Modeling of Turbulent Wall Fires

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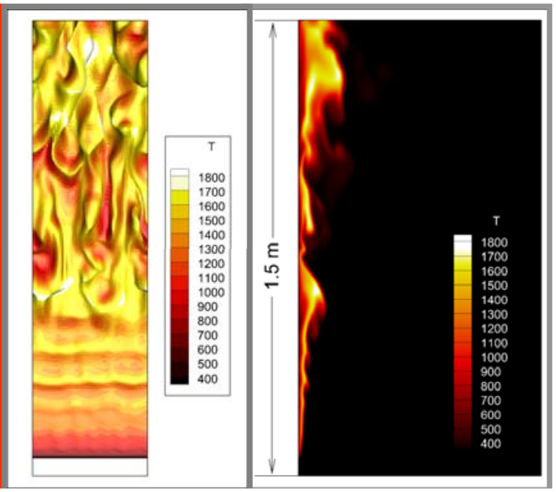


Modeling of Turbulent Wall Fires

- Outline
  - **Overview of Compartment Fire Dynamics**
    - **Multi-physics problem**
    - **Role of wall flames**
  - Laminar Wall Fires
    - Analytical solution of a canonical wall flame problem – the Emmons problem (non-spreading; constant wall temperature; no thermal radiation)
  - Turbulent Wall Fires
    - Large eddy simulation of a canonical wall fire problem (non-spreading; vertical wall)

Compartment Fires

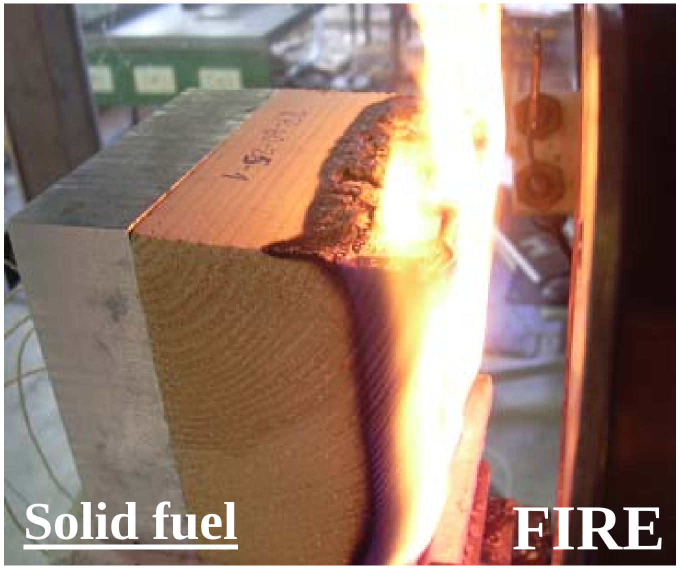
- **Example**: Station Nightclub Fire, 02/20/03, Rhode Island
  - *Sequence of events*: music band on stage using pyrotechnics; ignition of the insulation foam lining walls and ceiling around stage; rapid fire spread over dance floor (no sprinkler system); egress blocked by crowding at main entrance; 100 dead people
  - Technical investigation conducted by the National Institute of Standards and Technology (Final Report published in June 2005)

Compartment Fires

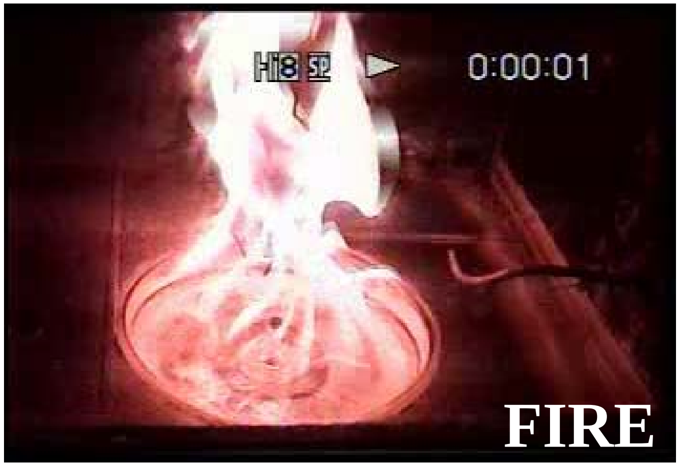
- **Example**: Station Nightclub Fire, 02/20/03, Rhode Island

Compartment Fires

- **Main features**: fire is an unusual combustion process in which the fuel supply corresponds to a large list of flammable objects and materials, usually in solid or liquid form
  - solids (wood, plastics, foams, fabric, linings, *etc*)
  - liquids (engine fuels, LNG, melted solids, *etc*)



Solid fuel

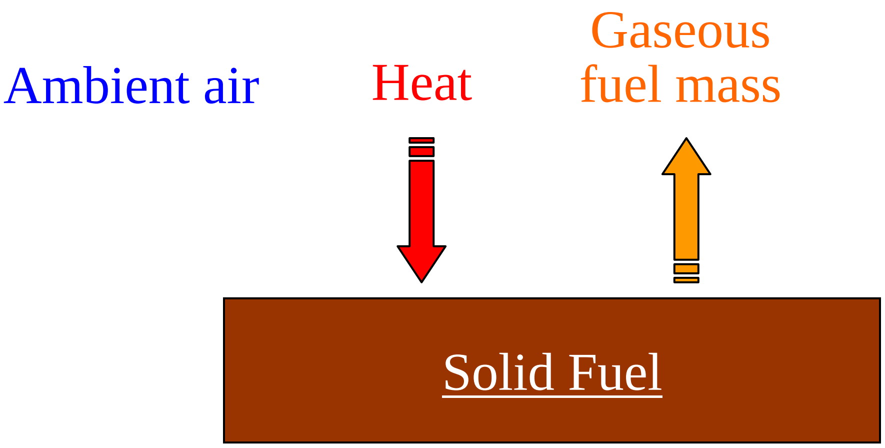


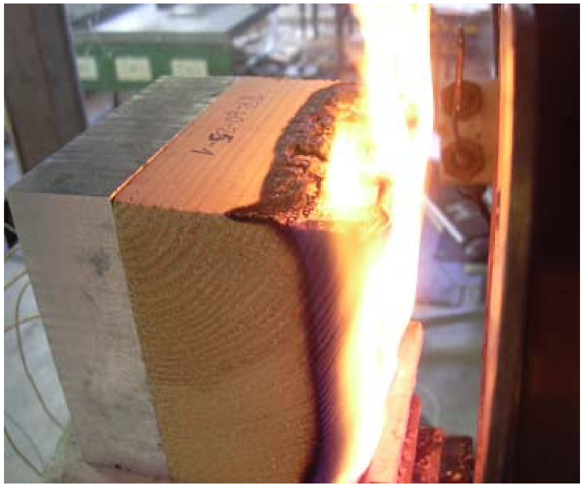
Liquid fuel

Gaseous fuel

Compartment Fires

- **Main features**: fire is an unusual combustion process in which the fuel supply is unknown
  - 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 (typically 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.

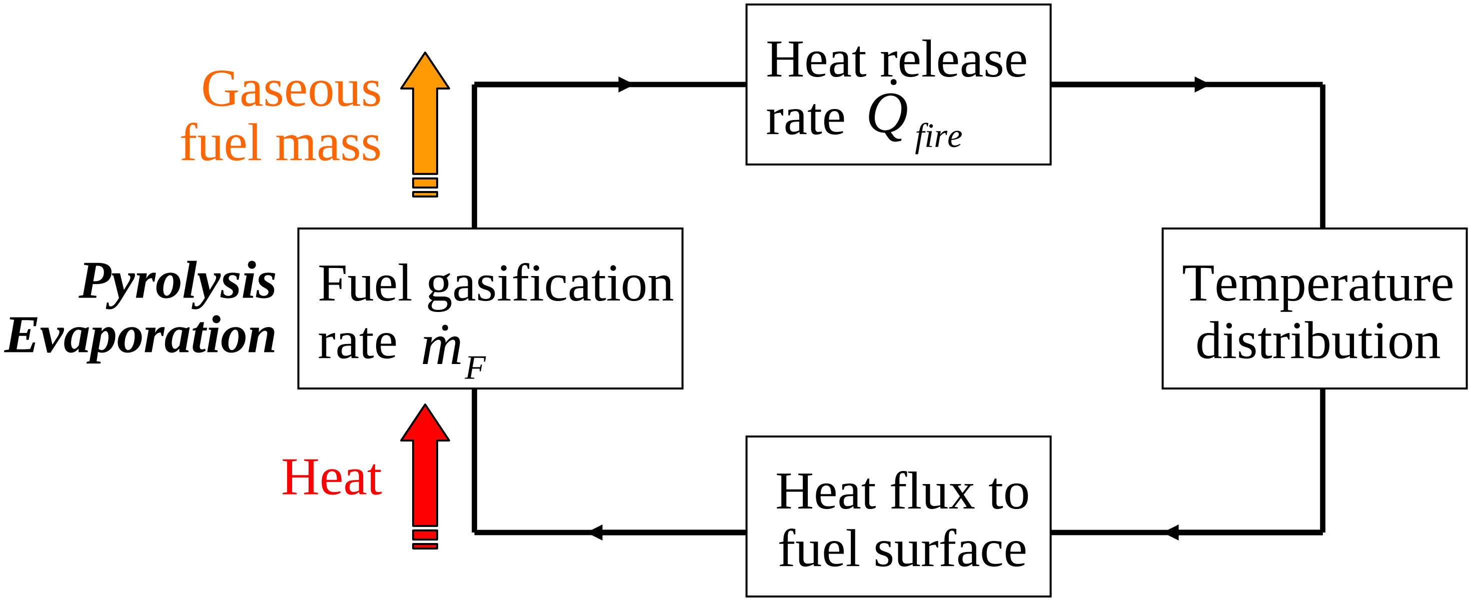

Ambient air
Heat
Gaseous fuel mass
Solid Fuel



Compartment Fires

- **Main features**: fire is an unusual combustion process in which the fuel supply is unknown
  - ➢ Typical production of flammable vapors in a fire:
    - The fuel gasification rate is determined by a heat feedback mechanism
      - 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

$$\boxed{\dot m''_F \Delta H_{pyro} \approx \dot q''_{net}}$$



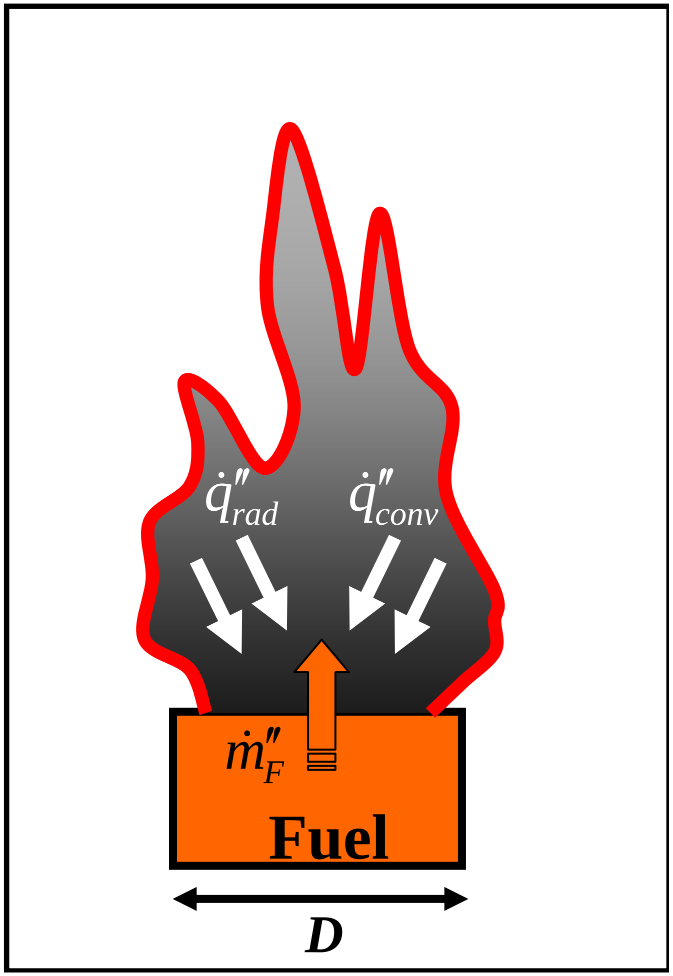
Compartment Fires

- **Main features**: fire is an unusual combustion process in which the fuel supply is unknown
  - Typical production of flammable vapors in a fire:
  - The gas-to-solid thermal feedback controls the fuel mass loss rate and thereby the overall fire size

    The fraction of energy fed back to the fuel source is typically a small fraction of the energy released by combustion:

$$\chi_{feedback} \approx \frac{\Delta H_{pyro}}{\Delta H_{comb}} \approx 0.01 - 0.10$$

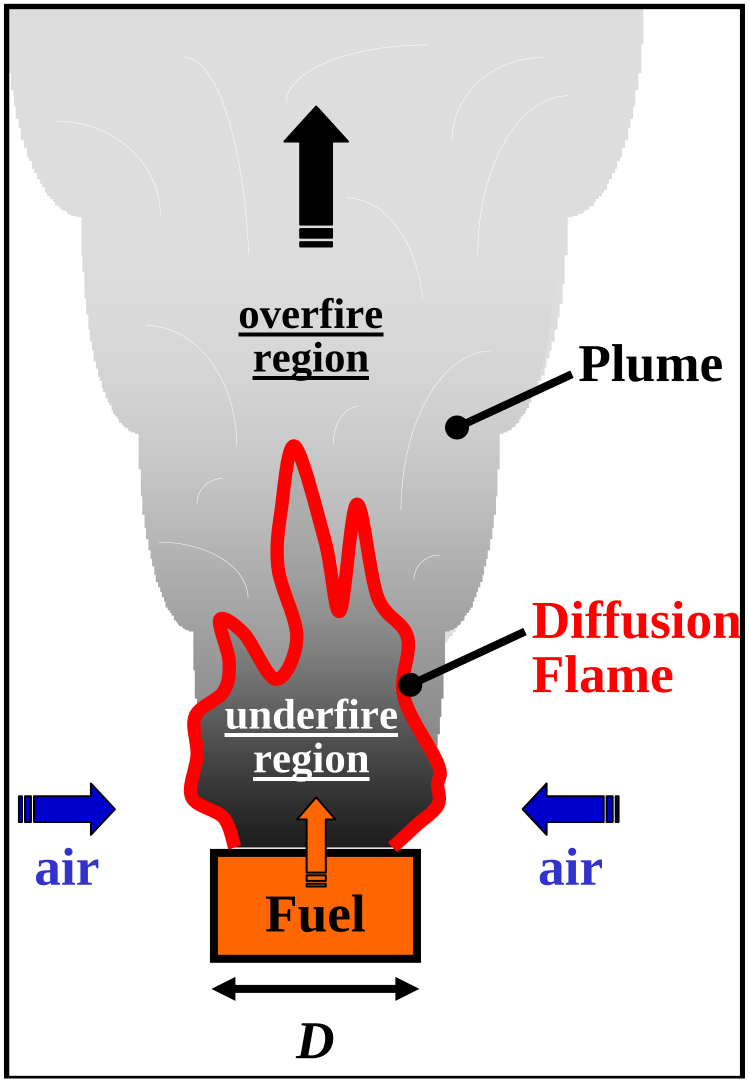
  - The thermal feedback has 2 components corresponding to convective and radiative heat transfer



Compartment Fires

- **Main features**: fire is a buoyancy-driven, relatively-slow, non-premixed combustion process
  - *Example*: pool fire configuration
    - Fuel source velocity is small (a few cm/s)
    - Buoyancy effects accelerate the flow up to several m/s; flow regime corresponds to moderate turbulence intensities
    - Flame corresponds to diffusion combustion and to a thin reaction sheet where fuel and air meet in stoichiometric proportions
    - Slow velocities and long residence times promote soot formation and radiant losses

$$\chi_{rad} = (\dot{Q}_{rad} / \dot{Q}_{comb}) \sim 35\%$$



Compartment Fires

- **Main features**: fire is a buoyancy-driven, relatively-slow, non-premixed combustion process
  - Example: pool fire configuration
    - Flame height scales with Froude number

$$Fr_F = \frac{u_F (Z_{st})^{3/2}}{[(\frac{\Delta T_f}{T_\infty}) g d_F (\frac{\rho_F}{\rho_\infty})^{1/2}]^{1/2}}$$

$$\dot{Q}^* = \frac{\dot{Q}_{comb}}{\rho_\infty c_{p,\infty} T_\infty \sqrt{g d_F}\, d_F{}^2} \sim Fr_F$$

$$\boxed{\dot{Q}^* \sim Fr_F}$$

Compartment Fires

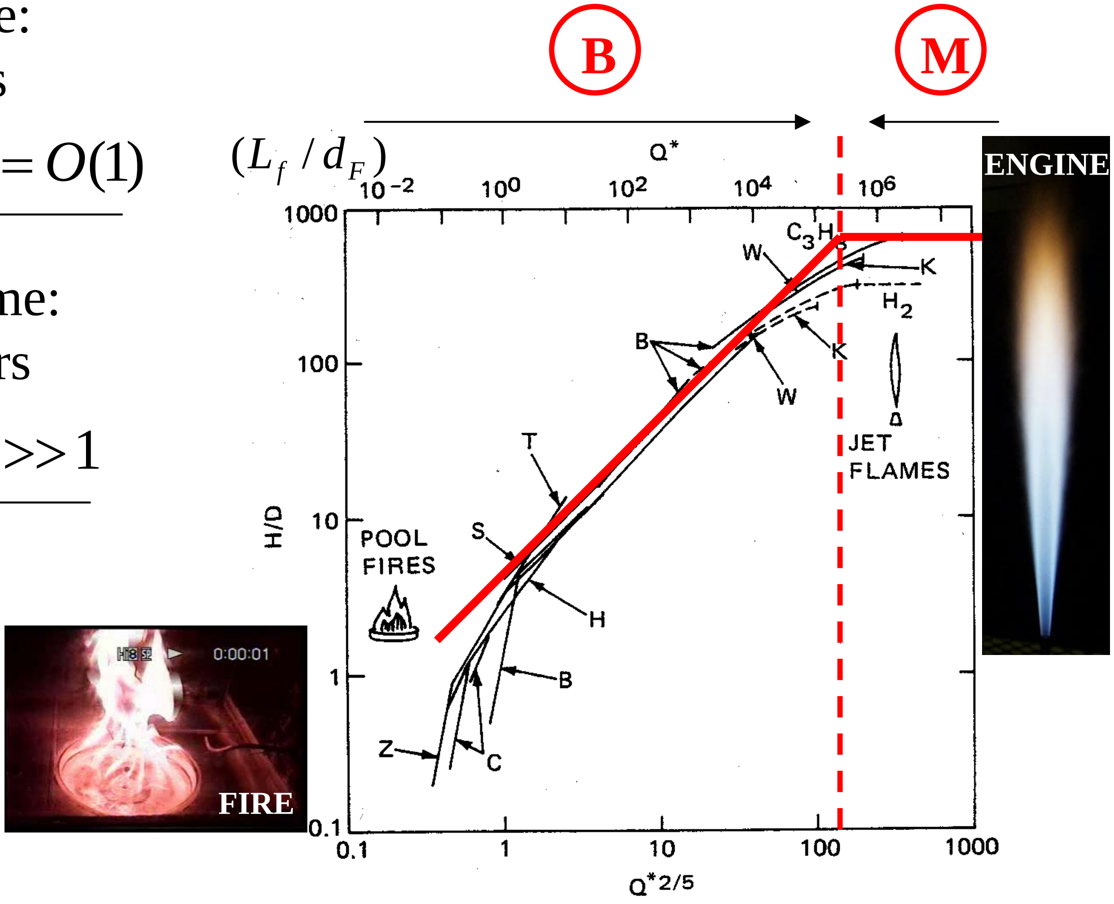
- **Main features**: fire is a buoyancy-driven, relatively-slow, non-premixed combustion process
  - Example: pool fire configuration

B *Buoyancy*-driven flame regime:
low velocities, large diameters

$$\dot{Q}^* < 10^5,\ Fr_f < 5,\ \underline{(L_f / d_F) = O(1)}$$

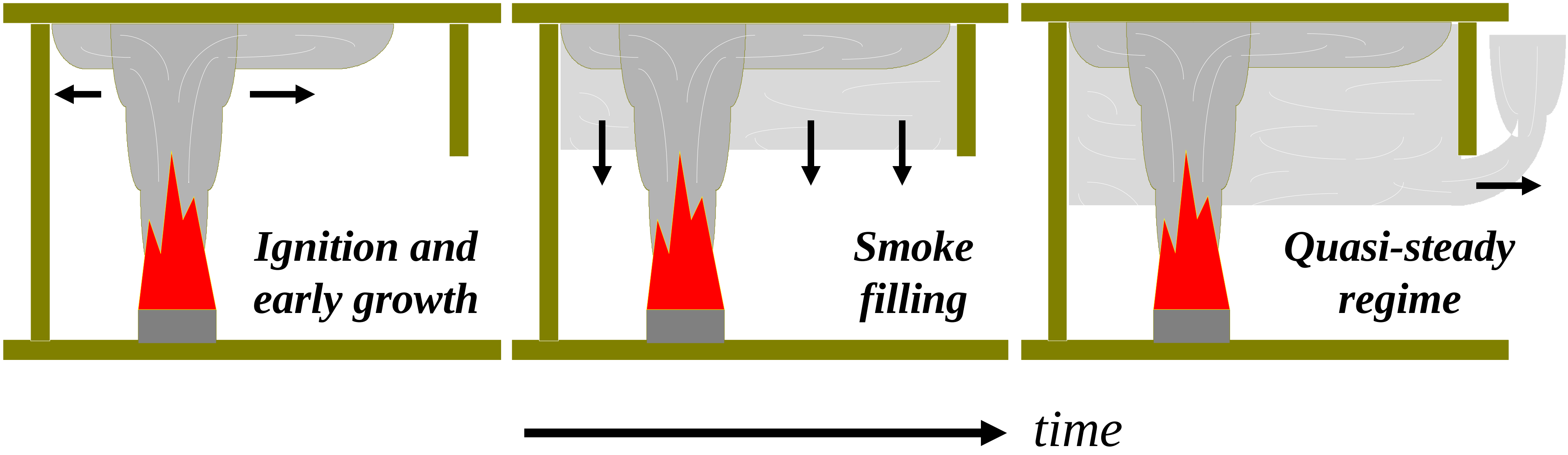
M *Momentum*-driven flame regime:
high velocities, small diameters

$$\dot{Q}^* > 10^5,\ Fr_f > 5,\ \underline{(L_f / d_F) >> 1}$$



Compartment Fires

- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer



Ignition and early growth

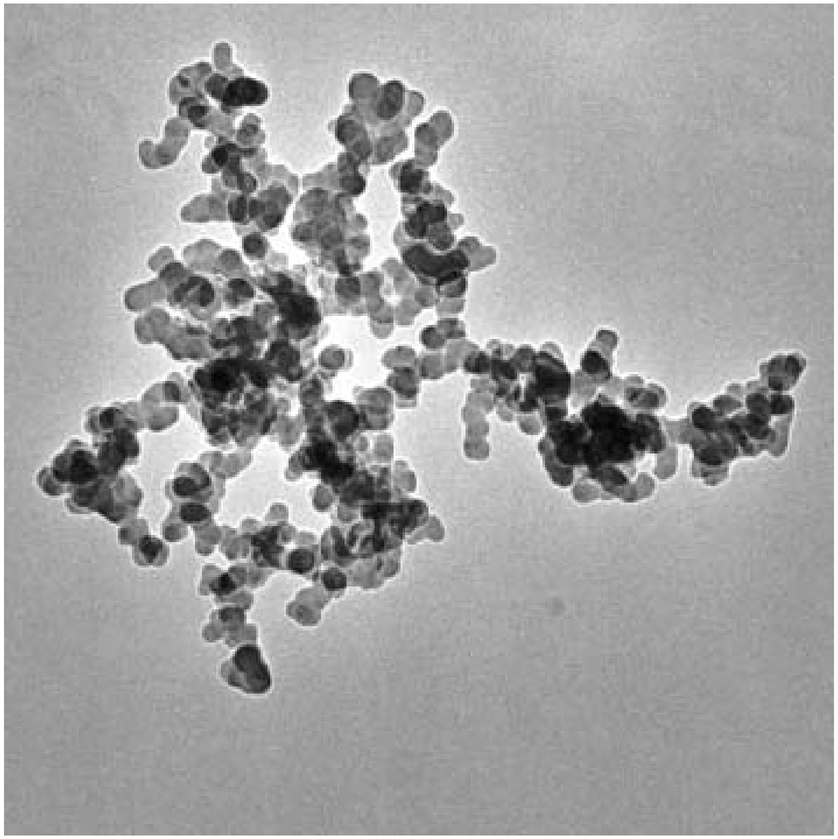
Smoke filling

Quasi-steady regime

time

Compartment Fires

- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
  - Smoke layer composition: hot combustion products mixed with ambient air; depending on fuel type and combustion conditions, may contain significant amounts of soot
  - Soot particles
    - Product of incomplete combustion
    - Phase: solid
    - Chemical composition: primarily made of carbon atoms
    - Particle size distribution: from a few nanometers (10^{-9} m) to several microns (10^{-6} m)
    - Particles geometry: complex shapes (agglomerates of elementary spherical particles)



Compartment Fires

- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
  - ➢ Smoke layer depth: depends on fire size and vent flow rates

Smoke filling and loss of visibility

Accumulation of smoke near ceiling

Fast fire growth and smoke descent to floor

Compartment Fires

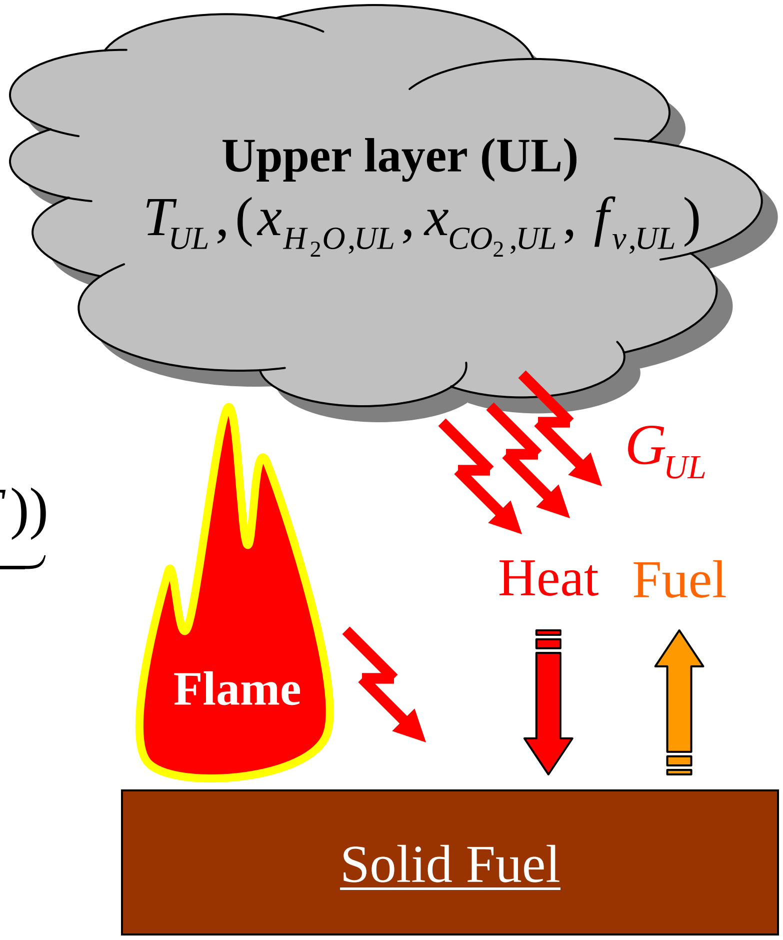
- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
  - Impact of smoke layer: increases (radiation-driven) heat feedback to fuel sources

$$\underbrace{G_{UL}}_{\text{emissive power}} = \underbrace{\varepsilon_{UL}}_{\text{emissivity}} \sigma T_{UL}^{4}$$

$$\underbrace{\varepsilon_{UL}}_{\text{emissivity}} = (1-\exp(-\underbrace{\kappa_{UL}}_{\text{Planck mean absorption coef}} \times \underbrace{d_{UL}}_{\text{mean beam length}}))$$

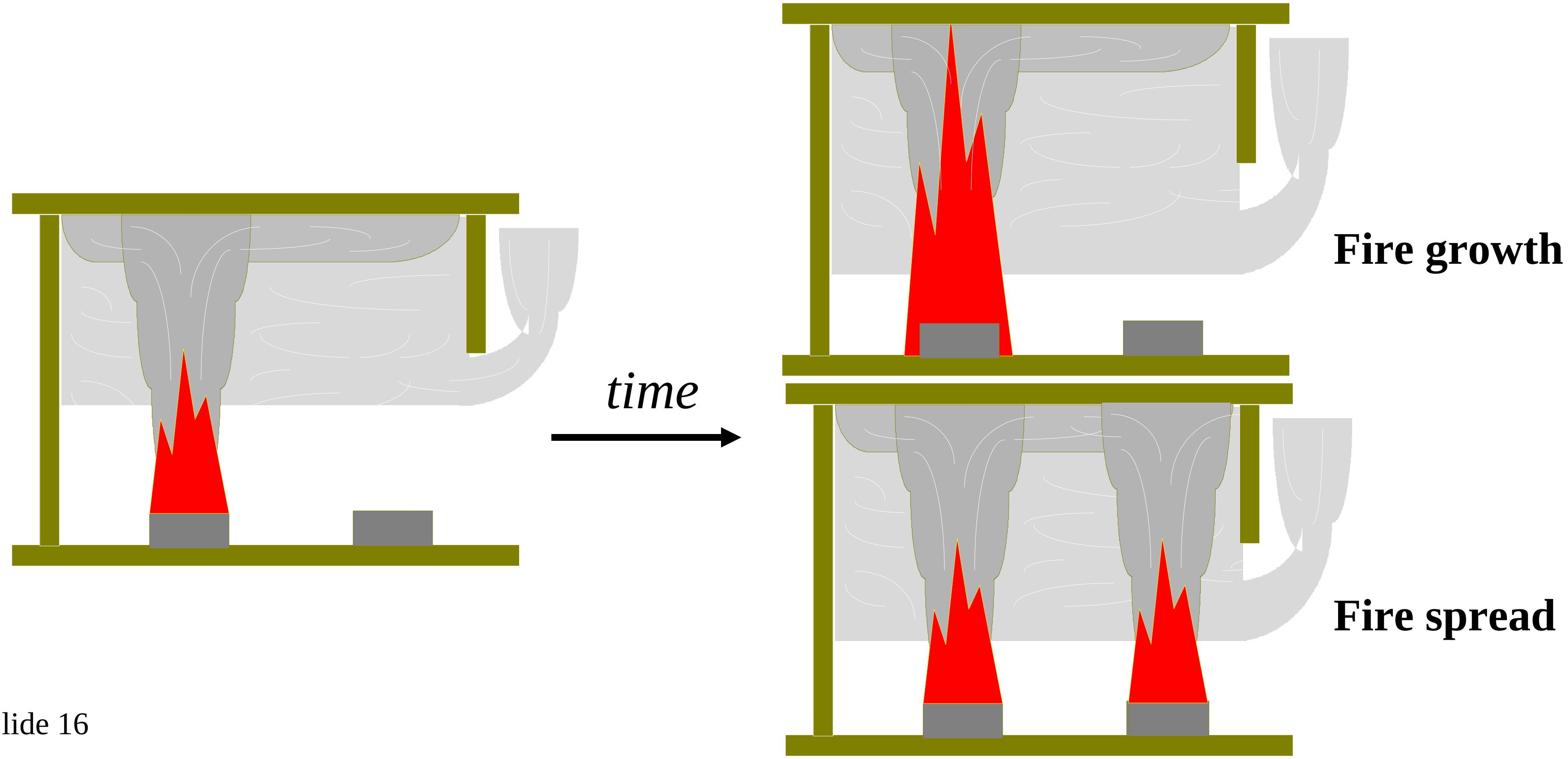
$$\underbrace{\kappa_{UL}}_{\text{Planck mean absorption coef}} = \underbrace{p(x_{H_2O,UL}\,a_{H_2O}(T) + x_{CO_2,UL}\,a_{CO_2}(T))}_{\text{gas component}} + \underbrace{C_{soot}\, f_{v,UL}\, T_{UL}}_{\text{soot component}}$$

often dominant



Compartment Fires

- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
  - Impact of smoke layer: increases heat feedback to fuel sources, therefore increases fuel gasification rate and heat release rate



Compartment Fires

- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
  - Impact of smoke layer: increases heat feedback to fuel sources, therefore increases fuel gasification rate and heat release rate (fire growth and fire spread)
  - Possible transition to *flashover* (rapid series of ignition events involving all flammable objects/materials present in the fire room)

Small fire

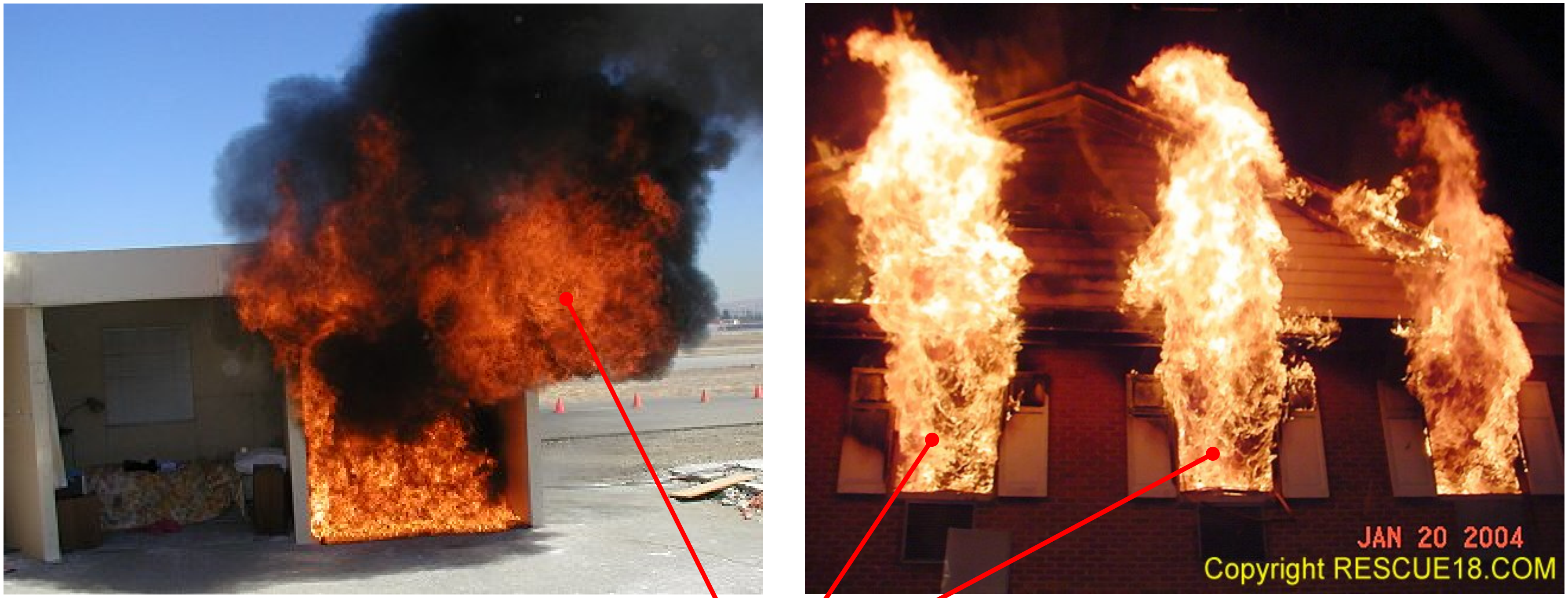
Flammable objects

time →

Flashover !

Compartment Fires

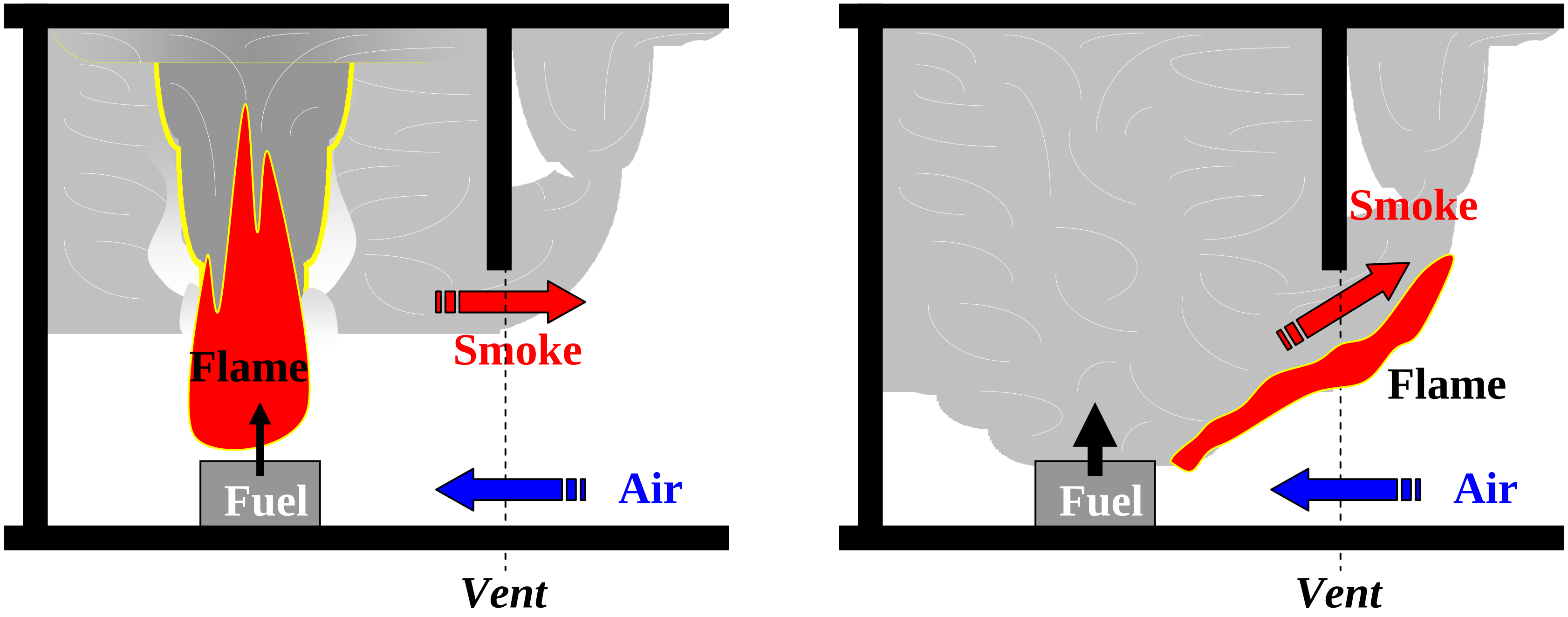
- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
  - Possible transition to *flashover*: may trigger in turn a transition to *under-ventilated* combustion



Flames extending out of the compartment of fire origin

Compartment Fires

- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
  - Possible transition to *under-ventilated* combustion
  - Flame location: (1) near the fuel source; (2) near the vents



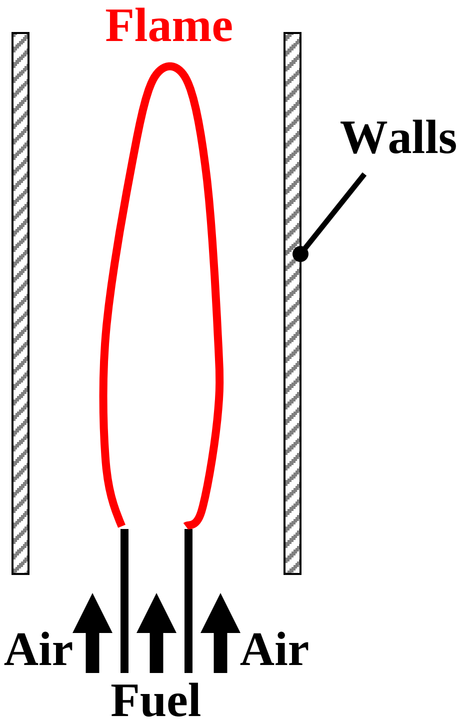
(1) Over-ventilated combustion,

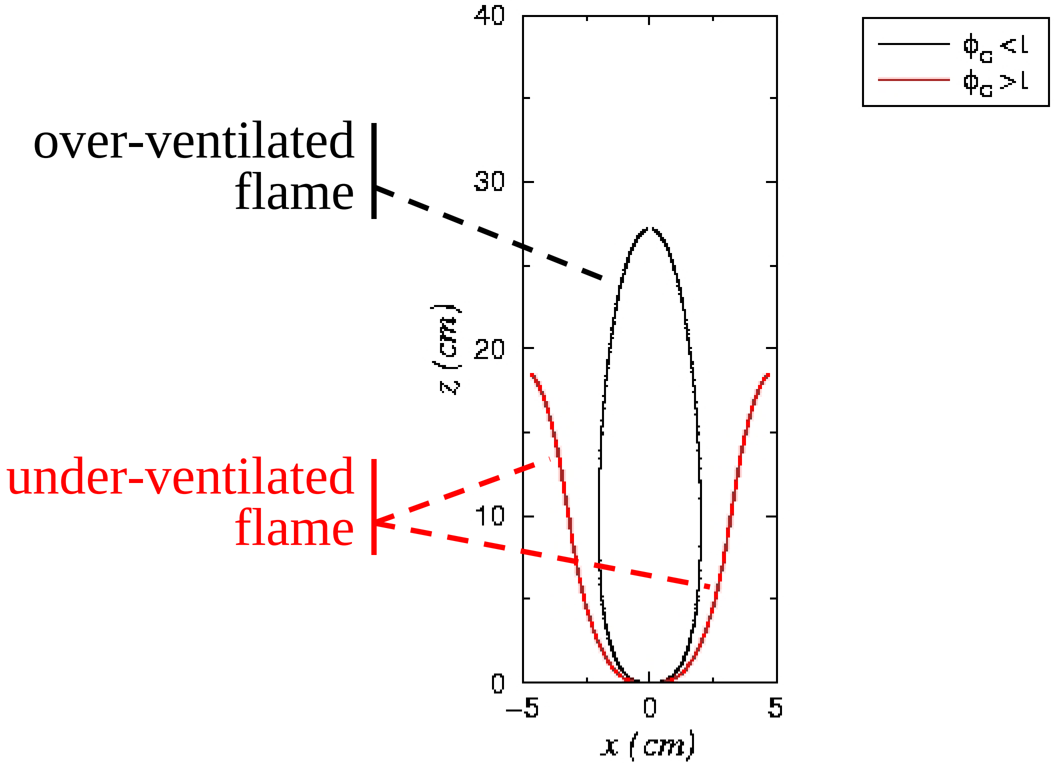
(2) Under-ventilated combustion

Compartment Fires

- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
  - Possible transition to *under-ventilated* combustion
  - Classical Burke-Schumann problem (1928): 2 possible regimes

Laminar flame-flow configuration

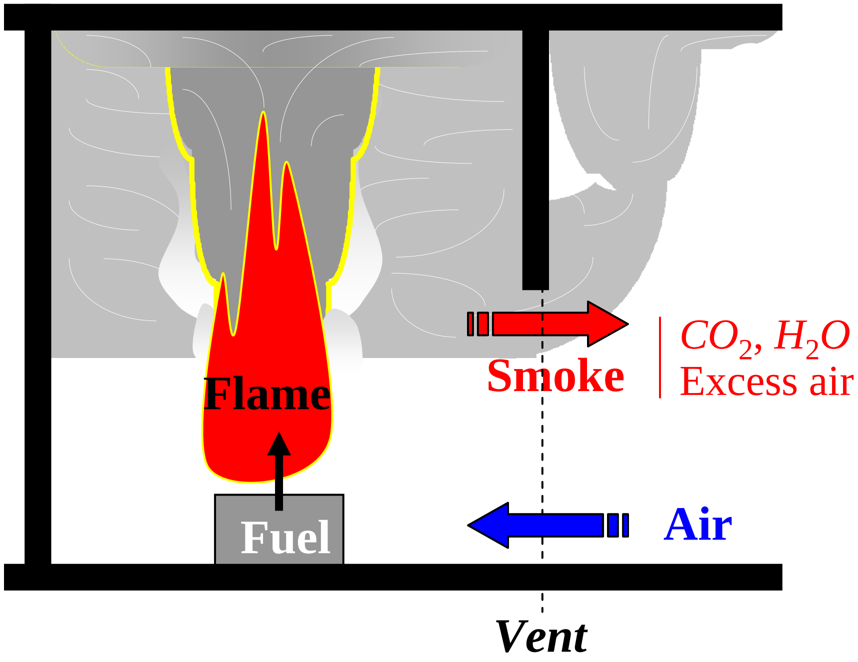



over-ventilated flame

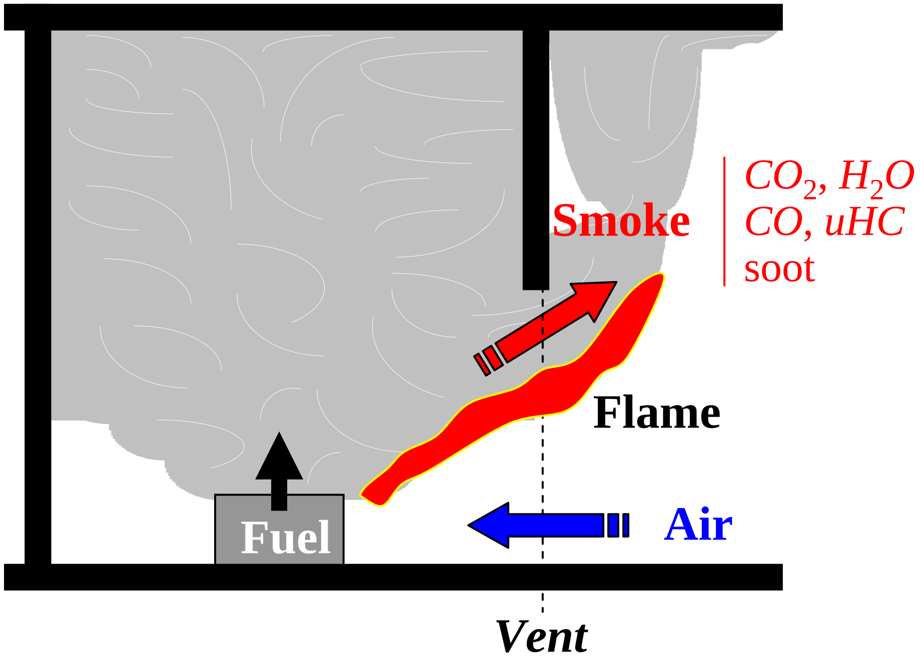
under-ventilated flame

Compartment Fires

- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
  - Possible transition to *under-ventilated* combustion
  - Smoke layer composition: (1) products of complete combustion mixed with air; (2) products of incomplete combustion



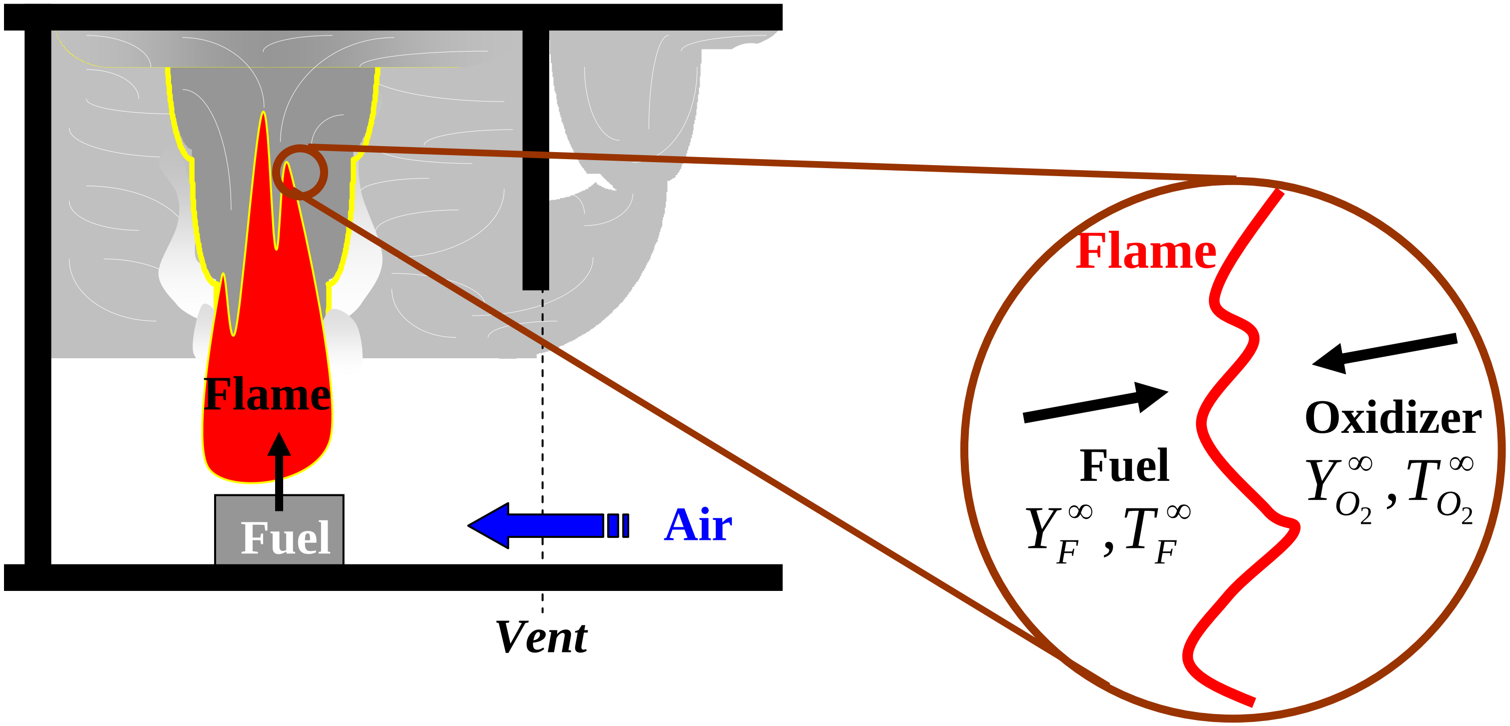
(1) Over-ventilated combustion,



(2) Under-ventilated combustion

Compartment Fires

- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
  - Impact of smoke layer: air vitiation as the compartment fire system evolves from well-ventilated to *under-ventilated* combustion
  - Air vitiation reduces the flame intensity and promotes flame extinction



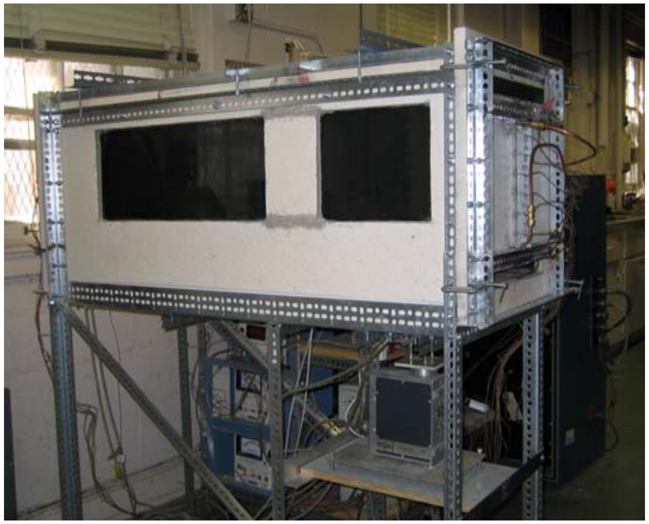
Air vitiation

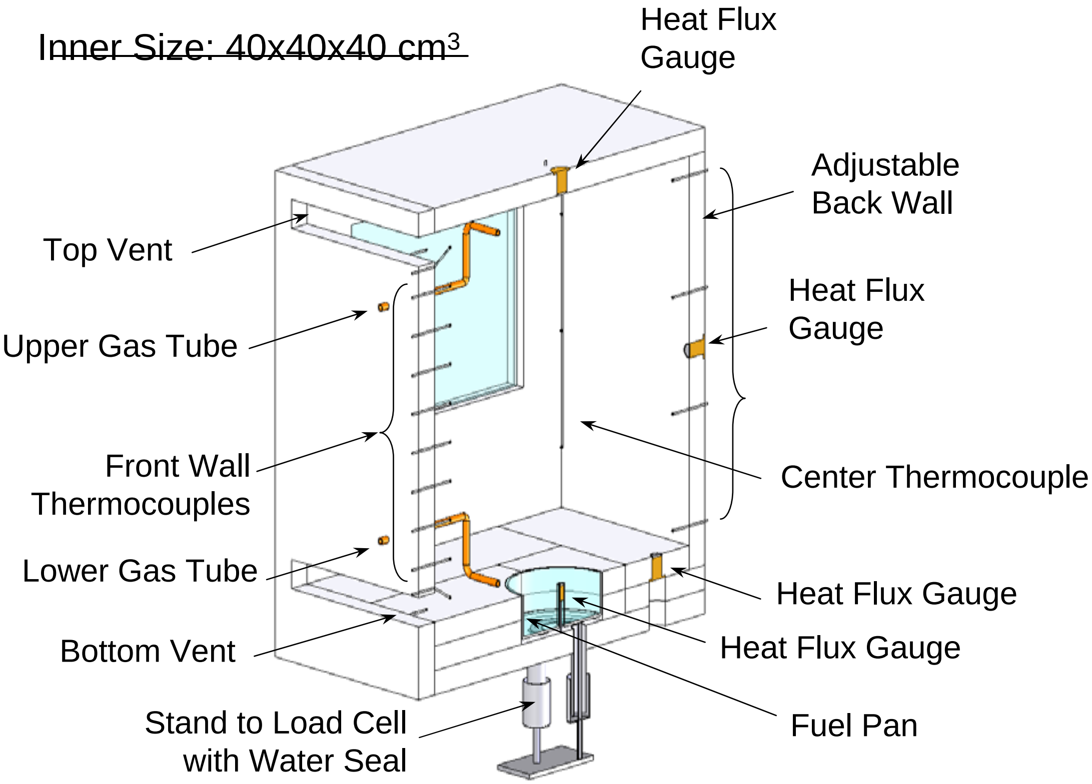
$$Y_{O_2}^\infty \leq Y_{O_2,air}$$

$$T_{O_2}^\infty \geq T_{air}$$

Compartment Fires

- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
    - Reduced-scale compartment fire experiments (Utiskul & Quintiere)
        - Vent size: variable width and height
        - Fuel pan: variable diameter

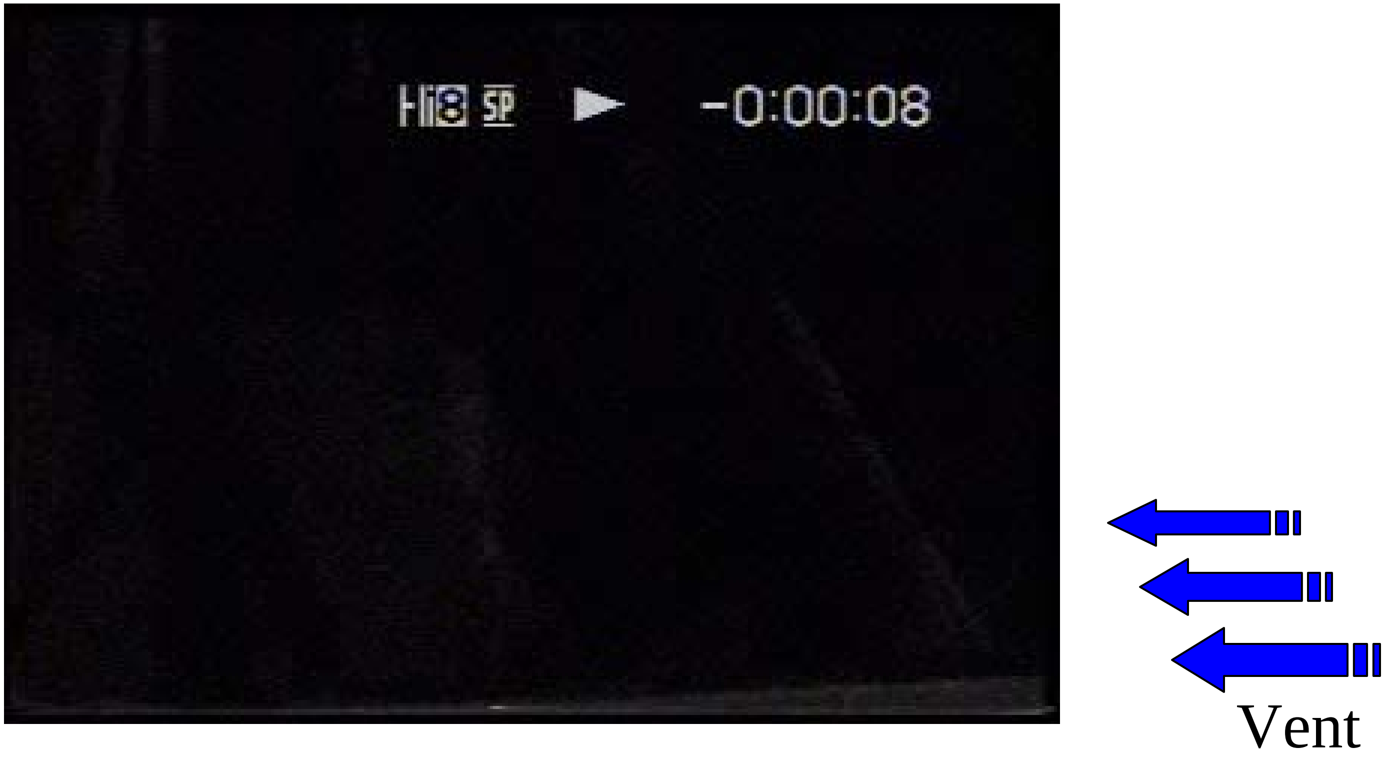




Inner Size: 40x40x40 cm^3

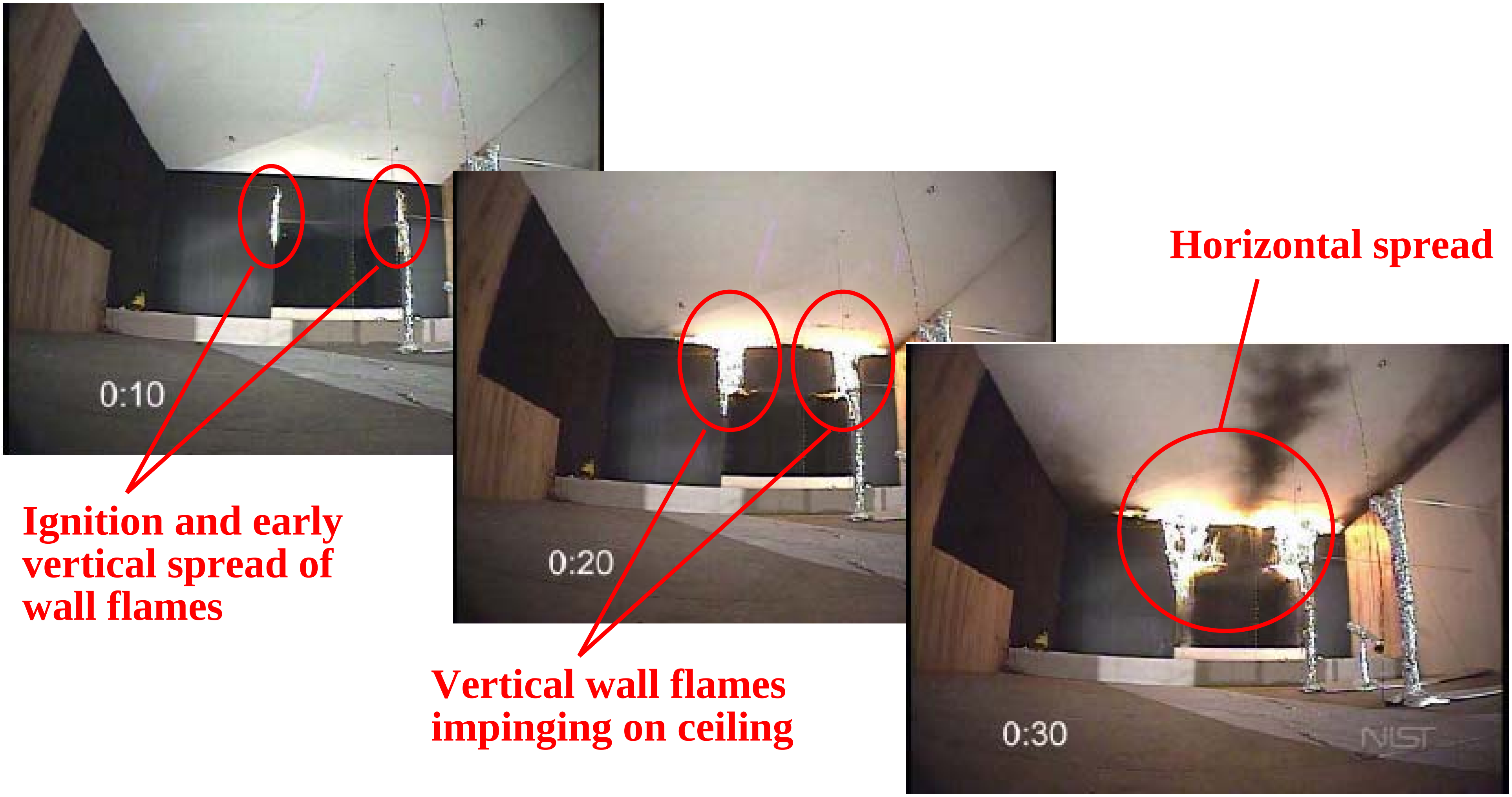
Compartment Fires

- **Main features**: flow confinement and buoyancy forces lead to the formation of a ceiling-level smoke layer
  - Reduced-scale compartment fire experiments (Utiskul & Quintiere)
  - Steady under-ventilated fire (flame stabilized at the vents)



Compartment Fires

- Role of wall flames
  - Control the ignition and fire growth/spread processes



Ignition and early vertical spread of wall flames

Vertical wall flames impinging on ceiling

Horizontal spread

Compartment Fires

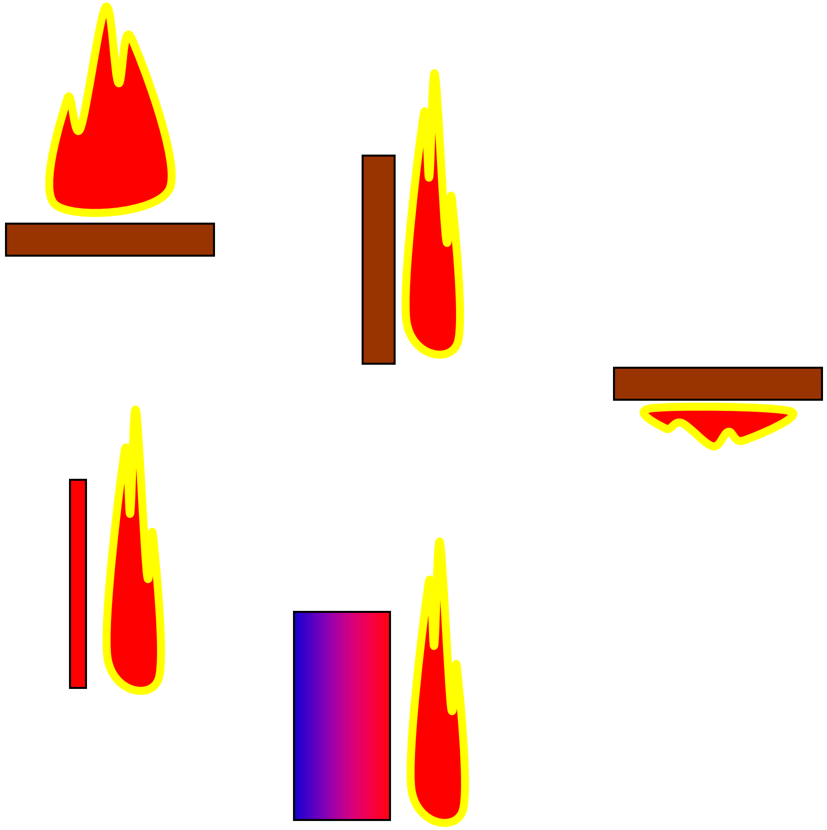
- **Summary**
  - Compartment fires feature rich multi-physics dynamics
    - Buoyancy-driven, low-to-moderate Reynolds number turbulent flow
    - Non-premixed combustion
    - Pyrolysis processes
    - Soot formation/oxidation
    - Thermal radiation transport
  - Wall flames are an essential ingredient of the fire dynamics

Modeling of Turbulent Wall Fires

- Outline
  - Overview of Compartment Fire Dynamics
    - Multi-physics problem
    - Role of wall fires
  - **Laminar Wall Fires**
    - **Analytical solution of a canonical wall flame problem – the Emmons problem (non-spreading; constant wall temperature; no thermal radiation)**
  - Turbulent Wall Fires
    - Large eddy simulation of a canonical wall fire problem (non-spreading; vertical wall)

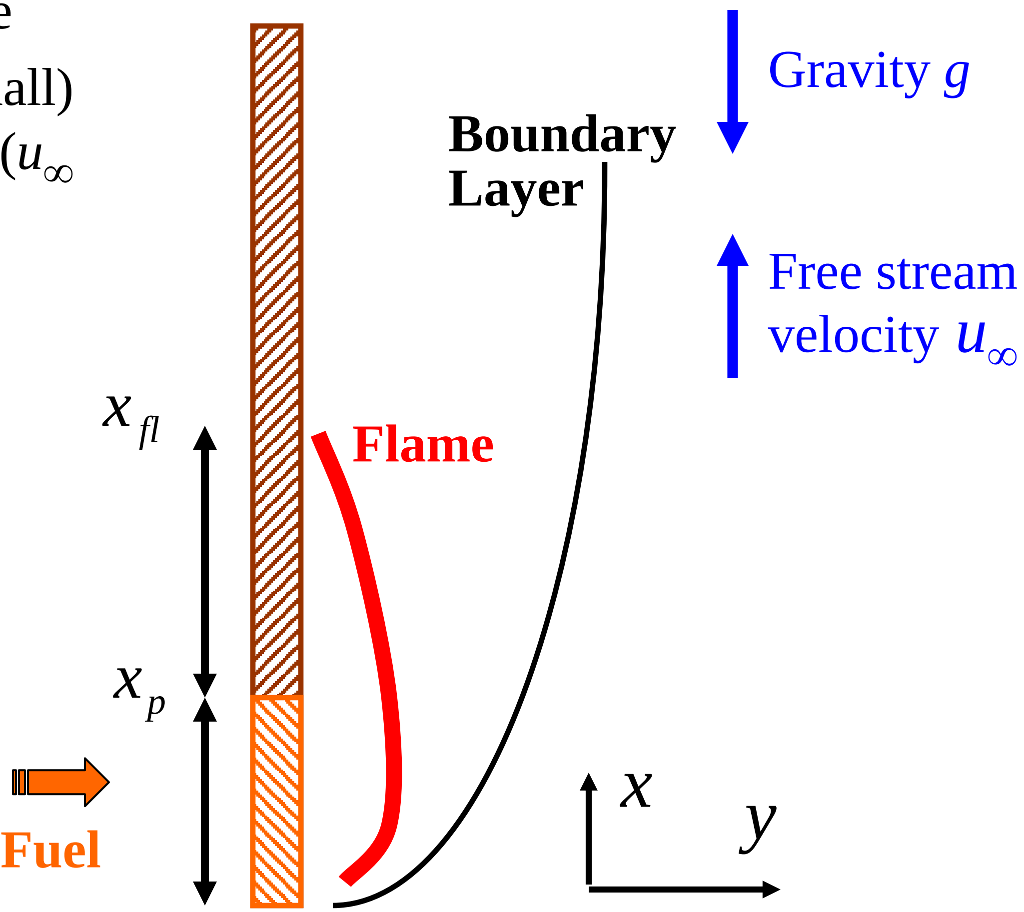
Laminar Wall Fires

- A variety of configurations:
  - Solid wall material
    - Chemically inert (*e.g.*, concrete)
    - Flammable (*e.g.*, plastic, wood, fabric)
  - Wall orientation
    - Floor fire (pool fire)
    - Wall fire
    - Ceiling fire
  - Wall thickness
    - Thermally thin
    - Thermally thick



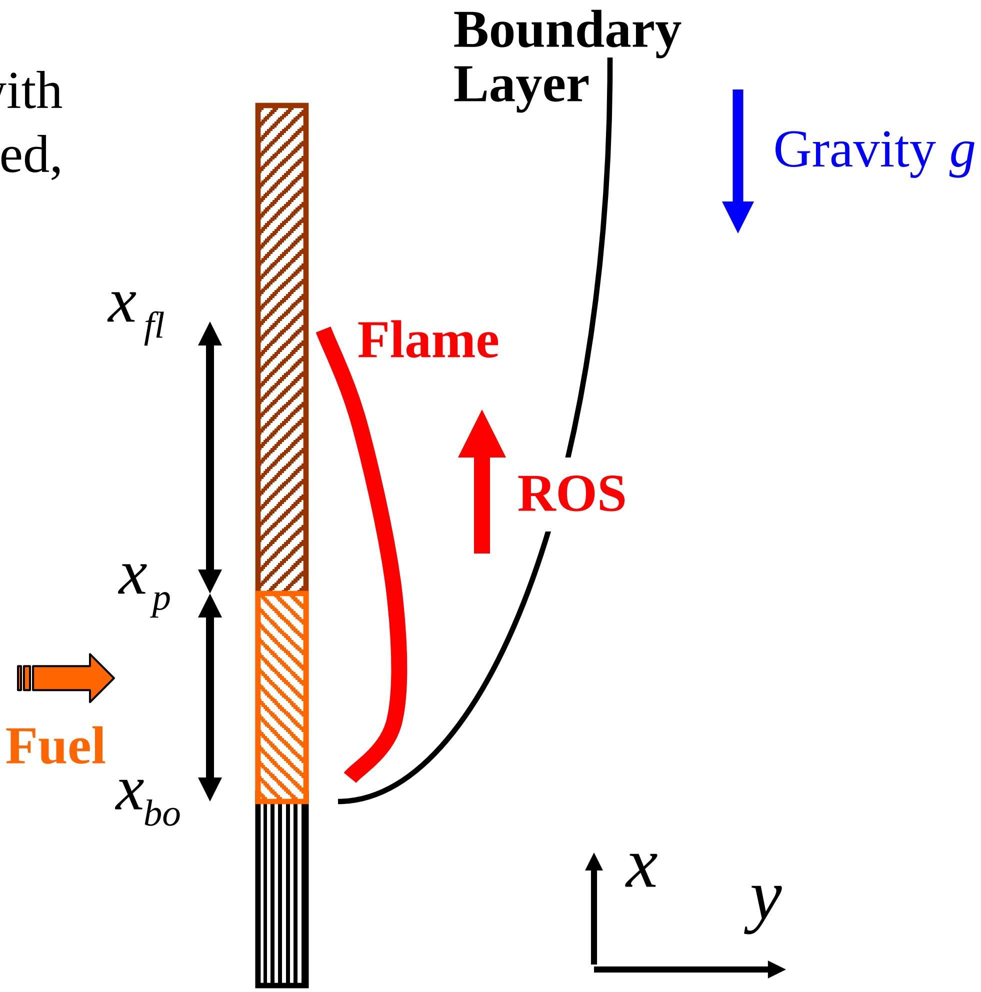
Laminar Wall Fires

- A variety of configurations:
  - Propagation
    - Non-spreading wall flame
    - Buoyancy-driven (u_∞ small) or momentum-driven (u_∞ large) flow
    - Pyrolysis region
      $0 \leq x \leq x_p$
    - Inert wall region
      $x_p \leq x$
    - Wall flame region
      $0 \leq x \leq x_{fl}$
    - Wall plume region
      $x_{fl} \leq x$



Laminar Wall Fires

- A variety of configurations:
  - Propagation
    - Spreading wall flame with upward spread (flow-aided, concurrent spread)
      - Pyrolysis region
        $x_{bo}(t) \le x \le x_p(t)$
      - Inert wall regions
        $x \le x_{bo}(t)$ and $x_p(t) \le x$
      - Wall flame region
        $x_{bo}(t) \le x \le x_{fl}(t)$
      - Wall plume region
        $x_{fl}(t) \le x$



Laminar Wall Fires

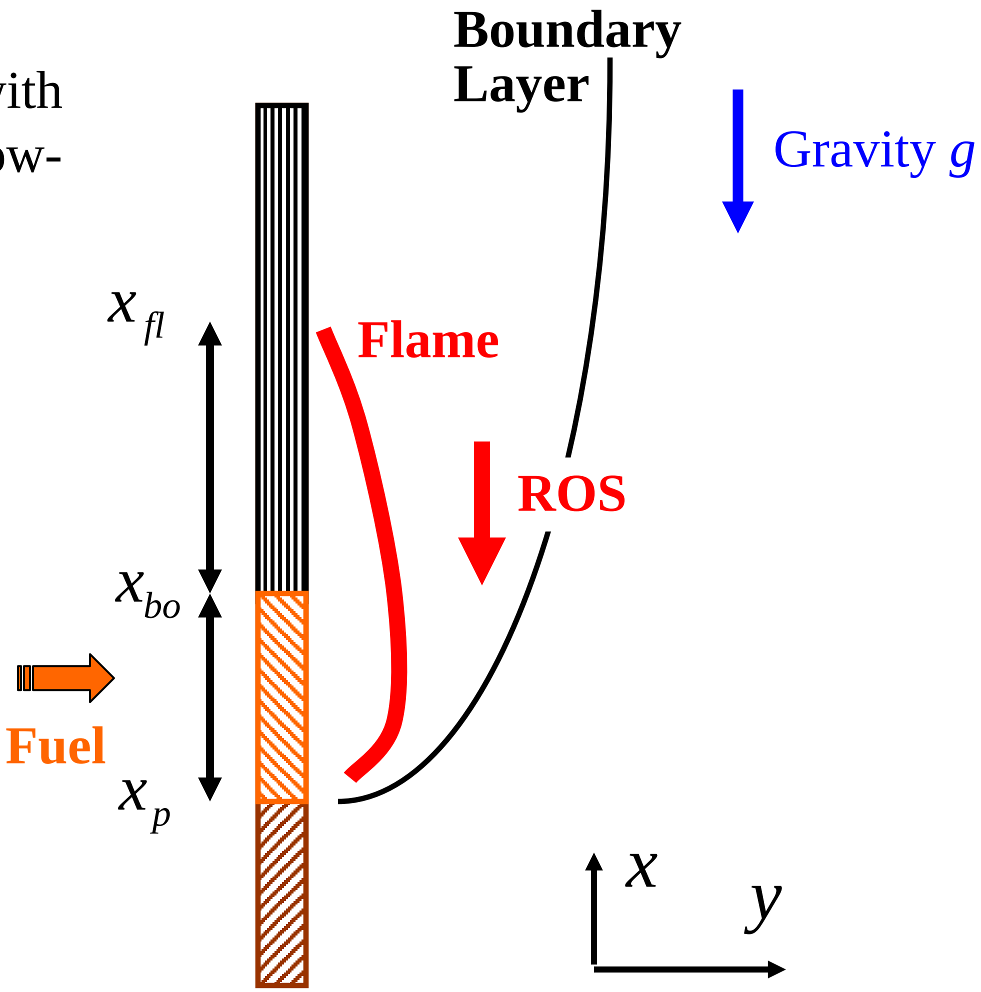
- A variety of configurations:
  - Propagation
    - Spreading wall flame with downward spread (flow-opposed spread)
    - Pyrolysis region

      $x_p(t) \leq x \leq x_{bo}(t)$
    - Inert wall regions

      $x \leq x_p(t)$ and $x_{bo}(t) \leq x$
    - Wall flame region

      $x_p(t) \leq x \leq x_{fl}(t)$
    - Wall plume region

      $x_{fl}(t) \leq x$

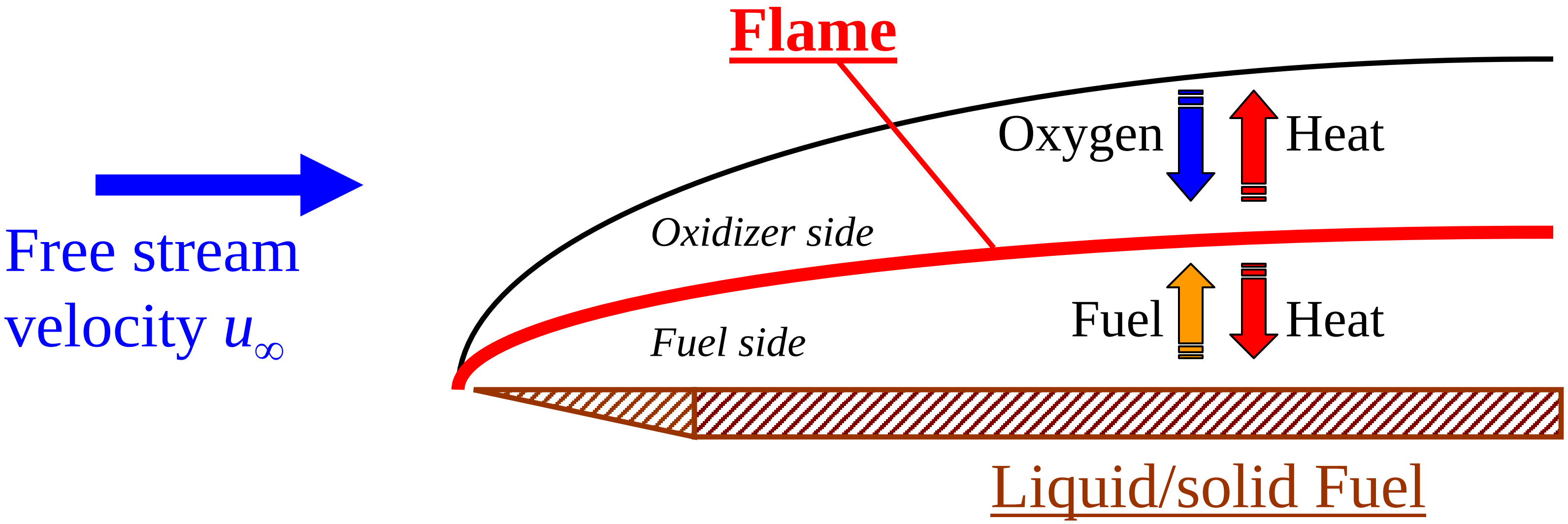


Laminar Wall Fires

- Emmons problem
  - A canonical boundary layer combustion problem corresponding to a **non-spreading** laminar wall flame with **forced convection** (external flow)
  - Assumptions:
    - Constant and uniform free stream conditions
    - No gravity
    - Boundary layer approximation
    - Infinitely fast, single-step chemistry (mixture-fraction based combustion model) $\boxed{F + r_s O_2 \rightarrow (1 + r_s) P}$
    - Constant wall temperature
    - No thermal radiation
  - H.W. Emmons (1956) “The Film Combustion of Liquid Fuel”, *Z. Angew. Math. Mech.*, **36**:1 pp. 60-71.

Laminar Wall Fires

- Flat (liquid or solid) fuel surface burning in a laminar gaseous cross-flow
  - ➢ Modified Blasius solution for the velocity field:
    - Variable mass density $\boxed{\rho(x,y)}$
    - Finite normal velocity at the fuel surface $\boxed{v(x,0)\neq 0}$
  - ➢ Infinitely-fast chemistry



Laminar Wall Fires

- Emmons solution
  - Governing equations for the flow field

$$\begin{cases} \dfrac{\partial}{\partial x}(\rho u)+\dfrac{\partial}{\partial y}(\rho v)=0 \\[2ex] \rho u\dfrac{\partial u}{\partial x}+\rho v\dfrac{\partial u}{\partial y}=\dfrac{\partial}{\partial y}(\mu\dfrac{\partial u}{\partial y}) \end{cases}$$

  - Boundary conditions

$$\begin{cases} u(x,0)=0 \\ u(x,\infty)=u_\infty \end{cases}$$

Laminar Wall Fires

- Emmons solution
  - Governing equations for the mixture composition

$$F + r_s O_2 \rightarrow (1 + r_s) P$$

$$\left|\begin{array}{l} \rho u \dfrac{\partial Y_F}{\partial x} + \rho v \dfrac{\partial Y_F}{\partial y} = \dfrac{\partial}{\partial y}(\rho D_F \dfrac{\partial Y_F}{\partial y}) - \dot{\omega}_F \\ \rho u \dfrac{\partial Y_{O_2}}{\partial x} + \rho v \dfrac{\partial Y_{O_2}}{\partial y} = \dfrac{\partial}{\partial y}(\rho D_{O_2} \dfrac{\partial Y_{O_2}}{\partial y}) - r_s \dot{\omega}_F \\ \rho u c_p \dfrac{\partial T}{\partial x} + \rho v c_p \dfrac{\partial T}{\partial y} = \dfrac{\partial}{\partial y}(\lambda \dfrac{\partial T}{\partial y}) + \dot{\omega}_F \Delta H_{comb} \end{array}\right.$$

$$+ \quad \underline{D_F = D_{O_2} = (\lambda / \rho c_p) = D}$$

Laminar Wall Fires

- Emmons solution
  - Boundary conditions at fuel surface ($y = 0$)
    - Total mass: $\underbrace{\rho_w v_w}_{\text{gas}} = \dot{m}''_w$
    - Fuel mass: $\underbrace{\rho_w v_w Y_{F,w} - \rho_w D_w (\frac{\partial Y_F}{\partial y})_w}_{\text{gas}} = \dot{m}''_w$
    - Oxygen mass: $Y_{O_2,w} = 0$
    - Energy: $\dot{m}''_w \Delta H_{pyro} = \underbrace{\lambda_w (\frac{\partial T}{\partial y})_w}_{\text{gas}}$

Laminar Wall Fires

- Emmons solution
  - Mixture fraction formulation

$$\rho u \frac{\partial Z}{\partial x} + \rho v \frac{\partial Z}{\partial y} = \frac{\partial}{\partial y}(\rho D \frac{\partial Z}{\partial y})$$

where $Z = \dfrac{Y_F - (Y_{O_2}/r_s) + (Y_{O_2,\infty}/r_s)}{Y_{F,w} + (Y_{O_2,\infty}/r_s)}$

$$= \frac{(Y_{O_2} - Y_{O_2,\infty})/r_s + c_p(T - T_\infty)/\Delta H_F}{c_p(T_w - T_\infty)/\Delta H_{comb} - (Y_{O_2,\infty}/r_s)}$$

$$= \frac{u_\infty - u}{u_\infty}$$

Laminar Wall Fires

- Emmons solution
  - Boundary conditions for mixture fraction:

$$\left| \begin{array}{l} Z(x,0)=1 \\ Z(x,\infty)=0 \end{array} \right.$$

and $B[-\rho_w D_w(\frac{\partial Z}{\partial y})_w]=\dot{m}''_w$

with

$$\boxed{B=\frac{Y_{F,w}+(Y_{O_2,\infty}/r_s)}{1-Y_{F,w}}=\frac{c_p(T_\infty-T_w)+(Y_{O_2,\infty}/r_s)\Delta H_{comb}}{\Delta H_{pyro}}}$$

(Spalding B number)

Ratio of heat released by unit mass of oxidizer divided by heat required to gasify unit mass of fuel

Laminar Wall Fires

- Emmons solution
  - Introduce a modified stream function $\psi(x, y)$

$$\rho u = \frac{\partial \psi}{\partial y} \;;\; \rho v = -\frac{\partial \psi}{\partial x}$$

  - Look for a similarity solution

$$\left|\begin{array}{l} \eta(x, y) = \int_0^y (\frac{\rho}{\rho_\infty}) dy \, \frac{\sqrt{\mathrm{Re}_x}}{x} = \int_0^y (\frac{\rho}{\rho_\infty}) dy \, \sqrt{\frac{u_\infty}{\nu_\infty x}} \\ \psi(x, y) = \rho_\infty \sqrt{u_\infty \nu_\infty x} \, G(\eta) \\ u(x, y) = u_\infty \frac{dG}{d\eta}(\eta) \;;\; Z(x, y) = 1 - \frac{dG}{d\eta}(\eta) \end{array}\right.$$

  - Re-formulate the problem as an ODE problem

$$2G''' + GG'' = 0 \qquad \left|\begin{array}{l} 2BG''(0) + G(0) = 0 \\ G'(0) = 0 \\ G'(\infty) = 1 \end{array}\right.$$

Laminar Wall Fires

- Emmons solution
  - Fuel mass loss rate

$$\boxed{\begin{array}{l}\dot{m}''_w = \dfrac{\rho_\infty u_\infty}{2\sqrt{\mathrm{Re}_x}}(-G(0)) \\ (-G(0)) = \text{function of } B\end{array}}$$

  - Scaling

$$\dot{m}''_s \sim 1/\sqrt{x}$$

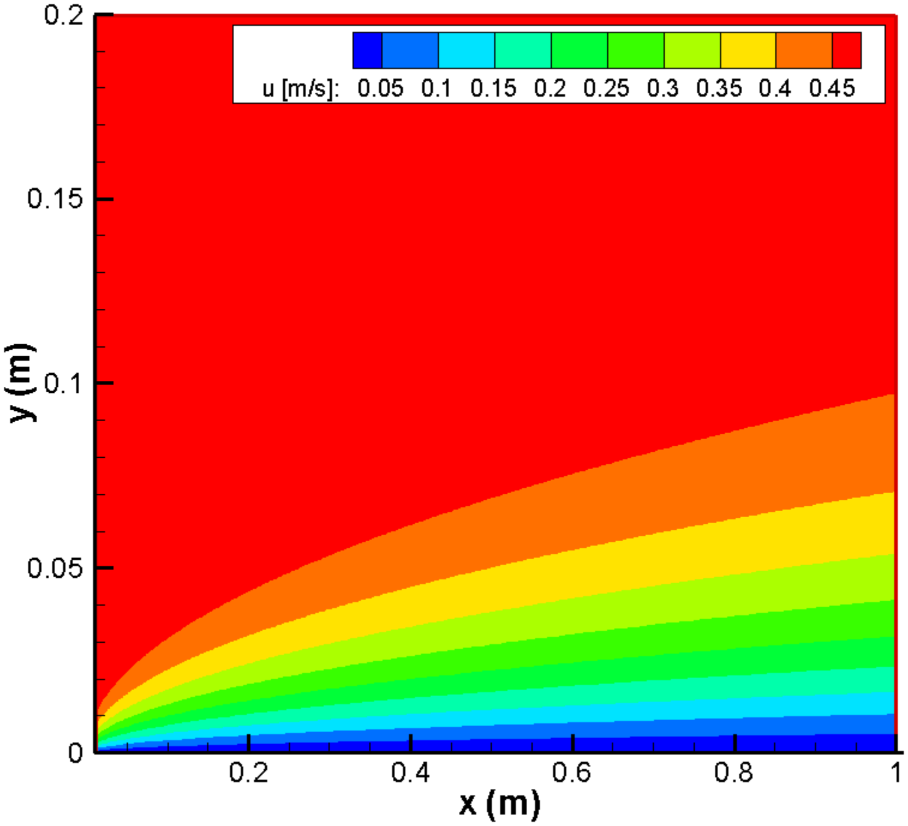
$$\dot{m}''_s \sim \sqrt{u_\infty}$$

Laminar Wall Fires

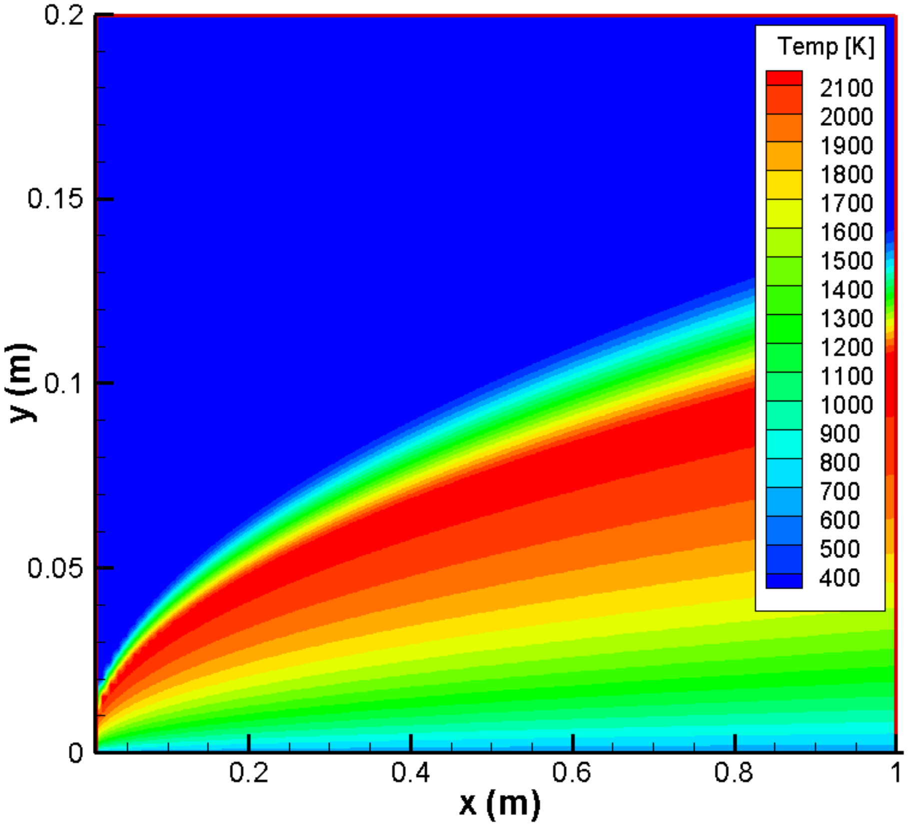
- Emmons solution

  (air flow; $u_\infty = 0.5\,\text{m/s}$; $B = 5$)

Streamwise velocity field



Temperature field (T_s = 630 K)

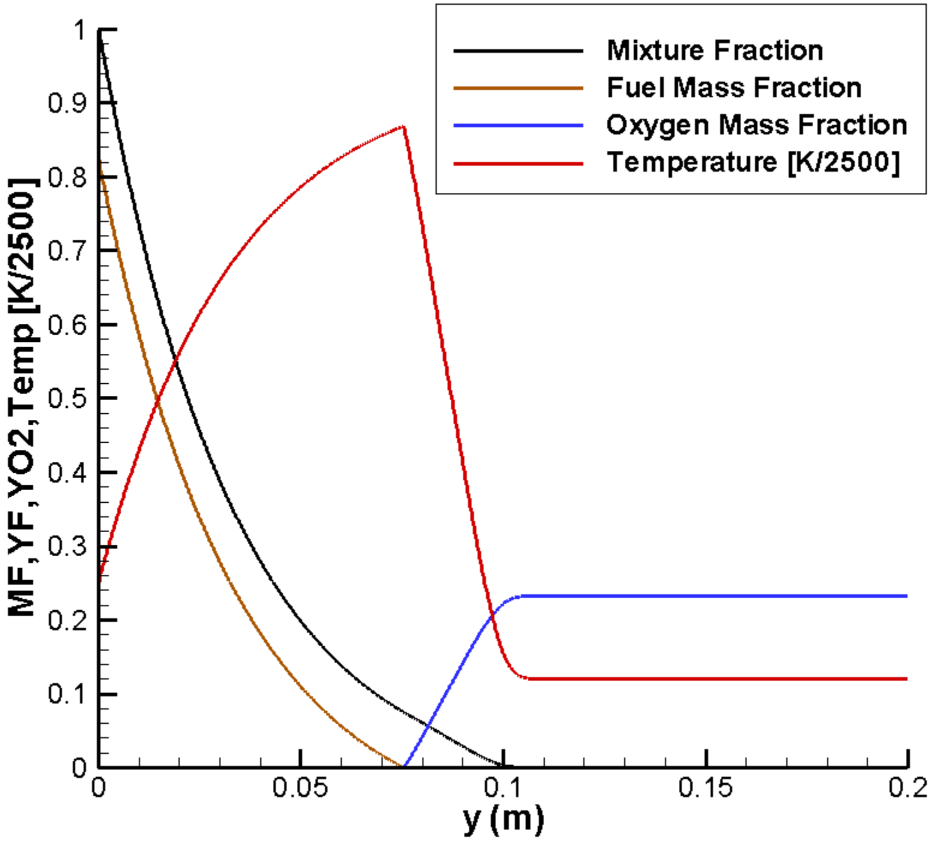


Laminar Wall Fires

- Emmons solution

  (air flow; $u_\infty = 0.5\,\mathrm{m/s}$; $B = 5$)

<u>Flame structure in *y*-direction</u> (*x* = 0.5 m)

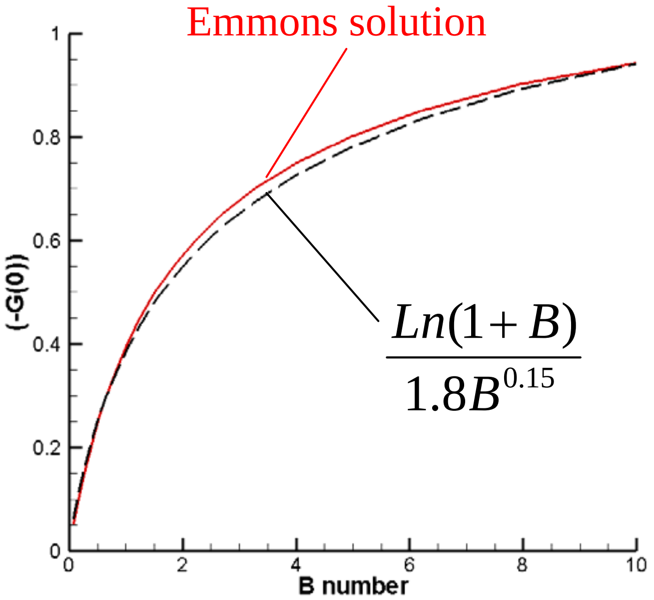


Laminar Wall Fires

- Emmons solution
  - Fuel mass loss rate

$$\dot{m}''_w = \frac{\rho_\infty u_\infty}{2\sqrt{\mathrm{Re}_x}}(-G(0))$$

$$(-G(0)) = \text{function of } B$$



  - Scaling: effect of material properties

$$\dot{m}''_w \sim (-G(0))$$

$$B = \frac{c_p(T_\infty - T_w) + (Y_{O_2,\infty}/r_s)\Delta H_{comb}}{\Delta H_{pyro}} \approx \frac{(Y_{O_2,\infty}/r_s)\Delta H_{comb}}{\Delta H_{pyro}}$$

Laminar Wall Fires

- Emmons solution: provides a metric to evaluate fire risk associated with different materials

$$\boxed{B \approx \frac{(Y_{O_2,\infty} / r_s)\Delta H_{comb}}{\Delta H_{pyro}}}$$

  - n-heptane (liquid fuel)

    $\Delta H_{comb} \approx 45 \text{ MJ/kg}; \Delta H_{pyro} \approx 0.48 \text{ MJ/kg}; r_s = 3.52; \underline{B \approx 6.2}$

  - Polymethylmethacrylate (PMMA)

    $\Delta H_{comb} \approx 24 \text{ MJ/kg}; \Delta H_{pyro} \approx 2 \text{ MJ/kg}; r_s = 1.92; \underline{B \approx 1.45}$

  - Wood (douglas fir)

    $\Delta H_{pyro} \approx 12.4 \text{ MJ/kg}; \Delta H_{pyro} \approx 6.8 \text{ MJ/kg}; r_s = 0.95; \underline{B \approx 0.45}$

Laminar Wall Fires

- Emmons solution: provides a metric to evaluate fire risk associated with different materials

$$\boxed{HRRPUA = \dot{m}''_w \Delta H_{comb} \sim \frac{Ln(1+B)}{B^{0.15}} \Delta H_{comb}}$$

  - n-heptane (liquid fuel)

    $$\underline{HRRPUA \sim 13}$$

  - Polymethylmethacrylate (PMMA)

    $$\underline{HRRPUA \sim 3.9}$$

  - Wood (douglas fir)

    $$\underline{HRRPUA = 1}$$

Laminar Wall Fires

- Emmons solution: extension to buoyancy-driven flow
  - Consider a vertical solid flammable surface
  - F. J. Kosdon, F. A. Williams & C. Buman (1969) “Combustion of vertical cellulosic cylinders in air”, *Proc*. *Combust*. *Inst*., **12**:253-264.
  - J. S. Kim, J. De Ris & F. William Kroesser (1971) “Laminar free-convective burning of fuel surfaces”, *Proc*. *Combust*. *Inst*., **13**:949-961.

Laminar Wall Fires

- Emmons solution
  - Fuel mass loss rate

$$\dot{m}''_w = \frac{3\rho_w \nu_w}{\sqrt{2}} \frac{(Gr_x)^{1/4}}{x} (-G(0))$$

$$(-G(0)) = \text{function of } B$$

$$Gr_x = \frac{g(T_w - T_\infty)x^3}{(\nu_w)^2 T_\infty}$$

  - Scaling

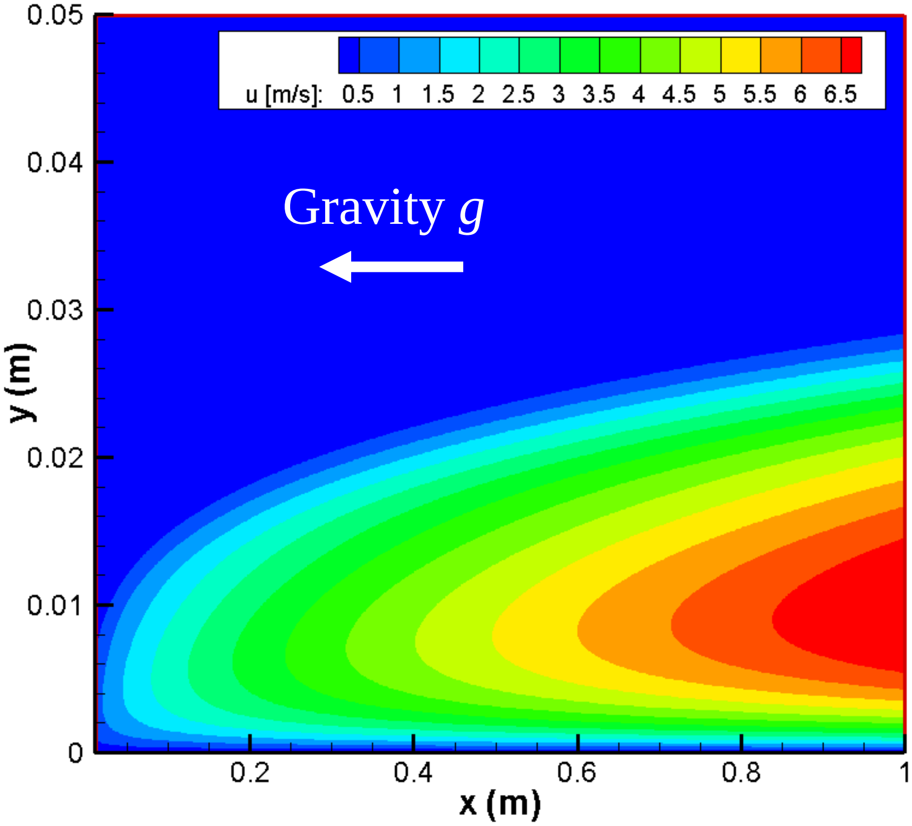
$$\dot{m}''_w \sim 1/x^{1/4}$$

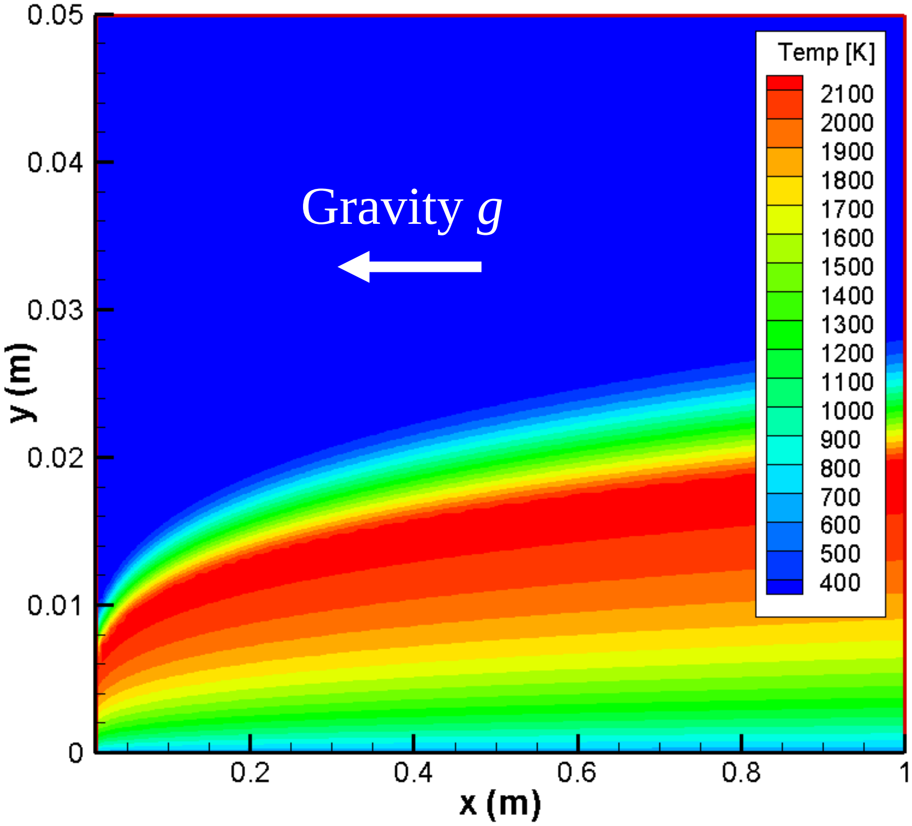
Laminar Wall Fires

- Emmons solution
  $(B = 5)$

Streamwise velocity field

Temperature field (T_s = 630 K)





Laminar Wall Fires

- Limitations of Emmons solution
  - ➢ Assumes laminar flow
  - ➢ Neglects role of thermal radiation

$$\dot{m}''_w \Delta H_{pyro} = \lambda_w \left(\frac{\partial T}{\partial y}\right)_w \quad \rightarrow \quad \dot{m}''_w \Delta H_{pyro} = \lambda_w \left(\frac{\partial T}{\partial y}\right)_w + \boxed{\dot{q}''_{w,rad}}$$

$$\Delta H_{comb} \quad \rightarrow \quad \boxed{(1 - \chi_{rad}) \Delta H_{comb}}$$

Laminar Wall Fires

- Limitations of Emmons solution
  - Neglects role of pyrolysis processes occurring inside condensed phase

$$T_w = T_\infty + \frac{(Y_{O_2,\infty}/r_s)\Delta H_{comb} - B\Delta H_{pyro}}{c_p} \rightarrow \boxed{T_w \neq \text{constant}}$$

$$\dot{m}''_w \Delta H_{pyro} = \lambda_w \left(\frac{\partial T}{\partial y}\right)_w \rightarrow \quad \dot{m}''_w \Delta H_{pyro} + \boxed{\lambda_{s,w}\left(\frac{\partial T_s}{\partial y}\right)_w} = \lambda_w \left(\frac{\partial T}{\partial y}\right)_w + \dot{q}''_{w,rad}$$

$$\rightarrow \boxed{\dot{m}''_w = \int_{-\Delta}^{0} \dot{\omega}'''_g(x,t)\,dx}$$

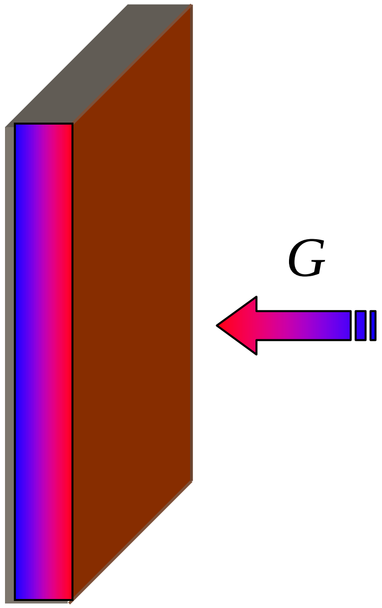
in-depth processes (rather than surface processes)

Laminar Wall Fires

- Pyrolysis modeling: description of fuel mass loss rate
  - Finite-rate chemistry model: explicit treatment of thermal decomposition chemistry
  - Thermal degradation across flammable solid described by a local one-dimensional problem in the direction normal to the exposed surface

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(k_s \frac{\partial T_s}{\partial x}\right) - \boxed{\underbrace{\dot{\omega}_g'''\Delta H_{pyro}}_{\substack{\text{energy consumed}\\ \text{by gasification}}} - \underbrace{\dot{m}_g'' c_g \frac{\partial T_s}{\partial x}}_{\substack{\text{convective transport}\\ \text{by gas flow}}}}$$

$$\underbrace{-k_s \frac{\partial T_s}{\partial x}(0,t)}_{\substack{\text{heat flux to wall interior}\\ \text{(conduction)}}} = \underbrace{-\varepsilon G + \varepsilon\sigma\left(T_s(0,t)^4 - T_\infty{}^4\right)}_{\text{radiation}} + \underbrace{h\left(T_s(0,t) - T_\infty\right)}_{\text{convection}}$$

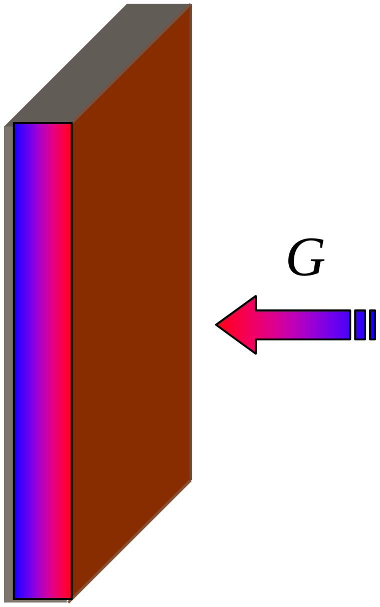


Laminar Wall Fires

- Pyrolysis modeling: description of fuel mass loss rate
  - Finite-rate chemistry model: explicit treatment of thermal decomposition chemistry
  - Thermal degradation across flammable solid described by a local one-dimensional problem in the direction normal to the exposed surface

$$\underbrace{\text{virgin solid}}_{1\,\text{kg}} \rightarrow \underbrace{\text{volatiles}}_{\eta_g = 1-\eta_c} + \underbrace{\text{char}}_{\eta_c}$$

$$\dot{\omega}_g''' = \rho_{vs}^0 \, x_{vs} \, A \exp(-E/RT_s)$$



$$\frac{\partial \rho_s}{\partial t} = -\dot{\omega}_g'''$$

mass conservation (solid phase)

$$\frac{\partial \rho_g}{\partial t} + \frac{\partial \dot{m}_g''}{\partial x} = \dot{\omega}_g'''$$

mass conservation (gas phase)

$$\boxed{\dot{m}_f''(t) = \int_{-\Delta}^{0} \dot{\omega}_g'''(x,t)\,dx}$$

Laminar Wall Fires

- Pyrolysis modeling: description of fuel mass loss rate
  - *Example*: particle board (Novozhilov, Moghtaderi, Fletcher & Kent, *Fire Safety J.* **27** (1996) 69-84)

$$k^0_{vs} = k^0_c = 0.126\ \mathrm{W/m\text{-}K}$$

$$\rho^0_{vs} = 663\ \mathrm{kg/m^3}$$

$$\rho^0_c = 133\ \mathrm{kg/m^3}$$

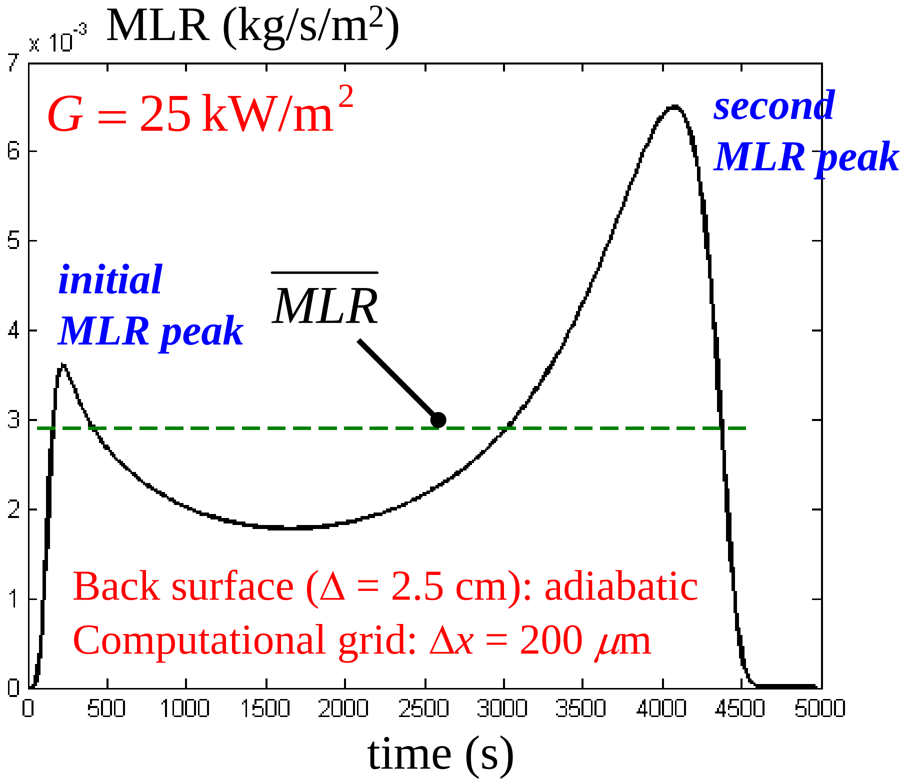
$$c^0_{vs} = c^0_c = 2520\ \mathrm{J/kg\text{-}K}$$

$$\varepsilon = 0.9$$

$$\mathrm{A} = 5.250\times 10^7\ \mathrm{1/s}$$

$$\mathrm{E} = 1.256\times 10^5\ \mathrm{J/mol}$$

$$\Delta H_{v,g} = 0\ \mathrm{J/kg}$$



$G = 25\ \mathrm{kW/m^2}$

initial MLR peak

$\overline{MLR}$

second MLR peak

Back surface (Δ = 2.5 cm): adiabatic

Computational grid: Δx = 200 μm

Laminar Wall Fires

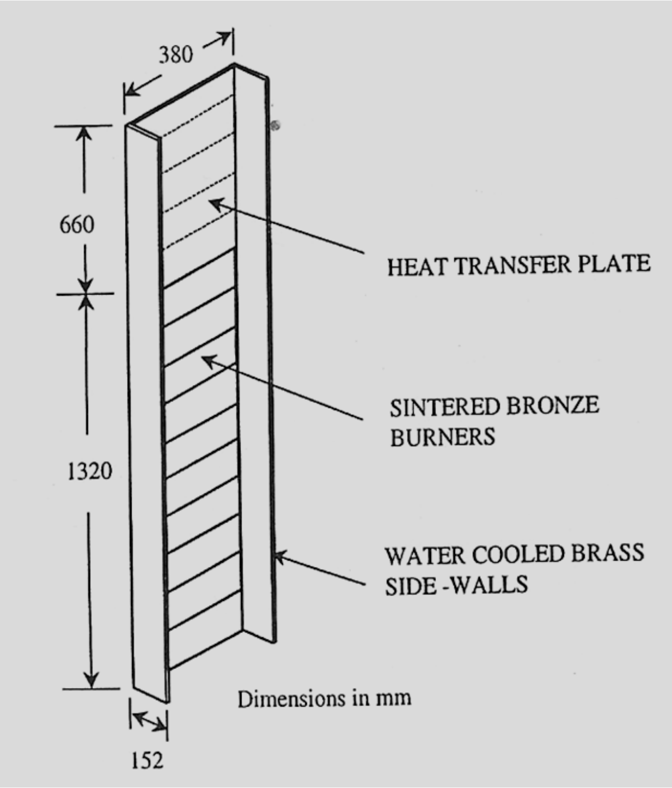
- **Summary**
  - Wall fires are characterized by a strong coupling between gas and solid phase processes
    - the gas-to-solid heat transfer drives pyrolysis
    - the solid-to-gas fuel mass transfer drives combustion
  - The Emmons solution identifies the B number as the main parameter to compare and rank different materials

Modeling of Turbulent Wall Fires

- Outline
  - Overview of Compartment Fire Dynamics
    - Multi-physics problem
    - Role of wall fires
  - Laminar Wall Fires
    - Analytical solution of a canonical wall flame problem – the Emmons problem (non-spreading; constant wall temperature; no thermal radiation)
  - **Turbulent Wall Fires**
    - **Large eddy simulation of a canonical wall fire problem (non-spreading; vertical wall)**

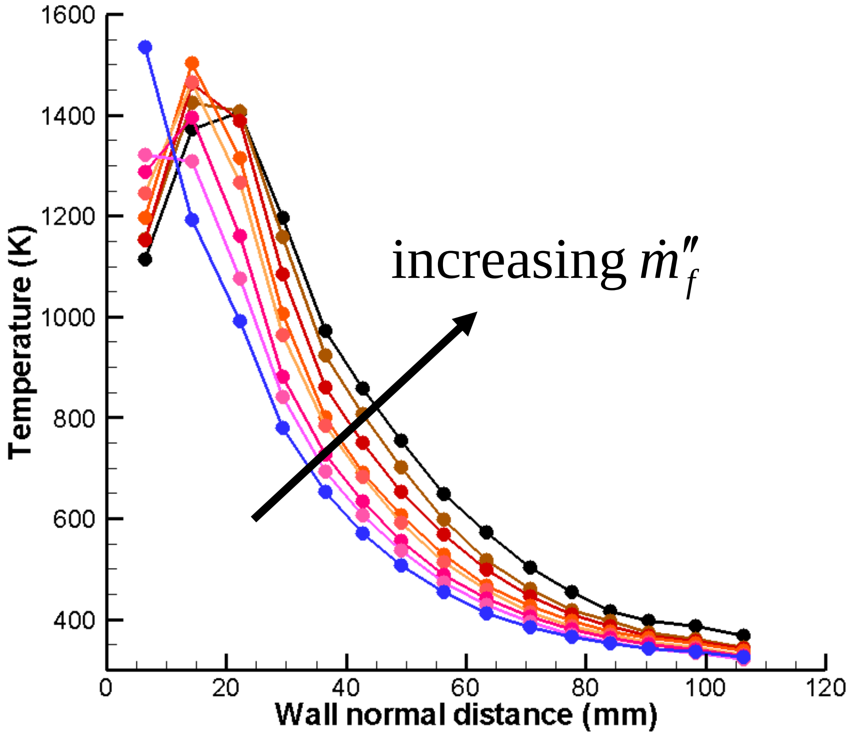
Turbulent Wall Fires

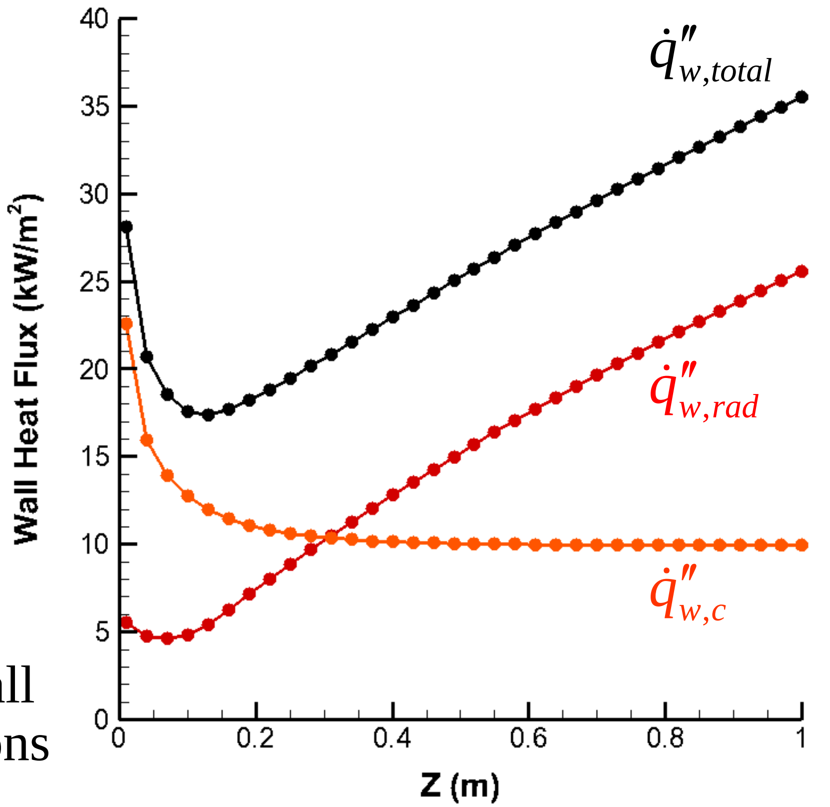
- Ongoing large eddy simulation study (N. Ren, S. Vilfayeau, Y. Wang, A. Trouvé)
- Experimental database: simplified vertical wall flame configuration (J.L. de Ris, FM Global 1999)
  - Porous burners with gaseous fuel (prescribed fuel mass loss rate); use different fuels (propylene, ethylene, ethane, methane) and different fuel injection rates
  - Quasi two-dimensional configuration
  - Main diagnostics: total wall heat flux (water cooling system); radiative wall heat flux (radiometers); soot layer thickness (soot deposition on glass rod); temperature profiles (thermocouples)



Turbulent Wall Fires

- Experimental database (J.L. de Ris, FM Global 1999)
  - ➢ Temperature profiles for different values of MLR





- ➢ Convective/radiative/total wall heat fluxes at different elevations

FireFOAM

- Open-source fire model supported by FM Global, USA
- Based on OpenFOAM: OpenFOAM is a general-purpose advanced CFD solver developed by OpenCFD, UK (*http://www.opencfd.co.uk*)
- Main features
  - Library of solvers: LES approach for turbulence; compressible flow formulation
  - Advanced physical models for LES, turbulent combustion, heat transfer
  - Numerical methods: finite volume scheme (2nd order in space); implicit time integration (2nd order in time)
  - Advanced meshing capabilities: structured or unstructured (polyhedral) computational grid (built-in mesh generation capability)
  - Software engineering: public domain (*http://code.google.com/p/firefoam-dev/*); open source (object-oriented C++ environment); Linux OS; massively parallel capability (MPI-based)
  - Post-processing: third-party visualization with ParaView (open source)

Turbulent Wall Fires

- LES computational grid design (wall-resolved LES)
  - Two characteristic length scales

    Boundary layer thickness δ_{BL}

    Viscous sub-layer thickness δ_{VSL}

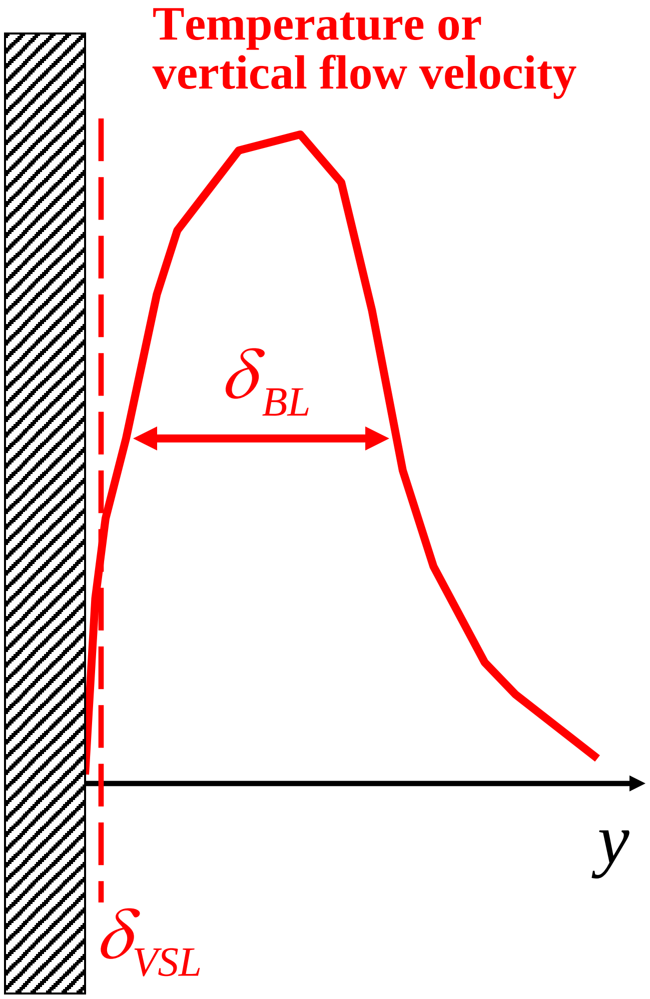
    - Momentum-driven flow

$$\delta_{VSL} \approx \frac{\nu_w}{(\tau_w / \rho_w)^{1/2}} \approx 0.2\,\text{mm}$$

    - Buoyancy-driven flow

      (Hölling & Herwig, *J. Fluid Mech.*, 2005)

$$\delta_{VSL} \approx \frac{(\nu_w / \Pr)^{3/4}}{(\dot{q}''_{w,c} / \rho_w c_{p,w})^{1/4} (g\beta_w)^{1/4}} \approx 0.5\,\text{mm}$$

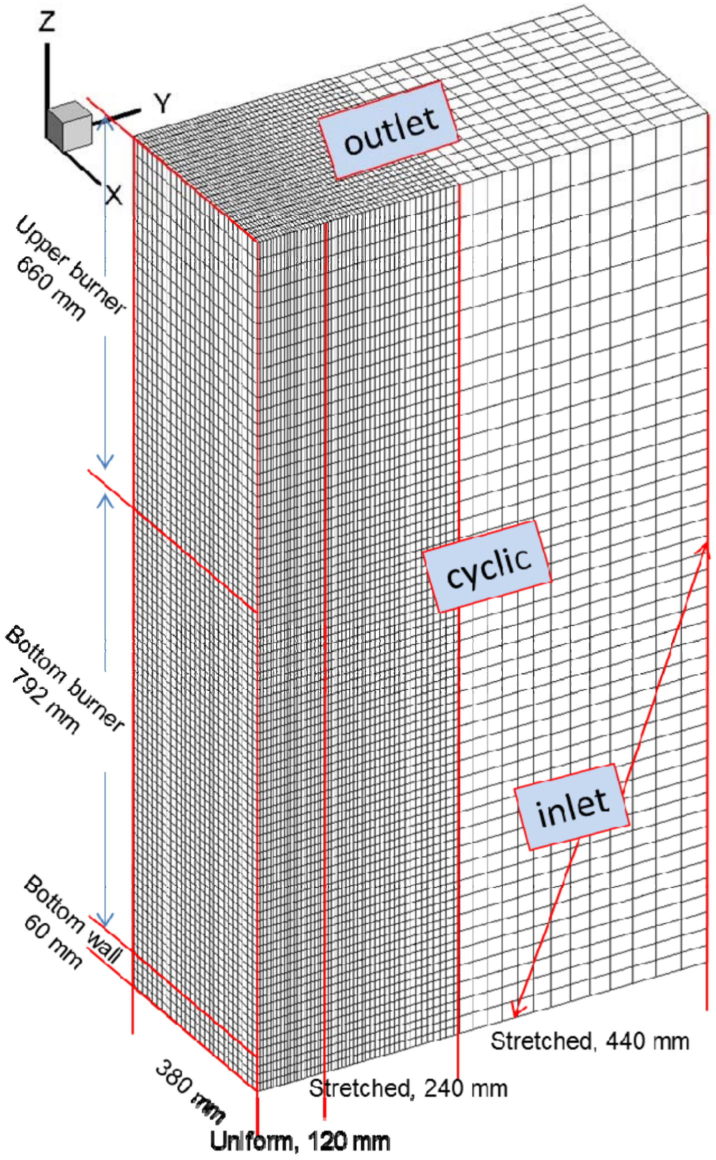


Turbulent Wall Fires

- Numerical configuration
  - Baseline case
    (propylene fuel C_3H_6; $\dot{m}_f'' = 17\ \mathrm{g/s/m^2}$)
    (isothermal wall; $T_w = 348$ K)
  - Block-structured grid (0.9 million cells)
  - Near-wall resolution

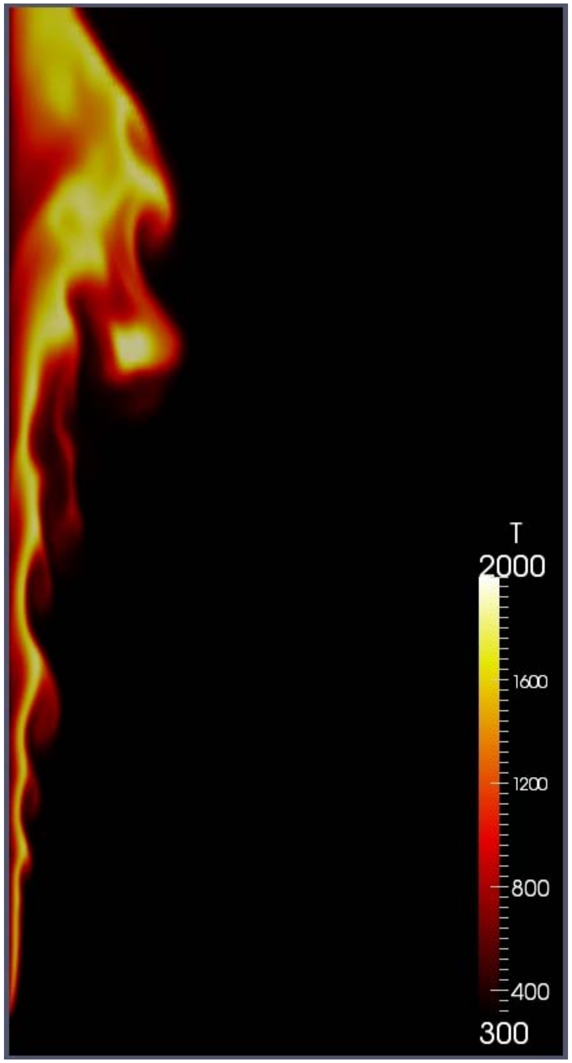
$$\Delta y_1 = 2\ \mathrm{mm}$$

$$\Delta z = \Delta x = 2.5 \times \Delta y_1 = 5\ \mathrm{mm}$$



Turbulent Wall Fires

- Modeling choices (FireFOAM v.1.7.x)
  - *Turbulence*: dynamic *k*-equation eddy viscosity model coupled with WALE model
  - *Combustion*: Eddy Dissipation Concept model
  - *Soot*: mixture-fraction-based flamelet correlation
  - *Radiation*: RTE solver; finite volume model (angular space discretized using 64 solid angles)



Turbulent Wall Fires

- Modeling choices (FireFOAM v.1.7.x)
  - *Turbulence*: dynamic *k*-equation eddy viscosity model coupled with WALE model (Nicoud & Ducros 1999)

$$S^d_{ij} = \overline{S}_{ik}\overline{S}_{kj} + \overline{\Omega}_{ik}\overline{\Omega}_{kj} - \frac{1}{3}\delta_{ij}\left(\overline{S}_{mn}\overline{S}_{mn} - \overline{\Omega}_{mn}\overline{\Omega}_{mn}\right)$$

$$\overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right), \qquad \overline{\Omega}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} - \frac{\partial \overline{u}_j}{\partial x_i}\right)$$

$$\mu_{sgs} = \rho\left(C_w\Delta\right)^2 \frac{\left(S^d_{ij}S^d_{ij}\right)^{3/2}}{\left(\overline{S}_{ij}\overline{S}_{ij}\right)^{5/2} + \left(S^d_{ij}S^d_{ij}\right)^{5/4}}$$

Turbulent Wall Fires

- Modeling choices (FireFOAM v.1.7.x)
  - *Combustion*: Eddy Dissipation Concept model (Magnussen & Hjertager 1976)

$$\boxed{F + r_s O_2 \rightarrow (1 + r_s) P}$$

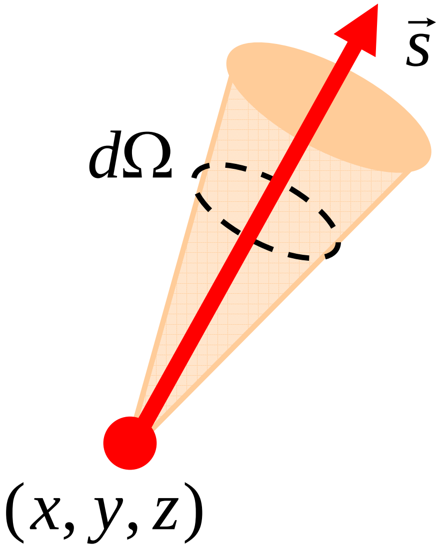
$$\overline{\dot{\omega}'''_F} = \overline{\rho} \times \frac{\min(\tilde{Y}_F ; \tilde{Y}_{O_2} / r_s)}{\min\left(\tau_t / C_{EDC},\ \tau_d / C_d\right)}$$

$$\text{where } \tau_t = (\Delta / k_{sgs}^{1/2}) \text{ and } \tau_d = (\Delta^2 / D_{th})$$

Turbulent Wall Fires

- Modeling choices (FireFOAM v.1.7.x)
  - *Radiation*: RTE solver; finite volume model (angular space discretized using 64 solid angles)

$$\frac{dI}{ds} = \underbrace{\kappa(\sigma T^4/\pi)}_{\text{Emission}} - \underbrace{\kappa I}_{\text{Absorption}}$$



Planck mean absorption coefficient [m^{-1}]

$$\kappa = p(x_{H_2O}a_{H_2O} + x_{CO_2}a_{CO_2}) + \kappa_{soot}$$

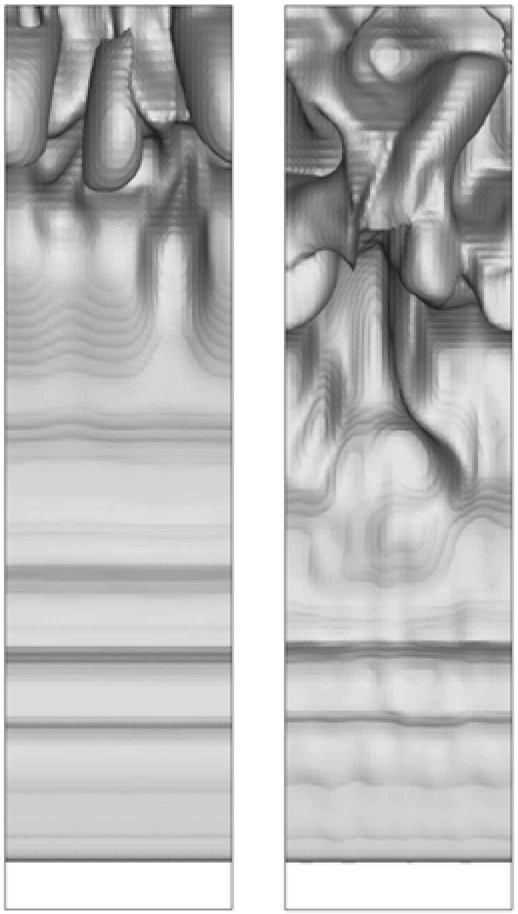
where:

- $a_{p,i}$ is the Planck mean absorption coefficient for species i [m^{-1} atm^{-1}] and is obtained from tabulated data
- κ_{soot} is the soot mean absorption coefficient [m^{-1}]

$$\kappa_{soot} = C_{soot} \times f_v T$$

Turbulent Wall Fires

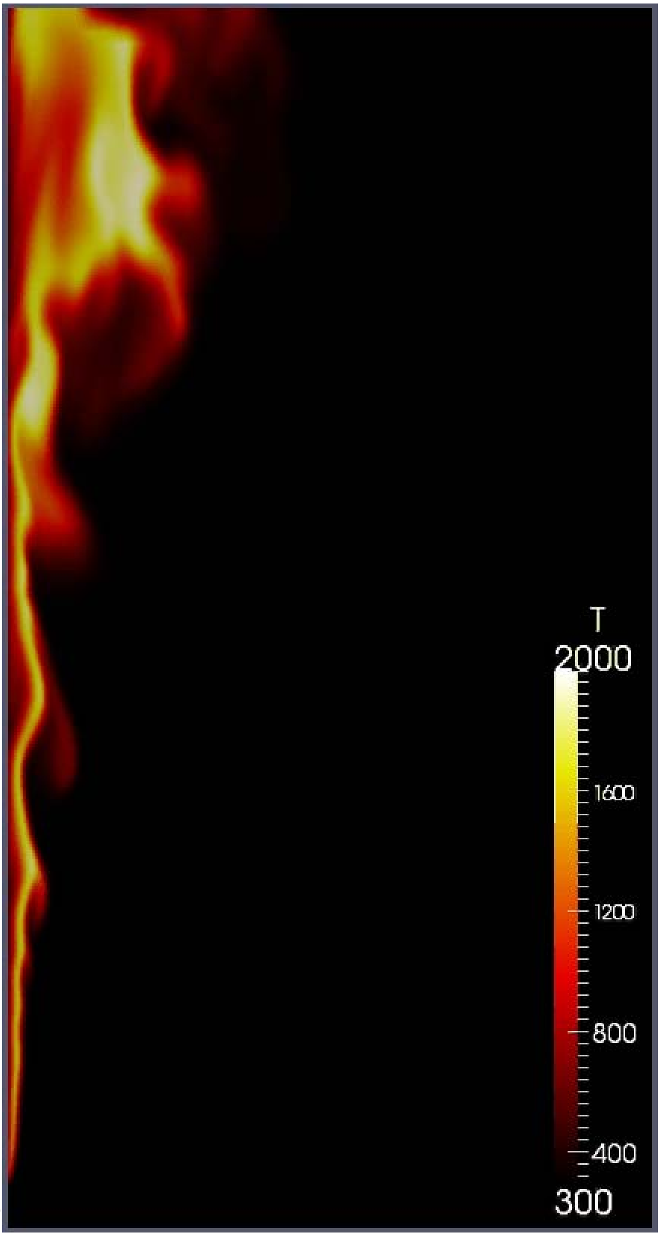
- Modeling choices (FireFOAM v.1.7.x)
  - Laminar-to-turbulent flow transition:
    - Flame at the base of the wall is laminar
    - Laminar region is over-estimated in the LES simulations
    - Force transition by using a forcing scheme acting on the fuel flow rate at the base of the wall

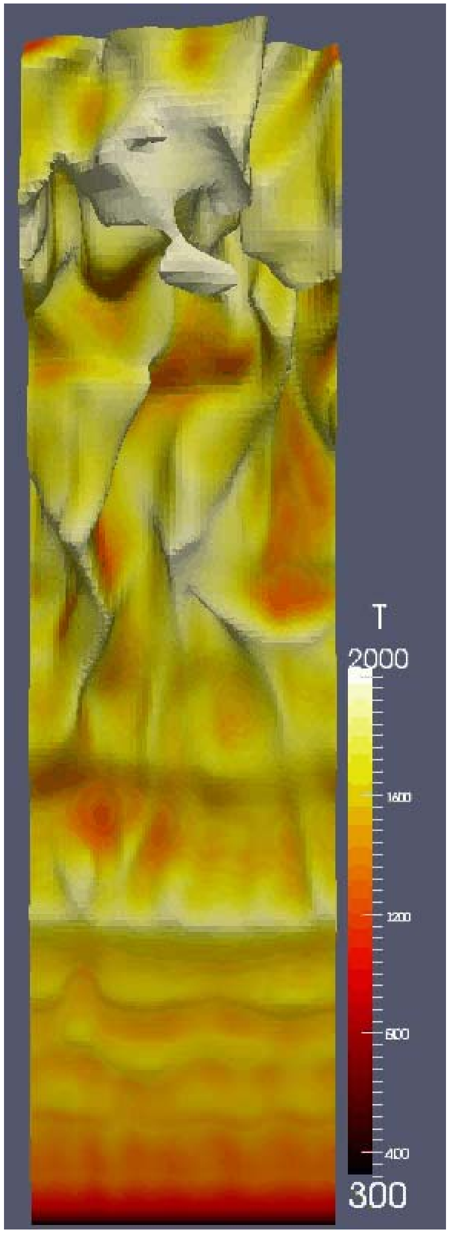


Constant flow rate

Perturbed flow rate

Turbulent Wall Fires

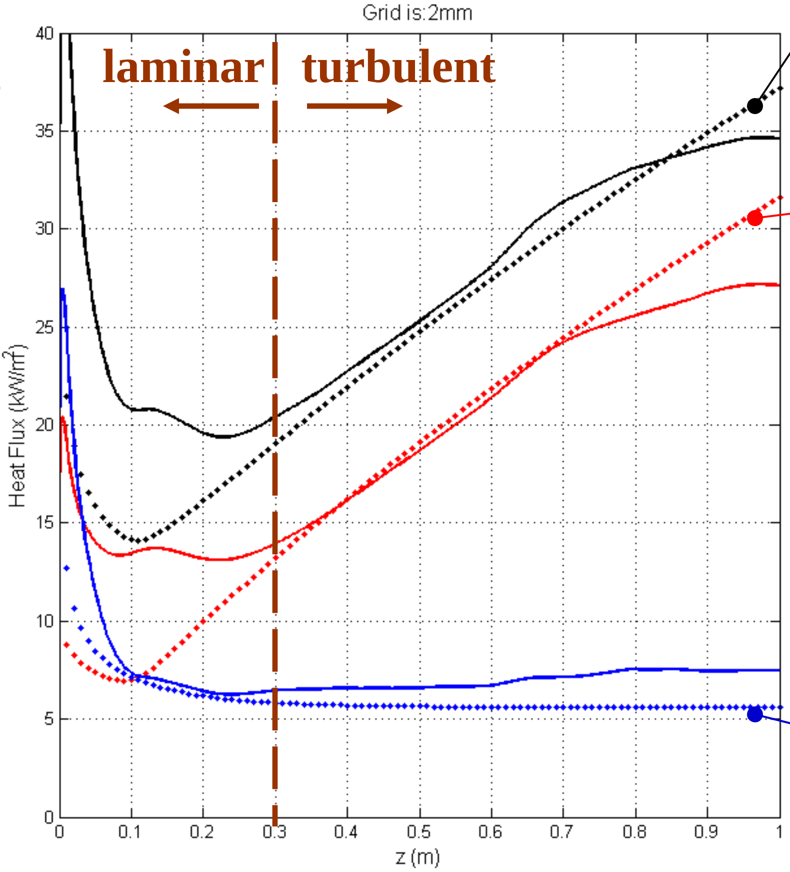




Turbulent Wall Fires

- Results
  - Wall heat flux versus elevation *z*

<u>Solid lines</u>: LES



Experimental data

$\dot{q}''_{w,total}$

FMG Model

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

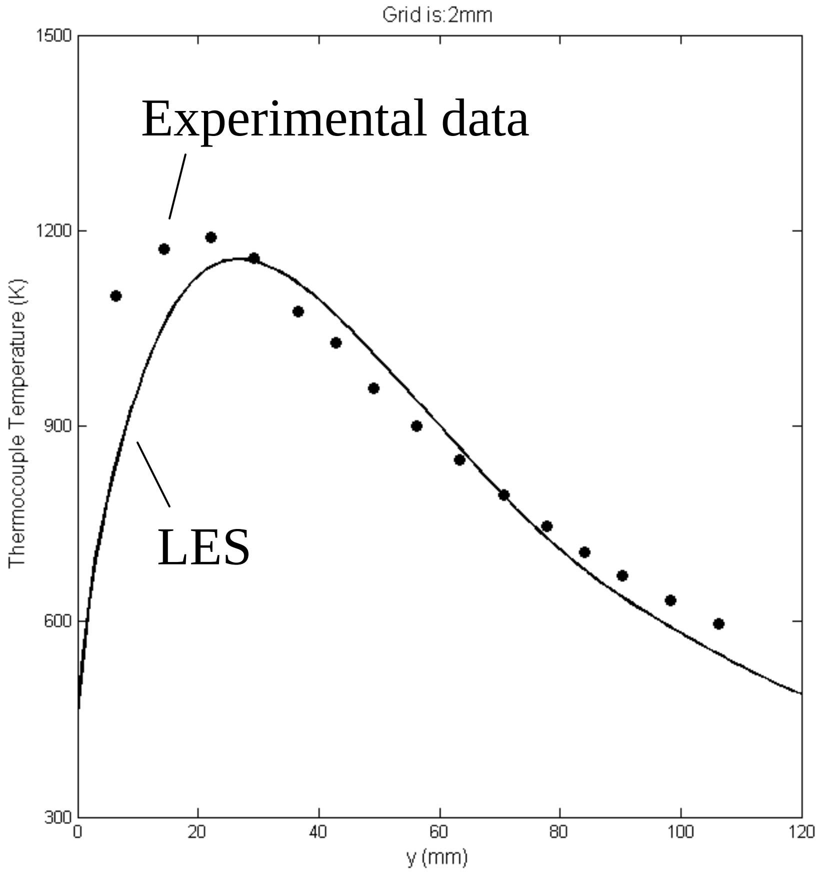
$\dot{q}''_{w,c}$

FMG Model

Turbulent Wall Fires

- Results
  - ➢ Wall-normal profile of mean temperature

$z = 77$ cm



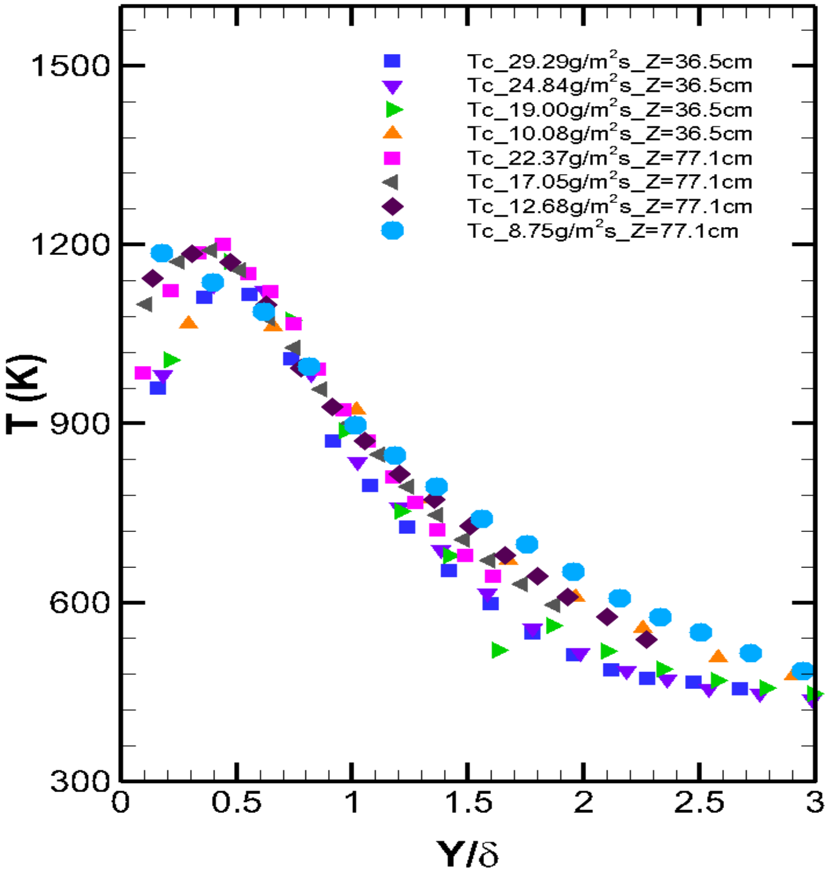
- Comparison between raw (uncorrected) thermocouple measurements and LES “thermocouple data”
- LES thermocouple (TC) data are obtained from a *virtual instrument* model:

$$\rho_{TC} C_{TC} \frac{V_{TC}}{A_{TC}} \frac{dT_{TC}}{dt} = \varepsilon_{TC}\left(G - \sigma T_{TC}^4\right) + h\left(T_{gas} - T_{TC}\right)$$

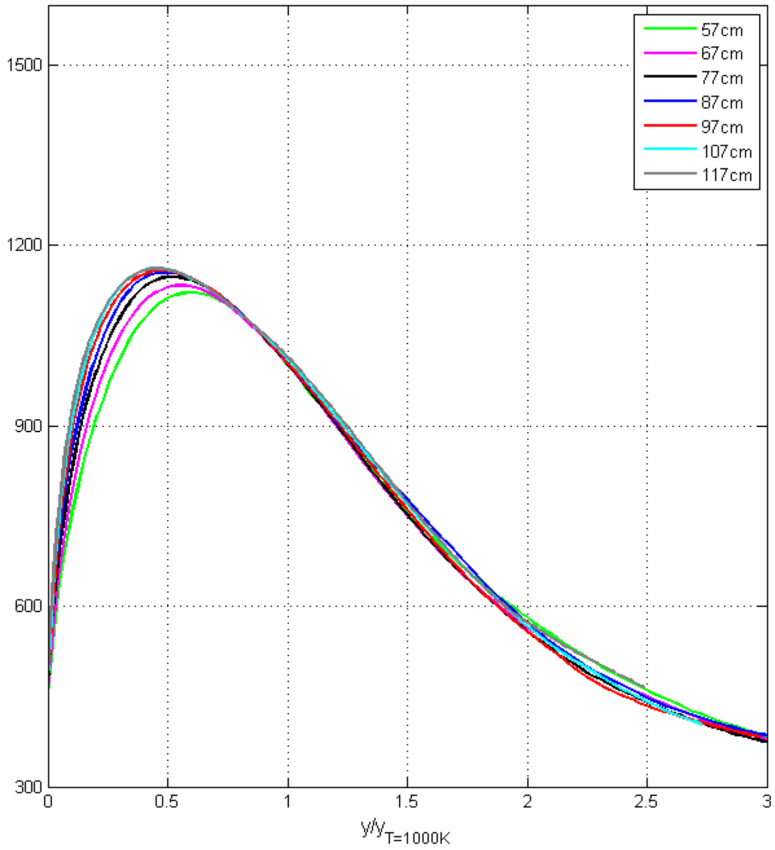
Turbulent Wall Fires

- Results
  - Evaluation of self-similarity in wall-normal profiles of mean temperature

Experimental data

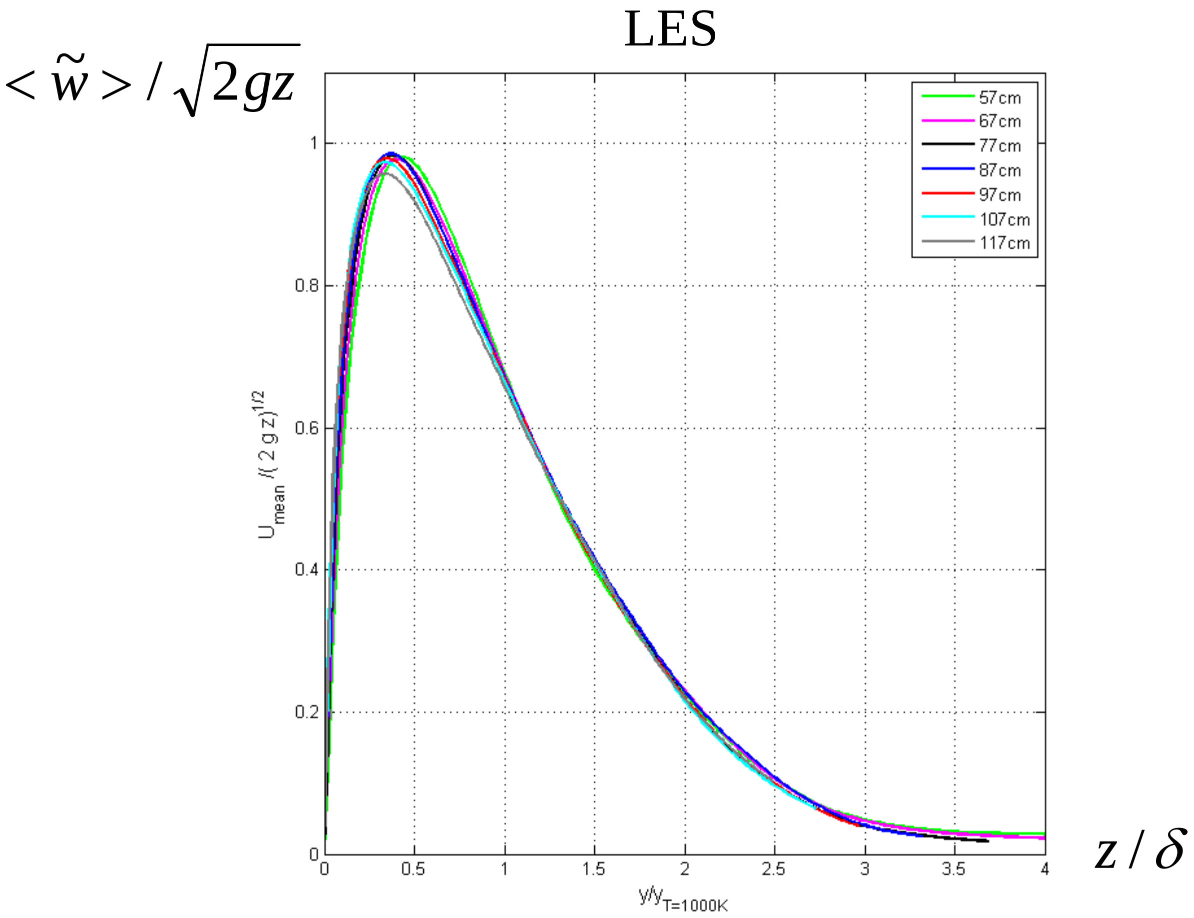


LES



Turbulent Wall Fires

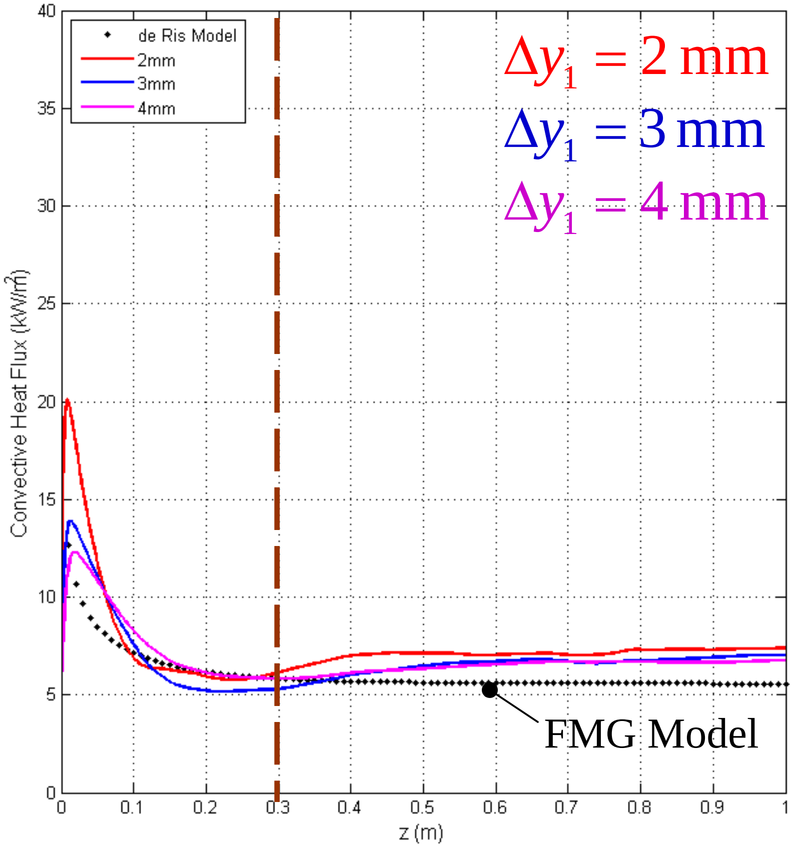
- Results
  - Evaluation of self-similarity in wall-normal profiles of mean *z*-velocity



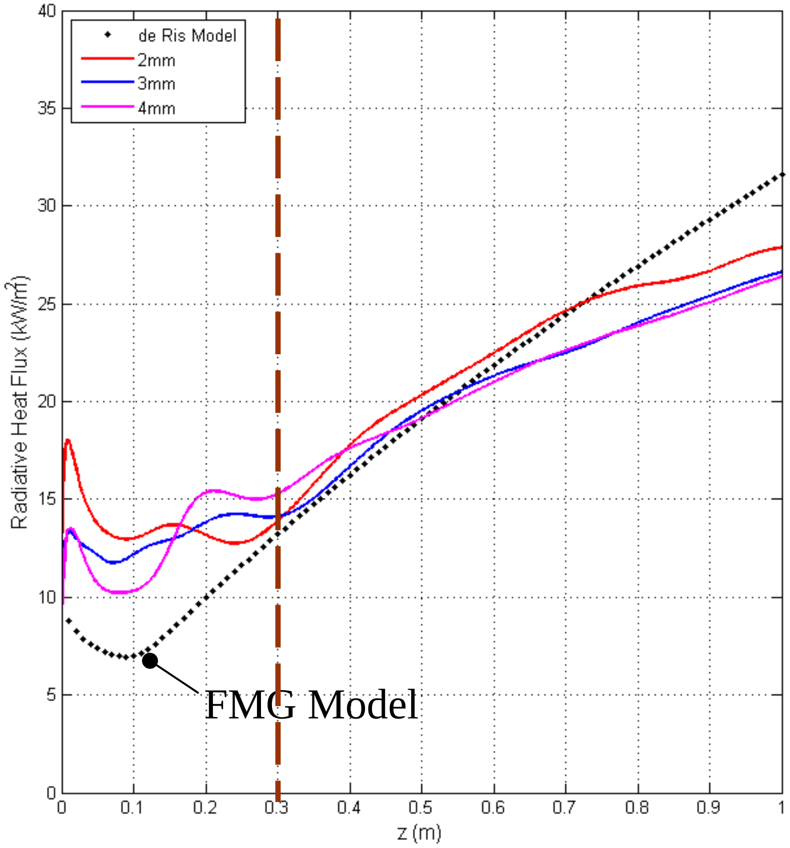
FireFOAM Results

- Results: grid convergence study
  - Wall heat flux versus elevation *z*

$\dot{q}''_{w,c}$



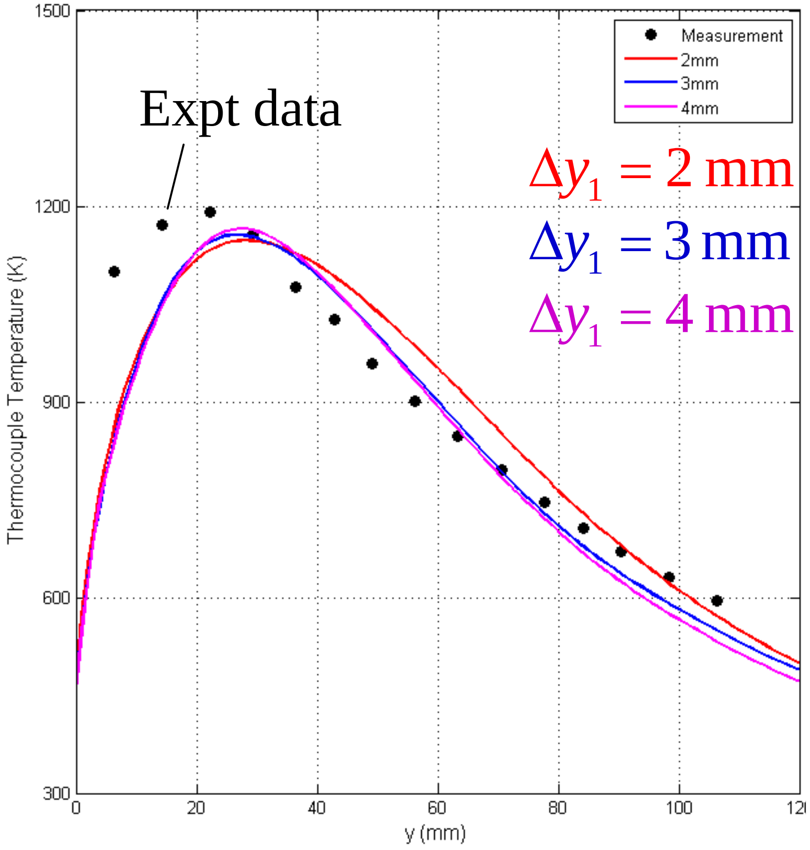
$\dot{q}''_{w,rad}$



FireFOAM Results

- Results: grid convergence study
  - Wall-normal profile of mean temperature and *z*-velocity

$< \tilde{T} >$



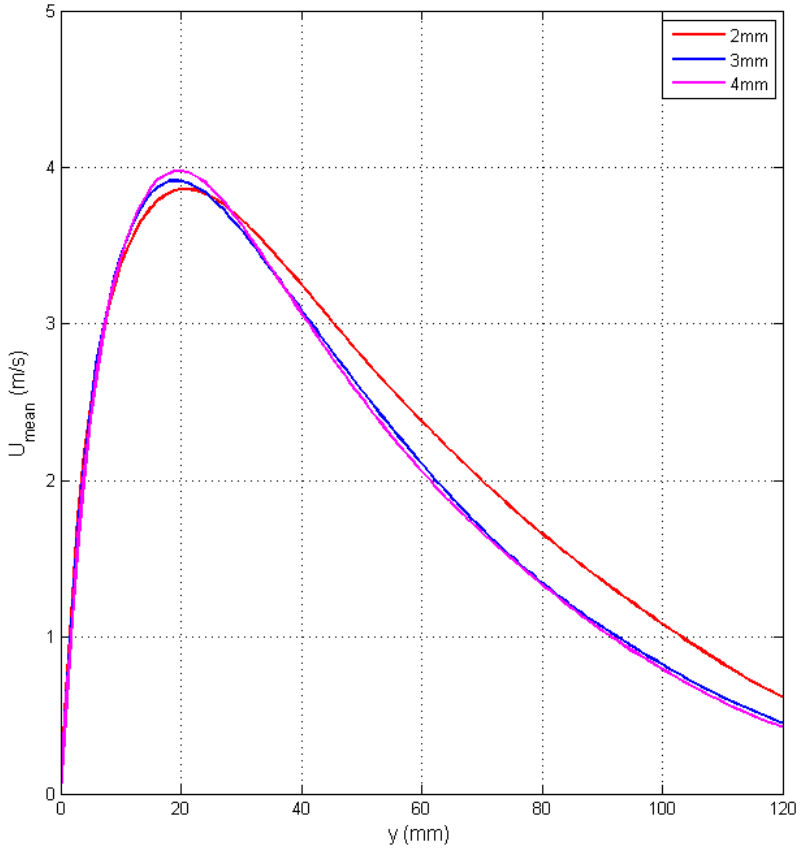
Expt data

$\Delta y_1 = 2\,\mathrm{mm}$

$\Delta y_1 = 3\,\mathrm{mm}$

$\Delta y_1 = 4\,\mathrm{mm}$

$< \tilde{w} >$



Conclusion

- **Summary**
  - First step in a model development/validation strategy: wall-resolved LES of a simplified configuration (non-spreading vertical wall flame; prescribed fuel flow rate)
    - Features: low (transition) Reynolds number conditions; laminar base region and a weakly turbulent downstream region
    - Results are encouraging. But: the size of the laminar base region is overestimated in the simulations; and the LES combustion and radiation models lack accuracy under laminar-like conditions
  - The experimental database is limited to first-order statistical moments and there is a need to extend the scope and quality of experimental data (velocity measurements, second-order moments, *etc*)