

Diesel Engine Emissions: Hydrocarbons (HC)

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The Tier 2 US federal emissions standards for diesel car and trucks, especially the Bin 5 level, are considered the most stringent requirement for engine manufacturers. This has been set five years ago and phase-in began in 2004. The most demanding standards are set for NO_x (nitric oxides) and particulates in that order. For example, the phase-in value (Bin 8) was 0.2 g/km, to be reduced to Bin 5, which requires 0.07 g/km averaged across an automaker's light-vehicle fleet. This is 50% reduction from its previous standard. The Bin 5 level is set for the year 2007 with full implementation for all cars and light-duty trucks planned by year 2009. The near-term option appears to be aftertreatment of emissions in the exhaust system such as selective catalytic reduction (SCR) using urea injection along with diesel oxidation catalyst and particulate filters. The Lean-NO_x trap may come in later when satisfactory durability is demonstrated. The SCR has better system durability and superior NO_x reduction abilities at the time of this writing.

Considering the above, it appears timely to discuss the mechanism of formation and emission of three important pollutants from diesel engines (mostly direct injected type), namely, NO_x, particulates, and hydrocarbon. In this first part of the series, focus is made on the hydrocarbon emissions. In the following, the mechanism of formation of hydrocarbons from diesel engines is briefly explained.

Before discussion of the HC emission, it is useful to concisely review the combustion in diesel engines. The combustion in diesel engine is very complex due to its heterogeneous nature, where fuel evaporation, fuel-air and burned-unburned gas mixing, and combustion occur simultaneously. Consequently, there are many processes that could contribute to diesel engine hydrocarbon emissions. Diesel engine's compression-ignition combustion process is usually divided into four stages. First is the *ignition delay period* which is the time between the start of injection and the instant when autoignition occurs. During this period, the liquid fuel is atomized, vaporized and mixes with air which starts the pre-ignition chemistry until autoignition happens in one or multiple locations where favorable air-fuel mixture ratio exist. Second, is the *premixed or rapid combustion phase*, during which the gaseous fuel that has mixed to within combustible limits during the delay period burns. In the third stage, the rate of the burning depends on the rate of fuel-air mixing to within the combustible limits and is referred to as *mixing-controlled combustion phase*. The fourth and the last phase is the *late combustion phase* where heat release continues at a low rate controlled by the mixing of residual combustible gases with excess oxygen and the kinetics of the oxidation process. Out of these concurrent processes (i.e., atomization, evaporation, mixing, and chemistry), the mixing has been shown to be the slowest one and hence the burning of the fuel in diesel engine is characterized and dominated by fuel mixing rate, and the engine load is determined by the amount of fuel injected. In this way, the limitations of low compression ratio, crevice volume losses, throttling losses, lean flame speed limits, and cyclic variability inherent in spark-ignited gasoline engines are avoided. Mixing is the fluid mechanical phenomena and can be enhanced by, for example, swirl and enhancements on turbulence levels.

There are basically two primary ways that fuel can escape the normal combustion process in diesel engines. One is if the local fuel-air mixture becomes too lean to either autoignite or allow propagation of a flame at diesel engine conditions. The other, which occurs during the primary combustion process, is when the local mixture may become too rich to either ignite or support a flame. The fuel which escapes can only be consumed during the expansion process if it mixes with additional air in a slower thermal oxidation process. Considering the substantial pyrolysis (i.e., thermal decomposition) which occurs within the fuel during diesel combustion, the composition of hydrocarbon is more complex than gasoline engines. Also, HC species exit the engine in two forms: gaseous and as hydrocarbon absorbed in the soot particles.

During the ignition delay period, the liquid fuel is atomized, vaporized, and mixed with the air which produces a wide variety of equivalence ratios. Locally overlean or locally overrich mixtures, the former being of high importance, are two major causes of the hydrocarbon emissions in diesel engines. In a locally overlean scenario, these mixtures will not autoignite or support a propagating flame. Later autoignition sites or flame propagation from these sites consume the combustible mixture, unless they are *quenched by boundary layer or rapid mixing with air*. For the locally overrich mixtures, their complete combustion depends on additional mixing with air before rapid expansion and cooling of the cylinder contents.

After the ignition delay period, and during the mixing-controlled phase, the fuel and products of fuel pyrolysis will burn completely if rapid oxidation occurs as they mix with air. Otherwise, slow mixing with air causes overrich mixture or quenching, leading to incomplete combustion products, pyrolysis products, and unburned fuel in the exhaust.

A more clear picture can be drawn of the HC emission process by resorting to Fig. 1. Here, one spray of a multi-hole injector is shown. The hatched area indicates the *locally overlean zones*. The HC levels for these overlean zones are primarily dependant on the amount of fuel injected during the ignition delay period. Therefore, a good correlation between the ignition delay period and exhaust hydrocarbon emissions can be demonstrated. See Fig. 2 for this dependency. Another process contributing to the hydrocarbon emissions in diesel is *undermixing* (leading to *overrich zones*) which is caused in situations where fuel is injected at low velocity, such as towards the end of injection (from sac volume and due to secondary injection), and when excess fuel is used under overfueling conditions. For example, overfueling can occur under transient conditions as engine is accelerated.

Finally, *quenching of the reaction and misfire* are the last two processes that can contribute to the total HC emission from diesel engines. Wall quenching can be significant depending on the degree of spray-wall impingement. Note that the cyclic variability of diesel engine is much lower than the spark ignited engines due to the nature of combustion in diesel engines. However, for diesel engine it can become important if temperature and pressure is low at the end of compression and if injection is highly retarded.

In summary, two major sources of HC emissions in diesel engines under normal operating conditions are: first, fuel mixed to leaner than the lean combustion limit during the delay period, and second, undermixing of fuel which leaves the fuel injection nozzle at low velocity, late in the combustion process. The following approximate emission levels are observed:

- $HC_{(\text{idling and light load})}$ (due to overleaning (or overmixing) especially at light load) > $HC_{(\text{Full load})}$
- $HC_{(\text{overfuel})}$ (due to undermixing) >> $HC_{(\text{idling and light load})}$

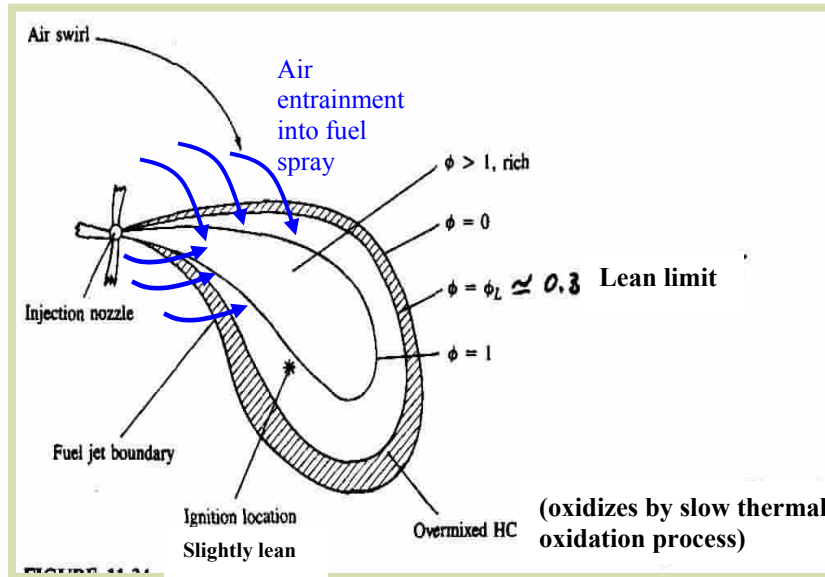


Figure 1. Schematic diagram showing different regions within a single spray of a multi-hole injector. Φ is fuel-air equivalence ratio (lean if less than 1, stoichiometric if equal to 1, and rich if greater than 1).

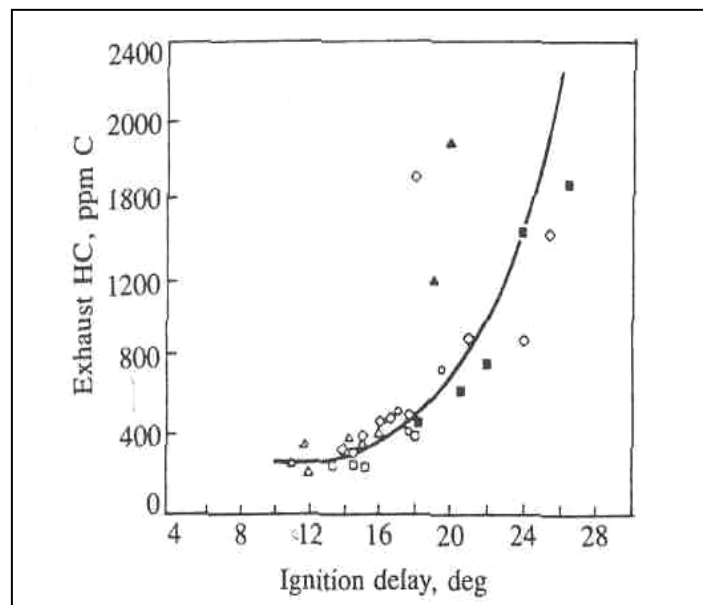


Figure 2. Correlation of the exhaust HC emission with ignition delay period for DI diesel engines.