Fires

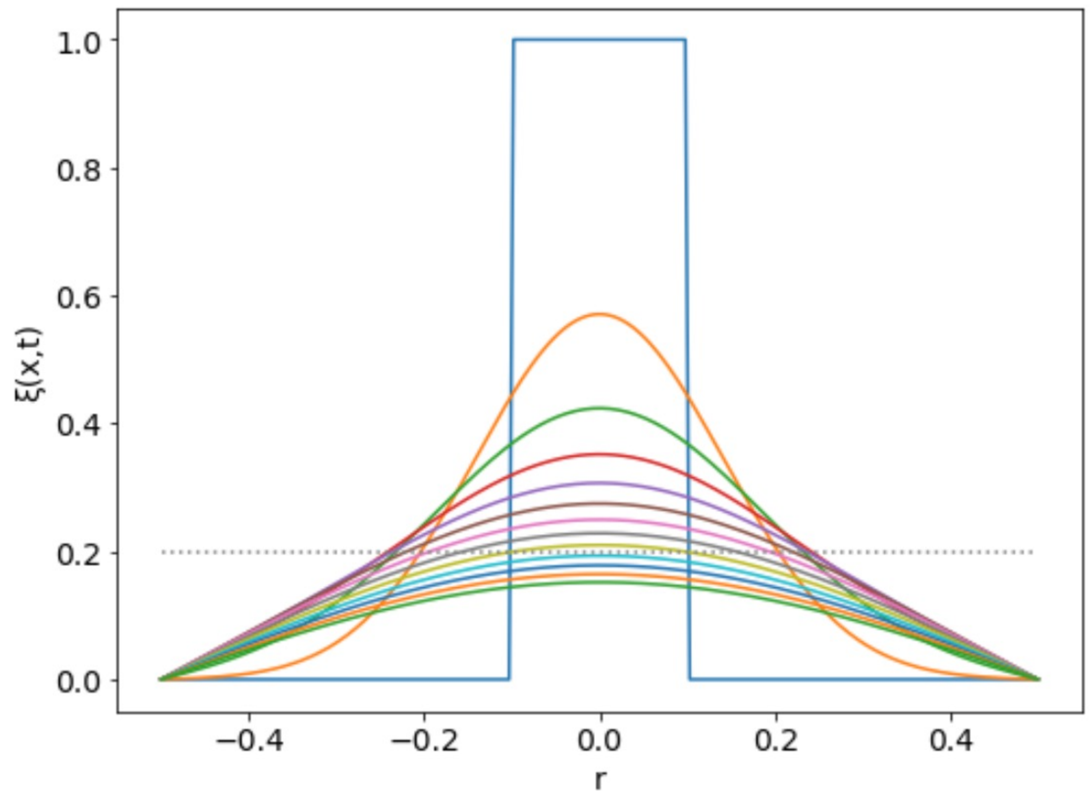
Flares

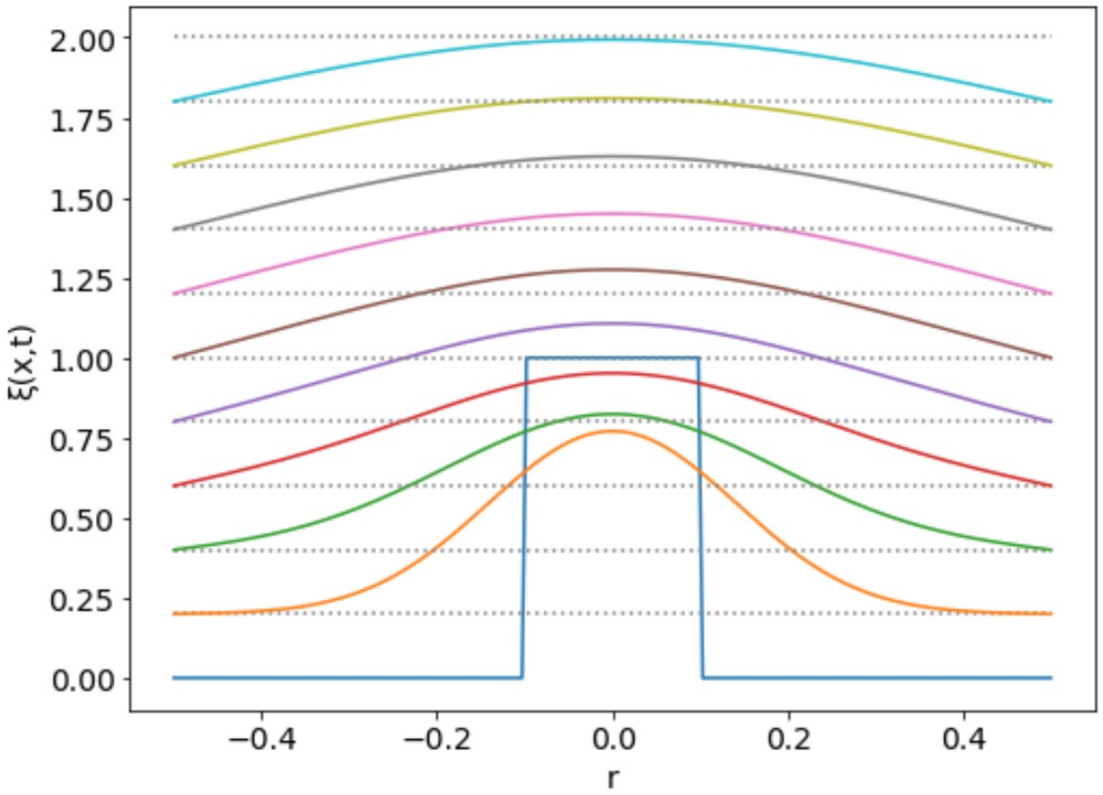
Candle

Candle “smoke”

Grover Schrayer

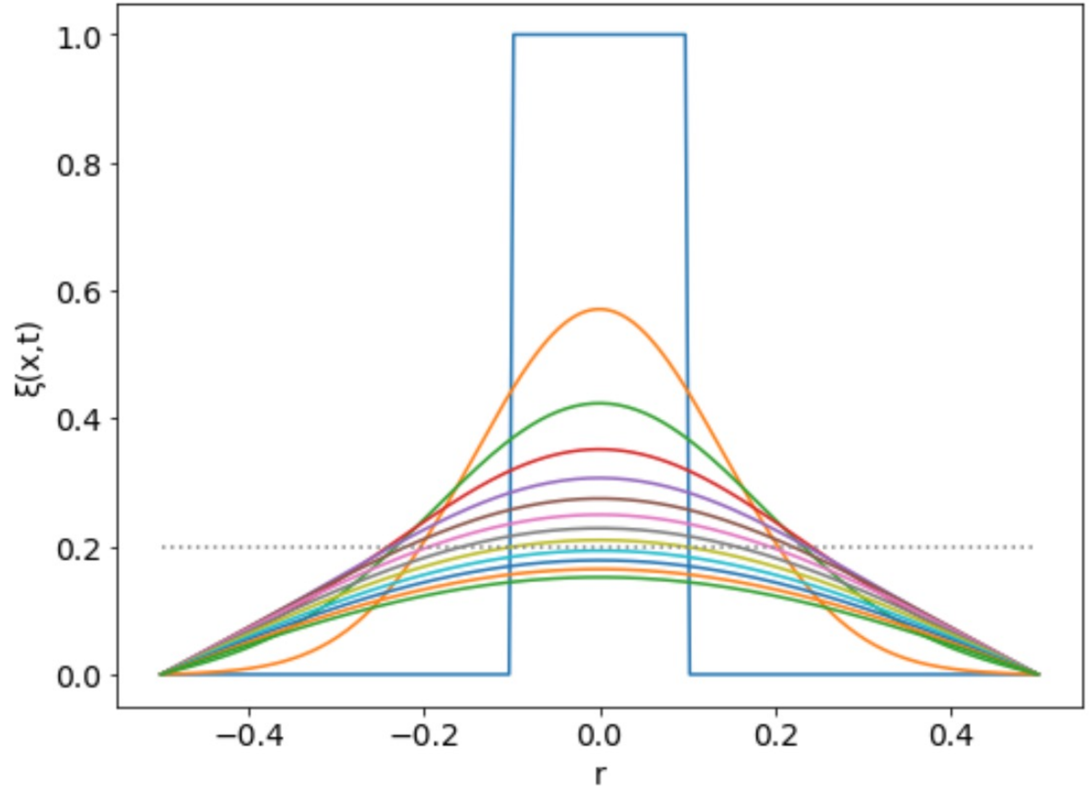
Flame structure

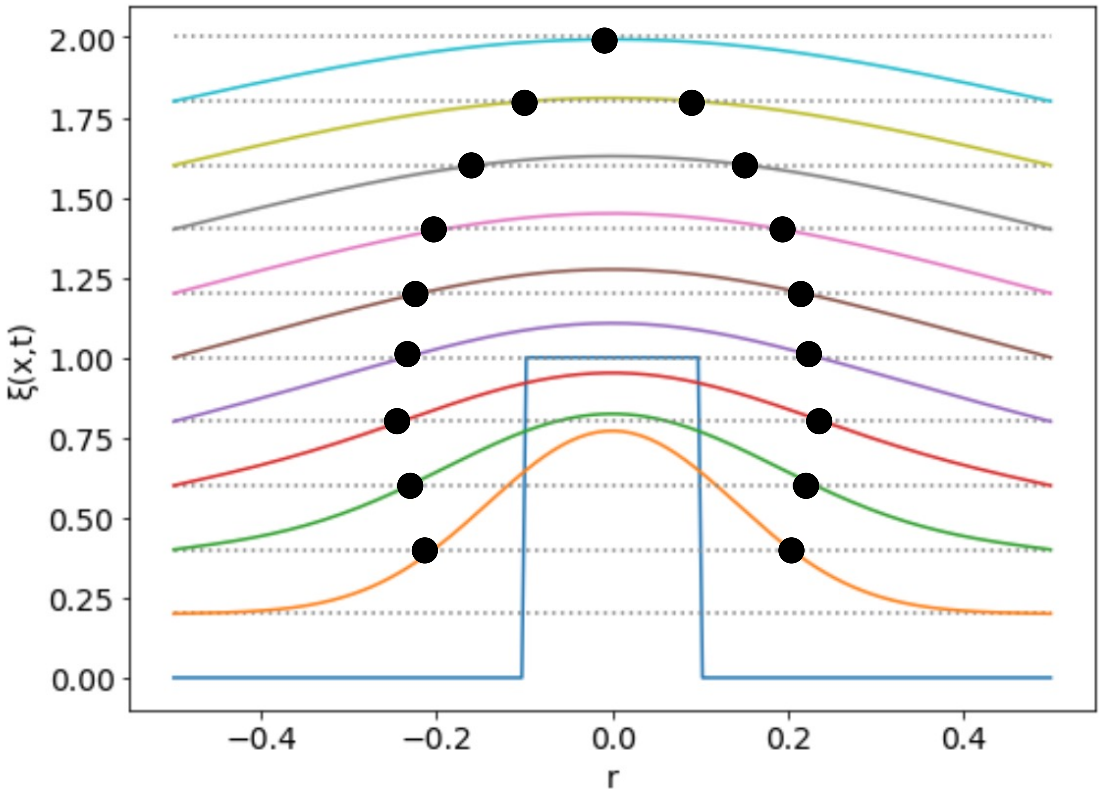




Mixture fraction profiles: advected downstream, and diffused

Flame structure





Mixture fraction profiles: advected downstream, and diffused

Equations

Mass

$$\frac{\partial v_x}{\partial x} + \frac{1}{r}\frac{\partial r v_r}{\partial r} = 0$$

Axial momentum

$$v_x \frac{\partial v_x}{\partial x} + v_r \frac{\partial v_x}{\partial r} = \nu \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial v_x}{\partial r}\right)$$

Conserved scalar

$$v_x \frac{\partial \xi}{\partial x} + v_r \frac{\partial \xi}{\partial r} = D \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial \xi}{\partial r}\right)$$

Similarity Solution

$$\zeta = \sqrt{\frac{3\rho_e J_e}{16\pi}} \frac{1}{\mu} \frac{r}{x}$$

Similarity variable (has r/x)

$$J_e = \rho_e v_e^2 \pi R^2$$

Axial jet exit momentum

$$v_x = \frac{3}{8\pi} \frac{J_e}{\mu x} \left[1 + \frac{\zeta^2}{4} \right]^{-2}$$

Axial momentum (velocity)

$$v_r = \sqrt{\frac{3 J_e}{16\pi\rho_e}} \frac{1}{x} \frac{\zeta - \zeta^3/4}{(1 + \zeta^2/4)^2}$$

Radial momentum (velocity)

Similarity Solution

$$\zeta = \sqrt{\frac{3\rho_e J_e}{16\pi}} \frac{1}{\mu} \frac{r}{x}$$

Similarity variable (has r/x)

$$J_e = \rho_e v_e^2 \pi R^2$$

Axial jet exit momentum

$$v_x = \frac{3}{8\pi} \frac{J_e}{\mu x} \left[1 + \frac{\zeta^2}{4}\right]^{-2}$$

Axial momentum (velocity)

$$v_r = \sqrt{\frac{3J_e}{16\pi\rho_e}} \frac{1}{x} \frac{\zeta - \zeta^3/4}{(1 + \zeta^2/4)^2}$$

Radial momentum (velocity)

Substitute J_e into v_x, and evaluate at r=0 (ζ=0)

$$\frac{v_{x,0}}{v_e} = 0.375 \underbrace{(\rho_e v_e R/\mu)}_{Re_j} \frac{R}{x}$$

Also ξ_0

Centerline axial velocity decays downstream as 1/x
Centerline axial velocity is proportional to the jet exit Re

These don't hold near the nozzle

Jet spread spreads linearly with downstream x

$$\frac{r_{1/2}}{x} = \frac{2.97}{Re_j} \rightarrow r_{1/2} \sim x$$

Jet Decay, Spread

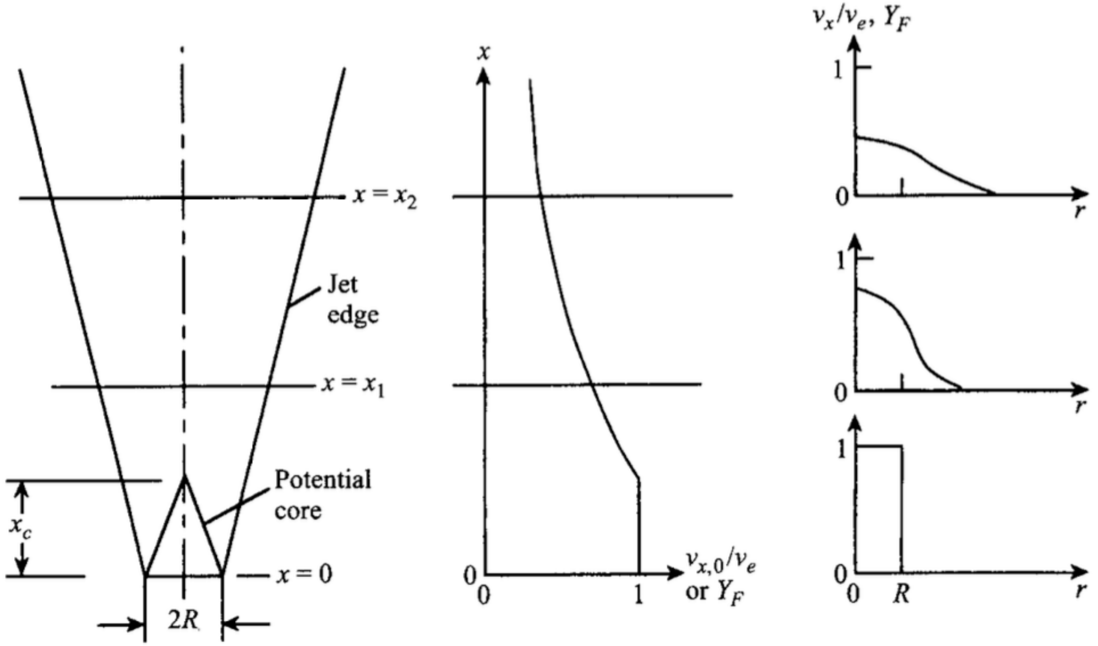


Figure 9.1 Nonreacting, laminar fuel jet issuing into an infinite reservoir of quiescent air.

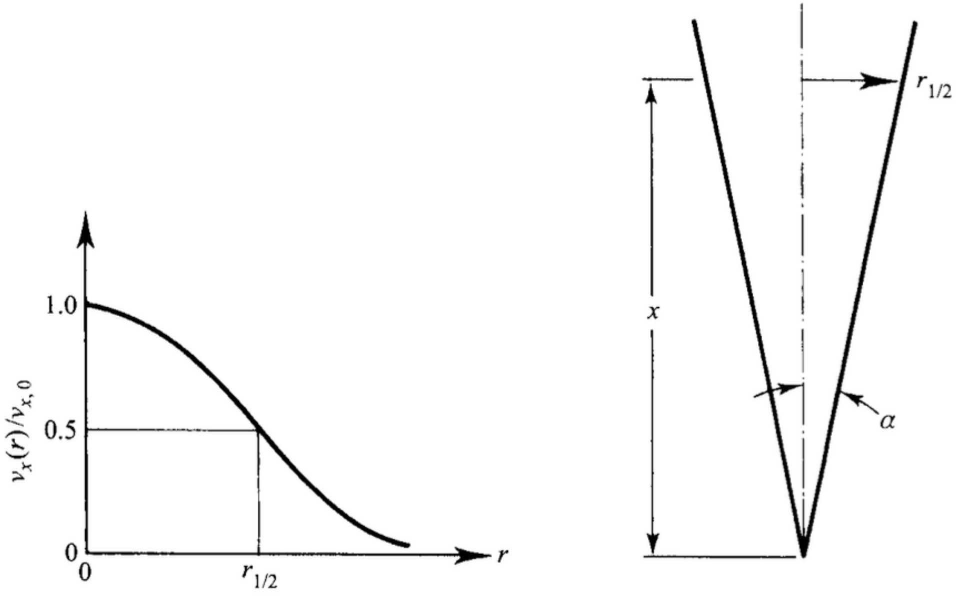


Figure 9.3 Definitions of jet half-width, $r_{1/2}$, and jet spreading angle, α.

“Flame” Length

Flame length is at the downstream distance where $\xi = \xi_{st}$

$$L_f = \frac{3}{8\pi} \frac{Q_F}{D\xi_{st}}$$

Q_F is volumetric fuel flow rate $Q_F = v_e \pi R^2$
D is diffusivity

Flame length is proportional to volumetric fuel flow rate!
Consider the implication in terms of jet exit velocity and jet exit diameter

Jet Flames

Now, density needs to be considered
Assume unity Lewis and Schmidt numbers
Use mixture fraction equation
Neglect buoyancy
Use nondimensional variables

→ ***One PDE solves three equations***

$$\frac{\partial}{\partial x^*}(r^*\rho^* v_x^* \zeta) + \frac{\partial}{\partial r^*}(r^*\rho^* v_r^* \zeta) - \frac{\partial}{\partial r^*}\left(\frac{1}{Re} r^* \frac{\partial \zeta}{\partial r^*}\right) = 0$$

$$\zeta = v_x^* = \xi = h^*$$

Solutions:

Burke-Schumann (assumed single constant velocity)
Roper (allowed for buoyancy)
Others…
Numerical solutions….

Focus on flame length

Roper Correlations

Circular Port

$$L_{f,\text{thy}} = \frac{Q_F(T_\infty/T_F)}{4\pi\mathcal{D}_\infty \ln(1+1/S)} \left(\frac{T_\infty}{T_f}\right)^{0.67} \qquad (9.59)$$

$$L_{f,\text{expt}} = 1330 \frac{Q_F(T_\infty/T_F)}{\ln(1+1/S)}, \qquad (9.60)$$

D_{oo} is air diffusivity at T_{oo}
Q_F is fuel flow rate (volumetric)
S is molar stoichiometric A/F ratio
T_{oo} is air temperature
T_F is fuel temperature
T_f is mean flame temperature

Square ports, slots, buoyancy considered too