Chemical Engineering 522

Combustion Processes

Final Review

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- Exam 1 review
  - Classes 1-13 (+review)
  - Chapters 1-5, 15
  - HW 1-4
- Exam 2 review
  - Classes 17-27
  - Chapters 6-8, 15
  - HW 5-6
- Final review
  - Classes 29-41
  - Chapters 9, 11-13,16, 10
  - HW 7-8

- Chapter 9
  - Laminar diffusion flames
- Chapter 11
  - Turbulent flows
- Chapter 12
  - Turbulent premixed flames
- Chapter 13
  - Turbulent diffusion flames
- Chapter 16
  - Detonation
- Chapter 10
  - Droplets and sprays

Exam 1 Review

- Classes 1-13 (plus review)
- Chapter 1
  - Introduction
- Chapter 2
  - Stoichiometry
  - Thermochemistry
  - Equilibrium
- Chapter 3
  - Mass transfer
- Chapter 4
  - Combustion Kinetics
- Chapter 5
  - Combustion Mechanisms
- Chapter 15
  - NOx

•Reading: Chps 1-5, 15
•Homework assignments 1-4
•Class discussions

Exam 2 Review

- Classes 17-27
- Chapter 15
  - Pollutant Emissions
- Chapter 6
  - Canonical Reactors
  - Batch, PFR, PSR
- Chapter 7
  - Governing Equations
  - Shvab-Zeldovich
  - Conserved Scalars
- Chapter 8
  - Premixed Flames
  - Premixed Analysis
  - Flame Speed
  - Extinction/Ignition

- ***Reading: Chps 6-8, 15***
- ***Homework assignments 5-6***
- ***Class discussions***

Diffusion flames

- Candle flame processes
  - Hollow, flame sheet
  - Flame colors
  - diffusion process: flame motion
- Laminar jets: nonreacting
  - boundary layer equations
  - assumptions
  - similar profiles: know what they look like
  - Length, velocity, width
- Reacting jets
  - Solution procedures (conserved scalar approach)
  - Correlations
    - Roper: theory, EXP (careful of notation here)

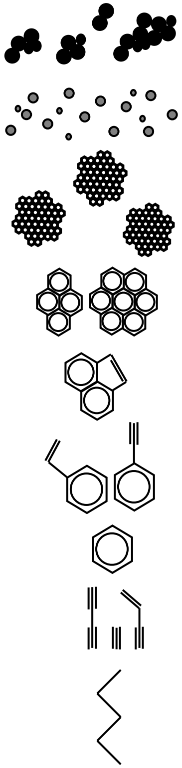
$$\frac{v_{x,0}}{v_e} = 0.375 Re \frac{R}{x}$$

$$\frac{r_{1/2}}{x} = 2.97/Re$$

$$L = \frac{3}{8\pi}\frac{Q}{DY_{f,st}}$$

Soot Formation

- Soot overview, general properties
  - growth process, key precursor species, structure
- Smoke point
  - empirical, laminar, flow rate → smoke emission. trends
- Soot mechanisms
  - empirical, semi-empirical, detailed
  - 4 general steps (global)
- Transport
  - particles → implications for diffusivity
  - Thermophoresis
- Size distribution: direct, sectional, MOM
- Soot radiation, formation timescales
- Simulation examples



Turbulence

- Most flows are turbulent
  - Examples
- Turbulent processes
  - Increase "surface" area and gradients for transport
  - Unstable flow
  - Cascade process: big eddies entrain, break down, diffuse as scales decrease.
- Scaling: scales, Re dependence
- Reynolds (and Favre) decomposition
  - Mean and fluctuation
  - Average the governing equations → unclosed terms (Reynolds stresses).
    - Know what "unclosed" means, and the physical meaning of these stresses (what are they, what do they account for).
    - Why do we bother averaging the equations
- Simple closure: mixing length:
- Jet solution
  - Use laminar solution with turbulent viscosity (const)

$$\frac{\bar{v}_{x,0}}{v_e} = 13.15\frac{R}{x} \qquad \frac{r_{1/2}}{x} = 0.08468$$

  - **Independent of Re!**

$$\tau_{turb} = \rho\nu_t\frac{d\bar{v}}{dx}$$

$$\nu_t = \rho L_m v_t$$

$$\nu_t = \rho L_m^2\left|\frac{d\bar{v}}{dx}\right|$$

$$\nu_t = 0.1365\rho L_m(\bar{v}_{max} - \bar{v}_{min})$$

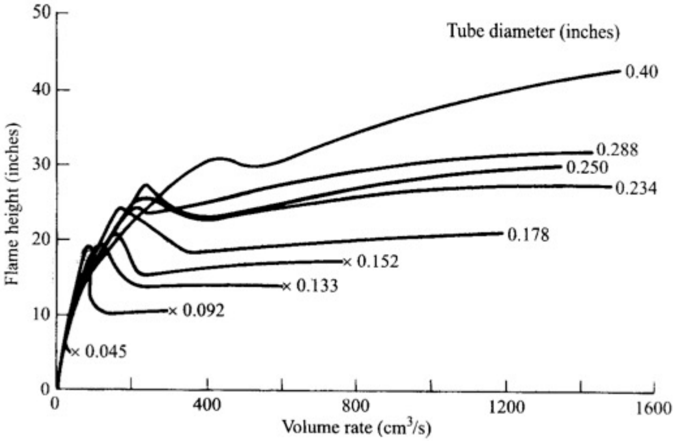
$$L_m = 0.075\delta_{99\%} = 0.075 * 2.5r_{1/2}$$

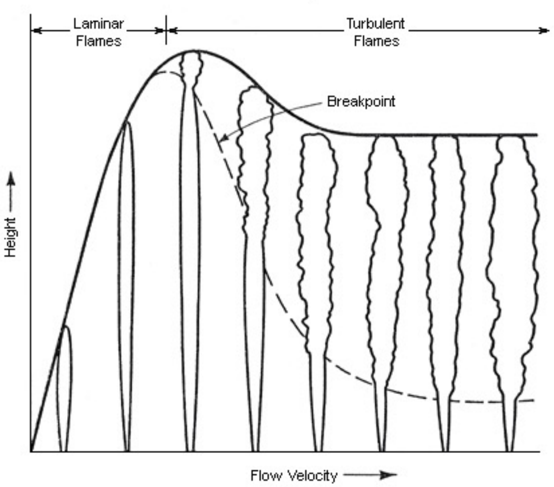
Turbulent Premixed Flames

- Applications: SI engines, gas turbines
- Issues: safety, flashback
- Benefits: emissions, efficiency
- Flame brush
- Turbulent flame speed $$S_t = S_L \frac{A_t}{A}$$
- Combustion regimes
  - Turbulent scales: length, time, velocity
  - Flame scales: length, time, velocity
  - Know these regimes, and what they mean physically (see notes)
    - Da, Re, Ka
- Correlations for flame speed (wrinkled)
  - Klimov, Fig 12.10

Turbulent Diffusion Flames

- Applications: Diesel engines, furnaces, fires
- Benefits: simple, “safe”
- Issues: emissions, soot, NO_x
- Simple jet flame
  - differences with premixed flames
  - Jet flame length versus flow rate (Re)
  - Effect of buoyancy
- Flame length correlations (p. 498)





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

$$L^* = \frac{13.5 Fr^{2/5}}{(1 + 0.07 Fr^2)^{1/5}}$$

$$L^* = 23$$

Turbulent Flames—Liftoff, Blowout, Demo

- Liftoff, blowout
  - Physical processes: turbulence decays
  - Three theories.
  - Correlations: lifted height, blowout velocities.
- Swirl effects
  - Higher mixing
  - Shorter flame
  - Noise
  - Less soot (why)
  - Eventual blowout
- Modeling (presumed PDF method)
  - State relationship with mixture fraction
  - Convolve over PDF to get mean quantities
  - β-PDF for mixture fraction

Didn't cover

Radiation

- Flame radiation
  - Radiant heat fraction
  - Time, T, soot
  - 5-60%
  - Variation with fuel type: 15, 45, 60% max for methane, propane, acetylene
- Radiation concepts
  - Intensity definition
  - Heat flux, Volumetric heat source
  - Plane parallel
  - WSGG model, examples

Detonations

- Definitions: Detonations, Deflagration, Explosion, Flame, Combustion wave.
- Qualitative behavior
  - How they form, why, under what conditions (e.g., closed tube.)
- Analysis
  - Mass
  - Momentum
  - Energy
- Hugoniot curve, Rayleigh line.
  - Regimes, names, feasibility
  - Detonation speeds

Droplet/Spray Combustion

- Diesels, turbines, rockets
- Evaporation rate is key, then combustion in gas phase
  - Flame strongly influences evaporation rate, hence combustion rate
  - Droplet size, heat of vaporization, vapor pressure are key
  - Droplet lifetime
- Idealized evaporation model
  - assumptions, the usual, plus Tsurf=Tboil → Energy balance only
  - E-bal at surface: conduction = vaporization
  - Get conduction temp gradient from T(r) in gas → gas energy balance.
  - Solve for evaporation rate.
  - D^2 law: $D^2 = D_0^2 - Kt$ → $t_D = D_0^2/K$
- Burning droplets: same process, but different B.C.'s; especially a flame
  - 5 unknowns: m_F, $Y_{F,s}$, T_s, T_f, r_f
  - 5 eqns: Species (fuel) inner; Species (oxid) outer; E-bal at surf; E-bal at flame; Phase EQ
  - Solution outlined. (easier if Ts=Tboil)

Final Exam

- Comprehensive
- Weighted towards material since last exam.
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