International Journal on Applications in Mechanical and Production Engineering

Volume 2: Issue 6: July 2016, pp 4-10. www.aetsjournal.com ISSN (Online) : 2395-3500

A Novel Charge Compression Ignition IC Engine Model

Kumar
Selection grade lecturer
Department of Mechanical Engineering
MEI Evening Polytechnic, Rajaji Nagar, Bangalore 560010
kumar.gavi@gmail.com

Hucheerappa H
Selection grade lecturer
Department of Mechanical Engineering
MEI Evening Polytechnic, Rajaji Nagar, Bangalore 560010
hucheer_kwt@yahoo.com

Abstract - *Internal combustion engine development that prioritises environmental sustainability and complies with strict emission requirements is becoming more and more important. Current engine research is focused on achieving these objectives, highlighting the importance of creating engines that are fuel-efficient and ecologically beneficial. It is recognised that combustion with controlled combustion ignition (CCI) can result in very low emissions and high efficiency. Compression-Ignition Direct-Injection (CCI) engines, also referred to as diesel engines, are more efficient than CCI engines at the same time that they produce incredibly low emissions of nitrogen oxides (NOx) and particulate matter (PM). CCI engines run on petrol, diesel and alternative fuels, demonstrating their adaptability. When compared to traditional Spark-Ignition (SI) petrol engines and CIDI engines used in transportation vehicles, this technology is a significant breakthrough. Advantageous elements from SI and CIDI engines are combined in CCI engines. Like SI engines, CCI engines have a well-mixed charge that lowers particle emissions. Like CIDI engines, CCI engines are highly efficient and ignite through compression without throttling losses. CCI engines, in contrast to conventional engines, have simultaneous combustion occurring across the cylinder volume as opposed to in a flame front. This paper offers a thorough analysis of CCI engine technology, stressing both its benefits and drawbacks. It also gives a summary of current developments and issues that have been experienced in this area.*

Keywords: *CIDI (compression-ignition direct-injection), controlled combustion ignition (CCI)*

I. Introduction

Even with the abundance of tools and methods developed specifically for the manufacturing sector, real-world difficulties arise when trying to simulate intricate operational procedures or make adjustments to settings that already exist. Simulation shows itself as a useful technique to save needless costs and give advance insight into the possible efficacy of systems. Bennett describes simulation as "a technique or a set of techniques whereby the development of models helps one to understand the behaviour of a system, real or hypothetical." Simulation is a commonly used tool for possibility exploration, system behaviour evaluation through external and internal changes, and support for process optimisation and organisational improvements.

Simulation provides a number of advantages, including the ability to analyse manufacturing processes without interfering with the actual system, the avoidance of the high implementation costs, the facilitation of training and learning opportunities, the validation of analytical solutions derived from mathematical models, the resolution of questions regarding the causes and mechanisms of phenomena, and the evaluation of the effects of minor modifications on the manufacturing system as a whole. Production efficiency can be increased by effective simulation, giving businesses where production planning and implementation are strategically important a major competitive edge. Reliability of input data and appropriate variable analysis are prerequisites for the accuracy of information produced by simulation models. Additionally, accurately analysing output data requires a solid grasp of statistics. Because high-speed computers are becoming more accessible and affordable, optimisation algorithms are becoming more and more prevalent in engineering applications. When solving engineering challenges, these algorithms are frequently employed to maximise or minimise particular objectives. In chemical engineering, examples include developing mechanical components to achieve either minimum manufacturing cost or highest production rate, and in aeronautical engineering, minimising overall weight through optimal process plant design or operation. Optimising an existing process that satisfies all imposed limits and constraints while meeting specified goals is the ultimate goal of optimisation; this process is known as the optimum process.

Speed, feed, and depth of cut are a few examples of machining factors that are crucial in forming the workpiece. These variables have a big influence on the machining process, therefore it's crucial to optimise them to get the results you want. Traditionally, the choice of machining parameters has been made based on the knowledge of planners or machinists, who frequently use accessible handbooks and catalogues. However, because planners differ in their expertise and judgement, manual selection presents difficulties. When production incorporates expensive Numerical Control (NC) machines, there is an increased focus on making the most use of these resources by selecting the right machining parameters. Modern enterprises use both NC and conventional machines, thus it becomes necessary to have automated processes to choose the best machining parameters. When selecting machining parameters automatically, computer-aided processes have shown to be dependable in terms of speed, accuracy, and consistency when compared to human approaches. For a given operation, the best machining settings can be found using a variety of optimisation approaches. A CNC simulation programme called MASTERCAM makes it easier to simulate machining parts on a computer before they are really cut. This allows for the removal of mistakes that could endanger the part, break cutting tools, damage fixtures, or cause machine crashes. Furthermore, MASTERCAM ensures error-free and effective programmes by optimising the cutting process. The identification of collisions and near-misses between all machine tool components—such as axis slides, heads, turrets, rotary tables, spindles, tool changers, fixtures, workpieces, and cutting tools—depends heavily on Machine Simulation in MASTERCAM. Establishing "near-miss zones" around components allows users to look for near misses and identify over-travel issues. By lowering the possibility of machine crashes—which can be costly and interfere with production schedules—this feature provides an effective means of preventing errors and validating programmes.

II. Charge Ignition

Advanced engine technologies are the subject of intensive research and development (R&D) initiatives in Europe and Japan, with significant contributions from the public and private sectors. Two engines that use novel techniques at particular stages of operation are currently being produced in Japan. Honda makes a 2-stroke cycle gasoline motorbike engine, while Nissan makes a light truck engine that runs on diesel fuel intermittently.

It is shown how crucial these developments are to attaining high efficiency and low emissions, and how they may be used with a variety of fuels and car kinds. Although these combustion techniques have great potential, there are many obstacles that must be overcome before they can be widely used and produced in large quantities. Controlling ignition timing and burn rate at various engine speeds and loads, increasing the operating range to high engine loads, handling cold starts and transient responses, and reducing emissions of hydrocarbons and carbon monoxide are some of the major technical obstacles. Realizing the full potential of these cutting-edge technology requires overcoming these obstacles.

Managing the timing of ignition and rate of burn across a broad spectrum of speeds and loads is recognized as an especially intricate challenge. Many control strategies are suggested, including variable compression ratio (VCR), variable valve timing (VVT), and exhaust gas recirculation (EGR) correction. Although VCR and VVT technologies appear promising, more research needs to be done on their dependability, affordability, and performance. Although these engines operate well at low to medium loads, problems occur when the load is large because of the quick and intense combustion processes that can cause noise, damage to the engine, and increased NOx emissions. Studies indicate that strategies such as partial charge stratification can be used to increase the working range at high loads. Stratification can be accomplished by adjusting mixing procedures, adding water or fuel in the cylinder, changing in-cylinder flows, and more. This makes cold starts difficult because of the basic combustion processes. Glow plugs, other fuels, a higher compression ratio using VCR or VVT, and even spark ignition are some of the suggested cold-starting techniques. Spark-ignition, however, might bring extra expenses and complications. These engines produce relatively high emissions of carbon monoxide (CO) and hydrocarbons (HC), but moderate emissions of NOx and PM.

At low loads, techniques like direct in-cylinder fuel injection can reduce engine-out HC and CO emissions; nonetheless, exhaust emission control systems are probably required to regulate these emissions efficiently. For this, a well-proven technique in gasoline-powered cars for the removal of HC and CO catalysts may be used. It is thought to be easier to control HC and CO emissions than other pollutants.

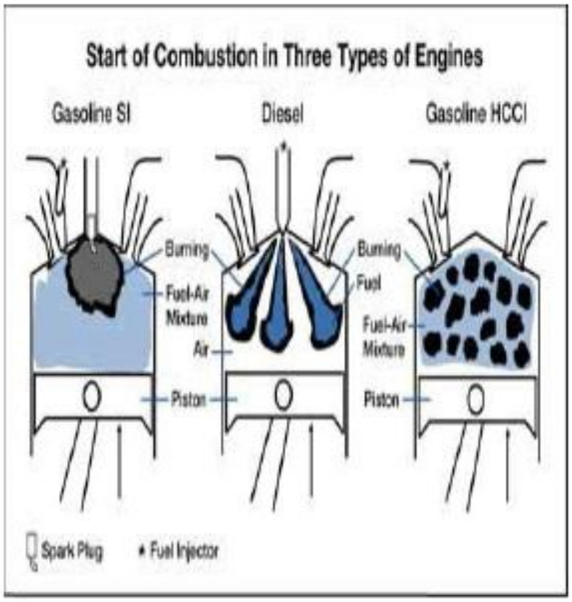

Figure 1. Charge Ignition

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III. Charge Compression Ignition

CCI is an alternative piston-engine combustion process that can provide efficiencies as high as compression-ignition, direct-injection (CIDI) engines, unlike CIDI engines, producing ultra-low oxides of nitrogen (NOx) and particulate matter (PM) emissions. CCI engines operate on the principle of having a dilute, premixed charge that reacts and burns volumetrically throughout the cylinder as it is compressed by the piston. In some regards, CCI incorporates the best features of both spark ignition (SI) and compression ignition (CI), as shown in Figure 1.

As in an SI engine, the charge is mixed, minimizing particulate emissions, and as in a CIDI engine, the charge is compression ignited, eliminating throttling losses and leading to high efficiency. However, unlike either of these conventional engines, the combustion occurs simultaneously throughout the volume rather than in a flame front. This important attribute of CCI allows combustion to occur at much lower temperatures, dramatically reducing engine-out emissions of NOx.

Most engines employing CCI to date have dual-mode combustion systems in which traditional SI or CI combustion is used for operating conditions where CCI operation is more difficult. Typically, the engine is cold-started as an SI or CI engine, then switched to CCI mode for idle and low- to mid-load operation to obtain the benefits of CCI in this regime, which comprises a large portion of typical automotive driving cycles. For high-load operation, the engine would again be switched to SI or CI operation. Research efforts are underway to extend the range of CCI operation.

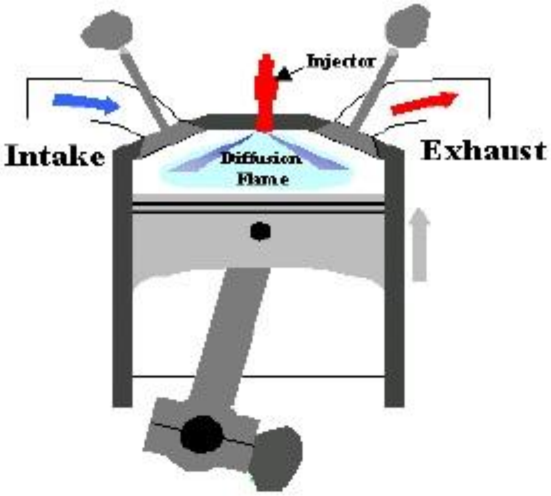

Figure 2. CIDI

IV. Advances in CCI

Numerous benefits of CCI vary depending on the combustion method that it is contrasted with. CCI gasoline engines are more efficient than SI engines; they are almost as efficient as a CIDI engine.

Three factors contribute to this increased efficiency: the removal of throttling losses; the use of high compression ratios (as in a CIDI engine); and a shorter combustion period (since a flame does not need to spread across the cylinder). In comparison to SI engines, CCI engines have less engine-out NOx. While three-way catalysts are sufficient to remove NOx from the exhaust of SI engines running on current technology, low NOx technology offers a significant advantage over spark-ignition, direct-injection (SIDI) technology, which is being explored for SI engines operating on future technology. CCI engines have significantly lower PM and NOx emissions than CIDI engines. (Extensive present research is focused on emissions of PM and NOx, which are the main obstacles to CIDI engines satisfying future emissions limits.) In addition to low combustion temperatures, diluted homogenous air and fuel mixture contribute to low PM and NOx emissions in CCI engines. In a CCI engine, the charge can be diluted by using exhaust gas recirculation (EGR), stratification, being extremely lean, or a combination of these methods. Flame propagation is not necessary, hence dilution levels can be far greater than what SI or CIDI engines will handle. Once the 800 to 1100 K ignition temperature is attained (depending on the kind of fuel), combustion will occur in nearly any fuel/air/exhaust-gas mixture. Combustion is induced throughout the charge volume by compression heating caused by the piston action. On the other hand, the minimum flame temperatures in conventional CI engines range from 1900 to 2100 K, which is high enough to produce NOx levels that are intolerable. Furthermore, because the CCI engine's combustion duration is not constrained by the rate of fuel/air mixing, it is substantially shorter than that of CIDI engines. Because of its shorter combustion period, the CCI engine has a performance advantage. Lastly, because CCI engines are probably going to use lower-pressure fuel injection, they might be less expensive than CIDI engines.

The fuel flexibility of CCI combustion is an additional benefit. Numerous fuels have been demonstrated to operate with CCI. Particularly well suited for CCI operation is gasoline. With gasoline's low cetane number, on the other hand, highly efficient CIDI engines cannot run on it. It is possible that the commercialization of CCI engines in light-duty passenger cars might save up to 500,000 barrels of oil per day. Additionally, tests have demonstrated that, in ideal circumstances, CCI combustion can be highly repeatable, leading to seamless engine functioning. Compared to SI or CIDI engines, the emission control systems for CCI engines may be less expensive and reliant on rare precious metals. Engines in cars and large trucks may both benefit from CCI. It could actually be adjusted to fit almost any size class of transportation engine, from big ship engines to tiny motorcycles. Piston engines used for applications other than transportation, like pipeline pumping and the production of electricity, are also covered by CCI.

a)TROUBLES

By regulating the air/fuel mixture's temperature, pressure, and composition to cause it to autoignite close to top dead center (TDC) while the piston compresses it, CCI combustion is accomplished. Compared to SI and CIDI engines, which use direct control mechanisms like fuel injectors or spark plugs to regulate ignition timing, this style of ignition is essentially more difficult. Although CCI has been around for almost 20 years, CCI combustion has not been given any consideration for use in commercial engines until the development of electronic engine controls. Nevertheless, a number of technological obstacles need to be removed before CCI engines can be produced in large quantities and used in a variety of automobiles. The more important obstacles to creating workable CCI engines for transportation are outlined below. This section goes into more detail about these technological obstacles, possible fixes, and the R&D required to get over them.

As previously said, some of these problems might be reduced or even avoided if the CCI engine was applied in a series hybrid-electric system.

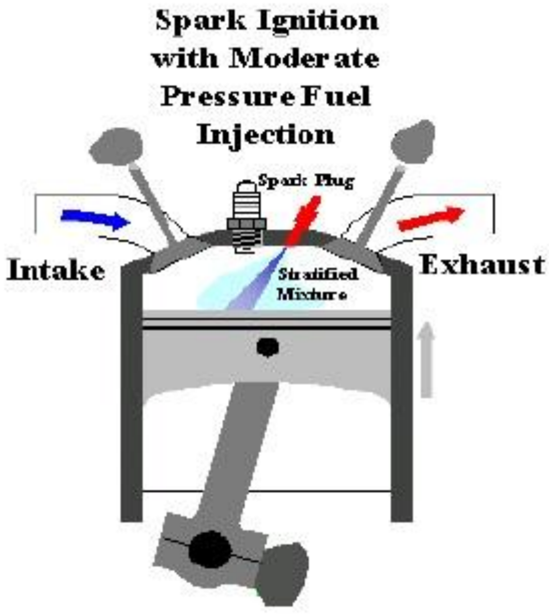

Figure 3. SIDI

V. Controlling Technique

A major difficulty is to extend the regulated operation of a CCI engine over a wide range of loads and speeds. The charge mixture's composition and temperature history (and to a lesser extent, pressure history) affect CCI ignition. A CCI engine's power output can only be adjusted by varying the fueling rate, which in turn modifies the charge mixture to preserve the engine's ideal combustion timing. Similar to this, changes in engine speed impact the amount of time autoignition chemistry has in relation to piston motion, necessitating modifications to the temperature history of the mixture. These control problems get very complicated with fast transients.

To account for variations in load and speed, a number of possible control strategies have been proposed. The most promising ones include adjusting the quantity of hot Exhaust Gas Recirculation (EGR) that is added to the incoming charge, adjusting temperatures close to Top Dead Center (TDC) with a Variable Compression Ratio (VCR) mechanism, and adjusting the effective compression ratio and/or amount of hot residual that is held in the cylinder with Variable Valve Timing (VVT). The ability to handle rapid transients with a fast time response makes VCR and VVT very appealing. These methods have a lot of promise, but they haven't been well tested yet, so it's critical to solve issues with cost and dependability.

For CCI engines, increasing the operating range to high loads is a significant problem. Although they have proven to operate effectively at low-to-medium loads, problems occur at high loads when combustion can become intense and quick, resulting in problems including excessive NOx emissions, noise, and possible engine damage.

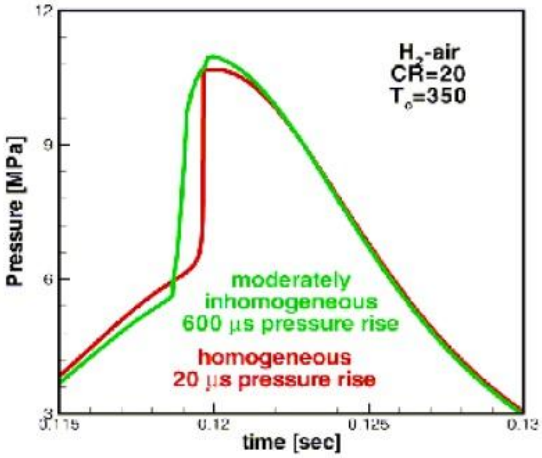

Figure 4: Pressure Traces

According to preliminary study, the working range may be increased by changing the heat-release event during high loads by partially stratifying the charge. Partial charge stratification can be accomplished by a number of methods, such as water injection, in-cylinder fuel injection, altering intake and in-cylinder mixing procedures, and changing cylinder flows.

Further investigation through research and development activities is necessary to determine the extent to which these strategies can extend the operational range. Due to the difficulties associated with high-load operation, early ideas frequently call for switching to conventional SI or CI combustion in situations where CCI operation is more difficult. This adds complexity but still offers the advantages of CCI for a sizable portion of the driving cycle.

VI. Genetic Design

A thorough literature search on global CCI-related R&D has been conducted. A review of current advancements in CCI technology can be seen in Table 1. In addition, CCI combustion research has been carried out by Ford, GM, and Cummins Engine Company.Ford Motor Company is actively researching CCI combustion. To do this, the company uses optical diagnostics in single-cylinder engines to test various CCI operating regimes and combustion control techniques. Chemical kinetic and cycle simulation models are also being used by researchers to investigate potential applications of CCI technology and to improve our understanding of its foundations. GM is investigating the possibility of integrating CCI combustion into engine systems. Developing suitable modelling tools, figuring out the best way to integrate CCI combustion into a workable powertrain, and evaluating the advantages and disadvantages of CCI operation in comparison to other cutting-edge concepts are all part of this assessment process. Fuels, combustion modelling, and the shift from compression ignition (CI) to spark ignition (SI) or traditional spark ignition (SI) combustion are the main areas of concentration for GM's research. University-level CCI research is also backed by GM.

Cummins has spent almost a decade studying CCI. Internally operated industrial engines that burn natural gas with CCI have demonstrated outstanding efficiency and emission outcomes. However, taking into account differences in ambient conditions, fuel quality, speed, and load, Cummins encounters difficulties in managing combustion phasing over a real-world operating range.

As part of its design palette and future engine strategy, Cummins is investigating a number of solutions, including CCI, as the new diesel emissions goals exceed the capacity of traditional diesel engines.

VII. Conclusion

For light-duty cars, a high-efficiency gasoline-fueled CCI engine is a major leap over SIDI engines. With no major influence on fuel-refining capability and without posing major issues related to NOx and PM emission management, CCI engines have the potential to match or even exceed the efficiency of diesel-fueled CIDI engines. Furthermore, because CCI engines most likely employ lower-pressure fuel injection, they should be more affordable than CIDI engines. The way that CCI burns may also make it possible to use emission control technologies that use fewer expensive and rare precious metals. Furthermore, the creation of the diesel-powered CCI engine is noteworthy since it provides a different approach for heavy-duty vehicles.

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