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HOMOGENEOUS CHARGE COMPRESSION IGNITION (HCCI) - A NEW TECHNOLOGY TO REDUCE POLLUTANTS IN GASOLINE INJECTED ENGINES

R. R. Saraf*, S. S. Thipse and P. K. Saxena**
Department of Mechanical Engineering, MNIT, Jaipur-302 017, Rajasthan, India
**ARAI, Pune, Maharashtra, India
*Current Address: Department of Mechanical Engineering, Government Polytechnic, Pune, India

ABSTRACT

Homogeneous charge compression ignition (HCCI), also called as controlled auto ignition combustion (CAI), is recent combustion technology which has caught attention of automotive manufacturers all over world because of its ability to eliminate NOx and particulate emissions. HCCI combines advantages of both spark ignition and compression ignition engines. This paper focuses on current research work on HCCI direct and port fuel injected gasoline engines. It contains basic comparison between performance of gasoline injected engines and carburetted engines. This comparison is related to parameters like power output, fuel consumption, brake thermal efficiency and emissions. Paper also contains information about HCCI combustion and its merits.

INTRODUCTION

Electronic gasoline fuel injection system is a new technology used in gasoline engines. Gasoline injection systems give better fuel economy and reduce emissions due to improved combustion performance. Main advantages of electronic gasoline injection systems over carburetted engines are:

- Better fuel economy and reduced specific fuel consumption.
- Increased power output and cleaner exhausts.
- Simple in construction and operation.
- Increase in volumetric efficiency.
- Faster acceleration due to atomized fuel supplied directly at intake valve in PFI system.
- Optimal combustion of precise measured quantity of fuel.
- Higher torque obtained at low engine speed.
- Performance of cold start, acceleration and warm up operations improved.
- Exact metering of the fuel under all operating conditions of engine possible.
- Electronic fuel injection can fulfil stringent requirements of lower exhaust gas emissions, lower fuel consumption, better drivability and improved performance.

Direct injection

Gasoline direct injection engines (GDI) can meet the demand of higher power output with fuel economy in engines. Gasoline direct injection was first used in 1937 in aeroplane engine. In 1952 it was used for the first time in passenger car. Nowadays gasoline direct engines are rediscovered by researchers. In GDI engines air is sucked only during suction stroke through open inlet valve in engine cylinder. Fuel is injected inside cylinder by injector at high pressure, where air fuel mixture is formed and then it is ignited. Fuel is injected at a pressure of about 5-12 MPa, which is supplied by high-pressure pump. High-pressure injectors are installed on rail and inject fuel directly into combustion chamber when signalled by engine ECU.

Port fuel injection

Stringent emission norms for pollutants produced by engine combustion such as unburnt hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NOx), mainly in heavy traffic areas of metro cities, have given rise to technological evolution of carburettor. Due to legal pressures of emission of pollutants, automobile manufacturers are looking for more technologically advanced fuel system with improved quality and standard. In view of this, electronic fuel injection systems have been recently developed. Port fuel injection system is one such type of electronic fuel injection system.

Need of replacing carburettor with alternative system was originated because construction of carburettor became more and more complicated as it required to satisfy all functional requirements.

Catalytic converter was introduced to meet stringent pollution norms. In order to achieve effective functioning of catalytic converter accurate control of air fuel ratio is required. In electronically controlled engines oxygen sensor is used which monitors the amount of oxygen in the exhaust and electronic control module (ECM) receives this information from oxygen sensor. It uses this information to adjust air fuel ratio by deciding duration of opening of injector. This is called as closed loop control. This accurate control can not be achieved by carburettor alone. Therefore, initially carburettors were replaced by throttle body fuel injection (TBI) system which is also called as single point or central fuel injection system. In this system one or two fuel injectors are located above throttle valves and fuel injector sprays fuel in the air above throttle valve.

Gradually as new engines were designed, throttle body injection system was replaced by port fuel injection (PFI) system or multiport fuel injection MPFI system. It is also called as multipoint or sequential fuel injection. In these systems fuel injector is used for each cylinder, located in such a manner that it sprays fuel exactly near intake valve. In port fuel injection a fuel injector in each intake port sprays fuel into the intake air just before it passes the open intake valve and enters the cylinder. Port or multiport injection system provides more accurate control of air fuel ratio than throttle body injection (Juttu et al. 2007).

Table 1 shows comparison of gasoline injection mode and carburation mode for power output, fuel consumption and brake thermal efficiency. Table 2 shows comparison of gasoline injection mode and carburation mode for emissions.

Concept of HCCI combustion

In HCCI combustion, fuel and air are mixed before starting of combustion and this mixture is auto ignited due to increase in temperature from compression stroke. Thus, HCCI is similar to SI engine because both the engines use premixed charge (Fig. 1), as well as it is also similar to CI engine because both have auto ignition.

HCCI or CAI combustion is achieved by controlling the temperature, pressure and composition of the fuel and air mixture so that it spontaneously ignites in engine. HCCI combustion takes place spontaneously and homogeneously without flame propagation. This eliminates heterogeneous air fuel mixture regions. It has multiple ignition points through the chamber. Due to this and as HCCI is a lean combustion process, formation of nitrogen oxides is prevented. In this type of combustion

Table 1: Comparison of gasoline injection mode and carburation mode for power, fuel consumption and brake thermal efficiency..

Mode of operation	Power in KW				Fuel Consumption kg/hr				Brake thermal efficiency %			
	13% T.O.	25% T.O.	38% T.O.	50% T.O.	13% T.O.	25% T.O.	38% T.O.	50% T.O.	13% T.O.	25% T.O.	38% T.O.	50% T.O.
Injection mode	0.94	2.81	4.24	4.70	0.90	1.07	1.30	1.40	8.53	21.69	26.82	27.56
Carburation mode	0.07	2.28	3.13	4.20	1.72	2.03	2.20	2.08	0.32	9.21	11.67	16.59

T.O. (Throttle opening)

Table 2: Comparison of gasoline injection mode and carburation mode for emissions.

Mode of operation	CO Emissions in %				Hydrocarbon emissions				Emission index			
	0.125% Th	0.25% Th	0.375% Th	0.5% Th	0.2% Th	0.25% Th	0.375% Th	0.5% Th	0.2% Th	0.25% Th	0.375% Th	0.5% Th
Injection mode	2.38	0.08	0.06	0.05	712	83	61	58	53.21	5.84	4.63	4.52
Carburation mode	8.09	9.82	6.89	3.3	904	350	145	89	48.78	16.23	6.59	4.23

Th (Throttle)

very lean or diluted mixtures can be burnt which results in low temperatures that reduce engine NOx emissions. Combustible charge is premixed like SI engine, hence it does not produce particulate emissions. Part load fuel economy is also improved, as there is no throttling losses. CAI or HCCI combustion can be achieved by trapping residuals with early exhaust valve closure in port fuel injected four stroke gasoline engines. Injection timing is very important in this case as it affects air fuel mixing in cylinder and temperature of mixture, which ultimately affects CAI combustion and engine performance. Unlike traditional SI or CI engine, HCCI combustion takes place spontaneously and homogeneously without flame propagation. This eliminates heterogeneous air fuel mixture regions. Exhaust gas recirculation can be used to control and improve performance of HCCI engine.

HCCI combustion is characterized by local chemical kinetic reaction rates with no necessity of flame propagation. If exact homogeneous mixture is achieved at the time of combustion, HCCI combustion is not affected much by turbulence. HCCI ignition is controlled by hydrogen peroxide

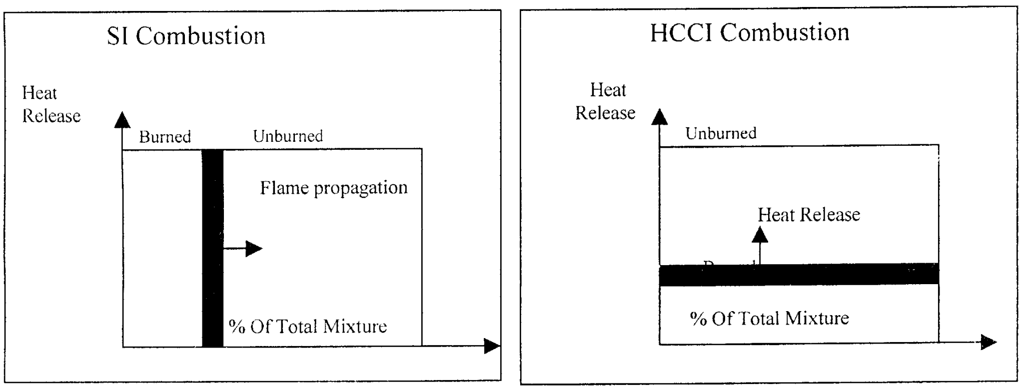

Fig. 1: Principles of SI and HCCI combustions.

(H_2O_2) decomposition. Hydrogen peroxide decomposes into two OH radicals, which burn the fuel and release energy. Decomposition of hydrogen peroxide occurs at a temperature range between 1050 and 1100 K.

Advantages of HCCI engine

- HCCI engines have potential to give high thermal efficiency and low NOx and PM emissions.
- HCCI technology can be applied to both light and heavy-duty engines. It can be used for any size or class of engine from small two wheeler engines to large ship engines. They can also be used for series hybrid vehicles.
- HCCI engines have benefits like use of high compression ratios, shorter combustion duration, lean operation, and no throttling losses, which makes them more efficient than SI gasoline engines. HCCI combustion is closer to ideal Otto cycle than spark ignition combustion.
- HCCI operation can be used for wide range of fuels like gasoline, diesel, propane natural gas, biofuels and hydrogen.
- HCCI engines combine benefits of SI and CI engines.

Limitations of HCCI engine

- HCCI engines produce comparatively more precatalyst carbon monoxide and hydrocarbon emissions.
- HCCI engines are characterized by high peak pressures and higher heat release rate.
- It is difficult to control ignition timing and combustion over wide range of engine speeds and loads.
- HCCI engines have difficulty in cold starting operation and transient operation.
- HCCI engines can function satisfactorily at medium and low loads, but can't function satisfactorily at high loads.

R & D need in HCCI operation

In order to achieve successful HCCI operation, certain barriers must be overcome. Following problems and difficulties must be solved in order to develop practical HCCI engine for transportation application.

Hydrocarbon and Carbon monoxide emissions: HCCI engines produce low NOx and PM emissions but produce relatively high carbon monoxide and hydrocarbons. These emissions can be reduced by proper exhaust emission control device. In order to meet future emission standards for HC and CO, proper catalytic converter having oxidation catalysts for low temperature exhaust should be developed.

Control on ignition timing and combustion for wide range of speeds and loads: It is difficult to have HCCI operation over wide range of speeds and loads. At high power operation of HCCI engine, fuel supply is increased and hence mixture composition is changed, accordingly auto ignition process and temperature should be adjusted to control ignition and combustion timing and operation. Similarly, when engine speed changes, auto ignition process and temperature should be adjusted accordingly. This control becomes important at rapid transient operations. Some methods have been proposed to control ignition and combustion timing in HCCI engine. One of them is to change the proportion of hot exhaust gas recirculation (EGR) introduced in incoming charge. This can be achieved by using variable compression ratio (VCR) mechanism which alters top dead centre temperatures and by using variable valve timing (VVT) which alters effective compression ratio and amount of hot residual retained in cylinder.

HCCI operation at high loads: HCCI operation at high loads becomes difficult because at high loads combustion becomes rapid and may cause noise, engine damage and more NOx emissions. HCCI operation can be extended to higher loads by stratification of charge. Methods used for charge stratification are varying fuel injection, injecting water and changing intake and cylinder mixing processes. More research is required in this area.

Cold starting operation: At cold start in HCCI engine, compressed charge temperature is reduced and hence engine may not fire. Different methods to cold start HCCI engine have been proposed such as use of glow plug, using fuel additives and increasing compression ratio by using VCR or VVT. Another approach used is to start engine in spark ignition mode and switch over to HCCI mode after warm-up.

Proposed methods for HCCI engine control

Variable compression ratio (VCR): HCCI combustion strongly depends on compression ratio of engine. In VCR engine compression ratio can be adjusted according to change in operating conditions. As operating conditions change rapidly in engine operation, VCR system should be able to modify compression ratio in fractions of second. As VCR system is capable of controlling HCCI ignition timing to optimize combustion process, a VCR system with fast response time is good alternative for controlling HCCI operation at different loads and speeds. Various methods to achieve variable compression ratio are:

- By mounting plunger in cylinder head whose position can be varied to change compression ratio. Plunger is controlled by hydraulic system which changes its position during engine operation.
- By using opposed piston engine design and by providing variable phase shifting between two crankshafts.
- By using method which has been recently announced based on hinged tilting cylinder arrangement.
- By using mechanism in which distance between cylinder head and crankshaft is varied.

By using additives: HCCI engine control can be achieved by using two fuels with different octane ratings. The system can be designed to have a main fuel with high octane number, and secondary fuel with low octane number is injected as per requirement to advance combustion. This procedure has been recently studied for a combination of methane and dimethyl ether. Ozone can also be added to intake to achieve improvement in HCCI ignition, which advances combustion at very low concentrations.

Variable valve timing: In this method temperature and composition of incoming charge can be changed by trapping residual gases from previous cycle in cylinder. Temperature and charge mixture can be adjusted by varying amount of hot residual gases. Temperature of charge is increased so that HCCI combustion can commence at low geometric ratios and under cold engine conditions. VVT can be used to change the trapped compression ratio or amount of compression after the gases are trapped by intake valve closure. Thus VVT can achieve a similar effect on HCCI combustion as varying geometric compression ratio of engine. VVT system in engine uses mechanical, magnetic or hydraulic valve actuators.

Electro hydraulic VVT system has also been tried by researchers at Stanford University. It has been also shown that VVT system can be used to control combustion timing and to change between SI and HCCI operation from one cycle to next cycle.

Exhaust gas recirculation: HCCI combustion can be controlled by controlling the temperature, pressure and composition of mixture at the start of compression stroke. In this method thermal energy from exhaust gas recirculation (EGR) and compression work from supercharger are either recycled or rejected to obtain satisfactory combustion. This method is simple and does not require major engine modifications. Drawback of this system is that it is slow to react to rapidly changing conditions.

Thermal control: HCCI combustion can be controlled by controlling temperature, pressure and composition of mixture at the beginning of compression stroke. In this method thermal energy is either recycled or rejected to obtain satisfactory combustion. This method is simple and does not require engine modifications or fuel additives.

Fuels used in HCCI combustion: Different fuels have been tried for HCCI combustion. Fuels with any octane or cetane number can be burned in HCCI operation. Main fuels which are used for HCCI operation are diesel, gasoline, propane and natural gas. Gasoline with high octane number enables use of high compression ratio in HCCI engines. Compression ratio should be very low to use diesel in HCCI combustion. HCCI engine with propane gives high efficiency as propane has high octane number. Propane is gaseous fuel and can be easily mixed with air. HCCI engine with natural gas as fuel can be operated at high compression ratios, which results in high efficiency. It is associated with high cylinder pressures.

CONCLUSION

As it is difficult to meet stringent pollution norms with carburetted engines, port fuel and direct injection engines are need of the hour for automobile industry. HCCI combustion produces lower NOx and PM emissions but has more CO and HC emissions. In the present scenario reduction of hydrocarbons and CO emissions and obtaining precise control on HCCI combustion are major challenges to researchers. Suitable catalytic converter need to be designed and developed for emission reductions and suitable control strategy for combustion in HCCI engine need to be developed. HCCI engines can be good alternative to achieve future emission norms like EURO-IV and EURO-V if HC and CO emissions are reduced after treatment. Difficulties in HCCI operation like control on ignition and combustion, operation at different loads and speeds, cold starting operation, reducing hydrocarbons and carbon monoxide emissions, and transient operation can be solved by using methods like variable compression ratio, variable valve timing, exhaust gas recirculation and use of fuel additives.

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