Hydrocarbon Emission from Spark-Ignited Engines

By

B. Chehroudi, PhD
Chief Scientist, Raytheon

The term "hydrocarbon (HC)" refers to molecules having hydrogen and carbon as their primary forming atoms. In the context of the engine emission it is more appropriate to call them "organic compound emission." As long as we use nonrenewable fossil fuels, hydrocarbons are the major components burned inside the combustion chamber of internal combustion engines. It is therefore natural to expect some HC emission in the exhaust pipe of these engines. From human health and photochemical smog formation point of views these organic compound emissions must be minimized, particularly those with high degree of reactivity and with carcinogenic effects. The incentives to understand the mechanisms of HC formation and/or their escape from the primary combustion process are therefore justified. Detailed analysis of the exhaust emission using Gas Chromotography indicates that not all of the organic compounds emitted from the untreated exhaust is the original fuel molecules. In fact, by some estimates only about a third of the unburned HC found in the engine-out exhaust is the original fuel molecule. The remainder are due to fuel pyrolysis (i.e. thermal decomposition of the molecules) and partial oxidation compounds.

Figure 1 shows the overall picture where the burned and unburned HC end up in an engine. Under normal warmed-up engine operating conditions a large fraction of the fuel (~90%) is fully burned into (non-HC) CO_2, CO, H_2O, H_2, etc. through primary combustion process. The primary combustion process in spark-ignited engines is the flame and its propagation. The remainder of the fuel escapes the primary combustion process, a fraction of which ends up in the exhaust as engine-out HC emission via several different mechanisms. Most of these mechanisms occur near the combustion chamber walls and for this reason engineers responsible for designing the chamber for low HC emission attempt to minimize chamber surface-to-volume ratio. In the following brief descriptions of these mechanisms are given.

One major source of the unburned HC in the exhaust has been traced to the crevices inside the combustion chamber. These are piston top-land volume, the volume within the top-ring groove not occupied by the ring, volume between the first and second compression rings, and other of lesser importance such as the cylinder head gasket crevices, the valve seat crevices, spark-plug-thread crevice, and the gap between the central electrode and the plug body. Fuel molecules can go into these crevices during the compression stroke and in this way escape burn-up by the propagating flame. This is because the flame is unable to penetrate deep into these crevices, where fuel molecules are forced into, and therefore is quenched (i.e. extinguished) . Typical production engine top-land crevice radial clearance is roughly from 0.39 to 0.48 mm and head gasket clearance vary from 1 to 1.5 mm. The quenching of the flame attempting to penetrate the crevices is because of the large surface-to-volume ratios of these crevices removing more heat from the flame than is released within the flame thickness as a result of the chemical reaction (or burn-up of the fuel). The unburned or partially-burned fuel is then out-flown from the crevices into the cylinder in the later phase of the expansion stroke. A large fraction of it is oxidized in the cylinder with the remainder ending partly as residual HC left in the cylinder and the rest into the exhaust system, see Fig. 1. A gas temperature of 1400 K is required for rapid HC oxidation and it can be approximately assumed that all the HC outflown prior to the exhaust valve opening is oxidized. The critical radial clearance (i.e. below which flame cannot penetrate into) under typical engine condition (i.e. chamber pressures above 10 atm, exhaust gas recalculation (EGR) of 0 to 15%, and stoichiometric fuel/air ratio) is about 0.4 mm. This is close to the production engine piston top-land value and the flame is expected to be quenched upon entrance.

Another source of HC emission comes from the flame quenching near the cylinder walls leaving a thin layer (~ 0.05 to 0.4 mm) of HC close to the wall which is then diffused into the in-cylinder burned gases and mostly oxidized. The physical mechanism of the flame quenching is the same as described above. The bulk quenching of the flame in what is referred to as partially-burned cycles, indicates a situation in which a flame is extinguished somewhere during its travel before having the chance to burn all the in-cylinder

fuel/air mixture. This is because of too rapid fall of the cylinder pressure and temperature. Such is very likely to happen in a fraction of cycles when engine is at idle or light load conditions where engine speed is low with high residual burned gases, when high EGR is used for NO_x control or with highly lean mixture, when highly retarded ignition is used, and finally when engine is under transient operations. Bulk quenching and misfire (a situation in which spark is unable to initiate a flame) are the two HC mechanisms that leave unburned HC in a large volume not necessarily near the cylinder walls. On method to reduce importance of the bulk quenching is a faster burn combustion chamber design. Burning the mixture faster so the combustion is completed before conditions conducive to slow and partial burning exits in the cylinder, does reduce engine-out HC emission coming from the flame bulk quenching mechanism.

There are two other HC mechanisms in which fuel molecules escape the primary combustion process. First, is as a result of adsorption of these molecules into the thin oil layer (1 to 10 micron) during the intake and compression strokes and their desorption from the oil layer in the expansion and exhaust strokes. Some of the desorbed fuel vapor will mix with the high-temperature in-cylinder burned gases and oxidize. However, a fraction that remains in the cool wall boundary layer can contribute to the HC level measured in the exhaust. Second, is the adsorption and desorption of the fuel molecules in the deposits built on the cylinder walls when vehicle is operated for over some thousands miles, similar to the oil layer. Only a small fraction of these desorbed molecules are later oxidized, see Fig. 1. Note that almost all of the HC mixing with the burned gases in the cylinder prior to the exhaust blowdown is oxidized. Although oxidation continues to some extent within the exhaust system, they are not discussed in this tutorial. Finally, a major source of the HC emission is during the cold-start phase of the engine operation, s separate topic on its own. For further information the reader is referred to Internal Combustion Engine Fundamentals by J. B. Heywood and SAE technical papers 932708 and 952537 for starting points.
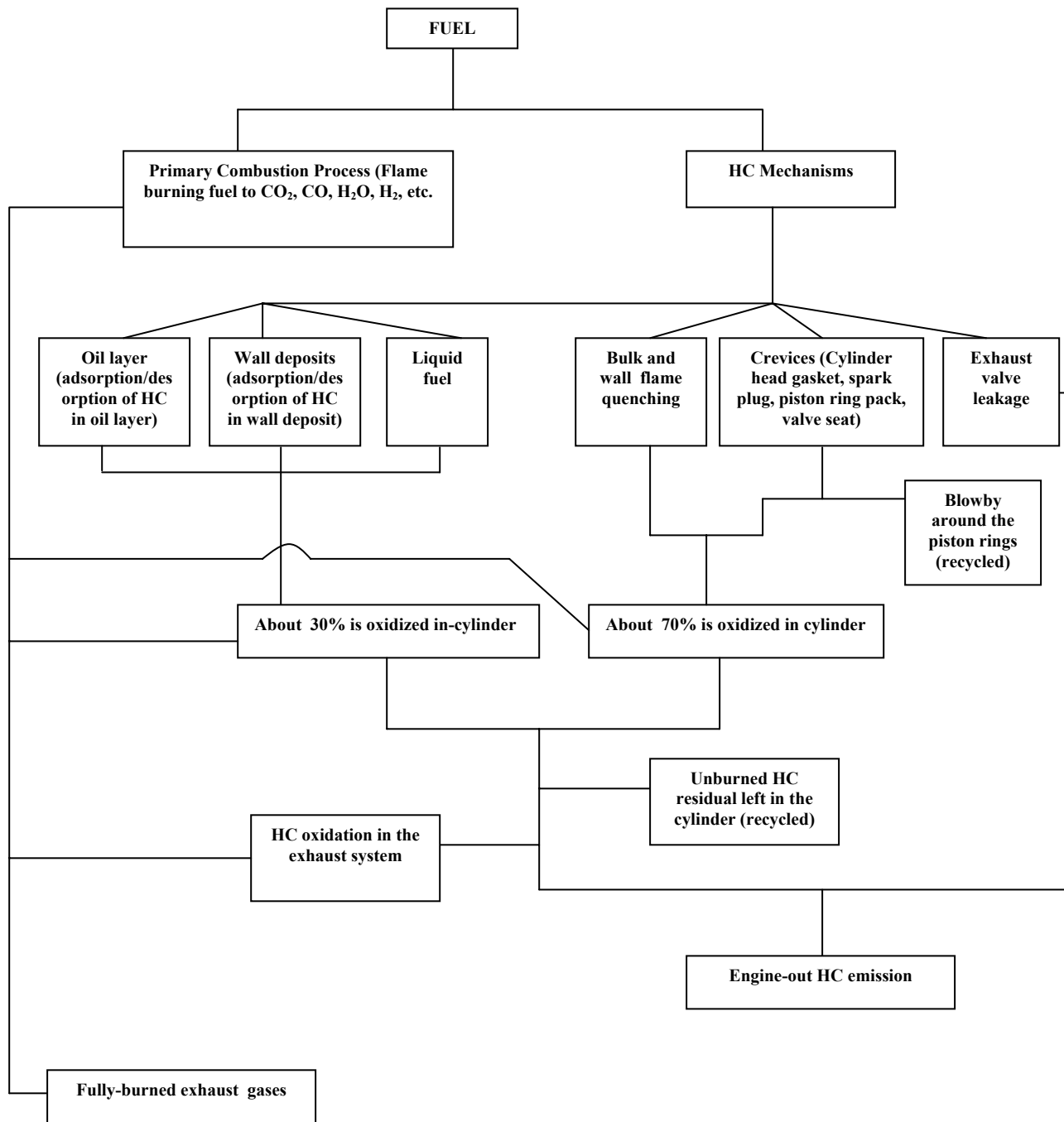
```
                          ┌───────────────┐
                          │     FUEL      │
                          └───────┬───────┘
              ┌───────────────────┴───────────────────┐
    ┌─────────────────────────────┐        ┌───────────────────┐
    │ Primary Combustion Process  │        │   HC Mechanisms   │
    │ (Flame burning fuel to CO2, │        └───────────────────┘
    │  CO, H2O, H2, etc.          │
    └─────────────────────────────┘
```

| Oil layer (adsorption/desorption of HC in oil layer) | Wall deposits (adsorption/desorption of HC in wall deposit) | Liquid fuel | | Bulk and wall flame quenching | Crevices (Cylinder head gasket, spark plug, piston ring pack, valve seat) | Exhaust valve leakage |

Blowby around the piston rings (recycled)

About 30% is oxidized in-cylinder

About 70% is oxidized in cylinder

Unburned HC residual left in the cylinder (recycled)

HC oxidation in the exhaust system

Engine-out HC emission

Fully-burned exhaust gases

Figure 1. A flow chart indicating the fate of the fuel inside the combustion chamber of an engine.
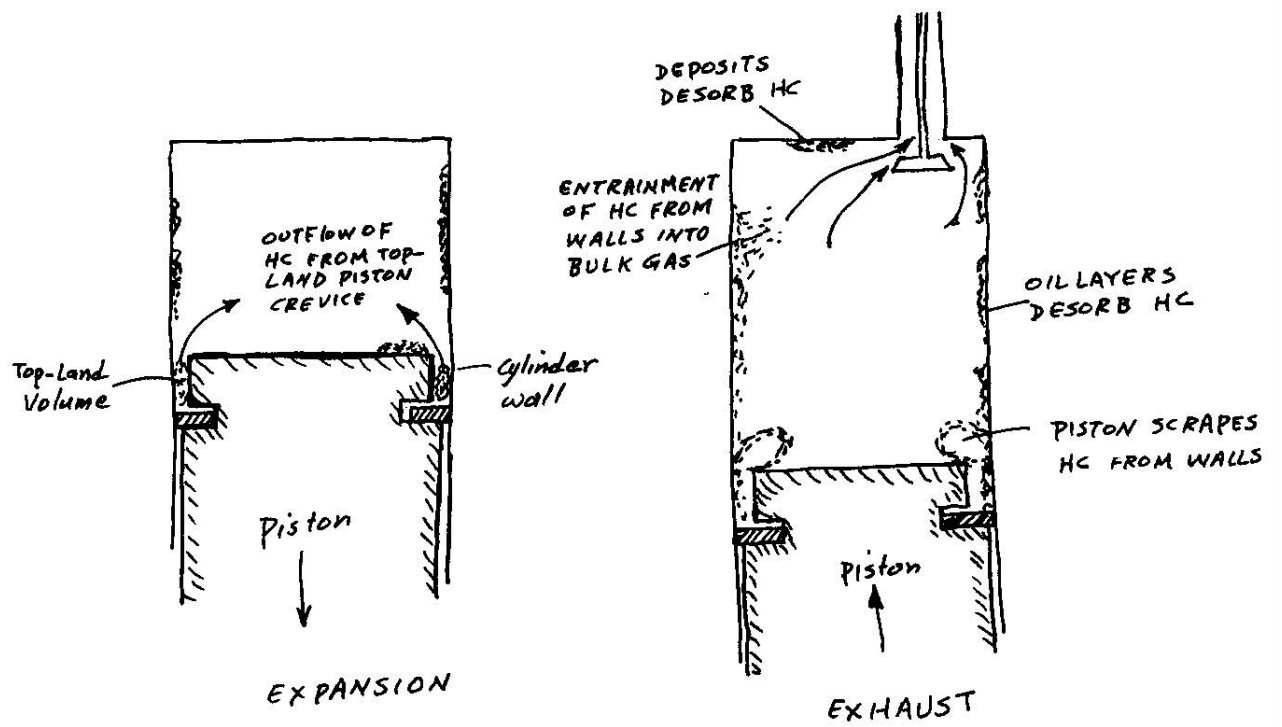
3

Figure 2. Schematic diagram of unburned HC emission mechanism in spark-ignited engines. Only first top ring is shown.