Prehistoric fires:

Heat and Mass Transfer in soil

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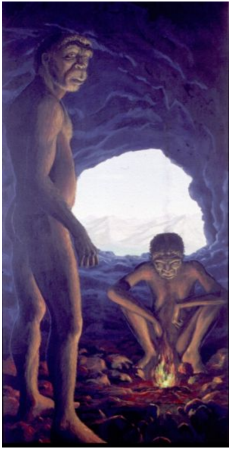
Introduction

- Rules of human behavior
- Function of the combustion structures
- Reconstitution of the thermal history of each hearth



Background and Motivation

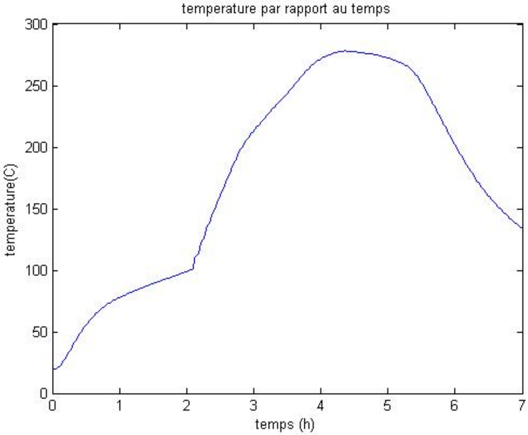
- Determination of the minimal duration of lighting
- Laloy & Massard (1980) analytical model
  (1D – dry ground)
- March & Ferreri (1991) numerical model
  (phase change – no gas dynamic)

$\longrightarrow$ more complete physical model

$\longrightarrow$ extension to 3D geometries

$\longrightarrow$ fast and accurate code: inverse problem

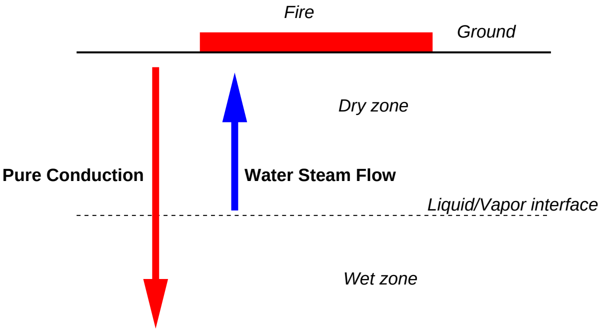
March & Ferreri results



Physical Modeling

- natural evaporation (Chammari, 2002; Caceres-Slazar, 2006)
- forced evaporation (fire: soil at 300 to 600 °C) => strong coupling between energy (temperature) and gas dynamic (water steam flow)
  1. energy (soil/fluid components at equilibrium)
  2. momentum (reduced to steady Darcy law)
  3. mass conservation
  4. fluid constitutive law (liquid/vapor water)

Forced evaporation in soil



Set of equations

Energy:

$$(\rho C)\frac{\partial T}{\partial t} + (\rho C)_f \vec{V}_f.\nabla T = \mathrm{div}\,[\lambda \nabla T]$$

with $(\rho C) = \phi(\rho C)_f + (1-\phi)(\rho C)_s$

+ *Boundary Conditions* at dry/wet interface:

$$T_g = T_l \qquad k_g \frac{\partial T_g}{\partial x} - k_l \frac{\partial T_l}{\partial x} = -\rho L \frac{d\xi}{dt}$$

Set of equations (cont.)

Momentum (Darcy law):

$$\vec{\nabla} P = -\frac{\mu_f}{K} \vec{V_f}$$

Mass conservation:

$$\frac{\partial(\phi \rho_f)}{\partial t} + \mathrm{div}(\rho_f V_f) = 0$$

Fluid constitutive law:

$$\rho_f = F(p, T)$$

Phase change modeling: two approaches

1°/ Apparent Heat Capacity (AHC) method
(Bonacina et al., 1970)

- continuous medium
- artificially modified physical properties

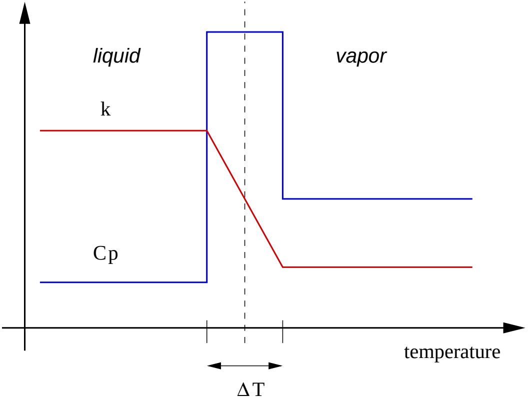
2°/ Latent Heat Accumulation (LHA) method
(Prapainop et al., 2004)

- accumulation of heat in each cell
- comparison with coefficient of latent heat

Test on the classical Stefan problem (1D)

1°/ Apparent Heat Capacity (AHC) method

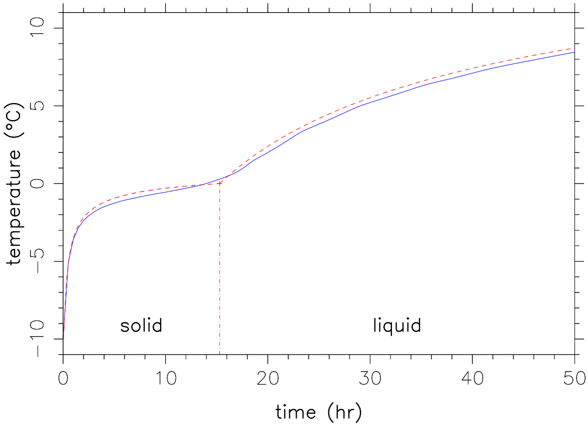
- easy to implement
- leads to stiff system
- no heuristics to find the good parameter ΔT



Result for the AHC method

- method of lines (spatial discretization via FV method)
- use of a BDF solver for the ODE system

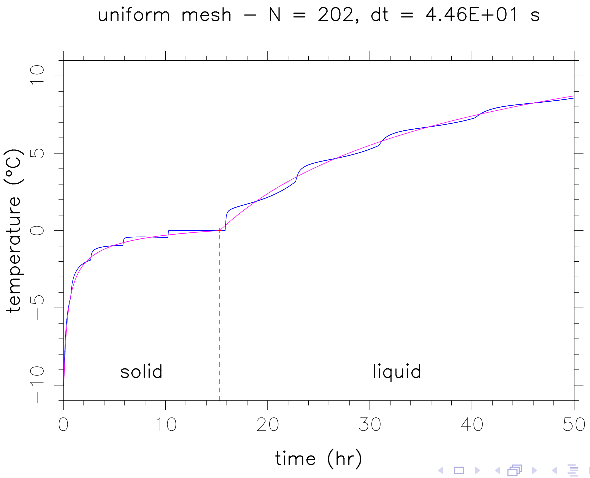
red(−−) : analytical sol. / blue : numerical sol.



Test on the classical Stefan problem (1D)

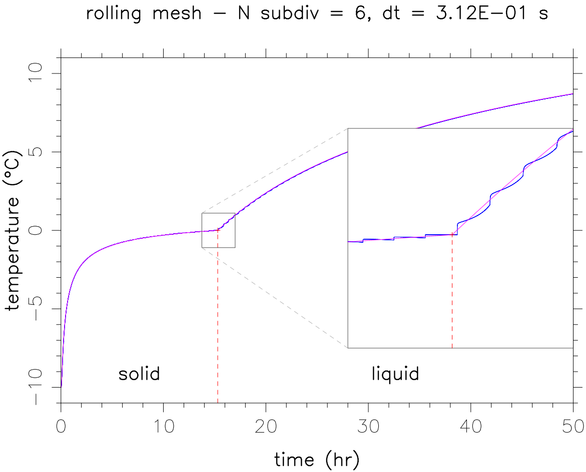
1°/ Latent Heat Accumulation (LHA) method

- spatial discretization: FV with uniform mesh
- time discretization: first order explicit



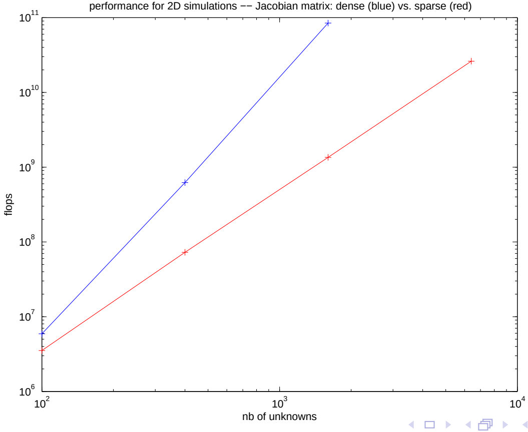
Result for the LHA method

- reduction of the fluctuations: use of a self-adaptive mesh
- limited to 1D discretizations

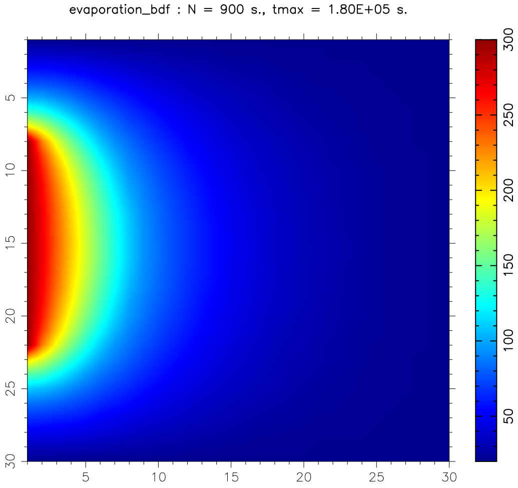


Improvements of the AHC method

- continuous matched functions (Gaussian + Erf)
- Jacobian matrix coded by hand
- solver ODE-BDF (ddebdf of SLATEC) modified to support sparse Jacobian matrix + UMFPACK



2D Result for the AHC method

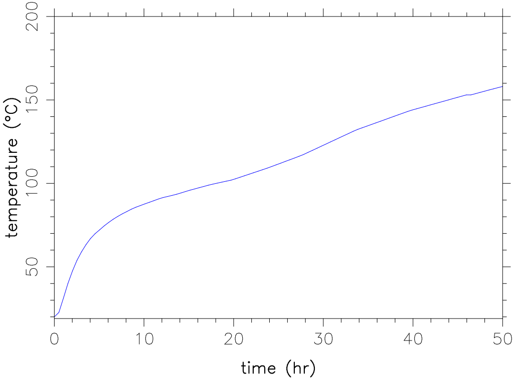


CPU time = 10 minutes with sparse Jacobian
(instead of 6 hours)

Complete model: first approach

- energy equation (AHC): ODE $\rightarrow$ whole 1D domain
- gas dynamic: parabolic equ. $\rightarrow$ dry zone only

Coupling done by a fix-point method



Disadvantage: requires the knowledge of the phase-change location

Complete model: better approach

- all equations and properties treated as in AHC
- all equations apply to the whole domain

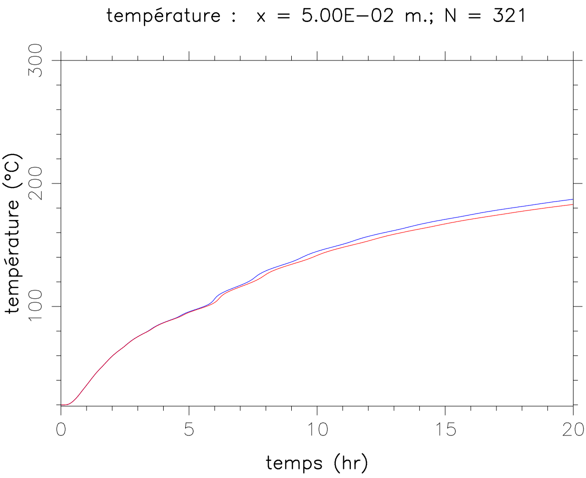
Energy $\longrightarrow$ ODE $\qquad \frac{\partial T}{\partial t} = \ldots$

Gas dynamic $\longrightarrow$ DAE $\qquad G(\frac{\partial T}{\partial t}, \frac{\partial p}{\partial t}, T, p) = 0$

Solver DAE (DASSL of SLATEC)

Results for 1D, 2D
3D-axisymmetric: in progress

Effects of the water steam flow



Blue curve: without coupling
Red curve: with coupling

Conclusion / Perspective

- "method of lines + solver ODE/DAE": good approach
- effect of the water steam flow is small
- but all parameters must be explored

$\longrightarrow$ 3D-axi must be finished: comparison with experiments

$\longrightarrow$ fully 3D problem requires parallel solvers

$\longrightarrow$ difficulty to derive the Jacobian matrix by hand: automatic differentiation?