Combustion & Flame Basics

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ME 417: Internal Combustion Engines

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Combustion & Flame

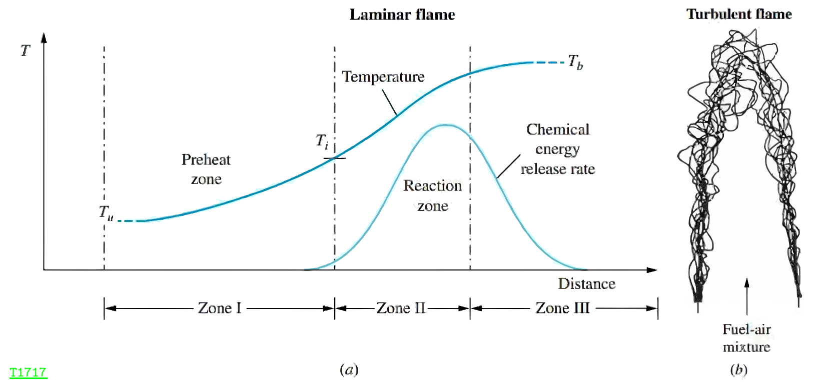
- **Combustion** of fuel-air mixture inside engine cylinder is one of the processes that controls engine power, efficiency and emissions.
- Combustion commonly observed involves **flame**, which is a thin region of rapid exothermic chemical reaction.
- Flame propagation is the result of strong coupling between chemical reaction, transport processes of mass diffusion, heat conduction and fluid flow.
- Conventional spark-ignition (SI) flame is premixed unsteady turbulent flame, and the fuel-air mixture through which it propagates is in the gaseous state.
- Diesel engine (CI) combustion process is predominantly an unsteady turbulent diffusion flame, and the fuel is initially in the liquid phase.

Classifications of Flames

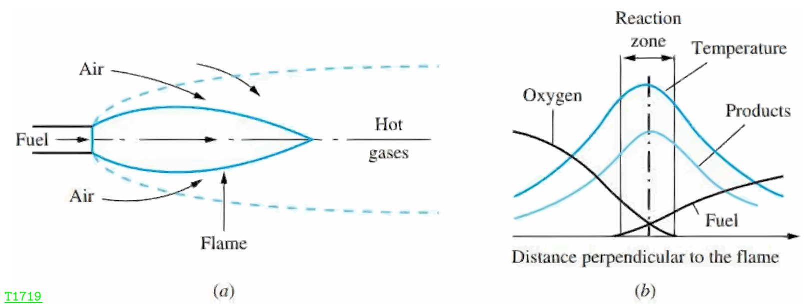
1. **Premixed Flame:** fuel and oxidizer are essentially uniformly mixed prior to combustion. It is a rapid, essentially isobaric, exothermic reaction of gaseous fuel and oxidizer, and flame propagates as a thin zone with speeds of less than a few m/s.
2. **Diffusion Flame:** reactants are not premixed and must mix together in the same region where reactions take place. It is dominated by the mixing of reactants, which can be either laminar or turbulent, and reaction takes place at the interface between the fuel and oxidizer.

1. **Laminar:** flow, mixing and transport are by molecular process.
2. **Turbulent:** flow, mixing and transport are enhanced by macroscopic relative motion of fluid eddies of turbulent flow.

- Steady / Unsteady
- Solid phase / Liquid phase / Gaseous phase.



Premixed flame structure: (a) Temperature and chemical energy release-rate profiles through a premixed laminar flame; (b) multiple short time-exposure realizations of a turbulent premixed flame.



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Diffusion flame structure: (a) Fuel, air, and flame location in a jet diffusion flame; (b) concentration profiles of fuel, oxidizer, products, and temperature, through the flame.

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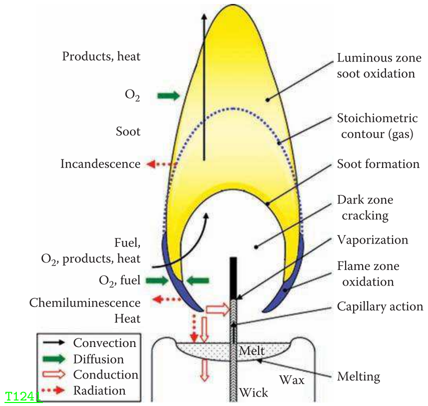

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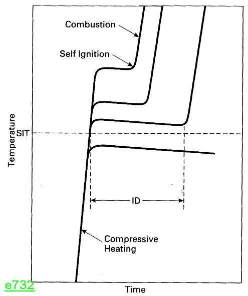
Physical and chemical processes in a candle.

Auto-ignition & Self-ignition Temperature (SIT)



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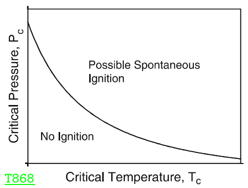

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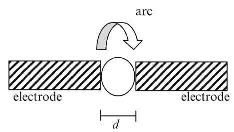
If the temperature of an air-fuel mixture is raised high enough, the mixture will self ignite without the need of an external igniter. The temperature above which this occurs is called the **SIT**.

- If the mixture temperature is lower than SIT, no ignition will occur and the mixture will cool off.
- If mixture temperature is above SIT, self-ignition will occur after a short time delay called **ignition delay (ID)**.
- The higher mixture temperature above SIT, the shorter will be the ID.
- ID depends on initial temperature, pressure, density, turbulence, swirl, fuel-air-ratio presence of inert gases, etc.

Minimum Ignition Energy



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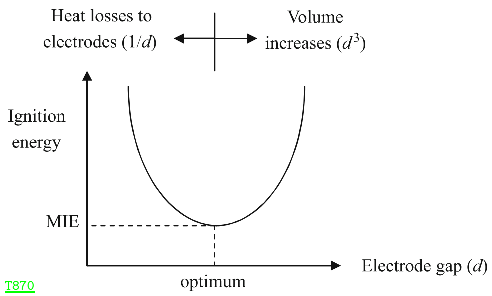

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Fuel	MIE (mJ)
Methane	0.30
Ethane	0.42
Propane	0.40
n-Hexane	0.29
Isooctane	0.95
Acetylene	0.03
Hydrogen	0.02
Methanol	0.21

Flammability Limits

- As the combustible mixture gets too rich or too lean, flame temperature decreases and consequently, flame cannot propagate when the equivalence ratio is larger than an upper limit or smaller than a lower limit.
- These two limits are referred to as the rich and the lean flammability limits (RFL and LFL respectively), and they are often expressed as fuel percentage by volume in the mixture.

Fuel vapor	Lean limit	Rich limit	Fuel vapor	Lean limit	Rich limit
Hydrogen (H_2)	4	75	Isopropyl	2	12
Methane (CH_4)	5	15	Ethanol (C_2H_5OH)	3.3	19
Gasoline	1.4	7.6	n-Heptane (C_7H_{16})	1.2	6.7
Diesel	0.3	10	Iso-octane (C_8H_{18})	1	6.0
Ethane (C_2H_6)	3.0	12.4	Propane (C_3H_8)	2.1	9.5
n-Butane (C_4H_{10})	1.8	8.4	n-Pentane (C_5H_{12})	1.4	7.8
n-Hexane (C_6H_{14})	1.2	7.4	Dimethylether (C_2H_6O)	3.4	27

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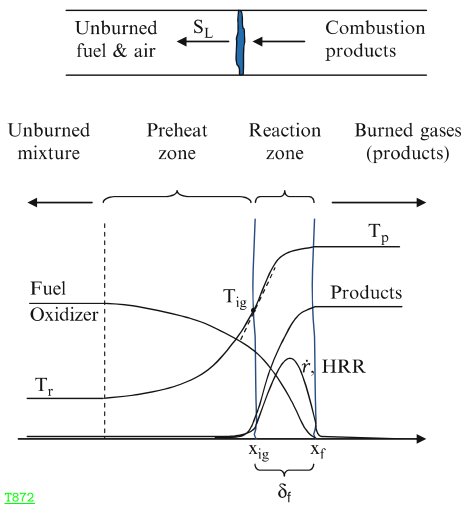
Premixed Flame

- **Flame** is the result of the self-sustaining chemical reaction occurring within a region of space called **flame front** where unburned mixture is heated and converted into products.
- Flame reaction zone temperatures are around 2800 K. At these temperatures, flame contains highly reactive atoms and radicals.
- Flame propagation arises from heat transfer and diffusion of active particles from the hot flame to the relatively cold mixture.
- Flame speeds are significantly increased by **turbulence** which distorts flame front to increase burning area and enhances heat and mass diffusion.



S_L ≡ laminar burning velocity
T_{ig} ≡ ignition temperature
δ_l ≡ laminar flame thickness
HRR ≡ Heat release rate

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Laminar Flame Propagation

- **Laminar burning velocity, S_L** is an intrinsic property of a fuel-air mixture. It is defined as 'the velocity, relative to & normal to the flame front, with which unburned gas moves into the front & is transformed to products under laminar flow conditions'.

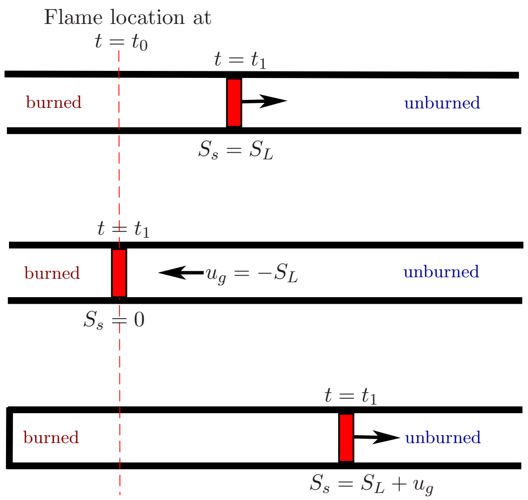
$$S_L = \frac{1}{\rho_u A_f}\frac{dm_b}{dt} \quad : \quad S_s = S_L + u_g$$

dm_b/dt is mass burning rate & A_f is flame front surface area.

- $S_s \equiv$ flame speed: space velocity of flame front normal to itself. It is not a unique property of combustible fuel-air premixture.
- $u_g \equiv$ gas expansion velocity & is a function of ρ_u & ρ_b.

$$S_L = f(fuel, T, P, \phi) \cong S_{L,0}\left(\frac{T}{T_o}\right)^{\alpha}\left(\frac{P}{P_o}\right)^{\beta}$$

- $_u \equiv$ unburned mixture, $_0 \equiv$ datum pressure & temperature.



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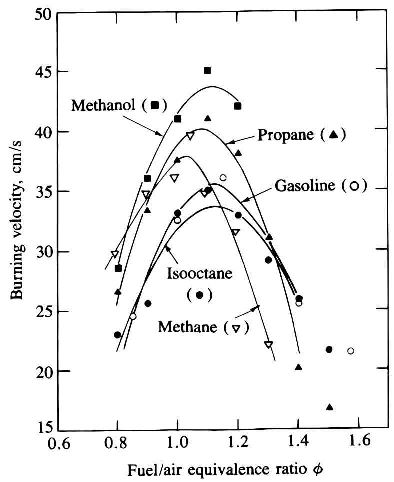
Effect of Equivalence Ratio, ϕ



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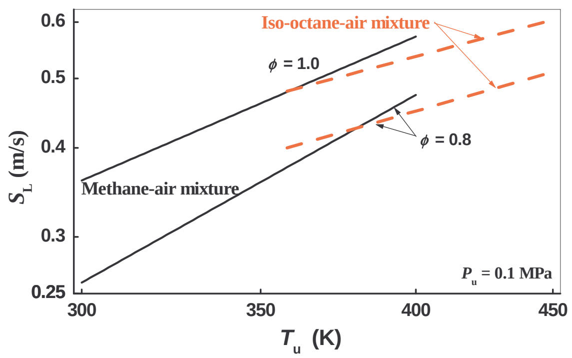
Effect of Unburned Mixture Temperature, T_u



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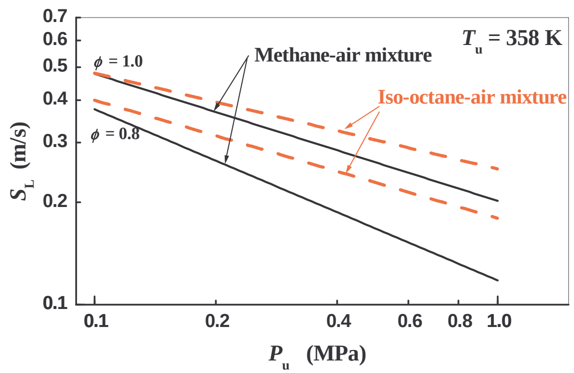
α is +ve. Increase in temperature increases chemical reaction rates and dissociations. So, more active radicals are produced to enhance flame propagation.

Effect of Unburned Mixture Pressure, P_u



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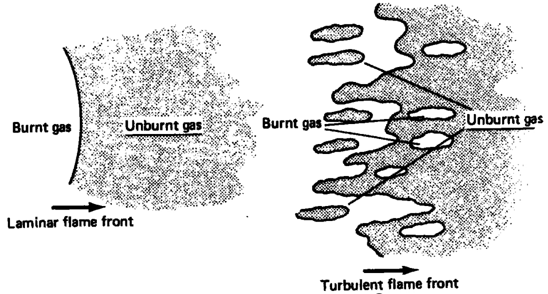
β is either zero or negative. Increased pressure increases flame temperature because of less dissociation, and less dissociation means less active radicals are available to diffuse upstream to enhance flame propagation.

Turbulent Flame Propagation



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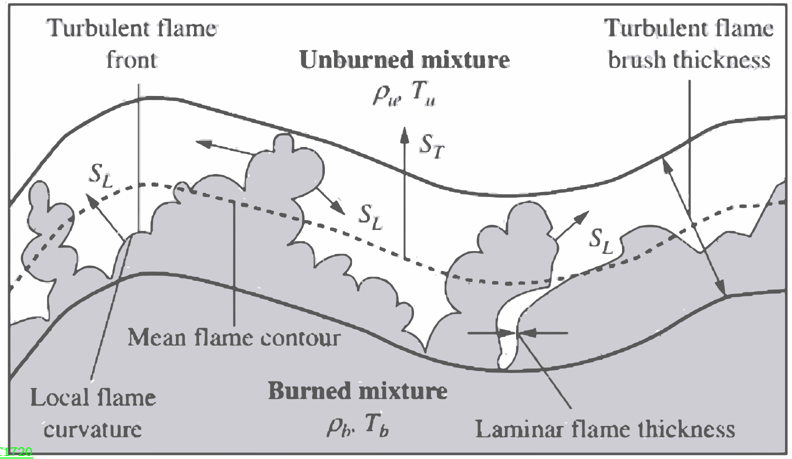
$$S_T = f(fuel, T, P, \phi, turbulence) \Rightarrow \frac{S_T}{S_L} \cong f(turbulence)$$

In engines, propagating flame fronts are wrinkled by turbulence which result in higher burning rate. The effect of turbulence is not always beneficial as too much turbulence can lead to extinction of flame.



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Schematic of the structure of the turbulent SI engine flame.