# Lecture 36 - Turbulent Nonpremixed Flames.

## Outline

- Flame Radiation
- Liftoff, Blowout
- Flame Stability
- Demo

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## Radiation

- Calculation of Radiation is complicated
    - Action at a Distance.
    - Gas absorbsion, emission $\rightarrow CO_2, H_2O$
    - Soot absorbtion, emission
    - Turbulent fluctuating Flow field.
- Detailed Radiation Transport fully accounts for these properties, but is complex and requires sophisticated Computer modeling.
- Radiant Fraction : Heat loss factor.

$$\boxed{\chi_R = \frac{\dot{Q}_{Rad}}{\dot{m}\Delta h_c}} = \frac{a_p V_d \sigma T_f^4}{\rho V_e A \Delta h_c} \propto \frac{a_p d^3 T^4}{V_e d^2} \propto \frac{a_p T^4 d}{V_e} \propto a_p T^4 \tau$$

- Time - Need sufficient time to lose heat (Soot, $T^4$, time)
- Fuel - Sooting propensity
- Flame Shape - Bigger flames → more radiation (more soot, more time)
- But Note: Flame size ~ const as $\dot{m}$ increases, while time Decreases → $\chi_R$ Drops as Firing Rate increases for a fixed size.
- Again, for fixed Firing Rate : $\dot{m}$, $\chi_R$ increases w/ flame size.

Note $\underline{\chi_R \propto a_p T^4 \tau}$

$\boxed{\text{See Fig 13.13}}$

* Note Loss Fractions : 60% 45% 15% max for $C_2H_2$, $C_3H_8$, $CH_4$

# Chemical Engineering 633

## *Combustion Processes*

### Turbulent Nonpremixed Flames

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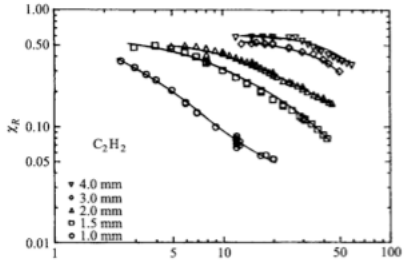
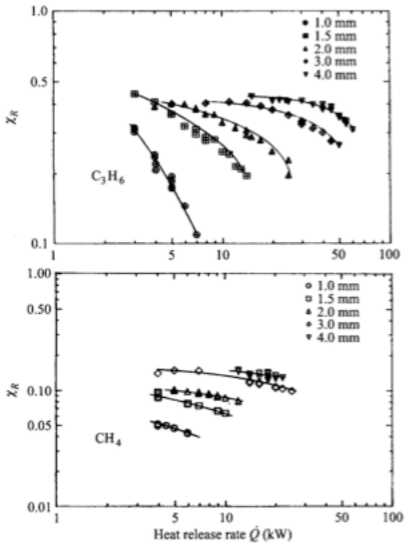
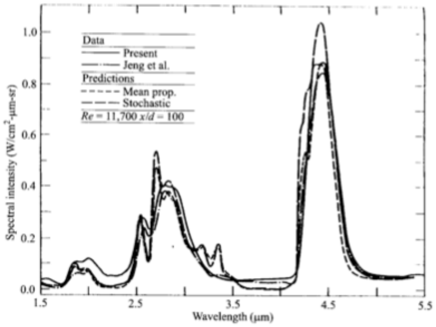
# Radiation



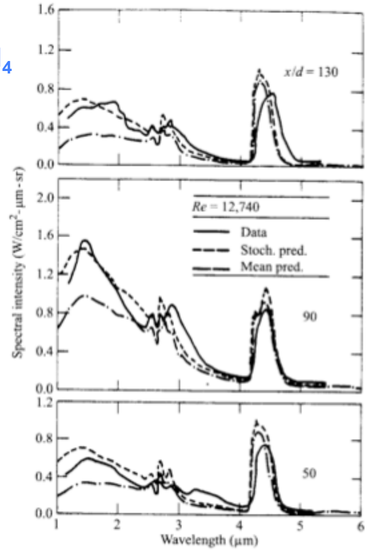


# Radiation

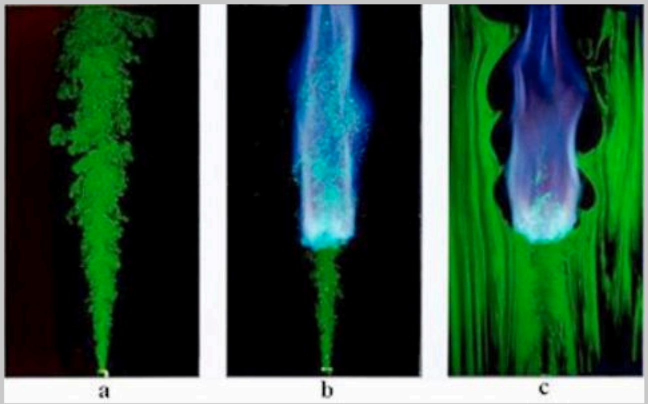
CH$_4$



C$_2$H$_4$



# Flame Stability



**Title:** Lifted flames

**Description:** The pictures show turbulent jet visualization (Re = 4100, methane) through Mie scattering (instantaneous, green) and flame emission (1/30 s average, blue).

a) Nonreacting, jet seed is alumina.

b) Lifted flame, jet seed is alumina.

c) Lifted flame, co-flow seed is glycerol-water fog.

The axial view is about 50 nozzle diameters or 24 cm.

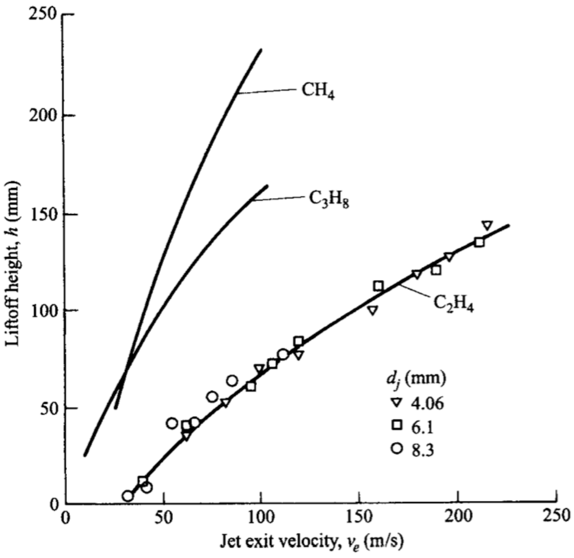
**Credits:** M. G. Mungal

**References:** Muniz, L. and Mungal, M. G., Instantaneous Flame-Stabilization Velocities in Lifted-Jet Diffusion Flames, *Combustion and Flame*, **111**, 1997, 16-31.

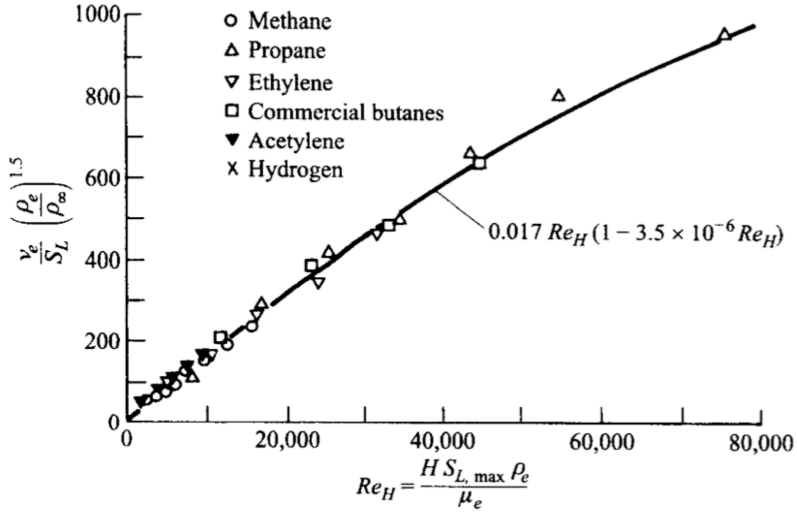
# Liftoff Theories

- Theory 1
  - – Turbulent premixed flame: $v(S_{L,max})=S_T$
- Theory 2
  - – Local strain: $\varepsilon > \varepsilon_{crit}$
- Theory 3
  - – Backmixing hot products: $t_{local\ mixing} < t_{chem,\ crit}$
- Others:
  - – Edge/triple flames
  - – Combination of several

# Flame Liftoff Height



# Jet Flame Blowout



# Correlations

- Flame height

$$\frac{\rho_e S_{L,max} h}{\mu_e} = 50\left(\frac{v_e}{S_{L,max}}\right)\left(\frac{\rho_e}{\rho_\infty}\right)^{1.5}$$

- Flame blowout condition

$$\frac{v_e}{S_{L,max}}\left(\frac{\rho_e}{\rho_\infty}\right)^{1.5} = 0.017 Re_H (1 - 3.5 \times 10^{-6} Re_H)$$

$$Re_H = \frac{\rho_e S_{L,max} H}{\mu_e}$$

$$H = 4d_j\left[\frac{Y_{f,e}}{Y_{f,stoic}}\left(\frac{\rho_e}{\rho_\infty}\right)^{1/2} - 5.8\right]$$

H is $H_{stoic}$

# Swirl

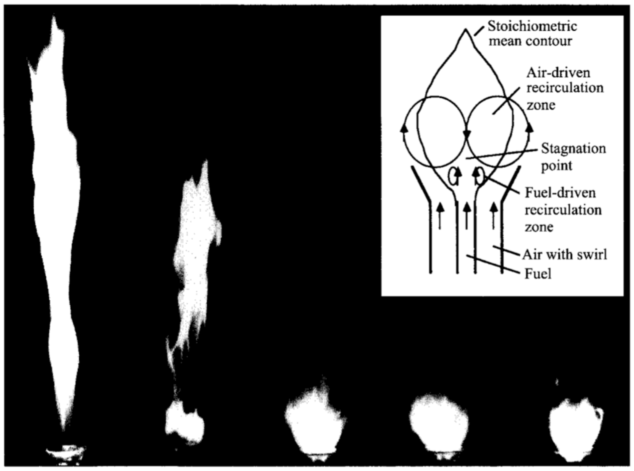


**Figure 13.22** Effect of swirl on flame length. Photographic sequence showing no swirl (left) progressing to a swirl number of $S = 1.1$.

SOURCE: Reprinted from Ref. [38] with permission of The Combustion Institute.

- Flame Length
- Stability
- $S=G_\theta/R*G_x$

# Liftoff, Blowoff.

- Turbulence is highest near jet exit and Turbulence intensity Decays Downstream.
- The high Turb. can lead to flame extinction near the exit →
  Liftoff : Flame base is not "attached" to the burner, but is located Downstream.
- This is an unstable situation as turbulence fluctuations can result in velocities high enough to cause Global blowout.
- Premixing can occur in region below the flame base.

Key Theory :

- Liftoff height is where local velocity for max $S_L$ matches turbulent premixed flame speed.
- Blowout occurs when turb Burning velocity falls faster w/ Dist. than local velocity at position of $S_{L,max}$
  - That is, at the Downstream Distance of the stoich point ($S_L$ max) $V > S_t$ and $S_t$ falls faster w/ Downstream Distance than V Does → Blowoff.
- Dangerous since w/o a flame, we're feeding a combustor (nominally hot) w/ fuel / air → can ignite → explosion.

- Turns provides correlations for Liftoff height and Blowout flow-rates.

Liftoff height.

$$\frac{\rho_e S_{L\,max} h}{\mu_e} = 50\left(\frac{v_e}{S_{L\,max}}\right)\left(\frac{\rho_e}{\rho_\infty}\right)^{1.5}$$

Blowout Flow

$$\frac{v_e}{S_{L,max}}\left(\frac{\rho_e}{\rho_\infty}\right)^{1.5} = 0.017\, Re_H\left(1-3.5\times10^{-6}\, Re_H\right) \quad ; \quad Re_H = \frac{\rho_e S_{L,max} H}{\mu_e}$$

$$H = 4\left[\frac{Y_{F,e}}{Y_{F,stoic}}\left(\frac{\rho_e}{\rho_\infty}\right)^{1/2} - 5.8\right] d_j$$

## Demo

Swirl.
- Stabilize a flame.
  - Recirculation zone.
- Control length.

Demo: Nonpremixed flame.
- Increase Coflow air (swirl) at increasing velocity of air at Const fuel flow
- $L_f$ Decreases
- Yellow → blue
- Shape: long → round
- Lifted
- Loud
- Blowout!

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Movie - Sugar