Lecture 2
Premixed flame

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What is a flame

Definition

A **flame** is a self-sustaining propagation of a localised combustion zone at subsonic velocities.

Prerequisites

- ❑ Fuel
- ❑ Oxidant
- ❑ Mixing
- ❑ Heat

Deflagration

combustion travels subsonically

Detonation

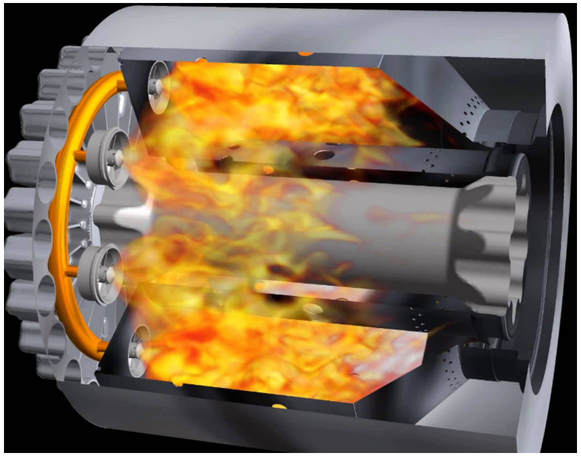
combustion waves propagate at supersonic velocities

Classification of flames

	Laminar	Turbulent
Premixed	Bunsen, jet flames	Gasoline engine, gas turbines
Non-premixed (or Diffusion)	wood fire, candle	Aircraft or rocket engines, pulverised coal…

Bunsen flame

Candle flame



gas turbine flame

Pulverised coal flame

Premixed flame

Premixed combustion used in combustion devices when high heat release rates are desired

- Small devices
- Low residence times

Advantage:
- Lean combustion possible
- Smoke-free combustion
- Low NOx

Disadvantage:
- Danger of Explosions
- Combustion instabilities

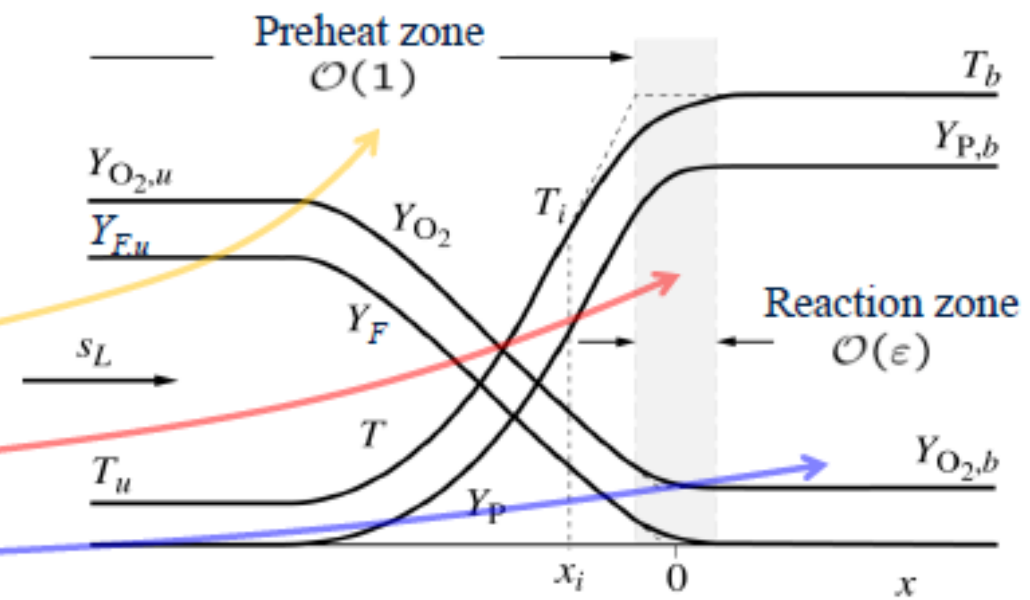
Large-scale industrial furnaces and aircraft engines are typically non-premixed

Flame Structure of Premixed Laminar Flames

adiabatic flame temperature T_b

The area around the flame front is divided in three zones by Zeldovich and Frank-Kamenetzki:

- Preheat zone
- Reaction zone
- Equilibrium zone

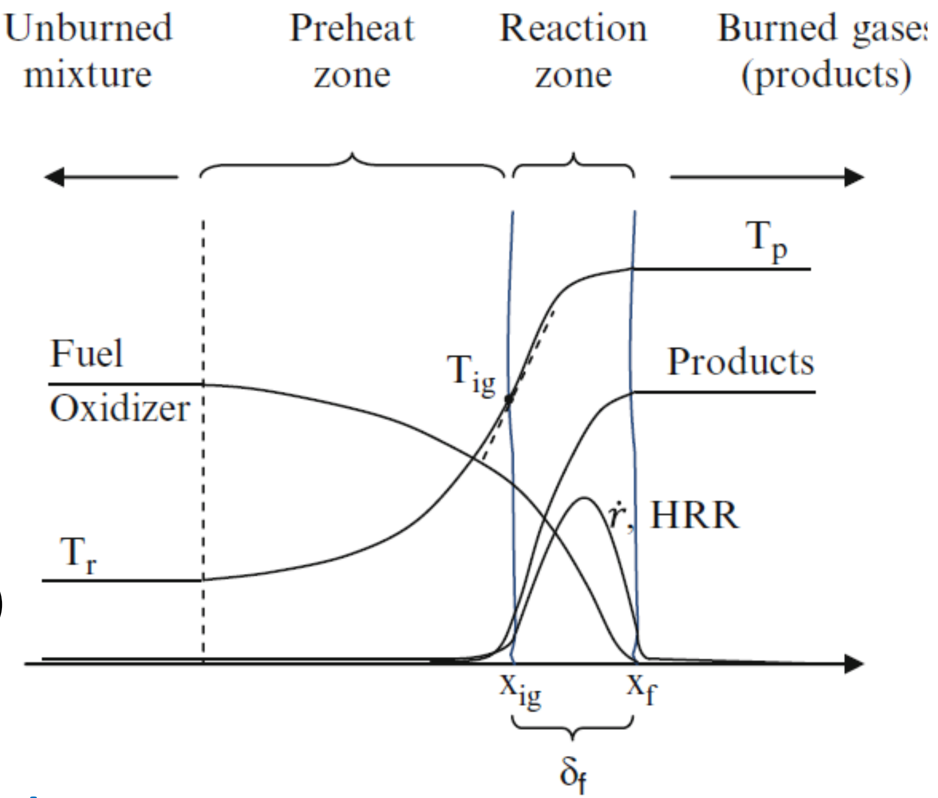


Temperature and concentration profiles, lean mixture

Key steps of making a premixed laminar flame (see above figure from left to right)

1) Fuel and oxidizer are convected from upstream with the burning velocity
2) Fuel and air diffuse into the reaction zone
3) Mixture heated up by heat conduction from the burnt gases
4) Fuel consumption, radical production, and oxidation when inner layer temperature is reached
5) Increase temperature and gradients
6) Fuel is entirely depleted
7) Remaining oxygen is convected downstream

Laminar premixed flame --simple thermal theory



Steady state energy equation of a control volume in Preheat Zone

$$\rho c_P u \frac{\partial T}{\partial x} = k \frac{\partial^2 T}{\partial x^2}$$

$$\underbrace{\rho_r c_P S_L (T_{ig} - T_r)}_{\text{convective energy}} \approx \underbrace{k \frac{T_P - T_{ig}}{\delta}}_{\text{conductive energy}} \qquad \text{(Eq.1)}$$

Steady state energy equation of a control volume in both Preheat and Reaction Zones

$$\rho c_P u \frac{\partial T}{\partial x} = k \frac{\partial^2 T}{\partial x^2} + \hat{\dot{r}}_{fuel} \hat{Q}_c$$

$$\underbrace{\rho_r c_P S_L (T_P - T_r)}_{\text{convective energy}} = 0 + \underbrace{\delta \hat{\dot{r}}_{fuel,ave} \hat{Q}_c}_{\text{energy from combustion}} \qquad \text{(Eq.2)}$$

Two unknowns

S_L δ

Flame speed S_L equal to the velocity that reactants enter the flame

Laminar premixed flame
-- simple thermal theory

$$S_L = \left\{\frac{k\left(T_P - T_{ig}\right)\hat{\dot{r}}_{fuel,ave}/[Fuel]_r}{\rho_r c_P\left(T_{ig} - T_r\right)}\right\}^{1/2} = \left\{\frac{\alpha\left(T_P - T_{ig}\right)}{\tau_{chem}\left(T_{ig} - T_r\right)}\right\}^{1/2} \qquad \text{(Eq.3)}$$

See details in derivation notes

Thermal diffusivity $\alpha = \dfrac{k}{\rho_r c_P}$

Time scale of chemical kinetics $\tau_{chem} = [Fuel]_r/\hat{\dot{r}}_{fuel,ave}$

the heat of combustion is approximately related to the flame temperature by

$$\hat{Q}_c[Fuel]_r = \rho_r c_P(T_P - T_r)$$

Eq.2

$$S_L = \frac{\delta}{\tau_{chem}}$$

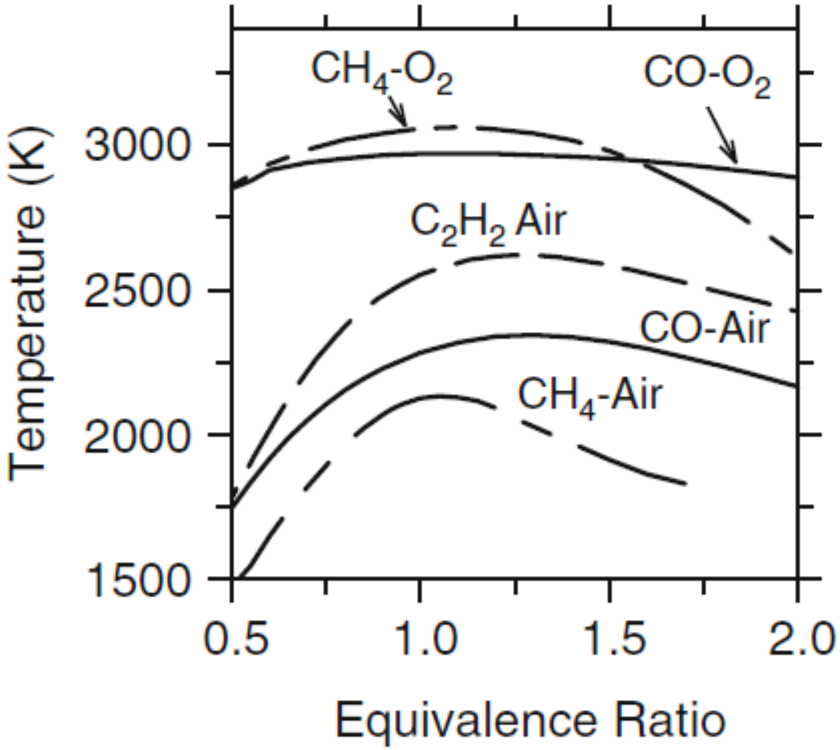
Eq.3

$$\delta = \left\{\alpha \cdot \tau_{chem}\frac{\left(T_P - T_{ig}\right)}{\left(T_{ig} - T_r\right)}\right\}^{1/2}$$

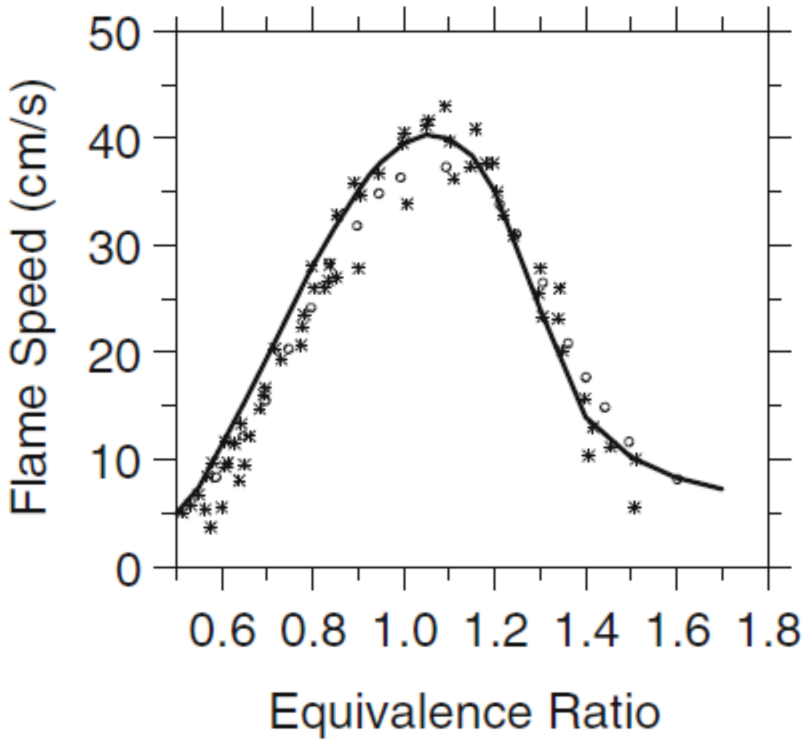
Eq.2

$$S_L \cdot \delta = \alpha\frac{\left(T_P - T_{ig}\right)}{\left(T_{ig} - T_r\right)}$$

Flame speed (S_L) vs. equivalence ratio (Φ)



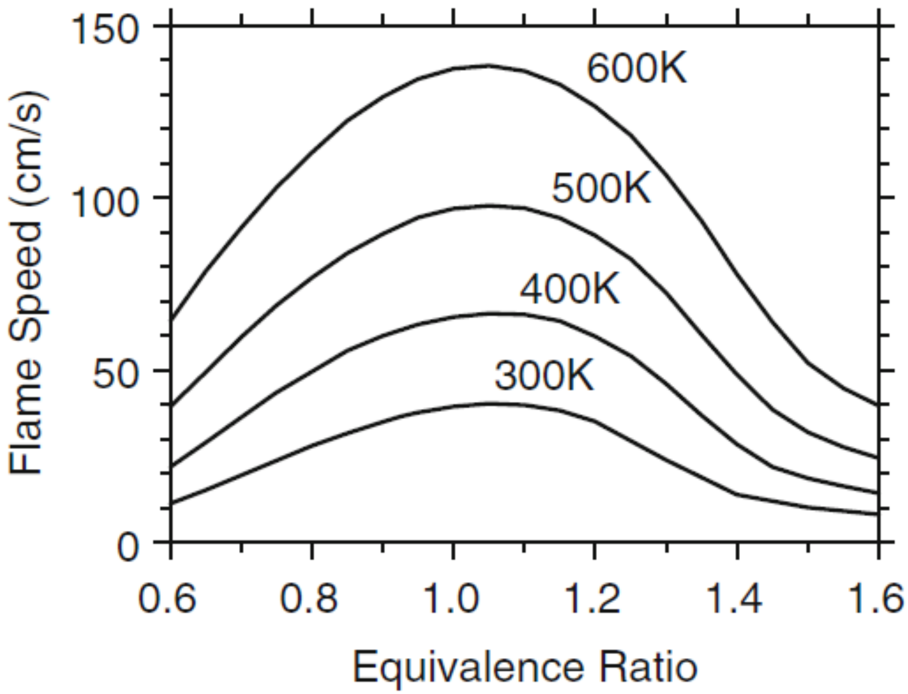
Peak flame temperature vs. ER ratio



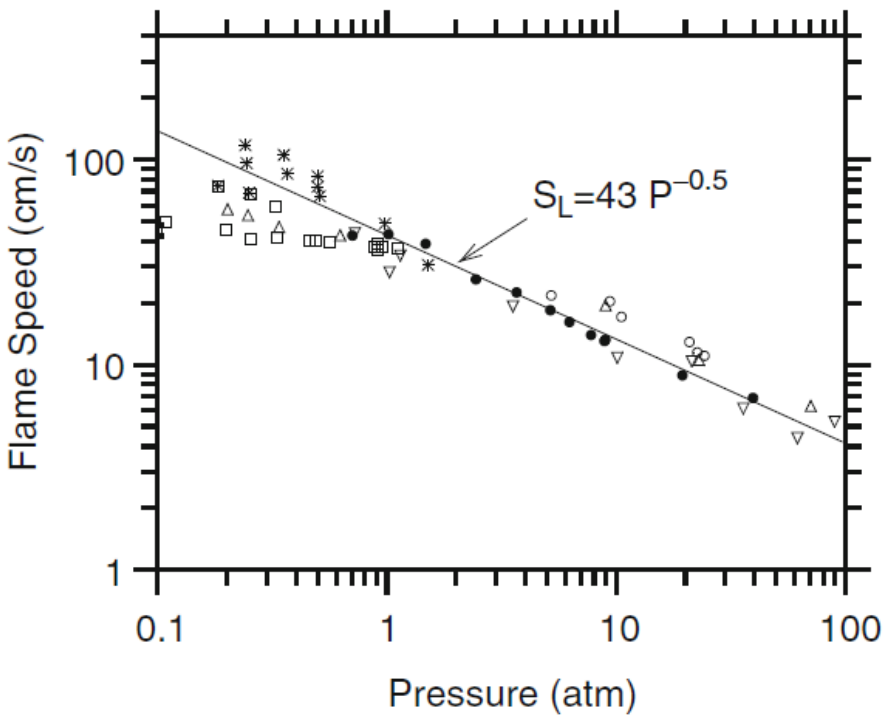
Measured flame speeds of CH_4-air mixture

Flame speed peaks at equivalence ratio near 1

Flame speed vs. Temperature/pressure



Flame speed of propane air at 1 atm vs. initial temperature



Flame speed of methane-air vs. pressure

Flame speed vs. fuel type, temp., pressure

$$S_L(\Phi, T, P) = S_{L,ref}(\Phi)\left(\frac{T_r}{T_{r,ref}}\right)^{\gamma}\left(\frac{P}{P_{ref}}\right)^{\beta}(1 - 2.1Y_{dil}) \quad for\ T_r \geq 350\ K$$

$$T_{r,ref} = 298K \qquad P_{ref} = 1\ atm$$

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

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

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

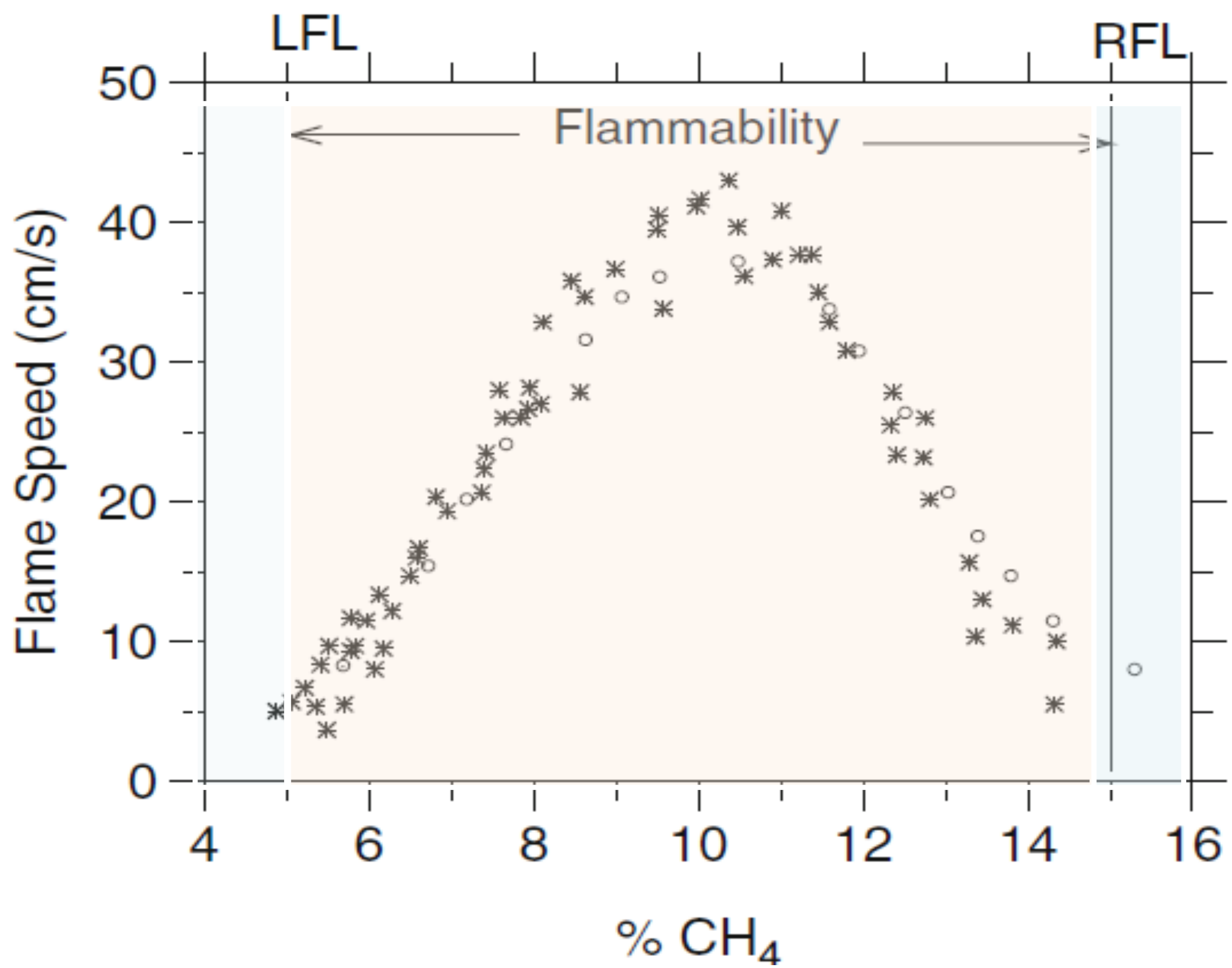
Y_{dil} is the mass fraction of diluent present in the air-fuel mixture.

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
Isooctane	1.13	26.32	−84.72
RMFD-303	1.13	27.58	−78.34

Flammability limits

***LFL**- lean flammability limit*

***RFL**- rich flammability limit*



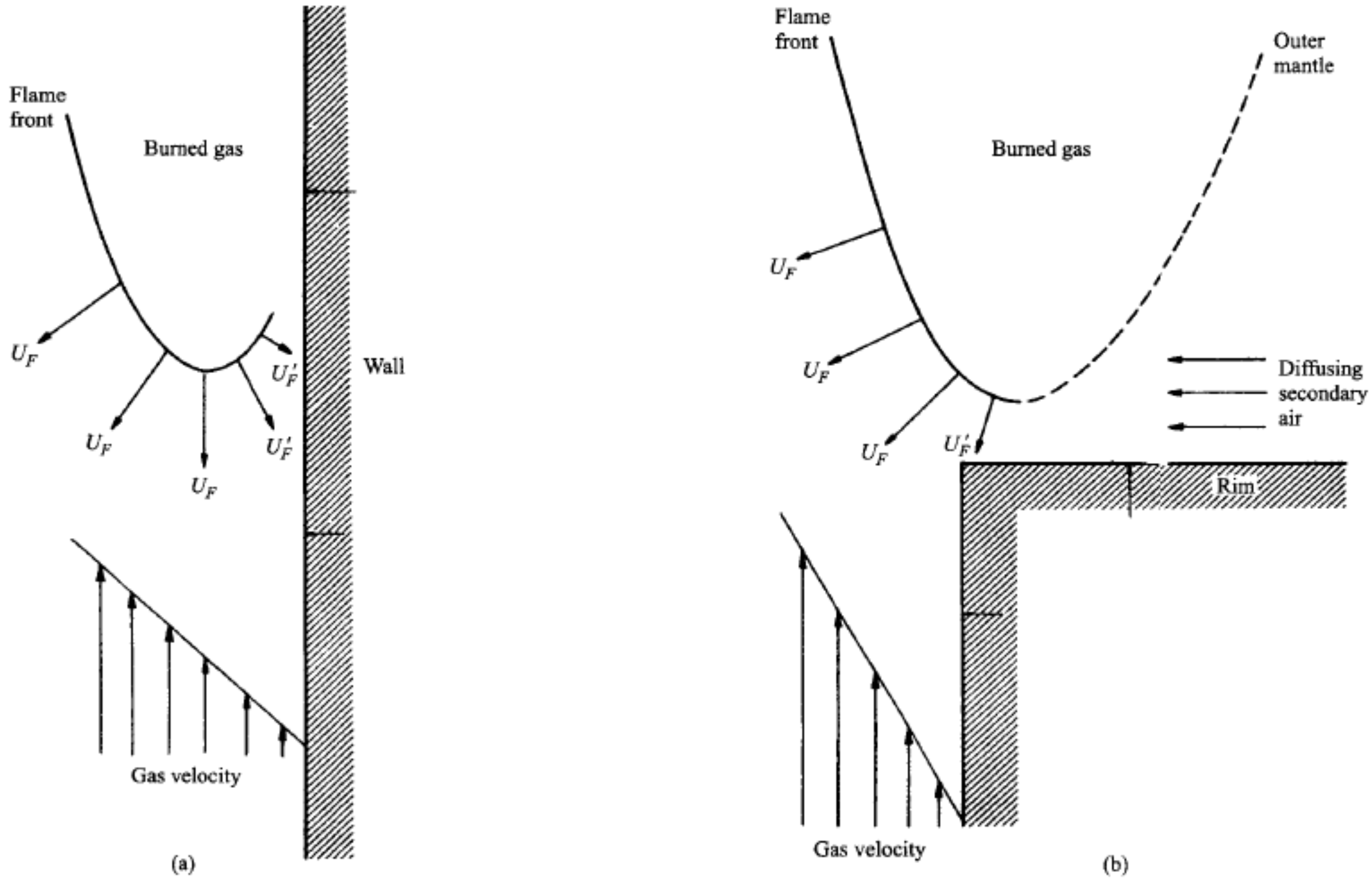
Flammability limits of different fuels

Fuel	Flammability Limits: Φ_{min} (Lean or Lower Limit)	Φ_{max} (Rich or Upper Limit)	Stoichiometric Mass Air–Fuel Ratio
Acetylene, C_2H_2	0.19[b]	∞[b]	13.3
Carbon monoxide, CO	0.34	6.76	2.46
n-Decane, $C_{10}H_{22}$	0.36	3.92	15.0
Ethane, C_2H_6	0.50	2.72	16.0
Ethylene, C_2H_4	0.41	>6.1	14.8
Hydrogen, H_2	0.14[b]	2.54[b]	34.5
Methane, CH_4	0.46	1.64	17.2
Methanol, CH_3OH	0.48	4.08	6.46
n-Octane, C_8H_{18}	0.51	4.25	15.1
Propane, C_3H_8	0.51	2.83	15.6

Flammability at standard conditions (% of fuel by volume in 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

Flame stabilization



Flashback

Liftoff

Turbulent Premixed Flames

Mass transfer $$m''_{total} = -\rho(D + \varepsilon_m)\frac{\partial \bar{Y}}{\partial x}$$

Heat transfer $$q''_{total} = -\rho c_p(\alpha + \varepsilon_H)\frac{\partial \bar{T}}{\partial x}$$

Momentum transfer $$\tau_{total} = \rho(v + \varepsilon_M)\frac{\partial \bar{u}}{\partial x}$$

eddy diffusivities are not properties of fluid, depend on the turbulence flow itself.

Two interaction regimes proposed for the enhancement of **flame speeds** in turbulent flows:

- ❑ *Increased transport processes of heat and mass by small scale turbulence;*
- ❑ *Increased surface area due to wrinkling of the flame by large turbulence eddies.*

Overview

1. How fast will the flame consume the unburned mixtures?

2. How will flame propagation change with operating conditions, i.e. equivalence ratio, temperature, and pressure?

3. How can flame propagation be stopped?

Nomenclature

B_M, B_2	Parameters
c_p	Specific heat (J/kg-K)
HRR	Heat release rate
k	Thermal conductivity (W/m-K)
$m^{"}$	Mass flux (kg/s-m^2)
P	Pressure (Pa)
$q^{"}$	Heat transfer rate per unit area (W/m^2)
$\hat{Q}_c$	Heat of combustion (J/kmol)
$\hat{r}$	Reaction rate (rate of production or destruction of a chemical species per unit volume)
$\hat{r}_{fuel,ave}$	Average fuel consumption (kmol/m^3-s)
S_L	Laminar flame speed (m/s)
T	Temperature (K)
u	Flame propagation speed into the unburned mixture (m/s)
x	Distance (m)

Greek Symbols

α	Thermal diffusivity (m^2/s)
β	Pressure exponent
ε	Eddy diffusivity
δ	Laminar flame thickness (m)
ρ	Density (kg/m^3)
τ	Characteristic time (s)
τ_{chem}	Chemistry time (s)
ϕ	Equivalence ratio
Φ_M	Parameter
ν	Specific volume
γ	Temperature exponent

Subscripts

b	Burned gas
dil	Diluent
f	Flame
F	Fuel

Nomenclature

Subscripts

H	Heat
i, ig	Ignition
m	Mass
M	Momentum
max	Maximum
min	Minimum
P	Product
r	Reactant
ref	Reference
u	Unburned gas

Other Notation

$[X]$	Molar concentration of X (kmol/m^3)