Lecture 5. Laminar Premixed Flames

Structures and Propagation

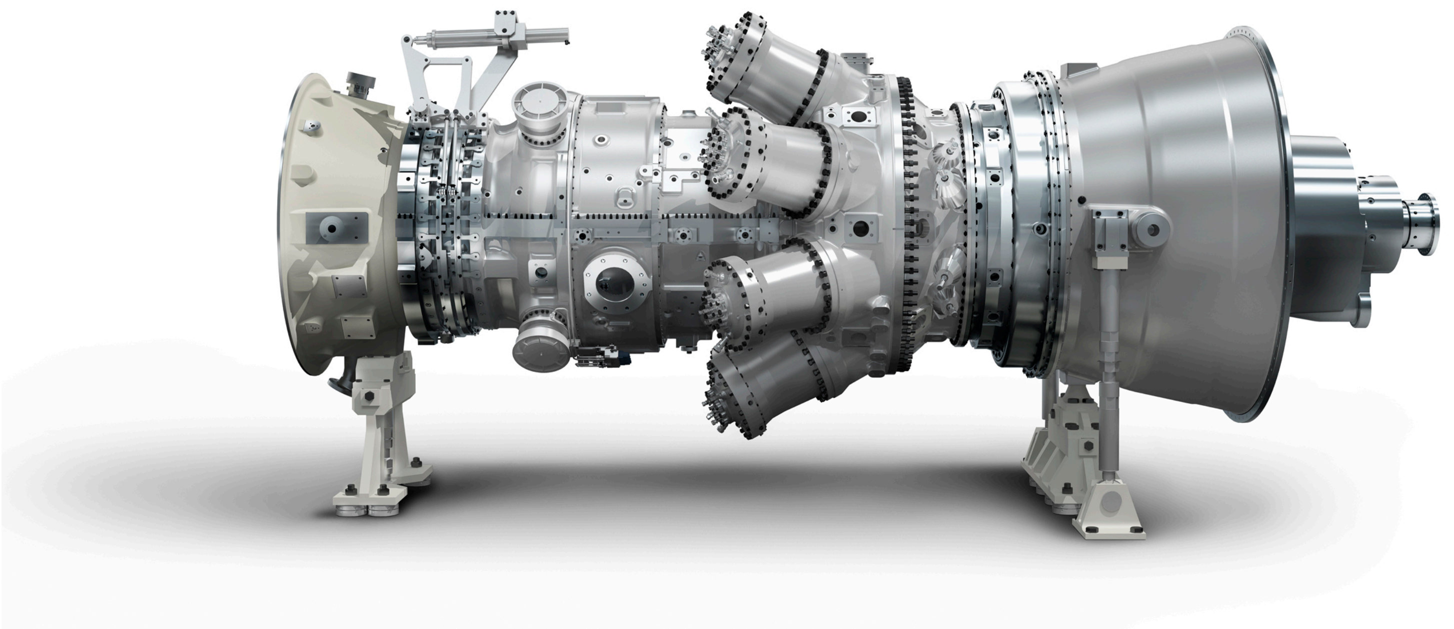
Premixed flames

Premixed flames causing coal mine explosion

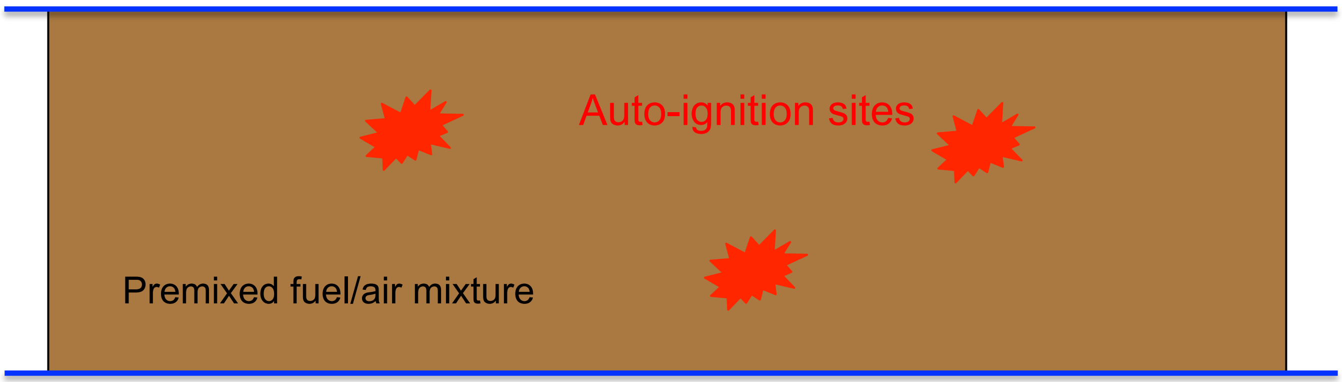
A mine explosion in the Ukraine resulted in 36 dead, 14 missing, and this guy looking very terrible indeed. The explosion was methane gas, and they were mining coal. August 2001. http://cellar.org/showthread.php?t=452


DesktopMachine.com

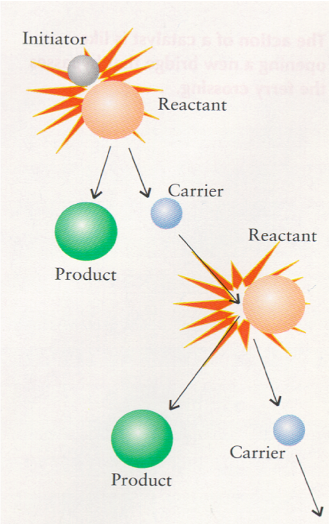
SGT-750
37 MW, 40%
Launched nov 2010



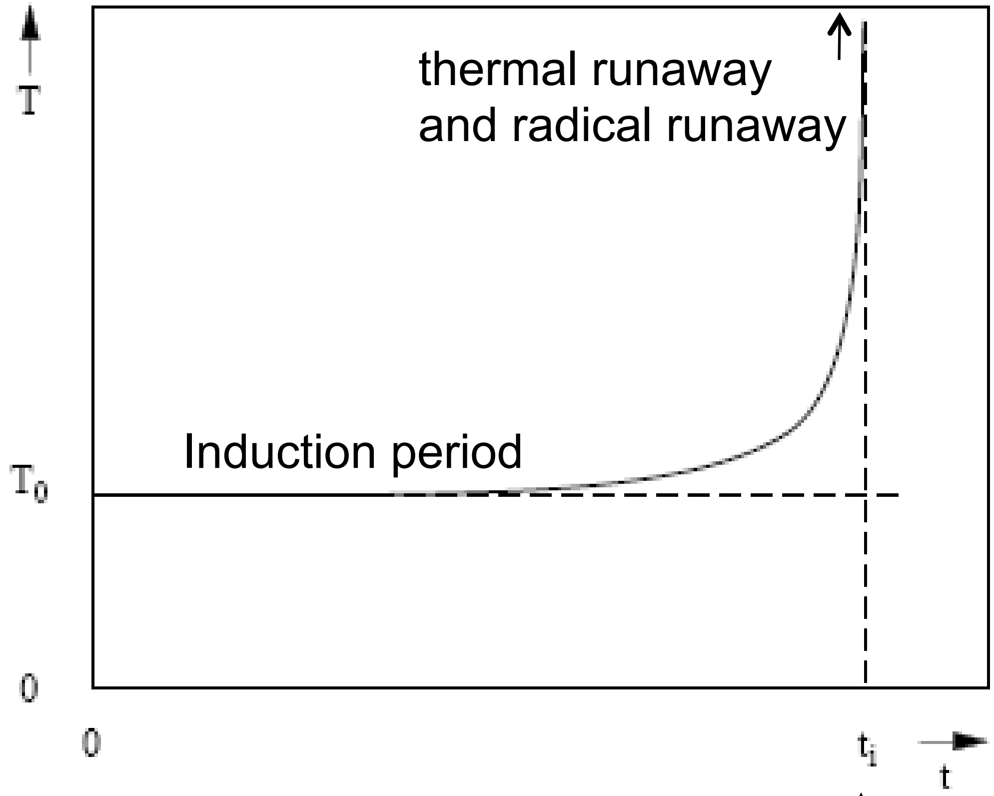
Premixed fuel/air mixture: auto-ignition



Hydrogen/air auto-ignition



Initial temperature →



$$
\begin{array}{lcl}
H + O_2 & \rightarrow & OH + O \\
O + H_2 & \rightarrow & OH + H \\
OH + H_2 & \rightarrow & H_2O + H \\
H + O_2 + M & \rightarrow & HO_2 + M \\
H_2 + O_2 & \rightarrow & H + HO_2 \,.
\end{array}
$$

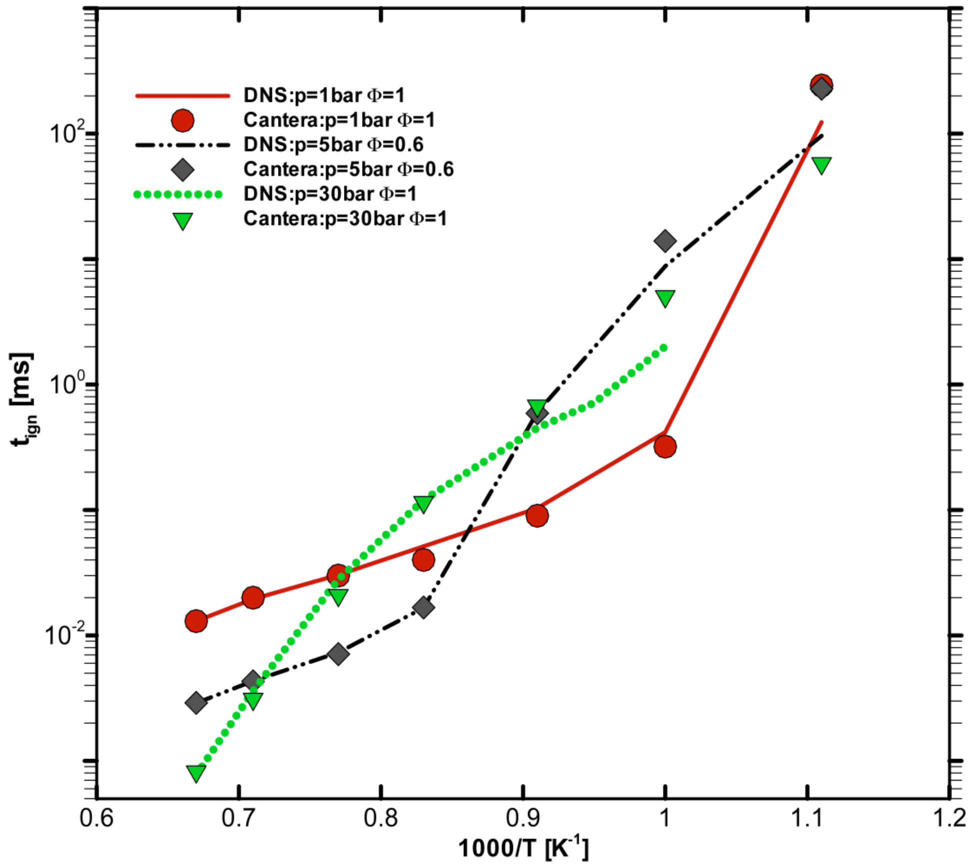
– Low T_0

$H_2 + M = H + H + M$ ← High T_0

Ignition delay time

Hydrogen/air auto-ignition

$$
\begin{aligned}
\mathrm{H} + \mathrm{O_2} &\rightarrow \mathrm{OH} + \mathrm{O} \\
\mathrm{O} + \mathrm{H_2} &\rightarrow \mathrm{OH} + \mathrm{H} \\
\mathrm{OH} + \mathrm{H_2} &\rightarrow \mathrm{H_2O} + \mathrm{H} \\
\mathrm{H} + \mathrm{O_2} + \mathrm{M} &\rightarrow \mathrm{HO_2} + \mathrm{M} \\
\mathrm{H_2} + \mathrm{O_2} &\rightarrow \mathrm{H} + \mathrm{HO_2}\,.
\end{aligned}
$$

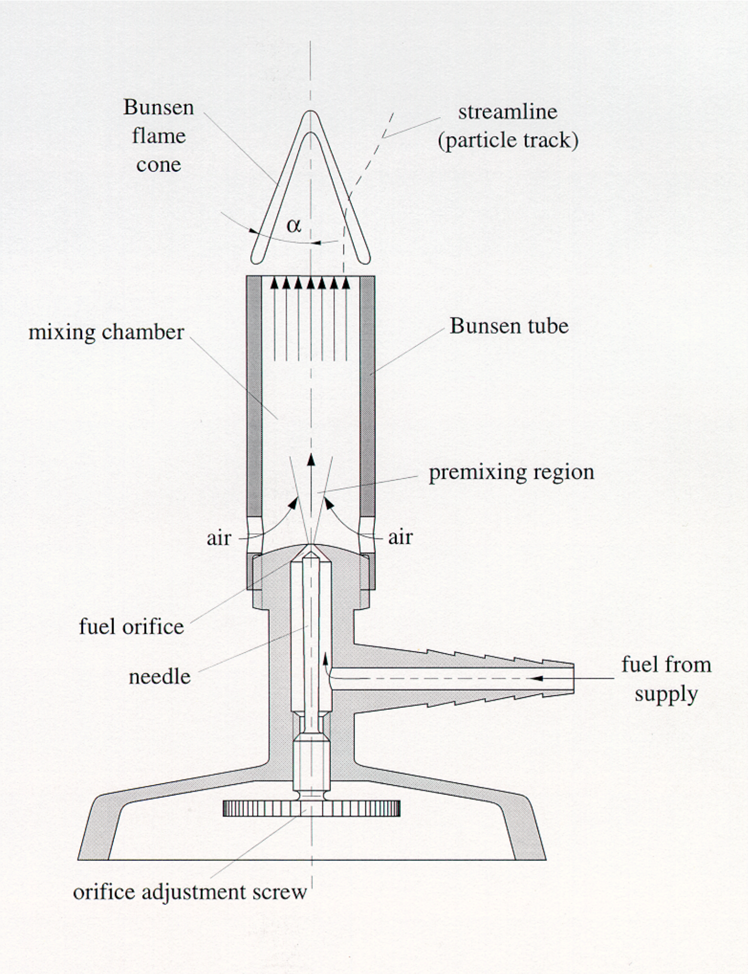


Ignition delay time of H2/air mixture

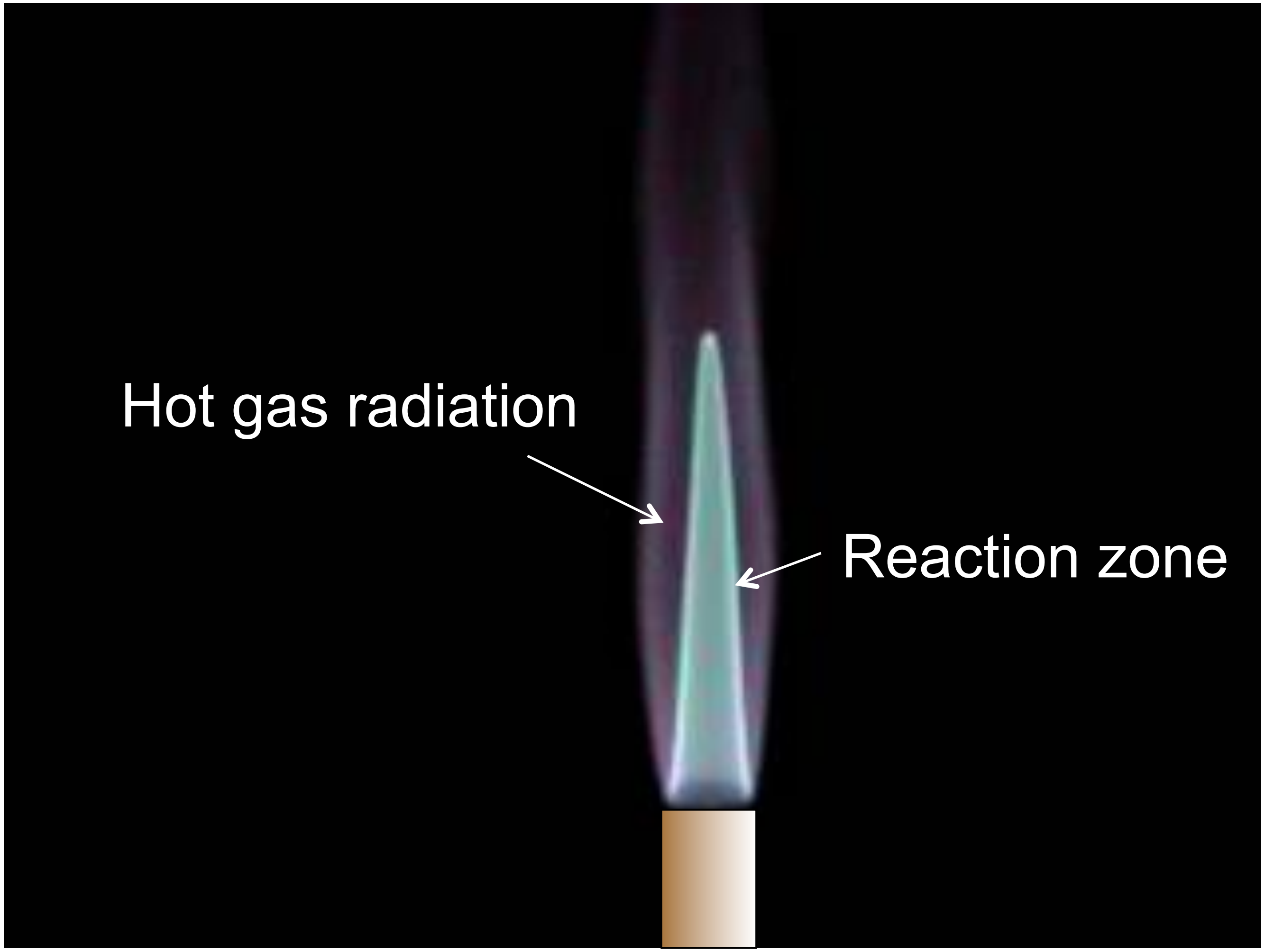
Structures and propagation of laminar premixed flames

- Structures of laminar premixed flames
- Burning velocity of lamniar premixed flames
- Propagation of laminar premixed flames in flow field
- Stabilization of premixed flames
- Laminar premixed flame instability

Laminar premixed flames: Bunsen burner

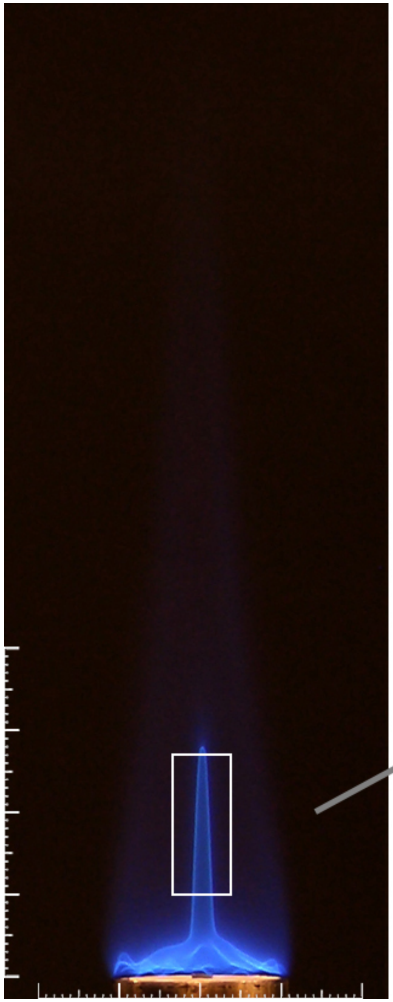


Laminar premixed flames

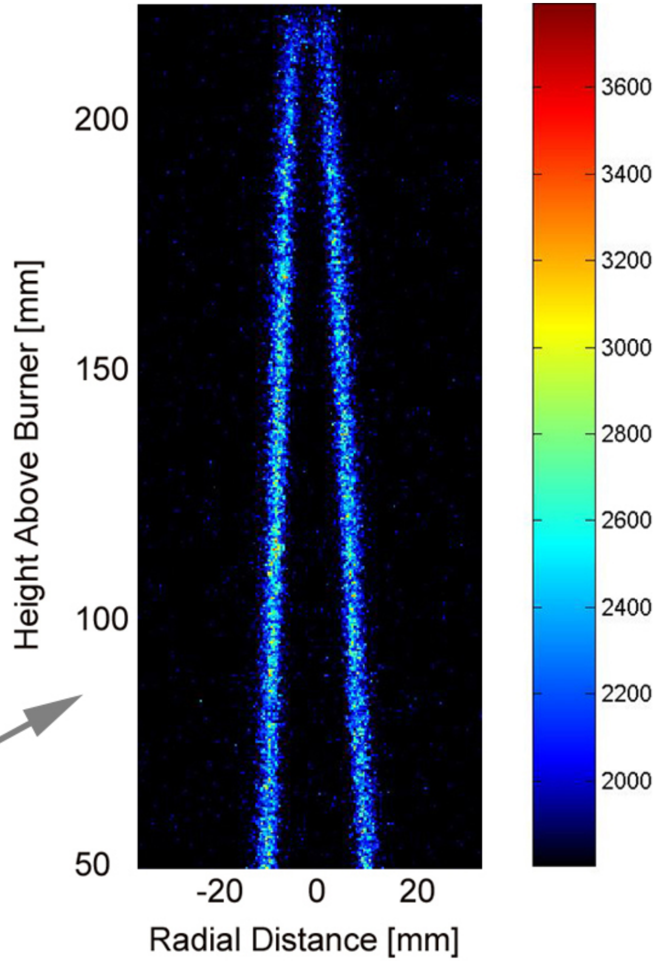


Experimental observations of flames

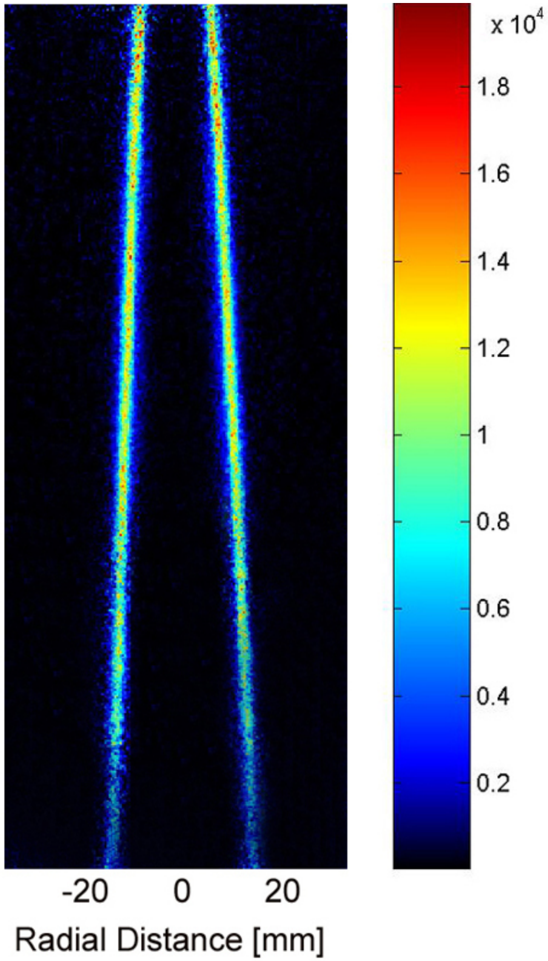
photo



CH2O

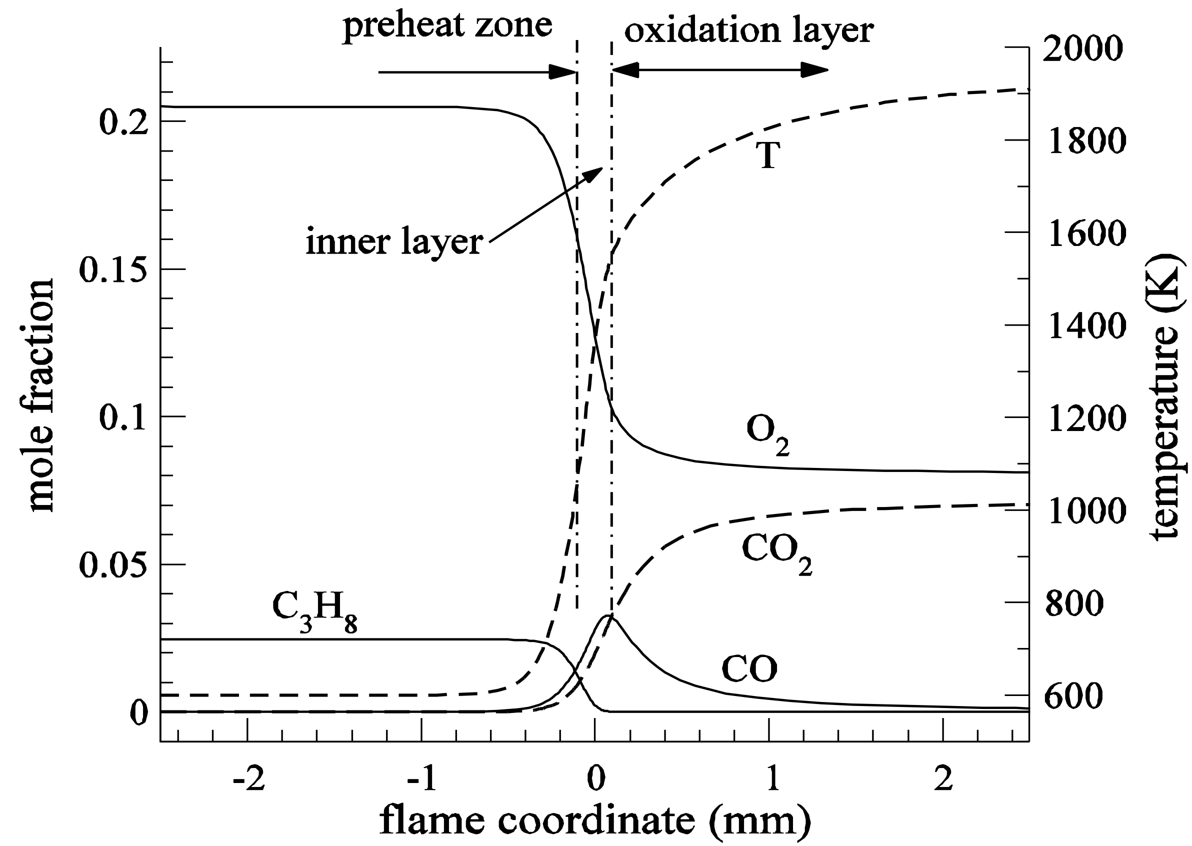


CH

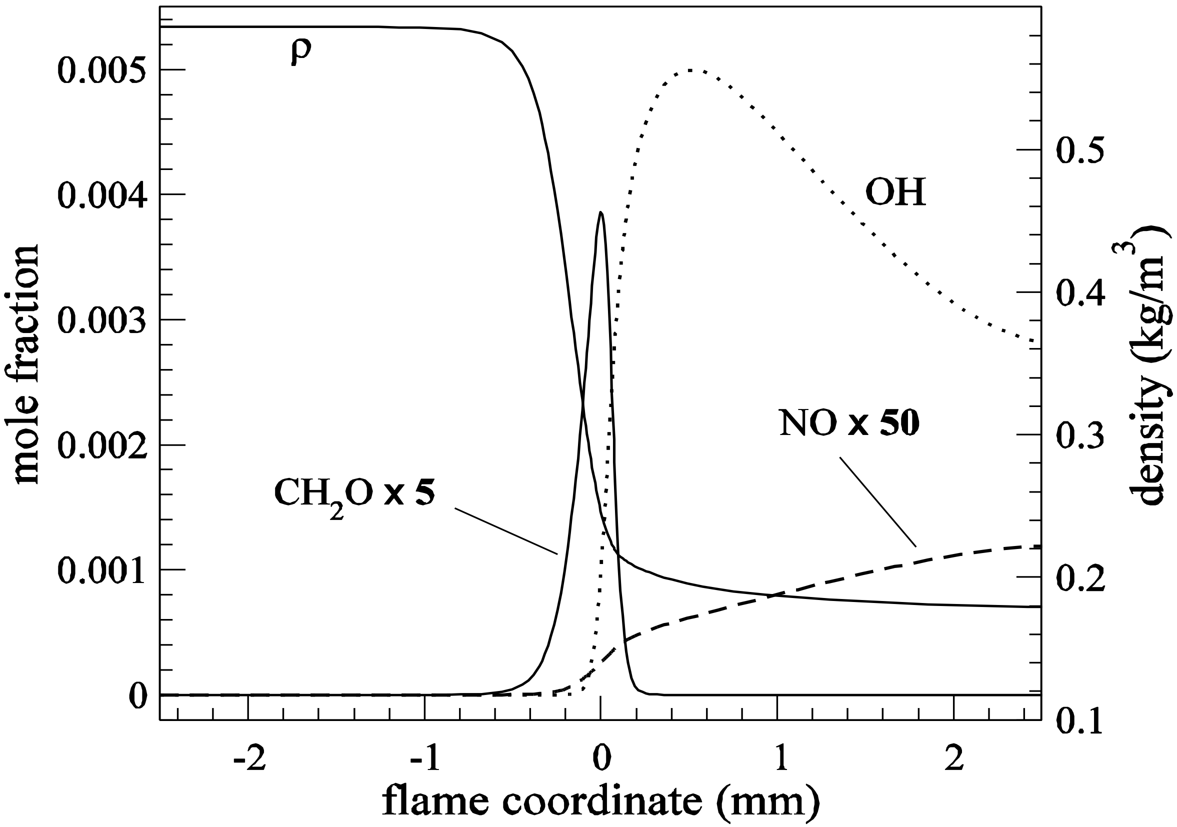


Vo=0.45 m/s, phi=1.17; Vin=11m/s, phi=1.1

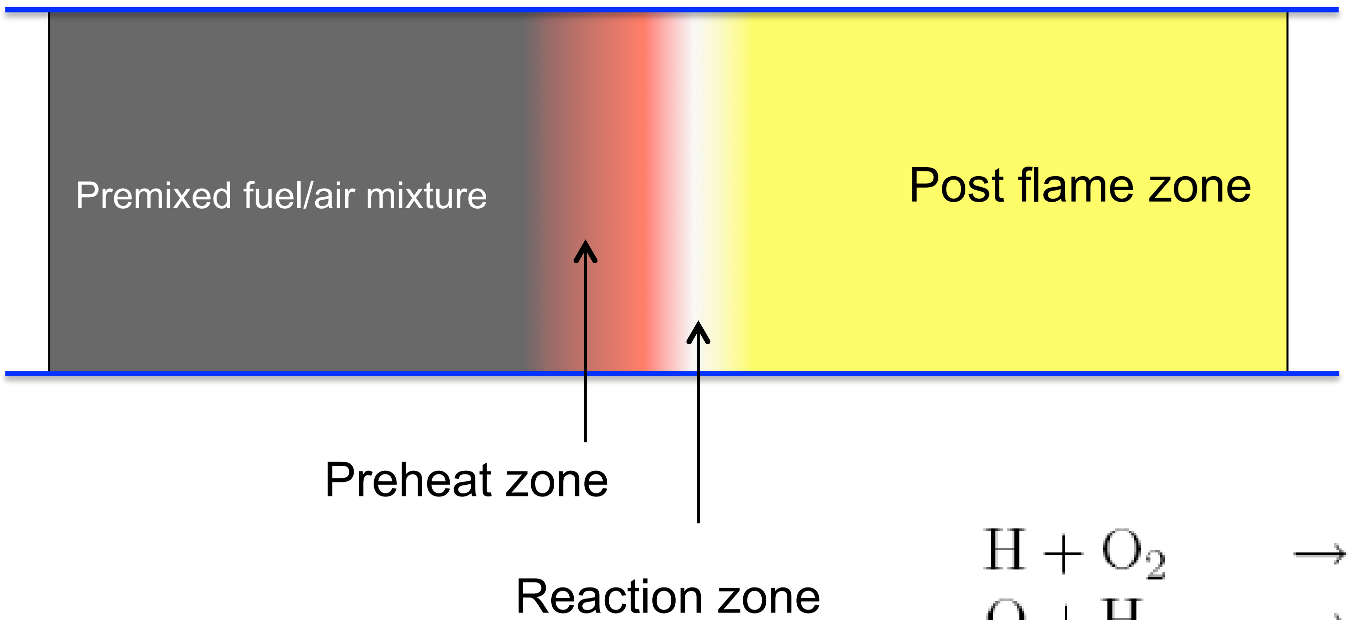
Structure of premixed flames



Structure of premixed flames



Premixed fuel/air mixture: flame propagation



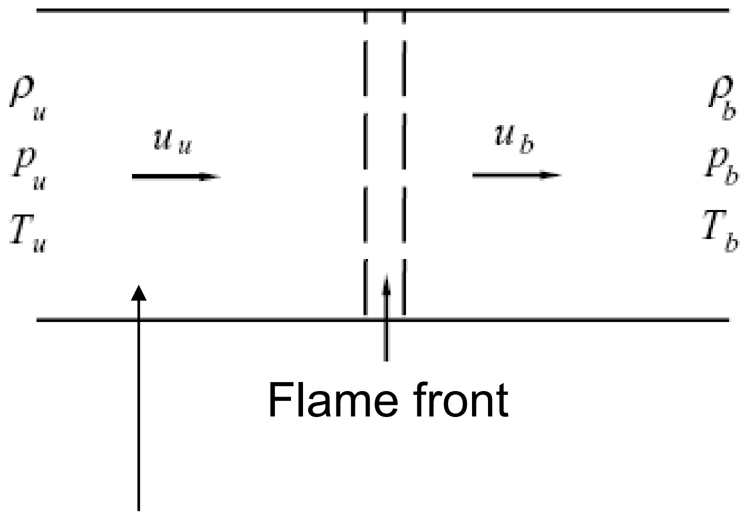
$$
\begin{aligned}
H + O_2 &\rightarrow OH + O \\
O + H_2 &\rightarrow OH + H \\
OH + H_2 &\rightarrow H_2O + H \\
H + O_2 + M &\rightarrow HO_2 + M \\
H_2 + O_2 &\rightarrow H + HO_2 \,.
\end{aligned}
$$

Structure of premixed flames

- Preheat zone: heating up the reactants
- Inner-layer: radical formation
- Oxidation-layer: finishing the remaining reactions
- Post-flame zone: hot products, NOx formation

Analysis of flames: the post-flame zone

Unburned
fuel/air mixture



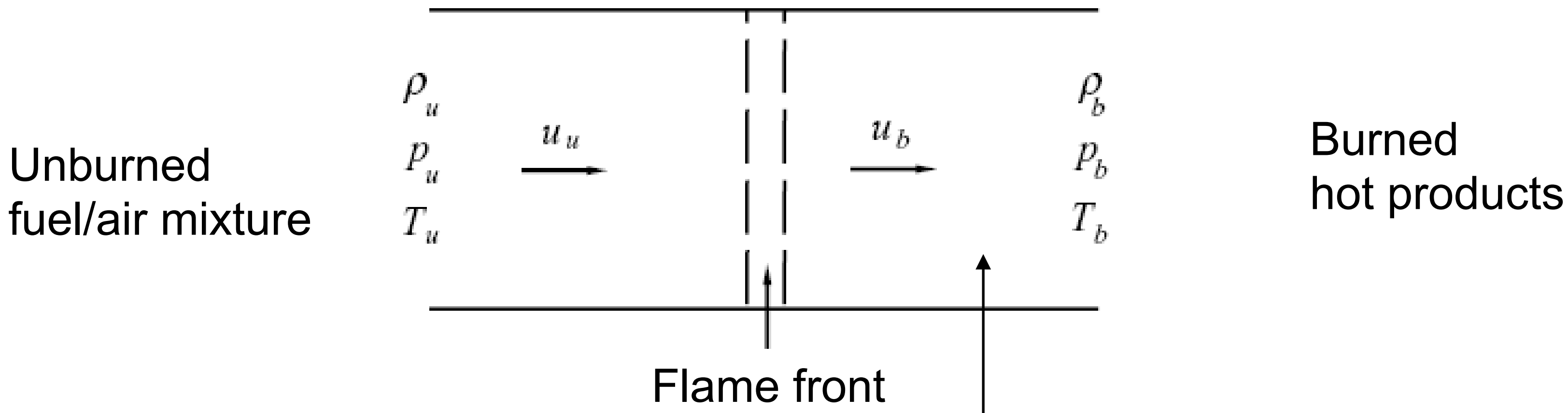
Burned
hot products

$$\begin{array}{ccccc} F & + & A & = & P \\ 1 & & \gamma_A & & 1+\gamma_A \end{array}$$

$$Y_{F,u}/Y_{A,u} = \Phi/\gamma_A, \text{ and } Y_{F,u} + Y_{A,u} = 1$$

$$Y_{F,u} = \frac{\Phi}{\Phi+\gamma_A},\ Y_{A,u} = \frac{\gamma_A}{\Phi+\gamma_A}, \text{ and } Y_{O,u} = \frac{0.233\gamma_A}{\Phi+\gamma_A},\ Y_{N,u} = \frac{0.767\gamma_A}{\Phi+\gamma_A},$$

Analysis of flames: the post-flame zone



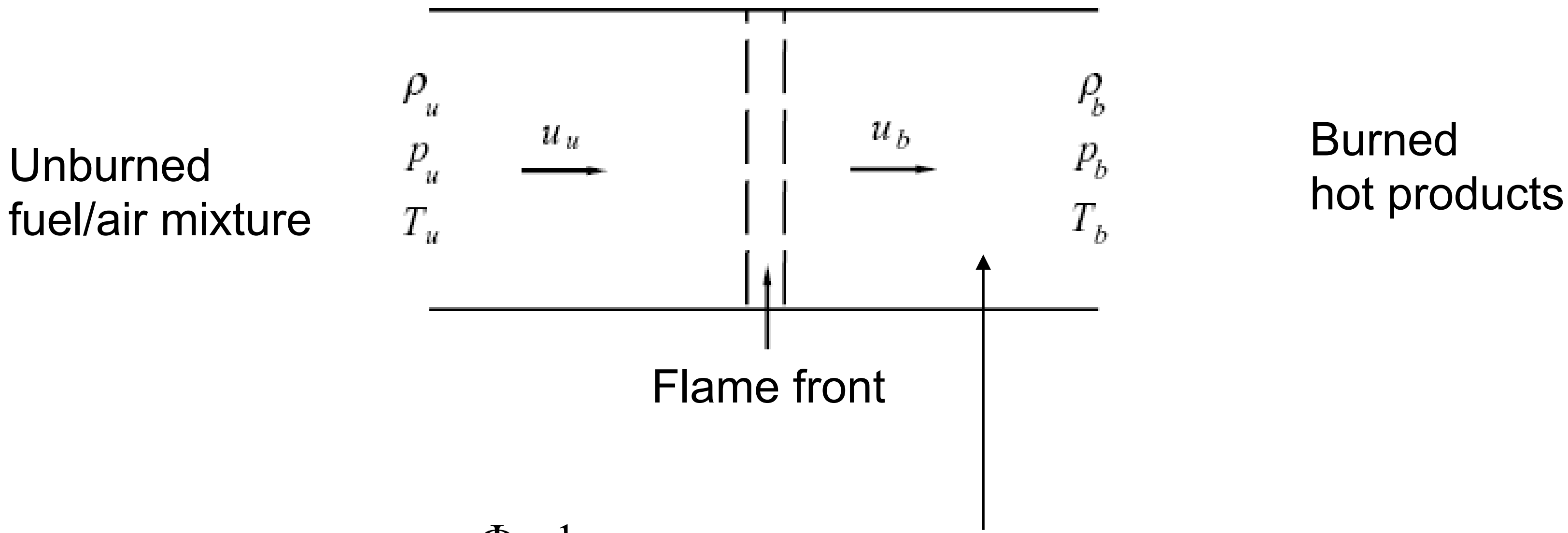
$\Phi > 1$

$$Y_{F,b} = Y_{F,u} - Y_{A,u} / \gamma_A = (\Phi - 1) Y_{A,u} / \gamma_A = Y_{F,u} \frac{\Phi - 1}{\Phi} = \frac{\Phi - 1}{\Phi + \gamma_A},$$

$$Y_{O,b} = 0, \ Y_{N,b} = Y_{N,u} = \frac{0.767\gamma_A}{\Phi + \gamma_A}$$

$$Y_{P,b} = 1 - Y_{F,b}, \text{ P includes N}$$

Analysis of flames: the post-flame zone



$$\Phi < 1$$

$$Y_{F,b} = 0$$

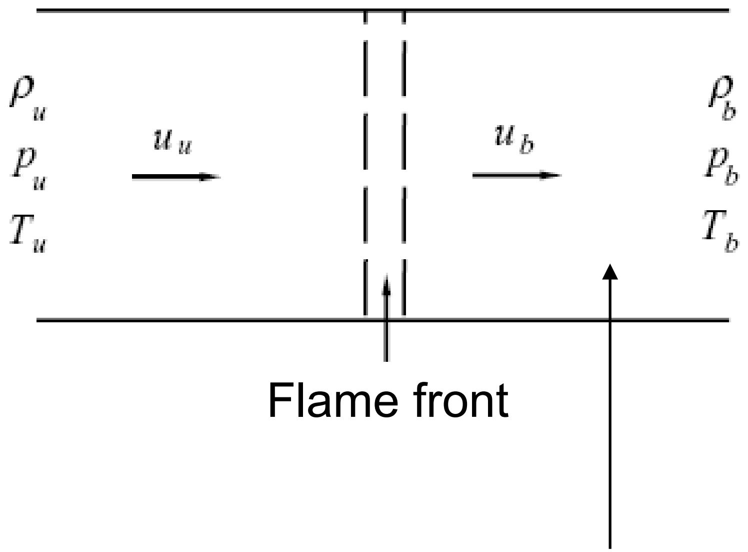
$$Y_{A,b} = Y_{A,u} - \gamma_A Y_{F,u} = (1-\Phi) Y_{A,u} = \gamma_A Y_{F,u} \frac{1-\Phi}{\Phi} = \gamma_A \frac{1-\Phi}{\Phi + \gamma_A},$$

$$Y_{P,b} = 1 - Y_{A,b}$$

Both A and P include N

Analysis of flames: the post-flame zone

Unburned
fuel/air mixture



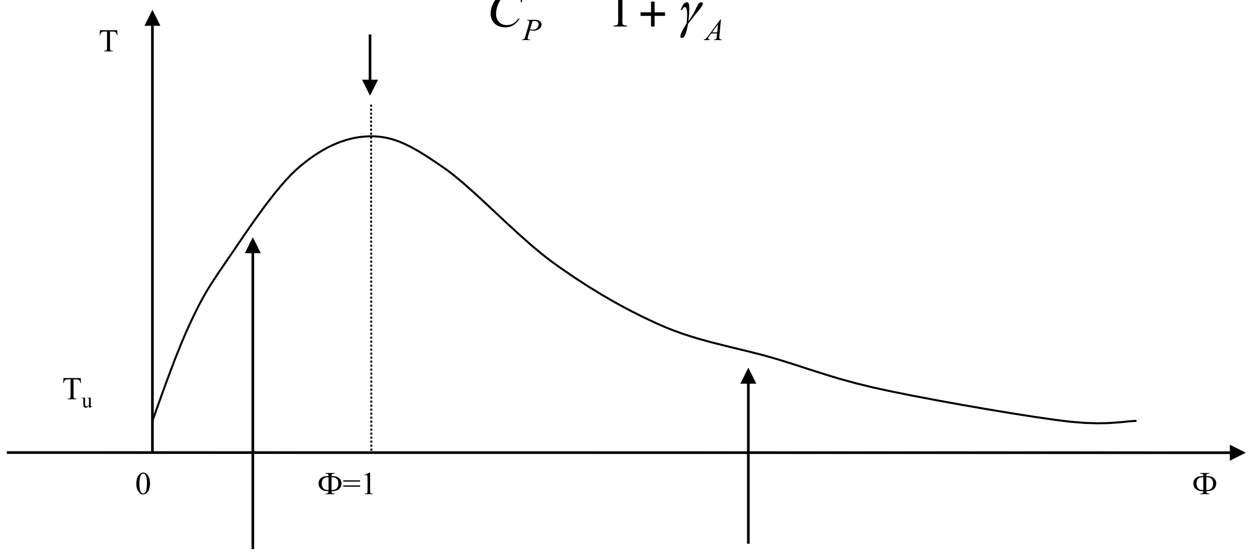
Burned
hot products

$$h_u = Y_{F,u}[h_F^0 + c_{p,F}(T_u - T_{ref})] + Y_{A,u}[h_A^0 + c_{p,A}(T_u - T_{ref})]$$

$$h_b = Y_{F,b}[h_F^0 + c_{p,F}(T_b - T_{ref})] + Y_{A,b}[h_A^0 + c_{p,A}(T_b - T_{ref})] + Y_{P,b}[h_P^0 + c_{p,b}(T_b - T_{ref})]$$

Analysis of flames: the post-flame zone

$$T_b = T_u + \frac{(-\Delta H_r)}{C_P} \frac{1}{1+\gamma_A}$$



$$T_b = T_u + \frac{(-\Delta H_r)}{c_p} \frac{\Phi}{\Phi+\gamma_A}$$

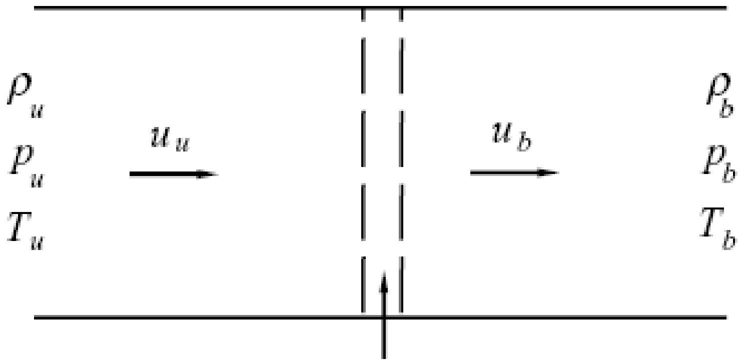
$$T_b = T_u + \frac{(-\Delta H_r)}{C_P} \frac{1}{\Phi+\gamma_A}$$

Laminar burning velocity

- How fast can a laminar flame propagate?
- What is the mechanism of flame propagation?
- What are the influencing factors?

Laminar burning velocity

Unburned
fuel/air mixture

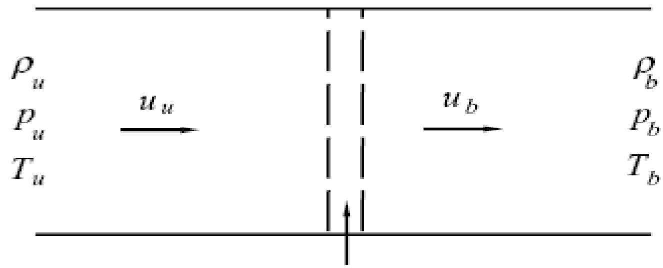


Burned
hot products

Flame front

Laminar burning velocity (also called laminar flame speed): the speed at which the flame front propagates towards the unburned mixture

Derivation of laminar burning velocity



$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v} = 0$$

$$\frac{\partial \rho Y_i}{\partial t} + \nabla \cdot \rho Y_i \vec{v} = \nabla \cdot \rho D_i \nabla Y_i + \omega_i$$

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho \vec{v} \cdot \nabla \vec{v} = \nabla \cdot \left(pI + \tau \right)$$

$$\rho \frac{Dh}{Dt} - \frac{Dp}{Dt} = \nabla \cdot \left(\rho \alpha \nabla h - \rho \alpha \sum_{i=1}^{N} \left(1 - \frac{1}{Le_i} \right) h_i \nabla Y_i \right) + \dot{Q}_r + \tau : \nabla \vec{v}$$

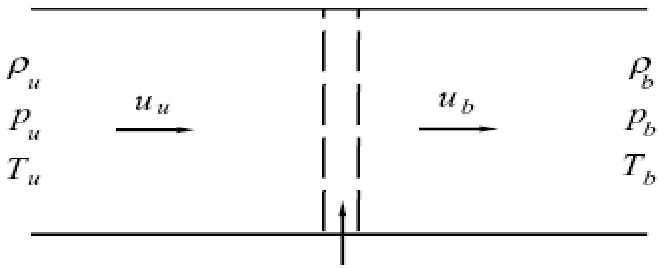
Assumptions
-1 D
- steady state
- unity Lewis number
- low Mach number

Development of flame speed theory

- Mallard:
  - Ann Mines 7, 355 (1875)
- Mallard & Le Chatelier:
  - Ann Mines 4, 274 (1883)
- Bernard Lewis and G Von Elbe (1937)
- Zeldovich, Frank-Kamenetskii (1938) and Semenov (1940)
- Peters, Seshadri, Williams (1990s)

Derivation of laminar burning velocity

Unburned
fuel/air mixture



Burned
hot products

Flame front

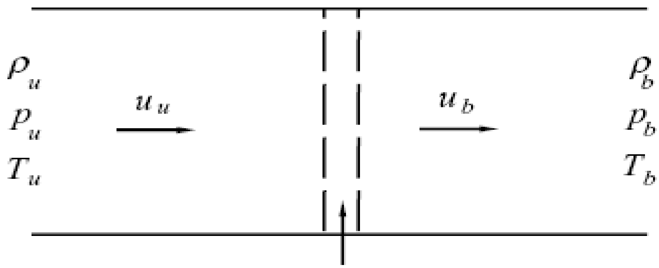
$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v} = 0$$

$$\frac{\partial \rho Y_i}{\partial t} + \nabla \cdot \rho Y_i \vec{v} = \nabla \cdot \rho D_i \nabla Y_i + \omega_i$$

Assumptions
-1 D
- steady state
- unity Lewis number
- low Mach number

Derivation of laminar burning velocity

Unburned
fuel/air mixture



Flame front

Burned
hot products

$$\cancel{\frac{\partial \rho}{\partial t}} + \nabla \cdot \rho \vec{v} = 0$$

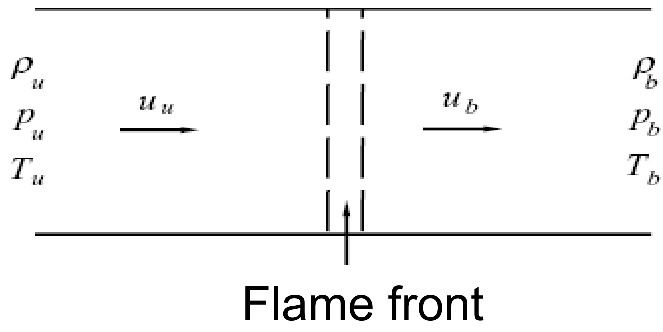
0

$$\cancel{\frac{\partial \rho Y_i}{\partial t}} + \nabla \cdot \rho Y_i \vec{v} = \nabla \cdot \rho D_i \nabla Y_i + \omega_i$$

Assumptions
-1 D
- steady state
- unity Lewis number
- low Mach number

Derivation of laminar burning velocity

Unburned
fuel/air mixture



Burned
hot products

$$\cancel{\frac{\partial \rho}{\partial t}} + \frac{d\rho u}{dx} = 0$$

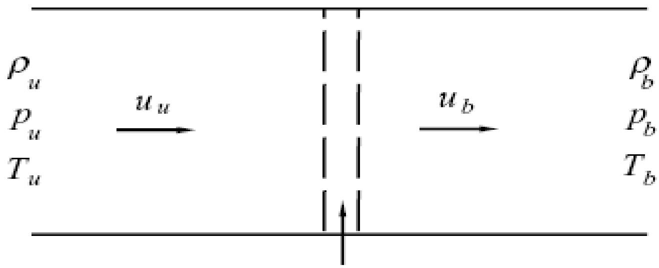
0

$$\cancel{\frac{\partial \rho Y_i}{\partial t}} + \frac{d\rho Y_i u}{dx} = \frac{d}{dx}\left(\rho D_i \frac{dY_i}{dx}\right) + \omega_i$$

Assumptions
-1 D
- steady state
- unity Lewis number
- low Mach number

Derivation of laminar burning velocity

Unburned
fuel/air mixture



Flame front

Burned
hot products

Assumptions
-1 D
- steady state
- unity Lewis number
- low Mach number

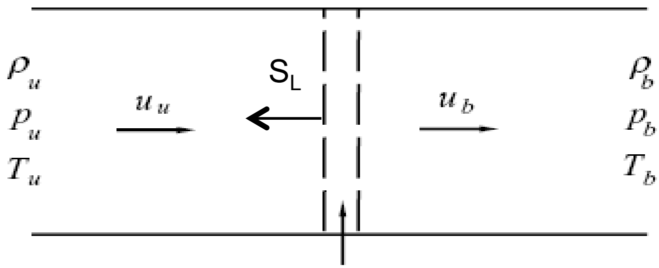
$$\cancel{\frac{\partial \rho}{\partial t}} + \frac{d\rho u}{dx} = 0$$

0

$$\cancel{\frac{\partial \rho Y_i}{\partial t}} + \frac{d\rho Y_i u}{dx} = \frac{d}{dx}\left(\rho D \frac{dY_i}{dx}\right) + \omega_i$$

Derivation of laminar burning velocity

Unburned
fuel/air mixture



Flame front

Burned
hot products

Assumptions
- 1 D
- steady state
- unity Lewis number
- low Mach number

$$\cancel{\frac{\partial \rho}{\partial t}} + \frac{d\rho u}{dx} = 0$$

0

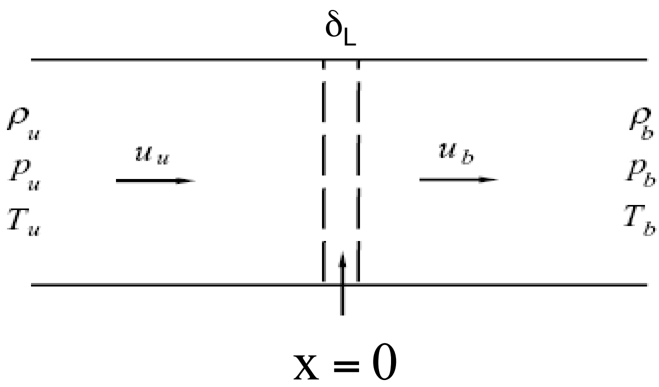
$$\Rightarrow \rho u = \rho_u S_L = \text{constant}$$

$$\cancel{\frac{\partial \rho Y_i}{\partial t}} + \frac{d\rho Y_i u}{dx} = \frac{d}{dx}\left(\rho D \frac{dY_i}{dx}\right) + \omega_i \Rightarrow \rho_u S_L \frac{dY_i}{dx} = \frac{d}{dx}\left(\rho D \frac{dY_i}{dx}\right) + \omega_i$$

Derivation of laminar burning velocity

$x \to -\infty$

$$Y_P = 0, \frac{dY_P}{dx} = 0$$



$x \to +\infty$

$$Y_P = Y_{P,b}, \frac{dY_P}{dx} = 0$$

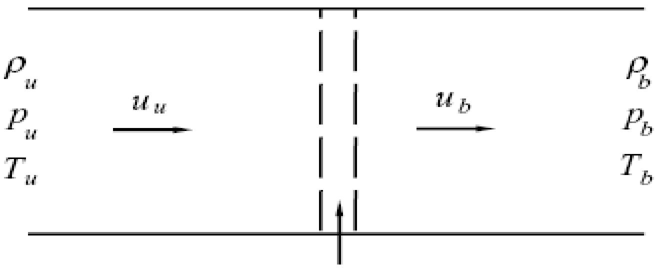
$$\rho_u S_L \frac{dY_i}{dx} = \frac{d}{dx}\left(\rho D \frac{dY_i}{dx}\right) + \omega_i \Rightarrow \int_{-\infty}^{+\infty}\left(\rho_u S_L \frac{dY_i}{dx}\right)dx = \int_{-\infty}^{+\infty}\left(\frac{d}{dx}\left(\rho D \frac{dY_i}{dx}\right) + \omega_i\right)dx$$

$$\Rightarrow \rho_u S_L (Y_{P,b} - 0) = \overline{\omega}_P \delta_L \Rightarrow S_L \propto \Omega \delta_L$$

Derivation of laminar burning velocity

$x \rightarrow -\infty$

$$Y_P = 0, \frac{dY_P}{dx} = 0$$



$x = 0$

$x \rightarrow +\infty$

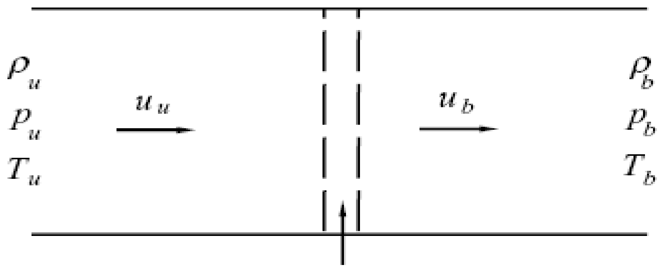
$$Y_P = Y_{P,b}, \frac{dY_P}{dx} = 0$$

$$\rho_u S_L \frac{dY_i}{dx} = \frac{d}{dx}\left(\rho D \frac{dY_i}{dx}\right) + \omega_i \Rightarrow \int_{-\infty}^{-\delta_L/2} \left(\rho_u S_L \frac{dY_i}{dx}\right) dx = \int_{-\infty}^{-\delta_L/2} \left(\frac{d}{dx}\left(\rho D \frac{dY_i}{dx}\right) + \omega_i\right) dx$$

$$\Rightarrow \rho_u S_L (Y_{P,b} / 2 - 0) = \rho D \frac{Y_{P,b} - 0}{\delta_L} \Rightarrow S_L \delta_L \propto D$$

Derivation of laminar burning velocity

Unburned
fuel/air mixture



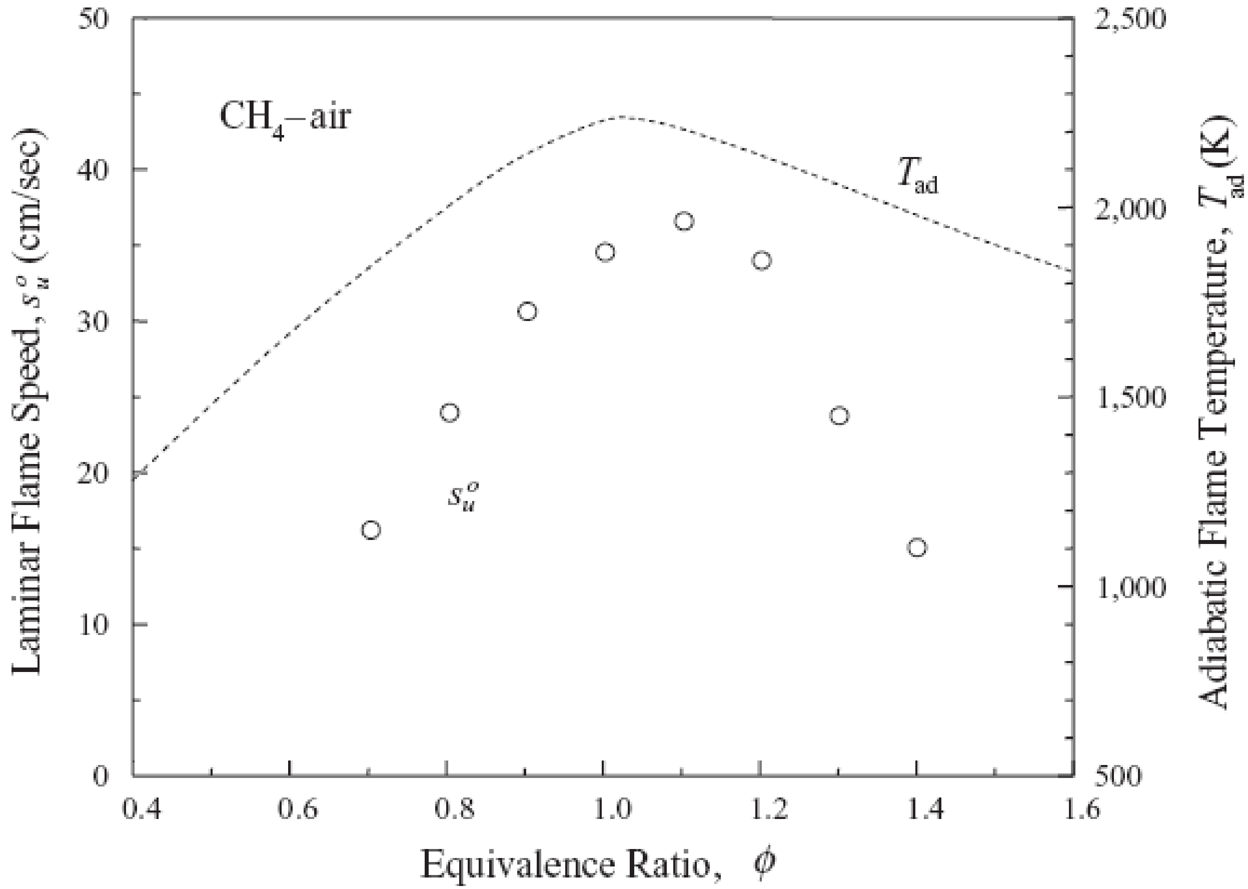
Burned
hot products

Flame front

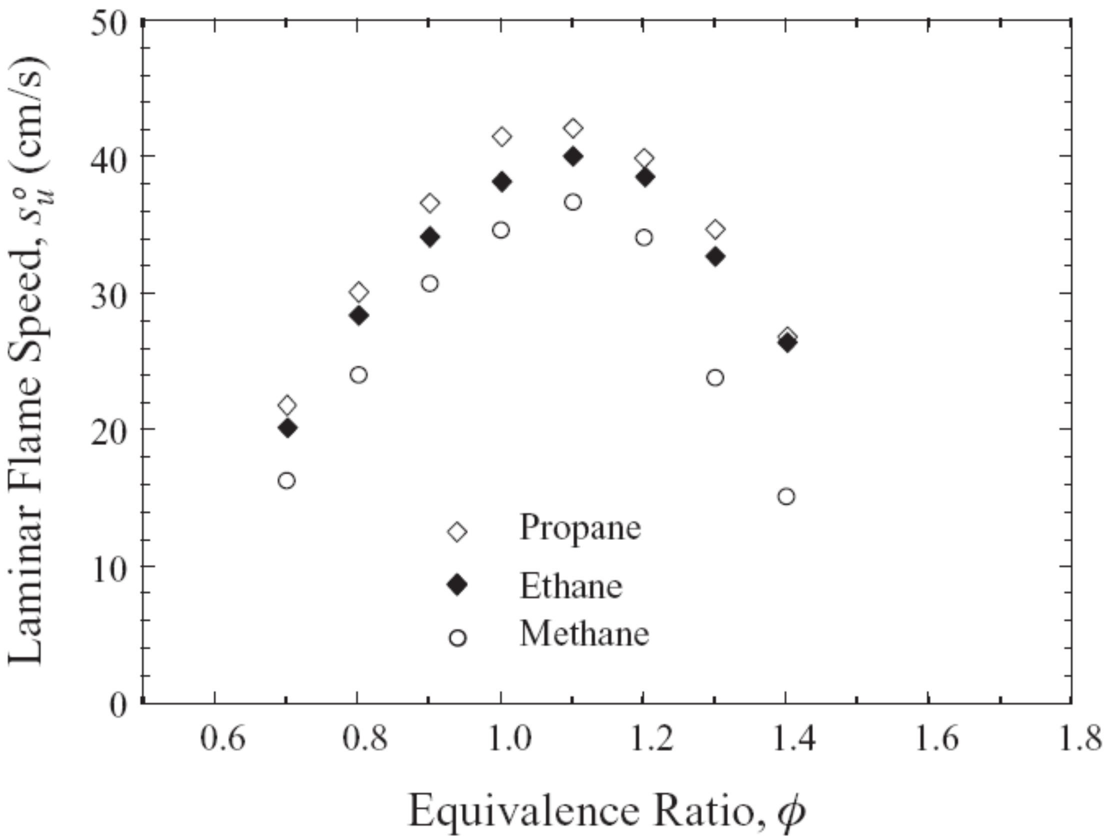
$$S_L \sim \sqrt{D\Omega}, \qquad D: \text{ mass diffusion cofficient } [m^2/s]$$

$$\delta_L \sim \sqrt{D/\Omega} \qquad \Omega: \text{ reaction rate } [1/s]$$

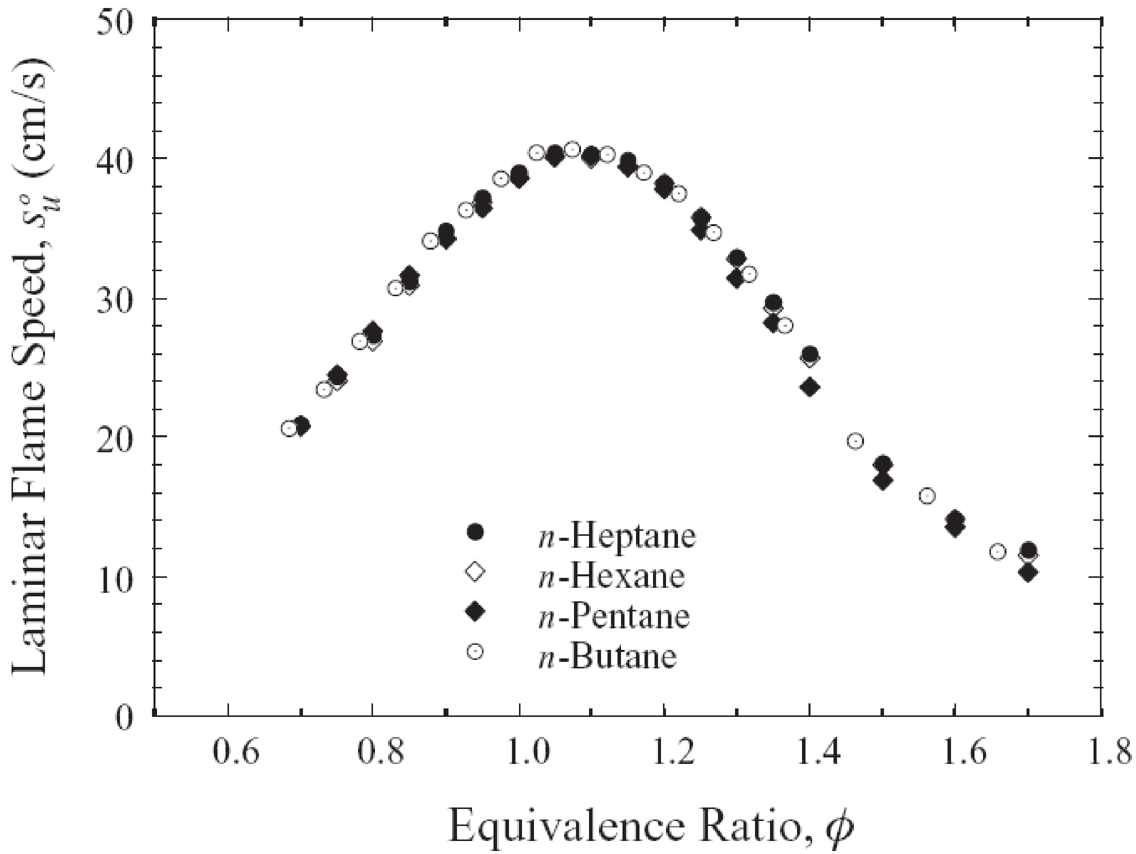
Dependence on fuel/air ratio



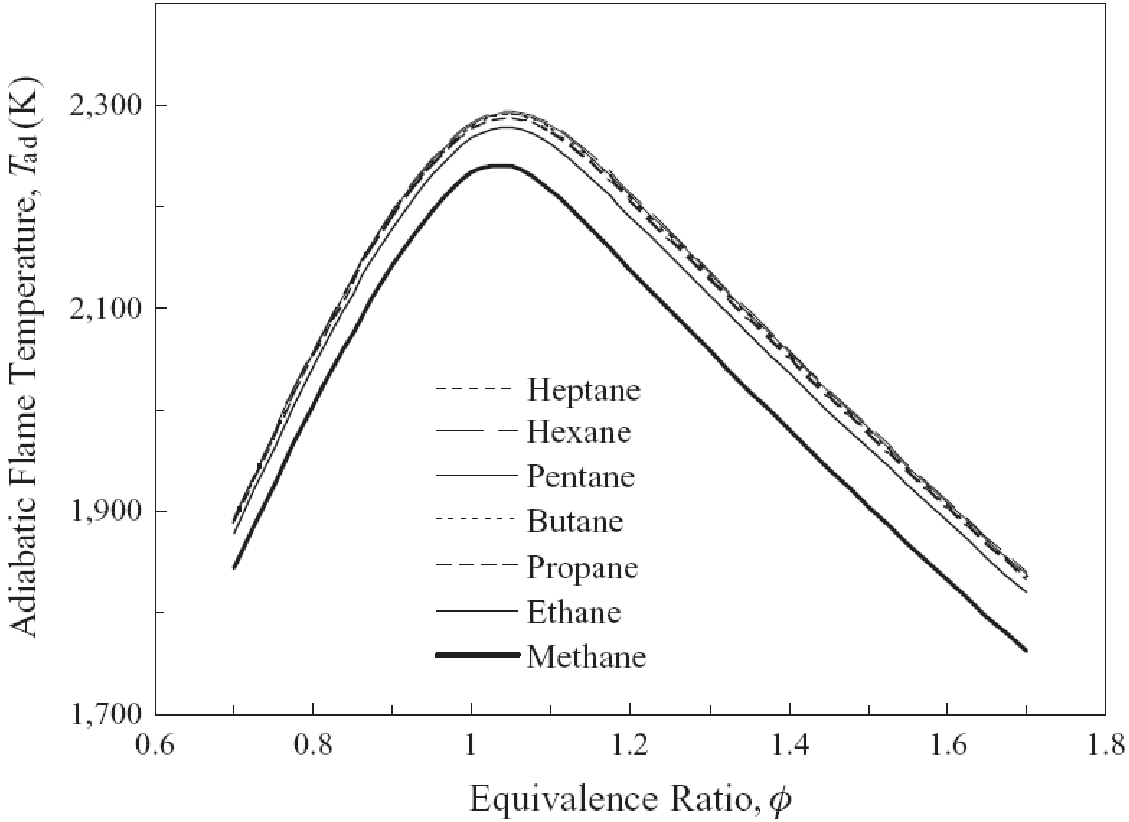
Dependence on flame temperature



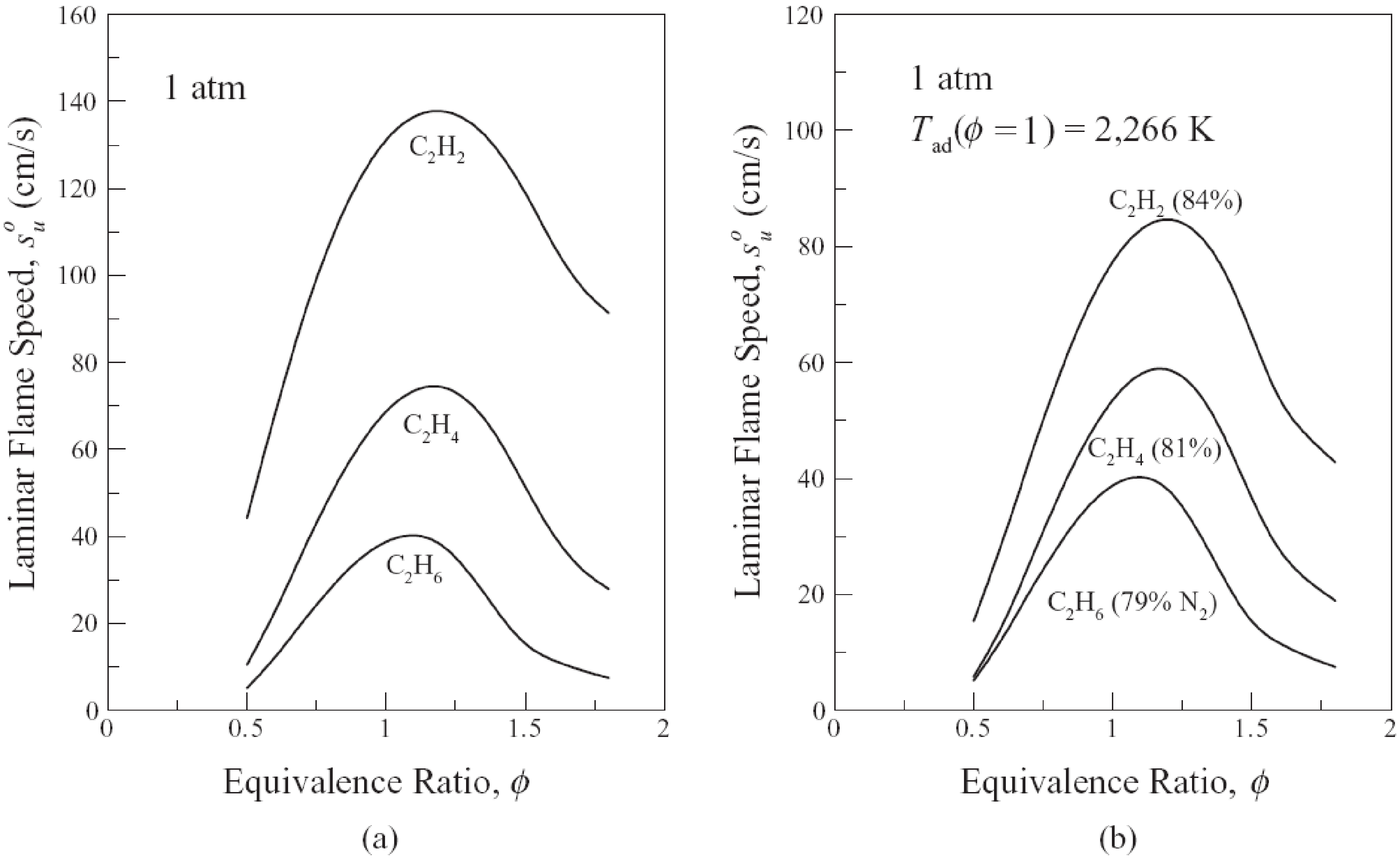
Dependence on flame temperature



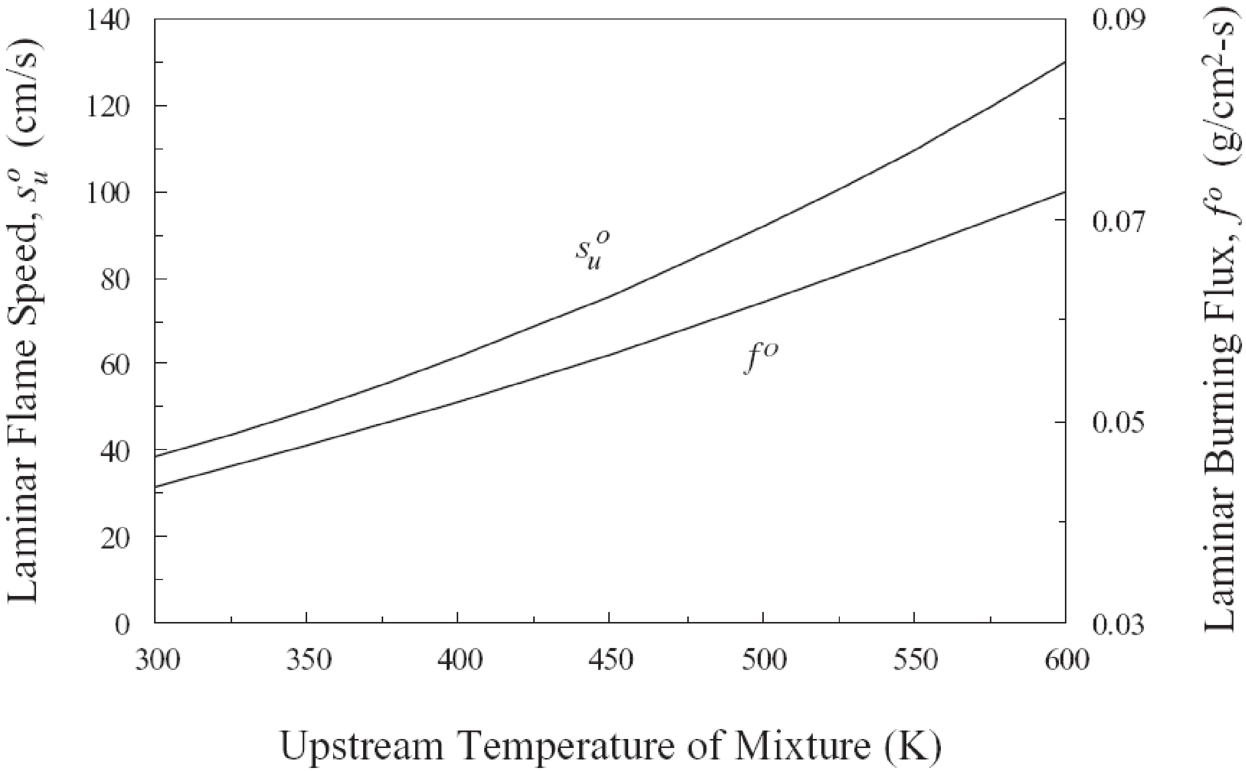
Dependence on flame temperature



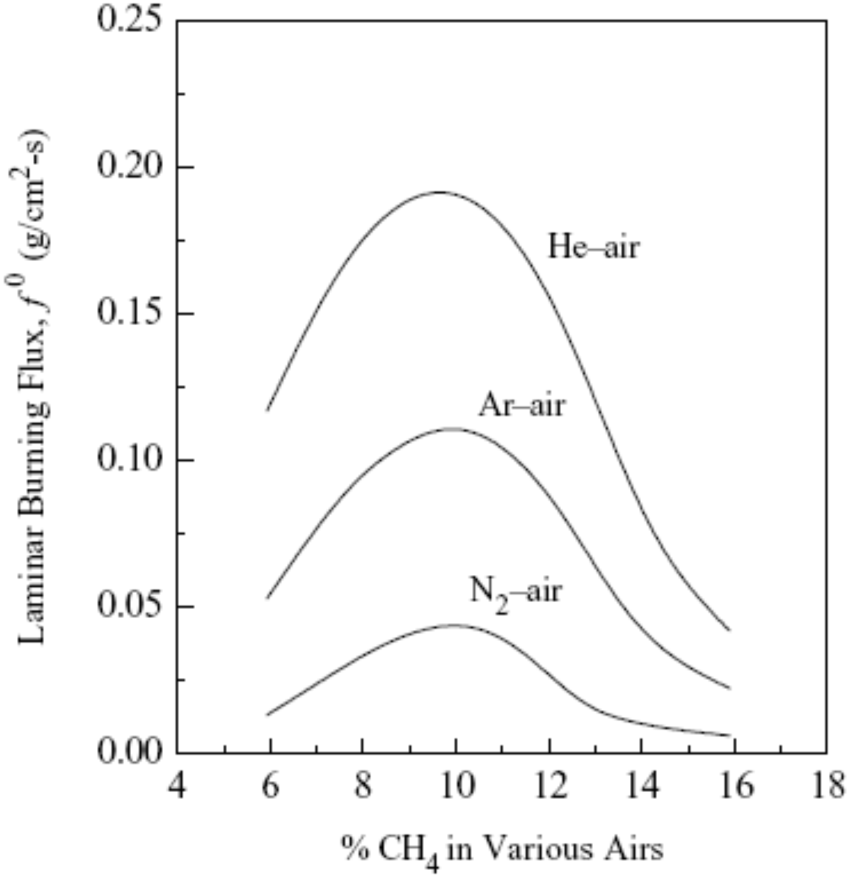
Dependence on reactivity



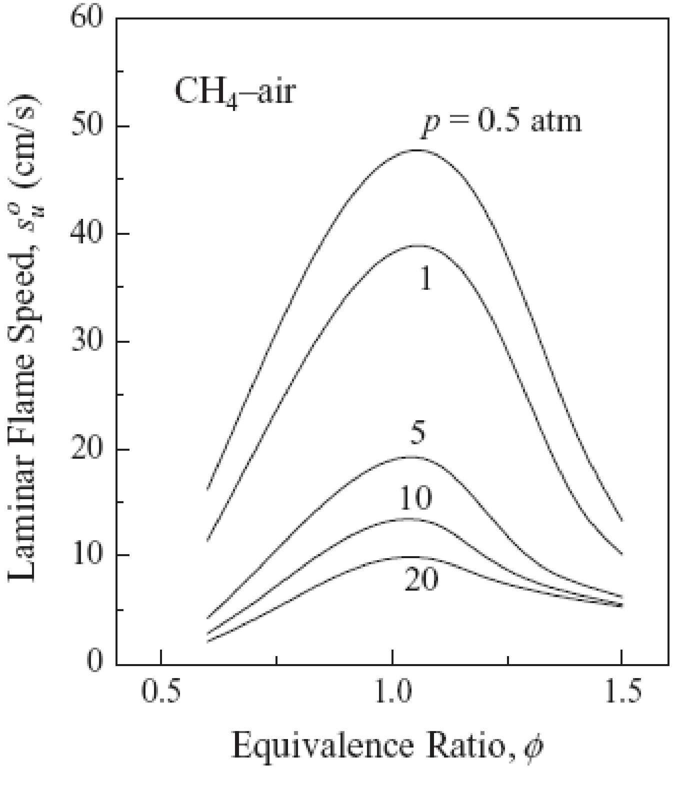
Dependence on preheat temperature



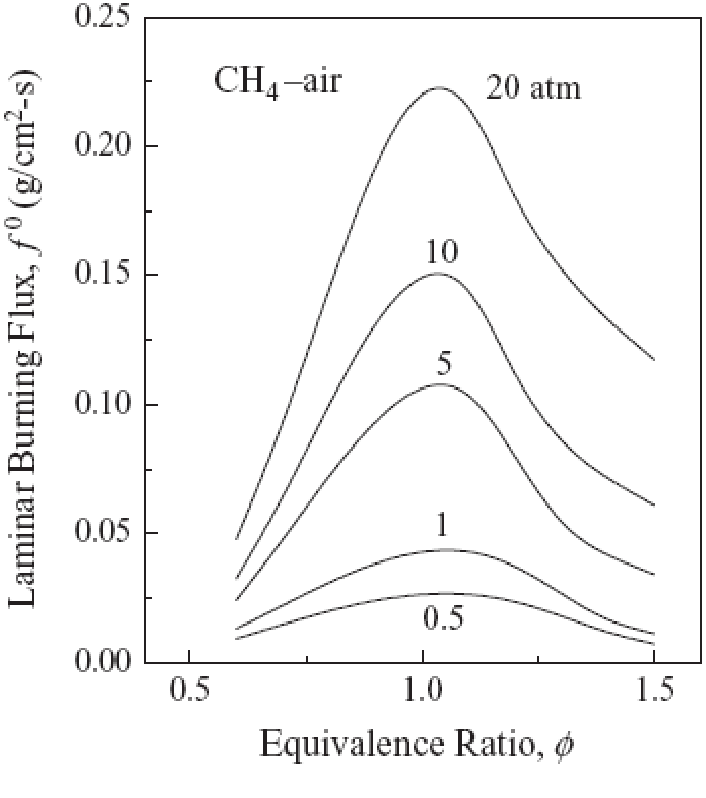
Dependent on transport properties



Dependence on pressure



(a)



(b)

Syngas/air (CO/H2/air) flames
– effect of reactivity and diffusivity

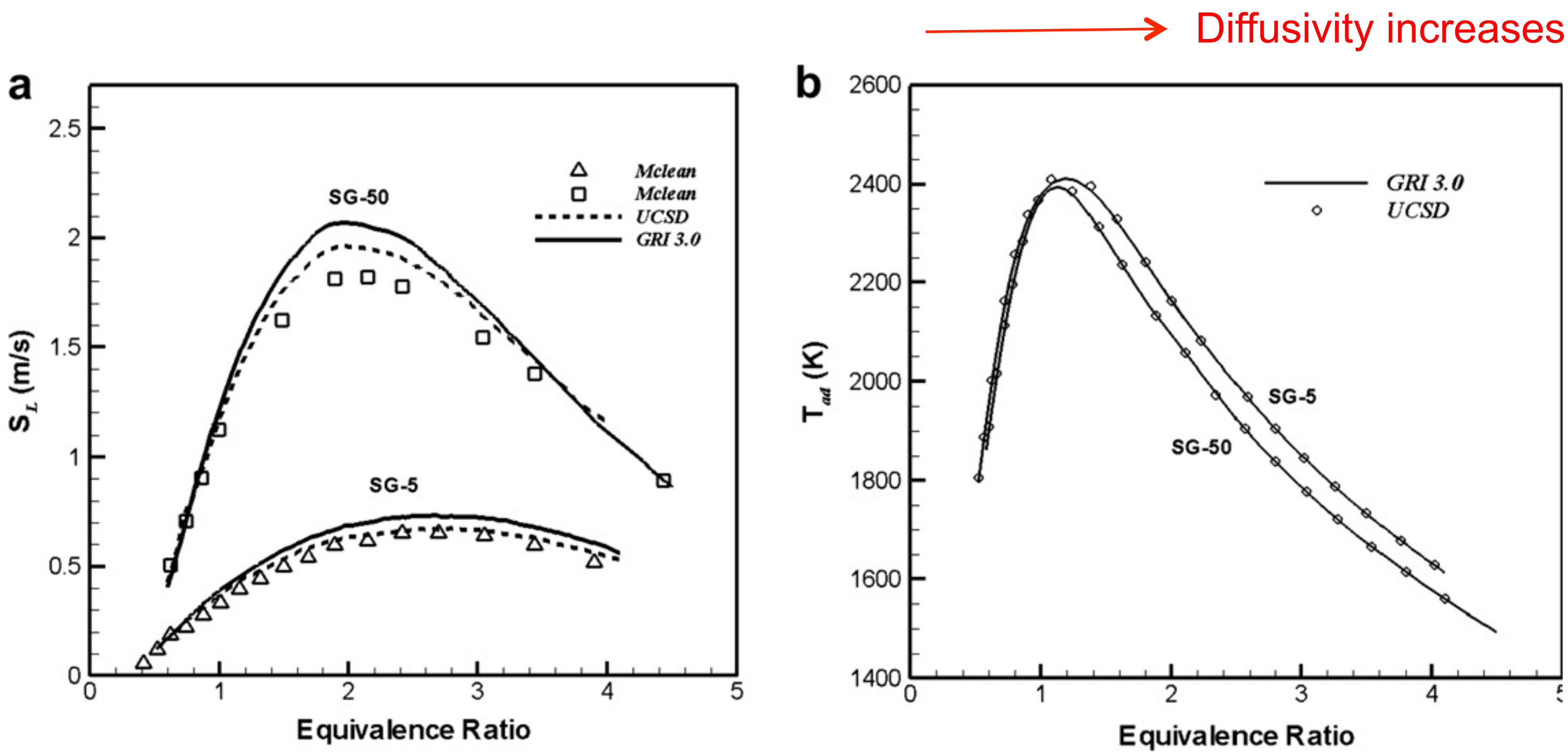
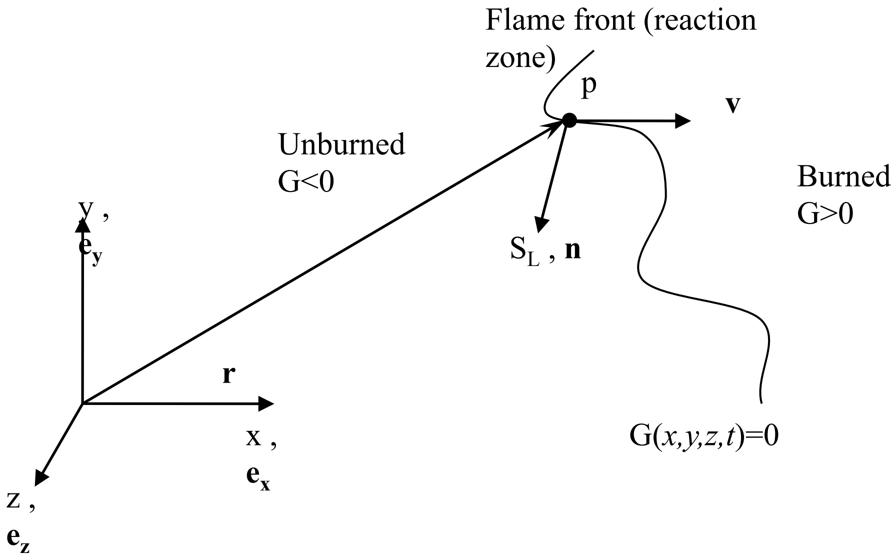


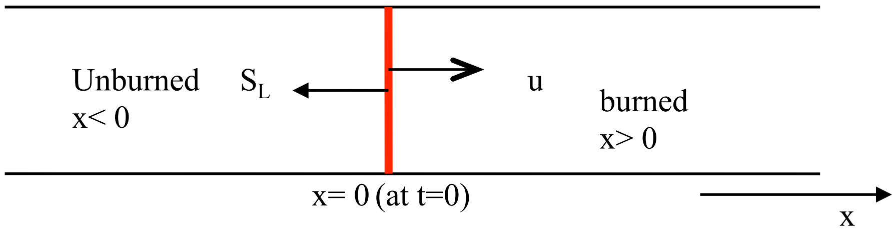
Fig. 10 – Laminar burning velocity and adiabatic flame temperature of syngas flames at atmospheric pressure and mixture temperature of 300 K.

Propagation of laminar premixed flame



$$\frac{\partial G}{\partial t} + \vec{v} \cdot \nabla G = S_L \left| \nabla G \right|$$

Planar flame in a pipe



- Stable flame
- Flash back
- Blow-off
- Wall effect

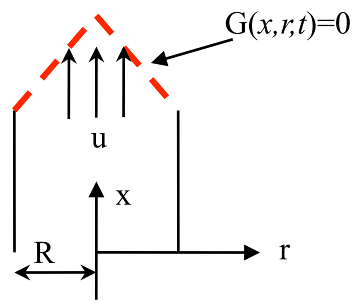
Bunsen flame

$$G(x, r, t) = x + f(r) = 0$$

$$u = S_L \sqrt{\left(f'\right)^2 + 1}$$

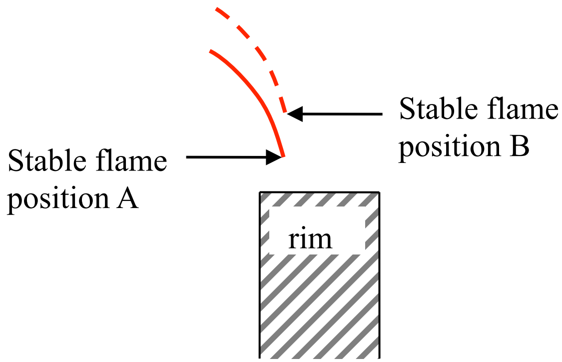
$$f(r) = \sqrt{\frac{u^2 - S_L{}^2}{S_L{}^2}} r + \text{constant}$$

$$x = (R - r)\sqrt{\frac{u^2 - S_L{}^2}{S_L{}^2}}$$



- Conical shape
- Flame length vs R, u, S_L

Bunsen flame stability



- Rim effect
- Lifted flame
- blowout

Stabilization of premixed flames

- Rim stabilization
- Pilot flame stabilization
- Bluff body stabilization