Turbulent Premixed Flames

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Turbulent Premixed Flames

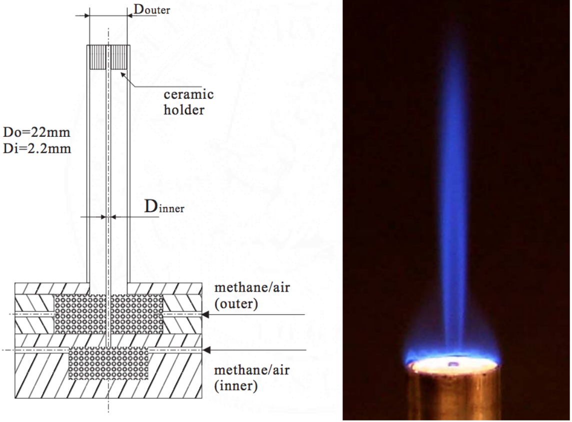


Figure: A premixed burner - X.S.Bai

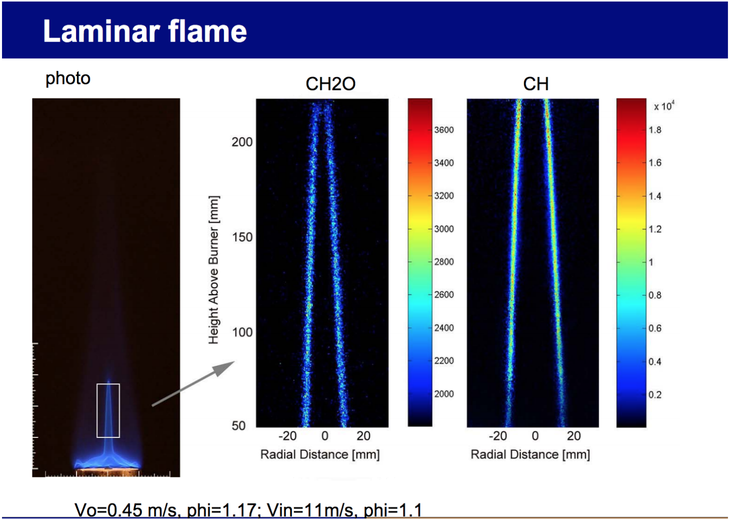


Figure: A laminar premixed flame - X.S.Bai

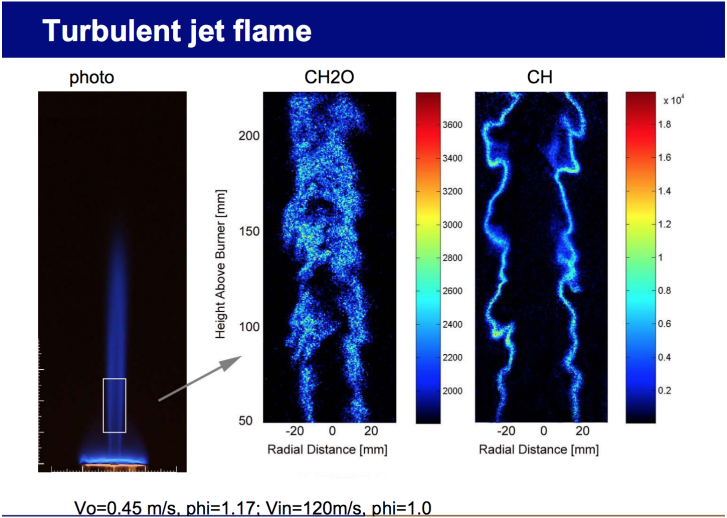


Figure: A turbulent premixed flame - X.S.Bai

Turbulent Premixed Flames

- Planar single pulse OH radical concentration, 50mm above the burner. Field size: 150x110 mm
- natural gas/air premixed flame measured by Buschmann et al (26th symp. Comb., pp.437, 1996)
- OH peak denotes the flame zone. Why flame zone is wrinkled? See next slide

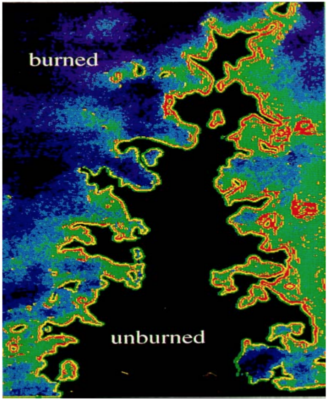


Figure: A turbulent premixed flame - closer look - X.S.Bai

Structure of a Laminar Premixed Flame

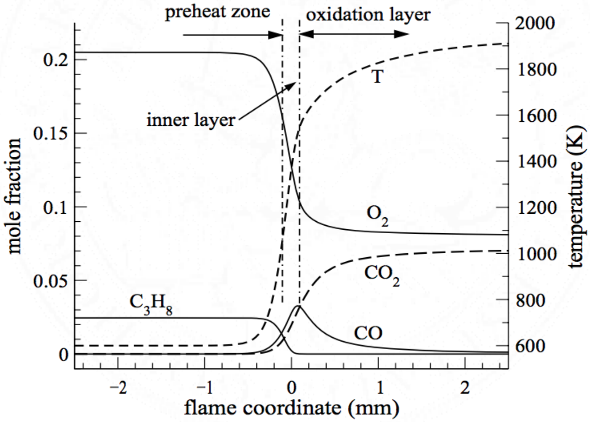


Figure: Propane laminar flame structure

Turbulent Premixed Flames

Influence of the velocities flutuations of the turbulent regime

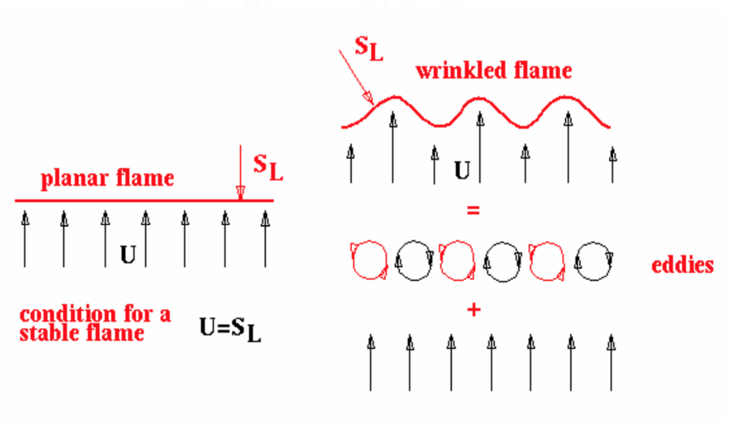


Figure: Wrinkling of the flame surface by turbulence - X.S.Bai

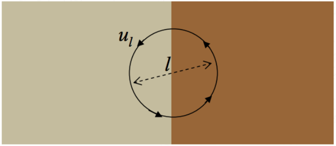
Flow and Flame scales in a Turbulent Premixed Flame

- Flow scales
  - Mean flow scales
    - Length (L), velocity (U), time ($t=L/U$)
  - integral scales
    - length (l_0), velocity ($v_0=u(l_0)$), time ($\tau_0= l_0/v_0$),
  - Kolmogrov scales
    - length (η), velocity ($v_\eta=u(\eta)$), time ($\tau_\eta= \eta/v_\eta$),

- Flame scales
  - flame speed (S_L)
  - flame thickness (δ_L)
  - time scale (t_c)
    - flame thickness/flame speed
    - chemical reaction time
  - the flame structure may not be laminar

Turbulent and Molecular Mixing Scales

Eddy size –	l
Eddy velocity –	u_l
Eddy turn over time –	$t_{eddy} = l/u_l$
Molecular mixing time of Material of size l_k –	$t_{mixing} = l_k^2/D = l_k/u_k$

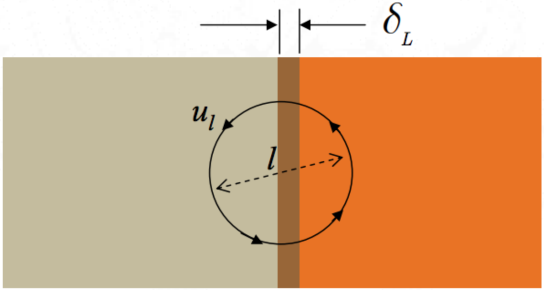


$$\frac{t_{eddy}}{t_{mixing}} = \frac{l}{u_l}\frac{u_k}{l_k} = \mathrm{Re}_l^{1/2}$$

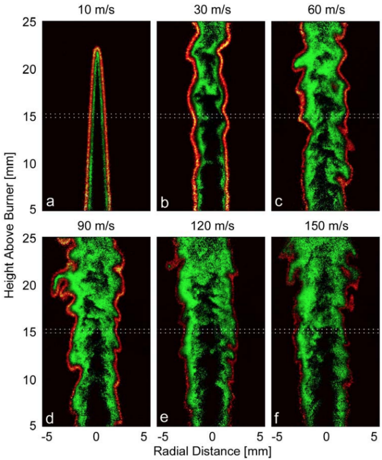
$$note : l_k = \eta, u_k = u_\eta$$

Flow and Flame scales in a Turbulent Premixed Flame

Turbulent eddy length scale and flame thickness



Transition from a Laminar to a Turbulent Premixed Flame



PLIF images of formaldehyde (green) and CH (red) in laminar (a) and turbulent (b-f) flames with different gas supply speeds in the inner tube.

Scales on a Turbulent Premixed Flame

$$\varepsilon \propto \frac{v_0^3}{l_0} \propto \frac{v_\eta^3}{\eta} \Rightarrow \frac{\tau_0}{\tau_\eta} \propto \frac{l_0}{v_0}\frac{v_\eta}{\eta} \propto \left(\frac{l_0}{\eta}\right)^{2/3}$$

$$\frac{v_\eta \eta}{\nu} \propto 1 \Rightarrow \frac{v_0 l_0}{v_\eta \eta} \propto \mathrm{Re}_{l0}$$

$$\frac{l_0}{\eta} \propto \frac{l_0}{\eta}\frac{v_0}{v_\eta}\frac{v_\eta}{v_0} \propto \frac{l_0 v_0}{\nu}\left(\frac{\eta}{l_0}\right)^{1/3}$$

$$\Rightarrow \frac{l_0}{\eta} \propto \mathrm{Re}_{l0}^{3/4}; \frac{v_0}{v_\eta} \propto \mathrm{Re}_{l0}^{1/4}; \frac{\tau_0}{\tau_\eta} \propto \mathrm{Re}_{l0}^{1/2};$$

Non-Dimensional Numbers in Turbulent Premixed Flames

Reynolds number
$$\mathrm{Re}_{l0} = \frac{v_0 l_0}{\nu}$$

Damköhler number
$$Da = \frac{\tau_0}{\tau_c} = \frac{l_0}{v_0}\frac{S_L}{\delta_L}$$

Karlovitz number
$$Ka = \frac{\tau_c}{\tau_\eta} = \frac{\delta_L}{S_L}\frac{v_\eta}{\eta} = \frac{\delta_L \delta_L}{S_L \delta_L}\frac{D}{\nu}\frac{v_\eta \eta}{\eta\eta} = \left(\frac{\delta_L}{\eta}\right)^2$$

Turbulent intensity
$$TI = \frac{v_0}{S_L}$$

Borghi-Diagramm - Reynolds Number

$$\mathrm{Re}_l = \frac{v_0 l_0}{\nu}$$

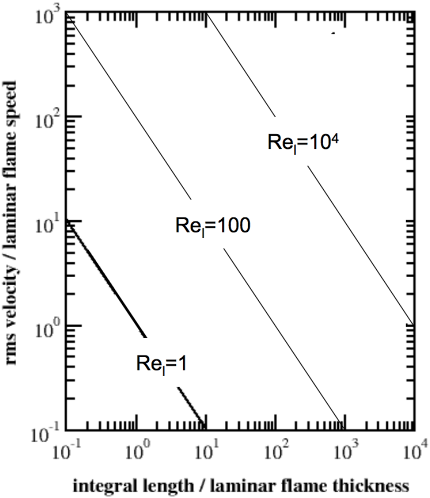
$$\therefore S_L \propto (D \cdot rr)^{1/2}, \delta_L \propto (D / rr)^{1/2}, S_L \delta_L \propto D \propto \nu$$

$$\mathrm{Re}_l = \frac{v_0 l_0}{\nu} \propto \frac{v_0 l_0}{D} \propto \frac{v_0 l_0}{S_L \delta_L}$$

$$\Rightarrow \log\left(\frac{v_0}{S_L}\right) = \log(\mathrm{Re}_l) - \log\left(\frac{l_0}{\delta_L}\right)$$

← Constant Re_l lines in the Borghi-diagram

Borghi-Diagramm - Reynolds Number



Borghi-diagram

Constant Re_l lines

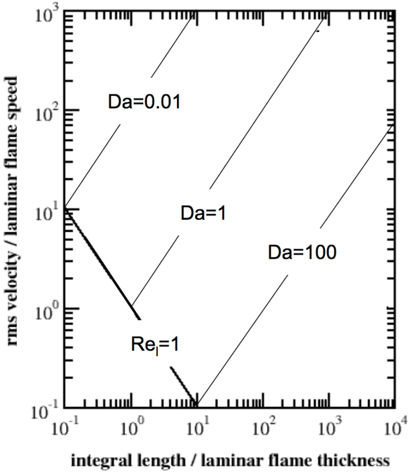
$$\log\left(\frac{v_0}{S_L}\right) = \log\left(Re_l\right) - \log\left(\frac{l_0}{\delta_L}\right)$$

Borghi-Diagramm - Damkoehler Number

$$Da = \frac{\tau_0}{\tau_c} = \frac{l_0}{v_0}\frac{S_L}{\delta_L}$$

$$\log(Da) = \log(\frac{l_0}{\delta_L}) - \log(\frac{v_0}{S_L})$$

Borghi-Diagramm - Damkoehler Number



Borghi-diagram

Constant Da lines

$$\log(Da) = \log(\frac{l_0}{\delta_L}) - \log(\frac{v_0}{S_L})$$

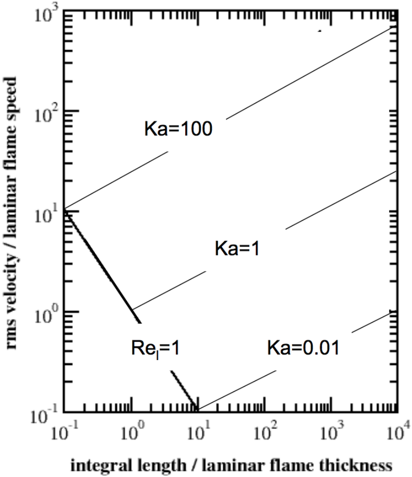
Borghi-Diagramm - Karlovitz Number

$$Ka = \frac{\tau_c}{\tau_\eta} = \frac{\delta_L}{S_L}\frac{v_\eta}{\eta} = \frac{\delta_L}{S_L}\frac{l_0}{l_0}\frac{v_\eta}{\eta}\frac{u'}{u'} = \frac{\delta_L}{l_0}\frac{u'}{S_L}\frac{l_0}{\eta}\frac{v_\eta}{u'}$$

$$= \frac{\delta_L}{l_0}\frac{u'}{S_L}\mathrm{Re}_{l0}^{\;1/2} = \left(\frac{\delta_L}{l_0}\right)^{1/2}\left(\frac{u'}{S_L}\right)^{3/2}$$

$$\log\left(\frac{u'}{S_L}\right) = \frac{1}{3}\log\left(\frac{l_0}{\delta_L}\right) + \frac{2}{3}\log(Ka)$$

Borghi-Diagramm - Karlovitz Number

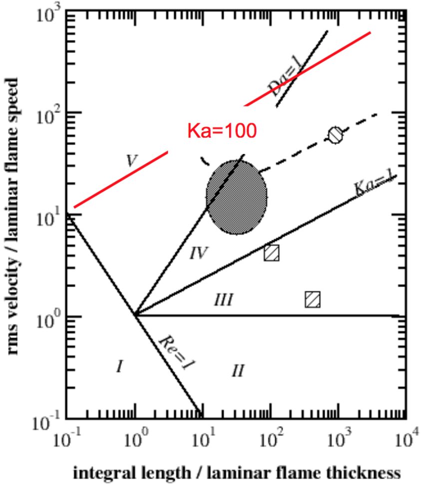


Borghi-diagram

Constant Ka lines

$$\log(\frac{u'}{S_L}) = \frac{1}{3}\log(\frac{l_0}{\delta_L}) + \frac{2}{3}\log(Ka)$$

Borghi-Diagramm



Borghi-diagram

dark region: GT engines
small circle: GE LM6000
squares: VR-1

I: laminar flames
II: wrinkled flamelet
III: corrugated flamelet
IV: thin reaction zone
V: distributed reactions

Turbulent Premixed Flames

It's difficult to quantify the turbulent fluctuations in a premixed flame.

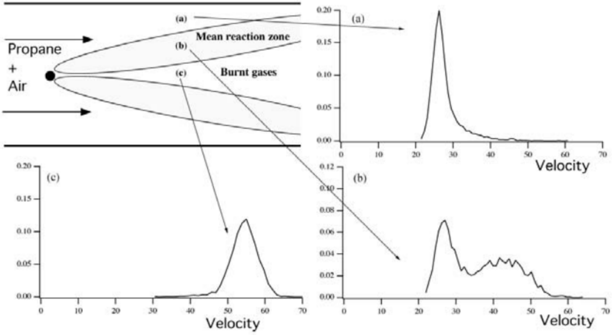


Figure: Velocity measurements in a V-shape turbulent premixed flame stabilized behind a small rod (top). Velocity probabilities are displayed in fresh gases (location a), in the mean reaction zone (b) and in burnt gases (c) (Veynante et al).

Laminar Flame Regime

- - $Re_l < 1$ - Turbulent fluctuations are dumped without influent on the laminar flame structure

Flamelet Regime

$$Ka = \frac{\tau_c}{\tau_\eta} = \frac{\delta_L}{S_L}\frac{v_\eta}{\eta} = \frac{\delta_L \delta_L}{S_L \delta_L}\frac{D}{\nu}\frac{v_\eta \eta}{\eta\eta} = \left(\frac{\delta_L}{\eta}\right)^2 < 1$$

- The thickness of reaction zone + preheat zone is thinner than the Kolmogrov scale, i.e. $\delta_L < \eta$
  - Tranport of mass and heat between the reaction zone and preheat zone is by molecular mixing
  - As a good approximation the local flame propagates at laminar flame speed and the thickness of the flame is laminar

Flamelet Regime - turbulent eddy X reaction zone

The flame structure is not perturbed by turbulent fluctuations and remains quasi-steady;

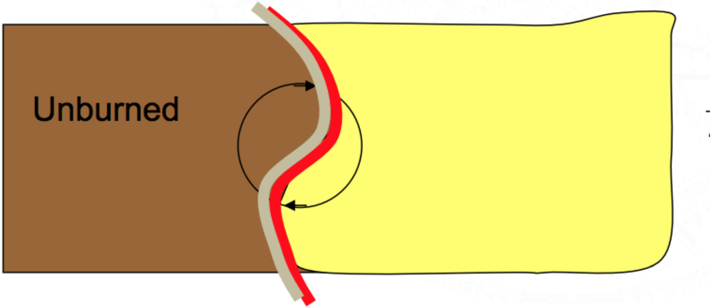
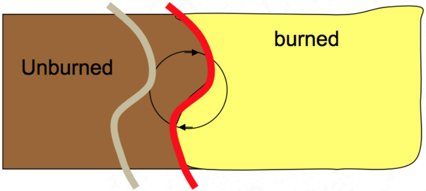


Figure: Flamelet Regime - $Ka < 1$

Turbulence will therefore wrinkle the flame, but will not disturb the laminar flame structure.

Thin Reaction Zone Regime

$$Ka = \frac{\tau_c}{\tau_\eta} = \frac{\delta_L}{S_L}\frac{v_\eta}{\eta} = \frac{\delta_L \delta_L}{S_L \delta_L}\frac{D}{\nu}\frac{v_\eta \eta}{\eta\eta} = \left(\frac{\delta_L}{\eta}\right)^2, 1 < Ka < 100$$



Reactant pockets
May not pass the
Inner layer of
The reaction zone

Figure: Thin Reaction Zone Regime - $Ka > 1$

$Ka > 1$ indicates that the smallest eddies of size η can enter into the pre-heat zone in the flame structure since $\eta < \delta_L$

Turbulent Premixed Flames - Thin Reaction Zone Regime

- The reaction inner layer thickness is one tenth of the preheat zone thickness, which is of the same order of magnitude as the flame thickness.
- The small eddies are still larger than the reaction inner layer thickness, $\delta \approx 0.1\delta_L$, and therefore they do not enter the inner layer.
- The upper limit for the influence of the turbulent eddy on the reaction inner layer is $\frac{0.1\delta_L}{\eta} = 1$, which corresponds to $Ka = 100$
- The thin reaction zone retains a laminar structure, whereas the preheat region is governed by turbulent mixing, which enhances the burning velocity.

Turbulent Premixed Flames - Distributed Reaction Zone Regime

Distributed Reaction Zone Regime - $Ka > 100$

$$Ka = \frac{\tau_c}{\tau_\eta} = \frac{\delta_L}{S_L}\frac{v_\eta}{\eta} = \frac{\delta_L \delta_L}{S_L \delta_L}\frac{D}{\nu}\frac{v_\eta \eta}{\eta\eta} = \left(\frac{\delta_L}{\eta}\right)^2, Ka > 100$$

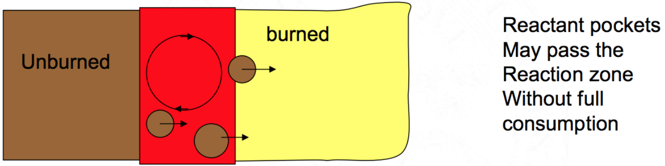


Figure: Distributed Reaction Zone Regime

Turbulent Premixed Flames - Distributed Reaction Zone Regime

Distributed Reaction Zone Regime - $Ka > 100$

- In the broken reaction zones regime, the Kolmogorov scale becomes smaller than the reaction inner zone thickness: $\eta < \delta$. They may therefore enter into the inner layer and perturb it with the consequence that chemistry breaks down locally due to enhanced heat loss to the preheat zone followed by temperature decrease and the loss of radicals.
- Local extinction may lead to the complete extinction of the premixed flame

Thank you!

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