Unsteady fire simulation with *Code_Saturne*

Bertrand SAPA

LCD Poitiers:

UPR 9028

Hui-Ying Wang

Hazem El-Rabii

Jean-Pierre Vantelon

EDF R&D Chatou:

Laurent Gay

Pierre Plion

Namane Mechitoua

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 :

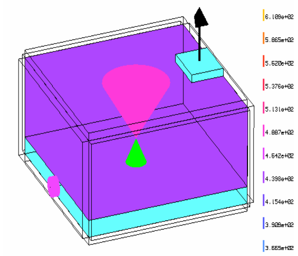
- Cattenom 2004 : 22 days off costing 300 k€ = 6.6 M€
- Fire security systems replacement in EDF's plants : 500 M€ (Plan Action Incendie 1999-2006).

⦿ 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.)

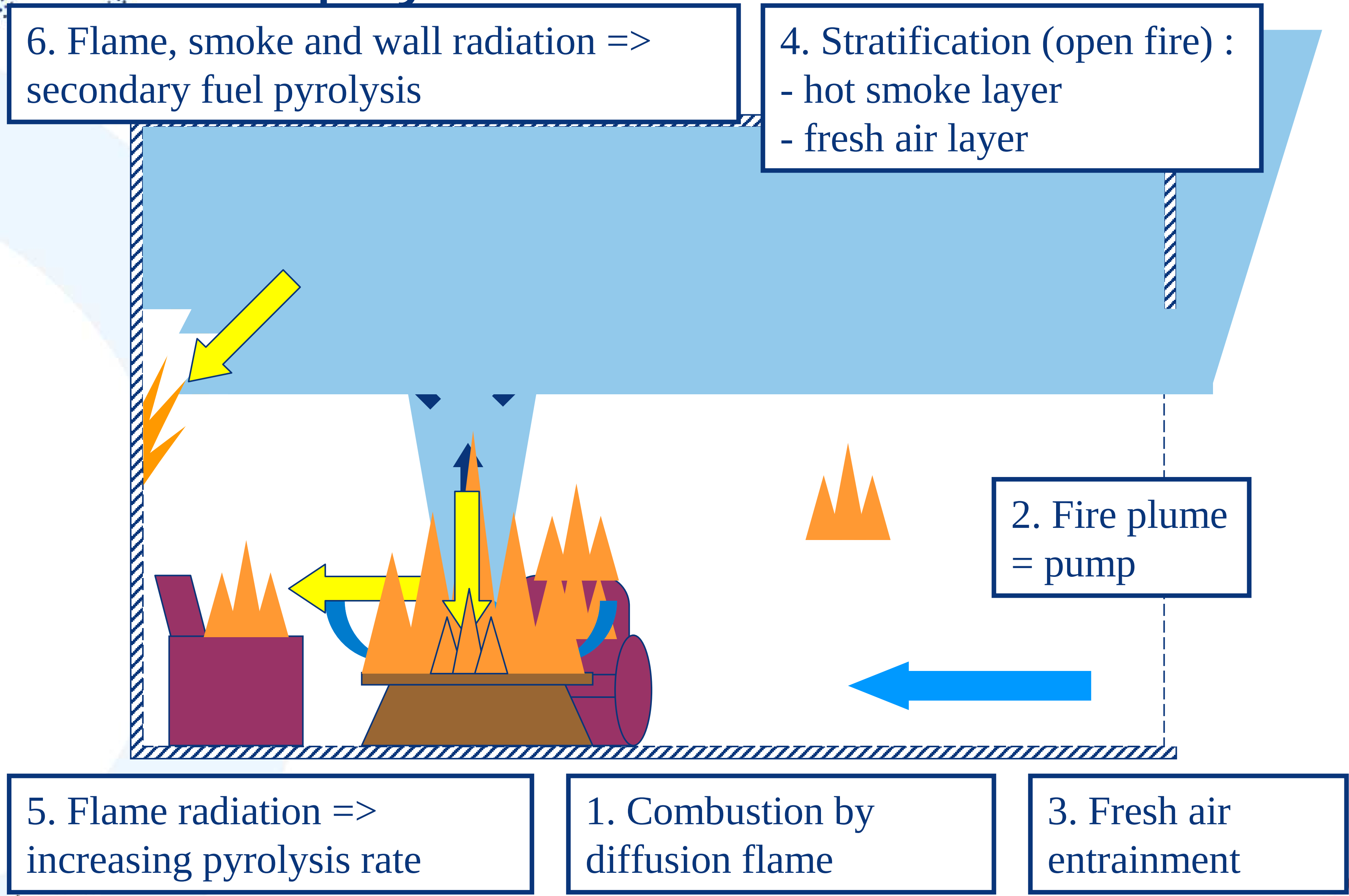
Why Code_Saturne ?

- 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/m²/s

  => inlet speed ~ mm/s

- Combustion : cold reactants → hot products : $\rho \sim 1$ to $0{,}1 kg/m^3$:
  - Strong buoyancy forces $(\rho - \rho_0)g$
  - Strong thermal expansion $\partial\rho/\partial t \neq 0$

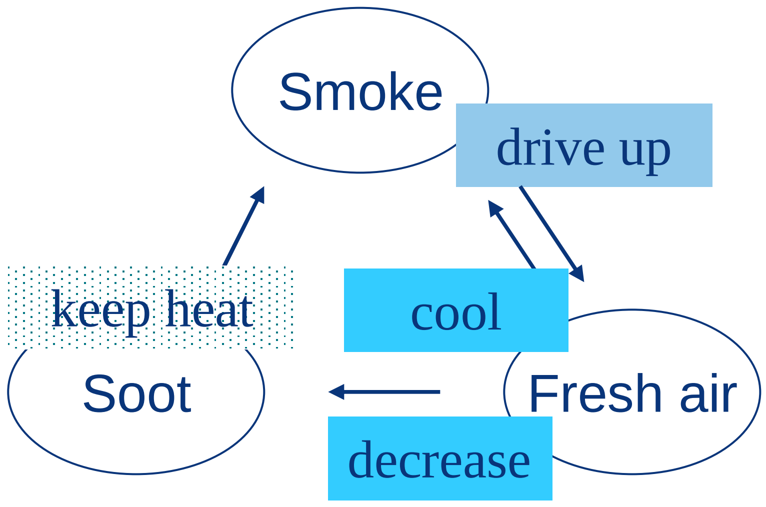
- Large eddy structures (~ pool dimension)
  - Hot gas puffs (2-3 Hz) burning rising + global oscillation (< 0,1 Hz)

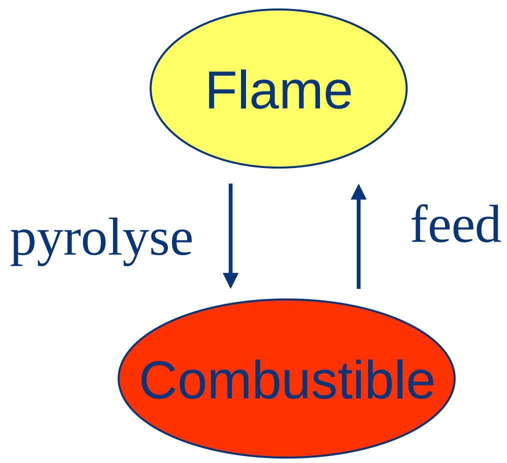
    => complex unsteady phenomena
  - Smoke dilution by fresh air (affect temperature, concentrations,…)

- 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

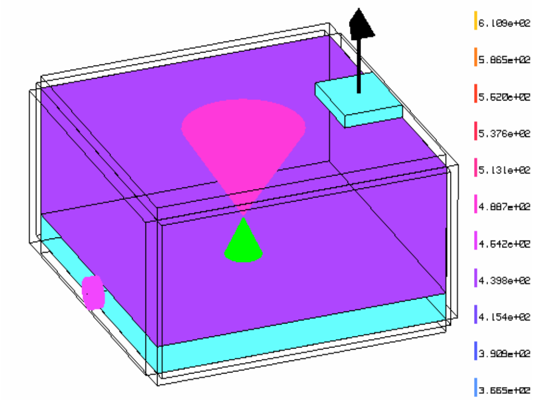
- **Unsteady RANS** (k-ε) (enough to pick up very large eddies)
- Infinitely fast combustion (diffusion flame): **F + Ox → P**
- Radiation of a grey gas and soot composition (radiant transfer equation solver)

Physic to improve

- **Unsteady** density variation effect $\partial_t \rho + div(\rho \underline{u}) = \Gamma$
- S**oot** effect
- Thermal **wall** effect $q_{loss} = \rho C_p \Delta T$
- **Gas extinction** and **reignition**
- **Pyrolysis** rate estimation
- Fire security systems

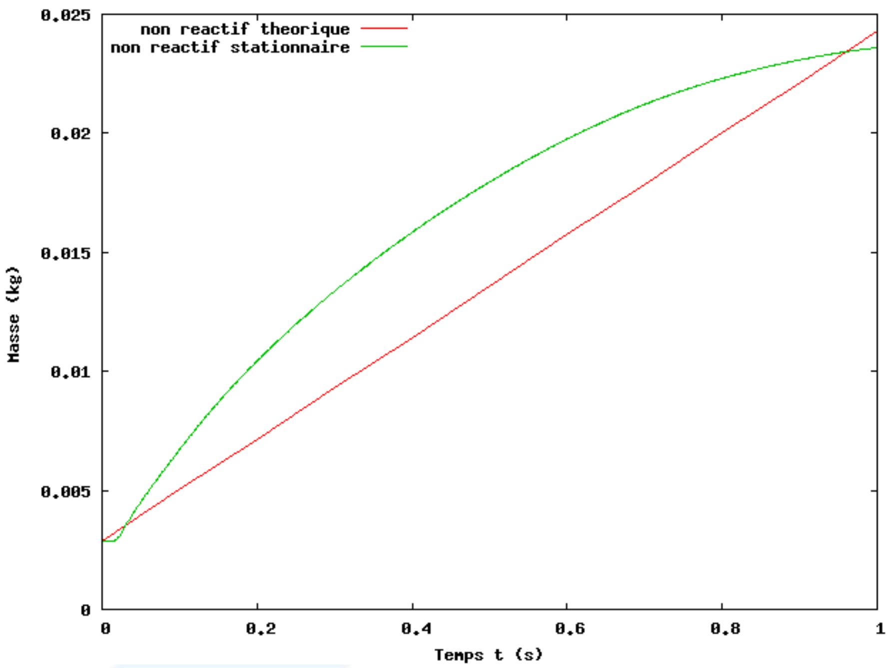
1st year objectives

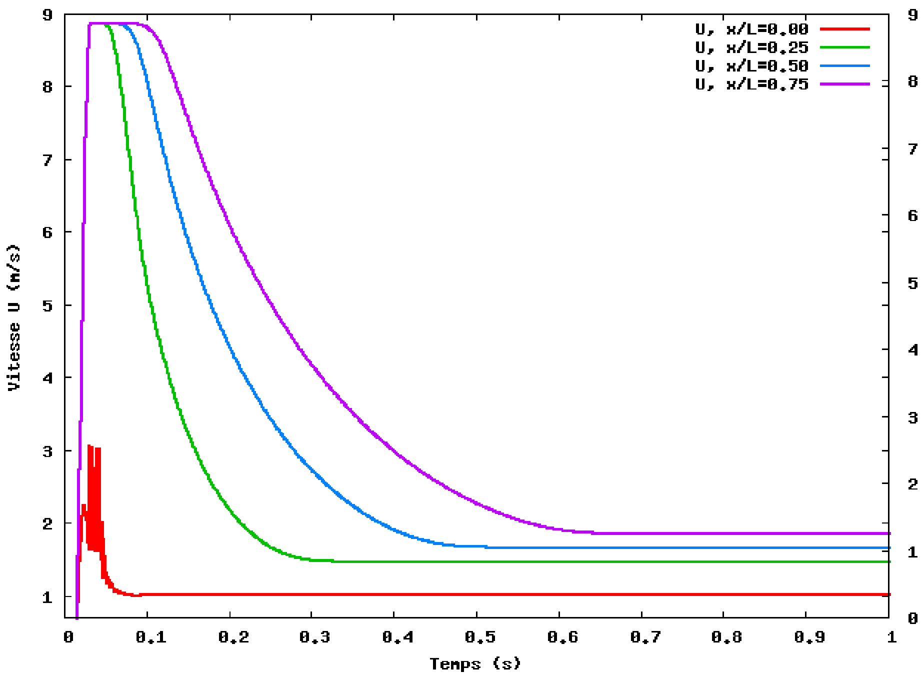
- Unsteady behaviour and radiation effect
- One open-room fire, end of 2008



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 δp^{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: $\rho(a)$

$$\begin{cases} \mathrm{d}_t \rho + \rho\, div(\underline{u}) = \Gamma & \times \dfrac{\rho}{\frac{\partial \rho}{\partial a}} \\ \rho\, \mathrm{d}_t a = div(\rho D_a\, g\underline{rad}\ a) + \rho S_a & \text{ac } \mathrm{d}_t a = \dfrac{1}{\frac{\partial \rho}{\partial a}} \mathrm{d}_t \rho \end{cases}$$

$$\Rightarrow \begin{cases} \dfrac{\rho}{\frac{\partial \rho}{\partial a}} \mathrm{d}_t \rho + \dfrac{\rho^2}{\frac{\partial \rho}{\partial a}} div(\underline{u}) = \dfrac{\rho}{\frac{\partial \rho}{\partial a}} \Gamma & (1) \\ \dfrac{\rho}{\frac{\partial \rho}{\partial a}} \mathrm{d}_t \rho = div(\rho D_a\, g\underline{rad}\ a) + \rho S_a & (2) \end{cases}$$

$$(1)-(2) \ \Rightarrow \ div(\underline{u}) = \frac{1}{\rho}\Gamma + \boxed{\frac{1}{\rho^2}\frac{\partial \rho}{\partial a}\left[div(-\rho D_a\ g\underline{rad}\ a) - \rho S_a\right] = -\frac{1}{\rho}\mathrm{d}_t \rho}$$

Unsteady Navier-Stokes (2/2)

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

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

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

$$div\left(\frac{\Delta t}{\rho} g\underline{rad}\, \delta p^{n+1}\right) = \frac{1}{\rho}\Gamma - div(\underline{\tilde{u}}^{n+1}) + \frac{1}{\rho^2}\frac{\partial \rho}{\partial a}\left[div(-D_a\, g\underline{rad}\, a) - \rho S_a\right]$$

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

Infinitely fast chemistry !

Combustible + Oxidant ⟶ Products

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

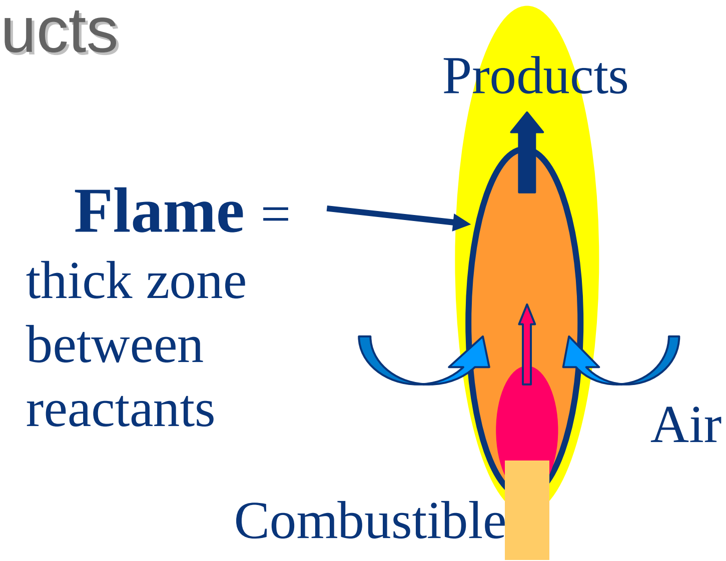
  Air: *f = 0*, combustible: *f = 1*

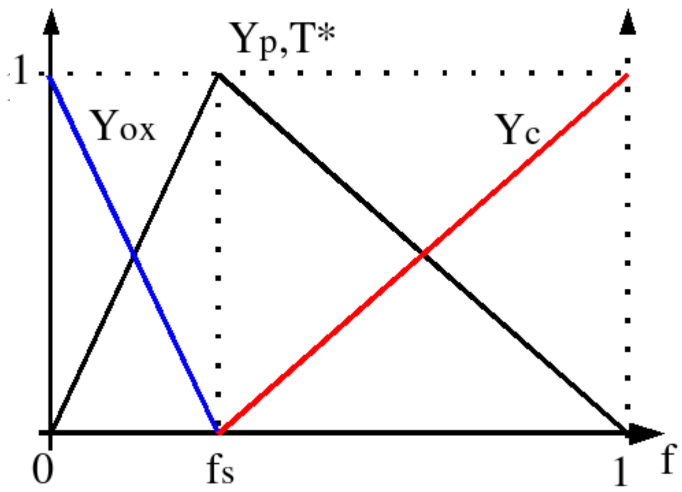
  Combustion products: *f = fs*

  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 *ρ(f)*



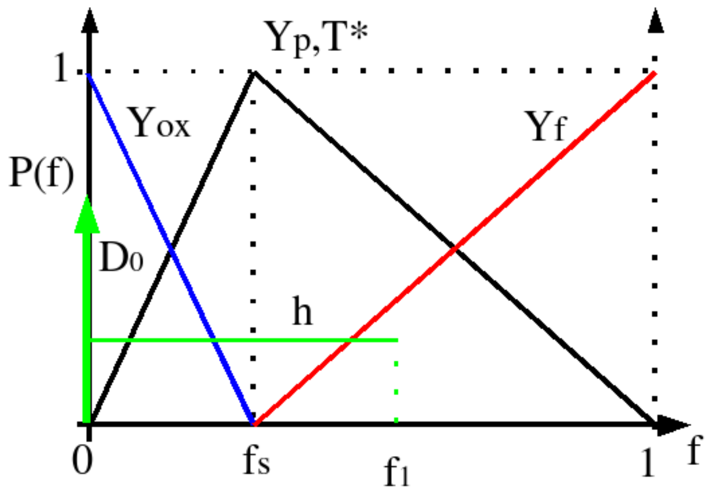


Fire: a turbulent child

- 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***



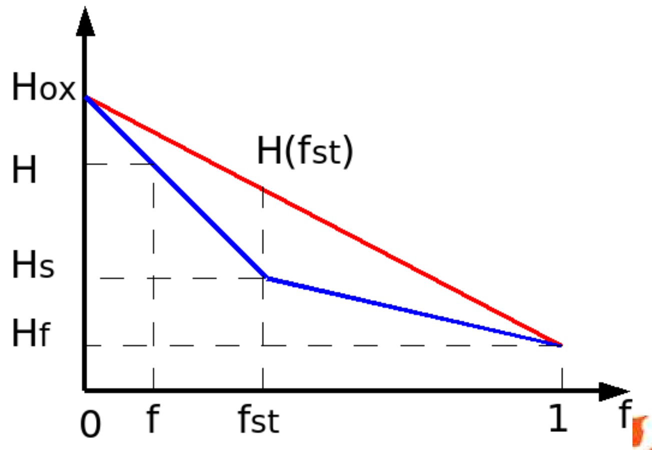
- Temperature calculation (*$T(H_s)$* is tabulated):

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

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

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

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



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***

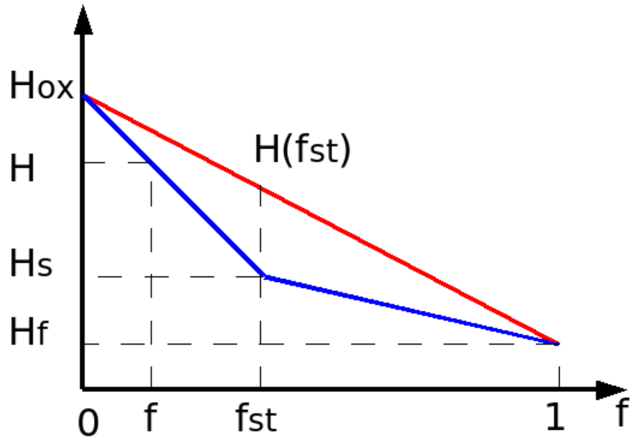
$$\frac{\partial\bar{\rho}}{\partial\tilde{f}} = \frac{\partial}{\partial\tilde{f}}\int_0^1 \rho\left(f, T(f, H_s)\right)df = \int_0^1 \sum \frac{\partial\rho}{\partial p_i}\frac{\partial p_i}{\partial\tilde{f}}df \qquad p_i = D_0, D_1, f_0, f_1, h$$

- *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 $\tilde{H} = \alpha + \beta.H_s$

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

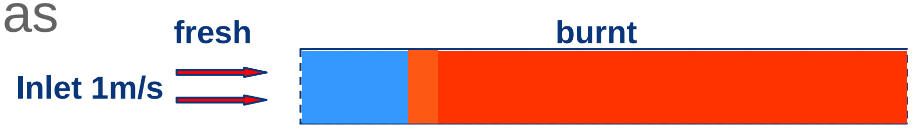
  - Derivative for H_s instead of *H*:

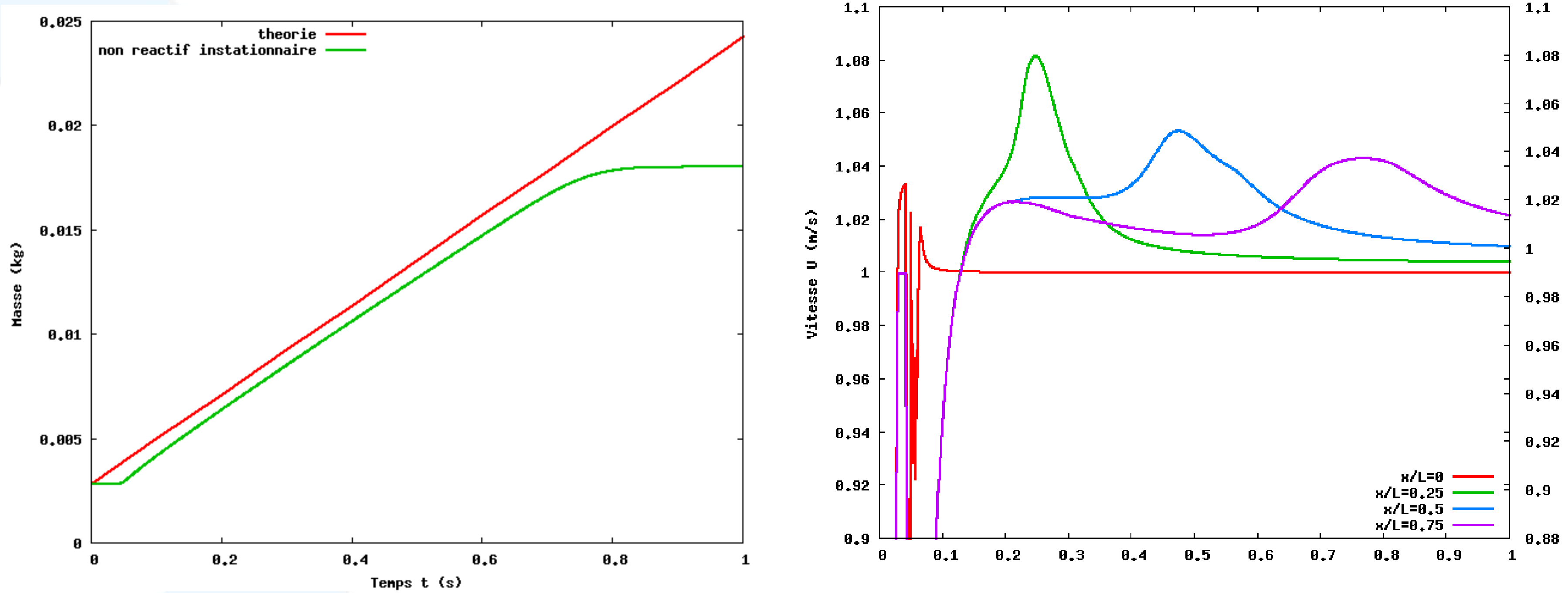
$$\frac{\partial\bar{\rho}}{\partial H_s} = \sum \frac{\partial\bar{\rho}}{\partial p_i}\frac{\partial p_i}{\partial T\left(f, H_s\right)}\frac{\partial T\left(f, H_s\right)}{\partial H_s}$$



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, Re < 4000*)

  (LCD Poitiers, 1989)

- Natural convection dominating:

  Froude : *Fr ~* 3.10^{-6}

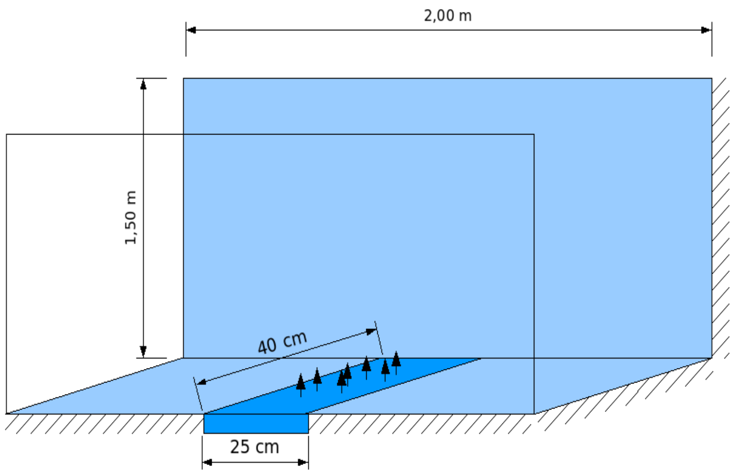
$$Fr = \frac{U_{inj}^2}{gD}$$

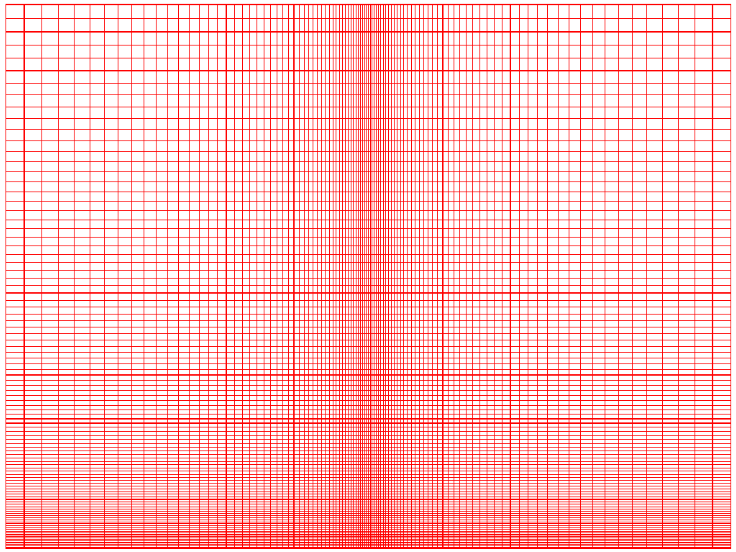
- "Pyrolysis rate" controlled: *5.3 g/m²/s*

  (~25 kW: a small paper basket fire)

  - Using **mass source terms** :
    - friction and boundary layer description

      (boundary layer blowing correlation ?)
    - easier for flame propagation and thermal transfer in combustible





- Representative of classic situations :

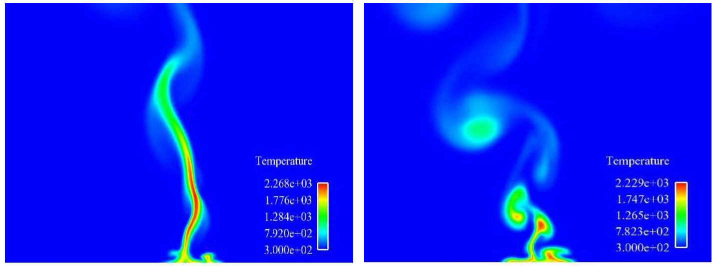
  Pool fire

  Fire closed to a inert wall

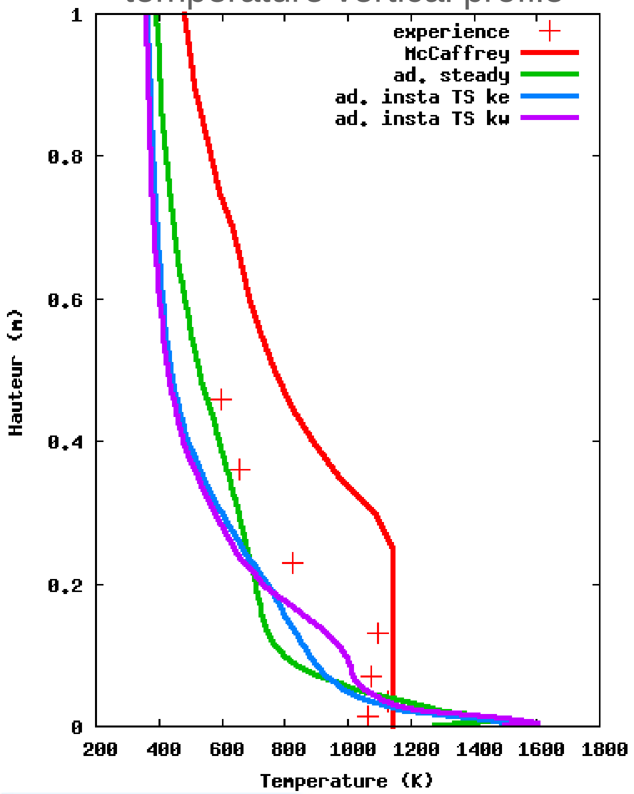
  Vertical wall fire

Pool fire

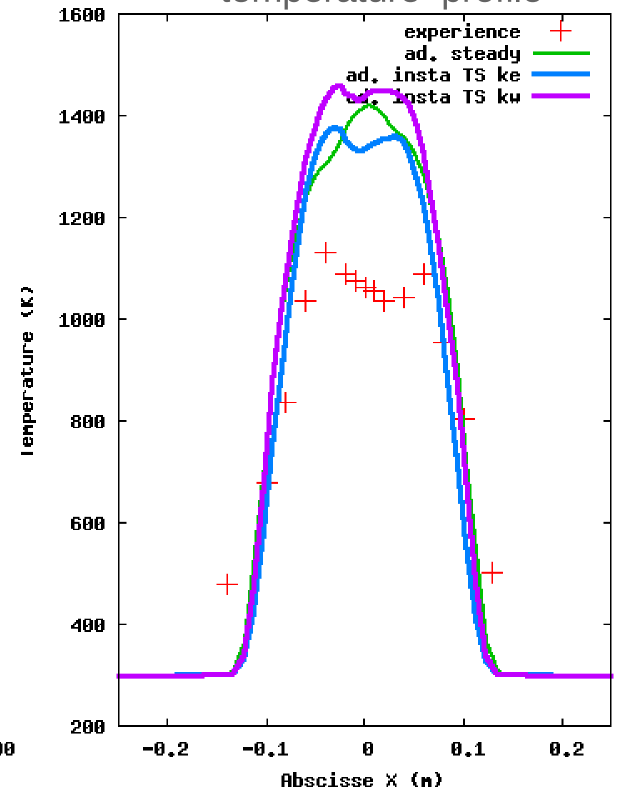
- **Good dynamic** behaviour and mean profiles
- Noticeably better mean profiles with k-ω (R_{ij}- ε, LES ?)
- 2D hypothesis justified by 3D simulation
- Need **frequency analysis** to validate !



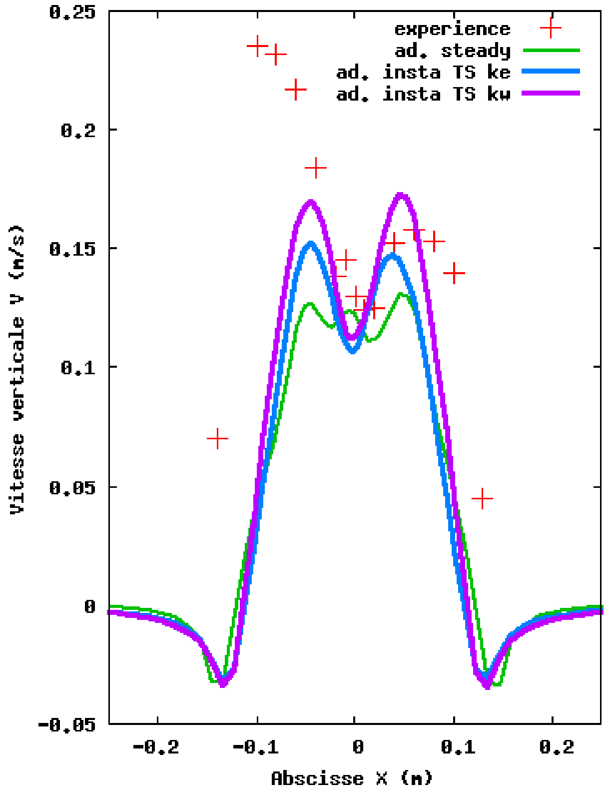
temperature vertical profile



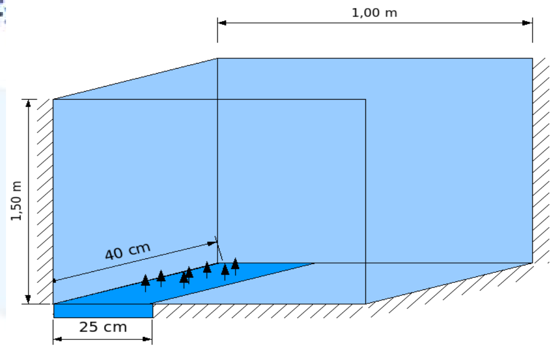
temperature profile



vertical velocities



Fire close to an inert wall

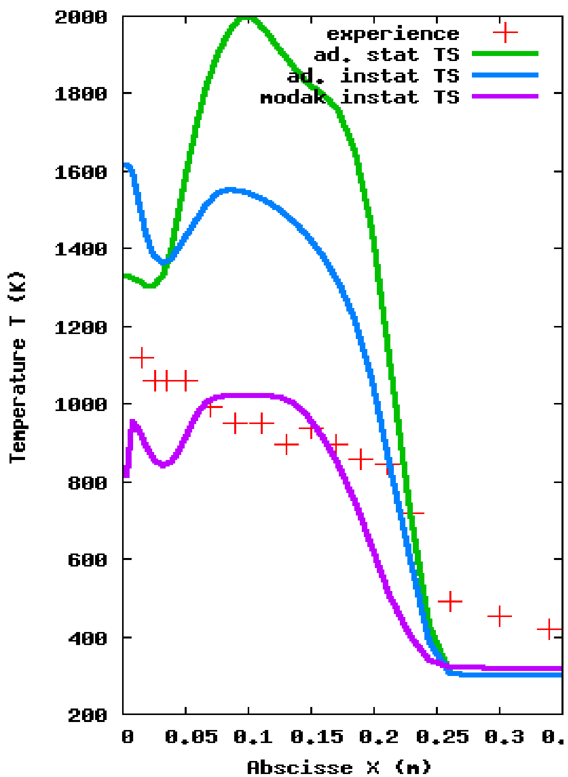


- Thermal loss on wall = temperature profile imposed
- Colder flame and hotter plume, due to less fresh air entrainment
- Simulation is too cold : thermal loss, soot effect ?

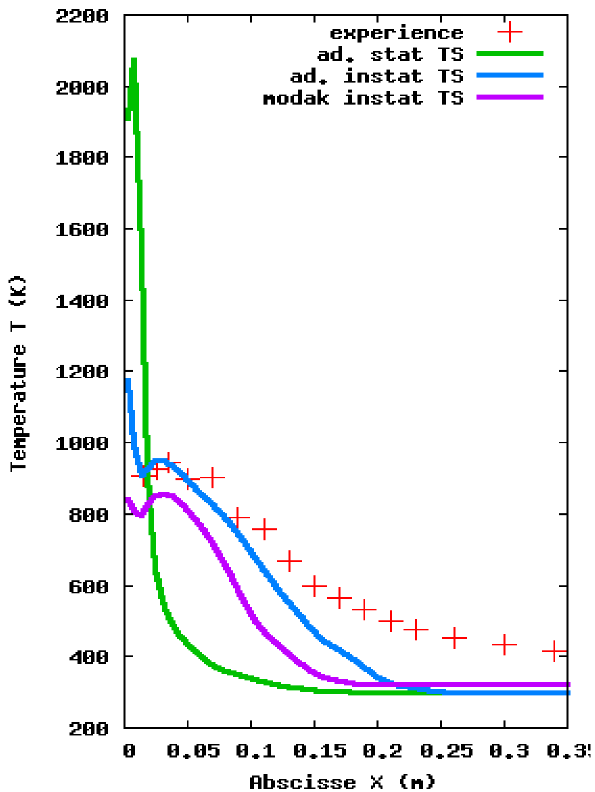
Temperature (K)

Vertical velocity (m/s)

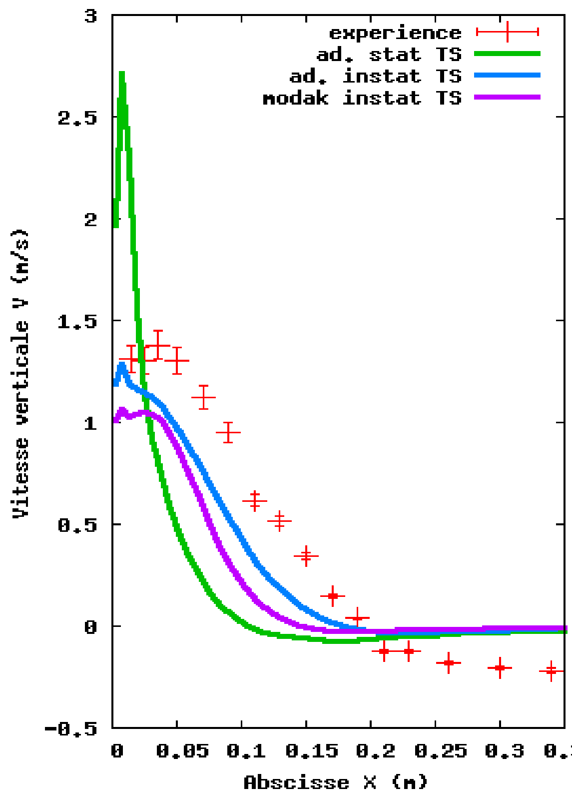
(0.015 m)



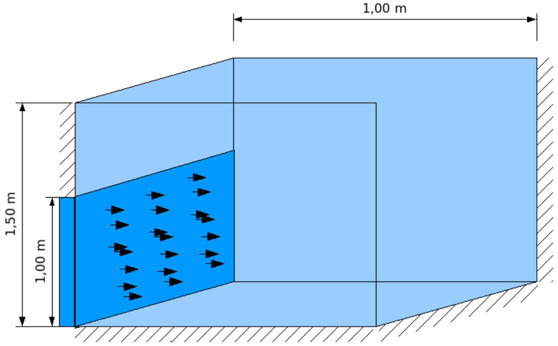
(0.130 m)



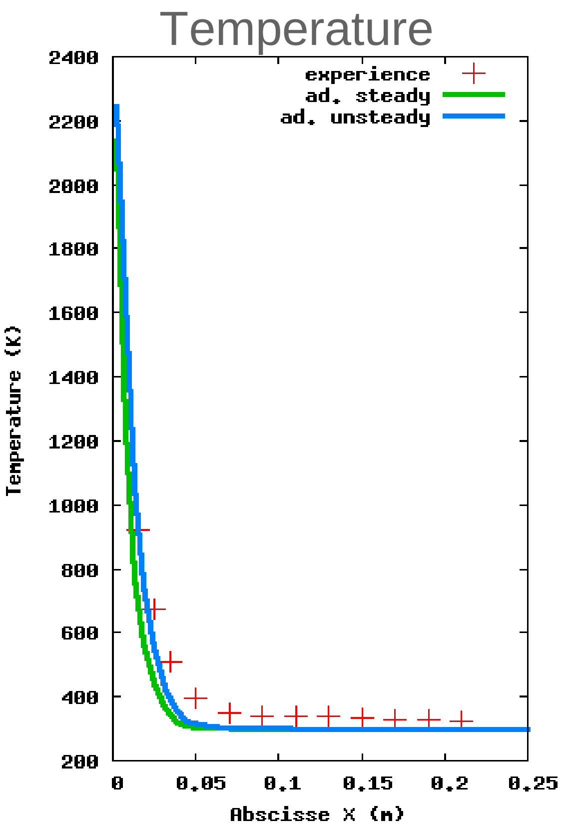
(0.130 m)

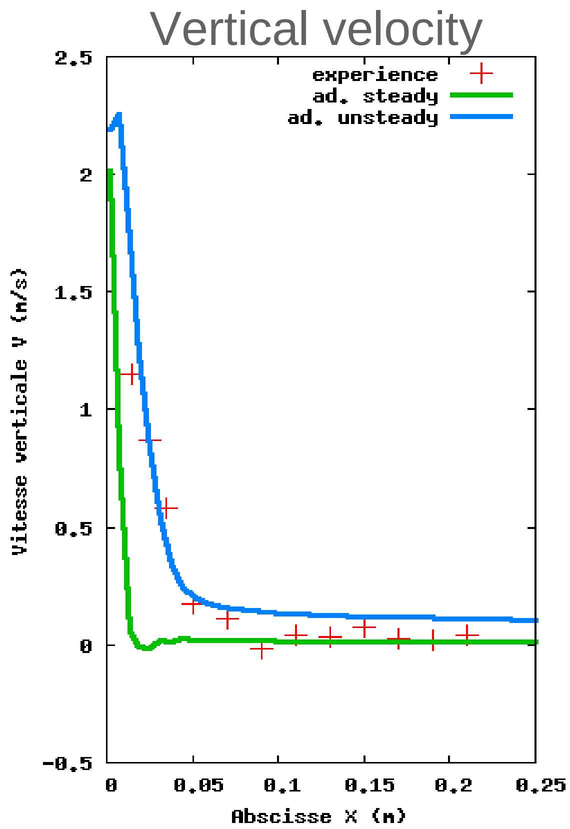


Vertical wall fire



0.230 m



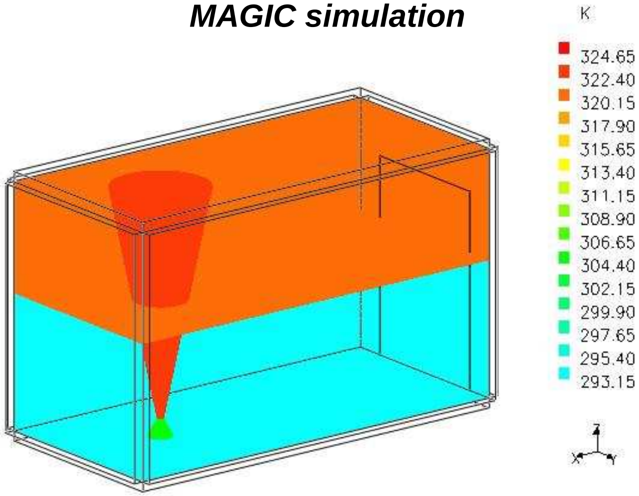


- Thermal loss on wall = temperature profile imposed
- Good agreement on mean profiles
- Better fit on velocities profile

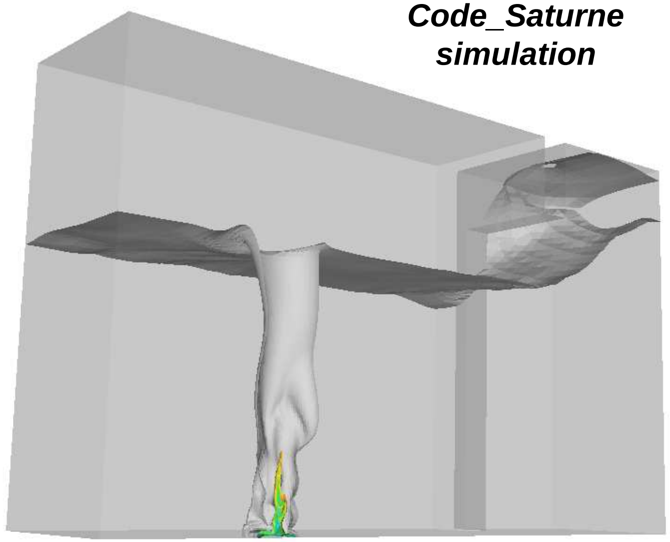
Confined porous burner

- Configuration:
  - 25 kW in a 2 x 4 x 2.5 m room
  - 2 x 1,40 m opened door
  - Adiabatic conditions
- Calculation characteristics:
  - 350.000 cells (could be decreased)
  - Time step: ~ 2.10^{-3} s
  - CPU time step: ~ 3 s with 16 processors
- *Code_Saturne* agrees with Magic:
  - ΔT~30℃ in smoke layer
  - Smoke layer height: ~ 1,50 m

MAGIC simulation



Code_Saturne simulation



Conclusion and work in progress

- Conclusion:
  - **Unsteady** density variation effect is considered
  - A **simple solution** is proposed, **efficient** for classic fire situations
  - Need **frequency analysis** to validate
  - Realistic open-room **fire calculation available**

- Work in progress:
  - **Thermal inertia** wall effect (validation expected)
  - **Soot** formation and effect
  - **Low Reynolds** modelling ?
  - Gas **extinction** and **reignition** (under-ventilated fire)
  - **Pyrolysis** (vaporization) rate estimation

- Collaborations:
  - LCD, LCPP, CEA
  - Feel free to contact us: bertrand.sapa@gmail.com, laurent.gay@edf.fr

Fluid dynamics

- Favre average : $\overline{\rho}\,\tilde{f} = \overline{\rho f}$ avoid $\overline{\rho Y} = \overline{\rho}\,\overline{Y} + \overline{\rho' Y'}$

- Continuity equation : $\partial_t \overline{\rho} + \partial_{x_j}\left(\overline{\rho}\tilde{u}_j\right) = \overline{\Gamma}$

- Momentum equation :

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

- Reynolds tensor : gradient approach

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

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

- Turbulent viscosity : k-ε model

Combustion model: diffusion flame

Combustible + Oxidant ⟶ Products

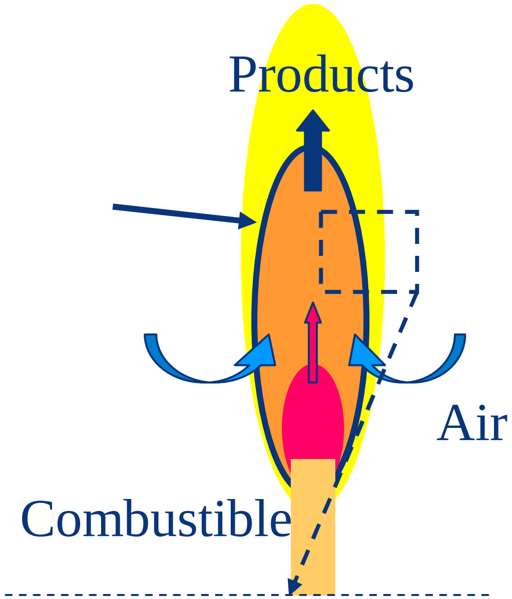
- Diffusion Combustible <=> Oxidant
  - Q Products => Reactants

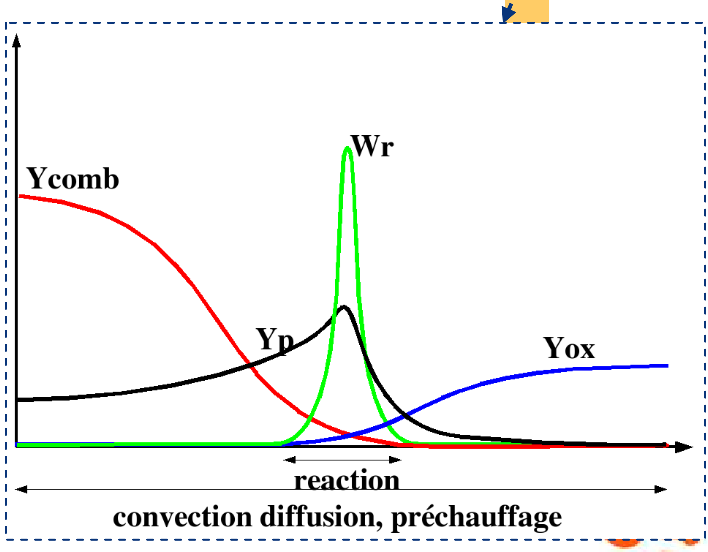
$$\frac{\partial}{\partial t}\rho Y_\alpha + \frac{\partial}{\partial x}\rho u_x Y_\alpha = \frac{\partial}{\partial x}\left(D_\alpha \frac{\partial}{\partial x} Y_\alpha \right) + \omega_\alpha$$

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

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

Flame = thick zone between reactants





Thermal transfers

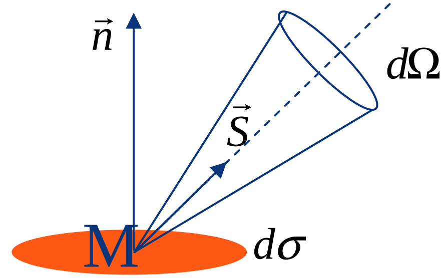
- Enthalpy transport equation:

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

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

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

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



- Radiant transfer equation:

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

k **: absorption coefficient, function of CO_2, H_2O and soot volume fraction, temperature, total pressure and mean beam length**