Flame Speed

Correlations

FLAME SPEED CORRELATIONS FOR SELECTED FUELS

- Metghalchi and Keck [11] experimentally determined S_L for various fuel-air mixtures over a range of temperatures and pressures typical of conditions associated with reciprocating internal combustion engines and gas turbine combustors.
- Eqn 8.33 similar to Eqn. 8.29 is proposed

$$S_L = S_{L,ref} \left(\frac{T_u}{T_{u,ref}}\right)^{\gamma} \left(\frac{P}{P_{ref}}\right)^{\beta} (1 - 2.1Y_{dil}) \quad (8.33)$$

for $T_u >\approx 350$ K.

- The subscript ref refers to reference conditions defined by

  $T_{u,ref} = 298$ K, $P_{ref} = 1$ atm and

  $S_{L,ref} = B_M + B_2(\Phi - \Phi_M)^2$ (for reference conditions)

  where the constants B_M, B_2, and Φ_M depend on fuel type and are given in Table 8.3.

- Exponents of T and P, γ and β are functions of Φ, expressed as

  $\gamma = 2.18 - 0.8(\Phi - 1)$ (for non-reference conditions)

  $\beta = -0.16 + 0.22(\Phi - 1)$ (for non-reference conditions)

- The term Y_{dil} is the mass fraction of diluent present in the air-fuel mixture in Eqn. 8.33 to account for any recirculated combustion products. This is a common technique used to control NO_x in many combustion systems

- **Table 8.3** Values for B_M, B_2, and Φ_M used in Eqn 8.33 [11]

Fuel	Φ_M	B_M (cm/s)	B_2 (cm/s)
Methanol	1.11	36.92	-140.51
Propane	1.08	34.22	-138.65
Iso octane	1.13	26.32	-84.72
RMFD-303	1.13	27.58	-78.54

Example 8.3

Compare the laminar flame speeds of gasoline-air mixtures with $\Phi = 0.8$ for the following three cases:

i. At ref conditions of $T = 298$ K and $P = 1$ atm
ii. At conditions typical of a spark-ignition engine operating at wide-open throttle: $T = 685$ K and $P = 18.38$ atm.
iii. Same as condition ii above, but with 15 percent (by mass) exhaust-gas recirculation

Solution

- RMFD-303 research fuel has a controlled composition simulating typical gasolines. The flame speed at 298 K and 1 atm is given by
- $S_{L,ref} = B_M + B_2(\Phi - \Phi_M)^2$
- From Table 8.3,
- B_M = 27.58 cm/s, B_2 = -78.38cm/s, Φ_M = 1. 13.
- $S_{L,ref}$ = 27.58 - 78.34$(0.8 - 1.13)^2$ = **19.05 cm/s**
- To find the flame speed at T_u and P other than the reference state, we employ Eqn. 8.33
- $S_L(T_u, P) = S_{L,ref} \left(\frac{T_u}{T_{u,ref}}\right)^{\gamma} \left(\frac{P}{P_{ref}}\right)^{\beta}$

where

$\gamma = 2.18 - 0.8(\Phi - 1) = 2.34$

$\beta = -0.16 + 0.22(\Phi - 1) = -\ 0.204$

Thus,

S_L(685 K, 18.38 atm) =

$19.05\ (685/298)^{2.34}(18.38/1)^{-0.204}$ =**73.8cm/s**

With dilution by exhaust-gas recirculation, the flame speed is reduced by factor (1-2.1 Y_{dil}):

S_L(685 K, 18.38 atm, 15%EGR) =

73.8cm/s[1-2.1(0.15)]= **50.6 cm/s**

QUENCHING, FLAMMABILITY, AND IGNITION

- Previously ⇨ steady propagation of premixed laminar flames
- Now ⇨ transient process: quenching and ignition. Attention to quenching distance, flammability limits, and minimum ignition energies with heat losses controlling the phenomena.

1. Quenching by a Cold Wall

- Flames extinguish upon entering a sufficiently small passageway. If the passageway is not too small, the flame will propagate through it. The critical diameter of a circular tube where a flame extinguishes rather than propagates, is referred to as the quenching distance.
- Experimental quenching distances are determined by observing whether a flame stabilised above a tube does or does not flashback for a particular tube diameter when the reactant flow is rapidly shut off.

- Quenching distances are also determined using high-aspect-ratio rectangular-slot burners. In this case, the quenching distance between the long sides, i.e., the slit width.
- Tube-based quenching distances are somewhat larger (~20-50 percent) than slit-based ones [21]

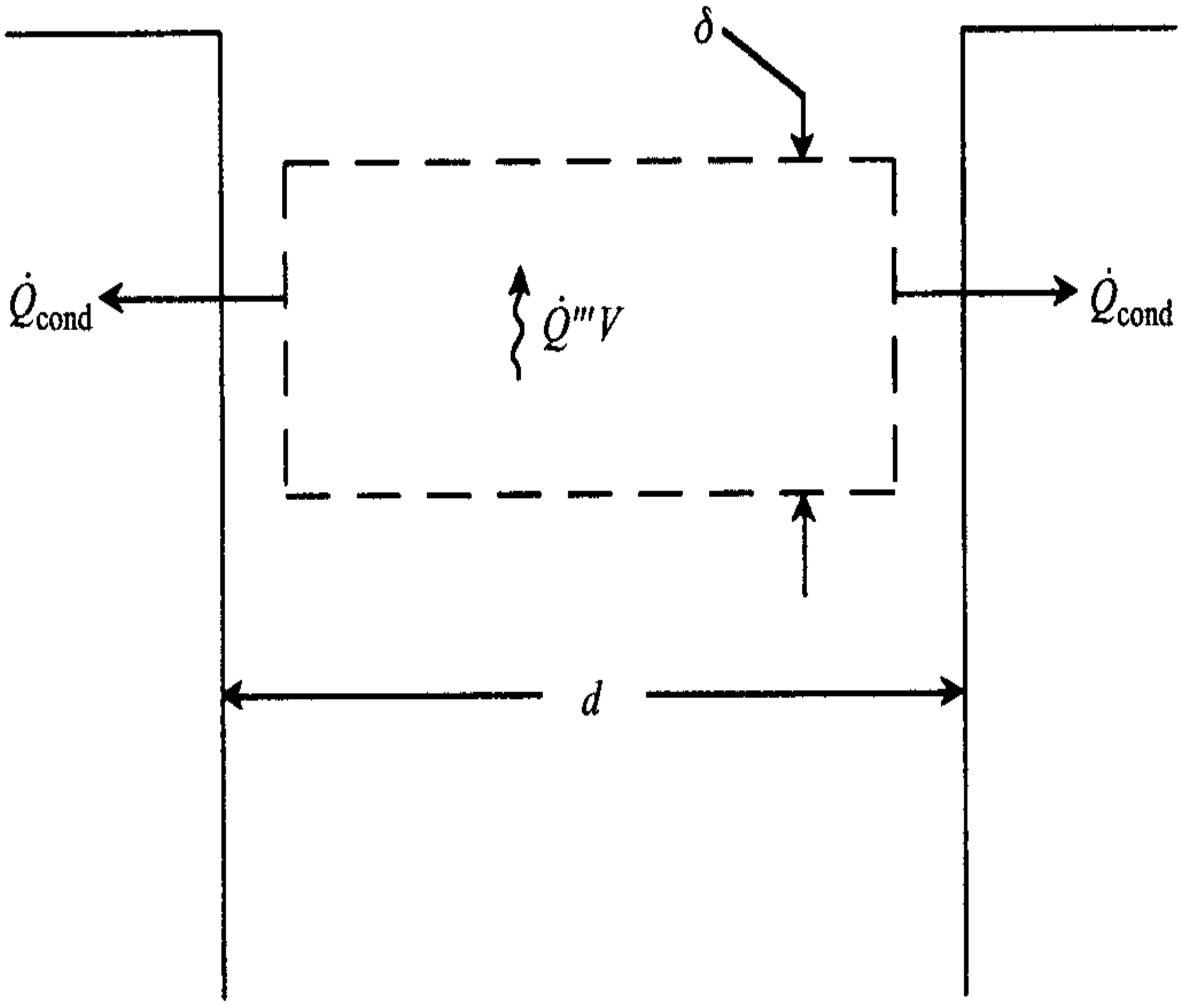


Figure 8.18 Schematic of flame quenching between two parallel walls.

2. Flammability Limits

- A flame will propagate only within a range of mixture the so-called lower and upper limits of flammability. The limit is the leanest mixture ($\Phi < 1$), while the upper limit represents the richest mixture ($\Phi > 1$). $\Phi = (A/F)_{stoich} / (A/F)_{actual}$ by mass or by mole
- Flammability limits are frequently quoted as %fuel by volume in the mixture, or as a % of the stoichiometric fuel requirement, i.e., (Φ x 100%). Table 8.4 shows flammability limits of some fuels

- Flammability limits for a number of fuel-air mixtures at atmospheric pressure is obtained from experiments employing "tube method".
- In this method, it is ascertained whether or not a flame initiated at the bottom of a vertical tube (approximately 50-mm diameter by 1.2-m long) propagates the length of the tube.
- A mixture that sustains the flame is said to be flammable. By adjusting the mixture strength, the flammability limit can be ascertained.

Table 8.4 Flammability limits, quenching distances and minimum ignition energies

	Flammability limit			Quenching distance, d	
	Φ_{min}	Φ_{max}	Stoich-mass air-fuel ratio	For $\Phi=1$	Absolute min, mm
C_2H_2	0.19	∞	13.3	2.3	-
CO	0.34	6.76	2.46	-	-
$C_{10}H_{22}$	0.36	3.92	15.0	2.1	-
C_2H_6	0.50	2.72	16.0	2.3	1.8
C_2H_4	0.41	> 6.1	14.8	1.3	-
H_2	0.14	2.54	34.5	0.64	0.61
CH_4	0.46	1.64	17.2	2.5	2.0
CH_3OH	0.48	4.08	6.46	1.8	1.5
C_8H_{18}	0.51	4.25	15.1	-	-
C_3H_8	0.51	2.83	15.6	2.0	1.8

Fuel	Minimum ignition energy	
	For Φ=1 (10^{-5} J)	Absolute minimum (10^{-5} J)
C_2H_2	3	-
CO	-	-
$C_{10}H_{22}$	-	-
C_2H_6	42	24
C_2H_4	9.6	-
H_2	2.0	1.8
CH_4	33	29
CH_3OH	21.5	14
C_8H_{18}	-	-
C_3H_8	30.5	26

3. Ignition

- Most of ignition uses electrical spark (pemantik listrik). Another means is using pilot ignition (flame from very low-flow fuel).

Simplified Ignition Analysis

- Consider Williams' second criterion, applied to a spherical volume of gas, which represents the incipient propagating flame created by a point spark. Using the criterion:
- Find a critical gas-volume radius, **R_{crit},** below which flame will not propagate
- Find minimum ignition energy, **E_{ign},** to heat critical gas volume from initial state to flame temperature (T_u to T_b).

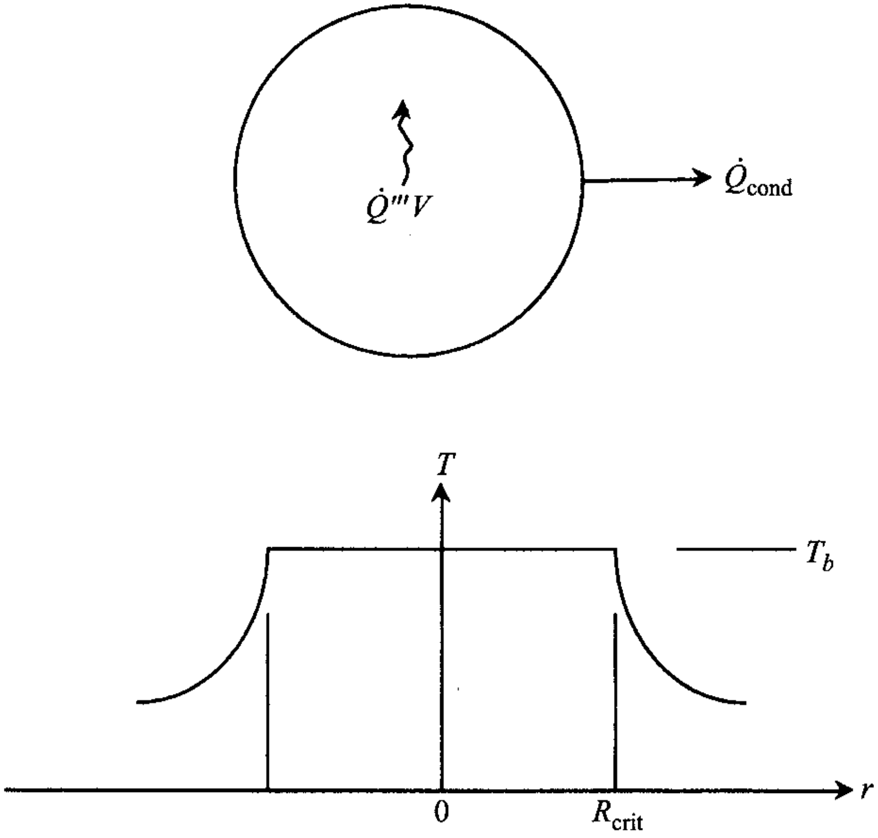


Figure 8.20 Critical volume of gas for spark ignition.

Figure 8.22. Effect of %fuel on E_{ign}

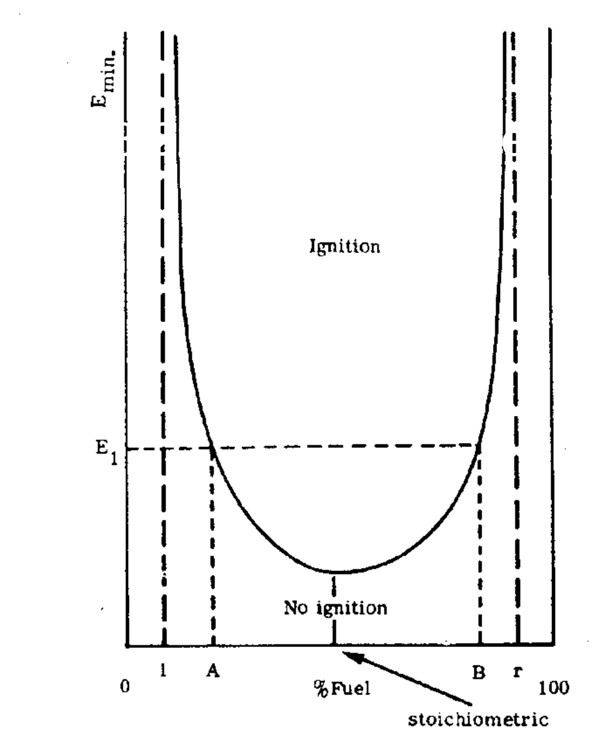


Figure 8.23. Effect of methane composition on E_{ign}

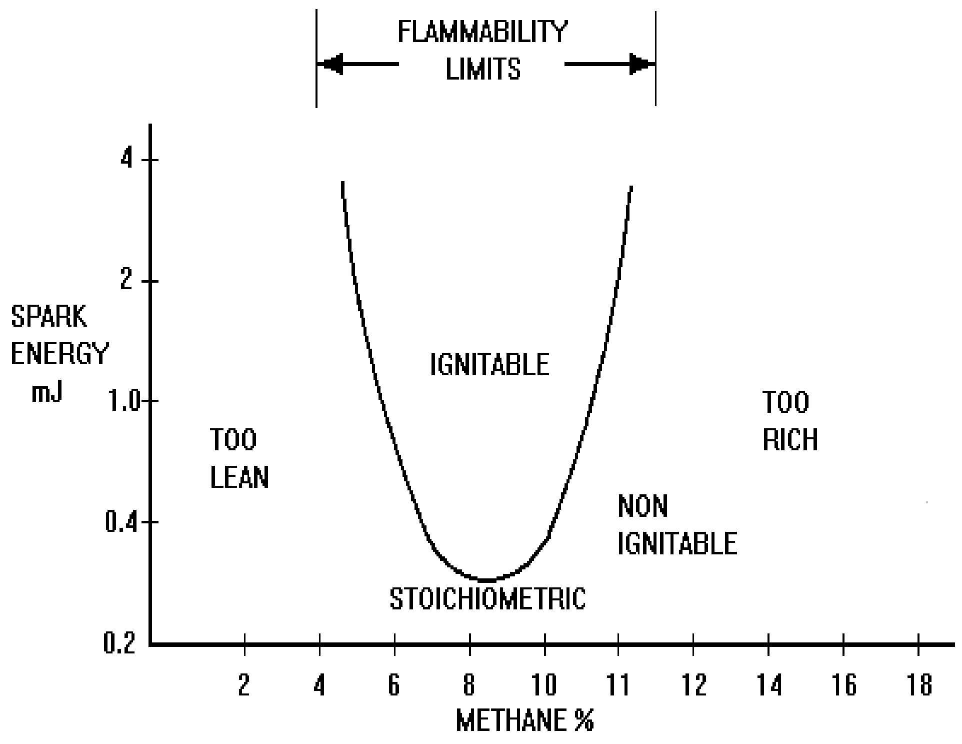
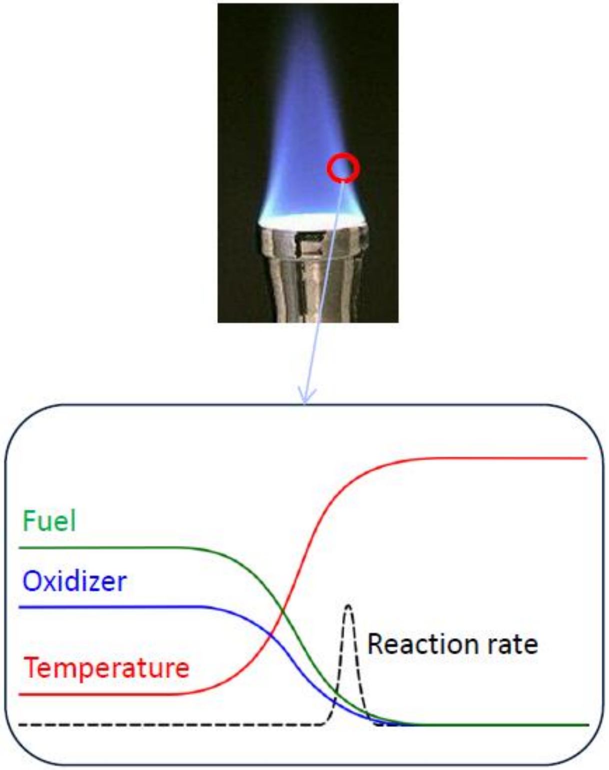


Table 8.5 Temperature influence on spark-ignition energy

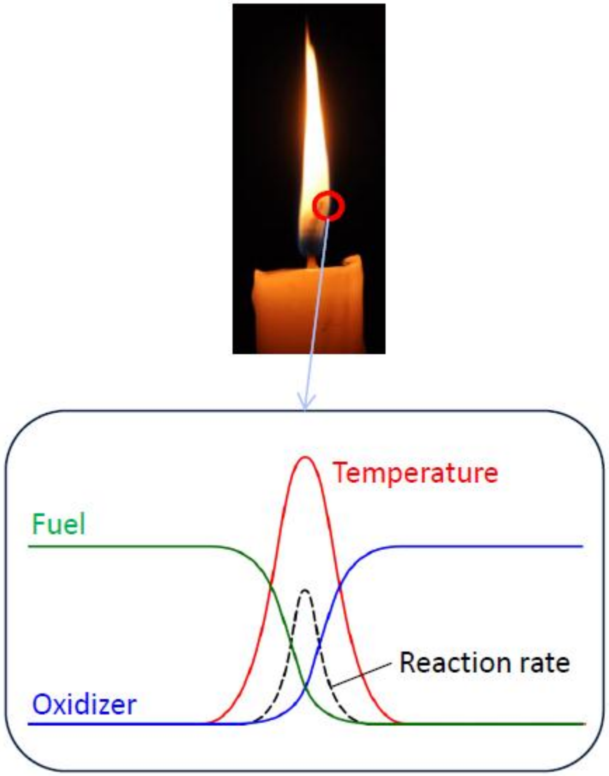
Fuel	**Initial temp (K)**	**E_{ign} (mJ)**
n-heptane	298	14.5
	373	6.7
	444	3.2
Iso-octane	298	27.0
	373	11.0
	444	4.8
n-pentane	243	45.0
	253	14.5

Fuel	**Initial temp (K)**	**E_{ign} (mJ)**
n-pentane	298	7.8
	373	4.2
	444	2.3
propane	233	11.7
	243	9.7
	253	8.4
	298	5.5
	331	4.2
	356	3.6
	373	3.5
	477	1.4

Premixed vs diffusion flames

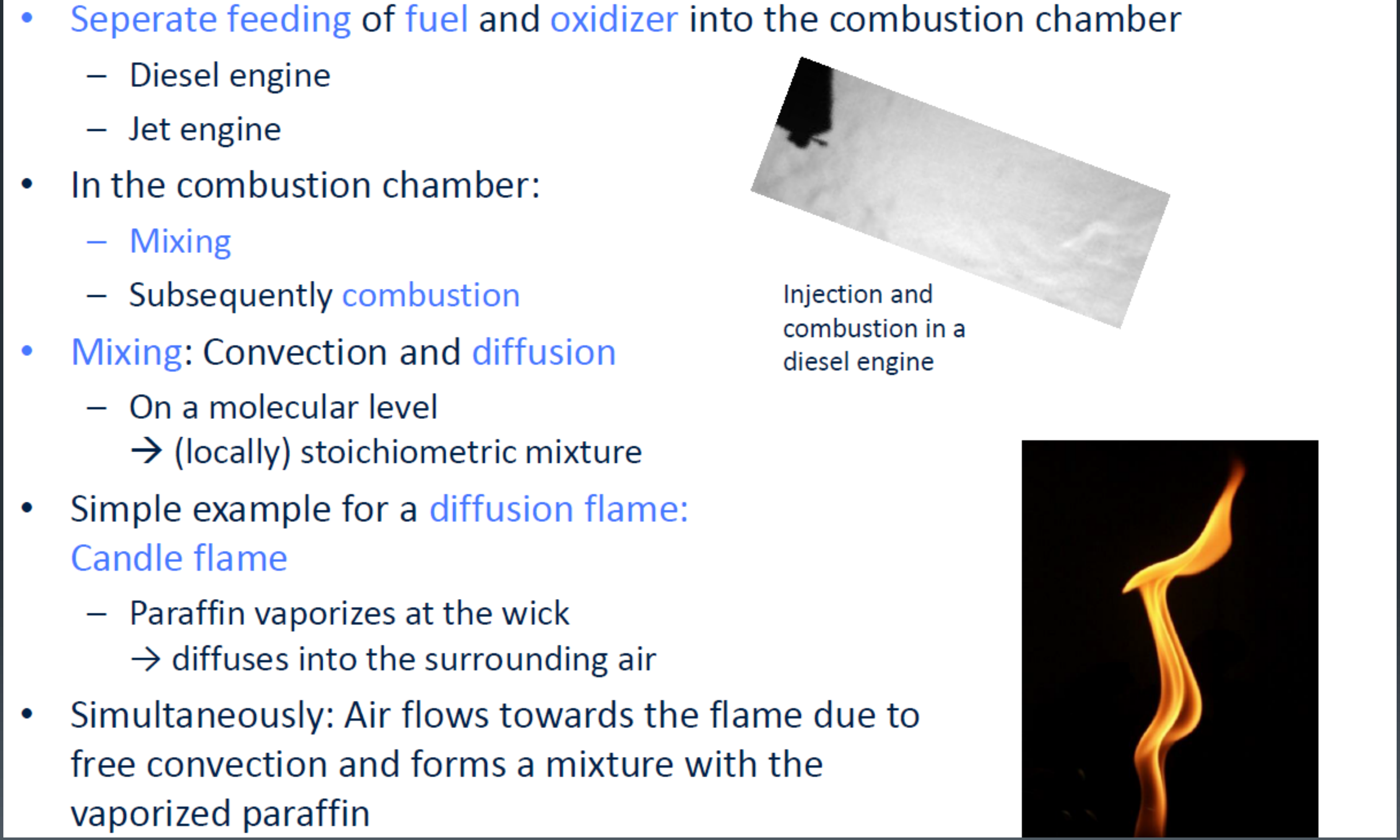


Structure of a premixed flame (schematic)



Structure of a diffusion flame (schematic)

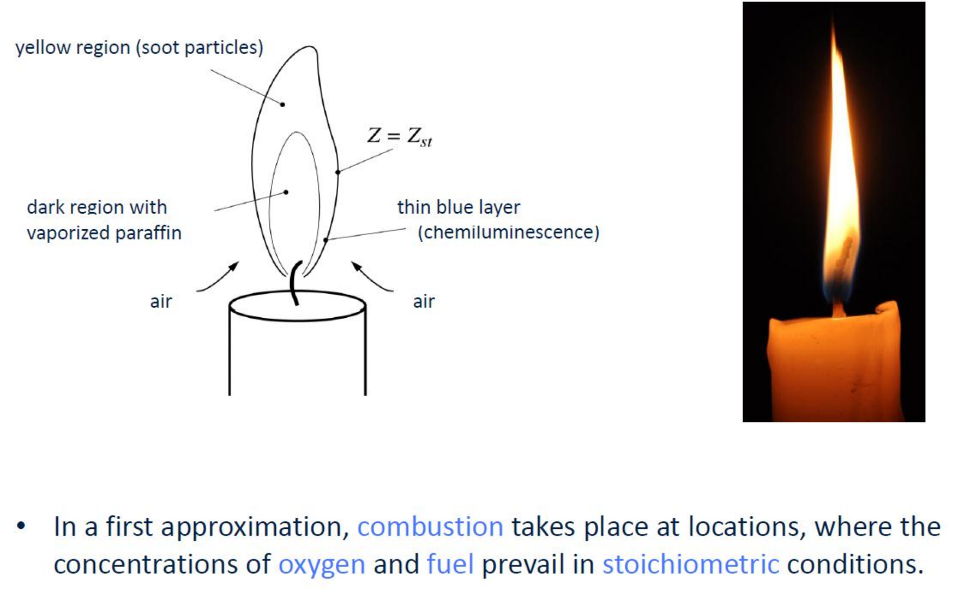
2- Laminar diffusion flames



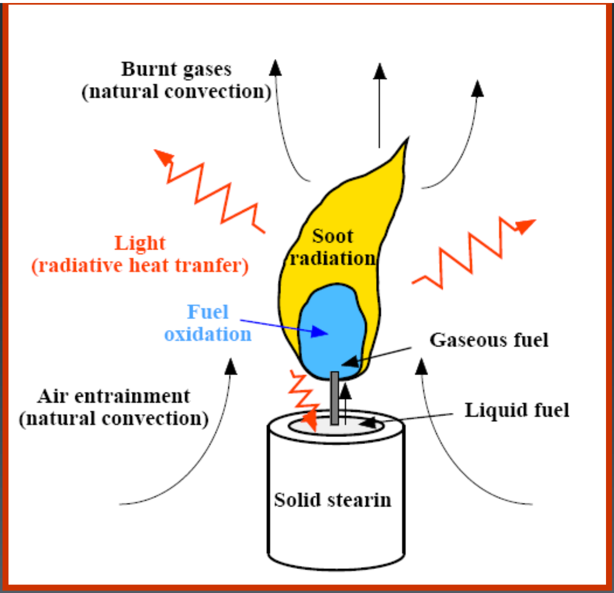
- Seperate feeding of fuel and oxidizer into the combustion chamber
  - Diesel engine
  - Jet engine
- In the combustion chamber:
  - Mixing
  - Subsequently combustion
- Mixing: Convection and diffusion
  - On a molecular level
    → (locally) stoichiometric mixture
- Simple example for a diffusion flame:
  Candle flame
  - Paraffin vaporizes at the wick
    → diffuses into the surrounding air
- Simultaneously: Air flows towards the flame due to free convection and forms a mixture with the vaporized paraffin

Injection and combustion in a diesel engine

A very difficult flame: the candle flame



- In a first approximation, combustion takes place at locations, where the concentrations of oxygen and fuel prevail in stoichiometric conditions.



- The solid fuel is first heated by heat transfer induced by combustion. The liquid fuel reaches the flame by capillarity along the wick and is vaporized.
- Fuel oxidation occurs in thin blue layers (the color corresponds to the spontaneous emission of the CH radical)
- Unburnt carbon particles are formed because the fuel is in excess in the reaction zone. The this soot is the source of the yellow light emission.
- Flow (entrainment of heavy cold fresh air and evacuation of hot light burnt gases) is induced by natural convection

Example : gas lighter

- Fuel enters into the combustion chamber as a round jet
- Forming mixture is ignited
- Example: Flame of a gas lighter
  - Only stable if dimensions are small
  - Dimensions too large: flickering due to influence of gravity
  - Increasing the jet momentum → Reduction of the relative importance of gravity (buoyancy) in favor of momentum forces
  - At high velocities, hydrodynamic instabilities gain increasing importance: laminar-turbulent transition