Aerospace Propulsion

Lecture 5

Combustion: Part III

IMAGINE

Combustion: Part III

- Flames
- Transport Phenomena
- Combustion Modes
- Turbulent Flames
- Combustion of Liquids/Solids

Flames

- Definition:
  - Turns: “A self-sustaining propagation of a localized combustion zone at subsonic velocities”
  - Interaction between transport and chemical reactions that gives rise to local heat release

Transport Phenomena

- Continuity
  - $$\frac{\partial \rho}{\partial t} + \underbrace{\nabla \cdot (\rho \boldsymbol{u})}_{\text{Advective transport (Bulk motion)}} = 0$$
- Momentum (Navier-Stokes)
  - $$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \underbrace{\nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u})}_{\text{Advective}} = \underbrace{-\nabla p + \nabla \cdot \boldsymbol{\tau}}_{\text{Molecular transport (Collisions)}} + \rho \boldsymbol{g}$$
  - $\boldsymbol{\tau}$ is the viscous stress tensor

Transport Phenomena

- Species
  - $$\frac{\partial \rho Y_k}{\partial t} + \underbrace{\nabla \cdot (\rho \boldsymbol{u} Y_k)}_{\text{Advective}} = \underbrace{\nabla \cdot (\rho D \nabla Y_k)}_{\text{Molecular}} + \underbrace{\dot{m}_k}_{\text{Chemical Source term}}$$

*Assumed Fickian diffusion

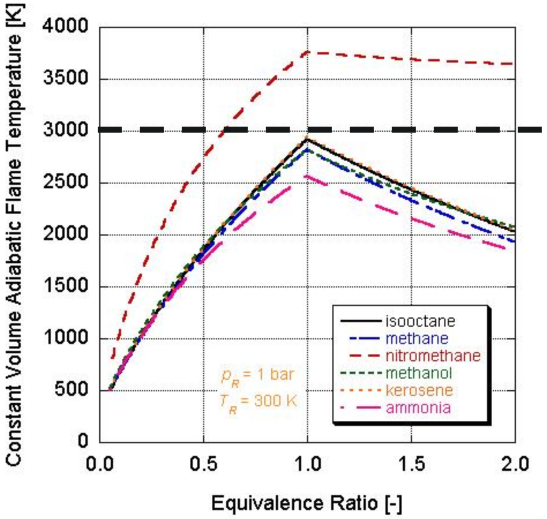
- Energy (Temperature form)
  - $$\rho c_p \frac{\partial T}{\partial t} + \underbrace{\rho c_p \boldsymbol{u} \cdot \nabla T}_{\text{Advective}} = \frac{dp}{dt} + \underbrace{\nabla \cdot (\lambda \nabla T)}_{\text{Fourier's Law (molecular)}} + \underbrace{\sum c_{p,k} \rho D \nabla Y_k \cdot \nabla T}_{\text{Transport of heat by species (molecular)}} - \underbrace{\sum h_k \dot{m}_k}_{\text{Heat release}}$$

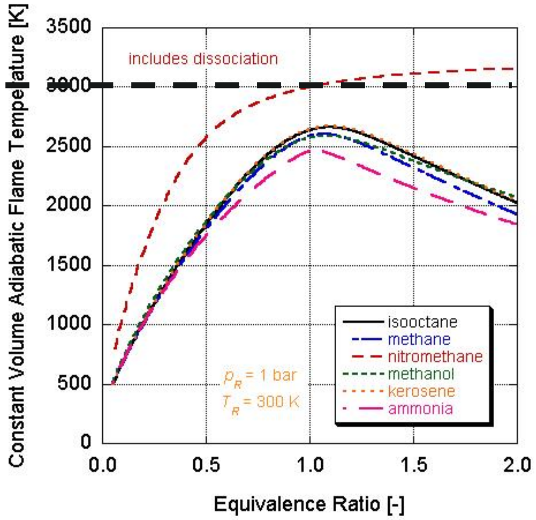
Transport Phenomena

- Transport coefficients
  - Scalings (from kinetic theory)
    - $\mu \propto T^{\frac{1}{2}} \overline{M}^{\frac{1}{2}}$
    - $\lambda \propto T^{\frac{1}{2}} \overline{M}^{-\frac{1}{2}}$
    - $D \propto T^{\frac{3}{2}} \overline{M}^{-\frac{1}{2}} p^{-1}$
  - Non-dimensional numbers
    - Prandtl Number: $\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\mu/\rho}{\lambda/(\rho c_p)}$
    - Schmidt Number: $\mathrm{Sc} = \frac{\nu}{D}$
    - Lewis Number: $\mathrm{Le} = \frac{\alpha}{D}$

Some Notes on AFT

- Adiabatic Flame Temperature reaches a maximum at approximately $\phi = 1$
  - Most CO2 and H2O production
- AFT is a function of pressure when considering more than just the global reaction
  - High pressure -> closer to ideal
  - Low pressure -> far from ideal
    - Decreases temperature
    - Shifts maximum to rich





1D Species: $\frac{\partial \rho Y_k}{\partial t} + \cancel{\nabla \cdot (\rho u Y_k)} = \cancel{\nabla \cdot (\rho D \nabla Y_k)} + \dot{m}_k$

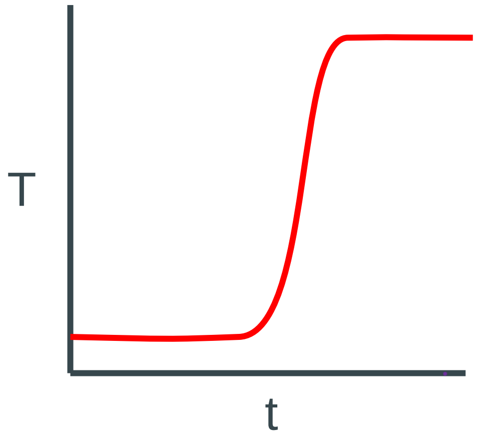
no convection

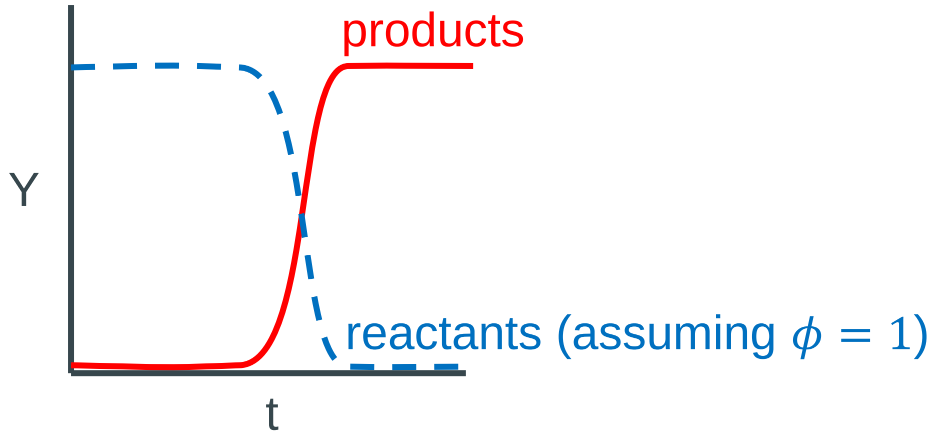
no gradient in space

$$\frac{\partial \rho Y_k}{\partial t} = \dot{m}_k$$

Modes of Combustion

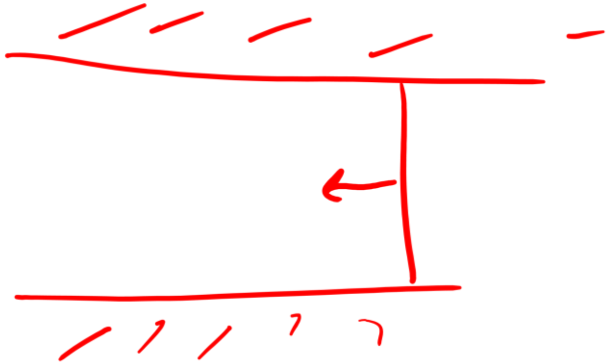
- Homogenous ignition
  - Consider an adiabatic box homogeneously filled with reactants
  - Given enough time, reactants will become products
  - This is **not** a flame (chemically controlled, no transport)



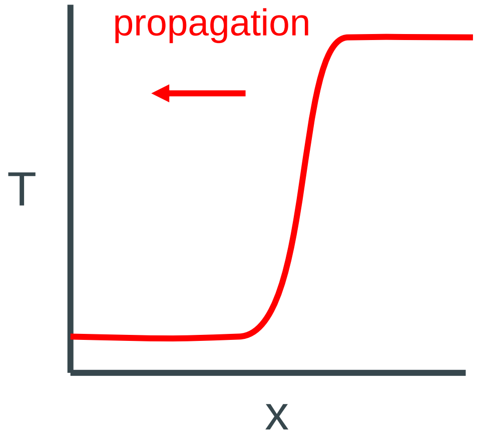


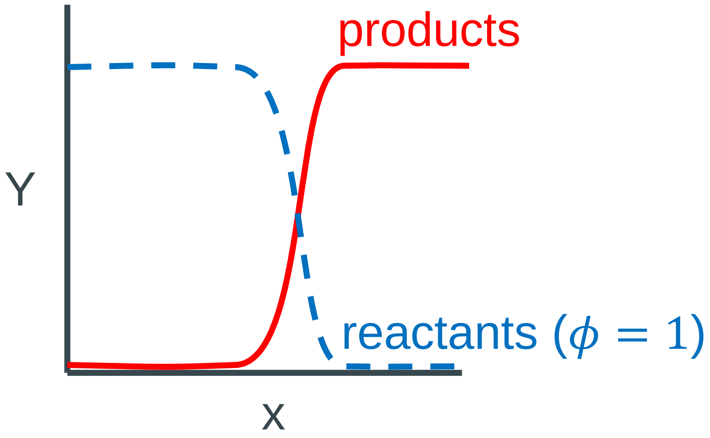
Modes of Combustion

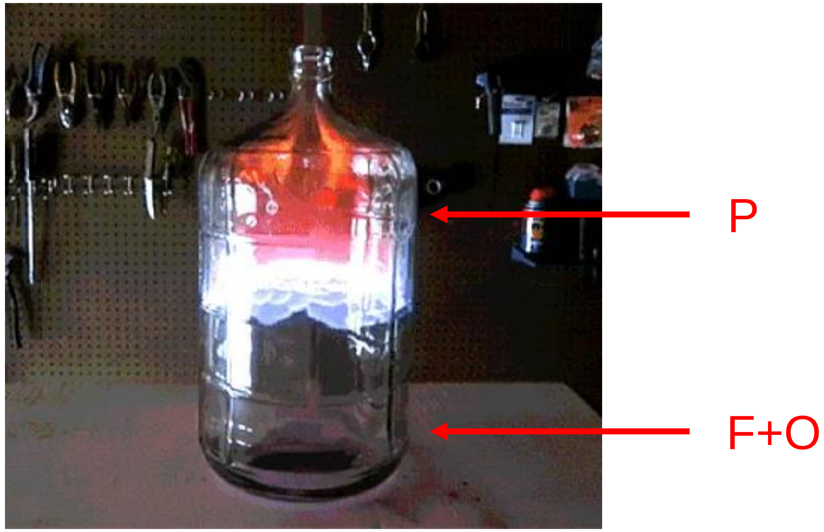
Fto



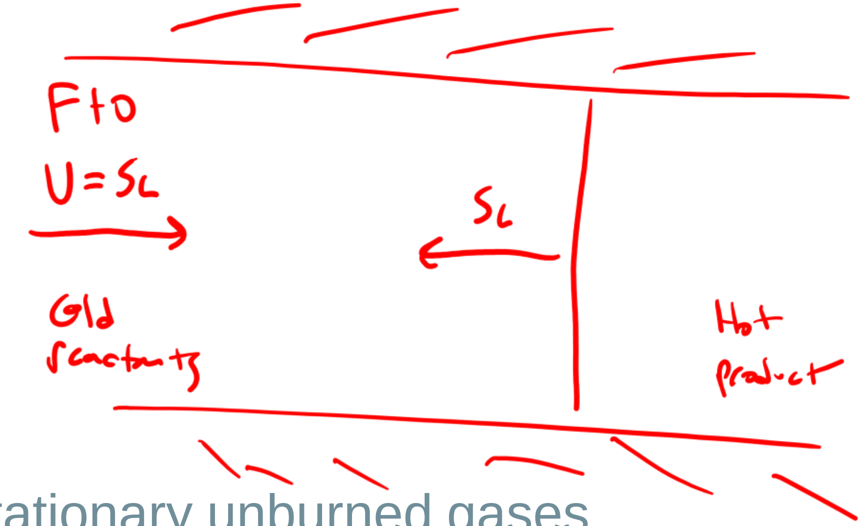
- Premixed Flame
  - Flame propagates through a homogenous reactant mixture (fuel + air)
  - Unburned reactants in front of flame, burned products behind





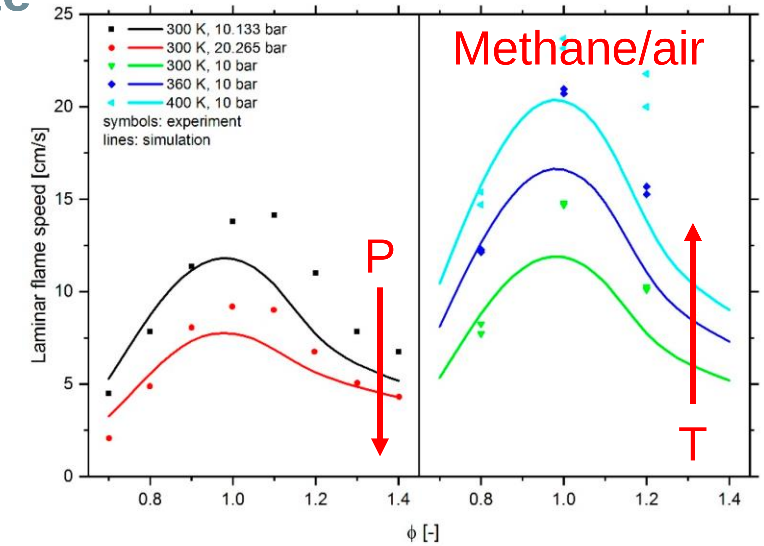


Modes of Combustion



- Premixed Flame
  - Laminar burning velocity S_L
    - Speed at which the flame moves relative to stationary unburned gases
    - Depends on equivalence ratio, pressure, and unburned gas temperature
    - **Property only of mixture/thermochemical state**

    - Maximum burning velocity near $\phi = 1$
      - Actually, slightly richer
    - Burning velocity always increases with T_0
    - Depending on fuel, might increase, decrease, or not change with pressure.

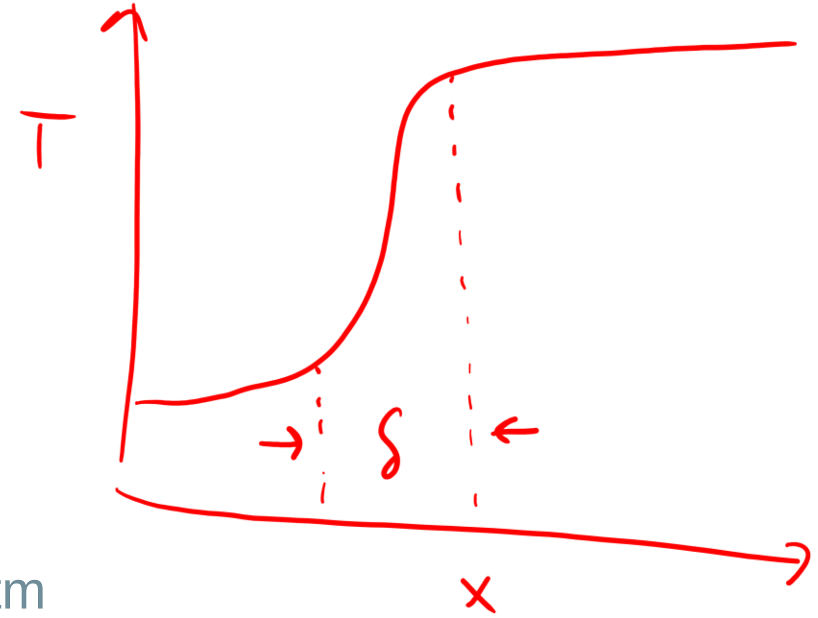


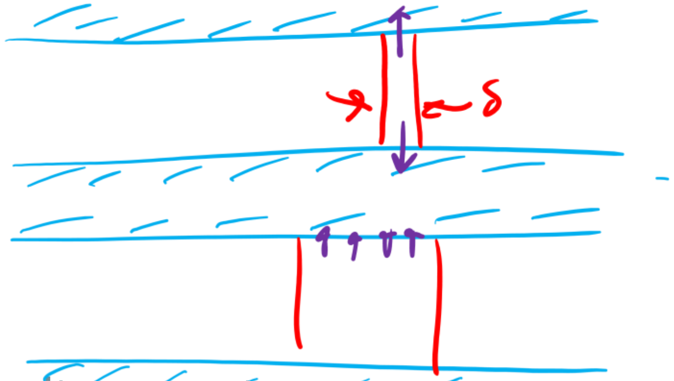
Modes of Combustion

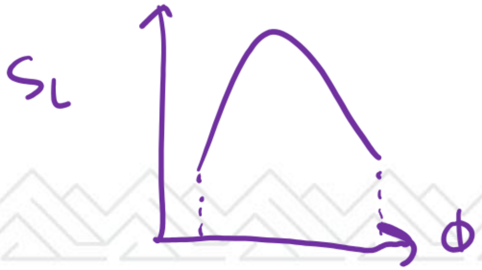
- Premixed Flame
  - Flame thickness $\delta \propto \frac{\alpha}{S_L}$

    thickness · thermal diffusivity · flame speed

    - Typical values: 1mm at 1 atm, 0.1mm at 20 atm
    - Decreasing with increasing pressure
  - Quenching distance $d_p \propto \delta$
    - Flame doesn't burn within one flame thickness of a wall
    - Heat/radical losses overcome chemistry
  - Flammability Limits
    - Lean and rich equivalence ratios at which the burning velocity goes to zero

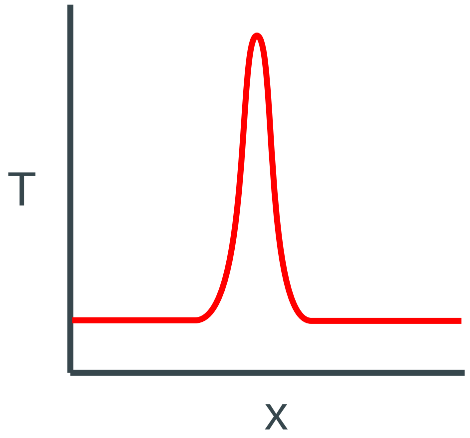


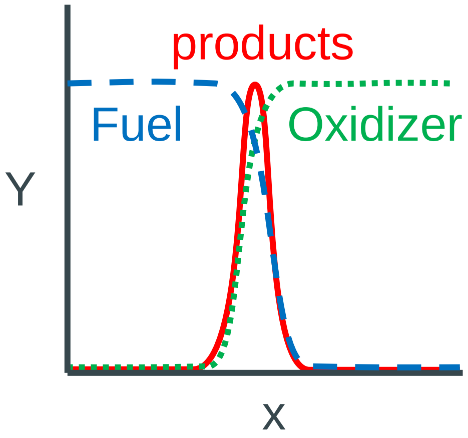


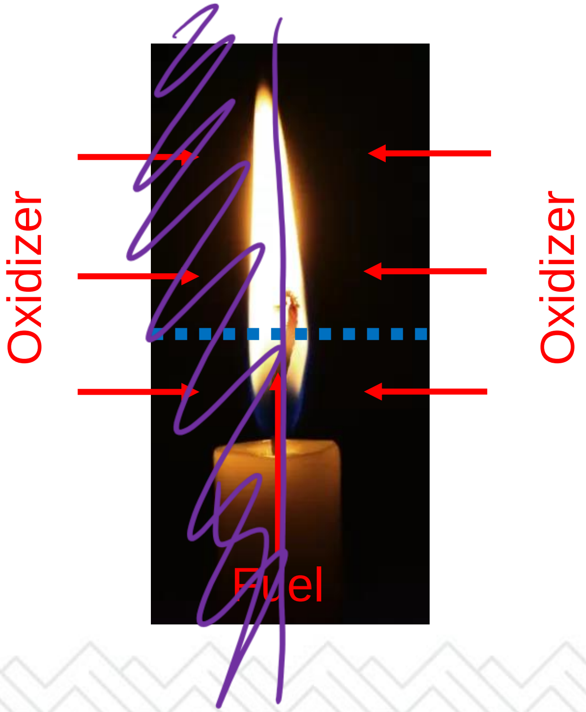


Modes of Combustion

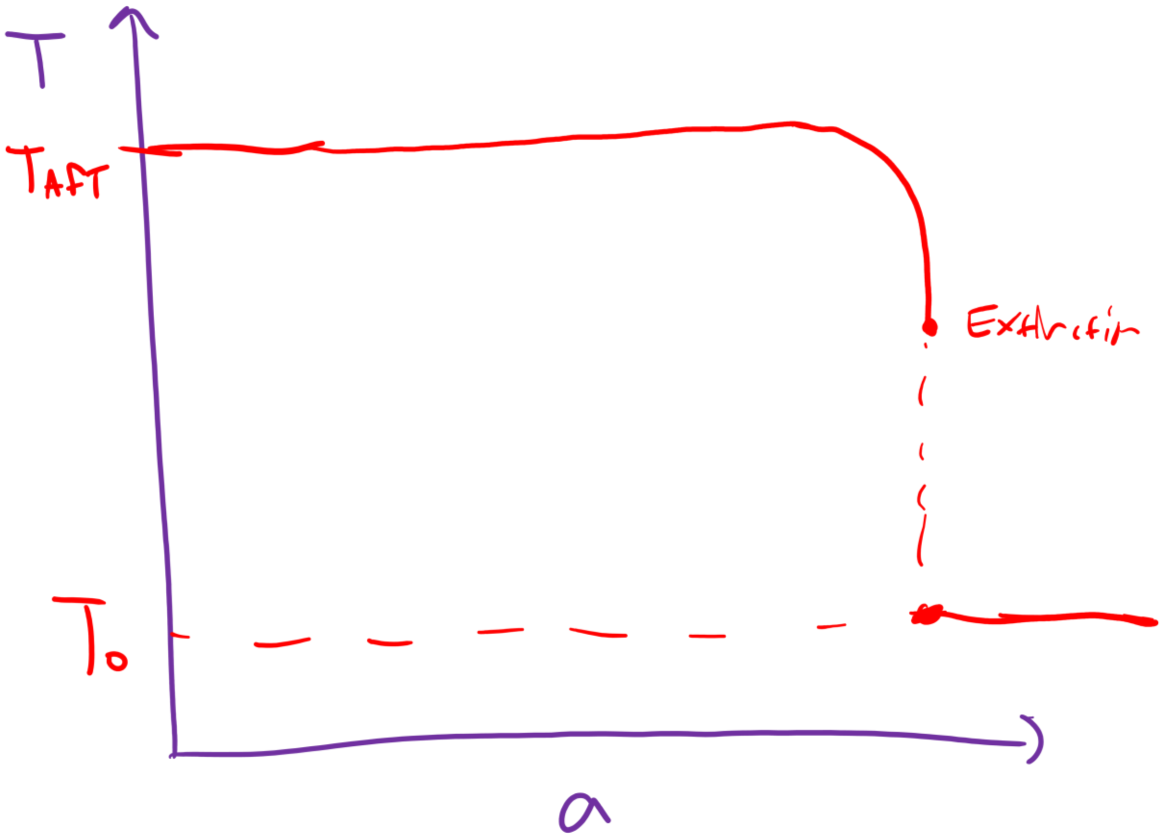
- Nonpremixed (Diffusion) Flame
  - Flame forms between initially unmixed fuel and oxidizer
  - Burning is limited by mixing between fuel and oxidizer







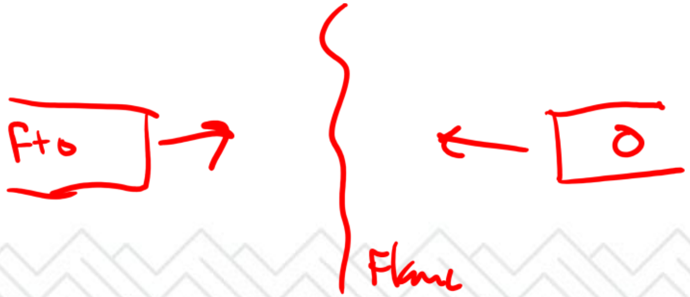
Modes of Combustion



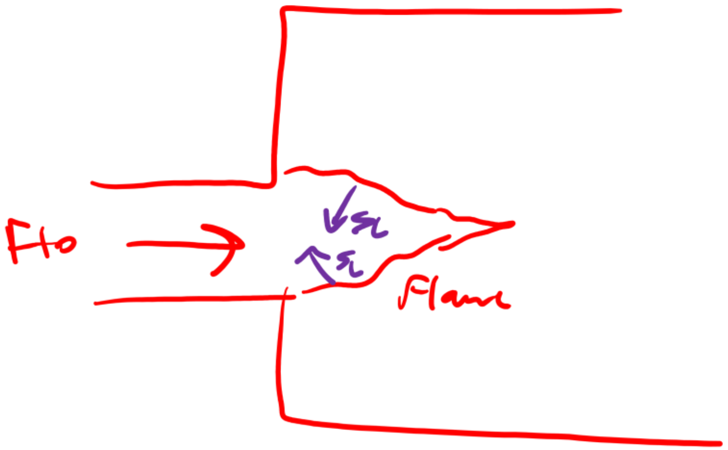
- Nonpremixed (Diffusion) Flame
  - Flame speed?
    - No! Location decided by mixing
  - Flame thickness?
    - No! Thickness decided by mixing
  - Extinction
    - Damköhler Number: $Da = \frac{t_{flow}}{t_{chem}}$
    - Chemical equilibrium is locally approached at each local equivalence ratio with increasing Da number

Modes of Combustion

- Partially Premixed Flames
  - In practice, combustion occurs somewhere between these modes
    - Maintaining homogenous mixtures is difficult
    - Sometimes, partially premixed has benefits
  - In partially premixed combustion, both premixed and nonpremixed behavior occurs simultaneously
    - Premixed flame propagation through a varying equivalence ratio with localized mixing-controlled burning
  - Partially premixed combustion is common when using liquid/solid fuels



Turbulent Flames

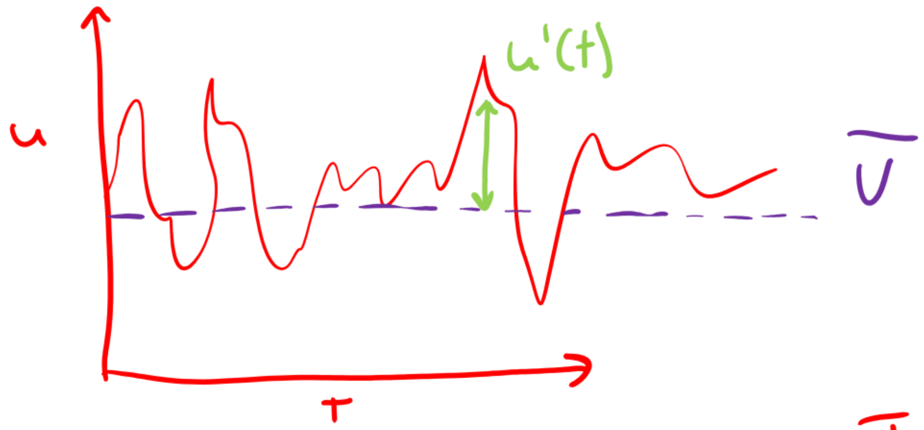


- Why do we care about turbulence?

- Approximate values for a jet engine combustor:
  - $U_{in} \approx 30\,m/s$ $\quad U_{in}/S_{L,JF,A} \approx 60$
  - $S_{L,JF-A} \approx 0.5\,m/s$
  - Flame is too slow to anchor within the combustor and would blow-off

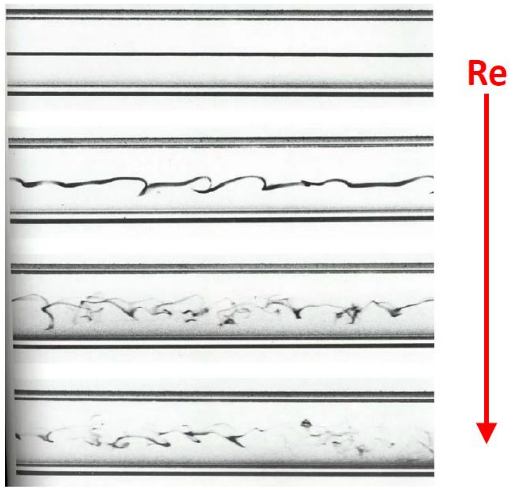
- Turbulence affects two important phenomena
  - Premixed burning velocity
  - Fuel-air mixing

Turbulent Flames

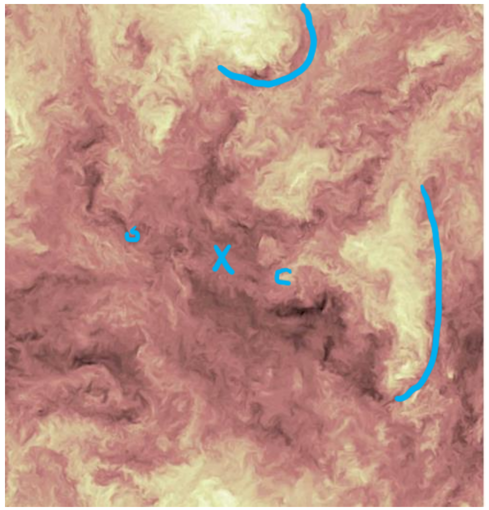


- What is turbulence?
  - Chaotic motion of fluid flow at large Reynolds numbers
  - Characterized by $Re = \frac{ul}{\nu}$
  - Smallest turbulent scale called the "Kolmogorov" scale

$u(t) = \bar{U} + u'(t)$



Recreation of experiment from Osborne Reynolds



Turbulent Flames

- How much does turbulence increase mixing? → By a factor of Re

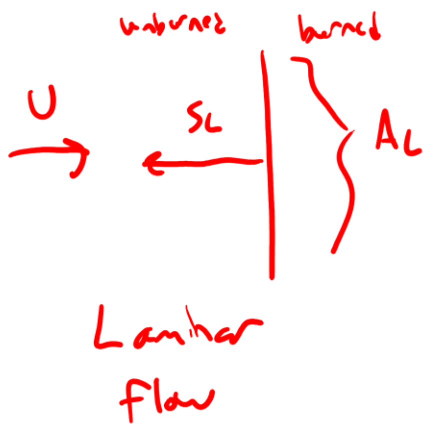
$$Re = \frac{ul}{\nu} \begin{matrix} \leftarrow \text{Turbulent mixing ("Turbulent viscosity)} \\ \leftarrow \text{Molecular mixing} \end{matrix}$$

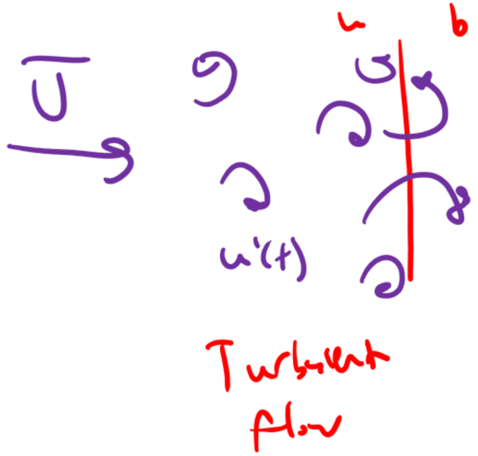
$$\frac{ul}{\nu} = \frac{\left.\frac{ul}{l^2}\right\} [=] \,1/t}{\left.\frac{\nu}{l^2}\right\} [=] \,1/t}$$

$$Re = \frac{\text{Molecular timescale}}{\text{Turbulent timescale}} = \frac{t_L}{t_T}$$

Turbulent Flames

- Premixed Flames
  - Turbulent Burning Velocity S_T

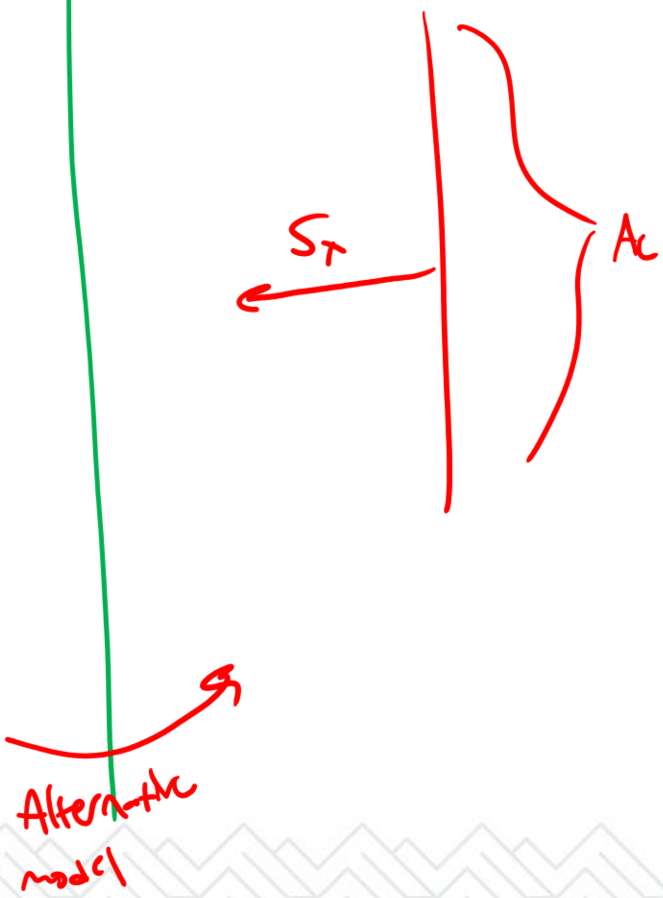




  - $\frac{S_T}{S_L} \sim O(1-100)$

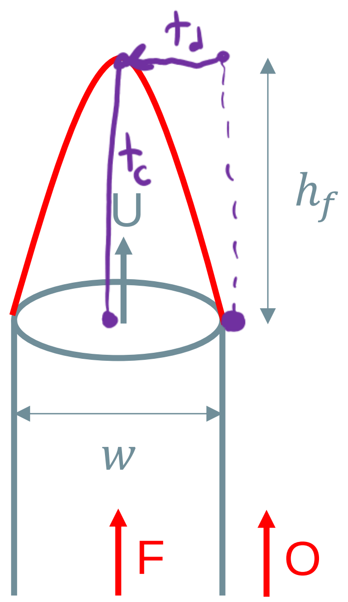
$$\dot{m}_u = \rho_u S_L A_T = \rho_u S_T A_L$$

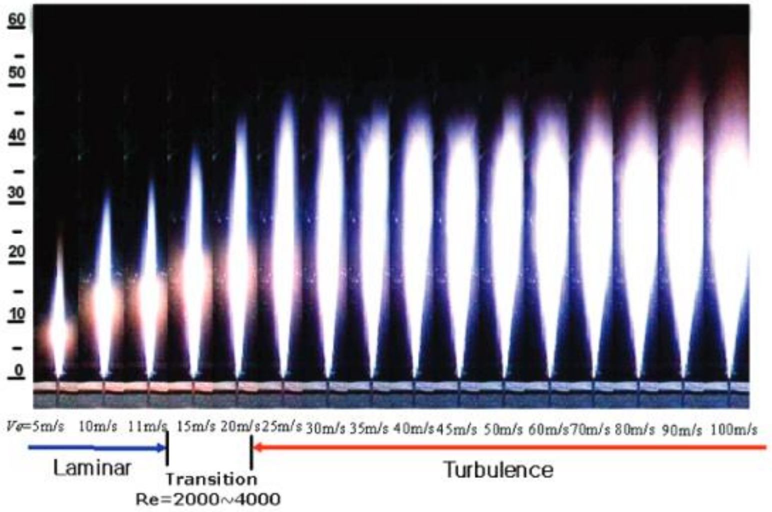
$$\frac{S_T}{S_L} = \frac{A_T}{A_L} \sim u'$$



Turbulent Flames

- Nonpremixed Flames
  - Accelerated fuel-air mixing
  - Makes flames more compact





Laminar flame

1) convective time from exit to tip (↑)

$t_c \approx h_f / U$

2) diffusive time from side to middle (←)

$t_d = \frac{w^2}{\nu}$

3) Equal at tip

$t_c = t_d$

$\frac{h_f}{U} = \frac{w^2}{\nu}$

$h_f = \frac{w^2 U}{\nu}$

Turbular

1) Convective

$t_c \approx h_f / U$

2) diffusive

$t_d = \frac{w}{u'} \approx \frac{w}{U}$

3) $t_c = t_d$

$\frac{h_f}{U} = \frac{w}{U}$

$h_f = w$

$h_{f,L} \approx \frac{w^2 U}{\nu}$ $\quad h_{f,T} \approx w$ $\quad \frac{h_{f,L}}{h_{f,T}} \approx Re$

Combustion of Liquids and Solids

- Burning a liquid or solid (at steady state):
  1. Heat from the burned products is transported (convection/radiation) towards the liquid/solid surface
  2. This heat causes the surface of the liquid/solid to melt/vaporize/decompose at the surface
     a) The surface is converted to a gaseous mixture
  3. Gaseous combustion proceeds as previously described
- Describing the burning of liquids/solids is one of the most complex problems in combustion