_{chem} = k_{chem} \cdot Fuel^n \cdot O^m_2$
Emission Characteristics	Cleaner with 3-way catalytic. Higher CO_2 (Model: Emission prediction based on fuel and air ratio) $CO_2 = a \cdot AFR + b$	Higher particulate matter, soot, NOx (without after treatment), Lower CO_2 (Model: Soot formation and NOx prediction) $Soot = k_{soot} \cdot Fuel \cdot O_2 \cdot e^{-T_{in}/T_{crit}}$	Higher unburned hydrocarbons, CO. Lower NOx, soot, particulates, and CO_2 (Model: Emission reduction through uniform charge preparation) $NOx = k_{NOx} \cdot e^{-(T_{max}-T_{in})^2}$

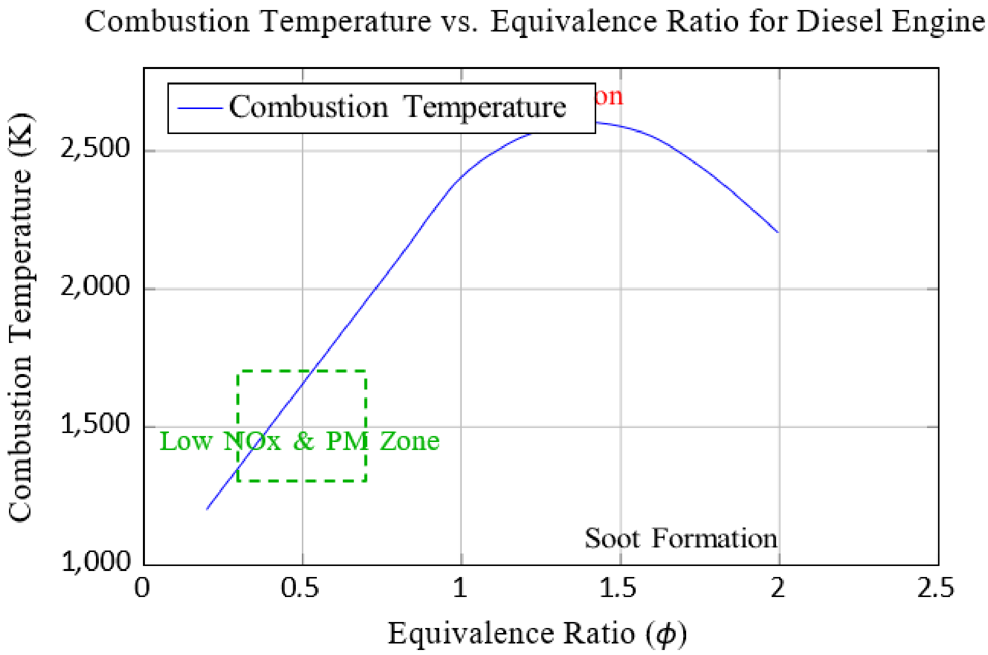

Figure 2: Combustion temperature vs. equivalence ratio for diesel engine

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3.1 Premixed/Direct-Injection HCCI Combustion

The Homogeneous Charge Diesel Combustion (HCDC) technique, one of the early methods aimed at achieving homogeneous charge in HCCI combustion [19]. In this energy, a portion of the fuel is injected into the intake port, forming an air-fuel mixture. This mixture is then drawn into the cylinder, where it undergoes compression and ignites (spontaneous ignition). The remaining fuel is injected into the cylinder during the compression stroke, reducing additional exhaust emissions. This dual-injection strategy greatly reduces soot NOx emissions, which are usually serious in diesel engines. By forming a mixed charge with part of the fuel, the HCDC technique aims to achieve better control over the combustion process and improve fuel efficiency [18].

The introduction of a premixed combustion strategy in diesel engines is a major solution to the HCCI combustion problem creating a uniform mixture of particulate fuel and air. Port injection is used for some types of fuels, while conventional fuel injection creates a uniform air-fuel mixture. However, this method does not eliminate all the problems associated with HCCI combustion, such as high-load conditions, instability in the overall combustion process, and false knocking or misfires [13].

Further research by Berntsson and Denbratt (2007) [1] use of port injection for the main fuel supply was investigated. An orbital injector, which was developed as an airassisted, spray-guided direct injection device, was used to create a stratified charge in the combustion chamber. This stratification creates a leaner mixture near the cylinder walls and higher temperatures in the center of the combustion chamber, which reduces combustion efficiency. Charge stratification allows for higher hydrocarbon (HC) emissions under certain operating conditions, but also increases CO (carbon monoxide) and HC emissions. Despite these difficulties, research has found that stratification can be useful in managing HCCI combustion under certain engine operating conditions.

Although the stratified charge approach is advantageous in some respects, it also has some significant disadvantages. Leaner mixture near the cylinder wall leads to incomplete combustion, and the resulting emissions are detrimental to engine performance and fuel economy. However, the ability to phase the injection system provides flexibility, allowing for better control of HC emissions and combustion stability during operation. This study demonstrated that a very fine balance of charge preparation techniques is required to maintain the balance between emissions and performance in HCCI engines [17].

3.2 Late Direct Injection HCCI

Late direct injection (LDI) is a technology used in HCCI engines to gain more control over the combustion process. The main feature of LDI is the timing of fuel injection, which is delayed, i.e., later in the compression stroke. The purpose of this method is to allow sufficient time for

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air-fuel mixing before ignition. The principle of late injection is that if fuel is injected late during the compression stroke, compression heat can be utilized properly, and at the same time early ignition can be avoided, which reduces the possibility of knocking.

Nissan Motor Company introduced the modulated kinetics (MK) piston structure, which operates on the late injection principle. According to Kimura et al. (2001) [20], MK combustion process extends the HCCI operating range to high load conditions, where the fuel injection timing is delayed from 7° BTDC (Before Top Dead Center) to 3° ATDC (After Top Dead Center). In addition, a high level of EGR (Exhaust Gas Recirculation) is used to reduce the oxygen concentration in the combustion chamber. EGR is used to increase the ignition delay period, which is essential for controlling the timing of auto- ignition and improving the stability of the combustion process.

A major challenge in LDI systems is that the injection timing and the use of EGR (Exhaust Gas Recirculation) must be controlled very carefully, otherwise problems such as incomplete combustion and high emissions can occur. In the MK system, fuel-air mixing in the combustion chamber is improved by using high-pressure injection and reverse squish flow. The straight toroidal combustion chamber with a large bore-to- diameter ratio results in better mixing. The second-generation MK system incorporated a common rail injection system, which made variable injection pressure possible. This provides more precise control over the injection process and allows for better efficiency and higher pressure injection even at low engine speeds. The results of these efforts were impressive, with NOx reduction rates exceeding 98%, compared to conventional systems that only achieved 90-92% reduction [21].

Although the MK system has shown promising results in terms of emissions reduction, it still has some limitations. Lowering the compression ratio for the MK combustion process negatively impacts fuel economy and increases HC emissions. In addition, the efficiency of the MK system remains limited under high-load conditions, as achieving optimal air-fuel mixing and avoiding knocking or misfiring is still a challenge.

3.3 Early Direct Injection HCCI

Early Direct Injection (EDI) is a strategy that attempts to create an air-fuel mixture during the compression stroke, with the aim of reducing problems such as wall wetting and oil dilution. By injecting fuel early in the cycle, the fuel is properly vaporized before the compression stroke begins. It is mixed with air, which reduces the likelihood of incomplete combustion and increases overall efficiency. However, this approach has its own challenges. In particular, the risk of wall wetting and increased HC emissions.

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Kim et al. (2007) [17] showed in their study that early direct injection (DI) in HCCI combustion causes wall wetting, which significantly affects combustion efficiency. Since the fuel adheres to the cylinder walls, it evaporates slowly and does not mix well with the air, resulting in high HC emissions and smoke. This leads to poor combustion and inefficient operation, especially at low engine loads. Also, early fuel injection leads to poor control over the combustion phase, especially the start of combustion (SOC), because the ignition timing cannot be predicted with high accuracy. For this reason, early DI injection in HCCI engines generally increases CO and HC emissions and reduces overall engine performance.

The main problem with early DI injection is that it is difficult to precisely control the fuel-air mixture formed during compression. Improper mixture preparation leads to inefficient combustion and increased emissions. Despite these difficulties, early DI injection is still a subject of active research. Research efforts are focused on improving the accuracy of fuel injection and achieving better control over combustion timing. [18].

3.3.1 PREmixed lean Diesel Combustion (PREDIC)

Premixed lean diesel combustion (PREDIC) is a method that attempts to address DI injection early, while also aiming to reduce emissions and improve fuel efficiency. PREDIC uses port fuel injection, which increases CO and HC emissions compared to conventional diesel combustion scenarios. These emissions are due to under-combustion and over-advanced combustion phases, structure formation, incomplete combustion, and high pollutant levels [22].

The problem of wall wetting, which is caused by fuel injection occurring too early, before Top Dead Center (TDC), is reduced by changing the injection parameters. Air density and cylinder temperatures are reduced, which reduces the likelihood of wall wetting. In addition, the PREDIC system uses three injectors—one in the center and two on either side—and each injector has independent control of the fuel quantity. This method prevents fuel from accumulating on the cylinder walls, because the fuel is directed to the center of the combustion chamber, where the streams from all the injectors converge [23]. To improve the PREDIC system, the nozzle size of the central injector has been reduced from 0.17 mm to 0.08 mm. This makes fuel atomization more effective and fuel delivery better. As a result, the engine runs more efficiently under the PREDIC regime. This makes it possible to experiment with different fuel blends, cetane ratings, intake temperatures and compression ratios. Such adjustments allow the combustion process to be optimized more precisely. This ultimately improves engine performance and helps reduce emissions [24].

The Multiple Stage Diesel Combustion (MULDIC) system represents an innovative approach to charge preparation that focuses on improving combustion efficiency and reducing emissions. This system introduced by Hashizume et al. (1998) [25], employs a unique combination of injectors and strategies to optimize the combustion process. The schematic representation of

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the MULDIC system is shown in Fig. 3, illustrating the components involved in the operation of this system [26].

3.3.2 Multiple Stage Diesel Combustion System (MULDIC)

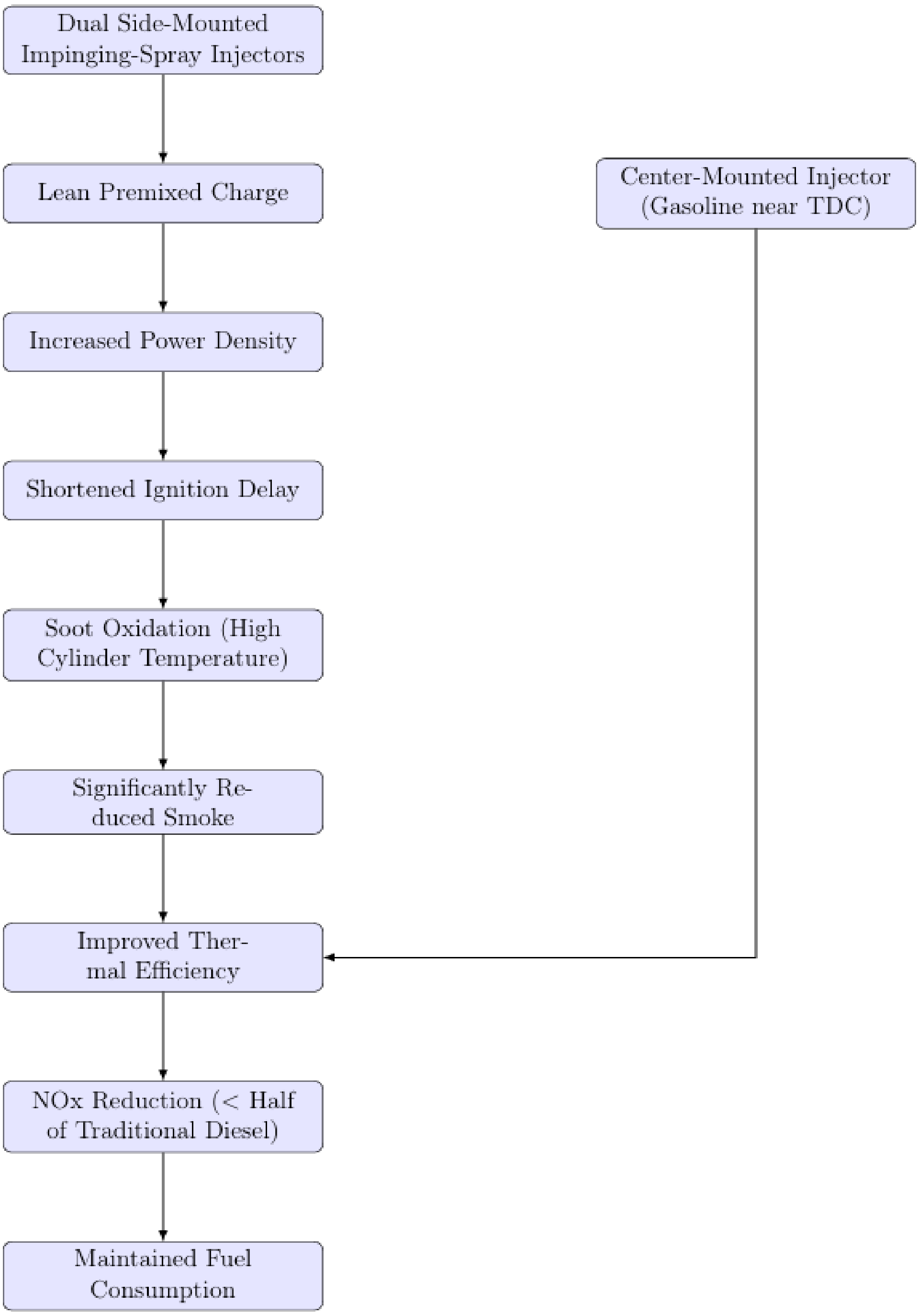

Figure 3: Schematic diagram of MULDIC system

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The MULDIC system uses two side-mounted impinging-spray injectors to create a lean premixed charge. The main purpose of these injectors is to prepare the air-fuel mixture properly and create a homogeneous mixture in the combustion chamber. This increases the power density of the engine, which is useful for increasing efficiency. In addition to the side injectors, a center-mounted injector is used to inject additional gasoline near top dead center (TDC). This additional injection is important for further improving the combustion process and increasing fuel efficiency [27].

One of the main advantages of the MULDIC system is that it is able to reduce the ignition delay. This makes combustion more efficient and initially a more soot-luminous flame is observed. This flame does not last long, because the high temperatures generated during combustion oxidize most of the soot. As a result, the smoke produced during MULDIC combustion is greatly reduced and the engine runs cleaner. Thermal efficiency is also an area where MULDIC has shown significant improvement. By optimizing the first stage of combustion, the level of constant volume combustion increases. This reduces heat dissipation and leads to higher energy extraction. This improved combustion strategy reduces NOx emissions. Compared to conventional diesel combustion, the MULDIC system emits less than half of NOx. While doing all this, fuel consumption remains the same as before [27].

Further improvements to the MULDIC system could potentially reduce NOx emissions even further. The second stage of combustion, where there is a higher fuel content (fuel- rich condition), is useful for reducing NOx. The remaining gasoline injected near TDC begins to oxidize as the cylinder temperature drops. This oxidation process contributes to the reduction of NOx and improves combustion efficiency. Thus, the MULDIC system is an innovative charge preparation method, especially for HCCI engines. This system combines modern injector technology with properly planned combustion stages. As a result, higher thermal efficiency, lower emissions, and better fuel economy are achieved.

3.3.3 Uniform Bulky Combustion System (UNIBUS)

Uniform Bulky Combustion System (UNIBUS) is an innovative technique for improving charge preparation and combustion in HCCI engines. Yanagihara, Sato, and Mizuta (1997) [28] combined pintle-type injector nozzles and mechanical feed pumps with piezo- actuator injectors to control fuel distribution. An obstacle was placed at the tip of the injection nozzle to reduce the spray velocity and improve fuel-air mixing. The entire setup was designed to produce a uniform and homogeneous fuel mixture well before the start of combustion (SOC). Compared to the conventional Compression Ignition (CI) technique, UNIBUS provides a well-prepared mixture well before SOC, which makes a significant difference in the diesel combustion process. This method significantly reduces harmful emissions such as NOx and soot. UNIBUS combustion has low flame luminosity and low combustion field temperature, which contribute to reduced emissions. Research has shown that soot emissions are completely eliminated and NOx remains at only 1/100 of conventional diesel combustion. However, this system is only effective at low engine loads, which limits its use in high load conditions. These limited results are due to the fact that the UNIBUS system relies on precise temperature and mixture control. Nevertheless, the UNIBUS system indicates a promising direction for improving the efficiency of HCCI engines by prioritizing emission reduction and mixture uniformity. This system represents an important step in the development of innovative charge preparation methods.

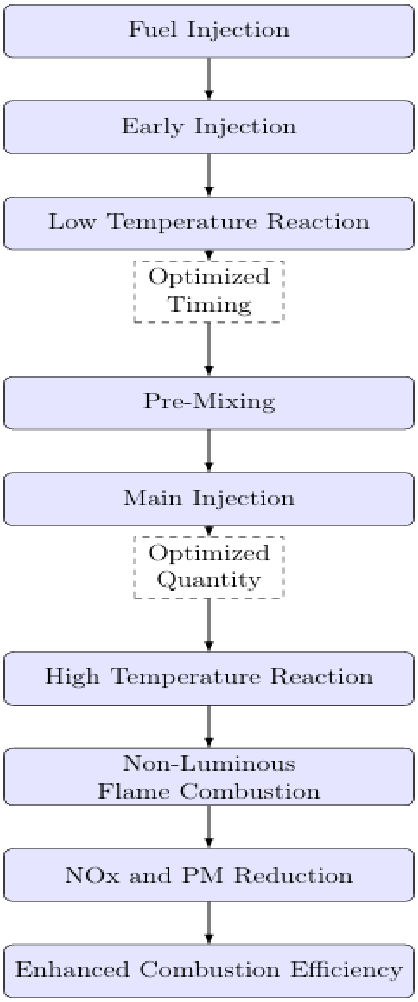

Figure 4: UNIBUS combustion - fuel injection diagram

As shown in Fig. 4, the Uniform Bulky Combustion System (UNIBUS) process shows a planned flow, the main objective of which is to achieve efficient and clean combustion in HCCI engines. The process begins with fuel injection, in which an early injection is given initially so

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that the chemical reactions start at a low temperature.This early injection keeps the combustion temperature low, causing a controlled chemical reaction. This is followed by pre-mixing of fuel and air, which creates a homogeneous mixture and prepares the charge for the subsequent main injection. The main injection starts combustion at a high temperature, in which a non-luminous flame is produced and thus the risk of soot formation is reduced. Both the correct timing for pre-mixing and the precise control of the injection quantity are important for increasing combustion stability. Ultimately, this significantly reduces NOx and particulate matter (PM) levels and improves combustion efficiency. This entire process demonstrates the effectiveness of the UNIBUS system, as it simultaneously reduces emissions and maintains engine performance [29].

3.3.4 Multi-Injection and BUMP Combustion Chamber (MULINBUMP)

The Multi-Injection and BUMP Combustion Chamber (MULINBUMP) system, proposed by Su, Lin, and Pei [18], represents a significant advance in charge preparation technology for HCCI engines.This system combines lean diffusion combustion and premixed combustion. Multiple short-duration injection pulses are used for premixing, as shown in Fig.5. To avoid wall wetting caused by these short pulses, the penetration of the spray is limited. After this, the main injection pulse is delivered near Top Dead Center (TDC), which is similar to the operation of a conventional diesel engine.

The BUMP combustion chamber uses flash mixing technology, which improves the air-fuel mixing rate and operates more efficiently than conventional Direct Injection (DI) engines. This improved mixing facilitates lean diffusion combustion and reduces emissions. Multi-pulse injection timing advance reduces auto-ignition noise, while over-mixing reduces NOx emissions but increases unburned hydrocarbons (HC).To balance this, it is necessary to provide the right pre-injection amount, so that NOx is reduced and smoke emissions are not increased. These techniques achieve controlled heat release and precise auto-ignition, especially during multi-pulse injection.

MULINBUMP technology shows good performance under various load conditions. At low loads, multiple injections keep NOx and particulate matter (PM) emissions below 10 ppm. For medium loads, a combination of premixed combustion and lean diffusion combustion is used, with high injection pressure and a high mixing-rate combustion chamber, which achieves fast and efficient air-fuel mixing. At full load conditions, multi- pulse injection enables clean and high-efficiency combustion, and an Indicated Mean Effective Pressure (IMEP) of up to 0.93 MPa can be achieved. This system increases the efficiency of HCCI engines and keeps emissions low, greatly expanding the overall operating range.

3.3.5 Narrow Angle Diesel Injection (NADI)

Duret et al. (2004) [7] and Kim and Lee (2007) [17] have reported that when the injection timing is advanced early in a Narrow Angle Diesel Injection (NADI) system, the possibility of fuel deposition on the cylinder wall and piston head increases. To overcome this problem, they used injector nozzles with narrow spray cone angles of 156° and 60°, respectively. To allow for the formation of pre-mixture due to early injection, the com- pression ratio was reduced from 17.8:1 to 15:1. Experiments showed that if the injection timing was advanced more than 20° before top dead center (BTDC), the Indicated Mean Effective Pressure (IMEP) and indicated specific fuel consumption (ISFC) were significantly reduced. Interestingly, if the injection timing is advanced further, i.e. to 30°–50° BTDC, the IMEP is halved. This clearly shows that engine performance is very sensitive to injection timing.

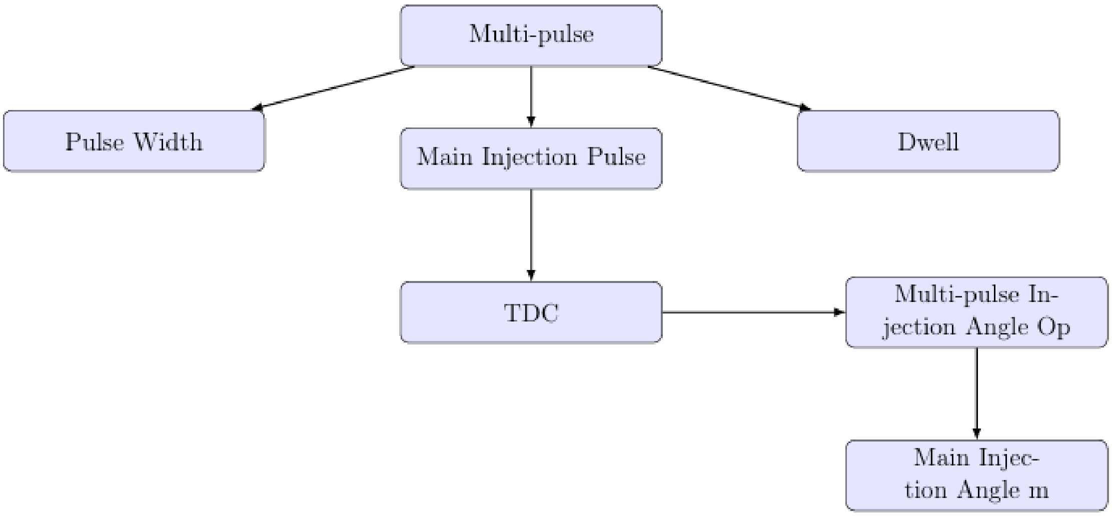

Figure 5: Multi-pulse Injection of MULINBUMP

In NADI systems, early injection of fuel is used to support HCCI combustion. How- ever, if the injection is done too early, fuel evaporation does not occur effectively and the spray does not align properly in the piston bowl. This error results in a weak fuel-air mixture outside the combustion chamber, which negatively affects combustion efficiency. Also, the combustion process is advanced too far, which increases the negative work during the compression stroke, which reduces the overall efficiency of the engine.Early injection in HCCI engines is a major problem, as hydrocarbon (HC) and carbon monoxide (CO) emissions increase significantly. The main reason for these emissions is low thermal efficiency and a large amount of incomplete combustion. Although the injection timing was advanced to 50°–60° before top dead center (BTDC) in the NADI configuration, only a slight improvement in IMEP was observed, even

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when compared to ISFC. This shows that it is difficult to achieve the right balance between early injection and combustion efficiency in HCCI conditions. The NADI system is able to maintain high ISFC and IMEP even during early fuel injection, while significantly reducing particulate matter (PM) and NOx emissions. This technology offers the benefits of HCCI combustion at partial load and conventional diesel combustion at full load.

This dual-mode operation meets the performance requirements of direct-injection (DI) diesel engines, and also significantly reduces emissions, making this system suitable for future engines. However, problems such as wall wetting and out-of-bowl injection remain when using early fuel injection for HCCI, which reduce combustion efficiency. Improvements in spray targeting and injector design are needed to overcome these problems. As research progresses, the NADI system can be made more suitable for HCCI engines by further fine-tuning the injection timing and spray angle properties, so as to balance efficiency, fuel economy, and low emissions.

4 Use of Inert Gases

To improve the efficiency of HCCI engines, Canakci conducted research using a variable compression ratio engine [13]. Their experiments showed that the thermal efficiency increased by about 6%, which is a significant improvement. At the same time, the emissions of carbon monoxide (CO) and hydrocarbons (HC) also decreased by about 6%, which proved that optimizing the combustion process can be beneficial in HCCI engines. This study investigated the use of CO as a thermal buffer. In the conventional method, nitrogen (N2) is used as a thermal buffer. However, Duret et al. [7] investigated the possibility of using CO instead of N for HCCI mode in a variable compression ratio engine. The aim of this approach was to see if using CO gave the same or better results as N and reduced emissions. The experiments showed that the engine operated successfully when CO was used as a thermal buffer. This change has shown promise in improving some engine performance and emissions control. However, the study revealed a significant limitation—the thermal efficiency was reduced when CO was used instead of N. This suggests that while CO offers some advantages, it is not a complete replacement for N in terms of efficiency. The use of such inert gases in HCCI engines has both advantages and limitations. Duret et al.'s research demonstrates that it is essential to strike a balance between efficiency improvement and emissions reduction when considering thermal buffers. These findings provide important insights into innovative charge preparation methods that could be useful for future HCCI technology development.

5 Conclusion

Charge preparation in HCCI engines plays a crucial role in efficient combustion and emission control. This process is mainly divided into two types—external charge preparation (via port or manifold injection) and internal charge preparation (via direct injection). Port fuel injection

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produces a homogeneous charge, which helps in reducing NOx emissions. However, wall wetting, misfire, and increased HC and CO emissions are its main disadvantages. On the other hand, direct injection in the combustion chamber provides more precise control over charge formation. Based on injection timing, direct injection is divided into two types—early and late injection. Various innovative concepts of early direct injection have been developed such as PCCI, CAI, MULINBUMP, UNIBUS, and MULDIC. All these concepts focus on creating a homogeneous charge, when single or multiple injection pulses and advance injector designs are used. These methods significantly reduce NOx and particulate matter (PM) emissions, but at the same time, wall wetting and HC emissions remain problematic. The NADI concept, due to its special piston geometry, represents a different approach to HCCI combustion optimization. Late direct injection strategies, such as those used in the Nissan-MK combustion chamber, reduce NOx emissions by using short injection duration and high EGR levels. However, these methods require a reduction in compression ratio and management of HC emissions. Currently, experiments are underway to replace nitrogen from the intake air with inert gases such as Argon and CO2, which represent a new way to improve engine performance. According to preliminary studies, Argon is a more effective alternative to N2, which represents a new and promising direction. In conclusion, various innovative charge preparation approaches for HCCI engines have significantly improved combustion efficiency and emissions control. However, the remaining challenges of wall wetting, HC emissions and proper optimization of inert gas use still need to be addressed so that further development of HCCI technology effectively achieved.

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