Module 7:Advanced Combustion Systems and Alternative Powerplants

Lecture 35:Alternative Powerplants

The Lecture Contains:

- ALTERNATIVE PROPULSION SYSTEMS
- HYBRID ELECTRIC VEHICLES (HEV)
- Main Components of HEV
- Types of HEVs
- FUEL CELL
- Fuel Cell Power Output
- Factors Favouring Fuel Cell
- Fuel Cell Types
- Energy Sources for Fuel Cell
- Prototype Fuel Cell Vehicles

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ALTERNATIVE PROPULSION SYSTEMS

Following factors provided motivation for the development of alternative propulsion systems for road vehicles;

- Global warming - Reduction desired in the emission of greenhouse gas, carbon dioxide
- Control of urban air pollution
- Higher energy efficiency - to prolong availability of petroleum fuels as the crude reserves are diminishing
- Energy security – to be independent of import of energy from other countries

The design of power unit of vehicles is governed by several factors e.g., type of available fuel/energy, economics of energy availability and environmental considerations. The following vehicle power plants have been under detailed investigations and some of them are already introduced in the market.

- Hybrid - electric propulsion
- Fuel cells
- Gas turbines
- Stirling engine
- Batteries for electric vehicle

The hybrid electric and fuel cell vehicles hold a greater promise of practical application. Hybrid electric vehicles are built around the existing reciprocating IC engines and some vehicle models are already in market. The fuel cell vehicle is a zero emission vehicle and all the major auto- companies are pursuing its development as a future power plant. Hence, only these two are discussed here.

HYBRID ELECTRIC VEHICLES (HEV)

Motivating factors for HEV development are;

- Power required by vehicle to operate within cities may be around 4 to 7 kW although the rated engine power ranges from 25 to over 100kW. The engine thus, operates in the city under very low load conditions giving high fuel consumption and emissions.
- Small engine can be employed and operated at constant load and speed at the point of its maximum efficiency, and another propulsion system can take care of the transient operation. High vehicle fuel efficiencies are thus, obtained.
- Engine can be tuned to its lowest emissions at the operating load and speed point
- Emission control and exhaust after-treatment at steady engine load and speed operation is more efficient.
- Hybrid electric vehicle (HEV) allows achieving precisely this objective.

The hybrid electric vehicle employs two different energy storage and two different propulsion systems:

- A *conventional propulsion* system like IC engine, and
- An on-board rechargeable electric energy storage system coupled with electric motor(s)

Main Components of HEV

The HEV is an intermediate step between conventional IC engine power train and full electric vehicle. It has the following main components:

- A prime mover: IC engines are most commonly used, gas turbine or Stirling engine can also be used
- Electric motor in parallel or series
- Electric generator
- Battery to store electricity and run motor
- Regenerative braking system using devices like flywheel, ultra-capacitor etc.
- Power transmission system

The high performance nickel-metal hydride (Ni-MH) batteries are more commonly used as the main energy storage device. Recently, Lithium-ion (Li- ion) batteries, which have higher energy storage capacity (˜2.5 kWh/kg) compared to the Ni-MH batteries (˜1.4 kWh/kg) are also being used on some hybrid vehicles. To supplement the batteries, other energy storage systems such as flywheel and ultra or super-capacitors are also used. The flywheel stores energy during vehicle braking/deceleration and the super-capacitors store energy when the power drawn from the batteries is low and the excess engine power is available. The super capacitors are capable of generating short bursts of very high power

Types of HEVs

Two basic types of HEV are

(i) Series and

(ii) Parallel type.

Other variants of the two basic types have also been developed. The HEV configurations are shown in Fig 7.14

Series Hybrid

In the series hybrid, electric motor is the only propulsion unit. It is connected with the drive wheels. The engine is coupled with an alternator/ generator that runs the motor as well as charges batteries. All the energy from the engine to the wheel passes through electric machine and hence, it is called as series HEV. The electric power is always generated on board. The engine is not required to follow the transient operation needs of the vehicle.

Parallel Hybrid

In the parallel hybrid, the engine and motor (run by battery) are mechanically connected to wheels and traction can be provided simultaneously by both the power units. When the engine is unable to meet the power requirement of the vehicle (such as under acceleration), energy from the battery supplements the vehicle demand. Engine is thus, subjected to transient demands and consequently fuel efficiency is poorer and emission penalties occur.

Mixed hybrid

In the mixed hybrid, an alternator run by the engine continues to charge batteries. The power to the wheels flow directly from the engine as well as from the batteries charged by the alternator simultaneously as in the parallel hybrids. Toyota Prius car, one of the most successful HEVs is a mixed hybrid vehicle.

Plug-in hybrid

Most cars run less than 50 to 60 km/day in cities. Thus, a near zero emission vehicle can be designed if a small size battery pack provides this range during city driving and when the vehicle needs to run more distance the IC engine drives the vehicle. The batteries are charged every day by the mains supply. Such hybrids are called as Plug-in- Hybrid Electric Vehicle (PHEV).

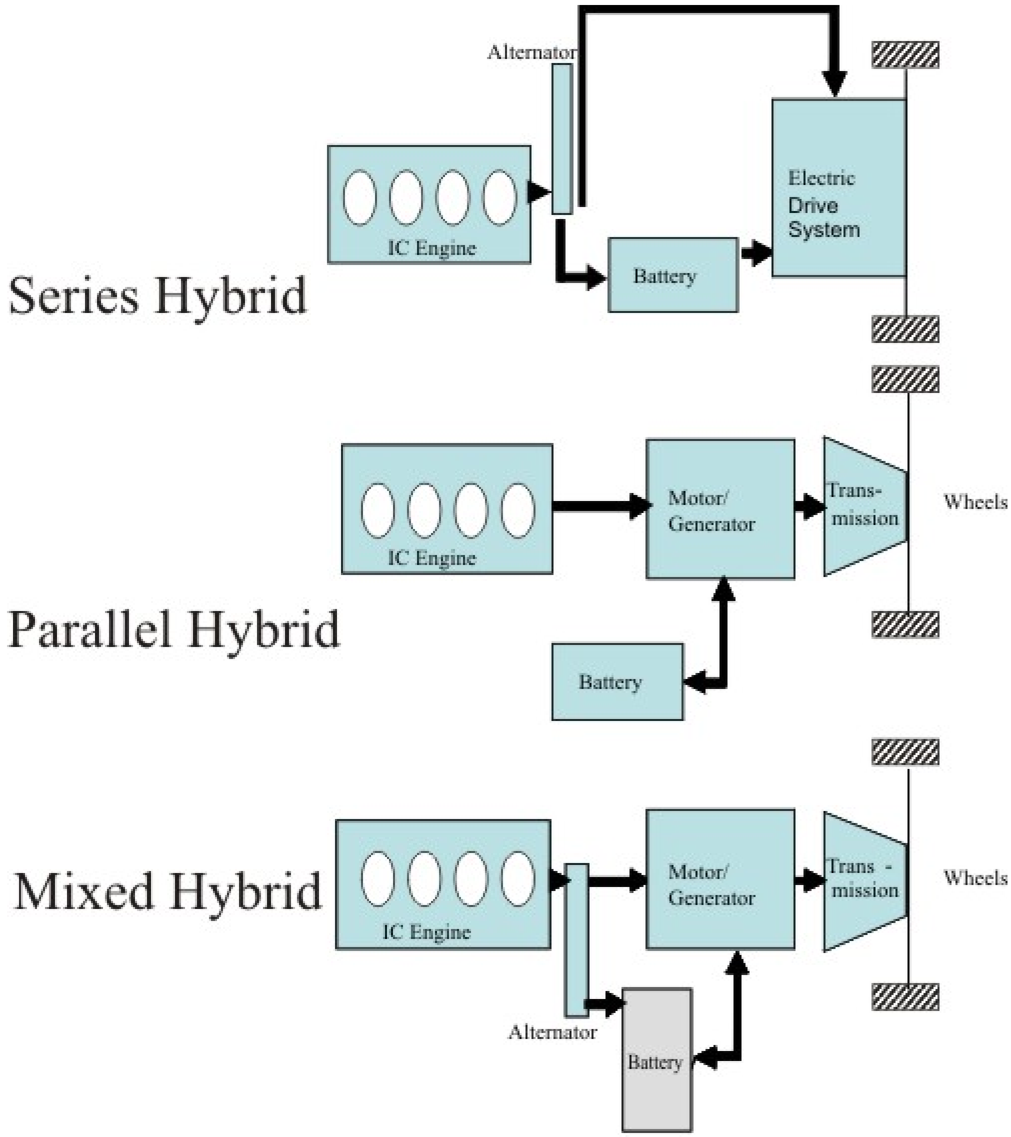

Figure 7.14	Hybrid Electric Vehicle Systems.

Already a few million HEVs are in use. The gasoline engines used on HEV run on Atkinson cycle to improve thermal efficiency with large reduction in pumping losses. The Atkinson cycle is implemented by late closing of intake valve (72 º to 105º after bdc) while keeping the expansion ratio close to 13:1. The power output of the engine is increased by supercharging.

- The fuel efficiency improvements of nearly 50% in city driving and 30% on combined city and highway driving have been obtained.
- HEVs have met the SULEV emission standards (NMHC = 0.01, CO = 1.0, NO_x = 0.02 g/mile).
- HEV powered by diesel engine have obtained 25 % better fuel economy than the comparable diesel vehicle. The NO_x and PM emissions are lower by nearly 45 and 65 %, respectively.
- The diesel hybrids produce up to 50% less CO_2 than the gasoline engines and 30 to 35% less than the diesel engines making the diesel-hybrid more fuel efficient and environment friendly than the gasoline engine hybrid.

FUEL CELL

Working Principle

Fuel cell was invented in 1839 by Sir William Groves. It is an electro-chemical device, which continuously converts the chemical energy of fuel directly to electricity. The working principle of H_2-O_2 fuel cell is shown on Fig. 7.15.

- The fuel-cell has two electrodes made of porous material coated with platinum as catalyst.
- The electrodes are separated by a solid semi-permeable electrolyte.
- Hydrogen flows into fuel cell on catalytic anode and gives up an electron.
- Negatively charged oxygen at cathode attracts hydrogen protons through the solid electrolyte membrane. On cathode, hydrogen and oxygen ions combine to produce water.
- The electrons flow through external circuit producing current.

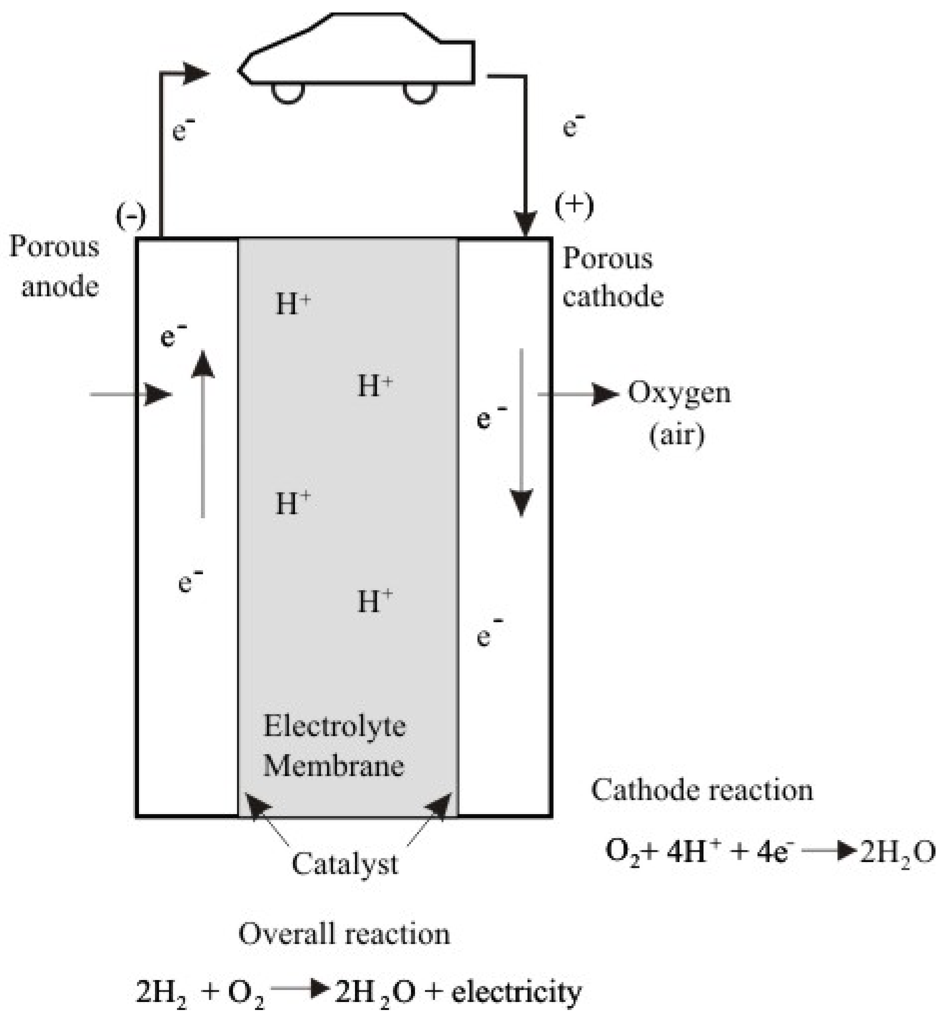

Figure 7.15	Schematic of $H_2 - O_2$ fuel cell.

Fuel Cell Power Output

Open circuit standard EMF of fuel cell at reference condition is given by

$$E_0 = \frac{-\Delta G_f^0}{nF} \qquad \textbf{(7.1)}$$

where:

$-\Delta G_f^0$ = Gibbs free energy of formation for the reaction at reference condition of 298 K, and 1 atm

n = no. of electrons per molecule of fuel e.g. for H_2 -O_2 fuel cell n = 2

F = Faraday constant = 96,485 Coulombs/ electron mol.

At the other operating conditions, EMF of the fuel cell is,

$$E = E_0 - \frac{RT}{nF}\ln\left(\frac{p_{H_2}p_{O_2}^{1/2}}{p_{H_2O}}\right) \qquad \textbf{(7.2)}$$

where PH_2, PO_2, PH_2O are the partial pressures in atm.

Fuel cells can also use and operate directly on other fuels like methanol and methane Theoretical EMF of some fuel cell systems is given in Table 7.3

Table 7.3

Theoretical EMF for Some Fuel Cells at reference conditions

Fuel	Reaction	n	E_0 , V
H_2	$H_2 + 0.5\ O_2 \rightarrow H_2O$	2	1.229
Methane	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O(l)$	8	1.006
Methanol	$CH_3OH\ (l) + 1.5O2 \rightarrow CO_2 + 2H_2O\ (l)$	6	1.214

Actual cell voltage is lower and is about 50 to 60% only of the theoretical EMF due to;

- Slow rate of chemical reactions
- Internal cell resistance
- As the current drawn is increased beyond about 0.7 A/cm^2, the concentration polarization causes a further voltage drop.

Typical fuel cell characteristics are shown on Fig. 7.16. The change in current and voltage efficiencies versus current drawn from the fuel cell are shown.

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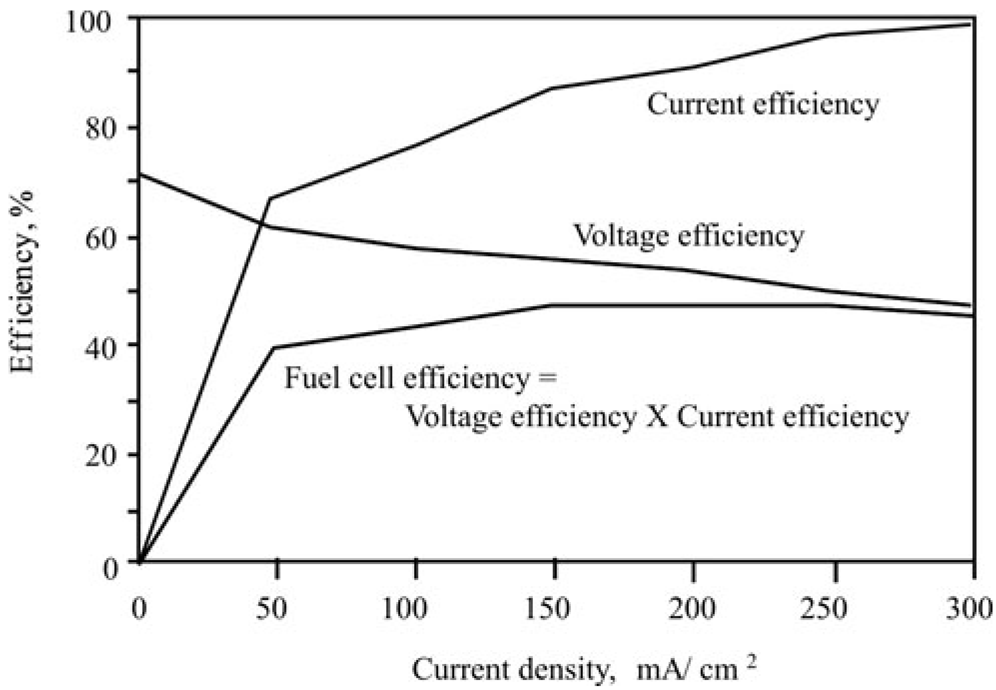

Figure 7.16	Fuel cell efficiency characteristics.

Factors Favouring Fuel Cell

- Varieties of sources for generating hydrogen are possible to reduce dependence on crude petroleum
- Vehicles with zero emissions of CO, HC, NO_x and PM can be built.
- On board reforming of methanol, ethanol or hydrocarbon fuels can be employed to generate hydrogen. Thus, the existing fuel distribution network can be used.
- Fuel cells are more efficient under part load operation than the IC engines. These are not limited by the Carnot efficiency. At full power output, the internal resistance and concentration polarization losses increase resulting in the loss of fuel-cell efficiency and it drops close to that of the IC engines. Efficiency of fuel cell is compared with that of gasoline and diesel engines on Fig. 7.17.

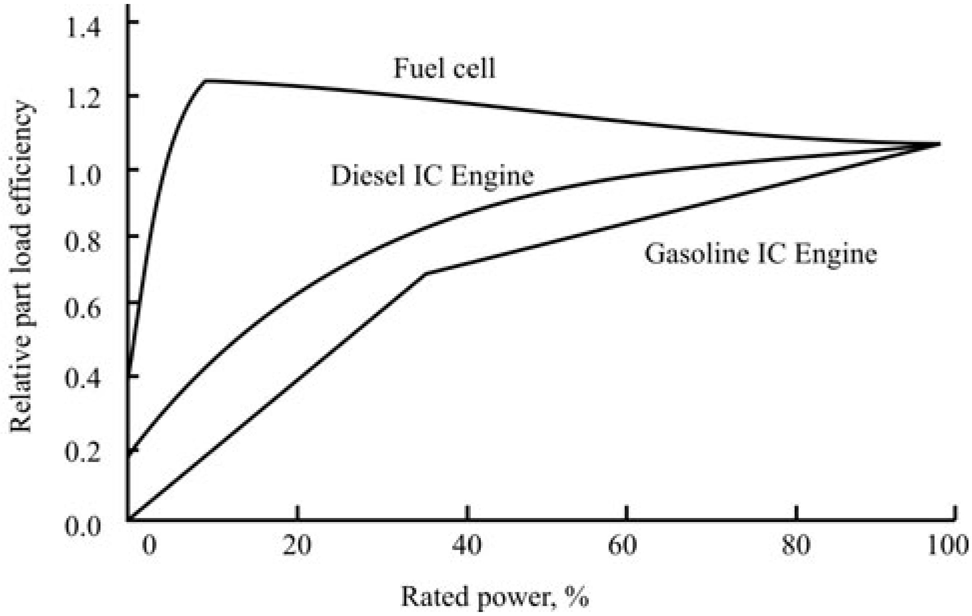

Figure 7.17	Comparison of efficiency of fuel cell with conventional internal combustion engines

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Fuel Cell Types

Fuel cells are classified by the electrolyte used. The different types of fuel cell developed for various applications are given in Table 7.4. For vehicle application, the temperature of fuel cell operation and start up time are important. The PEM (proton exchange membrane) fuel cell has been accepted presently as best suited for vehicle application as it can be started in about 30 seconds and it operates at acceptably low temperatures. The PEM fuel cell consists of an electrolyte membrane in the form of a thin film of approximately 0.1 mm thickness made of sulfonated fluorocopolymer or an aromatic polymer. A typical automotive fuel cell stack consisting of 640 PEMFC developed 129kW peak power with continuous rating of 102 kW, weighed 100 kg and occupied 58 litres of space

Table 7.4

Fuel Cell Types and their Characteristics

Type	Electrolyte	Temperature of operation, ºC	System Efficiency % HHV	Start-up time, hours	Power range and application
Alkaline (AFC)	KOH (OH-)	60-120	35-55	Very short	< 5kW, military, space
Proton Exchange Membrane (PEMFC)	Polymer Electrolyte (H+)	20-120	32-45	< 0.01(30 seconds)	5 – 250 kW, High power density, automotive
PAFC	Phosphoric Acid (H+)	160 -220	36-45	1 -4	200 kW, CHP
MCFC	Molten carbonates (CO-3)	550-650	43-55	5 -10	200 kW - MW, CHP and stand alone
Solid oxide (SOFC)	Solid doped Zr-oxide (O-)	850-1000	43-55	5 -10	2 kW - MW CHP and stand alone, High efficiency

Energy Sources for Fuel Cell

The following sources can supply energy to fuel cells

- Hydrogen
- Methanol
- Ethanol
- Hydrocarbon fuels, gasoline and diesel

Hydrogen-oxygen fuel cell provides the highest EMF and power density (W/cm^2). Hydrogen either can be directly stored on-board of vehicle or generated by steam- reforming of fuels such as methanol,

ethanol and hydrocarbons. The purity of hydrogen is very important for operation and longer life of fuel cell as even small concentrations of carbon monoxide and sulphur are highly detrimental. The products of fuel reforming are to be cleaned to supply hydrogen to the fuel cell. Although in principle, methanol, ethanol, gasoline, diesel and other hydrocarbons can be reformed to supply hydrogen, but so far only methanol reforming on board has been successfully used. Direct methanol fuel cell (DMFC) where methanol is fed directly to the fuel cell for oxidation and generation of electricity, is another option being developed for automotive use. . Electrolysis of water using nuclear energy and the renewable solar, wind, hydro and wave energy is the other route to generate hydrogen. The electrolysis route appears to be a long term solution once the low cost renewable or nuclear power is available. On board storage of hydrogen is another important factor for commercial success of FCV. Hydrogen can be stored in the form of gas, liquid, metal hydrides as hydrogen or in chemically combined form such as methanol and NaBH4 (sodium borohydride). High pressure storage systems of hydrogen at 700 bars have been developed. The different methods of hydrogen storage on board are compared in Table 7.5. So far most FCV prototypes have however, used the high pressure (350 – 700 bar) hydrogen tanks.

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Table 7.5

Comparison of Hydrogen Storage Methods for Fuel Cell Vehicles

	Name	Storage Temp, °C	Storage Pressure, MPa	Hydrogen by mass, %	Volume,litre/ kg of H_2
1	High pressure cylinder	Ambient	35 to 70	2 to 4.5	40 -70
2	Liquid H_2	- 252	Ambient	14	25
3	Fe-Ti hydride	- 10	2.5	< 2	36
4	Methanol	Ambient	Ambient	12.5	10
5	NaBH4	Ambient	Ambient	10.58	9.5

Prototype Fuel Cell Vehicles

From the early FCV prototypes such as Necar-1 by DaimlerChrysler, considerable progress has been made in the fuel cell vehicle development. Necar-1 had a 50kW fuel-cell stack with 30 kW propulsion system, hydrogen storage capacity of about 2 kg at 300 bar, maximum speed of 90 km/h and a range of 130 km. Honda FCX vehicle built in 2004 is powered by a fuel cell stack of 86 kW, 4.3 kg of hydrogen is stored at 350 bar. It is a normal size car having 150 km/h maximum speed and 395 km range. The vehicle on US FTP cycle achieved fuel economy of 91.8 km/kg of H_2. By the year 2006-07, through development of more efficient fuel cells and 700 bar cylinder pressure storage systems the range of vehicles exceeding 500 km has been attained. Presently the cost of fuel cells is higher by a factor of 2 to 3 compared to gasoline engines of the same power output. Honda Co. believes that by the year 2018 the FCV could be produced at costs that are commercially viable.

The FCV has varying impact on the CO_2 emissions as it depends on the hydrogen generation process.. Obviously, if the hydrogen or methanol is produced from natural gas the CO_2 advantage of FCV over the conventional IC engines is not significant. If methanol is produced from natural gas to provide fuel for the fuel cell, the effect on CO_2 reduction in fact, is negative. The comparative CO_2 emission scenario would again change when the IC engines are fuelled by the renewable fuels like ethanol or biodiesel.

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Questions

(7.1) Three different approaches are used to obtain charge stratification viz., spray jet controlled, wall controlled and flow controlled Discuss the differences in the duration of initial heat release rate (0 to 10%) and heat release rates towards the end of combustion (80 to 90%) with the three methods. What factors are responsible for these differences?

(7.2) What type of emission control technologies may be employed to reduce HC and NO_x emissions in the DISC engines operating in the different air-fuel ratio regimes?

(7.3) What are significant differences between CAI and HCCI engine systems from the point of mixture preparation and charge homogeneity?

(7.4) What are main methods being studied to HCCI combustion in the diesel type engines? Discuss their merits and demerits.

(7.5) Why is it not possible to build a practical engine to operate in HCCI mode in the whole speed and load range of a SI or CI engine?

(7.6) Discuss why a HEV is more energy efficient than the vehicles powered by the conventional IC engine

(7.7) Discuss why a HEV is more energy efficient than the vehicles powered by the conventional IC engine

(7.9) Discuss why the energy efficiency of fuel cells at part loads is much higher than for the IC engines.