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HCCI/CAI ENGINES

Stringent emission standards and the need to reduce greenhouse gas, CO_2 emissions from vehicles has led to intensive research on new combustion systems namely, the *homogeneous charge compression ignition* (HCCI) or *controlled autoignition* (CAI) engines. These combustion concepts have the following features;

- HCCI/CAI involves autoignition of very lean homogeneous mixtures of fuel and air so that the combustion temperatures are low.
- Due to low combustion temperatures NO_x formation is negligibly small. NO_x formation is two orders of magnitude lower than those from the current SI and CI engines
- Very little soot is formed as the homogeneous charge is burnt.
- High fuel efficiencies similar to DI diesel engines can be obtained as very lean mixtures are burned.

The first attempts to utilize HCCI/CAI combustion were made to control irregular and misfiring combustion in 2-stroke SI engines at light loads by Japanese researchers during late 1970s. Autoignition of the homogeneous charge was obtained by retaining large amounts of hot residual gas containing partially oxidized hydrocarbons and active chemical species in the cylinder. Honda motors applied this form of combustion on a motorcycle engine prototype during mid-1990s, which was termed as 'Active Radical Combustion (ARC)'. Fuel economy improvements of about 30% and HC reduction of 50% were obtained compared to normal 2-stroke engine operation. The autoignition of lean homogeneous charge has been called by a variety of names such as Active Thermo Atmosphere Combustion (ATAC), Premixed Charge Compression Ignition (PCCI), Premixed Lean Diesel Combustion (PREDIC), Active Radical Combustion (ARC), Controlled Autoignition (CAI), Homogeneous Charge Compression Ignition (HCCI) etc.

HCCI v/s CAI

Application of autoignition of lean homogeneous charge has been studied in the conventional gasoline as well as diesel engines. The processes adopted to auto-ignite homogeneous charge and the objectives of its application to SI and CI engines are some what different

In the gasoline engines, external heating of intake charge or use of hot residual gas has been employed to cause controlled autoignition of high octane gasoline or natural gas –air mixtures. Therefore, the auto-ignited combustion process when applied to gasoline engines has been termed as controlled autoignition (CAI). The main objective of CAI application to the gasoline engines is reduction in fuel consumption and NO_x emissions.

In the conventional diesel engines, the fuel air mixture is heterogeneous and compression of air to high temperature is used to auto-ignite diesel fuel. The diesel fuel has low self-ignition temperature. In application of this concept to diesel engines, the main approach is to premix as much fuel as possible before autoignition without encountering negative effects of auto ignition on combustion parameters and emissions. Autoignition may be caused by other forms of heating of fuel-air mixture in addition to compression heating. This process when applied to diesel engines is usually called as homogeneous charge compression ignition (HCCI). The main objective of HCCI application in the diesel engines is to reduce NO_x and particulate emissions.

It may be noted that fundamentally the HCCI and CAI processes are the same.

Basics of HCCUI/CAI Process

Control of emissions of nitrogen oxides and soot from the IC engines has proven to be most difficult. The origin of NO_x and soot during combustion conditions are shown on a Fuel- Air Equivalence Ratio – Temperature (ϕ–T) plot on Fig 7.5. This plot is based on calculations done for n- hydrocarbon and air combustion. In CI engine, the combustion conditions in terms of equivalence ratio and combustion temperature vary across the combustion chamber and also vary with respect to time. Regions of SI and CI engine combustion are identified on this plot and discussed as below:

Conventional SI engine combustion takes place in a premixed homogeneous charge with ϕ around 1 and is shown in the right hand bottom corner. A point is shown for stoichiometric homogeneous SI engine combustion. The combustion temperatures here are in the range of 2400 to 3000 K. NO formation is a function of oxygen content and temperature of the burned gases. NO concentration is shown qualitatively by the density of dotted points and is maximum at higher temperatures for slightly leaner than stoichiometric mixtures. At a given temperature, NO reduces for the further lean mixtures and for the rich mixtures with ϕ > 1.8 NO is negligible even at the high combustion temperatures.

The region of conventional diesel combustion is shown by a cluster of circular points on this plot. These points refer to local mixture conditions and not the overall fuel-air ratio. The conditions show formation of high concentrations of either soot or NO_x locally in CI engine combustion. During combustion of spray, in the core region ϕ > 3 and combustion temperatures are in the range 1800 to 2400K. This is the region of soot formation. Concentration of soot increases as ϕincreases at a given temperature of combustion. Here any hardly NO formation is expected. At the spray boundary, fuel burns as lean premixed charge or in near stoichiometric conditions as diffusion flame, which is shown by the cluster of points on the left side of SI combustion region. These ϕ and T conditions belong to NO formation in CI engine. Here, no soot but high NO_x is formed.

The region of desired HCCI/CAI operation is shown in the lower left corner on this plot which would result in low NO_x as well low soot formation. Here mixture is much leaner than ϕ =1and the combustion temperatures are lower than 1900 C. This is the combustion region which is being created in the combustion chamber for implementation of HCCI concept.

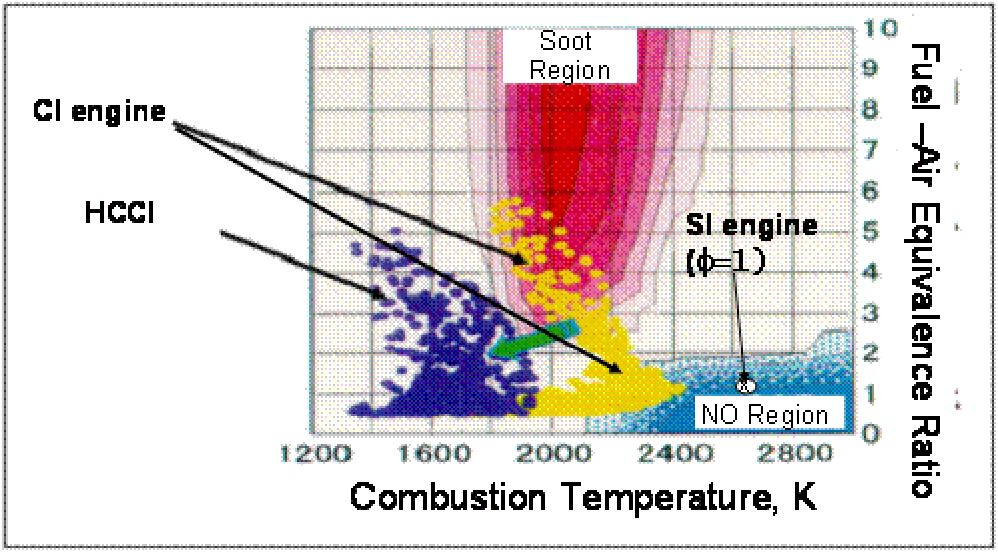

Figure 7.5	The Fuel –air equivalence ratio –Temperature diagram for hydrocarbon - air mixture conditions for formation of soot and NO_x. The conditions of normal SI and CI engine operation and target region for HCCI/CAI for low NO and soot formation are shown.

The HCCI/CAI combustion process has two main steps:

(i) Preparation of lean premixed, homogeneous fuel-air mixture, and
(ii) Autoignition leading to combustion of lean premixed charge.
Different approaches have been investigated to accomplish the above steps leading to HCCI/CAI combustion

CAI GASOLINE ENGINES

The objective of CAI combustion in gasoline engines is to obtain high fuel efficiency and low NO_x emissions, the PM emissions already being insignificant. Fig. 7.6 compares P-V diagrams for a SI and CAI engine operation. It may be noted that the combustion in CAI engine is much faster and it approaches close to constant volume combustion.

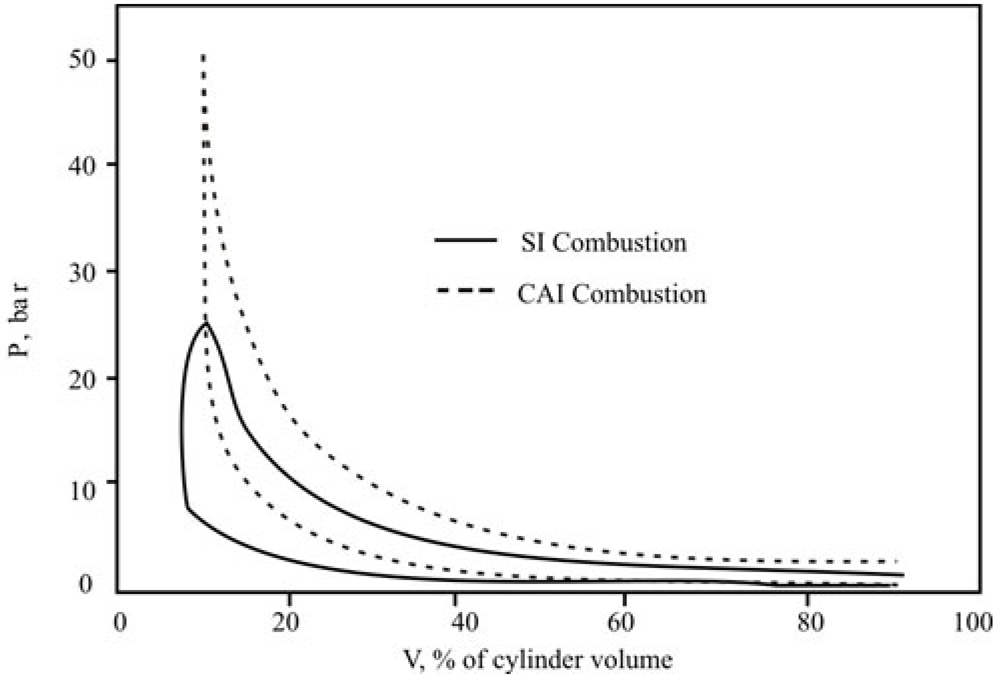

Figure 7.6	Comparison of P-V diagrams for SI and CAI combustion.

Controlled autoignition (CAI) of homogeneous charge requires:

- Charge is kept at a high temperature for sufficient duration
- Composition of charge to ensure acceptable rate of combustion and low NO_X formation

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Methods to Obtain CAI

The following parameters have been used to obtain the required temperature, pressure and composition of charge for CAI operation:

- Residual gas content or EGR
- Compression ratio
- Intake mixture temperature
- Intake mixture pressure
- Fuel-air ratio
- Coolant temperature
- Injection timing in gasoline direct injection engines

The practical engines have to operate in CAI/SI dual mode. The SI engine mode at high loads is required to have good specific power output. The autoignition of gasoline or natural gas requires CR > 20:1.Such high CR would be unacceptable at high loads when fuel-air ratio is to be increased as severe engine knock would result. The engine CR is to be limited to around 10:1. Hence, increase of CR to obtain CAI operation has not been a practical option. Intake mixture heating by using the waste heat of the exhaust gas although helpful but gives a further loss in volumetric efficiency as already a highly diluted charge is used to control the heat release rates subsequent to autoignition.

The most practical approach for CAI operation is use of large amounts of hot residual gases. Trapping of the residual gases inside the cylinder also termed as 'internal EGR' has been found a more acceptable approach. A negative valve overlap period is used to retain high amount of residual gases in the cylinder. The exhaust valve is closed before the piston reaches top dead centre in the exhaust stroke and to prevent backflow of the burned gases in the intake system, the intake valves open well after TDC. The relative valve timings for a standard SI engine and for CAI operation are compared in Fig. 7.7.

To get maximum expansion work ideally the exhaust valves are to be opened at the usual time in the cycle but are to be closed earlier. The intake valve is to open late while they should close as in the normal SI engine operation. To obtain this flexibility in SAI-SI dual mode operation fully flexible, variable valve actuation systems are necessary which are very complex in construction and presently are not in production. In the practical engines, use of low valve lift cam profile provides substantial reduction in valve opening period. This approach along with variable cam timing devices has been used in prototype engines. By varying the exhaust valve closing time load can be varied. As the exhaust valve closes earlier to trap more residual gases, less fresh charge is admitted resulting in lower engine output. The valve timings with lower valve lift are also shown on Fig. 7.7.

The trapping of residual gas in the cylinder results in high charge temperatures.. At high loads, the auto ignition however, may occur too early and high rates of pressure rise would result.

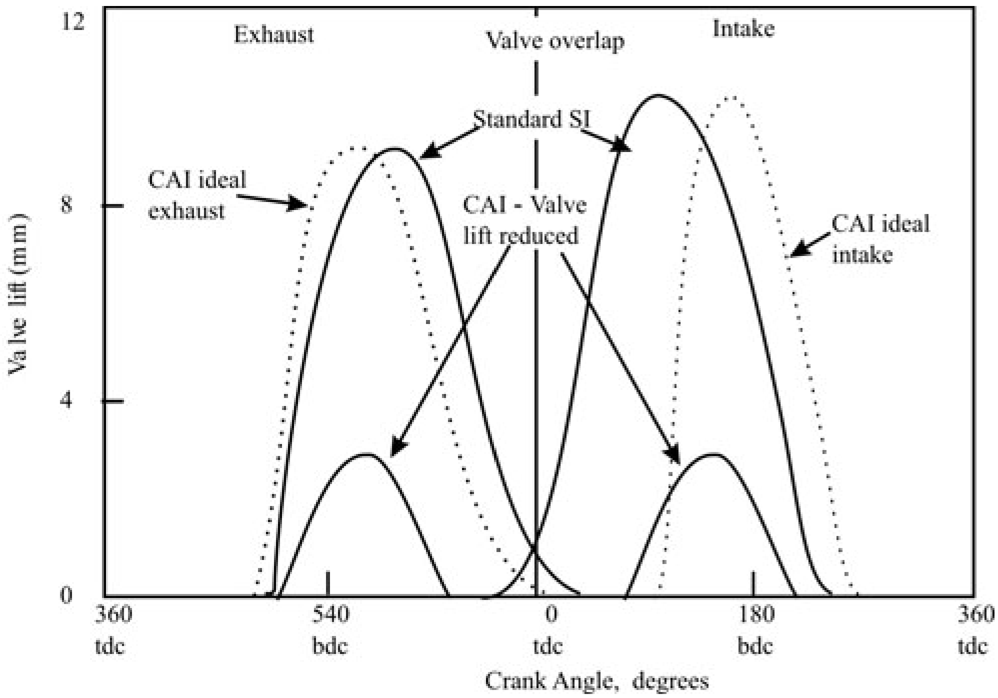

Figure 7.7	Valve timings and lift using residual gas trapping method for CAI operation.

Regime of CAI Operation

CAI operation was studied on a single cylinder engine using exhaust gas recirculation and heating the intake charge to 320 ± 1º C by an air heater. The fuel was injected at intake port . The CAI region is presented on a plot in Fig 7.8 with fuel-air equivalence ratio, ϕ and EGR mass rate as variables. The CAI region is enveloped by three engine operation regimes viz;

(i) Engine knock: It is experienced as ϕ increases. The knock limited ϕ increases as the rate of EGR increases

(ii) Misfire: Engine misfire of the charge results as EGR is increased and the engine bmep is decreased.

(iii) Partial burn: For the fuel-air equivalence ratio less than about 0.2. As the fuel-air equivalence ratio decreases, the heat released also decreases lowering the average combustion temperatures resulting in partial burn and misfire.

Knock limited imep of 3.8 bar was observed. For an imep = 3.0 bar, depending upon ϕ the EGR in the range of 40 to 55% was required to obtain CAI operation.

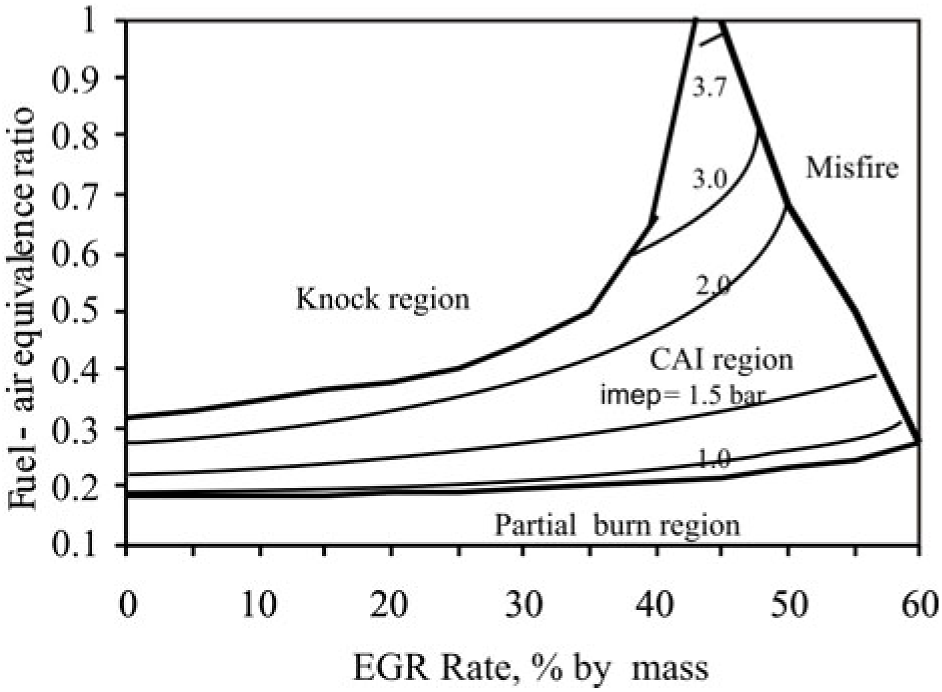

Figure 7.8	CAI operation regime enveloped by regions of partial burn, misfire and knocking combustion; single cylinder SI engine, CR = 11.5, 1500 rpm.

The region of CAI operation forms only a small fraction of the total engine speed-load operation regime with the present status of development. CAI operation of a SI engine is typically obtained for engine speeds from 1000 to 3500 rpm. At 1000 rpm, knock free CAI operation using EGR is possible up to about 5 bar bmep that reduces to nearly 2 bar bmep at 3500 rpm. On the other hand the SI engine full load bmep is about 10 bar and the rated engine speed typically is around 6000-7000 rpm. The practical engines could be operated in mixed CAI-SI mode. At low and medium loads and at

vehicle cruising speeds engine operates in CAI mode but during cold starting, at idling and at high load and speeds the engine operates in conventional SI mode.

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Emissions with CAI and SI Engine Operation

The emissions from an SI engine that operated in CAI mode at part loads are compared with the homogeneous stoichiometric SI engine on Fig. 7. 9. The engine used negative valve overlap ranging from 140-200º crank angle for CAI operation. Residual gas fraction varied from 40 to 70%. The intake air temperature was increased to 50º C by external heating. The NO_X emissions with CAI operation are extremely low. HC emissions were higher as use of very lean mixtures results in partial misfired combustion increasing HC emissions. CO emissions decreased by 80 % and the fuel consumption was lower by 15% at engine speeds of above 2000 rpm.

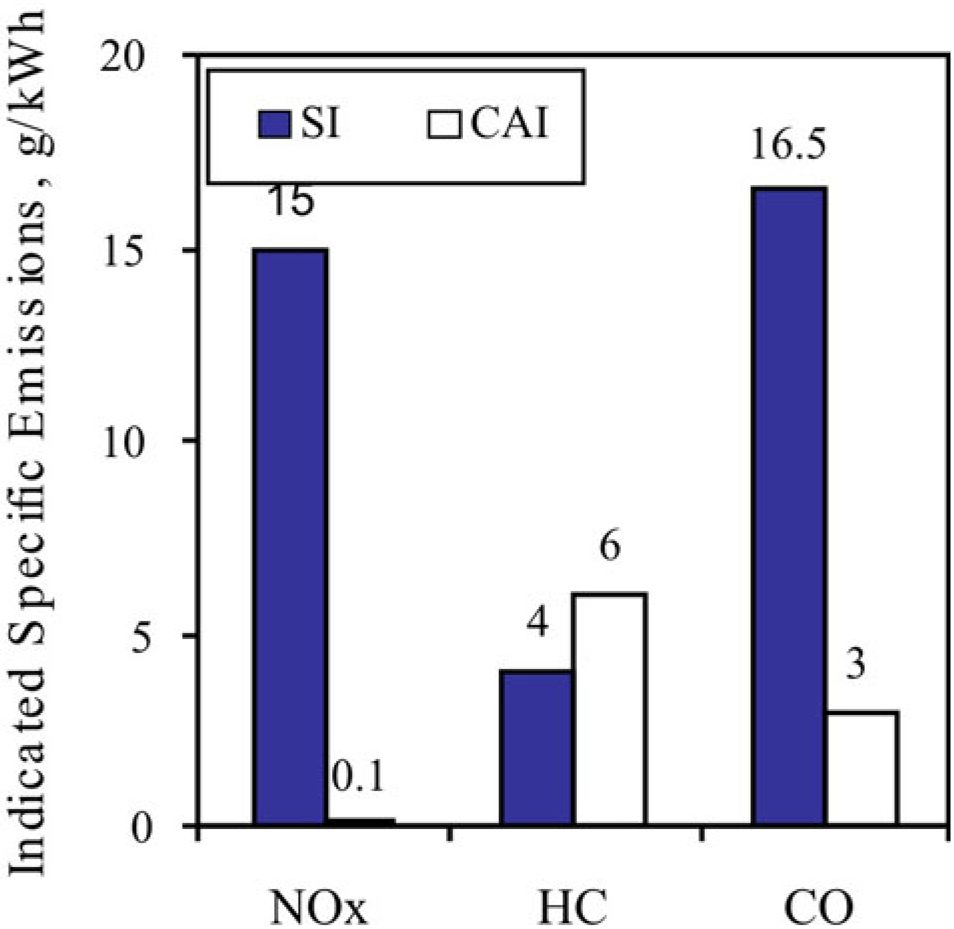

Figure 7.9	Comparison of indicated specific emissions of CAI (ϕ =0.77) and SI engine (ϕ= 1.0), IMEP = 2.6 bar, 3000 rpm..