Mechanisms of HC Formation in SI Engines

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Flame Quenching in SI Engines

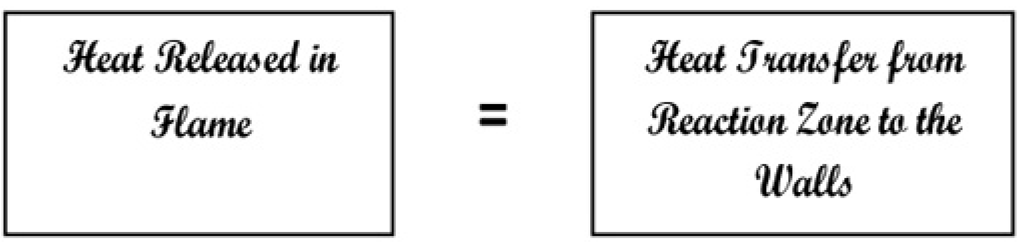
Photographic studies of flame region in a spark ignition engine immediately after arrival of flame close to the combustion chamber walls have shown existence of a thin non-radiating layer adhering to the combustion chamber. Flame propagates through unburned charge when the energy released on combustion is able to maintain the reaction zone temperatures at a high enough level to sustain the rapid combustion reactions. However, as the flame approaches combustion chamber walls, more and more heat is lost from the flame to the walls. Due to heat transfer from the flame to the walls, temperature of the reaction zone gets lowered that slows down combustion reactions reducing heat release rate. Finally, as the flame reaches in close proximity of the walls, the gas temperature ahead of flame falls below ignition point and the flame gets extinguished. This phenomenon is known as flame quenching.

The flame propagating normal to the single wall will quench at some distance away. When the flame is propagating through a tube it may not propagate if the tube diameter is smaller than a critical value. Similarly, flame may not propagate between the two parallel plates if the distance between the plates is below a critical limit. The normal distance from the wall where flame gets quenched, or the gap between two parallel plates, or diameter of the tube in which flame is just unable to propagate under the given charge conditions, is called *quench* distance or *quench layer thickness*. The wall-quenching effects are primarily due to heat transfer and not due to diffusion of species.

Quench Layer Thickness

Let us consider that flame is propagating normal to a single wall.

At the Instant of Flame Quenching



For a laminar flame and also as the flame is very close to the walls, heat from the reaction zone is mainly transferred by conduction and, the convection effects may be neglected. Thus,

$$k \cdot \frac{\Delta T_c}{\delta_q} (heat\,transfer) = \rho_u \cdot S_L \cdot h\,(heat\ released) = \rho_u \cdot S_L \cdot \bar{c}_{pb} \cdot \Delta T_f \qquad (2.30)$$

where

k	=	Thermal conductivity of the unburned mixture,
ΔT_c	=	Characteristic temperature difference for heat transfer,
δ_q	=	Quench distance,

ρ_u	=	Unburned mixture density,
S_L	=	Laminar flame speed,
h	=	Heat release per unit mass of the mixture burned,
$\bar{c}_{Pb}$	=	Average specific heat of burned gases, and
ΔT_f	=	Temperature rise on combustion in the flame.

Introducing thermal diffusivity, *a* in the equation 6.39, we get

$$\delta_q = \frac{\alpha_u}{S_L}\frac{\overline{C}_{pu}}{\overline{C}_{pb}}\frac{\Delta T_c}{\Delta T_f} \qquad (2.31)$$

A similar relationship for the flame quenching between two parallel plates is also obtained. The dimensionless quantity $\frac{\delta_q S_L}{\alpha_u}$ is Peclet number.

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From the above:

- Quench distance is inversely proportional to the laminar flame speed.
- For a given fuel- air mixture composition, pressure and temperature, δ_q is proportional to the Peclet number at the flame quenching conditions.

Quench distance or quench layer thickness depends on several parameters viz., wall geometry, fuel composition, mixture stoichiometry, flame speed, temperature and pressure of the reactants, thermal conductivity and turbulence. Typical quench layer thickness for stoichiometric mixtures of different fuels for laminar flame combustion are given in Table 2.2.

Table 2.2

Quench layer thickness, δ_q(mm) for different fuel-air mixtures,
ϕ =1, P = 1atm and T = 20 ºC

Fuel	δ_q, mm
Hydrogen	0.6
Methane	1.9
Propane	2.1
Isooctane	2.0
Methanol	1.8

In engine like conditions, typical two wall quench distance ranges from 0.2 to 1 mm. Peclet number for flame quenching between two parallel plates is nearly 5 times of the single wall quench distance. Thus, the single wall quench layer thickness would be in the range 0.04 to 0.2 mm. For example, in a SI engine operating on normal gasoline, at an average cylinder pressure = 10 bar, S_L= 0.2 m/s and a = 10-5 m2/s, single wall quench distance is estimated to be about 0.05 to 0.1 mm assuming ΔT_c and ΔT_f, to be about equal in Eq. (6.40).

HC Emissions from Wall Quenching

Single wall quench layer thickness typically varies from 0.05 to 0.1 mm. It decreases with increase of engine load as higher wall temperature results at higher engine loads, which reduces heat loss to the walls from the reaction zone, and consequently a smaller quench layer thickness is obtained. However, at top dead centre the surface to volume ratio of the combustion chamber is at its maximum and at this point the wall quench layer may comprise of 0.1 to 0.2 percent of the total charge inducted into the cylinder.

Studies on combustion of pre-mixed fuel air mixtures in combustion bombs show that when all the crevices in the bomb are eliminated by filling with solid material, unburned HC concentrations were just about 10 ppmC only. Such low concentrations result as after flame quenching the hydrocarbons in the quench layer thickness on the single walls diffuse in the hot burned gas quite early and get oxidized. Typically, most hydrocarbons would get oxidized on diffusion in the high temperature burned gases within 2-3 milliseconds of the flame quench. These studies showed that the contribution of single wall quench layers to the total unburned HC emission is quite small.

Crevice HC

- Crevices in the combustion chamber are narrow regions into which fuel-air mixture can flow but flame cannot propagate due to their high surface to volume ratio causing high heat transfer rates to walls.
- The largest crevice in the combustion chamber is between cylinder wall and piston top land, and second land.
- Other crevices present are along the gasket between cylinder head and block, around intake and exhaust valve seats, threads around spark plug and space around the central electrode of the spark plug.

Piston – ring - cylinder crevice is shown schematically in Fig. 2.12. Table 2.3 gives typical volumes contained in different the crevice regions in the cylinder of a production engine. Total crevice volume is about 3 to 5 percent of the clearance volume and the piston and cylinder crevice constitutes around 70 to 80 percent of the total crevice volume.

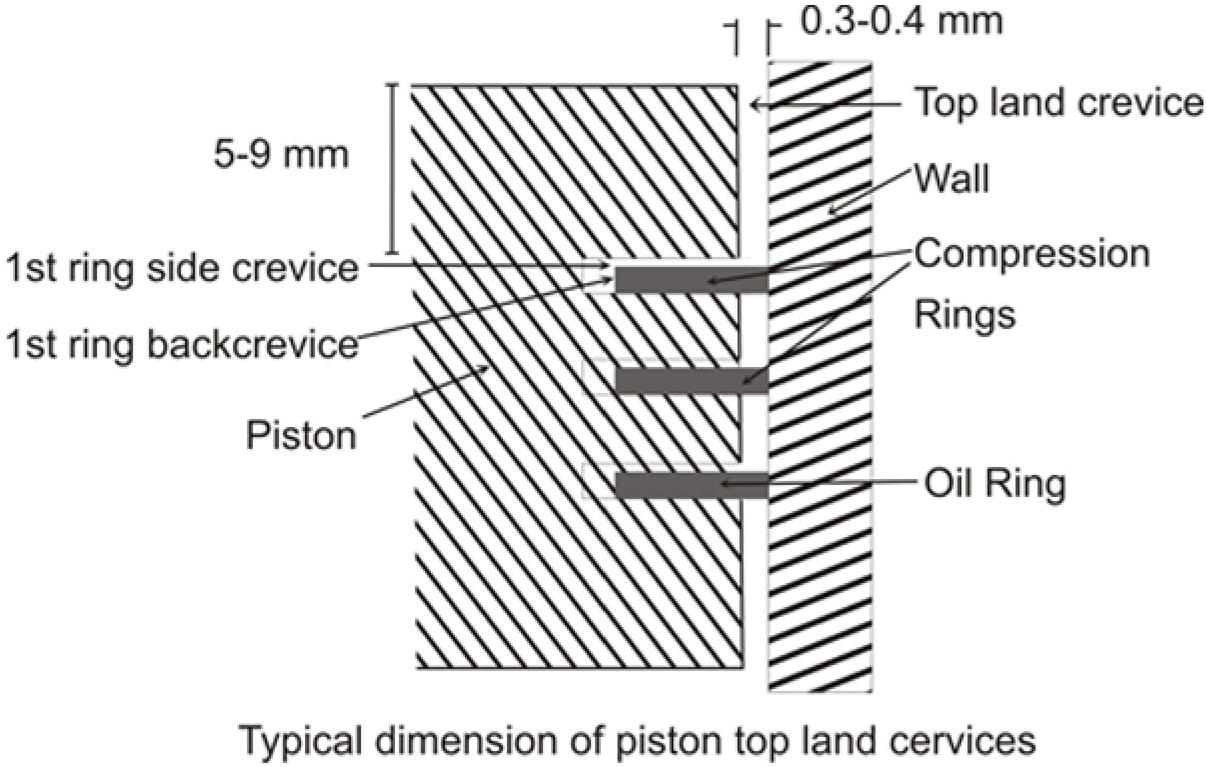

Figure 2.12	Typical dimensions of piston top land crevices.

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Table 2.3

Typical Volume Contained in Engine Crevices, cm^3
(Engine Displacement Volume/ Cylinder = 352 cm^3, CR = 9:1)

	Volume, cm^3	Percent
Clearance volume per cylinder	44	100
Volume above first ring (top land)	0.51	1.32
Volume behind first ring	0.32	0.86
Volume between Ist and 2nd rings (Second land)	0.40	0.88
Volume behind second ring	0.32	0.86
Total ring crevice volume	1.55	3.5
Spark plug thread crevice	0.20	0.45
Head gasket crevice	0.20	0..45
Total crevice volume	1.95	4.4

During compression and combustion, unburned charge is pushed into these crevices and at peak pressure, maximum gas would be stored in the crevices. The gas composition into the crevices depends on the location of spark plug. In the piston-cylinder crevices mostly unburned charge would be filled in unless the flame has reached piston top in some location nearest to the spark plug before the peak pressure occurs, which would result also in small amounts of burned gas being pushed into the crevice in this location. The other crevices close to spark plug would be filled with a larger fraction of the burned gas. During expansion, the stored gases in the crevices begin to flow back into the cylinder. Part of the unburned charge from crevices that expands back into the combustion chamber is oxidized on mixing with the hot burned gases.

Amount of HC Stored in Crevices include:

Contribution of crevice volume to HC emissions may be understood as follows. The crevice gas temperatures are nearly equal to the temperature of walls which are cooled. Hence, the density of the charge stored in the crevices is higher than in the cylinder. The maximum fraction of the unburned charge stored in crevices, *Es* occurs at peak pressure and is given by;

$$E_s = \frac{m_{cr}}{m_o} = \frac{V_{cr} P_{\max} T_o}{V_o P_o T_{cr}} \qquad (2.32)$$

where m, *V*, *T* and *P* are mass volume, pressure and temperature. The subscripts *cr* and *o* refer to the conditions in the crevices and at the end of intake stroke in the cylinder, respectively. P_{max} is the peak pressure in the cylinder.

Typically P_{max} /P_o = 40, T_o= 300 K and T_{cr} = 400 K. Taking piston top land crevice volume equal to 0.9 cm^3 and the engine cylinder volume of 300 cm^3 for a compact car, 9% of the charge is stored in the piston ring crevice. The crevice charge would consist of 10 to 15 percent residual gases and some burned gases forced into it when flame propagates across the crevice opening.

In a production engines ring crevice region may contribute 25 % to 50% to exhaust HC emissions depending upon the operating conditions.

Increase in radial clearance between the piston and cylinder beyond two-plate quench distance would allow flame penetration in the crevice. It would result in reduction of HC as the flame would be able to penetrate in the crevice volume. However, increase in radial clearance would lead to increase in blow by gases and loss in engine power output.

Under conditions of high residual gas dilution or use of very lean mixtures, the flame may quench much before it reaches the crevice region. Thus, increase in crevice volume by increasing radial clearance can result in an increase in HC emissions under engine operation on lean mixtures or with high EGR.

Example 2.2 A SI engine has bore x stroke = 76 x 76 mm and compression ratio equal to 9.0:1. Top piston land height is 7 mm and clearance between piston and cylinder liner is 0.35 mm. At the end of intake stroke the stoichiometric mixture of gasoline (C8H18) is at 0.09 MPa and 330 K. Peak cylinder pressure during combustion reaches 3.0 MPa. The temperature of gas in the piston crevice region due to heat transfer to the cylinder walls is 400 K. Calculate the amount of charge stored in the top land crevice at the instant of maximum cylinder pressure. What fraction of the charge inducted is stored in this crevice?

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Solution

Cylinder bore, B = Stroke, S =76 mm
Clearance between cylinder and piston, dc = 0.035 mm
Piston top land height, h = 7 mm Swept volume of the engine cylinder,

$$V_d = \frac{\pi B^2 S}{4} = \frac{3.14(76)^3 \times 10^{-9}}{4} = 345 \times 10^{-6}\,, m^3$$

Volume of the cylinder at the end of intake stroke,

$$V_0 = V_d \left(\frac{CR}{CR-1}\right) = 345 \times 10^{-6} \times \frac{9}{8} = 388 \times 10^{-6}$$

Volume of the top land crevice can be approximated,

$$V_{cr} = \pi B d_c h = 3.14 \times 76 \times 0.35 \times 7 = 585\,, mm^3$$

Mass of charge stored in the crevice

Molecular weight of the stoichiometric charge of C8H18 and air (O2 +3.76 N2)

$$M_m = \frac{(8 \times 12 + 18) + 12.5(32 + 3.76 \times 28)}{1 + 12.5 \times 4.76} = 30.25$$

Mass of charge stored in the crevice at peak pressure,

$$m_{cr} = \frac{P_{max} V_{cr}}{R.T_{cr}} = \frac{3 \times 10^6 \times 585 \times 10^{-9}}{(8314.3/30.25) \times 400} = 0.016 \times 10^{-3}\ \ , kg$$

Fraction of inducted charge stored in the crevice from Eq.2.32

$$E_s = \frac{585 \times 10^{-9} \times 3 \times 10^6 \times 330}{388 \times 10^{-6} \times 0.09 \times 10^6 \times 400} = 41.5 \times 10^{-3}\ or\ 4.15\%$$

Ans.

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