Laminar Premixed Flames

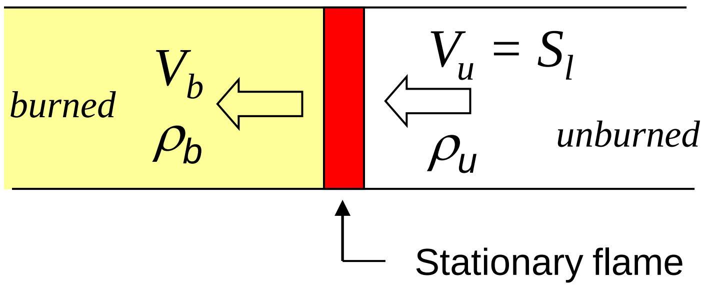
A flame represents an interface separating the unburned gas from the combustion products.

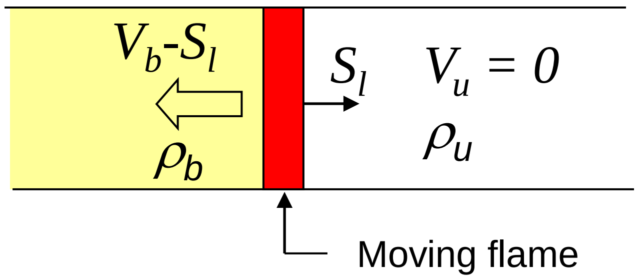
A flame can propagate as in an engine application or be stationary as in a burner application.

For a given P, T, ϕ and laminar conditions a flame has two basic properties:

a) adiabatic flame temperature, T_{ad}

b) laminar burning velocity, S_l





Note, S_l is defined in terms of the approaching unburned gas velocity

Pressure is roughly constant across the flame so $\rho \sim 1/T$

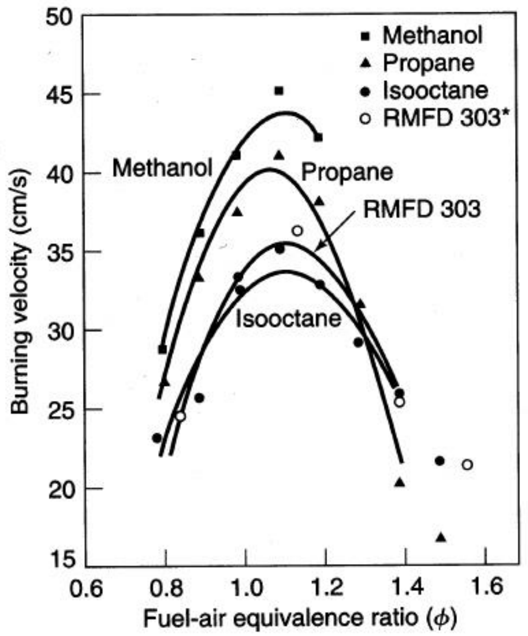
Laminar Burning velocity

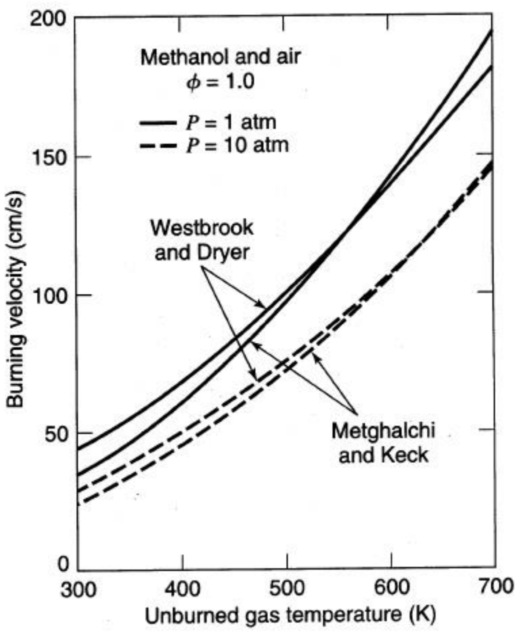
Maillard-LeChatelier theory gives:

$$S_l^2 \propto \alpha \cdot T_u \cdot P^{n-1} \exp(-E/\bar{R}T_{ad})$$

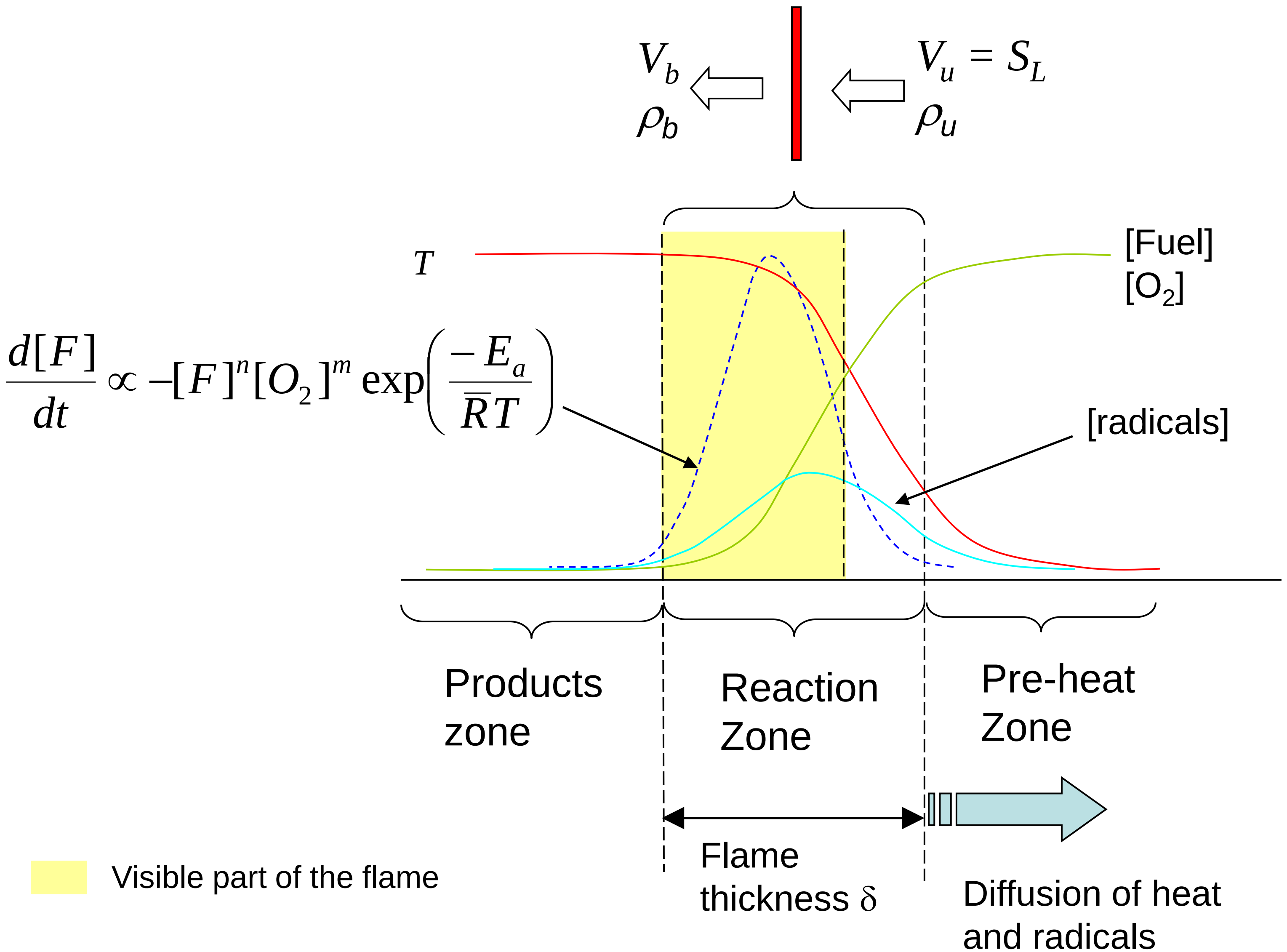
Higher flame velocity corresponds to:

1) higher unburned gas temperature
2) lower pressure
3) higher adiabatic flame temperature (chemical reaction)
4) higher thermal diffusivity α (= $k_{cond}/\rho c_p$)





Structure of Flame



Turbulent Flames

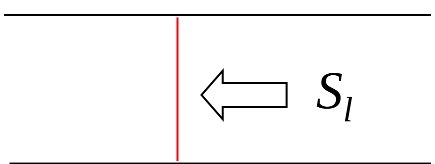
Unlike the laminar burning velocity, the **turbulent flame** velocity is not a property of the gas but instead it depends on the details of the flow.

The IC engine in-cylinder flow is always turbulent and the smallest eddies (Kolmogorov scale) are typically larger than the laminar flame thickness (1 mm)

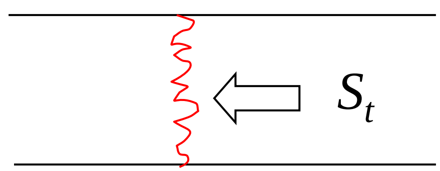
Under these conditions the flame is said to display a structure known as **wrinkled laminar flame**.

A wrinkled laminar flame is characterized by a continuous flame sheet that is distorted by the eddies passing through the flame.

The turbulent burning velocity depends on the turbulent intensity u_t and can be up to 30 times the laminar burning velocity



Laminar flame



Turbulent flame

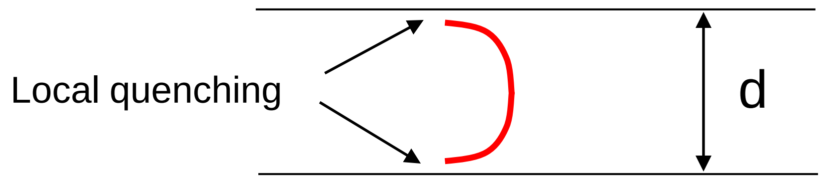
$$S_t / S_l = 1 + a(u_t / S_l)^b$$

Flame Thickness and Quenching Distance

A rough estimate of the laminar flame thickness δ can be obtained by:

$$\delta = \frac{2\alpha}{S_l} = \frac{2}{S_l}\left(\frac{k_{cond}}{\rho \cdot c_p}\right) \approx 1\,\text{mm}$$

As a flame propagates through a duct heat is lost from the flame to the wall



It is found experimentally that if the duct diameter is smaller than some critical value then the flame will extinguish

This critical value is referred to as the **quenching distance** d_{min} and is close in magnitude to the flame thickness.

$$d_{\min} \propto \delta$$

Minimum Ignition Energy and Flammability Limits

A flame is spark-ignited in a flammable mixture only if the spark energy is larger than some critical value known as the **minimum ignition energy** E_{ign}

It is found experimentally that the ignition energy is inversely proportional to the square of the mixture pressure.

Experiments show that a flame will only propagate in a fuel-air mixture within a range of mixture compositions known as the **flammability limits**.

The fuel-lean limit is known as the **lower (or lean) flammability limit** and the fuel-rich limit is known as the **upper (or rich) flammability limit**.

The flammability limit is affected by both the mixture initial pressure and temperature.