Summer School on Fire Safety Science – Wildland/WUI Fire Behavior

Combustion

Arnaud Trouvé

Department of Fire Protection Engineering
University of Maryland, College Park MD (USA)

atrouve@umd.edu

Outline

- Introduction
- Pyrolysis and Combustion
- Combustion: the Thermodynamics Viewpoint
- Combustion Chemistry
- Flame Structure
- Flame Effects

Introduction to Combustion

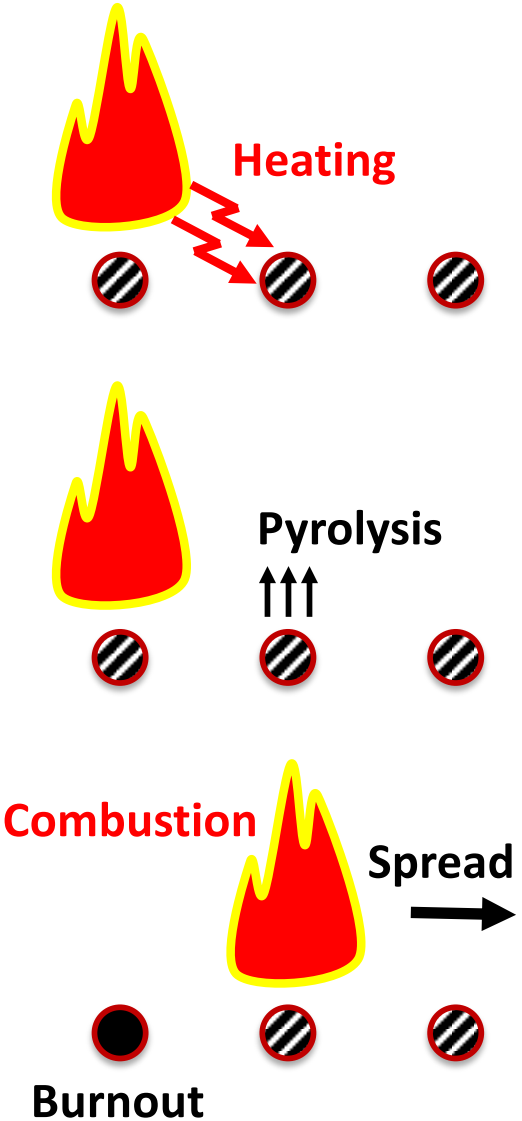
- The purpose of this lecture is to:
  - Introduce the basic physical concepts used to describe combustion phenomena
    - Gas/liquid/solid-fueled combustion; flaming vs non-flaming combustion; premixed vs non-premixed/diffusion flame; momentum-driven vs buoyancy-driven flame; laminar vs turbulent flame
    - Coupling between pyrolysis and combustion: thermal feedback; mass loss rate (MLR) vs heat release rate (HRR); thermal degradation processes inside the solid biomass (drying, pyrolysis, char oxidation)

Introduction to Combustion

- The purpose of this lecture is to:
  - Introduce the basic physical concepts used to describe combustion phenomena
    - Global combustion equation model; over-ventilated vs under-ventilated fire conditions
    - Combustion chemistry; infinitely fast chemistry assumption
    - Structure of diffusion flames: mixture fraction variable; correlations for flame height; air entrainment; transport of combustion heat through convection, thermal radiation and firebrands; emissions of chemical species, including soot particles

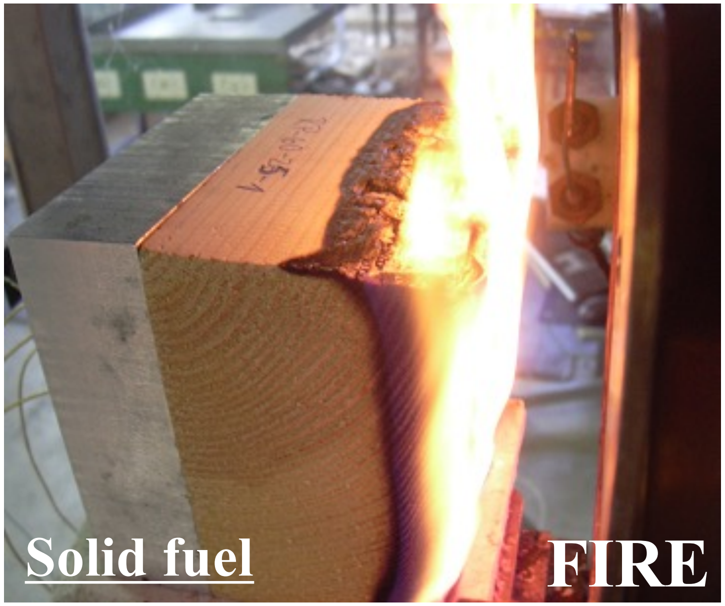
Ignition and Combustion

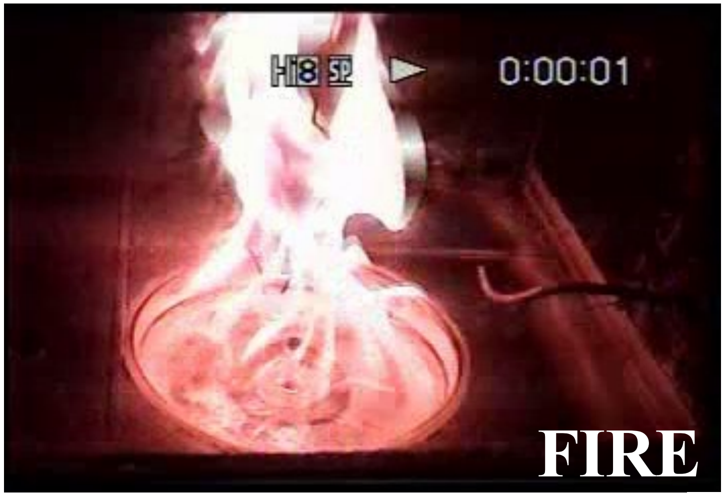
- Fire spread
  - A repeated cycle of: (1) heating; (2) production of flammable vapors by the thermal degradation of vegetation biomass; and (3) combustion of these flammable vapors with ambient air
  - *Pyrolysis* = production of flammable vapors from thermally-degrading solid-phase vegetation biomass
  - *Ignition* = start of pyrolysis or start of combustion
  - *Combustion* = gas-phase oxidation of flammable vapors with heat release



Introduction to Combustion

- Basic features
  - Source of oxygen (oxidizer): ambient air
  - Source of fuel (hydrocarbons): gas/liquid/solid
    - From thereon assume solid fuel (vegetation biomass)





Liquid fuel

Gaseous fuel

Introduction to Combustion

- Basic features
  - Non-flaming combustion mode (glowing/smoldering combustion): solid-gas phase reactions
  - Flaming combustion mode: gas-phase reactions
    - From thereon assume flaming combustion

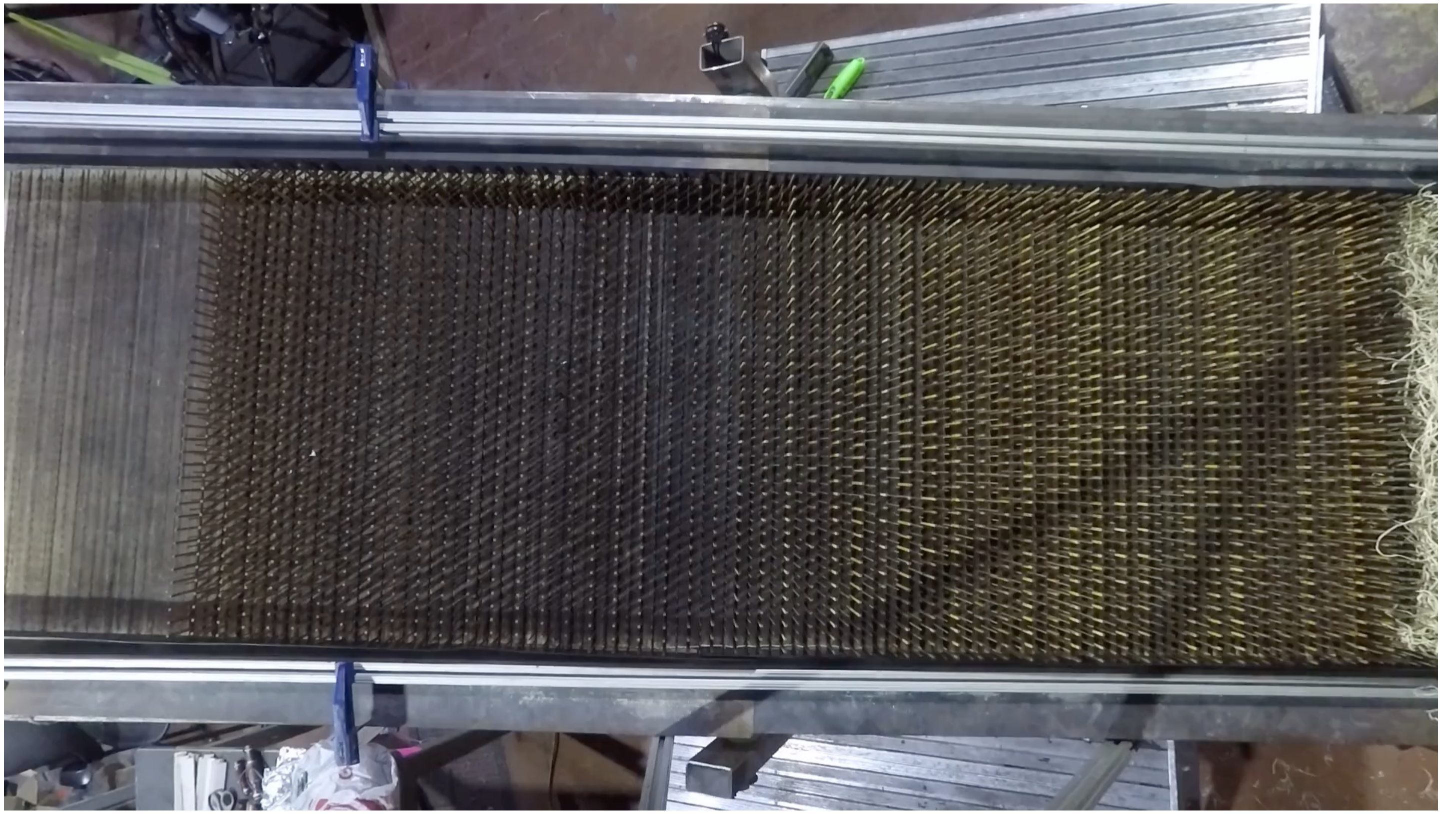
Introduction to Combustion

- Basic features
  - Flaming vs non-flaming combustion modes in flame spread

- Experiment performed at Missoula Fire Sciences Laboratory, USDA Forest Service

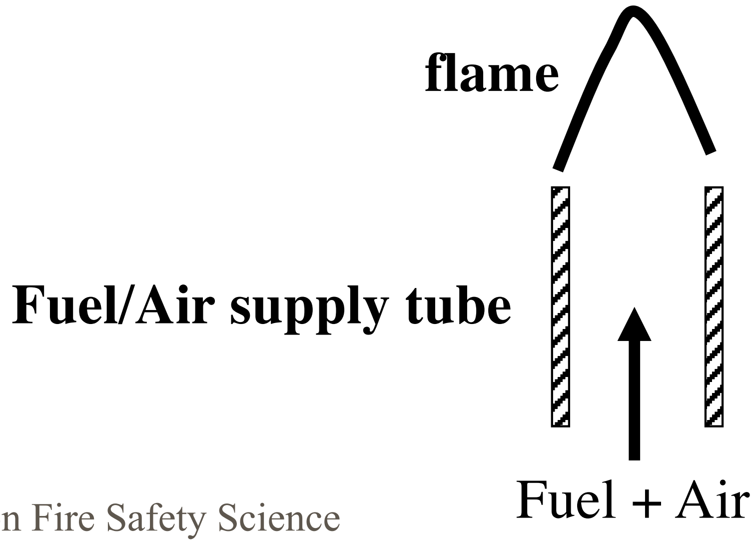
- Inclined surrogate fuel bed corresponding to an array of carboard sticks

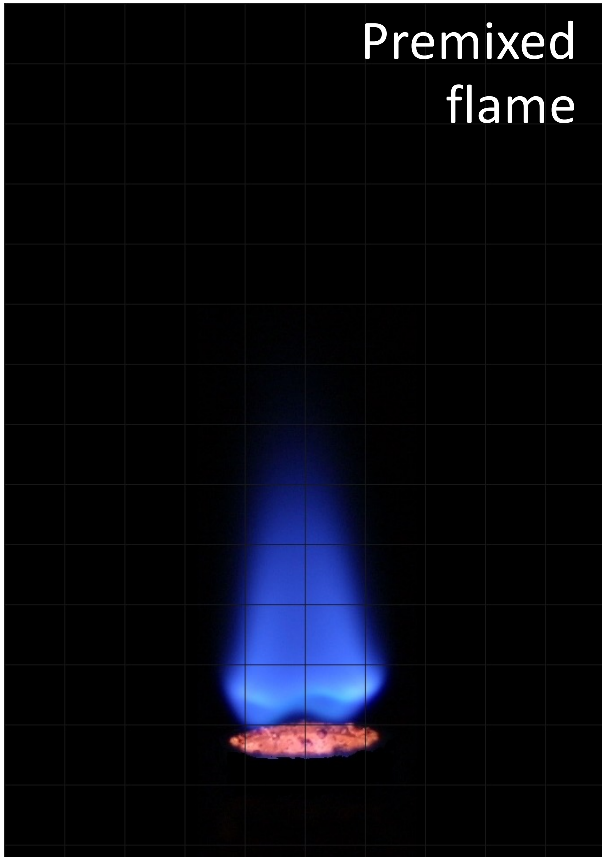
(Courtesy of M. Finney)



Introduction to Combustion

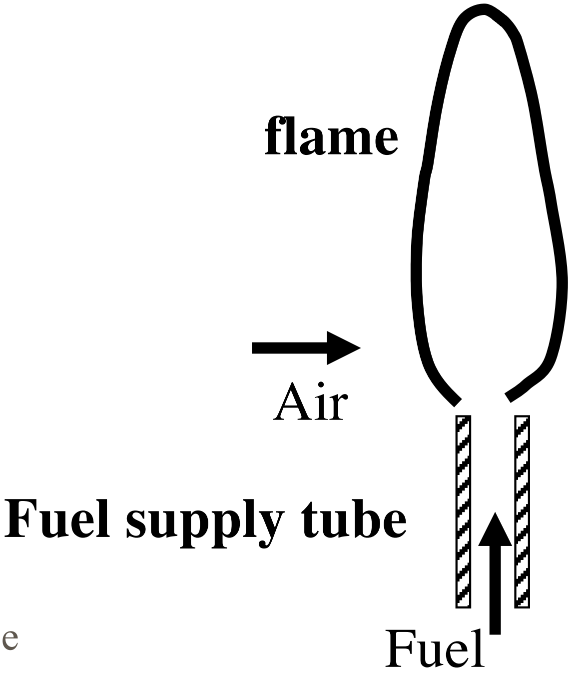
- Basic features
  - Premixed flame: fuel and air are mixed prior to entering the combustion zone

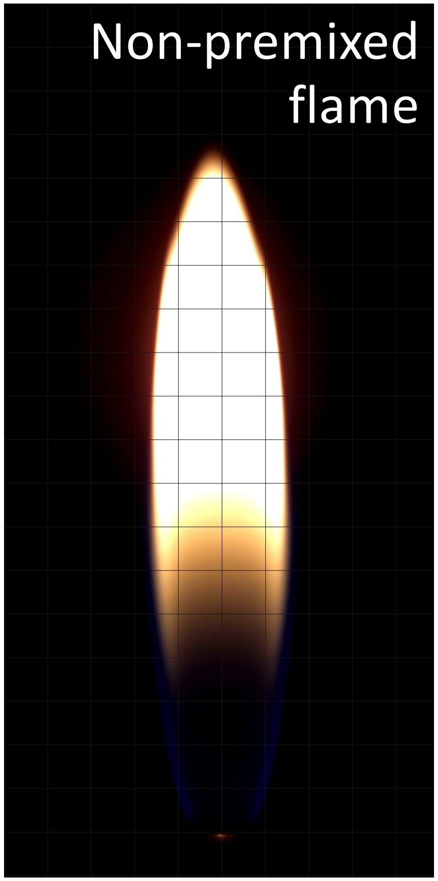




Introduction to Combustion

- Basic features
  - Non-premixed/diffusion flame: fuel and air remain separated prior to entering the combustion zone
    - From thereon assume non-premixed flame

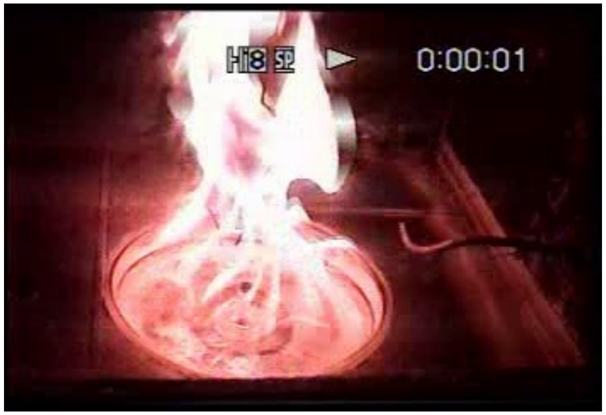




Introduction to Combustion

- Basic features
  - High-velocity fuel release: momentum-driven flame
  - Low-velocity fuel release: buoyancy-driven flame
    - From thereon assume buoyancy-driven flame

$$\boxed{Fr = \frac{u_{fuel}}{\sqrt{gL_{flame}}} \sim \frac{mometum}{buoyancy}}$$



small fuel velocity/large diameter
low Froude number

large fuel velocity/small diameter
high Froude number

Introduction to Combustion

- Basic features
  - Low-Reynolds-number flow: laminar flame
  - High-Reynolds-number flow: turbulent flame
    - From thereon assume turbulent flame

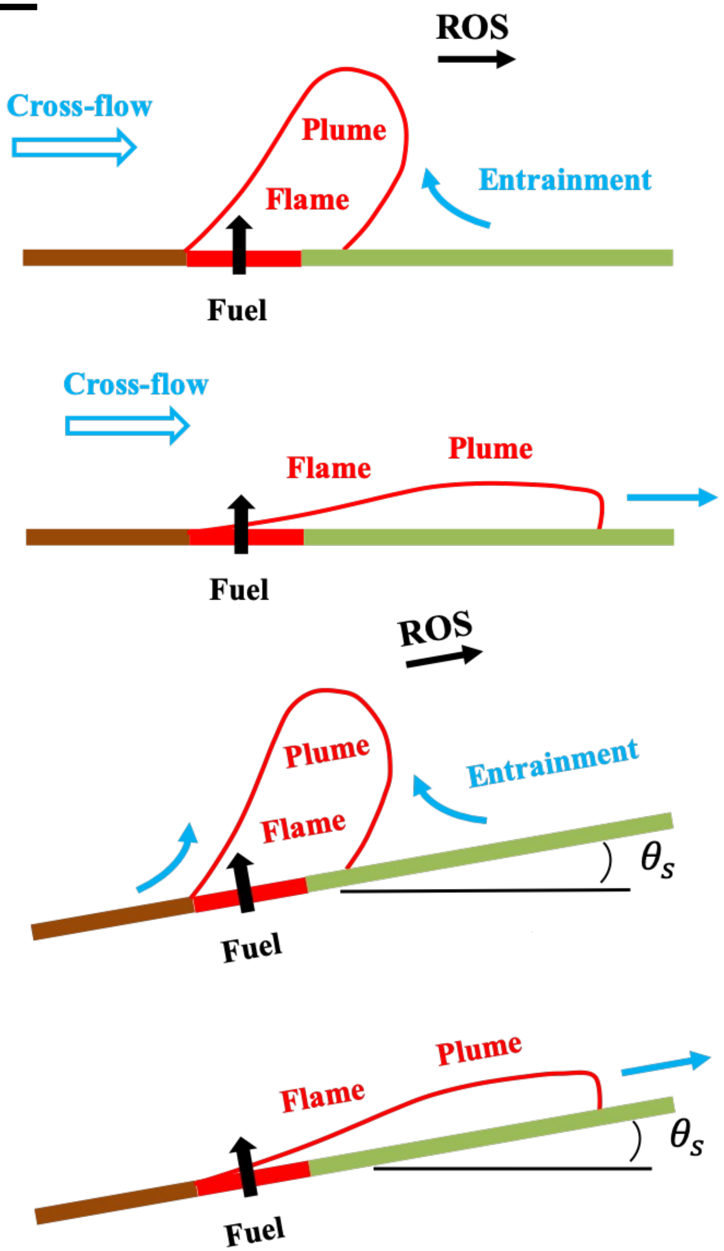
$$\boxed{Re = \frac{\sqrt{gL_{flame}}\times L_{flame}}{(\mu/\rho)} \sim \frac{convection}{diffusion}}$$

small fuel velocity/small diameter
low Reynolds number

large fuel velocity/large diameter
large Reynolds number

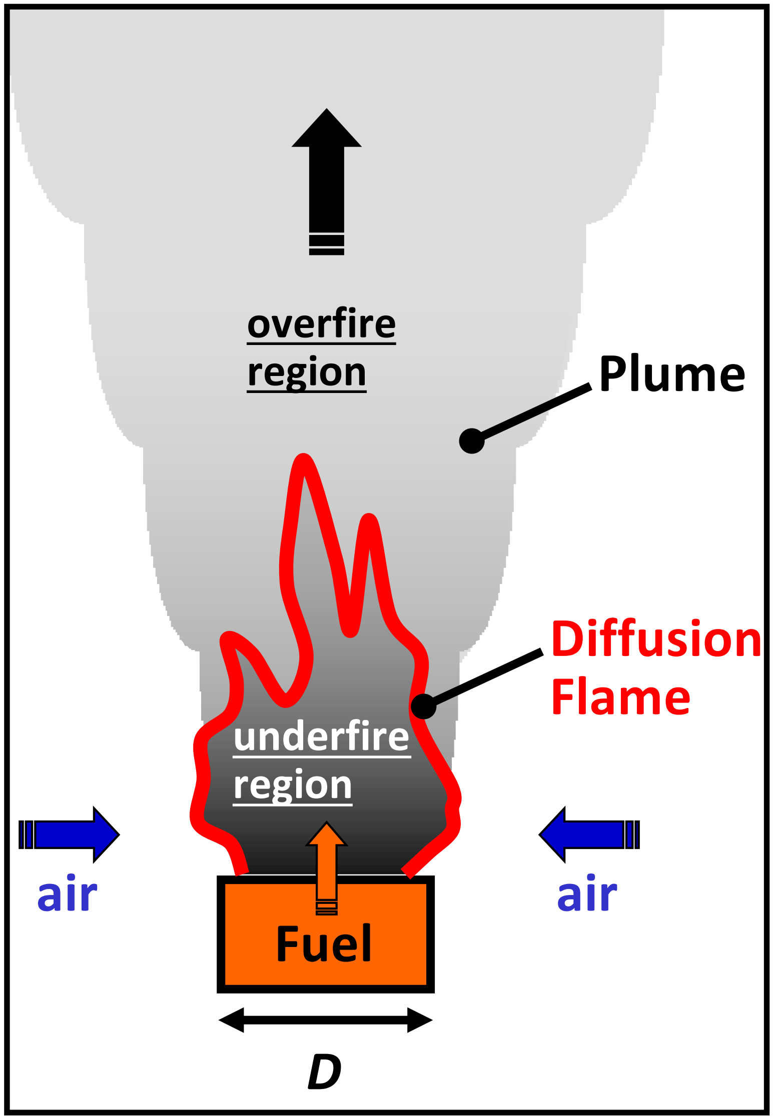
Introduction to Combustion

- Basic features
  - Flames are sensitive to their environment (wind, terrain topography)
    - Two limiting flame regimes: the *plume-dominated* regime in which the flame is mostly detached from the vegetation bed; and the *wind-driven* or *slope-driven* regime in which the flame is attached to the vegetation bed
    - From thereon assume flame under no wind and flat terrain conditions



Flame Structure

- Main features
  - Fuel is flammable vapors produced by pyrolysis of vegetation biomass ($T_s \geq 500 - 600$ K)
  - Fuel reacts with ambient air; combustion occurs in flaming mode ($T_{flame} \sim 2000$ K)
  - Flame is non-premixed
  - Fuel source velocity is small (~0.1-1 cm/s); buoyancy effects accelerate the flow up to several m/s
  - Flow regime corresponds to moderate-to-high turbulence intensities

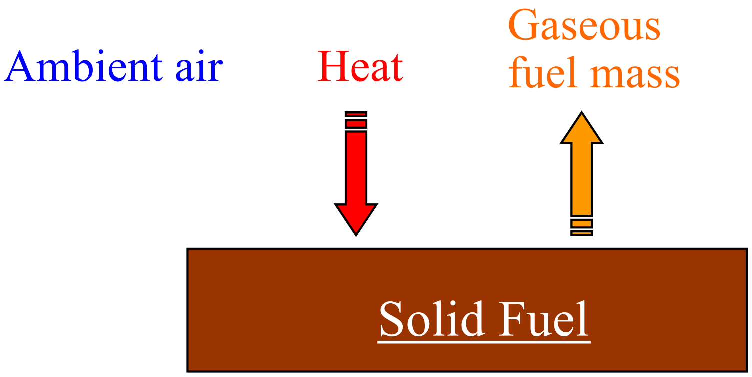


Outline

- Introduction
- Pyrolysis and Combustion
- Combustion: the Thermodynamics Viewpoint
- Combustion Chemistry
- Flame Structure
- Flame Effects

Pyrolysis and Combustion

- Fire is an uncontrolled combustion process characterized by coupled solid-gas phase phenomena
  - Typical production of flammable vapors in a fire
    - Consider a flammable solid object/material that is a potential fuel source
    - At ambient temperature, the fuel is in solid form, the oxygen (from air) in gaseous form, and there is no combustion
    - At moderately elevated temperatures (~200-400 degrees Celsius), a complex thermal degradation process is initiated in the solid object/material, that corresponds to a phase change and produces fuel in gaseous form. This gasification process is called pyrolysis.



Ambient air

Heat

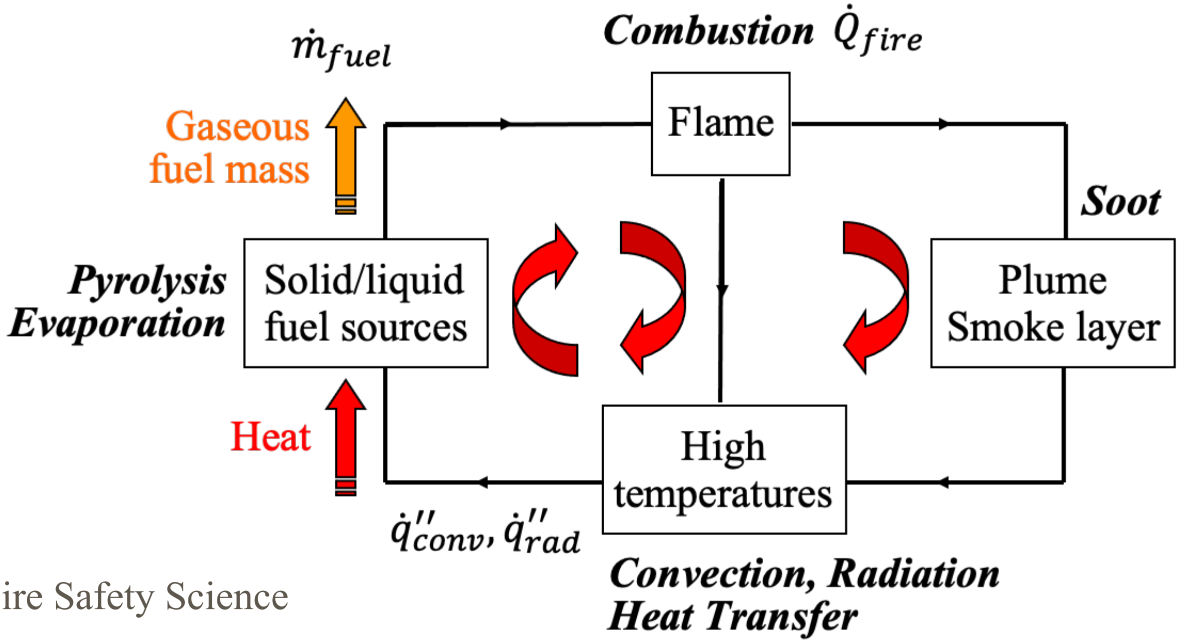
Gaseous fuel mass

Solid Fuel

Pyrolysis and Combustion

- Fire is an uncontrolled combustion process characterized by a thermal feedback loop
  - Typical production of flammable vapors in a fire
    - Fuel gasification is an endothermic process and heat comes from the gas-to-solid heat transfer; the fuel gasification rate is controlled by the rate of gas-to-solid heat transfer (called the heat/thermal feedback)

$$\boxed{\dot{m}''_{fuel} \times \Delta H_{pyrolysis} \approx (\dot{q}''_{conv} + \dot{q}''_{rad})}$$



Combustion $\dot{Q}_{fire}$

$\dot{m}_{fuel}$

Gaseous fuel mass

Flame

Soot

Pyrolysis Evaporation

Solid/liquid fuel sources

Plume Smoke layer

Heat

High temperatures

$\dot{q}''_{conv}, \dot{q}''_{rad}$

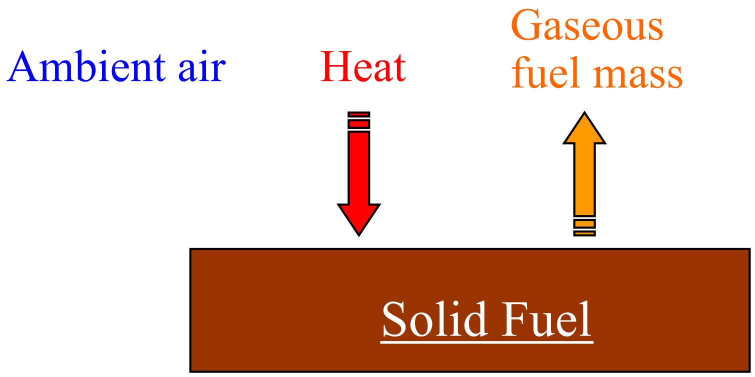
Convection, Radiation Heat Transfer

Pyrolysis and Combustion

- The fuel mass loss rate (MLR) [kg/s]
  - A property of the fuel source
  - Characterizes the intensity of the pyrolysis process

$$\dot{m}''_{fuel} \approx \frac{(\dot{q}''_{conv} + \dot{q}''_{rad})}{\Delta H_{pyrolysis}}$$

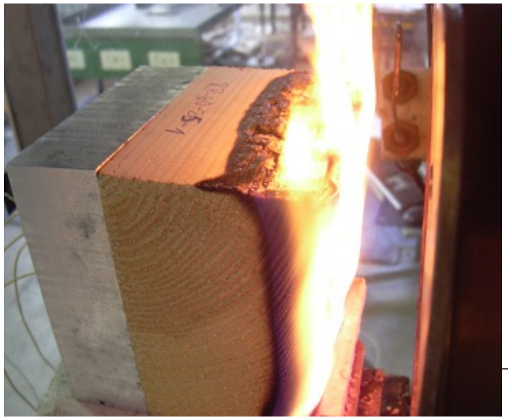
$$\boxed{\dot{m}_{fuel} = \iint_{A_{fuel}} \dot{m}''_{fuel}\, dA_{fuel} \approx \frac{\iint_{A_{fuel}} (\dot{q}''_{conv} + \dot{q}''_{rad})\, dA_{fuel}}{\Delta H_{pyrolysis}}}$$



Pyrolysis and Combustion

- The heat release rate (HRR) [W]
  - A property of the flame
  - Characterizes the intensity of the combustion process

$$\boxed{\dot{Q}_{fire} = \dot{m}_{fuel} \times \Delta H_{combustion}}$$



Pyrolysis

- Thermally-driven decomposition of vegetation biomass
  - Drying reaction

$$(1\ kg\ wet\ solid) \rightarrow (\eta_{H_2O,Rd}\ kg\ water\ vapor) + (\eta_{ds,Rd}\ kg\ dry\ solid)$$

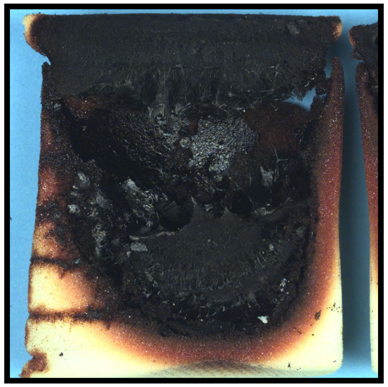
  - Thermal/oxidative pyrolysis reactions (production of fuel)

$$(1\ kg\ dry\ solid) \rightarrow (\eta_{f,Rp}\ kg\ fuel) + (\eta_{c,Rp}\ kg\ char)$$

$$(1\ kg\ dry\ solid) + \left(\eta_{O_2,Rop}\ kg\ O_2\right) \rightarrow \left(\eta_{f,Rop}\ kg\ fuel\right) + \left(\eta_{c,Rop}\ kg\ char\right)$$

  - Char oxidation reaction

$$(1\ kg\ char) + (\eta_{O_2,Rco}\ kg\ O_2) \rightarrow (\eta_{p,Rco}\ kg\ products) + (\eta_{a,Rco}\ kg\ ash)$$



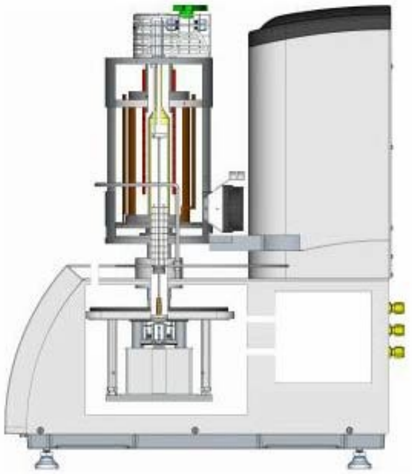
Pyrolysis

- Thermally-driven decomposition of vegetation biomass
  - Input data

Thermal properties of wet solid	$\rho_{s,ws}, k_{s,ws}, c_{s,ws}, \varepsilon_{ws}$
Thermal properties of dry solid	$\rho_{s,ds}, k_{s,ds}, c_{s,ds}, \varepsilon_{ds}$
Thermal properties of char	$\rho_{s,c}, k_{s,c}, c_{s,c}, \varepsilon_{c}$
Thermal properties of ash	$\rho_{s,a}, k_{s,a}, c_{s,a}, \varepsilon_{a}$
Porosity and permeability of wet solid	ψ_{ws}, K_{ws}
Porosity and permeability of dry solid	ψ_{ds}, K_{ds}
Porosity and permeability of char	ψ_{c}, K_{c}
Porosity and permeability of ash	ψ_{a}, K_{a}
Drying reaction	$A_{Rd}, E_{Rd}, n_{Rd}, \Delta H_{Rd}, \eta_{ds,Rd}$
Thermal pyrolysis reaction	$A_{Rp}, E_{Rp}, n_{Rp}, \Delta H_{Rp}, \eta_{c,Rp}$
Oxidative pyrolysis reaction	$A_{Rop}, E_{Rop}, n_{Rop}, n_{O_2,Rop}, \Delta H_{Rop}, \eta_{c,Rop}, \eta_{O_2,Rcp}$
Char oxidation reaction	$A_{Rco}, E_{Rco}, n_{Rco}, n_{O_2,Rco}, \Delta H_{Rco}, \eta_{a,Rco}, \eta_{O_2,Rco}$

Pyrolysis

- Basic study of phenomenology; evaluation of MLR and/or model input data
  - Micro-scale experiments (*e.g.* Thermogravimetric Analysis – TGA, Differential Scanning Calorimetry – DSC, Microscale Combustion Calorimetry – MCC)
  - Bench-scale experiments (*e.g.*, cone calorimeter, Fire Propagation Apparatus – FPA)
  - Fuel package experiments



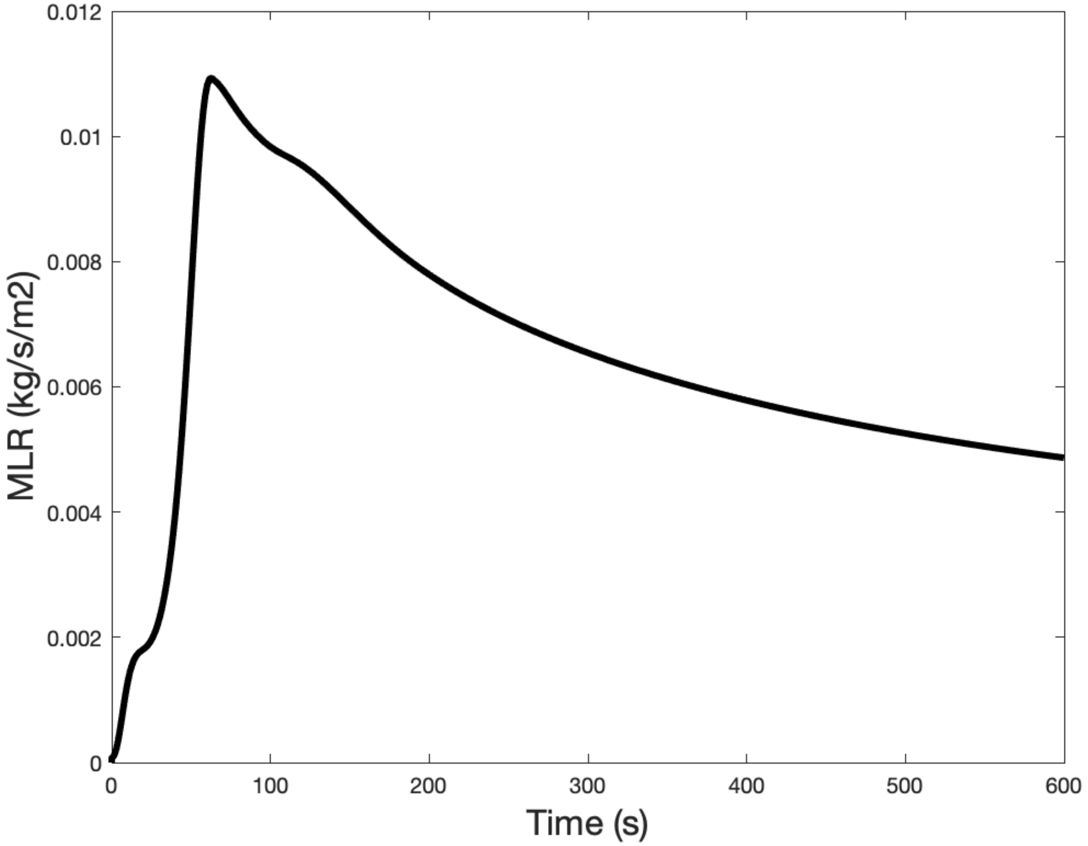
Pyrolysis

- Example of results from cone calorimeter test (model)
  - *Example*: white pine (Lautenberger & Fernandez-Pello, *Combust. Flame* **156**:1503-1513 (2009)

$\Delta = 3.8 \text{ cm}$

$G = 40 \text{ kW/m}^2$

$x_{O_2,g} = 0.21$



Pyrolysis

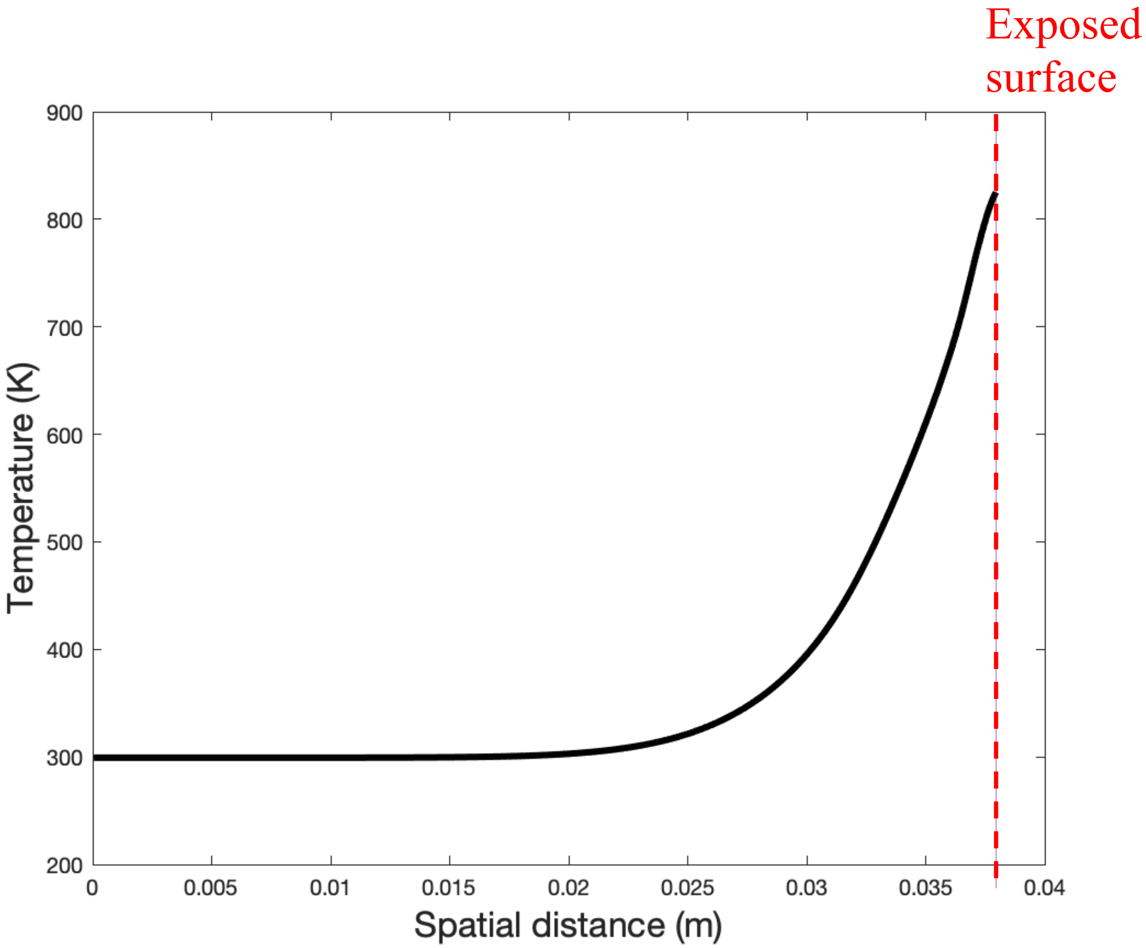
- Example of results from cone calorimeter test (model)
  - White pine (Lautenberger & Fernandez-Pello, *Combust. Flame* **156**:1503-1513 (2009))

$\Delta = 3.8\ \mathrm{cm}$

$G = 40\ \mathrm{kW/m^2}$

$x_{O_2,g} = 0.21$

$\boldsymbol{t = 100\ \mathrm{s}}$



Pyrolysis

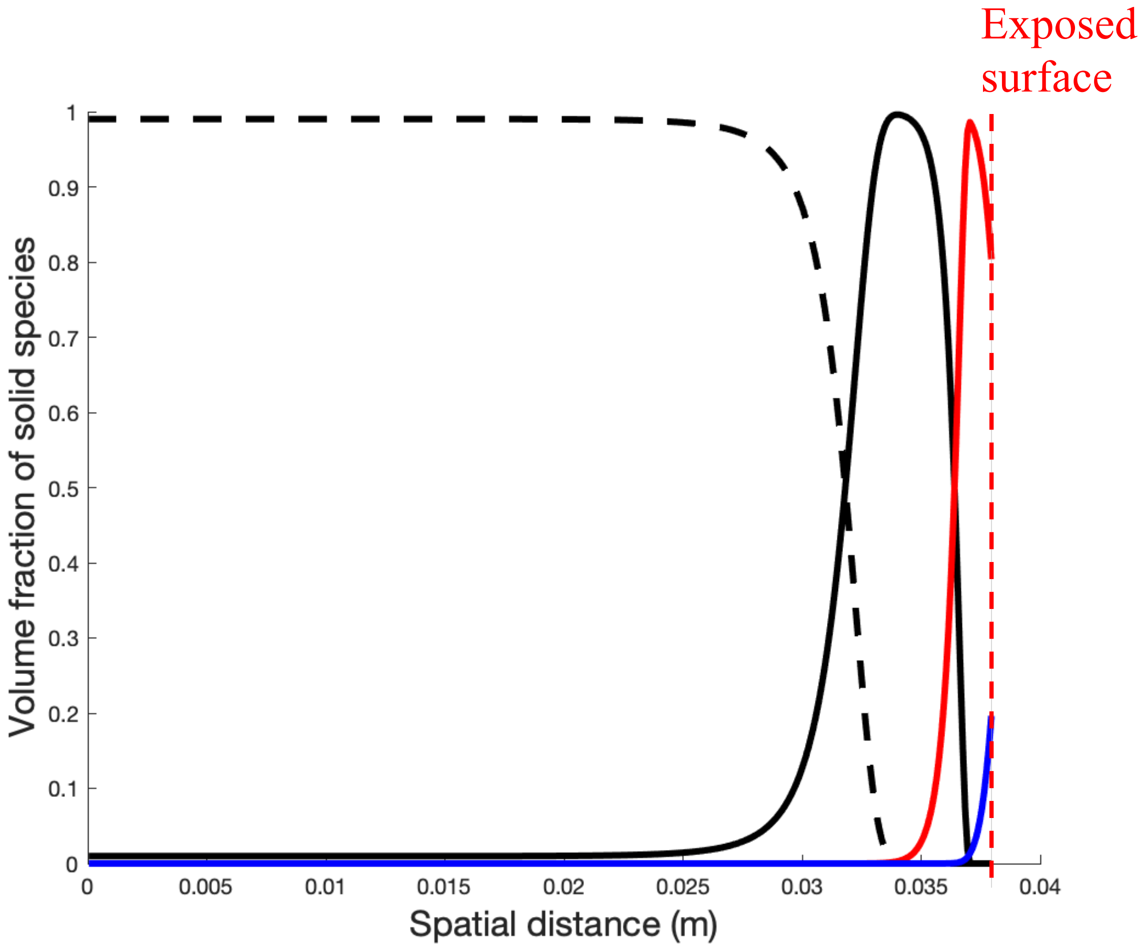
- Example of results from cone calorimeter test (model)
  - White pine (Lautenberger & Fernandez-Pello, *Combust. Flame* **156**:1503-1513 (2009))

$\Delta = 3.8\ \mathrm{cm}$

$G = 40\ \mathrm{kW/m^2}$

$x_{O_2,g} = 0.21$

$\boldsymbol{t = 100\ \mathrm{s}}$



Pyrolysis

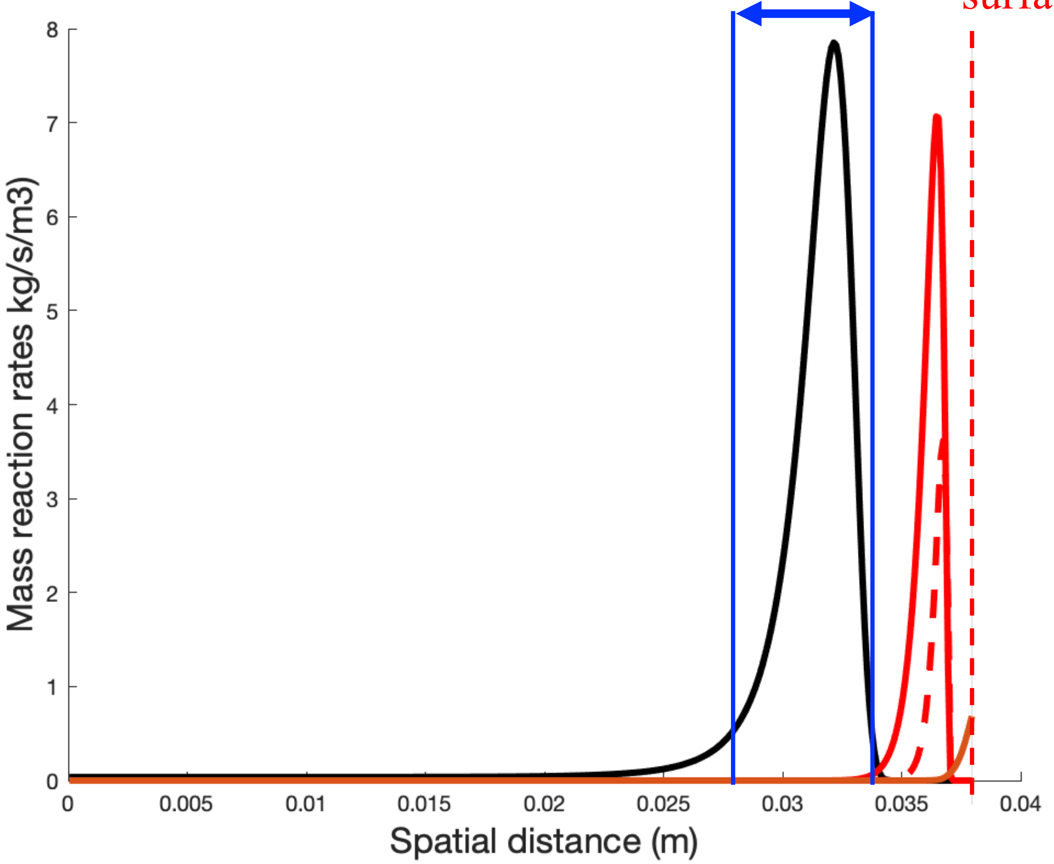
- Example of results from cone calorimeter test (model)
  - White pine (Lautenberger & Fernandez-Pello, *Combust. Flame* **156**:1503-1513 (2009))

$\Delta = 3.8\ \mathrm{cm}$

$G = 40\ \mathrm{kW/m^2}$

$x_{O_2,g} = 0.21$

$\boldsymbol{t = 100\ \mathrm{s}}$



$\boldsymbol{\delta_{RR} = O(1\ \mathrm{mm})}$

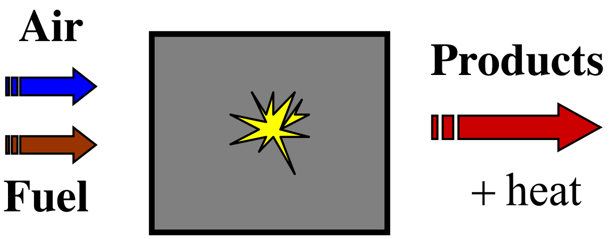
Exposed surface

Outline

- Introduction
- Pyrolysis and Combustion
- Combustion: the Thermodynamics Viewpoint
- Combustion Chemistry
- Flame Structure
- Flame Effects

Combustion

- Global combustion equation
  - Black box model
    - written for 1 mole of fuel



$$\underbrace{F}_{\text{fuel}} + \nu_{O_2}\underbrace{(O_2 + \beta N_2)}_{\text{air}} \longrightarrow \underbrace{\nu_{CO_2}CO_2 + \nu_{H_2O}H_2O}_{\text{products}} + (\nu_{O_2}\beta)N_2$$

(+ heat)

where $\beta = (n_{N_2}/n_{O_2})_{air}$

- or written for 1 kg of fuel

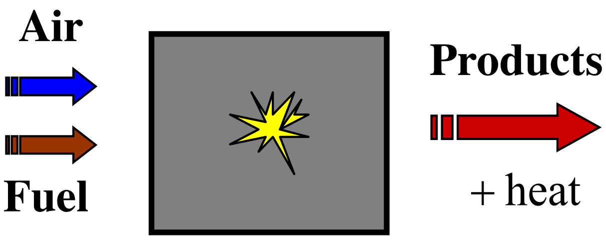
$$F + r_S(O_2 + \beta^* N_2) \longrightarrow \eta_{CO_2}CO_2 + \eta_{H_2O}H_2O + (r_S\beta^*)N_2$$

(+ heat)

where $\beta^* = ((n_{N_2}MW_{N_2})/(n_{O_2}MW_{O_2}))_{air}$

Combustion

- Global combustion equation
  - Assume $F = C_nH_mO_p$ (known)
    - for 1 mole of fuel



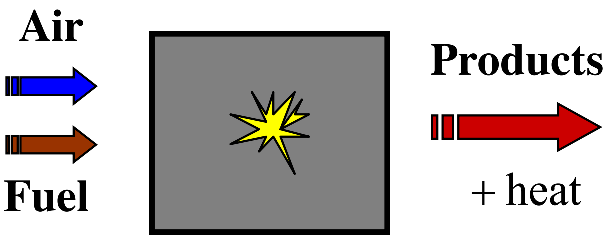
$$\underbrace{F}_{\text{fuel}} + \nu_{O_2}\underbrace{(O_2 + \beta N_2)}_{\text{air}} \longrightarrow \underbrace{\nu_{CO_2}CO_2 + \nu_{H_2O}H_2O}_{\text{products}} + (\nu_{O_2}\beta)N_2 \quad \text{(+ heat)}$$

- Conservation of *C*, *H*, *O* and *N* atoms

$$\nu_{CO_2} = n\,; \quad \nu_{H_2O} = \frac{m}{2}\,; \quad \nu_{O_2} = n + \frac{m}{4} - \frac{p}{2}\,; \quad \nu_{N_2} = \nu_{O_2}\times\beta$$

Combustion

- Global combustion equation
  - Assume $F = C_nH_mO_p$ (known)
    - for 1 kg of fuel



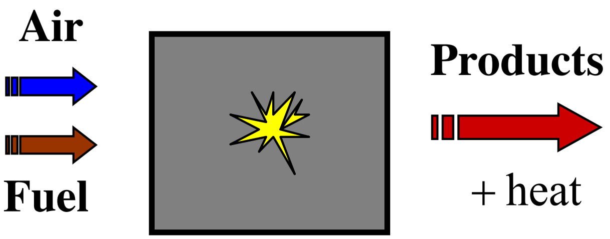
$$\underbrace{F}_{\text{fuel}} + r_S\underbrace{(O_2 + \beta^* N_2)}_{\text{air}} \longrightarrow \underbrace{\eta_{CO_2} CO_2 + \eta_{H_2O} H_2O}_{\text{products}} + (r_S\beta^*)N_2 \quad \text{(+ heat)}$$

- Conservation of C, H, O and N atoms

$$\eta_{CO_2} = \frac{\nu_{CO_2} MW_{CO_2}}{MW_F} \; ; \quad \eta_{H_2O} = \frac{\nu_{H_2O} MW_{H_2O}}{MW_F} ; \quad r_S = \frac{\nu_{O_2} MW_{O_2}}{MW_F}$$

Combustion

- Global combustion equation
  - Assume $F = C_nH_mO_p$ (known)
    - for 1 kg of fuel



$$\underbrace{F}_{\text{fuel}} + r_S\underbrace{(O_2 + \beta^* N_2)}_{\text{air}} \longrightarrow \underbrace{\eta_{CO_2} CO_2 + \eta_{H_2O} H_2O}_{\text{products}} + (r_S\beta^*)N_2$$

(+ heat)

- Heat of combustion (per unit mass of fuel)

$$\Delta H_F = r_S \times \Delta H_{O_2}$$

$$\Delta H_{O_2} \approx 13.1 \text{ MJ/kg}[O_2]$$

Combustion

- Global combustion equation
  - *Stoichiometric* conditions
    - The proportions of fuel and oxygen are those required by the combustion equation
    - All the fuel and oxygen mass are consumed by the combustion process
    - Corresponds to a chemical optimum: maximum emissions of carbon dioxide/water vapor as well as maximum heat release (maximum flame temperature)

Combustion

- Idealized combustion equation
  - *Non-stoichiometric* conditions

$$\phi = \frac{(n_F^i/n_{O_2}^i)}{(1/\nu_{O_2})} = \nu_{O_2}(\frac{x_F^i}{x_{O_2}^i})$$

$$\underline{\phi} = \frac{(m_F^i/m_{O_2}^i)}{(MW_F/(\nu_{O_2}MW_{O_2}))} = r_S(\frac{Y_F^i}{Y_{O_2}^i})$$

Equivalence ratio
(control volume analysis)

Combustion

- Idealized combustion equation
  - *Fuel lean* (fuel-limited, over-ventilated) conditions

$$\boxed{\phi \leq 1}$$

    - There is more oxygen than required by the combustion chemistry
    - All the fuel mass is consumed by the combustion process; there is some excess oxygen mass in the products

Combustion

- Idealized combustion equation
  - *Fuel lean* (fuel-limited, over-ventilated) conditions

$$F + (\frac{\nu_{O_2}}{\phi})(O_2 + \beta N_2)$$

$$\longrightarrow \nu_{CO_2} CO_2 + \nu_{H_2O} H_2O + (\frac{\nu_{O_2}}{\phi}\beta)N_2 + \underbrace{(\frac{\nu_{O_2}}{\phi} - \nu_{O_2})O_2}_{\text{excess oxygen}}$$

Combustion

- Idealized combustion equation
  - *Fuel rich* (oxygen-limited, under-ventilated) conditions

$$\boxed{\phi \geq 1}$$

    - There is less oxygen than required by the combustion chemistry
    - All the oxygen mass is consumed by the combustion process; there is some excess fuel mass in the products

Combustion

- Idealized combustion equation
    - *Fuel rich* (oxygen-limited, under-ventilated) conditions

$$F + (\frac{\nu_{O_2}}{\phi})(O_2 + \beta N_2)$$

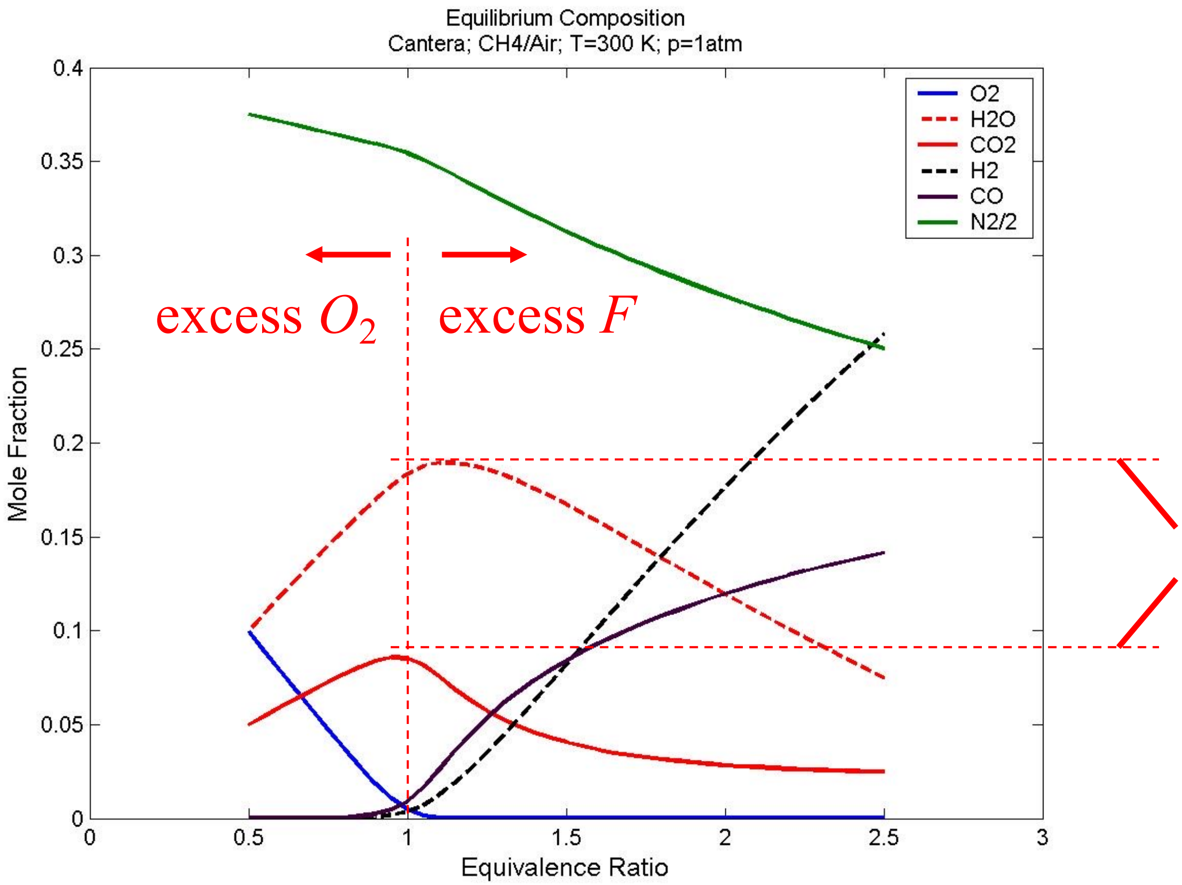
$$\longrightarrow (\frac{\nu_{CO_2}}{\phi})CO_2 + (\frac{\nu_{H_2O}}{\phi})\, H_2O + (\frac{\nu_{O_2}}{\phi}\beta)N_2 + \underset{\text{excess fuel}}{\underline{(1 - \frac{1}{\phi})F}}$$

Combustion

- Idealized combustion equation
  - Limitations
    - Under high temperature conditions, CO_2 and H_2O experience chemical *dissociations* (*i.e.* breakdown of large molecules into smaller molecules and atoms); combustion products include CO_2 and H_2O, as assumed so far, but also additional minor species (CO, H_2, OH, H, O, *etc*)
    - Excess fuel mass present in fuel-rich combustion does not remain as virgin fuel, as assumed so far, but decomposes into CO, H_2, and also other hydrocarbon species (*uHC*), and soot

Combustion

- Calculation of equilibrium mixture composition with state-of-the-art software (CHEMKIN, Cantera, *etc*)



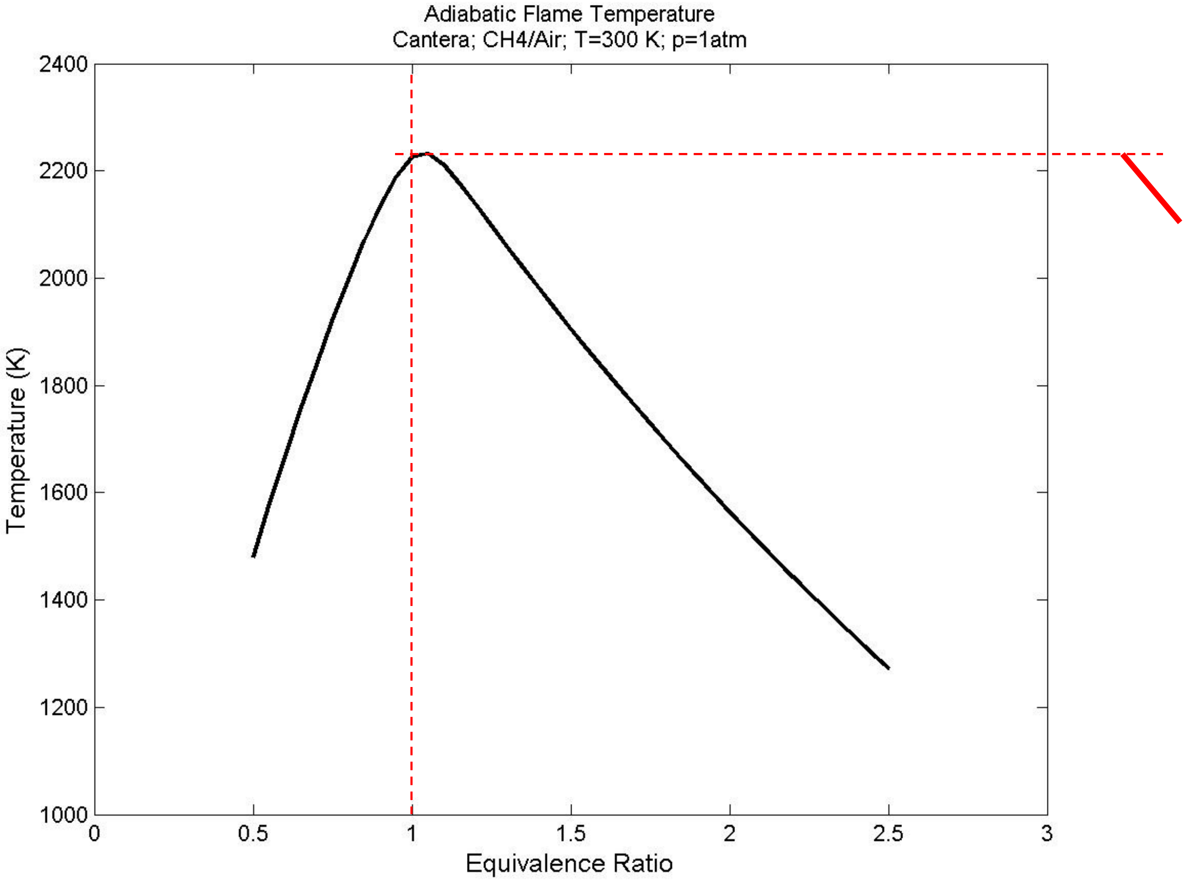
excess O_2

excess F

maximum product yield near $\phi = 1$

Combustion

- Calculation of adiabatic flame temperature with state-of-the-art software (CHEMKIN, Cantera, *etc*): measure of heat released by combustion process



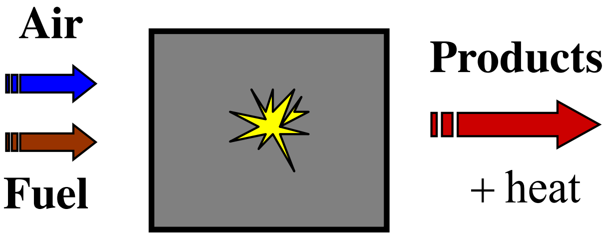
maximum temperature near $\phi = 1$

maximum temperature ~ 2,200–2,300 K for most practical fuels (STPC)

Outline

- Introduction
- Pyrolysis and Combustion
- Combustion: the Thermodynamics Viewpoint
- Combustion Chemistry
- Flame Structure
- Flame Effects

Combustion



- Global combustion equation
  - A black-box model
    - Describes the inputs and outputs of the combustion transformation
    - Also a statement on global mass (and energy) conservation
    - But not a statement on the speed of combustion
      - The speed of combustion is described in studies of combustion chemical kinetics and/or flame studies

Chemistry

- Detailed chemical kinetic mechanism
  - A “first-principles” description of combustion chemistry (*elementary reactions*)
    - A series of statements about probable outcome of collisions between molecules at the quantum level
    - Based on the kinetic theory of gases (statistical thermodynamics)
    - Provides estimates of the reaction rates (RR) for each elementary reaction (*i.e.*, estimates of the speed of combustion)

Chemistry

- Detailed chemical kinetic mechanism
  - Reaction rate (RR) of an elementary bimolecular reaction

    $R_1 + R_2 \longrightarrow P_1 + P_2$

    - Kinetic theory of gases

$$-\frac{dC_{R_1}}{dt} \sim \left\{\underbrace{\begin{matrix}\mathit{frequency\ of\ collisions}\\ \mathit{between}\ R_1\ \mathit{and}\ R_2\end{matrix}}_{\sim C_{R_1}C_{R_2}}\right\} \times \left\{\underbrace{\begin{matrix}\mathit{probability\ of\ a}\\ \mathit{successful\ collision}\end{matrix}}_{\sim \exp(-\underbrace{E_A}_{\text{activation energy}}/RT)}\right\}$$

$$-\frac{dC_{R_1}}{dt} \sim C_{R_1}C_{R_2} \times \underbrace{k(T)}_{\text{RR coefficient}}$$

Chemistry

- Detailed chemical kinetic mechanism
  - Reaction rate (RR) of an elementary bimolecular reaction

    $R_1 + R_2 \longrightarrow P_1 + P_2$

    - *Arrhenius* model

temperature exponent

activation energy [J/mol]

$$k(T) = AT^b \exp\left(-\frac{E_A}{RT}\right)$$

pre-exponential factor

Chemistry

- Detailed chemical kinetic mechanism
  - Reaction rate (RR) of an elementary bimolecular reaction $R_1 + R_2 \longrightarrow P_1 + P_2$
    - *Arrhenius* model: RR varies exponentially with temperature

$$-\frac{dC_{R_1}}{dt} = C_{R_1} C_{R_2} \times A T^b \ \exp(-\frac{E_A}{RT})$$

where $C_k = (x_k \frac{p}{RT}) = (Y_k \frac{\rho}{MW_k})$

Chemistry

- Arrhenius model applied to global combustion equation (example: propane-air combustion)

$$C_3H_8 + 5(O_2 + \beta N_2) \longrightarrow 3CO_2 + 4H_2O + (5\beta)N_2$$

  - Reaction rate [mol/cm^3/s] (C.K. Westbrook, F.L. Dryer, *Combustion Science and Technology* 1981)

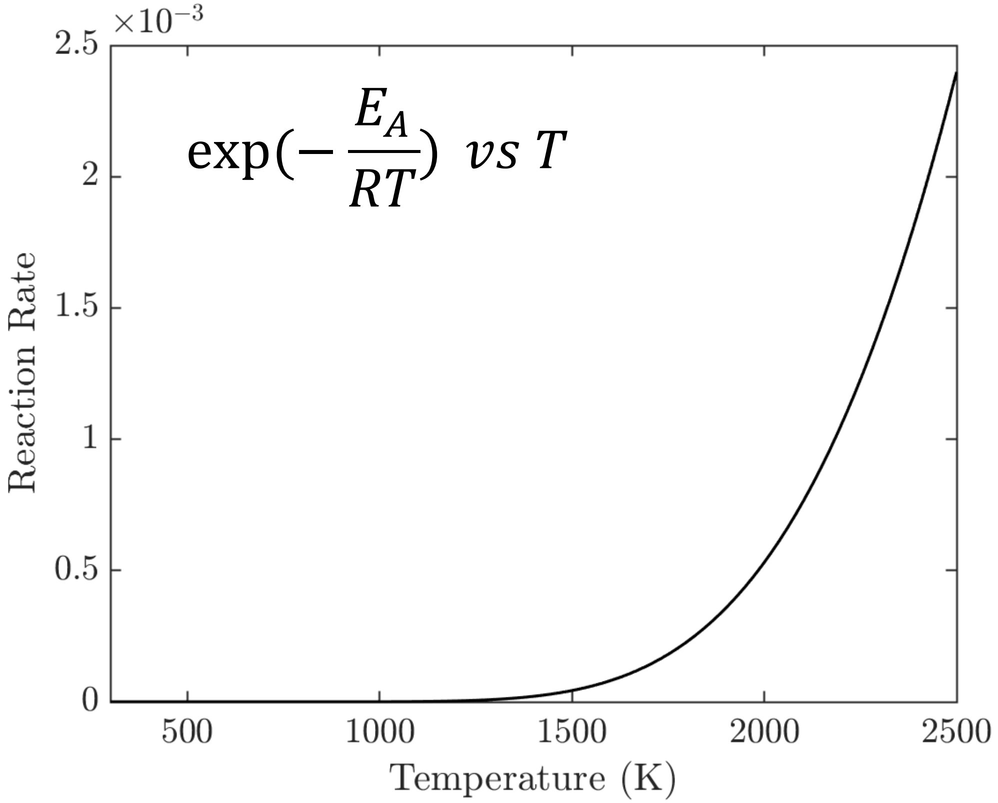
$$-\frac{dC_{C_3H_8}}{dt} = \left(C_{C_3H_8}\right)^{0.1}\left(C_{O_2}\right)^{1.65} \times 8.6\times 10^{11}\ \exp\left(-\frac{15{,}098}{T}\right)$$

  - Heat release rate [W/m^3]

$$\dot{q}'''_{combustion} = \left(-\frac{dC_{C_3H_8}}{dt}\right)\times MW_{C_3H_8}\times 10^6\times \Delta H_{C_3H_8}$$

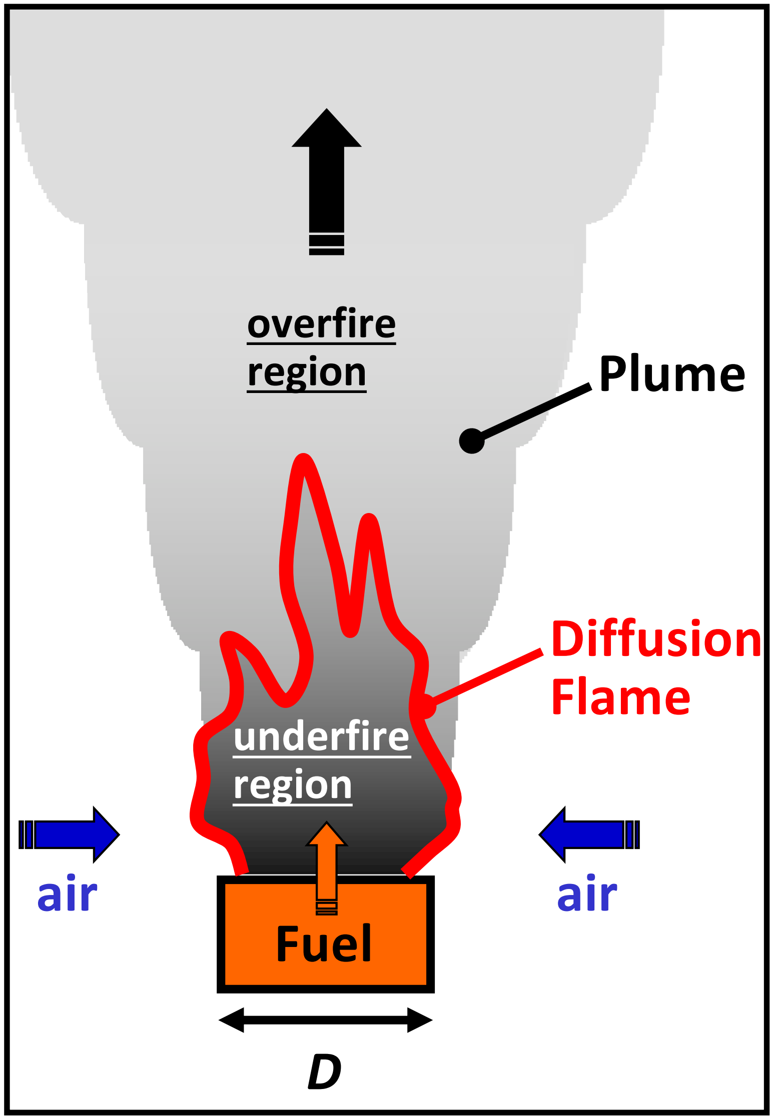
Chemistry

- Arrhenius model
  - High temperatures correspond to (exponentially) fast chemistry



Flame Structure

- Main features
  - Flame topology corresponds to a thin surface (sheet)
  - Burning rate limited by diffusion of fuel and air into the flame surface (combustion chemistry is *usually* very fast)
  - The flame structure is characterized in terms of a mixing variable called the *mixture fraction*



Outline

- Introduction
- Pyrolysis and Combustion
- Combustion: the Thermodynamics Viewpoint
- Combustion Chemistry
- Flame Structure
- Flame Effects

Flame Structure

- Mixture fraction
  - Non-dimensional variable Z used to describe the mixture composition
  - Field variable, $Z(x, y, z, t)$, defined as the local fraction of mass that originates from the fuel supply stream (convention: $Z = 1$ in pure fuel; $Z = 0$ in pure air)

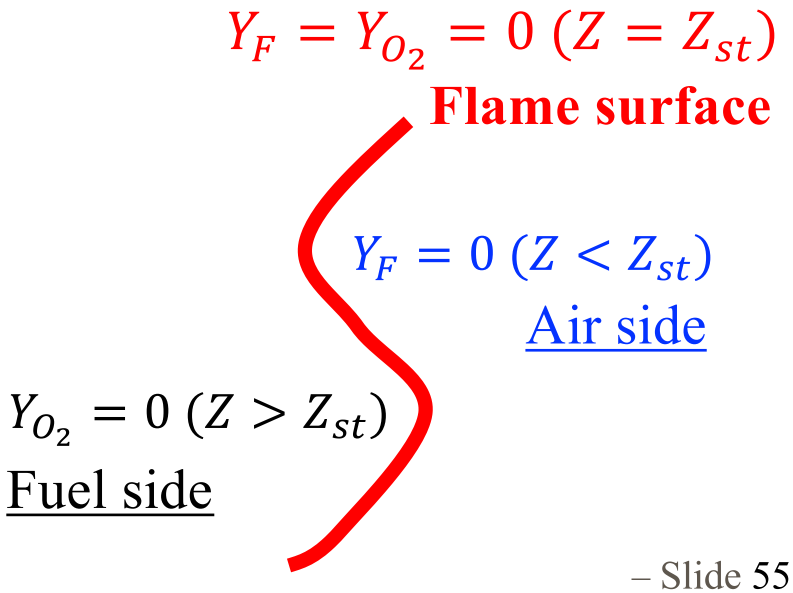
$$Z = \frac{r_s Y_F - Y_{O_2} + Y_{O_2,air}}{r_s + Y_{O_2,air}}$$

Flame Structure

- Mixture fraction
  - Assuming combustion chemistry to be infinitely fast
    - The flame topology corresponds to a surface (*i.e.* a front or a sheet)
    - The flame is located where fuel and oxygen mass meet in stoichiometric proportions, at $Z = Z_{st}$

$$Z_{st} = \frac{Y_{O_2,air}}{r_s + Y_{O_2,air}}$$

    - Fuel and oxygen mass do not coexist ($Y_F \times Y_{O_2} = 0$)



$Y_F = Y_{O_2} = 0 \; (Z = Z_{st})$

Flame surface

$Y_F = 0 \; (Z < Z_{st})$

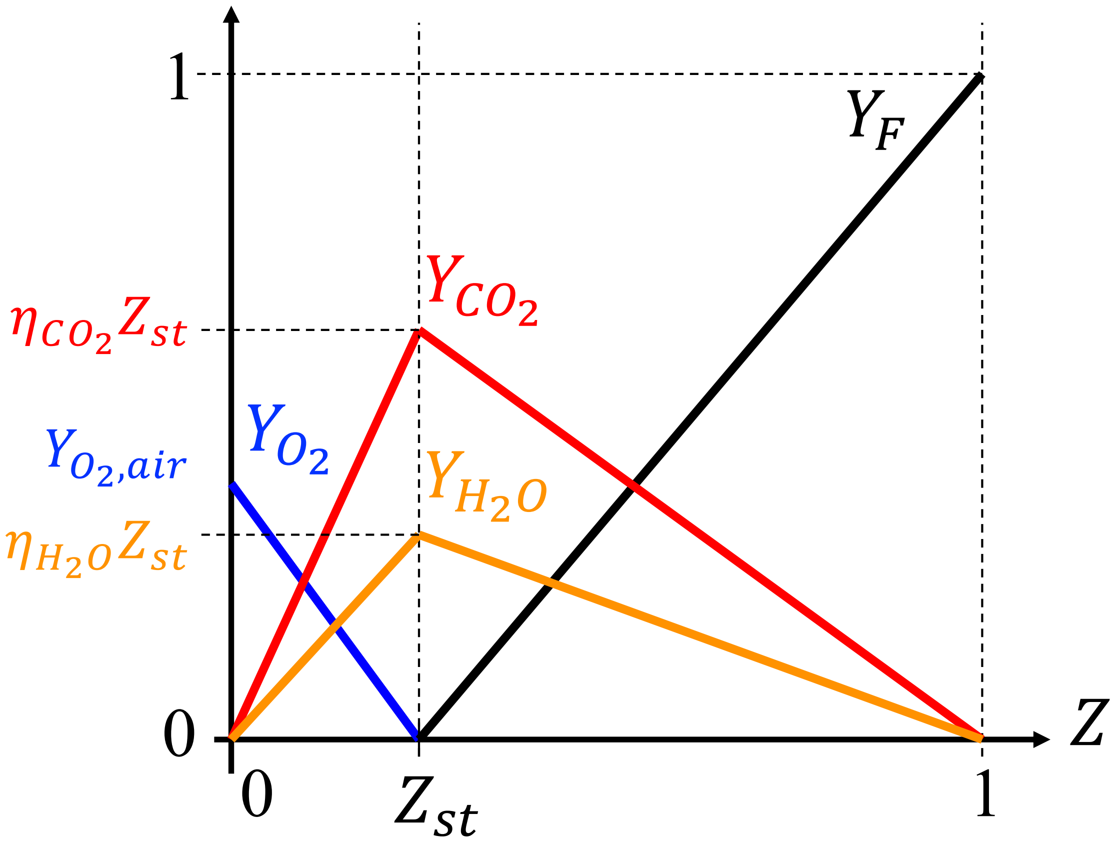
Air side

$Y_{O_2} = 0 \; (Z > Z_{st})$

Fuel side

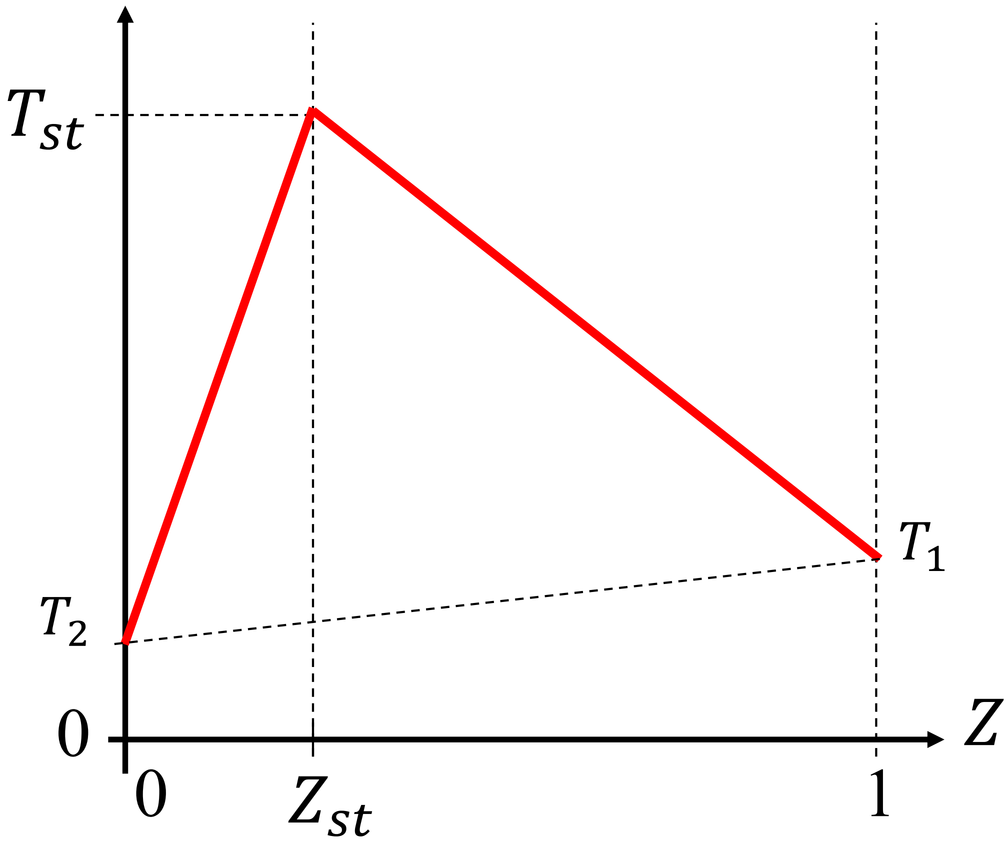
Flame Structure

- Mixture fraction
  - Description of mixture composition in terms of the mixture fraction (Burke-Schumann model)



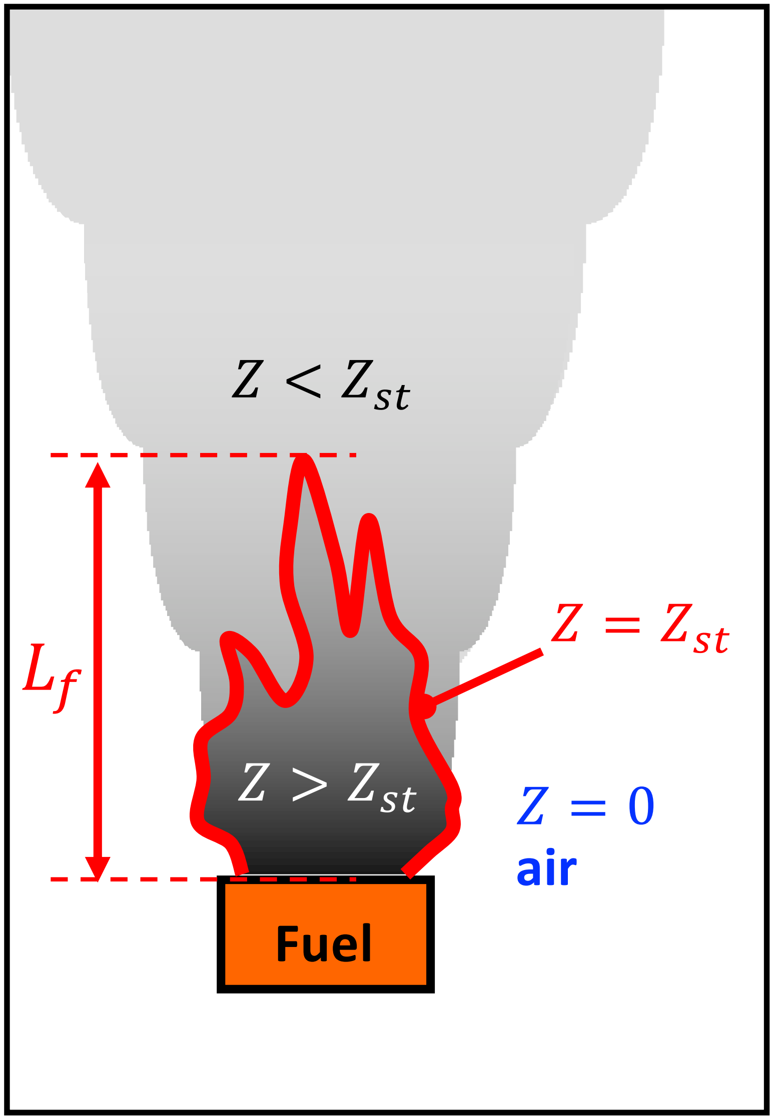
Flame Structure

- Mixture fraction
  - Description of temperature in terms of the mixture fraction (Burke-Schumann model with assumption of adiabatic combustion)



Flame Structure

- Mixture fraction
  - Field variable, $Z(x, y, z, t)$, solution of an unsteady convection-diffusion equation
  - Characteristic length scale of the flame geometry: the mean flame height L_f
  - Characteristic time scale of the flame: the mean flame residence time $\sim (L_f/\sqrt{gL_f}) = \sqrt{L_f/g}$

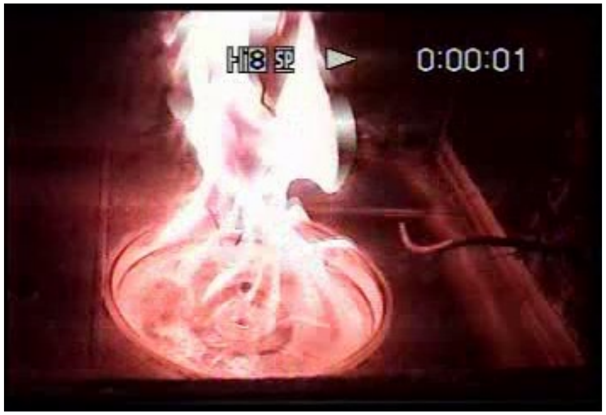


Flame Structure

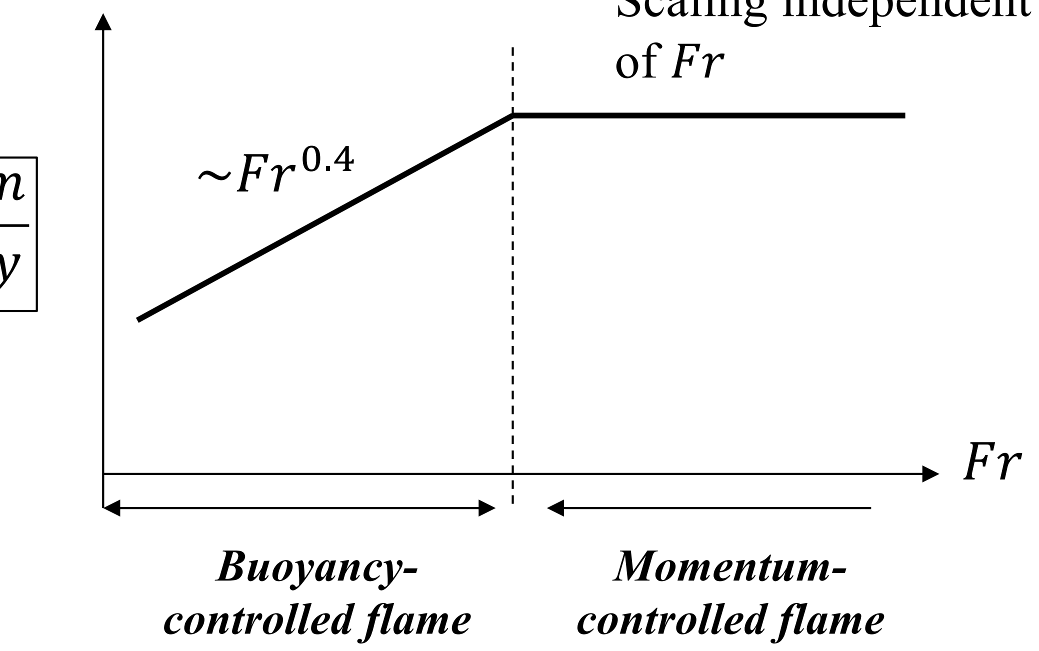
- Mean flame height (pool fire configuration)

$$Fr = \frac{u_{fuel}}{\sqrt{gD_{fuel}}} \sim \frac{mometum}{buoyancy}$$

low Froude number



Non-dimensional flame length (L_f/D_{fuel})



high Froude number

Flame Structure

- Mean flame height (pool fire configuration)
  - For fire applications (buoyancy-controlled flames, small values of Fr), flame length correlations based on the following *Q-star* parameter

$$\dot{Q}^* = \frac{\dot{Q}_{fire}}{(\rho c_p T)_{air}\sqrt{g D_{fuel}}\, D_{fuel}^2}$$

Flame Structure

- Mean flame height (pool fire config.)
  - Correlation (Heskestad)

$(1 \leq \dot{Q}^{*} < 10^{5})$

$$\left(\frac{L_f}{D_{fuel}}\right) = 3.7 \times \dot{Q}^{*\,2/5} - 1.02$$

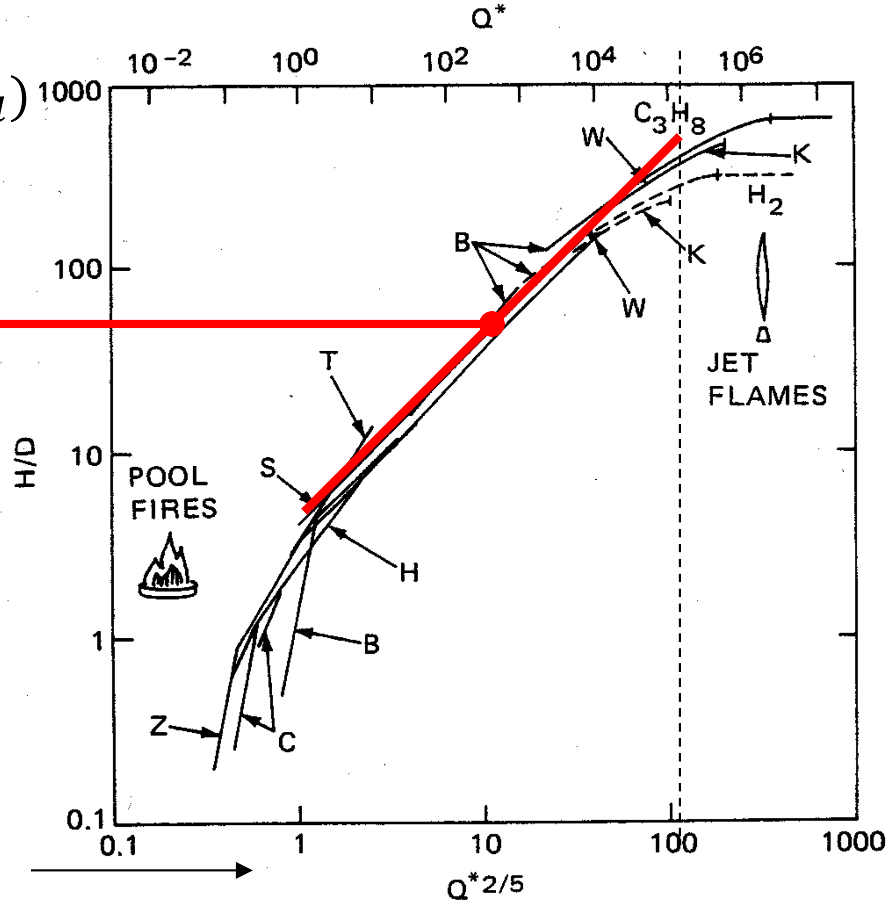
$$L_f = 0.235 \times \dot{Q}_{fire}^{2/5} - 1.02 \times D_{fuel}$$

$(\dot{Q}_{fire}$ in kW)

Buoyancy-controlled flame

Momentum-controlled flame

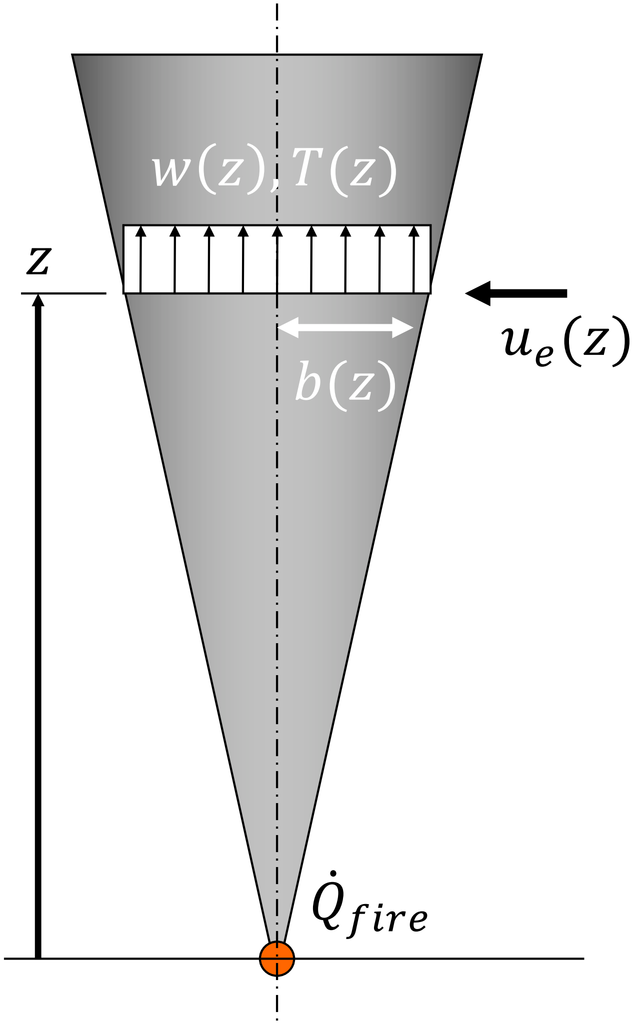
(L_f / D_{fuel})



*small Q*regime*

Plume Structure

- Ideal buoyant plume (pool fire config.)
  - Axisymmetric geometry
  - Point source release of heat
    (far field plume theory)
  - “Fire induced wind”: $u_e(z) = \alpha \times w(z)$, empirical entrainment factor α
    $(\alpha \sim 0.1-0.2)$



Plume Structure

- Ideal buoyant plume (pool fire config.)

$$b(z) = C_b \times z$$

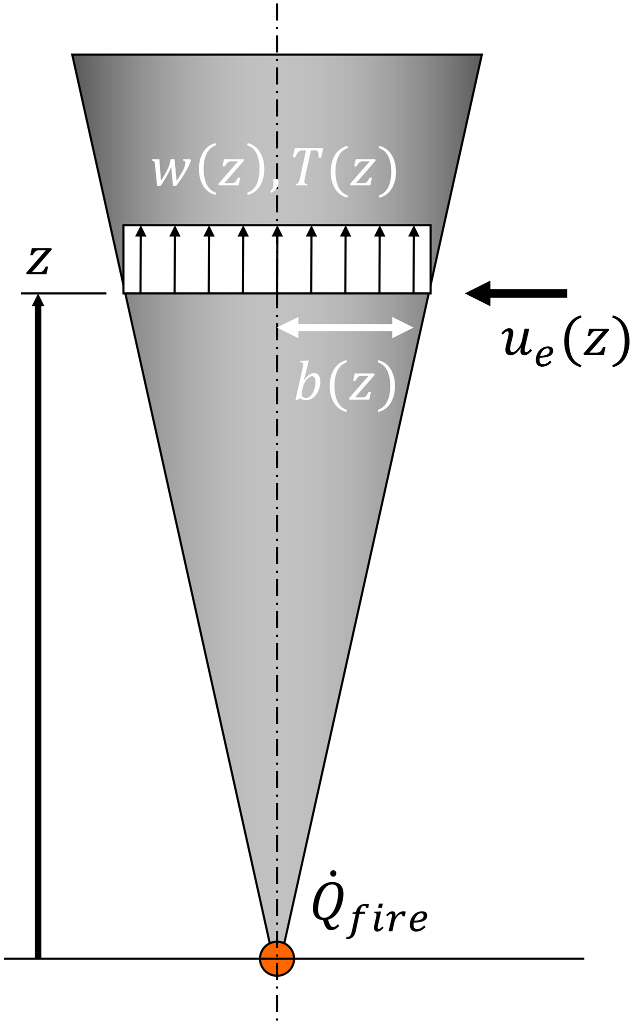
$$w(z) = C_w \times \dot{Q}_{fire}^{1/3} \times z^{-1/3}$$

$$\frac{T(z) - T_{air}}{T_{air}} = C_T \times \dot{Q}_{fire}^{2/3} \times z^{-5/3}$$

$$\dot{m}_z(z) = \rho(\pi b^2)w = C_{\dot{m}} \times \dot{Q}_{fire}^{1/3} \times z^{5/3}$$

$$C_b = \frac{6\alpha}{5}; \quad C_w = (\frac{25}{48\pi\alpha^2} \frac{g}{(\rho c_p T)_{air}})^{1/3}$$

$$C_T = \frac{1}{\pi C_b^2 C_w (\rho c_p T)_{air}}; \quad C_{\dot{m}} = \frac{1}{C_T (c_p T)_{air}}$$

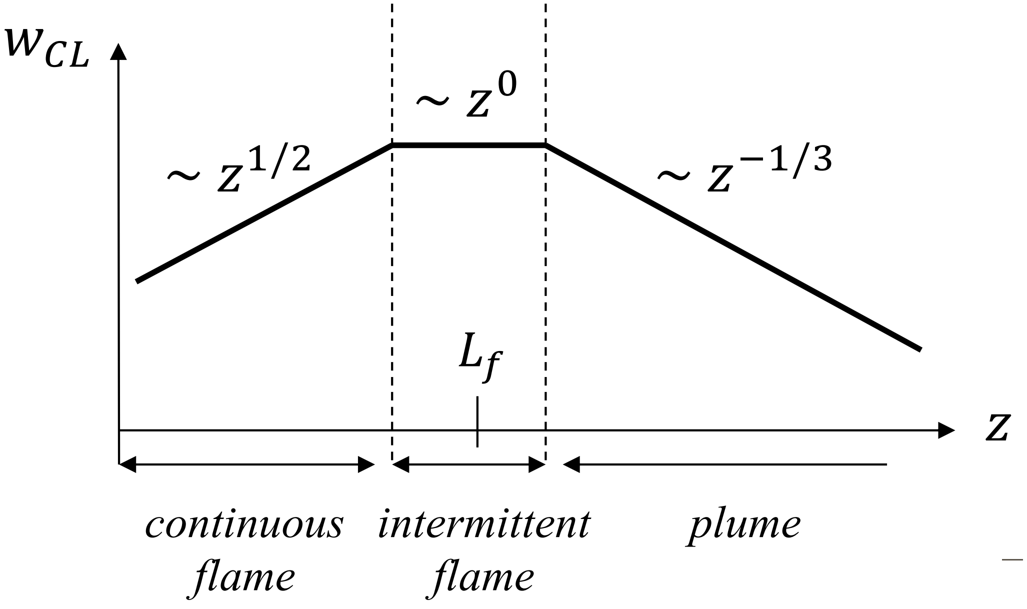


Plume Structure

- McCaffrey correlations (pool fire config.)
  - Description of near-field/flame region as well as far-field/plume region

$$\left|\begin{array}{ll} w_{CL}(z) = 6.8\times z^{1/2}, & z < (0.08\times\dot{Q}_{fire}^{2/5}) \\ w_{CL}(z) = 1.9\times\dot{Q}_{fire}^{1/5}, & (0.08\times\dot{Q}_{fire}^{2/5}) \leq z \leq (0.2\times\dot{Q}_{fire}^{2/5}) \\ w_{CL}(z) = 1.1\times\dot{Q}_{fire}^{1/3}\times z^{-1/3}, & (0.2\times\dot{Q}_{fire}^{2/5}) < z \end{array}\right.$$

($\dot{Q}_{fire}$ in kW)

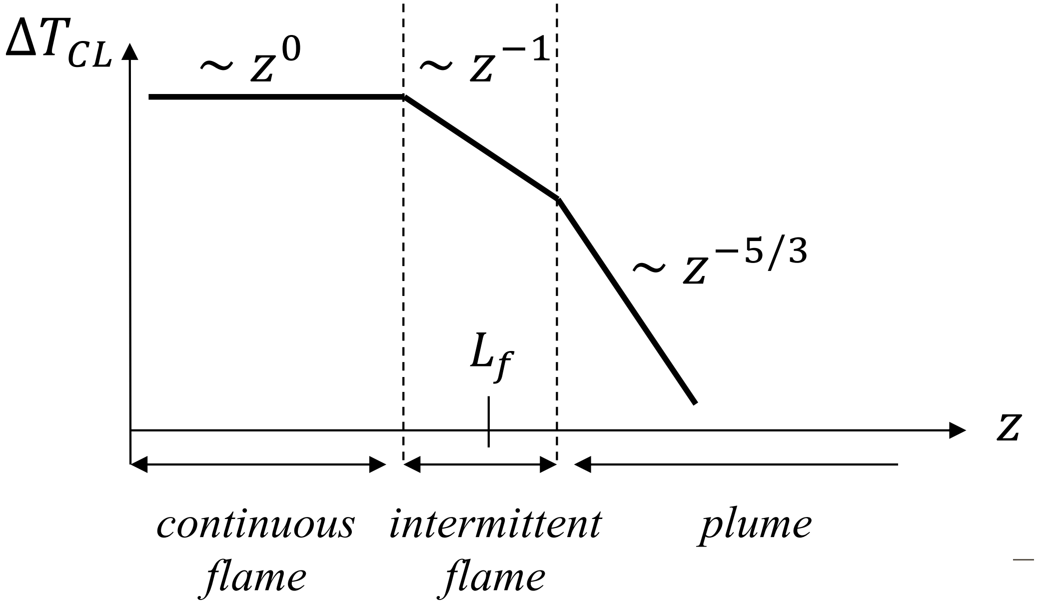


Plume Structure

- McCaffrey correlations (pool fire config.)
  - Description of near-field/flame region as well as far-field/plume region

$$
\begin{cases}
\Delta T_{CL}(z) = T_{CL}(z) - T_{air} = 850, & z < (0.08\times\dot{Q}_{fire}^{2/5}) \\
\Delta T_{CL}(z) = T_{CL}(z) - T_{air} = 67\times\dot{Q}_{fire}^{2/5}\times z^{-1}, & (0.08\times\dot{Q}_{fire}^{2/5}) \leq z \leq (0.2\times\dot{Q}_{fire}^{2/5}) \\
\Delta T_{CL}(z) = T_{CL}(z) - T_{air} = 22\times\dot{Q}_{fire}^{2/3}\times z^{-5/3}, & (0.2\times\dot{Q}_{fire}^{2/5}) < z
\end{cases}
$$

(T_{CL} in K, $\dot{Q}_{fire}$ in kW)

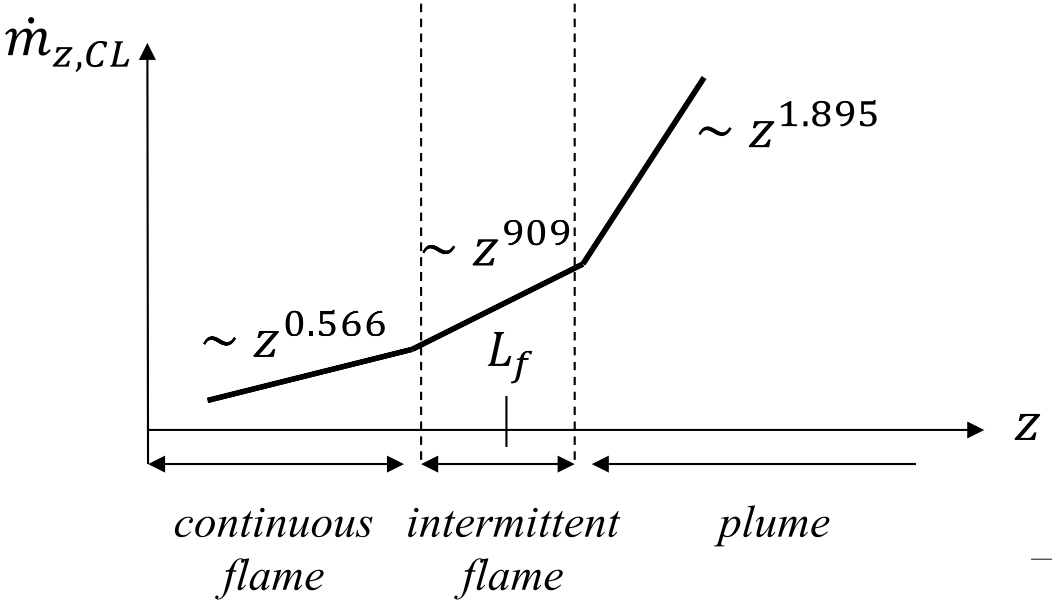


Plume Structure

- McCaffrey correlations (pool fire config.)
  - Description of near-field/flame region as well as far-field/plume region

$$\left|\begin{array}{ll}
\dot{m}_{z,CL}(z) = 0.011\times\dot{Q}_{fire}\times(z/\dot{Q}_{fire}^{2/5})^{0.566}, & z < (0.08\times\dot{Q}_{fire}^{2/5}) \\
\dot{m}_{z,CL}(z) = 0.026\times\dot{Q}_{fire}\times(z/\dot{Q}_{fire}^{2/5})^{0.909}, & (0.08\times\dot{Q}_{fire}^{2/5}) \leq z \leq (0.2\times\dot{Q}_{fire}^{2/5}) \\
\dot{m}_{z,CL}(z) = 0.124\times\dot{Q}_{fire}\times(z/\dot{Q}_{fire}^{2/5})^{1.895}, & (0.2\times\dot{Q}_{fire}^{2/5}) < z
\end{array}\right.$$

($\dot{Q}_{fire}$ in kW)



Flame Structure

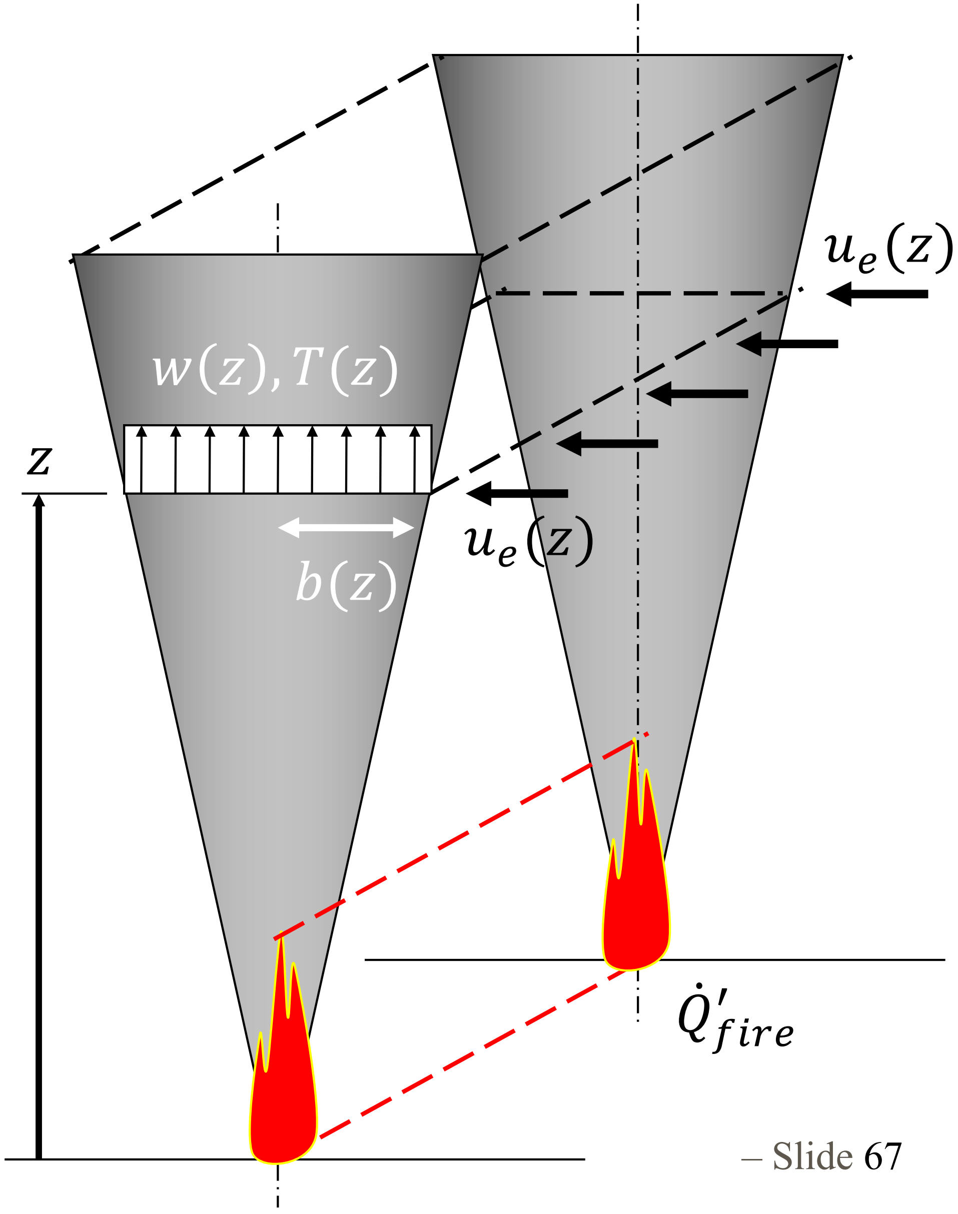
- Mean flame height (line fire configuration)
  - 2D plane geometry
  - Fire intensity: HRR per unit length of fireline [W/m], $\dot{Q}'_{fire}$
  - Buoyant flames

(Byram 1959) (Yuan & Cox 1996)

$$L_f = 0.0775 \times (\dot{Q}'_{fire})^{0.46}$$

$$L_f = 0.034 \times (\dot{Q}'_{fire})^{2/3}$$

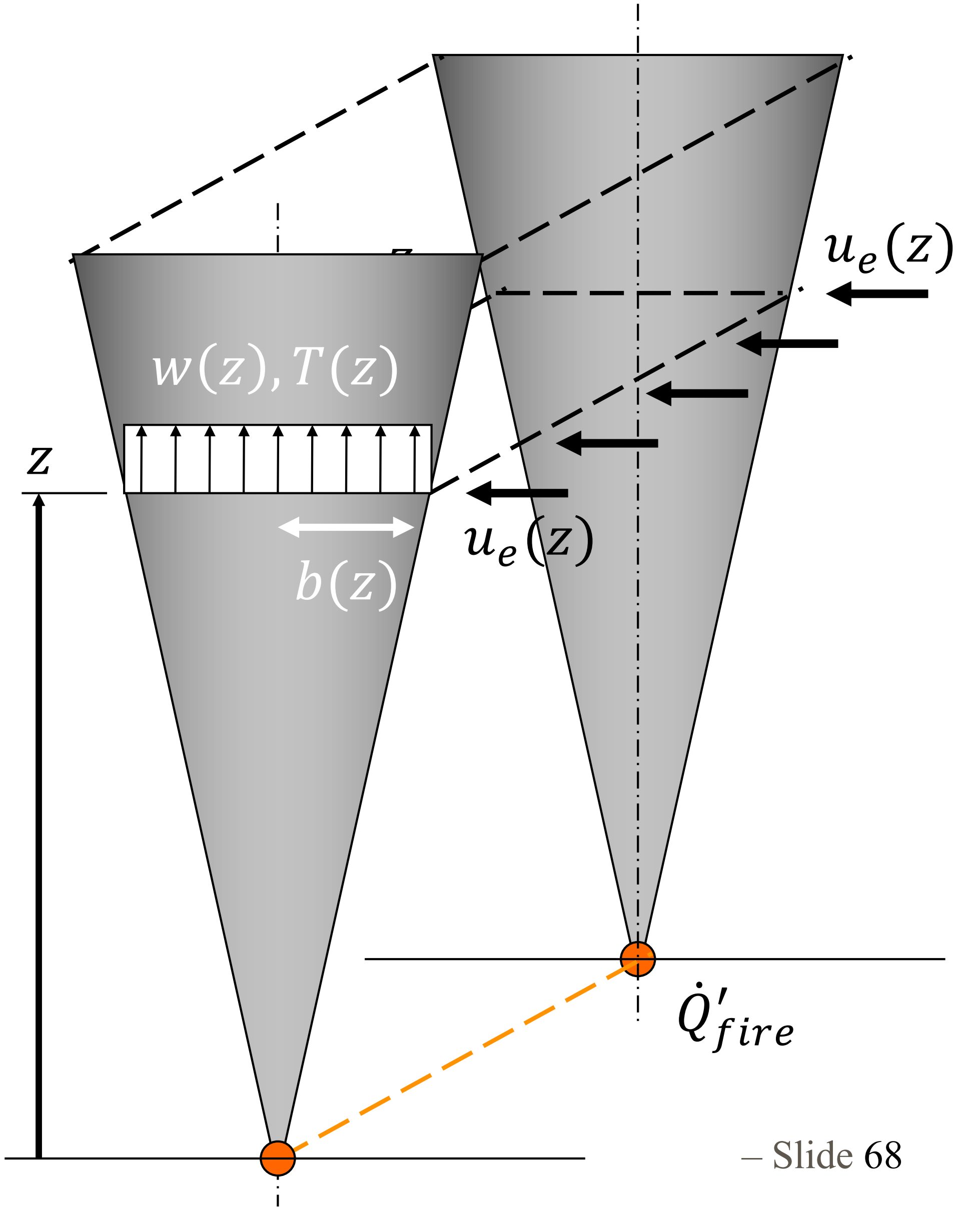
($\dot{Q}'_{fire}$ in kW/m)



Plume Structure

- Ideal buoyant plume (line fire configuration)
  - Two-dimensional plane geometry
  - Line source release of heat (far field plume theory)
  - "Fire induced wind": $u_e(z) = \alpha \times w(z)$, empirical entrainment factor α

    $(\alpha \sim 0.1\text{–}0.2)$



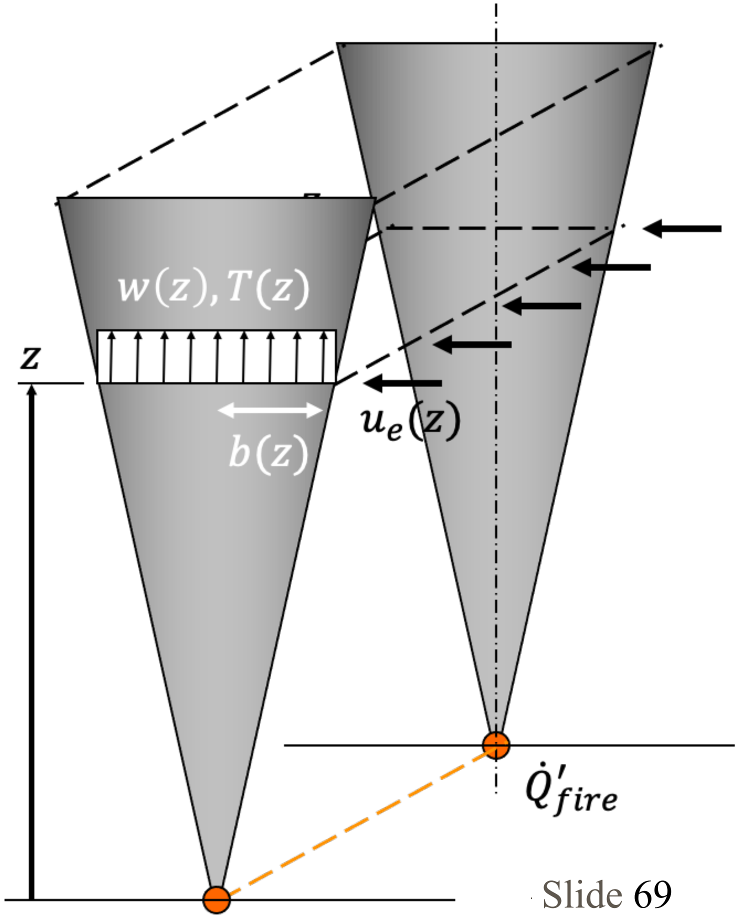
Plume Structure

- Ideal buoyant plume (line fire configuration)

$$\left|\begin{aligned}
&b(z) = C_b \times z \\
&w(z) = C_w \times (\dot{Q}'_{fire})^{1/3} \\
&\frac{T(z) - T_{air}}{T_{air}} = C_T \times (\dot{Q}'_{fire})^{2/3} \times z^{-1} \\
&\dot{m}'_z(z) = \rho(2b)w = C_{\dot{m}'} \times (\dot{Q}'_{fire})^{1/3} \times z
\end{aligned}\right.$$

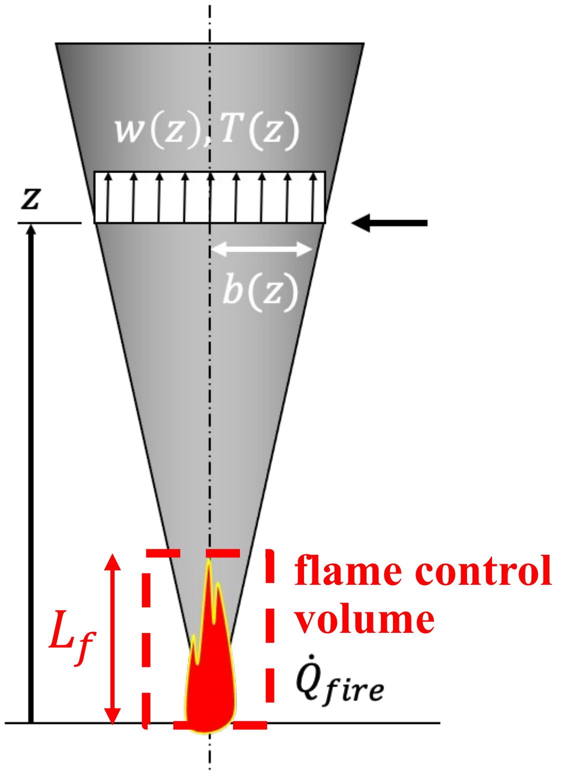
$$C_b = \alpha; \quad C_w = \left(\frac{1}{2\alpha}\frac{g}{(\rho c_p T)_{air}}\right)^{1/3}$$

$$C_T = \frac{1}{2 C_b C_w (\rho c_p T)_{air}}; \quad C_{\dot{m}'} = \frac{1}{C_T (c_p T)_{air}}$$



Flame Structure

- Importance of air entrainment, $u_e(z)$ (fire-induced/external wind)
  - Pool fire configuration
  - Global equivalence ratio for the flame region



$$\phi = \frac{(m_F^i/m_{O_2}^i)}{(MW_F/(v_{O_2}MW_{O_2}))} = r_S(\frac{m_F^i}{m_{O_2}^i})$$

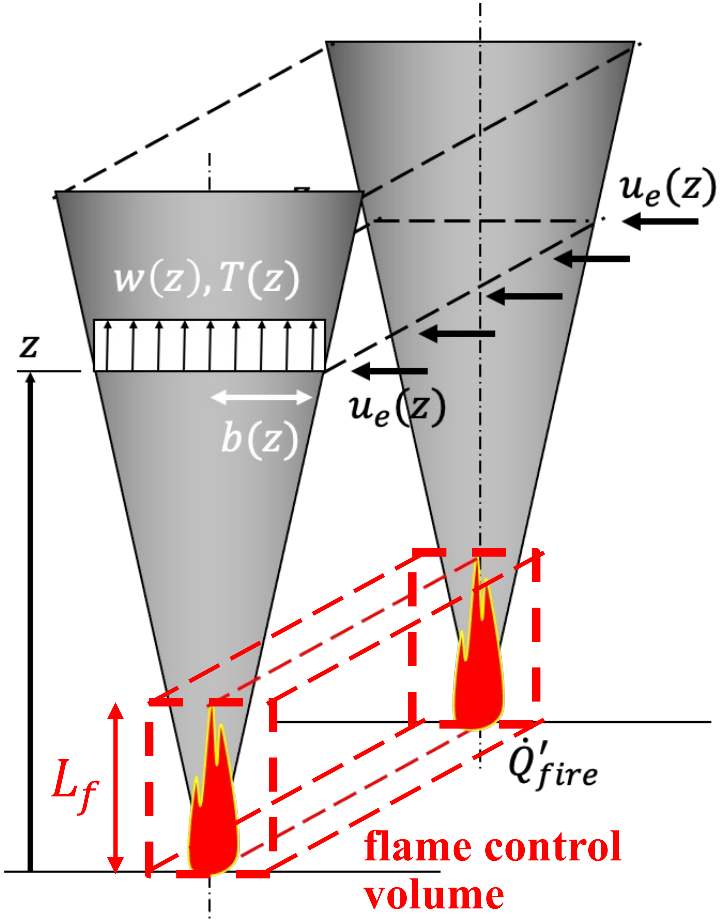
$$\Rightarrow \phi \approx r_S \times (\frac{\dot{m}_{fuel}}{\dot{m}_{air} \times Y_{O_2,air}})$$

$$\Rightarrow \phi \approx r_S \times (\frac{\dot{m}_{fuel}}{\int_0^{L_f} (\rho u_e \times 2\pi b)\, dz \times Y_{O_2,air}}) \longrightarrow \boxed{\phi \approx 0.1}$$

over-ventilated fire

Flame Structure

- Importance of air entrainment, $u_e(z)$ (fire-induced/external wind)
  - Line fire configuration
  - Global equivalence ratio for the flame region



$$\phi = \frac{(m_F^i/m_{O_2}^i)}{(MW_F/(\nu_{O_2} MW_{O_2}))} = r_S(\frac{m_F^i}{m_{O_2}^i})$$

$$\Rightarrow \phi \approx r_S \times (\frac{\dot{m}_{fuel}}{\dot{m}_{air} \times Y_{O_2,air}})$$

$$\Rightarrow \phi \approx r_S \times (\frac{\dot{m}'_{fuel}}{\int_0^{L_f} (\rho u_e \times 2)\, dz \times Y_{O_2,air}}) \longrightarrow \boxed{\phi \approx 0.1}$$

over-ventilated fire

Flame Structure

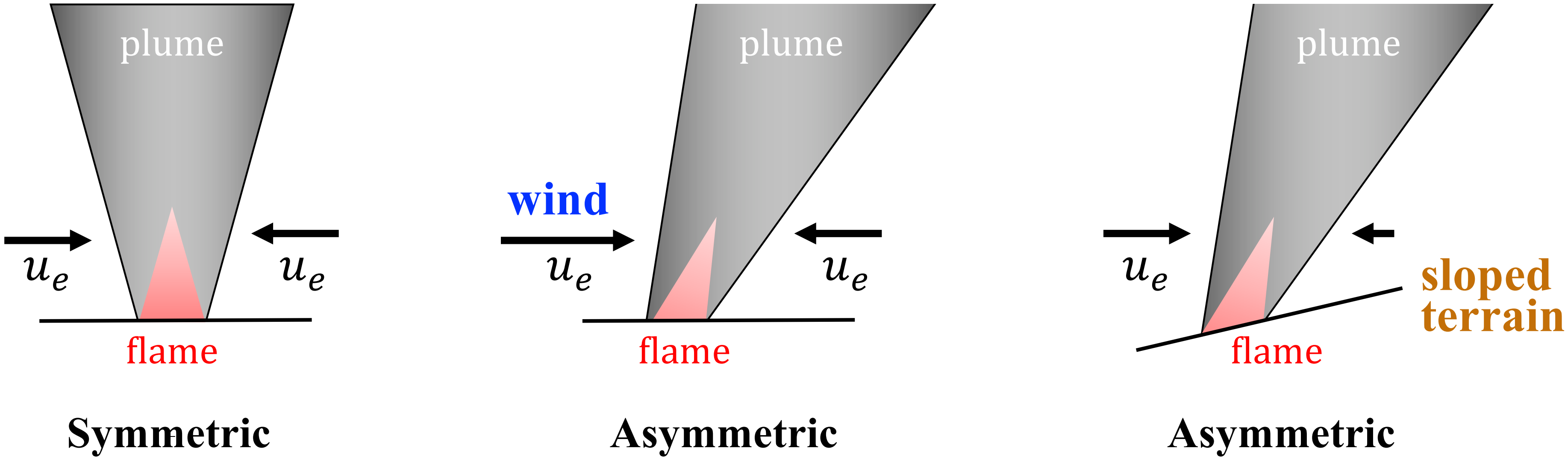
- Importance of air entrainment
  - Fuel package experiments: wood cribs (S. McAllister & M. Finney, *Fire Technology* 2015)

Under-ventilated wood crib
(flame stabilized on the outer edge of the crib, $\phi > 1$)

Over-ventilated wood crib
(flames stabilized around individual sticks, $\phi < 1$)

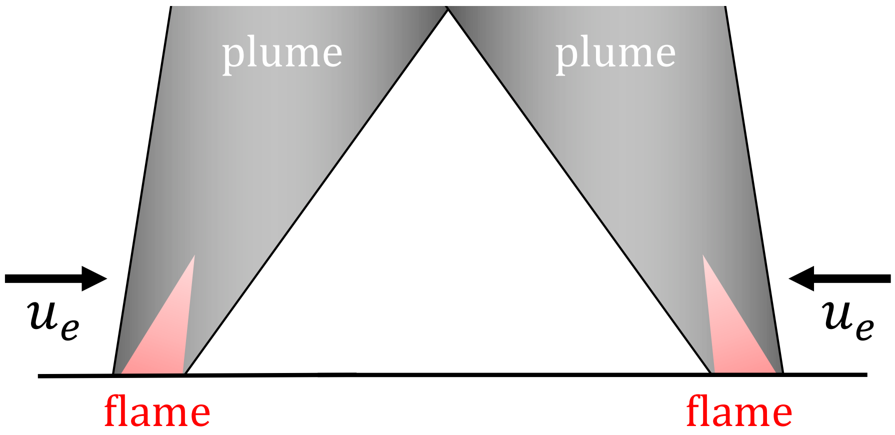
Flame Structure

- Importance of air entrainment
  - Asymmetry in the entrained air flow will change the flame geometry

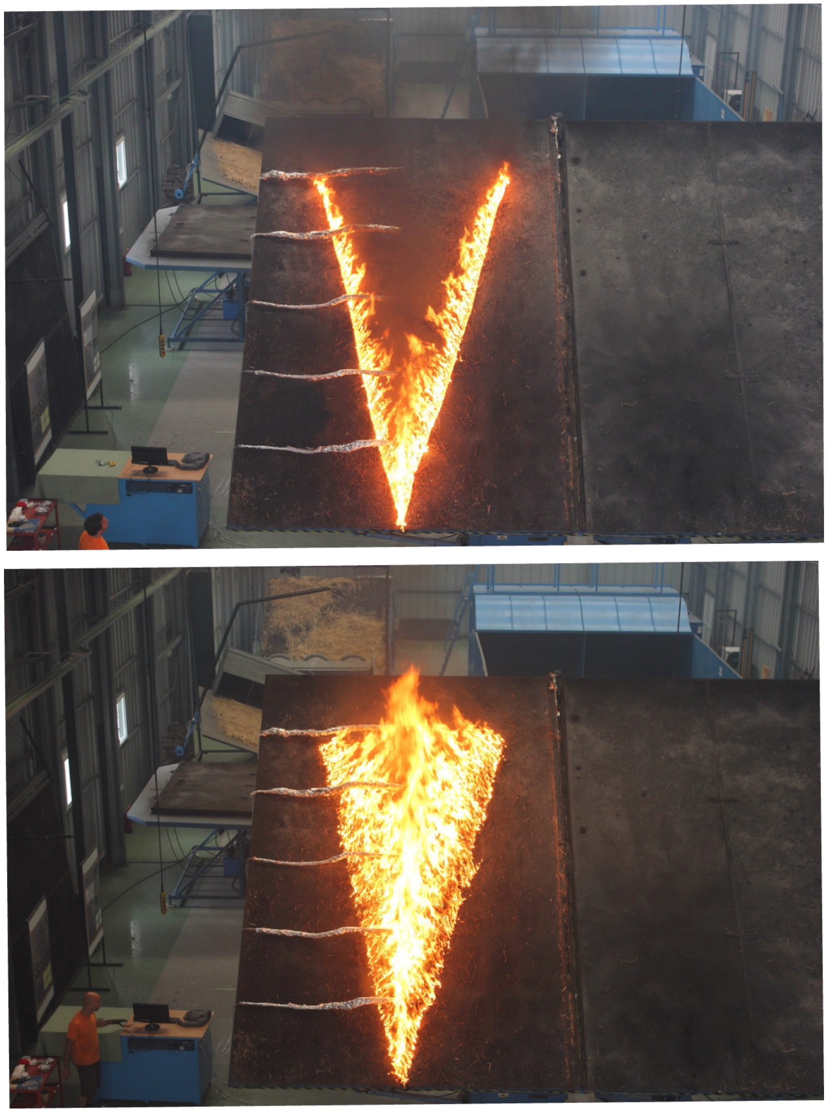


Flame Structure

- Importance of air entrainment
  - Asymmetry in the entrained air flow will change the flame



Merging of fire fronts



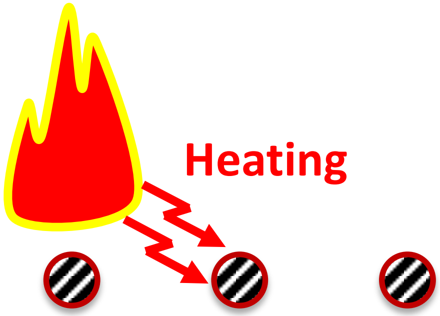
Raposo *et al.*, *Intl. Journal of Wildland Fire* 2018

Outline

- Introduction
- Pyrolysis and Combustion
- Combustion: the Thermodynamics Viewpoint
- Combustion Chemistry
- Flame Structure
- Flame Effects

Flame Effects

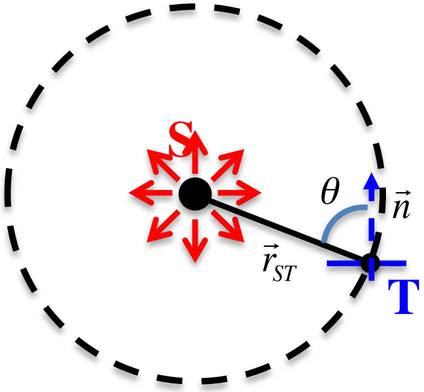
- Hazards
  - Transport of combustion heat and mechanisms for further flame spread



- Radiative heat transfer – flame radiation and/or particle-to-particle radiation
- Convective heat transfer – flame/plume contact
- Transport of firebrands – spotting

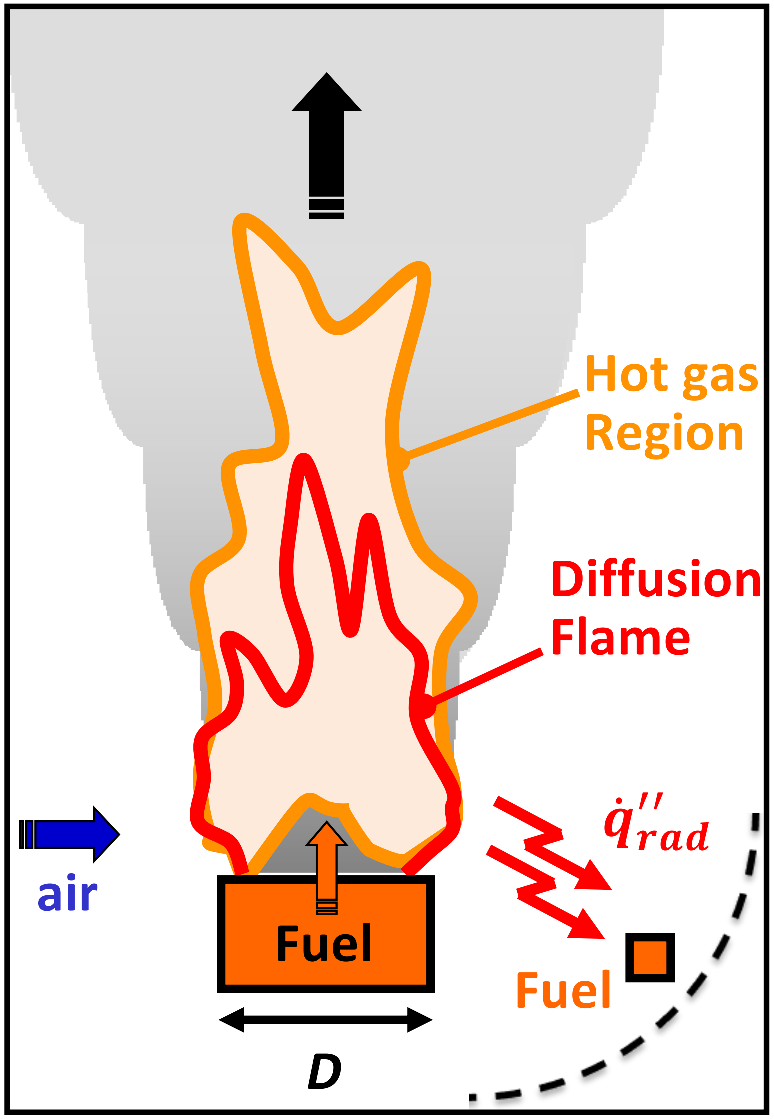
Flame Effects

- Hazards
  - Mechanisms for flame spread
  - Radiative heat transfer
    - **Critical exposure conditions for spread**: $\dot{q}''_{rad} > CHF$ to achieve ignition conditions
    - Point source model



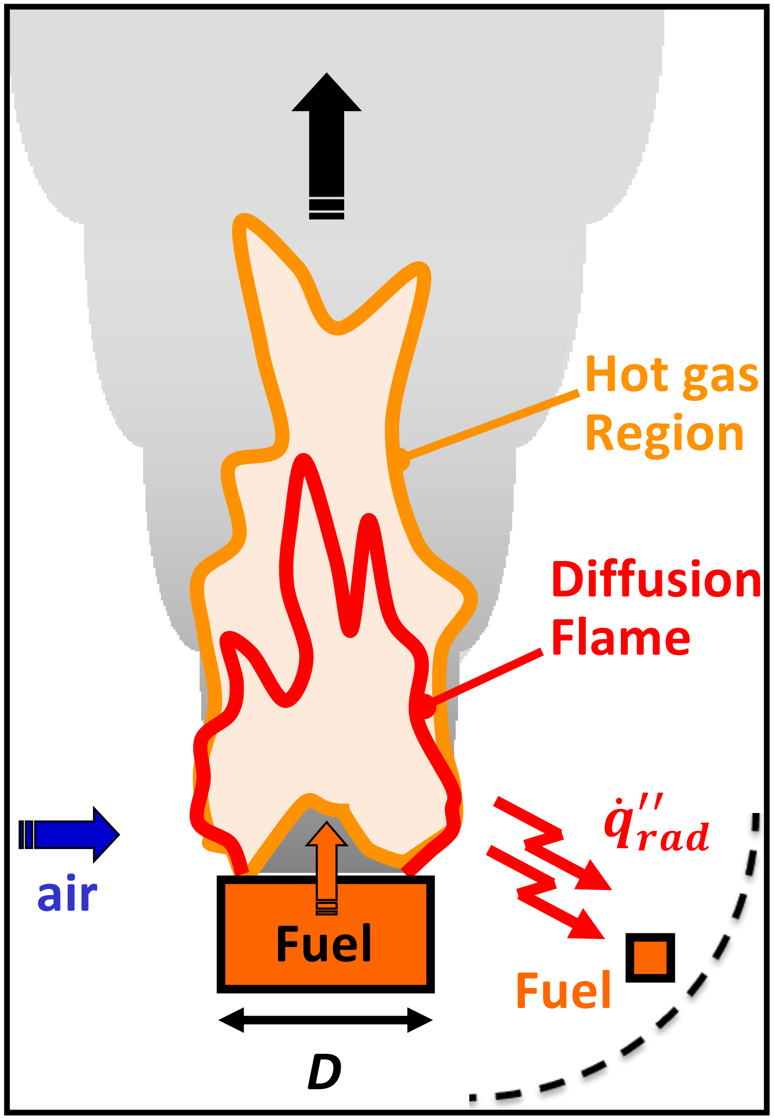
$$\dot{q}''_{rad} = \frac{(\chi_{rad} \times \dot{Q}_{fire})}{(4\pi d^2)} \times \cos(\theta)$$

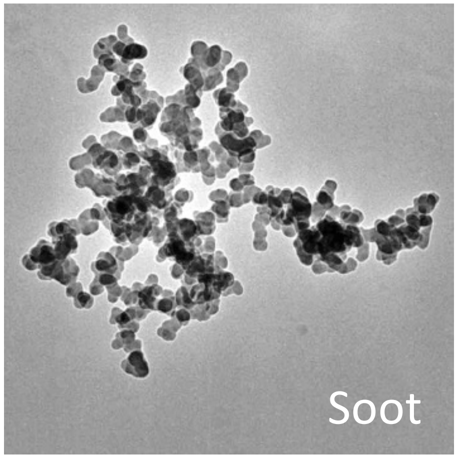
$$\chi_{rad} = (\dot{Q}_{rad}/\dot{Q}_{fire}) \sim 0.3$$



Flame Effects

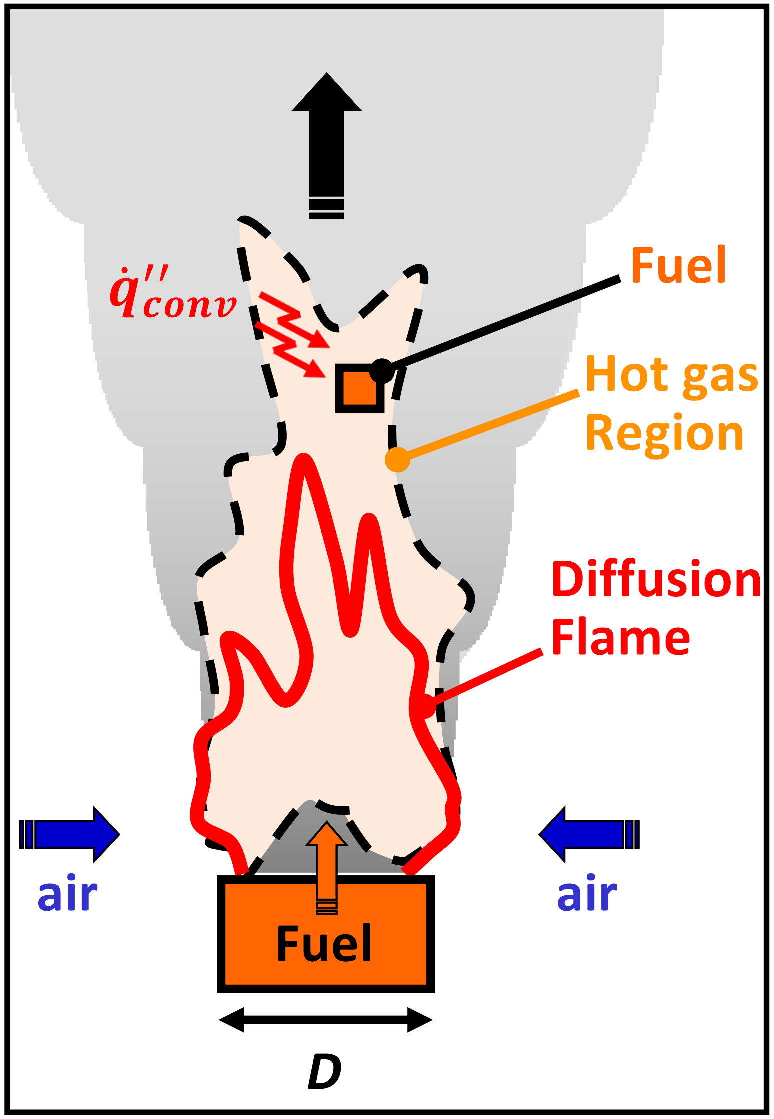
- Hazards
  - Mechanisms for flame spread
  - Radiative heat transfer
    - Radiative power of the flame/plume (*i.e.* value of χ_{rad}) determined by chemical composition of the gas: CO_2, H_2O, and soot particles





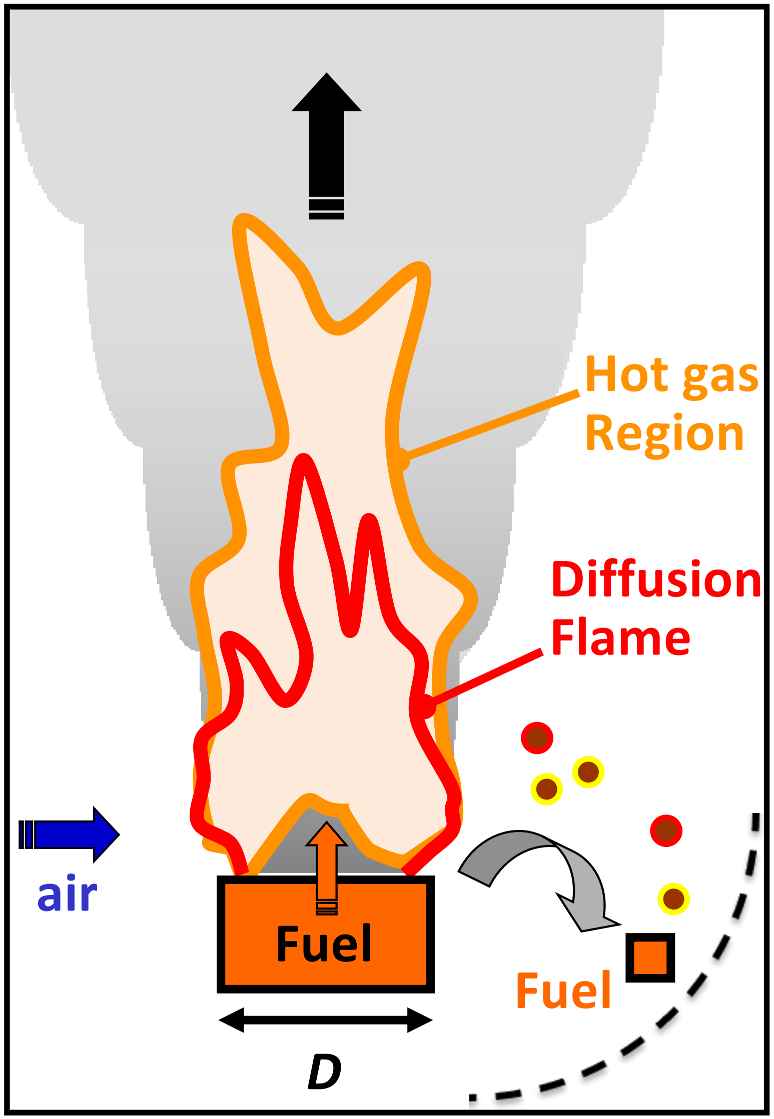
Flame Effects

- Hazards
  - Mechanisms for flame spread
  - Convective heat transfer
    - **Critical exposure conditions for spread**: $T > T_{pyro} \sim 600\text{ K}$ to achieve ignition conditions



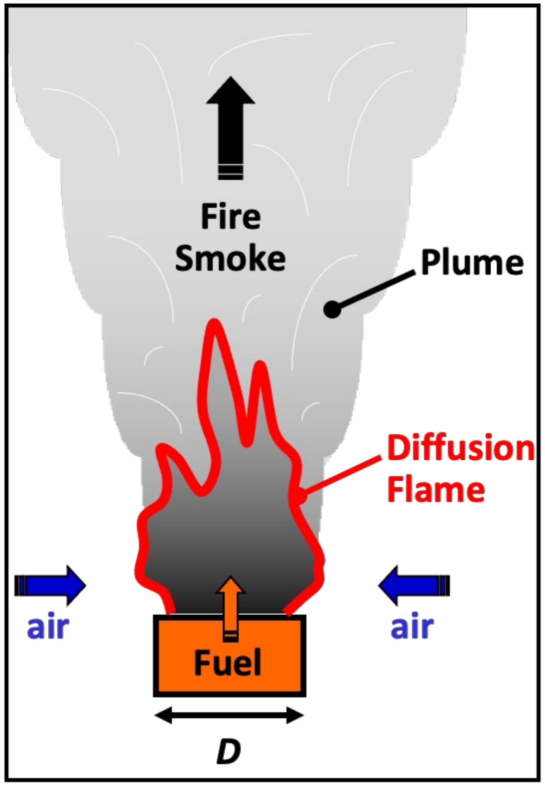
Flame Effects

- Hazards
  - Mechanisms for flame spread
  - Transport of firebrands
    - **Critical exposure conditions for spread**: $\dot{m}''_{embers} > threshold$ to achieve ignition conditions



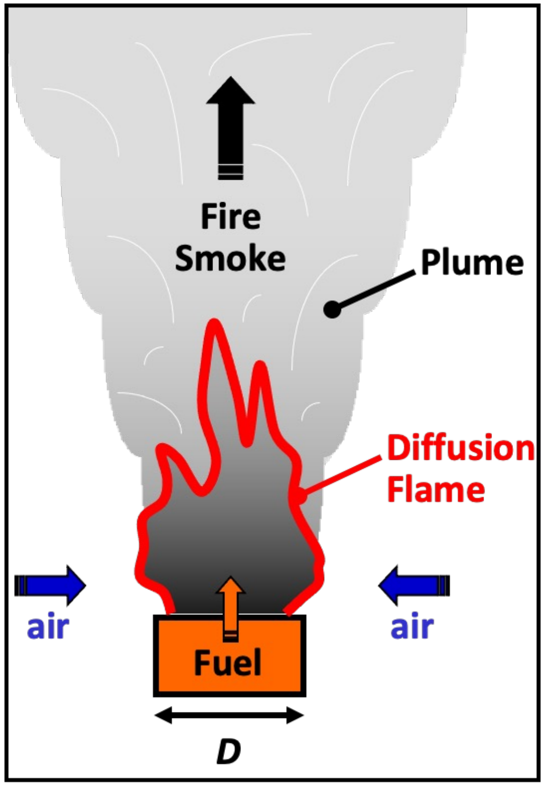
Flame Effects

- Hazards
  - Emissions of chemical species that may have a negative impact on human/environment/climate systems
    - Fire smoke contains toxic chemical species: *CO*, *HCN*, fine particulate matter (PM2.5), *etc*
    - Fire smoke contains atmospheric pollutants: *CO*, NO/NO_2, *PAH*s, particulate matter, *etc*
    - Fire smoke contains greenhouse gases: CO_2, CH_4, N_2O, *etc*



Flame Effects

- Hazards
  - Emissions of chemical species that may have a negative impact on human/environmental health
    - **Fire-smoke-exposed region**: not well understood
      - High-temperature combustion chemistry
      - Plume dynamics
      - Low-temperature atmospheric chemistry



Conclusion

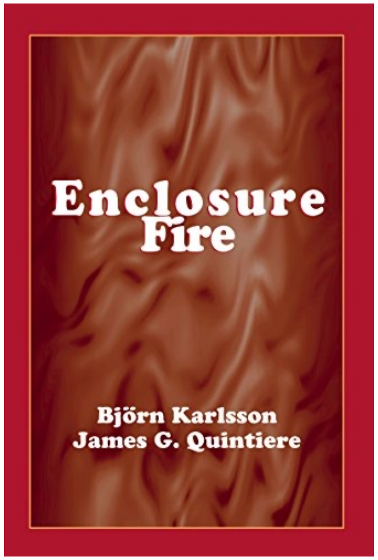
- The basic physical concepts used to describe combustion phenomena have been introduced
  - Scope of discussion
    - Solid fuel (vegetation biomass)
    - Flaming combustion
    - Non-premixed flame
    - Buoyancy-driven flame
    - Turbulent flame
    - No wind and flat terrain conditions
    - Non-spreading flame

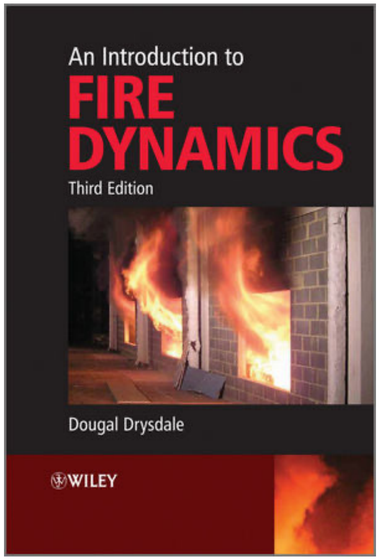
Conclusion

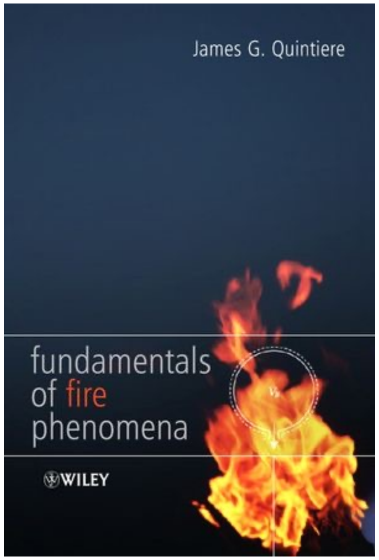
- Flame structure
  - Global combustion equation
  - Over-ventilated vs under-ventilated fire conditions
  - Combustion chemistry (Arrhenius model); infinitely fast chemistry assumption; rate of combustion controlled by mixing of $Fuel/O_2$; flame structure described by mixture fraction variable
  - Flame height as the characteristic length scale of the combustion region; correlations for flame height
  - Mechanisms for flame spread: convective heat transfer; radiative heat transfer (importance of soot particles); firebrands
  - Emissions of chemical species: toxic chemical species, atmospheric pollutants, greenhouse gases

Further Reading

- Fundamentals of compartment fire dynamics
  - Karlsson B., Quintiere J.G., *Enclosure Fire Dynamics*, CRC Press LLC, 2000
  - Drysdale D., *An Introduction to Fire Dynamics*, 3rd , Wiley, 2011
  - Quintiere J.G., *Fundamentals of Fire Phenomena*, Wiley, 2006







Further Reading

- Fundamentals of wildland fire behavior
  - Finney M., McAllister S., Grumstrup T., Forthofer, J., *Wildland Fire Behavior - Dynamics, Principles and Processes*, CSIRO Publishing, 2021