# Unsteady fire simulation with Code_Saturne


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# Schedule

- Context
- Fire physical basics and modelling
  - Fire scenario
  - Characteristics
  - Couplings
- Unsteady density variation effect
  - Density variation disabled
  - Density variation estimation
  - Application to combustion
- Application: Low Froude number flames
- Conclusion and future works

# Fire in EDF's nuclear field

Fire is the **first internal aggression** :

~ 60 fire starts/year for 58 nuclear plant units

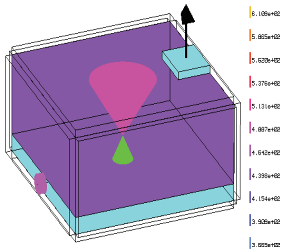
- Costs :
  - Cattenom 2004 : 22 days off costing 300 k€ = 6.6 M€
  - Fire security systems replacement in EDF's plants : 500 M€ (Plan Action Incendie 1999-2006).

- Causes :

| | |
|---|---|
| *Electric* | the main causes, dynamic (short-circuit, over-current, under-calibrated cable section) or static (friction, lightning). |
| *Mechanic* | overheating by friction. |
| *Thermal* | hot spots (cigarette), sparks (engine), welding works (fire authorization), heating system (building maintenance), surface overheating |
| *Chemical* | product reaction (paints, varnishes, solvents), combustion (greased rag mix, oil in basket, etc.) |

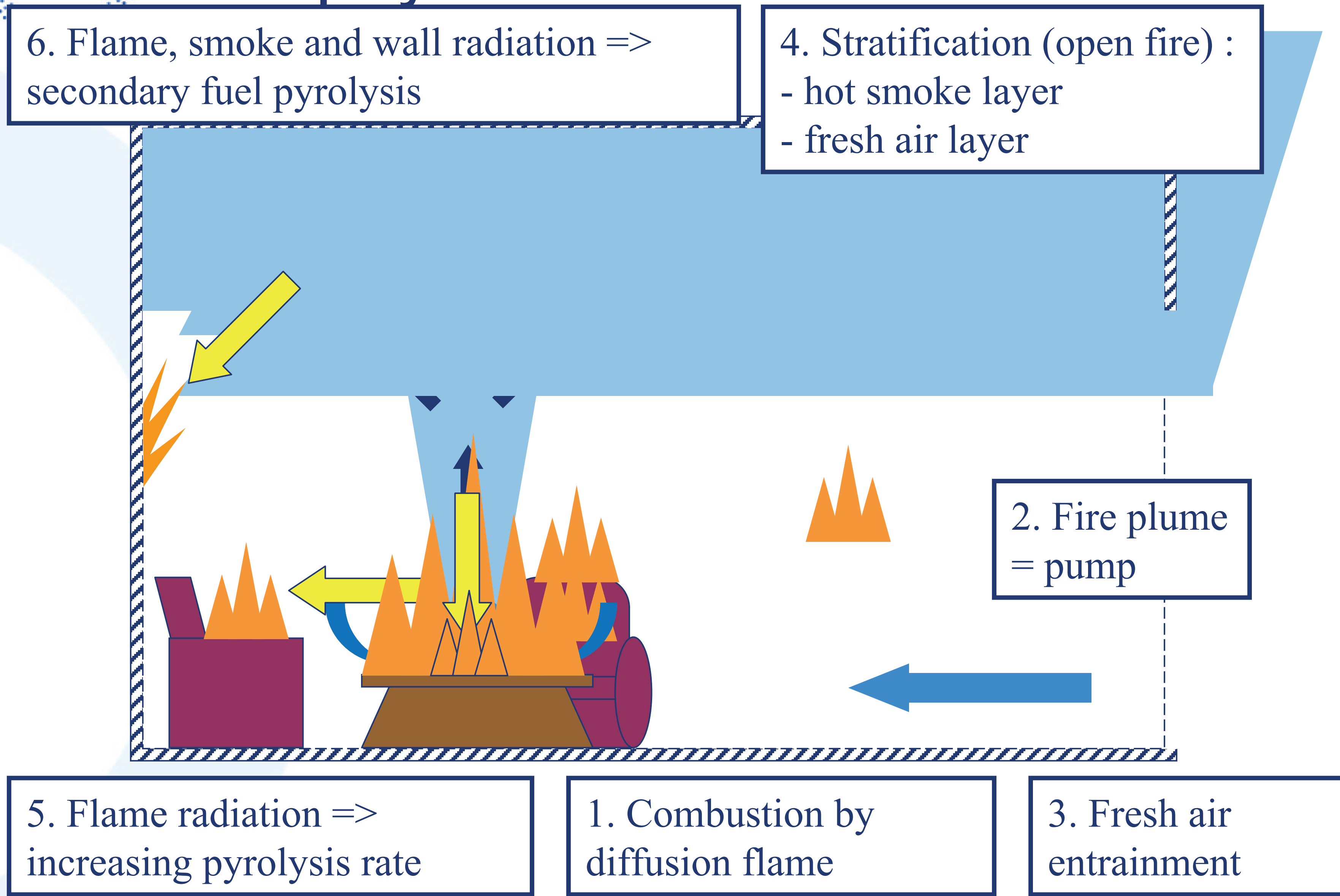
# Why Code_Saturne ?

- MAGIC
  - Zone model developed at EDF R&D for 20 years,
  - Industrially mature and international accreditation (EPRI + NRC).



- MAGIC limitations
  - Due to gas stratification, two zones, global values
  - Spatial description simpler than CFD (ex. pool position effect on wall temperature).
- CFD advantages
  - Local scalar values, better flow description (ex aeraulic short-circuits),
  - MAGIC validation range enlargement (larger volumes, complex geometry).
- EDF R&D views: *Code_Saturne* based development
  - code IPS (Important Pour la Sûreté), final engineering fire version expected,
  - Code rationalisation (*Code_Saturne* already used at SEPTEN),
  - Technical skills and intern/extern synergy

# Fire physical basics



# Fire physical basics: characteristics

- Vaporization or pyrolysis : weak combustible emission rate ~ g/m$^2$/s

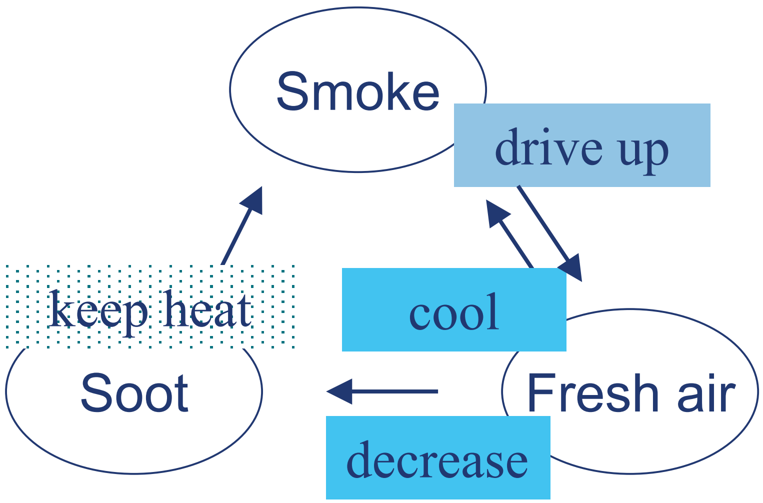
  => inlet speed ~ mm/s

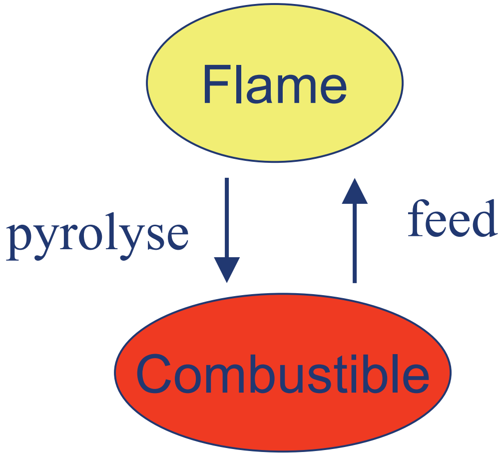
- Combustion : cold reactants $\rightarrow$ hot products : $\rho$ ~ 1 to 0,1kg/m$^3$ :
  - Strong buoyancy forces $(\rho - \rho_0)g$
  - Strong thermal expansion $\partial\rho/\partial t \neq 0$
- Large eddy turbulent structures (~ pool dimension)
  - Hot gas puffs (2-3 Hz) burning rising + global oscillation (< 0,1 Hz)

    => complex unsteady phenomena
  - Smoke dilution by fresh air (affect temperature, concentrations,…)
- Confinement effect
  - Stratification: hot smoke vs. fresh air
  - Extinction, reignition, flashover

# Fire physical basics: couplings

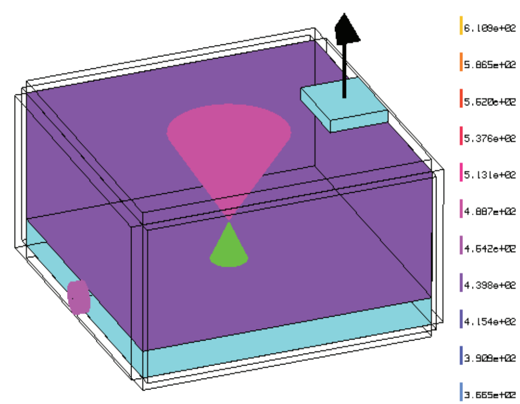
- Velocity / Density: thermal expansion
  - flow speeded up by expansion
  - variation density modified by the flow
- Smoke/fresh air: natural convection
  - hot smoke raise in the plume and drive up fresh air
  - smoke temperature and natural convection decrease
  - but, less soot formed by the complete combustion which keep smoke temperature and air entrainment high
- Flame/fuel, wall, interface : radiation
  - pyrolysis (or vaporization) is incident heat flux-dependant from flame
  - pyrolysis products feed the radiant flame



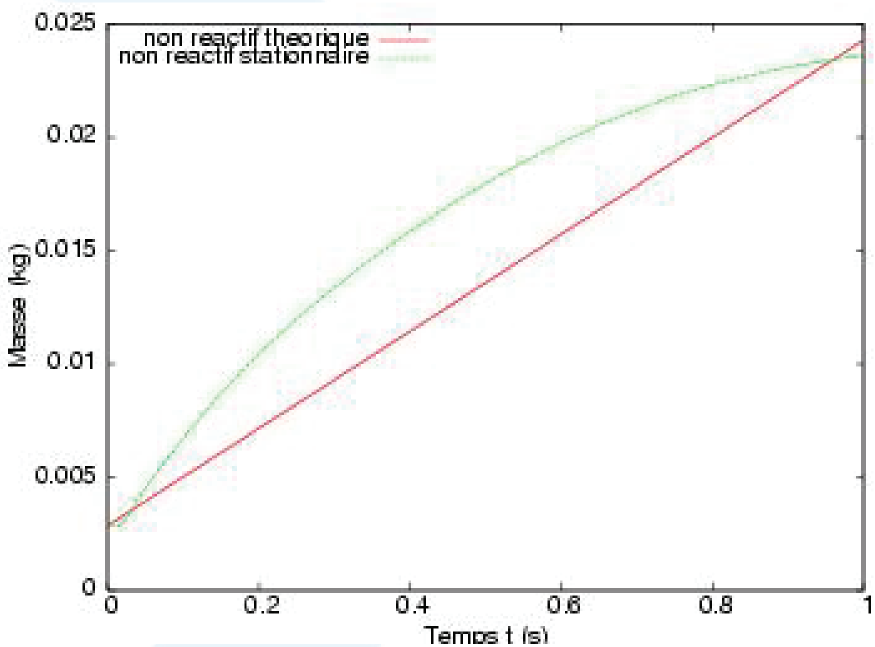
# Modelling with Code_Saturne

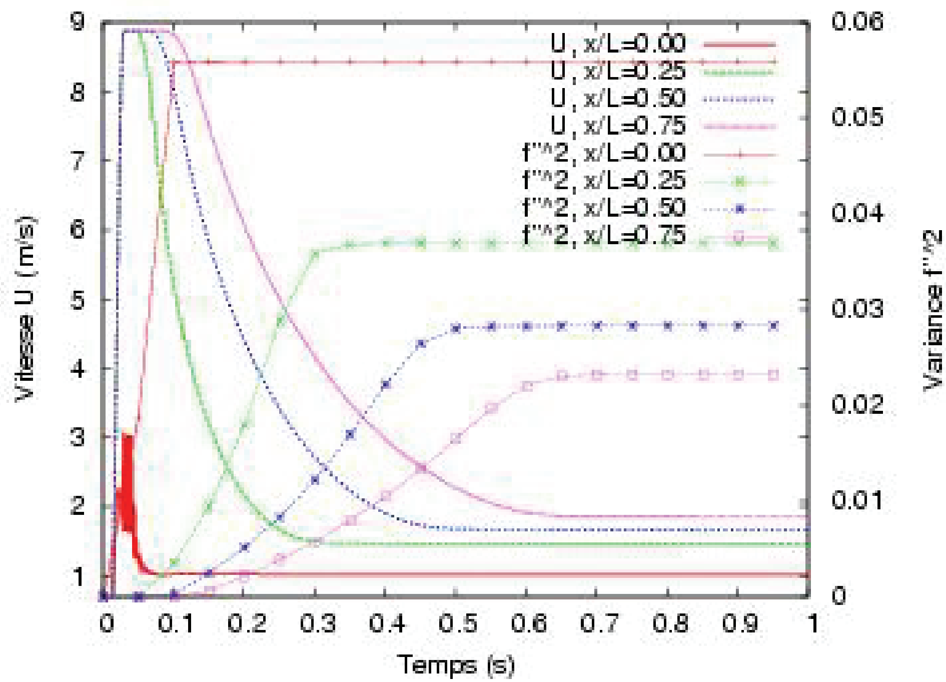
- Physical modelling
  - **Unsteady RANS** (k-ε) (enough to pick up very large eddies )
  - Infinitely fast combustion (diffusion flame): **F + Ox → P**
  - Radiation of a grey gas and soot composition (radiant transfer equation solver)
- Physic to improve
  - **Unsteady** density variation effect $\partial_t \rho + div(\rho \underline{u}) = \Gamma$
  - **Absorption** coefficient calculation and **soot** effect
  - **Pyrolysis** rate estimation
  - **Gas extinction** and **reignition**
  - Thermal **wall** effect $q_{loss} = \rho C_p \Delta T$
  - Fire security systems
- 1srt year objectives
  - Unsteady behaviour and radiation effect
  - One open-room fire, end of 2008



# Unsteady effects: fault

- Replacement of burnt gas by fresh gas ( calculation 1D, 100 meshes)


→ *Code_Saturne* = unsteady weakly compressible flows

# Steady Navier-Stokes

- Prediction : $\partial_t(\rho \underline{u}) + div(\rho \underline{u} \otimes \underline{u}) = -\underline{grad}\, p + div(\underline{\underline{\tau}}) + \rho \underline{g}$
  - Explicit pressure $p=p^n$ $\Rightarrow$ predicted velocity $\underline{\tilde{u}}^{n+1}$
- Correction :
  - Pressure increment addition $\delta p^{n+1}$

$$\rho \partial_t \underline{u} = -\underline{grad}\ \delta p^{n+1} \Rightarrow \rho \underline{u}^{n+1} - \rho \underline{\tilde{u}}^{n+1} = -\Delta t\, \underline{grad}\ \delta p^{n+1}$$

  - Continuity equation $div(\rho \underline{u}^{n+1}) = \Gamma - \partial_t \rho$ → 0

$$div(\Delta t\ \underline{grad}\ \delta p^{n+1}) = div(\rho \underline{\tilde{u}}^{n+1}) - \Gamma + \partial_t \rho$$ → 0

→ $$\underline{u}^{n+1} = \underline{\tilde{u}}^{n+1} - \frac{\Delta t}{\rho} \underline{grad}\ \delta p^{n+1}$$

# Unsteady Navier-Stokes (1/2)

- Derivative calculation by **independent** scalar fields, ex: $\rho(f)$

$$\begin{cases} \mathrm{d}_t\rho + \rho\, div(\underline{u}) = \Gamma & \times \dfrac{\rho}{\frac{\partial\rho}{\partial f}} \\ \rho\,\mathrm{d}_t f = div(D_f\, \underline{grad}\ f) + \rho S_f & \text{ac } \mathrm{d}_t f = \dfrac{1}{\frac{\partial\rho}{\partial f}}\mathrm{d}_t\rho \end{cases}$$

$$\Rightarrow \begin{cases} \dfrac{\rho}{\frac{\partial\rho}{\partial f}}\mathrm{d}_t\rho + \dfrac{\rho^2}{\frac{\partial\rho}{\partial f}} div(\underline{u}) = \dfrac{\rho}{\frac{\partial\rho}{\partial f}}\Gamma & (1) \\ \dfrac{\rho}{\frac{\partial\rho}{\partial f}}\mathrm{d}_t\rho = div(D_f\, \underline{grad}\ f) + \rho S_f & (2) \end{cases}$$

$$(1)-(2) \quad \Rightarrow \quad div(\underline{u}) = \frac{1}{\rho}\Gamma + \boxed{\begin{aligned} &\frac{1}{\rho^2}\frac{\partial\rho}{\partial f}\left[div(-D_f\ \underline{grad}\ f) - \rho S_f\right] \\ &= -\frac{1}{\rho}\mathrm{d}_t\rho \end{aligned}}$$

# Unsteady Navier-Stokes (2/2)

- Prediction : $\partial_t(\rho \underline{u}) + div(\rho \underline{u} \otimes \underline{u}) = -\underline{grad}\, p + div(\underline{\underline{\tau}}) + \rho \underline{g}$
  - Explicit pressure $p=p^n \Rightarrow$ predicted velocity $\underline{\tilde{u}}^{n+1}$
- Correction :
  - Pressure increment addition $\delta p^{n+1}$

$$\partial_t \underline{u} = -\frac{1}{\rho}\underline{grad}\, \delta p^{n+1} \Rightarrow \underline{u}^{n+1} - \underline{\tilde{u}}^{n+1} = -\frac{\Delta t}{\rho}\underline{grad}\, \delta p^{n+1}$$

  - Continuity equation $$div(\underline{u}^{n+1}) = \frac{1}{\rho}\Gamma - \frac{1}{\rho}\mathrm{d}_t \rho$$

$$div\left(\frac{\Delta t}{\rho}\underline{grad}\, \delta p^{n+1}\right) = \frac{1}{\rho}\Gamma - div(\underline{\tilde{u}}^{n+1}) + \frac{1}{\rho^2}\frac{\partial \rho}{\partial f}\left[div(-D_f\, \underline{grad}\, f) - \rho S_f\right]$$

$$\underline{u}^{n+1} = \underline{\tilde{u}}^{n+1} - \frac{\Delta t}{\rho}\underline{grad}\, \delta p^{n+1}$$

# Infinitely fast chemistry !

Combustible + Oxidant $\longrightarrow$ Products

- Infinitely fast chemistry :
  - No reactants coexistence
  - Complete reaction at stoechiometry
- Mixture fraction : describe Comb/Ox mix

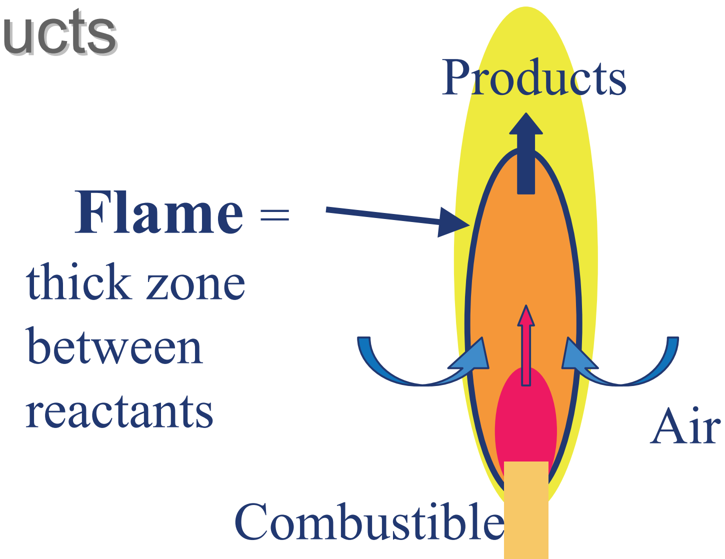
  Air: $f = 0$, combustible: $f = 1$

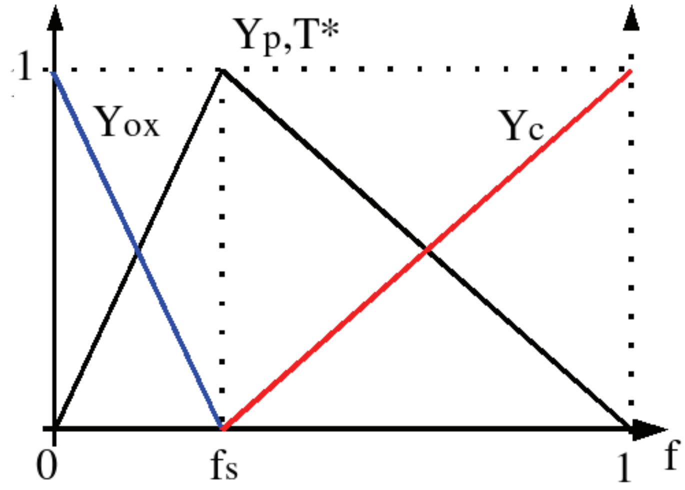
  Combustion products: $f = fs$

  No source term:

$$\partial_t(\rho f) + \partial_{x_j}(\rho u_j) = \partial_{x_j}(\rho D \partial_{x_j} f)$$

- Mass fractions $Y(f)$ and temperature $T(f)$ and density $\rho(f)$



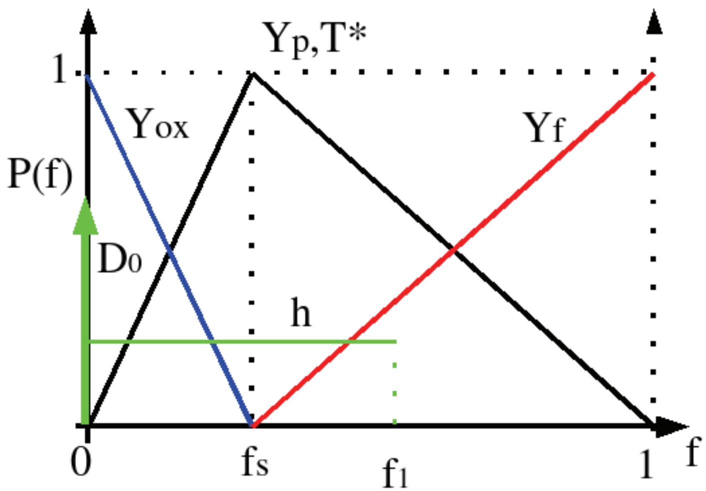



# Fire: a turbulent child

- Turbulence : fluctuations $\widetilde{f''^2}$ around the mean $\tilde{f}$ (2 transport equations)

$$\bar{\rho} = \int_0^1 \rho(f, T(f, H_s)) P(f) df$$

  - Presumed PdF determined by the two first moments and his shape
  - Lead to five parameters : $D_0, D_1, f_0, f_1, h$



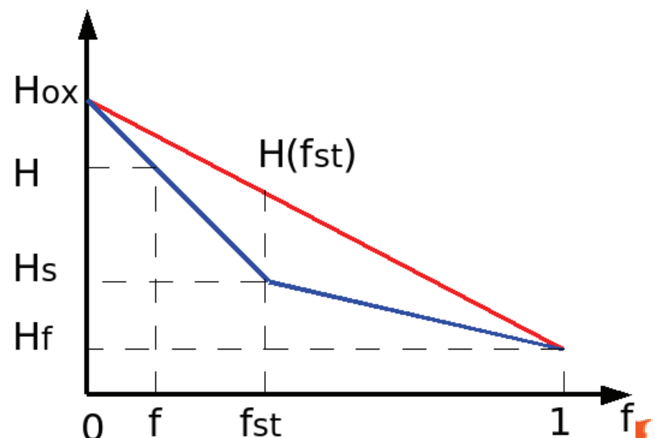

- Temperature calculation ($T(H_s)$ is tabulated):

$$T(f, H_s) = a(f, H_s) + b(f, H_s) T(H_s)$$

  - $H_s = f_{st}.H_f + (1-f_{st}).H_{ox}$ if adiabatic calculation
  - else $H_s$ is deduced from $H$ calculation:

$$\tilde{H} = \int_0^1 H(f) P(f) df = \alpha + \beta . H_s$$

$$\boxed{\bar{\rho} = \bar{\rho}\left(\tilde{f}, \widetilde{f''^2}, \tilde{H}\right)}$$



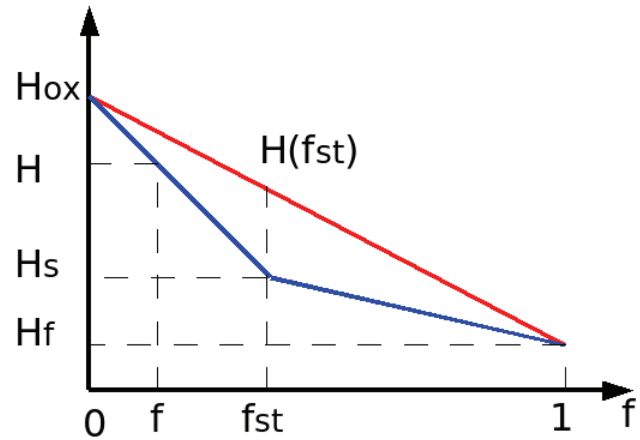
# Unsteady combustion

- Density derivative calculation for *f* and *f''*² : $\bar{\rho} = \bar{\rho}\left(\tilde{f}, \tilde{f}''^2, \tilde{H}\right)$
  - Use PdF parameters ***$D_0$, $D_1$, $f_0$, $f_1$, h***

$$\frac{\partial \bar{\rho}}{\partial \tilde{f}} = \frac{\partial}{\partial \tilde{f}} \int_0^1 \rho\left(f, T(f, H_s)\right) df = \int_0^1 \sum \frac{\partial \rho}{\partial p_i} \frac{\partial p_i}{\partial \tilde{f}} df \qquad p_i = D_0, D_1, f_0, f_1, h$$

- *H* and *f* are coupled by temperature $T\left(f, H_s\right) = a(f, H_s) + b(f, H_s) T\left(H_s\right)$
  - Some enthalpy effect already considered in *f* derivative $\tilde{H} = \alpha + \beta . H_s$

$$\frac{\partial \rho}{\partial \tilde{f}} = \frac{\partial \rho}{\partial T} \frac{\partial T}{\partial \tilde{H}} \frac{\partial \tilde{H}}{\partial \tilde{f}} \qquad \frac{\partial \rho}{\partial \tilde{H}} = \frac{\partial \rho}{\partial T} \frac{\partial T}{\partial \tilde{H}}$$

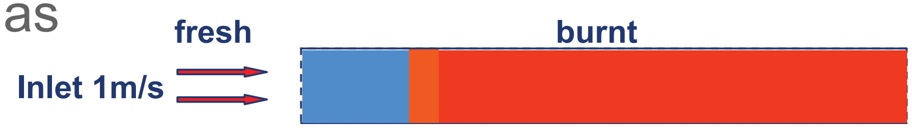


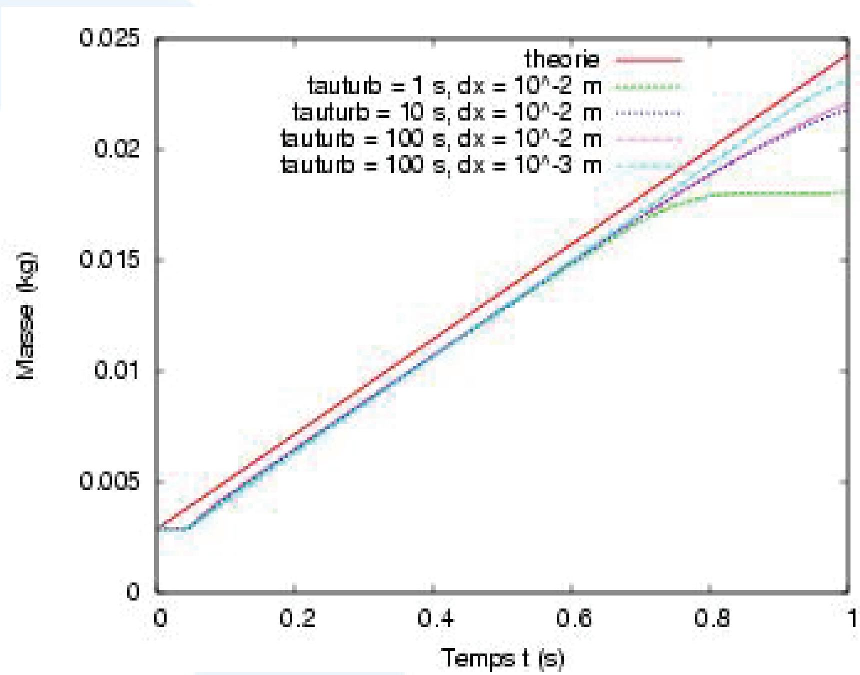

  - Derivative for $H_s$ instead of *H*:

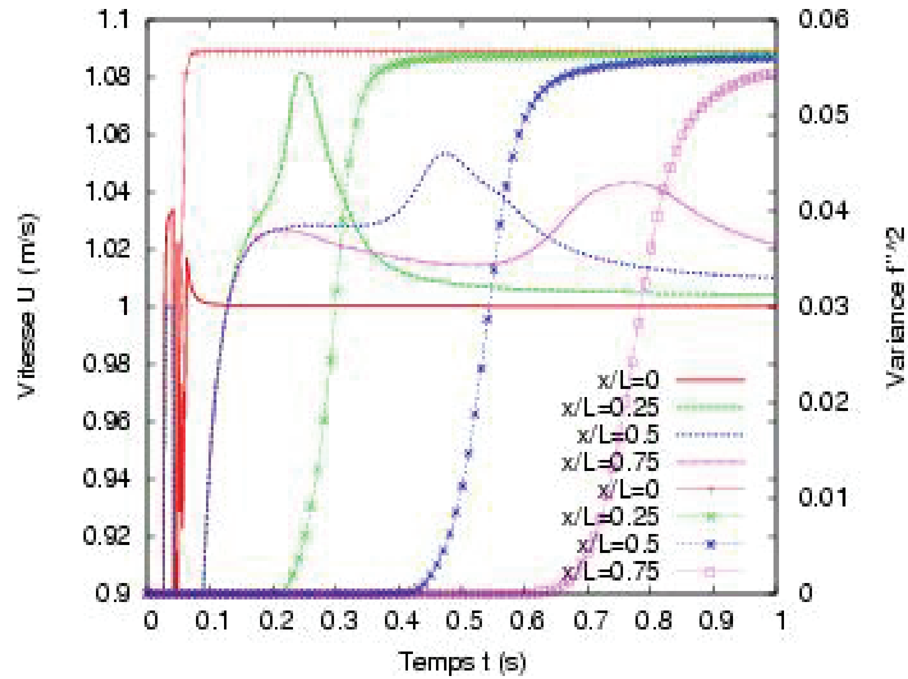
$$\frac{\partial \bar{\rho}}{\partial H_s} = \sum \frac{\partial \bar{\rho}}{\partial p_i} \frac{\partial p_i}{\partial T\left(f, H_s\right)} \frac{\partial T\left(f, H_s\right)}{\partial H_s}$$

# Unsteady effects : it works !

- Replacement of burnt gas by fresh gas




- Better mass behaviour
- Coherent velocities
- No density transport equation solved

# 3 types of fire

- Propane flame stabilized on a porous burner ($U_{in}$ ~ mm/s)

  (LCD Poitiers, 1989)

- Natural convection dominating:

  Froude : $10^{-6} < Fr < 10^{-4}$

$$Fr = \frac{U_{inj}^2}{gD}$$

- "Pyrolysis rate" controlled: 5.3 g/m²/s

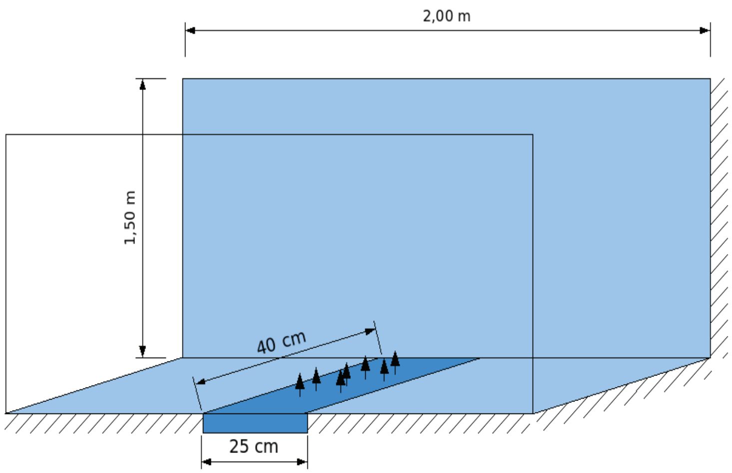
  (~25 kW: a small paper basket fire)

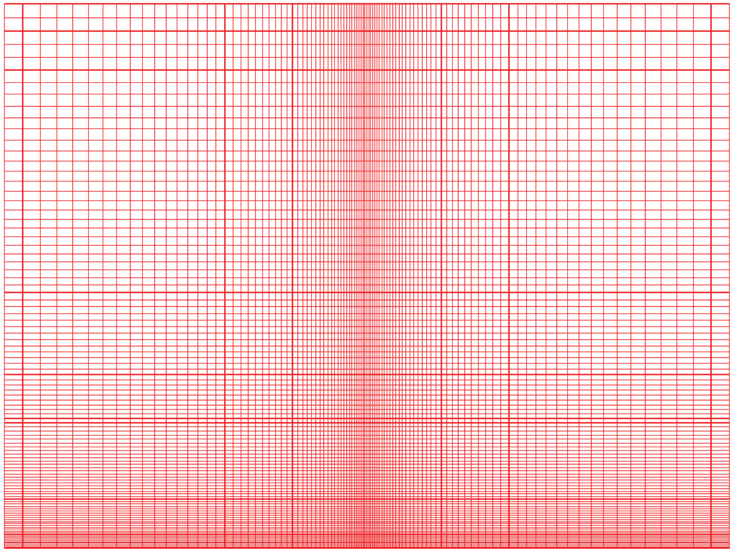
- Representative of classic situations :

  Pool fire

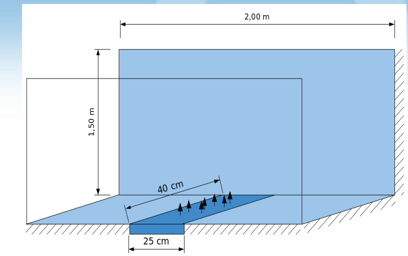
  Fire closed to a inert wall

  Vertical wall fire



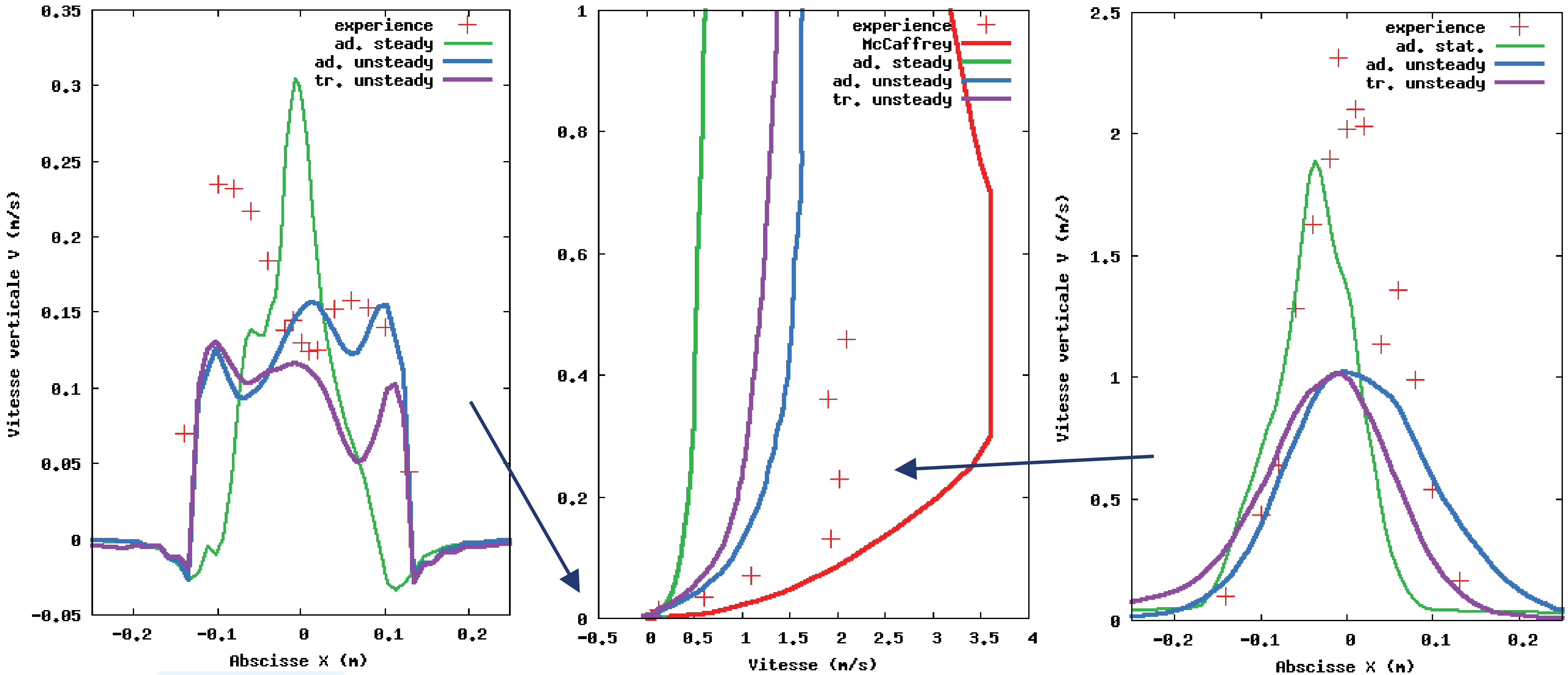



# Pool fire




## ◉ Pool fire : vertical velocities

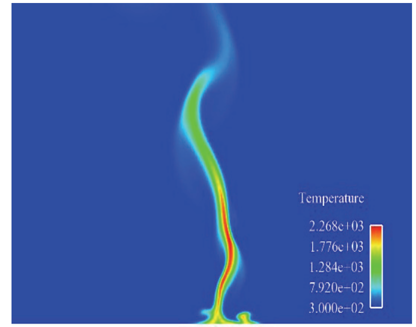
0.015 m — vertical profile — 0.230 m

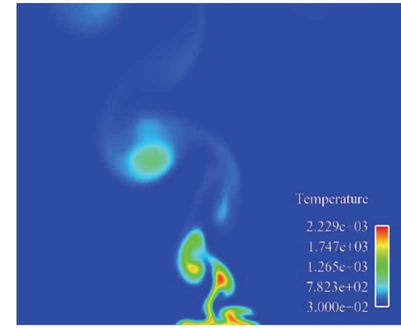



- Correct general shape, larger flame (no jet effect)
- Thermal expansion effective

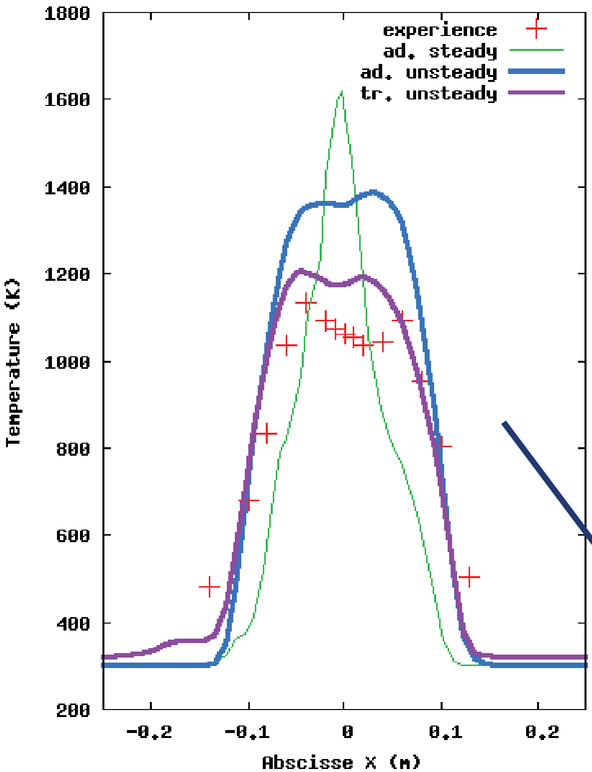
# Pool fire

- Pool fire : temperatures
  - Better profiles, better dynamic
  - Too hot close to the floor
  - Too cold in the fire plume

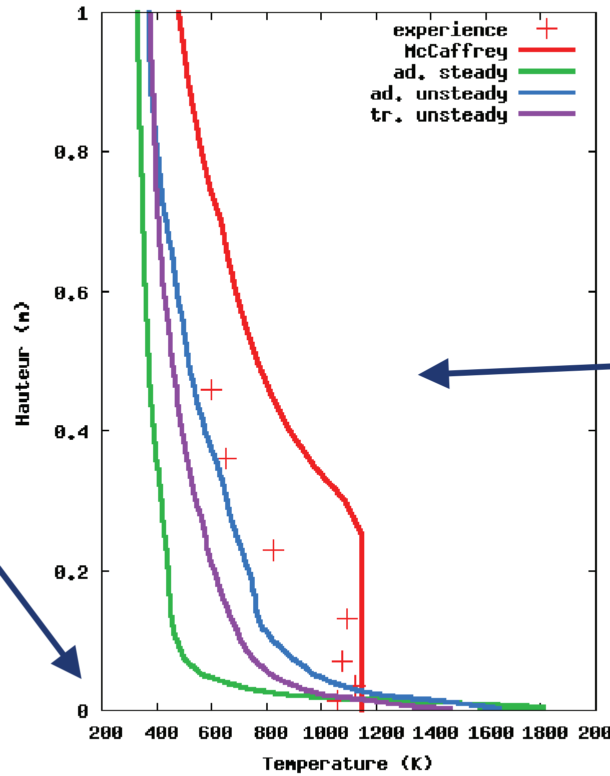


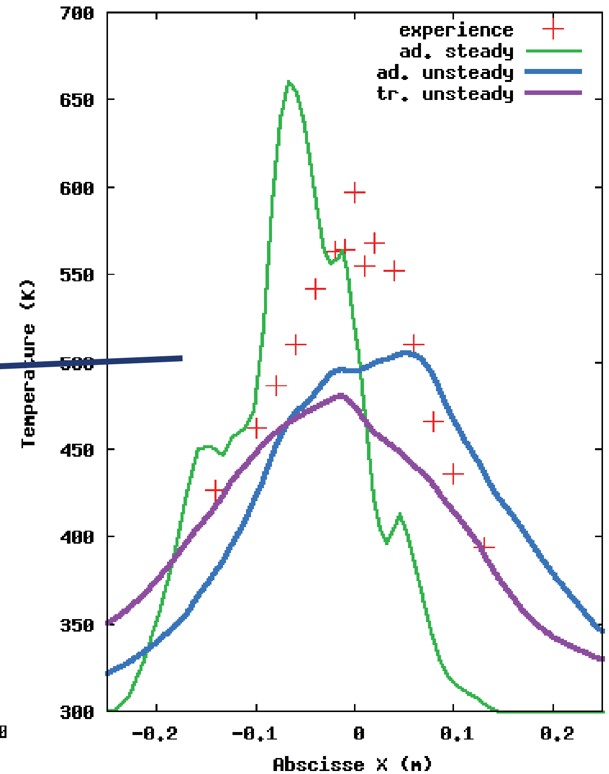

0.015 m



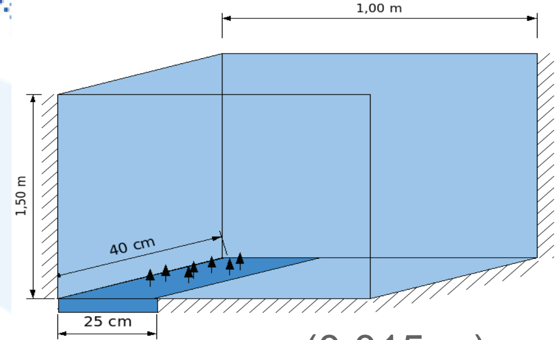

vertical profile




0.460 m



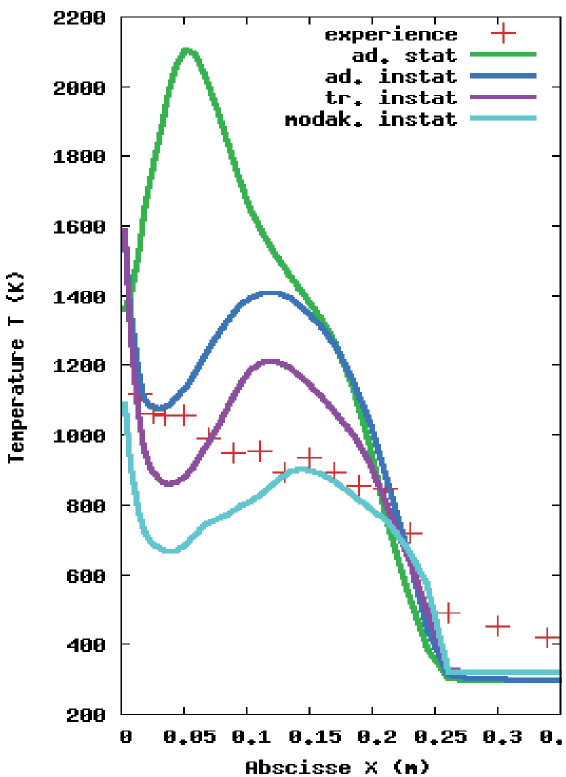
# Fire close to an inert wall



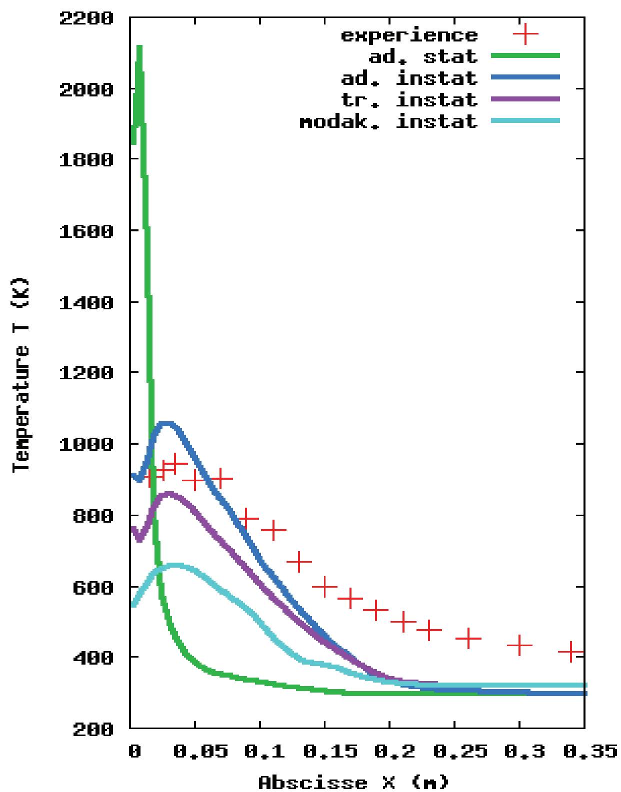

- Colder flame than free fire due to less oxygen rate
- Hotter plume, due to less cool by fresh air entrainment
- Simulation is too cold : thermal loss, soot effect ?

Temperature (K) | Vertical velocity (m/s)

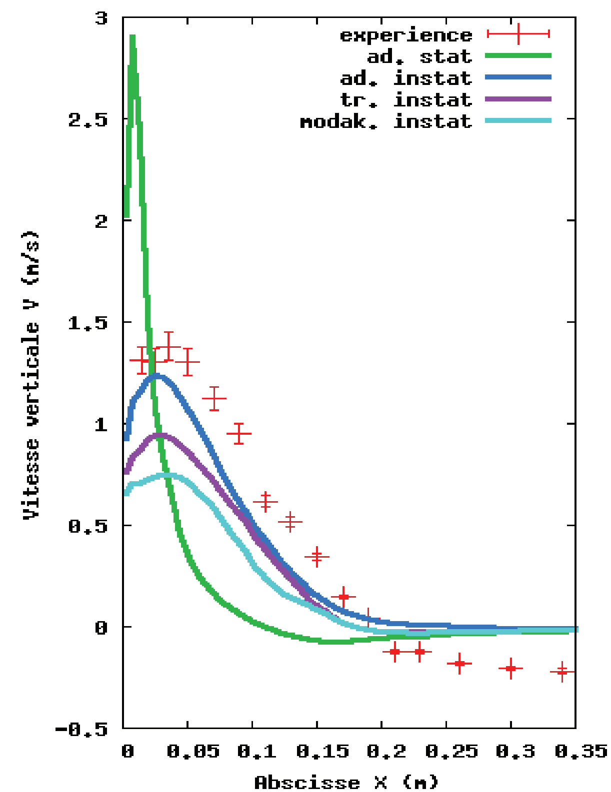
(0.015 m)



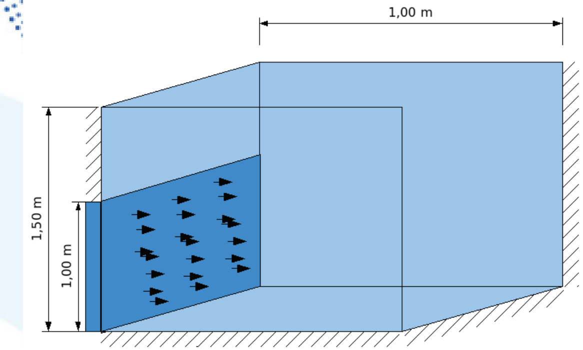

(0.130 m)



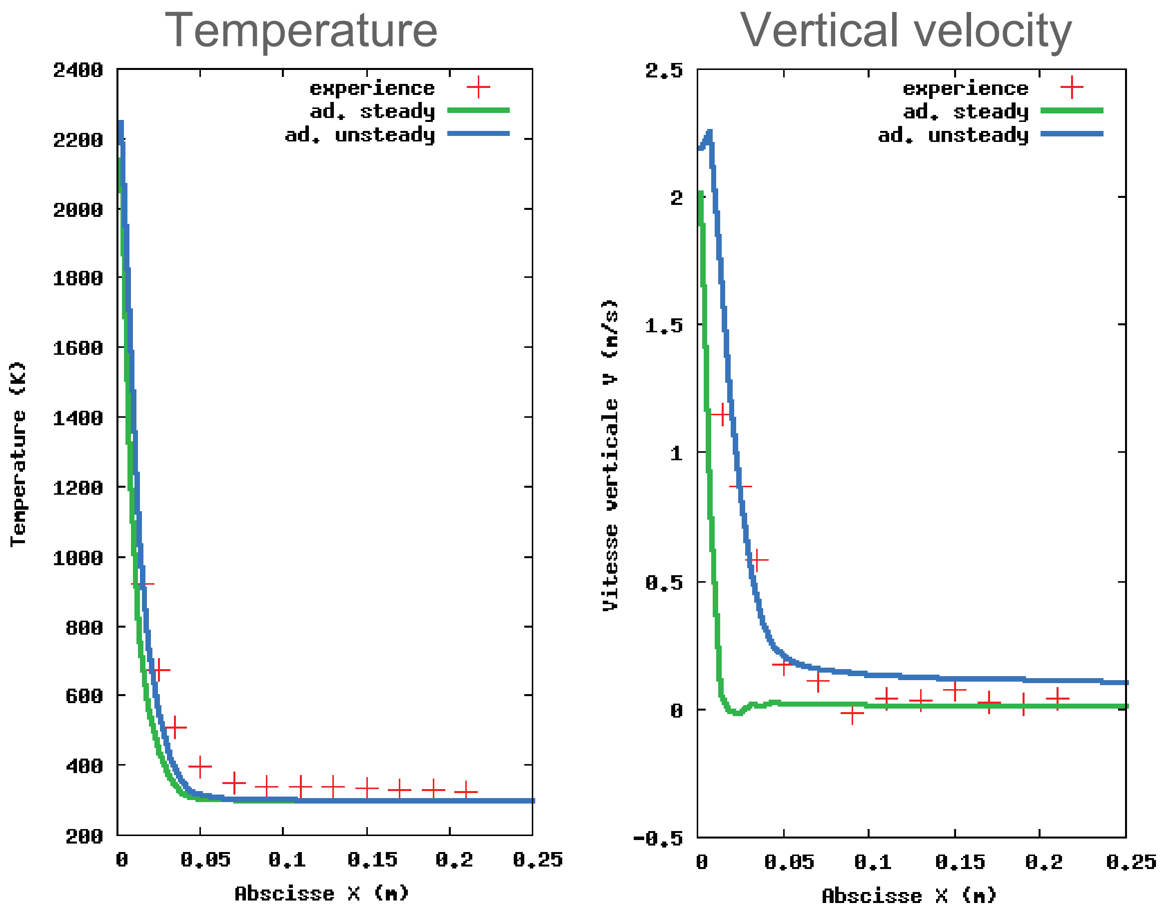

(0.130 m)



# Vertical wall fire




0.230 m




- Standard algorithm results already correct
- Need friction description (mass source term instead fuel inlet)

# Conclusion and work in progress

- Conclusion:
  - Unsteady density variation effect is considered
  - A simple solution is proposed
  - Efficient for classic fire situations

- Work in progress:
  - Realistic open-room fire calculation available, need validation
  - Soot formation and effect
  - Pyrolysis (vaporization) rate estimation
  - Gas extinction and reignition
  - Thermal wall effect
  - …

# Fluid dynamics

- Favre average : $\overline{\rho}\widetilde{f} = \overline{\rho f}$ avoid $\overline{\rho Y} = \overline{\rho}\overline{Y} + \overline{\rho' Y'}$
- Continuity equation : $\partial_t \overline{\rho} + \partial_{x_j}\left(\overline{\rho}\widetilde{u}_j\right) = \overline{\Gamma}$
- Momentum equation :

$$\partial_t\left(\overline{\rho}\widetilde{u}\right)_i + \partial_{x_j}\left(\overline{\rho}\widetilde{u}_j\widetilde{u}_i\right) + \partial_{x_j}\overline{\rho u_i'' u_j''} = -\partial_{x_i}\overline{p} + \partial_{x_j}\overline{\tau_{ij}} + \overline{\rho}\widetilde{g}_i$$

- Reynolds tensor : gradient approach

$$-\overline{\rho u_i'' u_j''} + \frac{2}{3}\overline{\rho}\widetilde{k}\delta_{ij} = \overline{\rho}\nu_t\left(\partial_{x_j}\widetilde{u}_i + \partial_{x_i}\widetilde{u}_j\right)$$

$$\nu_t = C_\mu \frac{k^2}{\varepsilon}$$

- Turbulent viscosity : k-$\varepsilon$ model

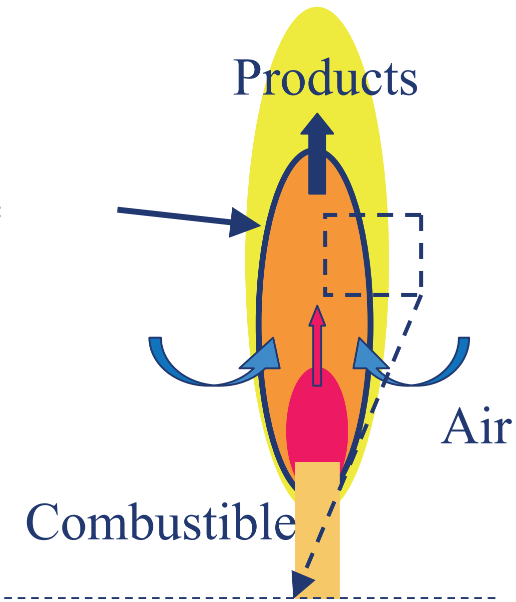
# Combustion model: diffusion flame

Combustible + Oxidant ⟶ Products

- Diffusion Combustible <=> Oxidant

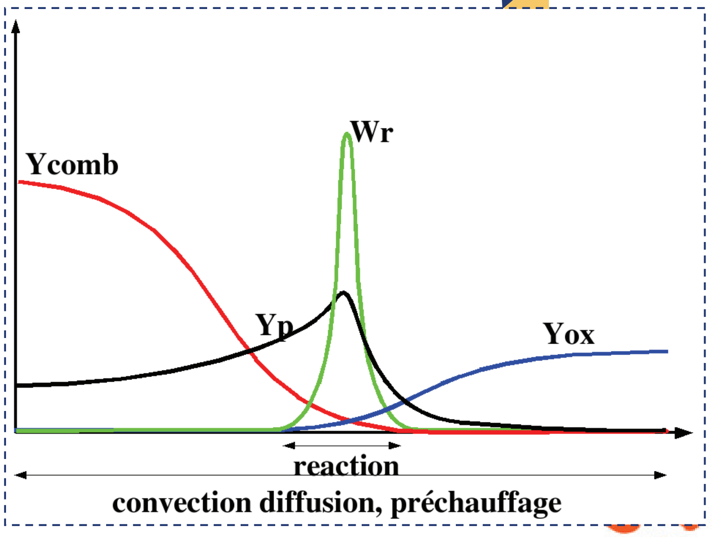
  Q Products => Reactants

**Flame** = thick zone between reactants




$$\frac{\partial}{\partial t}\rho Y_\alpha + \frac{\partial}{\partial x}\rho u_x Y_\alpha = \frac{\partial}{\partial x}\left(D_\alpha \frac{\partial}{\partial x} Y_\alpha\right) + \omega_\alpha$$

$$\omega_\alpha = A_\alpha e^{\frac{-Ea}{RT}} [C]^n . [Ox]^m$$



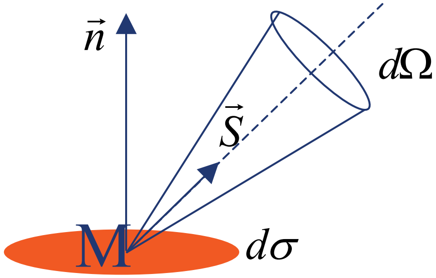

- Source term calculation:
  - Infinitely fast / limited chemistry
  - Global / detailed chemistry

# Thermal transfers

- Enthalpy transport equation:

$$\partial_t\left(\bar{\rho}\widetilde{H}\right)+\partial_{x_j}\left(\bar{\rho}\widetilde{u}_j\widetilde{H}\right)-\partial_{x_j}\left(\frac{\mu_t}{\mathrm{Pr}}\partial_{x_j}\widetilde{H}\right)=\partial_{x_j}\left(\frac{\lambda}{C_p}\partial_{x_j}\widetilde{H}\right)+\dot{m}\widetilde{H}-\nabla q$$

$\dot{m}\widetilde{H}$ : heat release rate from combustion




$$\vec{q}(\vec{x})=\int_{4\pi}L(\vec{x},\vec{S})\vec{S}\,d\Omega$$

: radiant puissance emitted on direction *S* (W/m²)

- Radiant transfer equation:

$$\nabla\left(L(\vec{x},\vec{S})\vec{S}\right)=-k\,L(\vec{x},\vec{S})+k\,\frac{\sigma T^4}{\pi}$$

***k*** **: absorption coefficient, function of**

**$CO_2$, $H_2O$ and soot volume fraction, temperature, total pressure and mean beam length**