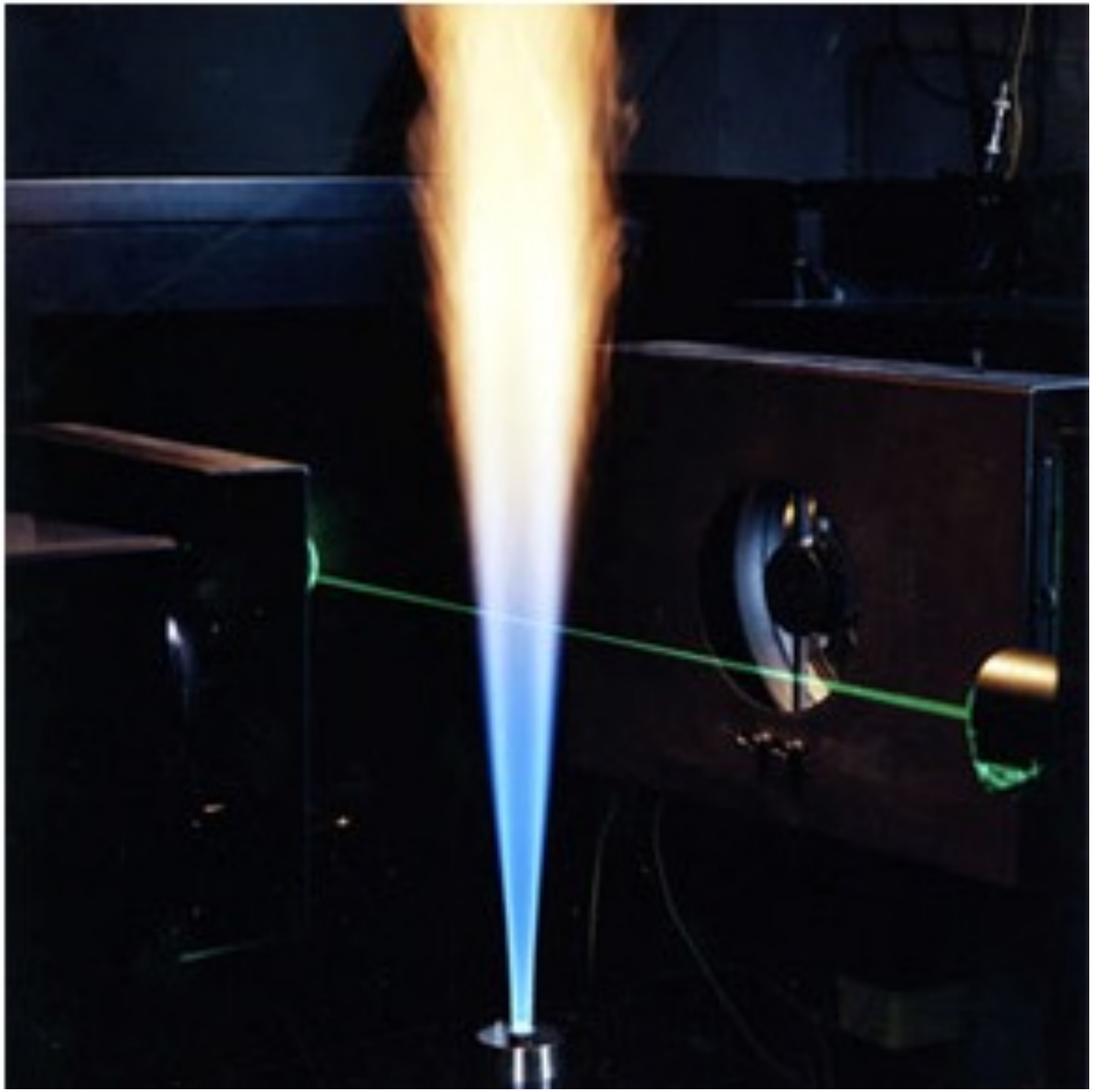
Chemical Engineering 522

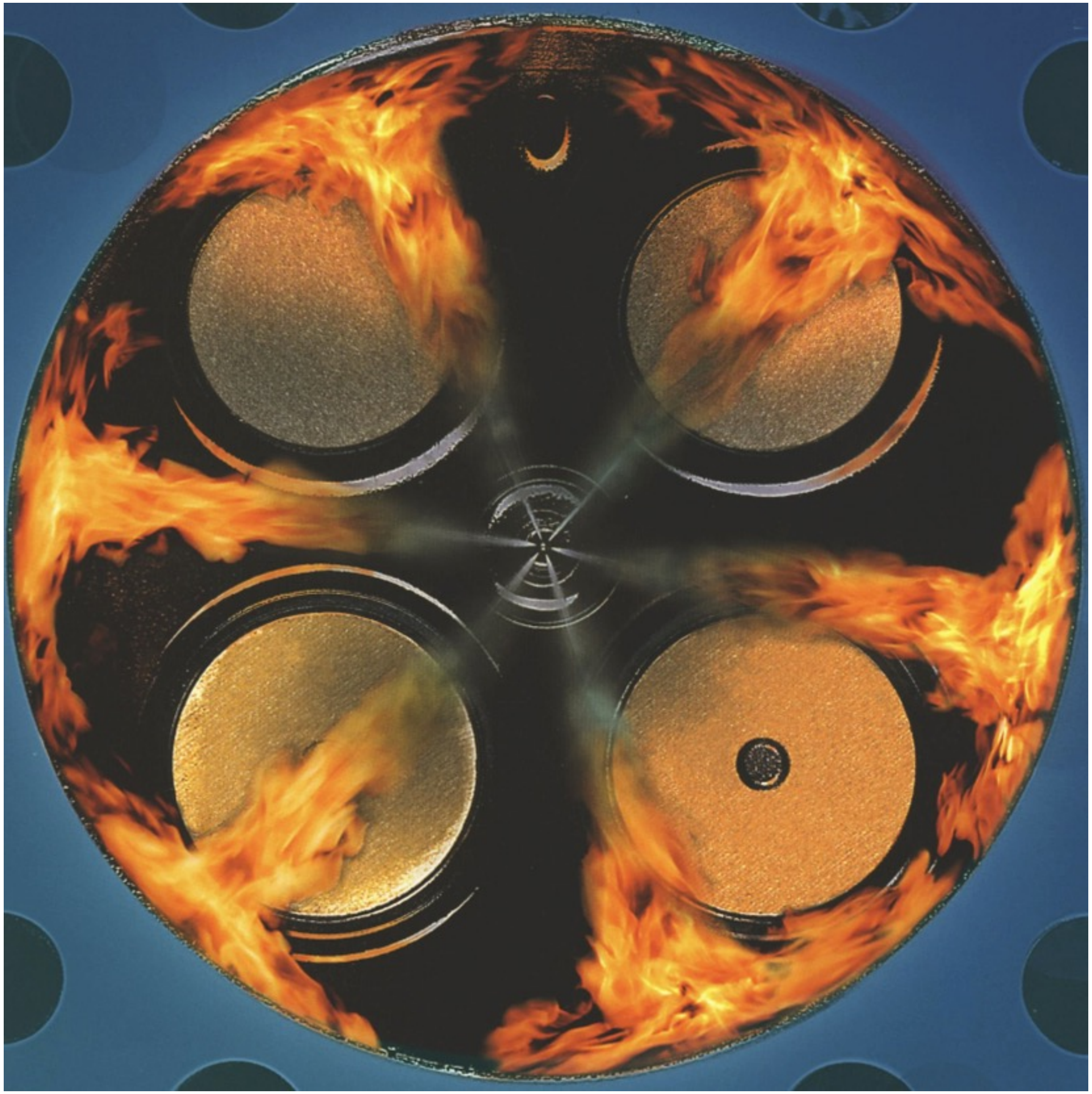
Combustion Processes

Turbulent Nonpremixed Flames

Laboratory Jet Flame



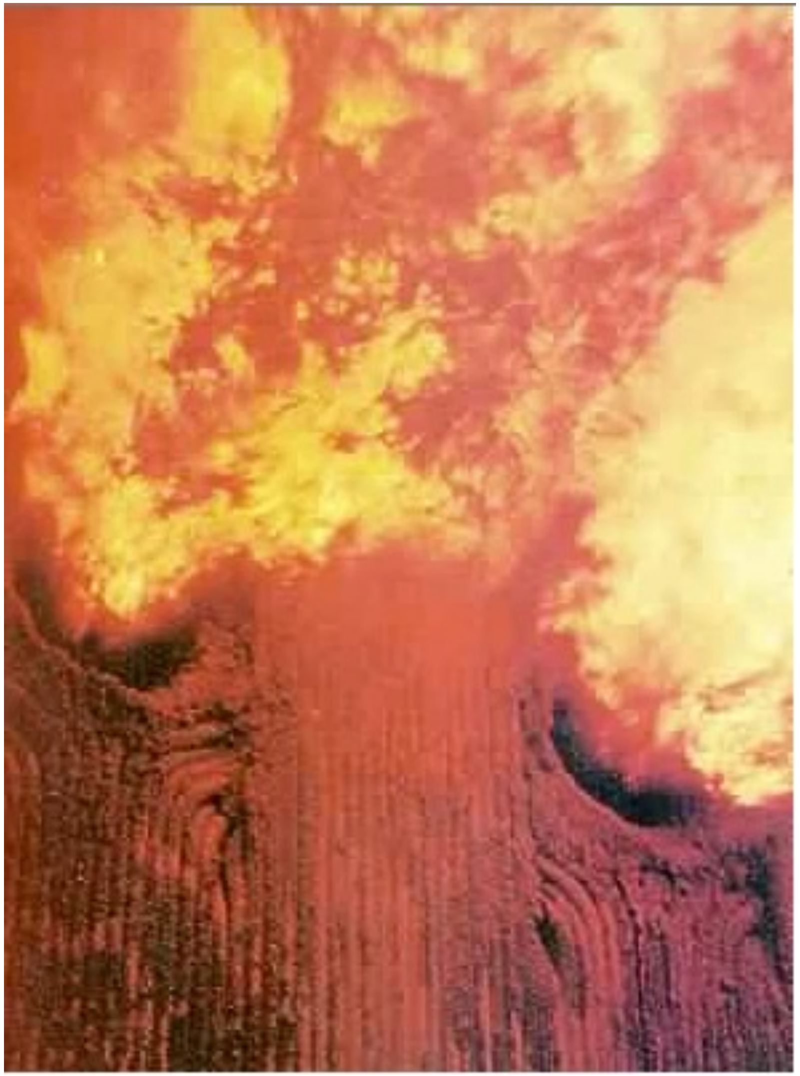
Diesel Spray



Fire

Flares

Coal Furnace



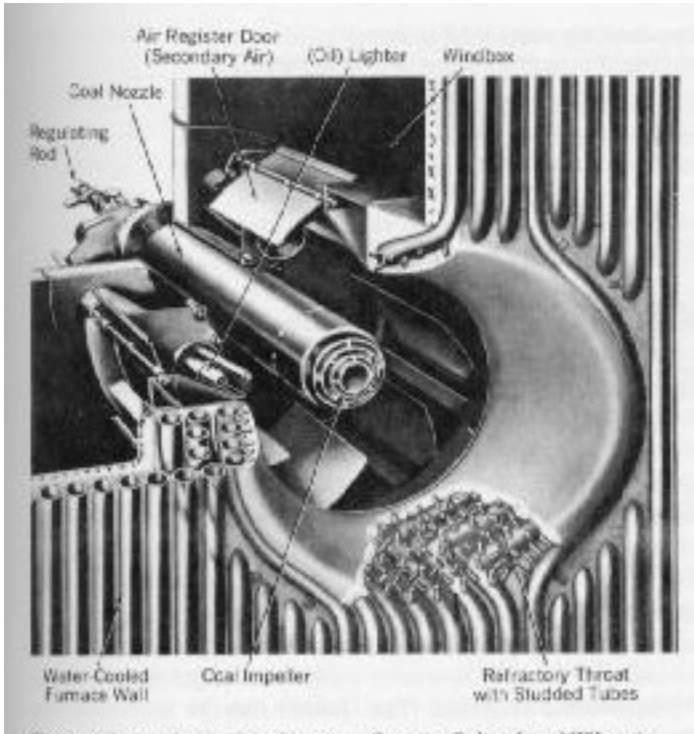


Figure 4-9 A pulverized-coal burner. *(Courtesy Babcock and Wilcox.)*

Characteristics

- Turbulent diffusion flames are most common in practical combustion systems
  - Simple
  - Easy to control
  - Pollutant issues are a challenge
- Applications
  - Glass furnaces
  - Cement kilns
  - Coal boilers
  - Diesel engines
  - Flares
  - Fires
- Key issues
  - Flame length
  - Flame stability
  - Heat transfer: often highly radiative, sooting
  - Pollutant emissions

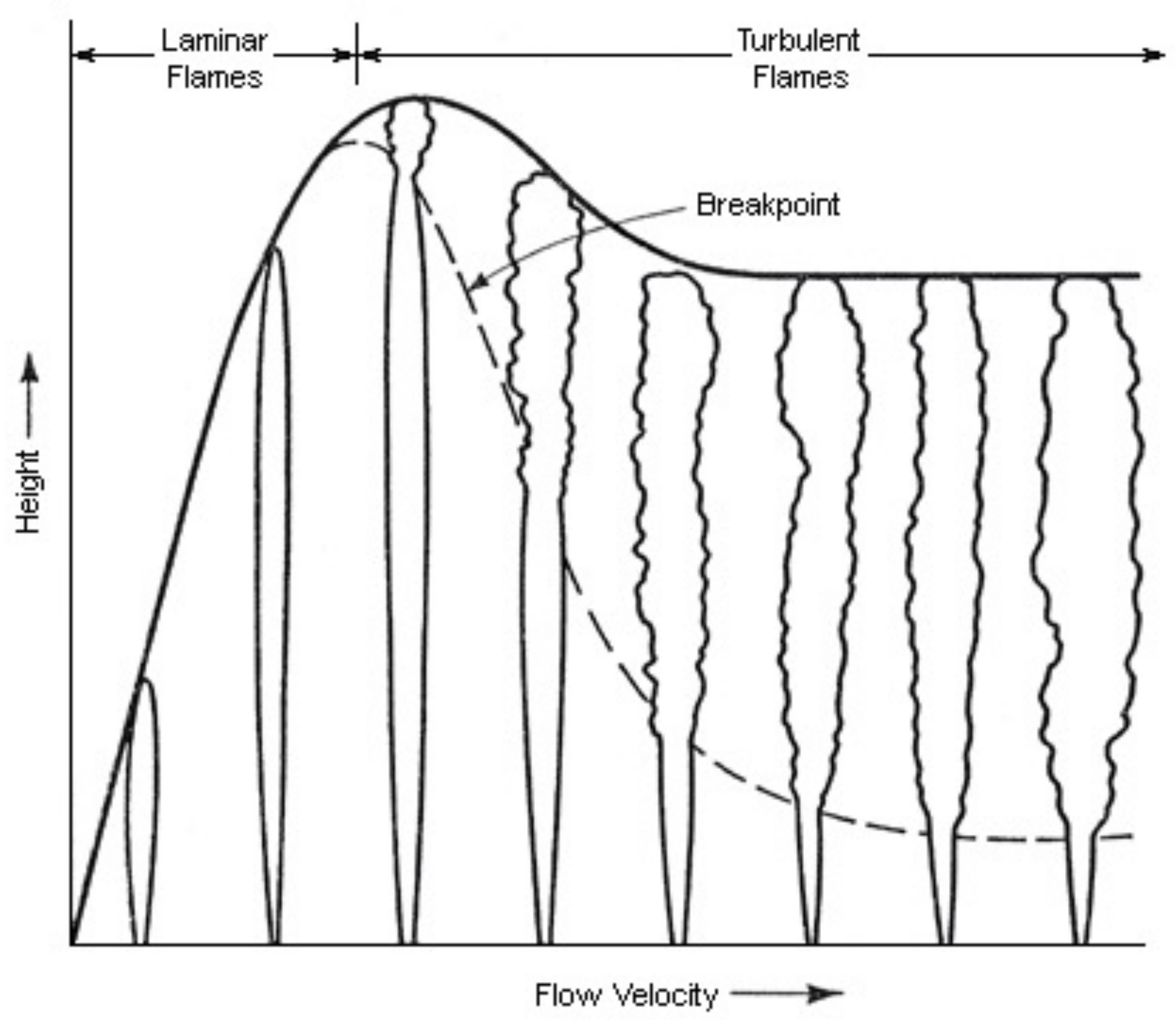
Primary Configuration

- Simple jet flame
  - Swirled jets are important too, as well as free buoyant flows
- As for premixed flames, we can define the concept of a turbulent flame brush.
  - Similar to premixed flames in this sense
    - have a thin flame surface
    - turbulent wrinkles the flame
  - Differences
    - No flame speed
    - No intrinsic flame thickness
      - Flame thickness determined by the local strain field
- Combustion rate is dictated not by how turbulence wrinkles the flame, as in a premixed flame, but how fast turbulence brings fuel and oxidizer together at the molecular scale.
- However
  - Reactions happen at the stoichiometric surface.
  - Turbulence increases combustion rate by increasing this surface area, *and* by increasing gradient at this surface.

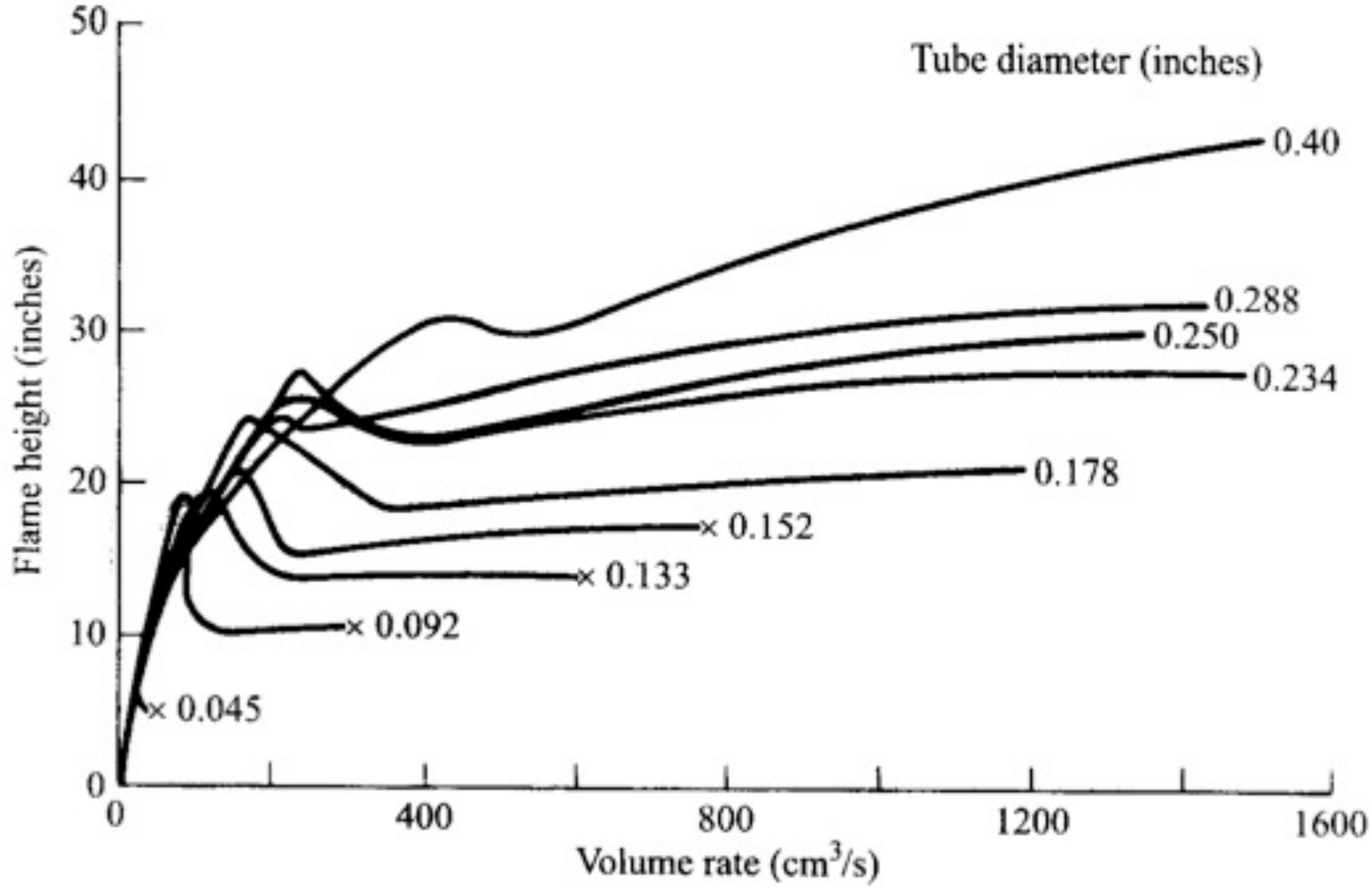
Jet Flame Length

- Use cold flow jet observations
  - Laminar jets:
    - $L \propto Q$
    - Length is proportional to flow rate, not velocity or diameter alone. Length depends on the exit momentum.
  - Turbulent jets:
    - L is **independent** of Q
    - L does depend on the jet exit diameter
    - (See next slide)

Jet flame length



Jet Flame Length



Jet Flames

- Key differences of jet flames from cold jets
  - Density variation
  - Effect of T, y_i on viscosity.
  - Buoyancy (more important at lower jet velocity)
- Flame length
  - Visual
  - T_{max} → downstream location where the average ξ has decayed from 1 to ξ_{st}.
  - Lower ξ_{st}, longer flame (jet has to entrain more air)

Analysis

- Ignore buoyancy, radiation
- Constant MW, c_p
- Unity Sc, Pr, Le
- State relations for $\rho(\xi)$ → solve ξ equation
- Boundary layer assumptions
- Ignore ρ' correlations
- Constant eddy viscosity
- → looks like the laminar equations
- Numerical solution → Length:width = 11:1

Length Correlations

- Dependencies:
  - Momentum vs Buoyancy: Fr
  - ξ_{st}
  - ρ_e/ρ_∞
  - d_j
- Buoyant flames are shorter (all things equal): more mixing
- Lower → longer flames
- As d_j increases, L increases
- As ρ_e/ρ_∞ increases, L increases
  - Use $(\rho_e/\rho_\infty)^{1/2}$ since we care about exit momentum:

$$\dot{\mathrm{mom}} = \dot{m}v = \rho A v^2 \propto \rho d^2 v^2$$

  - Now, $L \propto d \rightarrow L \propto \sqrt{\rho}$

Length Correlations

$$L_f \propto \frac{d_j(\rho_e/\rho_\infty)^{1/2}}{\xi_{st}} f(Fr)$$

- Here, f(Fr) is some function of the Froude number
- Can define a dimensionless length L^* as

$$L^* = \frac{L_f}{d_j(\rho_e/\rho_\infty)^{1/2}/\xi_{st}}$$

- Plot L* vs Fr
  - Fr < 5 → $L^* = \dfrac{13.5Fr^{2/5}}{(1+0.07Fr^2)^{1/5}}$
  - Fr > 5 → L*=23