Formation of HC Emissions in CI Engines

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HC Emissions from CI Engines

The unburned hydrocarbons in diesel exhaust consist of original fuel molecules, products of pyrolysis of fuel compounds and partially oxidized hydrocarbons, in all numbering to almost 400 organic compounds ranging from methane to heaviest fuel components. In diesel engines, several events like liquid fuel injection, fuel evaporation, fuel-air mixing, combustion, and mixing of burned and unburned gases may take place concurrently and combustion is heterogeneous in nature. Thus, several processes are likely to contribute to unburned hydrocarbon emissions as below;

- Overmixing of fuel and air beyond lean flammability limits during delay period,
- Under-mixing of fuel injected towards the end of injection process resulting in fuel-air ratios that are too rich for complete combustion,
- Impingement of fuel sprays on walls due to spray over-penetration,
- Poorly atomized fuel from the nozzle sac volume and nozzle holes after the end of injection, and
- Bulk quenching of combustion reactions due to cold engine conditions, mixing with cooler air or during expansion.

Overmixing of Fuel

Overmixed region in a diesel spray injected in swirling air is explained schematically in Fig. 2.17. The outer boundary of spray will have smaller droplets. Also, swirling air carries smaller droplets towards downstream of the leading edge of the spray. The smaller droplets vaporize more rapidly and due to air entrainment at the spray boundary the mixture is leaner. The central core of the spray consists of larger droplets that evaporate relatively at a slower rate and air entrainment in the spray core is also low.
The local fuel-air ratio distribution varies with the radial distance from the spray axis. The fuel-air ratio distribution expected in diesel spray is qualitatively noted on Fig.2.17. The outermost boundary of the spray is characterized by the fuel-air ratio being zero at the boundary. A large lean mixture region containing fuel vapours exists inside the outer boundary where equivalence ratio is less than the lean limit ($\phi \sim 0.3$). This region is termed as lean flame blow out region (LFOR).
The overmixing of fuel in the LFOR region near the spray boundary may result due to high air swirl and/or longer time available before combustion starts (longer ignition delay). Overmixing results in over-leaning of the mixture beyond the lean flammability limit and it will not auto-ignite or support combustion. In the overmixed region, only slow oxidation reactions are likely to occur resulting in partially oxidized products and unburned fuel. Most of the unburned hydrocarbons especially under idling and light loads are expected to originate from the overmixed region.

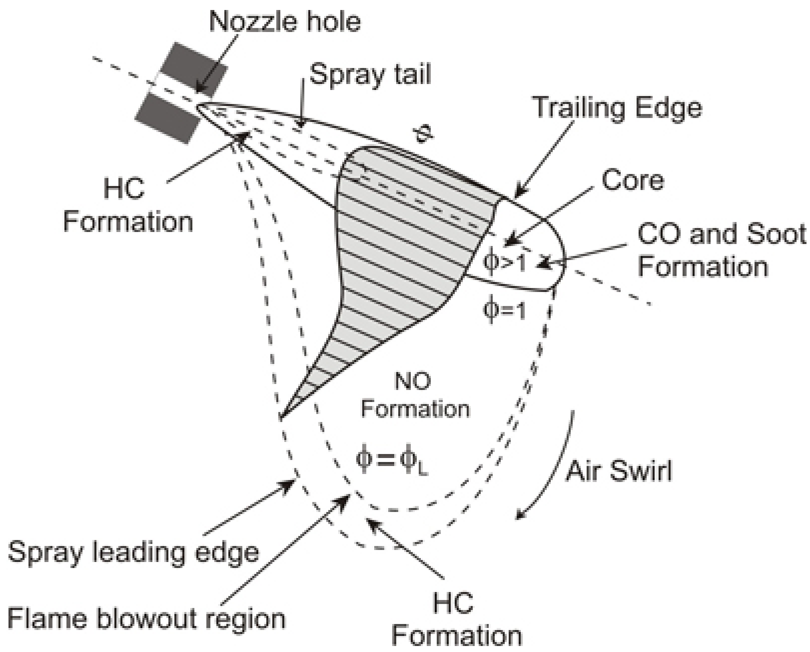

Figure 2.17	Schematic of diesel fuel spray and fuel-air equivalence ratio distribution at the time of ignition. Formation of pollutants in different spray regions is qualitatively marked.

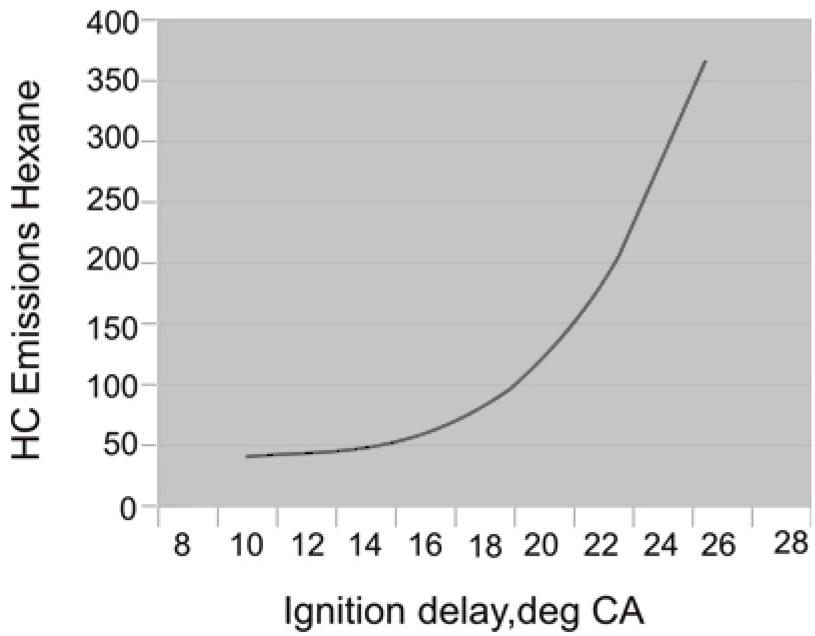

Figure 2.18	Effect of ignition delay on HC emissions in a DI diesel engine

The width of the LFOR region primarily depends on ignition delay, pressure and temperature in the chamber, fuel type and air swirl. Increase in temperature and pressure would reduce width of LFOR as the lean limit of combustion is extended. The magnitude of contribution of LFOR to unburned HC would depend on the length of ignition delay, amount of fuel injected and rate of fuel –air mixing during the delay period. A longer ignition delay allows more time for the fuel vapours to diffuse farther into air and a higher percentage of fuel would be contained in the LFOR. An increase in HC emissions with increase in the ignition delay is observed for DI diesel engines as shown in Fig 2.18.

Under-mixing of Fuel

HC emissions also result from under-mixing of fuel with air. This can happen for the fuel injected later in the cycle or because of over-fuelling of the engine. The fuel left in the injector sac volume and nozzle holes at the end of injection on heating during combustion gets fully or partially vaporized. The vaporized fuel from the nozzle sac and holes enter the engine cylinder at low velocity later in the cycle during expansion stroke and has little time to mix with air when the gas temperatures are still high. This portion of fuel therefore remains mostly unburned and is emitted in the exhaust. Nozzle sac volume has been observed to be the main contributor to HC emissions in a DI engines
through the process of under-mixing of fuel. Effect of nozzle sac volume on HC is shown on Fig. 2.19. Two types of nozzle designs one with low sac volume and another valve covered orifice (VCO) design are also shown. In VCO nozzles the nozzle sac is eliminated. The VCO nozzles however, are not preferred as their durability is low due to overheating of the nozzle tip as in the other nozzles fuel in the sac absorbs latent heat of vaporization and the nozzle temperatures are lower.

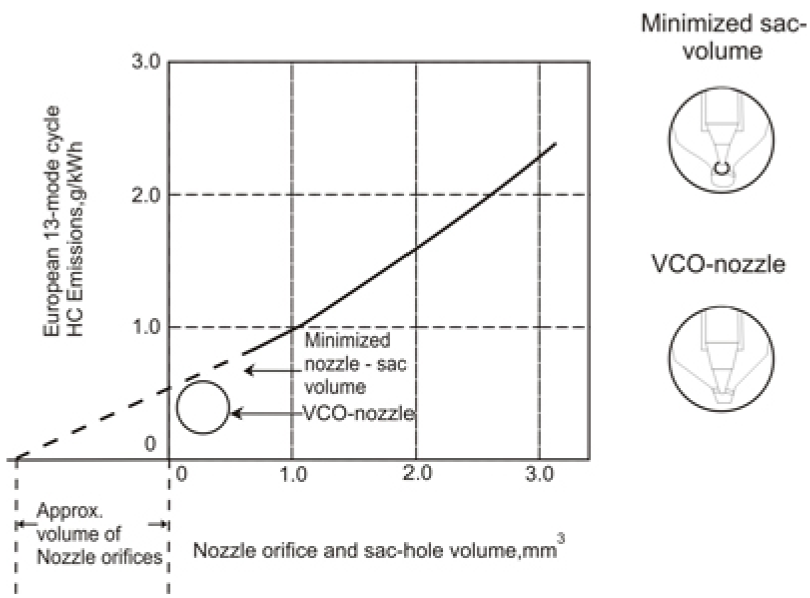

Figure 2.19	Effect of nozzle sac volume and type of nozzle hole on HC emissions from DI diesel engine.

Fuel contained in the nozzle holes also contributes to the HC emissions as seen when the curve is extrapolated to zero sac volume.
For the DI engines, at full load a minimum of about 40 percent excess air (f< 0.7) is usually supplied to limit smoke emissions. Over-fuelling may occur during acceleration especially in turbocharged engines, as the response of turbocharger to increase airflow rate is slower than the increase in fuel injection rate. With increase in engine load (increase in fuel-air equivalence ratio), engine and cylinder gas temperatures increase and therefore, HC emissions generally decrease until a critical fuel-air ratio is reached. When excess air is reduced to around 10 percent (f = 0.9) or below HC emissions increase sharply.
At low ambient temperatures during engine warm up or with retarded injection timing, some engine cycles may misfire resulting in bulk quenching and high HC
emissions. Under these conditions, liquid fuel droplets may appear in the exhaust giving the exhaust a white coloured appearance, known as ‘white smoke’

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