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€

○ 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

Unsteady fire simulation
Fire physical basics

1. Combustion by diffusion flame
2. Fire plume = pump
3. Fresh air entrainment
4. Stratification (open fire):
   - hot smoke layer
   - fresh air layer
5. Flame radiation => increasing pyrolysis rate
6. Flame, smoke and wall radiation => secondary fuel pyrolysis
Fire physical basics: characteristics

- Vaporization or pyrolysis: weak combustible emission rate $\sim g/m^2/s$
  
  $\Rightarrow$ inlet speed $\sim$ mm/s

- Combustion: cold reactants $\rightarrow$ hot products: $p \sim 1$ to 0.1 kg/m$^3$:
  - Strong buoyancy forces $(p - p_0)g$
  - Strong thermal expansion $\partial p/\partial t \neq 0$

- Large eddy turbulent structures (~ pool dimension)
  - Hot gas puffs (2-3 Hz) burning rising + global oscillation ($< 0.1$ Hz)
    $\Rightarrow$ 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-\(\varepsilon\)) (enough to pick up very large eddies)
- Infinitely fast combustion (diffusion flame): \(F + Ox \rightarrow P\)
- Radiation of a grey gas and soot composition (radiant transfer equation solver)

Physic to improve

- **Unsteady** density variation effect \(\partial_t \rho + \text{div}(\rho \mathbf{u}) = \Gamma\)
- **Absorption** coefficient calculation and **soot** effect
- **Pyrolysis** rate estimation
- **Gas extinction** and **reignition**
- Thermal **wall** effect \(q_{\text{loss}} = \rho C_p \Delta T\)
- 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)

Inlet 1 m/s  

fresh  

burnt  

Outlet 1 m/s

Symmetry

Code_Saturne = unsteady weakly compressible flows
Steady Navier-Stokes

- **Prediction**: \[ \partial_t (\rho u) + \text{div}(\rho u \otimes u) = -\text{grad} p + \text{div}(\tau) + \rho g \]
  - Explicit pressure \( p = p^n \) \( \Rightarrow \) predicted velocity \( \tilde{u}^{n+1} \)

- **Correction**:
  - Pressure increment addition \( \delta p^{n+1} \)
    \[ \rho \partial_t u = -\text{grad} \delta p^{n+1} \Rightarrow \rho u^{n+1} - \rho \tilde{u}^{n+1} = -\Delta t \text{grad} \delta p^{n+1} \]
  - Continuity equation
    \[ \text{div}(\rho u^{n+1}) = \Gamma - \partial_t \rho \]
    \[ \text{div}(\Delta t \text{grad} \delta p^{n+1}) = \text{div}(\rho \tilde{u}^{n+1}) - \Gamma + \partial_t \rho \]

\[ u^{n+1} = \tilde{u}^{n+1} - \frac{\Delta t}{\rho} \text{grad} \delta p^{n+1} \]
Unsteady Navier-Stokes (1/2)

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

\[
\begin{align*}
    \frac{d_t \rho}{dt} + \rho \text{div}(u) &= \Gamma \\
    \rho d_t f &= \text{div}(D_f \text{grad } f) + \rho S_f \\
    \text{ac } d_t f &= \frac{1}{\rho} d_t \rho
\end{align*}
\]

\[
\begin{align*}
    \frac{\rho}{\partial \rho} d_t \rho + \frac{\rho^2}{\partial \rho} \text{div}(u) &= \frac{\rho}{\partial \rho} \Gamma \\
    \frac{\rho}{\partial \rho} d_t \rho &= \text{div}(D_f \text{grad } f) + \rho S_f
\end{align*}
\]

(1) - (2) $\Rightarrow$ $\text{div}(u) = \frac{1}{\rho} \Gamma + \frac{1}{\rho^2} \frac{\partial \rho}{\partial f} \left[ \text{div}(-D_f \text{grad } f) - \rho S_f \right] = -\frac{1}{\rho} d_t \rho$
Unsteady Navier-Stokes (2/2)

Prediction: \[ \partial_t (\rho u) + \text{div}(\rho u \otimes u) = -\text{grad} \, p + \text{div}(\tau) + \rho \, g \]

- Explicit pressure \( p = p^n \) \( \Rightarrow \) predicted velocity \( \tilde{u}^{n+1} \)

Correction:

- Pressure increment addition \( \delta p^{n+1} \)

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

- Continuity equation

\[ \text{div}(u^{n+1}) = \frac{1}{\rho} \Gamma - \frac{1}{\rho} \frac{\partial}{\partial t} \rho \]

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

\[ u^{n+1} = \tilde{u}^{n+1} - \frac{\Delta t}{\rho} \text{grad} \, \delta p^{n+1} \]
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: \( f = f_s \)

- No source term:
  \[
  \partial_t (\rho f) + \partial_x (\rho u f) = \partial_x (\rho D \partial_x f)
  \]

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

Flame = thick zone between reactants

Unsteady fire simulation
Fire: a turbulent child

Turbulence: fluctuations $\tilde{f}^2$ around the mean $\bar{f}$ (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:

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

$\bar{\rho} = \rho(\bar{f}, \tilde{f}^2, \tilde{H})$
Unsteady combustion

Density derivative calculation for $f$ and $f'^2$:

$$\frac{\partial \tilde{\rho}}{\partial f} = \frac{\partial}{\partial f} \int_0^1 \rho(f, T(f, H_s)) df = \int_0^1 \frac{\partial \rho}{\partial p_i} \frac{\partial p_i}{\partial f} df$$

$p_i = D_0, D_1, f_0, f_1, h$

$H$ and $f$ are coupled by temperature

Some enthalpy effect already considered in $f$ derivative

Derivative for $H_s$ instead of $H$:

$$\frac{\partial \tilde{\rho}}{\partial H_s} = \sum \frac{\partial \tilde{\rho}}{\partial p_i} \frac{\partial p_i}{\partial T(f, H_s)} \frac{\partial T(f, H_s)}{\partial H_s}$$
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 ($U_{in} \sim \text{mm/s}$)
  (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

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

Unsteady fire simulation
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)

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<thead>
<tr>
<th>(0.015 m)</th>
<th>(0.130 m)</th>
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Vertical wall fire

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

Unsteady fire simulation
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**: \[ \overline{\rho f} = \overline{\rho f} \]
  - avoid \[ \overline{\rho Y} = \overline{\rho Y} + \overline{\rho'Y'} \]

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

- **Momentum equation**: \[
  \partial_t (\overline{\rho \tilde{u}})_i + \partial_{x_j} \left( \overline{\rho \tilde{u}_j \tilde{u}_i} \right) + \partial_{x_j} \overline{\rho u_i u_j} = -\partial_{x_i} \overline{\rho} + \partial_{x_j} \overline{\tau_{ij}} + \overline{\rho \tilde{g}_i}
\]

- **Reynolds tensor** : gradient approach \[
  - \overline{\rho u_i u_j} + \frac{2}{3} \overline{\rho k} \delta_{ij} = \overline{\rho v_t} \left( \partial_{x_j} \tilde{u}_i + \partial_{x_i} \tilde{u}_j \right)
\]

- **Turbulent viscosity** : k-\(\varepsilon\) model \[
  \nu_t = C_\mu \frac{k^2}{\varepsilon}
\]
Combustion model: diffusion flame

Combustible + Oxidant → Products

- Diffusion Combustible ↔ Oxidant
- $Q$: Products => Reactants

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

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

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

Unsteady fire simulation
Thermal transfers

Enthalpy transport equation:

\[
\frac{\partial}{\partial t} (\rho \tilde{H}) + \sum_{j} \left( \frac{\rho}{\text{Pr}} \frac{\partial}{\partial x_j} \tilde{H} \right) - \sum_{j} \left( \mu_t \frac{\partial}{\partial x_j} \tilde{H} \right) = \sum_{j} \left( \frac{\lambda}{C_p} \frac{\partial}{\partial x_j} \tilde{H} \right) + \dot{m} \tilde{H} - \nabla q
\]

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

\[
\bar{q}(\bar{x}) = \int_{4\pi} L(\bar{x}, \bar{S}) \bar{S} \, d\Omega
\]

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

Radiant transfer equation:

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

\( k \) : absorption coefficient, function

CO₂, H₂O and soot volume fraction, temperature, total pressure and mean beam length