Combined strategies to extinguish underground coal fires and extract geothermal energy
-THC modelling

9-12 Sep. 2013 – Liege

Centre for Geotechnical and Materials Modelling
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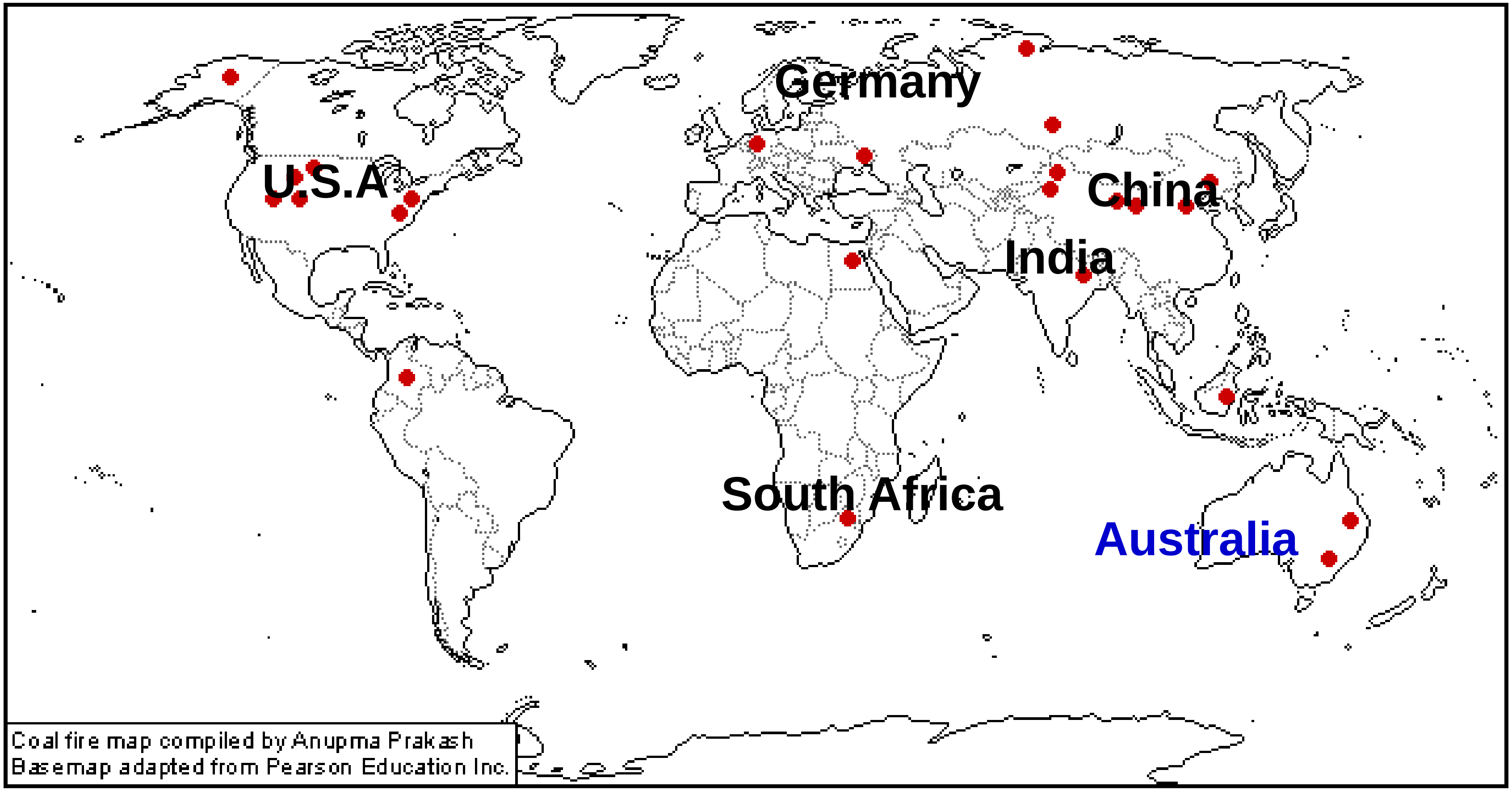
Outline of the talk

- Introduction of Underground coal seam fires
- Physical-chemical model of UCSF
- THC modelling of UCSF
- Future Research

Underground Coal Fires

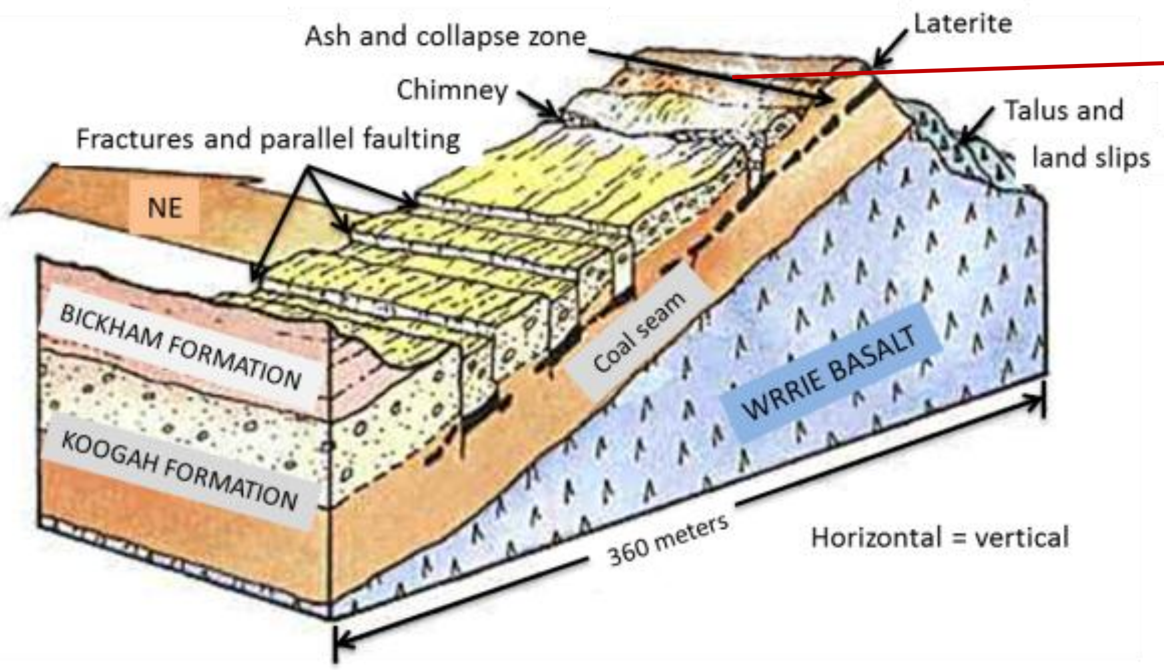
- Many underground coal fires worldwide (different origins)
- Natural resources consumption/CO_2 emissions/damage to infrastructure, fauna, flora



Underground Coal Fires

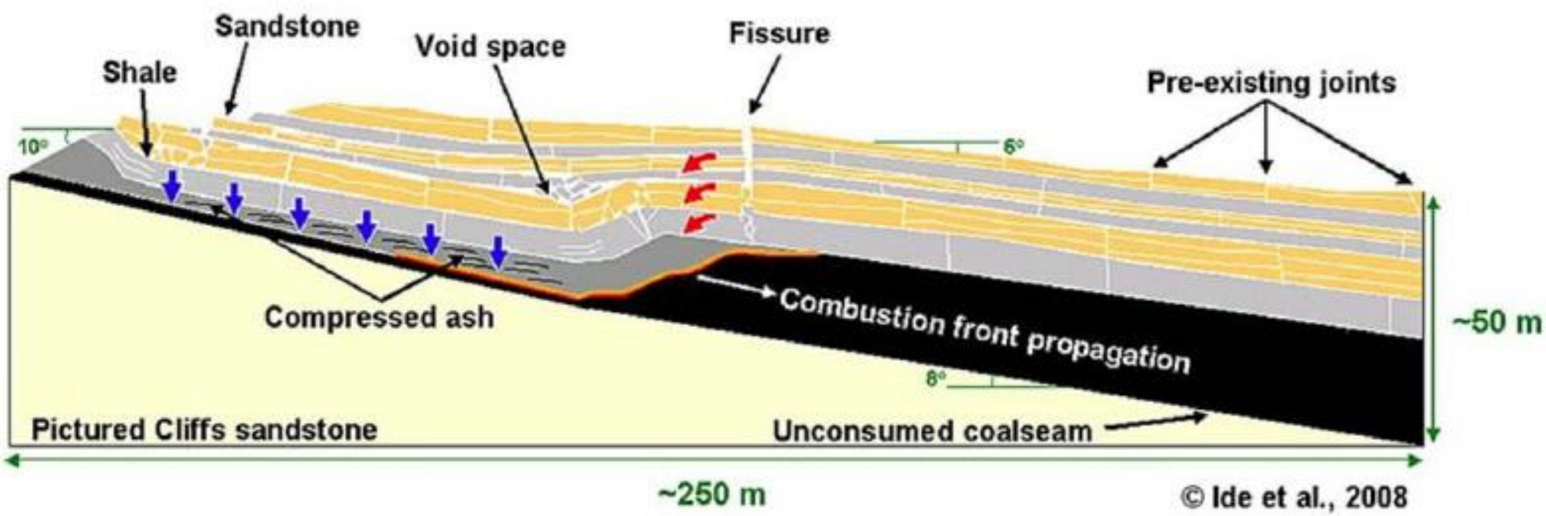
- Town of Centralia, Pennsylvania, USA, has been totally evacuated
- Fires are burning slowly (smouldering), very high temperature (in excess of 1000 degrees) and are extremely difficult to put out
- Big challenge for researchers and engineers to extinguish coal fires

Australia coal fires - Burning Mountain



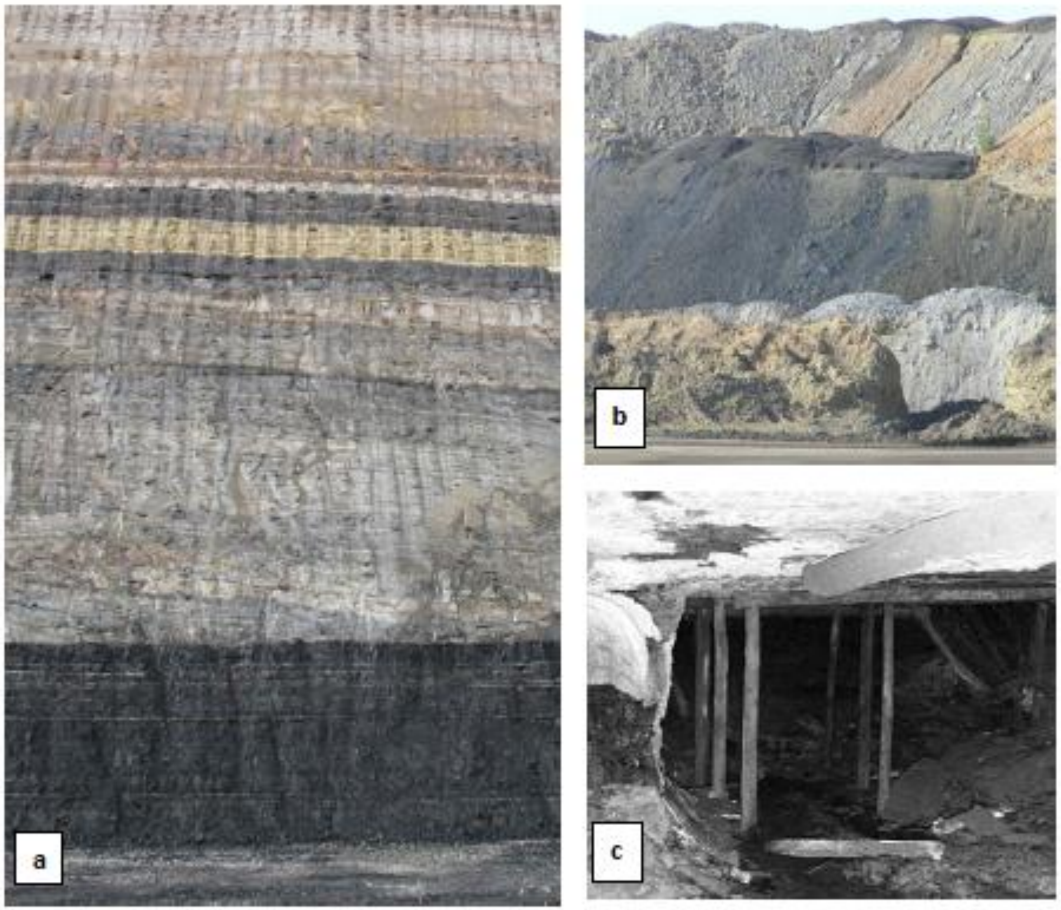
- 30 m depth in average and seam thickness: 7.6-10.3m (Hanlon, 1946)
- About 1 m southwards per year
- 5500 years continuous burning
- Soil collapse as the burning front progresses

Australia coal fires - Burning Mountain



- As soils collapses, cracks open -> Oxygen supply for the fire
- Coupled THMC problem
- Other configurations are more problematic (spoil pile or abandoned workings)

Underground coal fires



In intact seam (a):

- Fuel is plentyful, continuous and at at known location
- Very high temperatures
- Subsidence is an issue

In spoil piles (b)

- Fuel is scattered with waste material
- Low quantity (5-6%)
- Low temperatures (>100 degrees)
- Structure of spoil is highly variable

In abandoned workings (c)

- Pillars standing
- Coal on roof and floor
- Significant ventilation

Underground coal fires

Why extinguishing the underground coal fires?

- In all cases: to reduce pollution
- Intact seams:
  - To limit loss of resources
  - To limit damage to land and infrastructure
  - Government's liability and responsibility
- Above abandoned workings:
  - To limit damage to land and infrastructure
  - Government's liability and responsibility
- In spoil piles:
  - Land rehabilitation
  - Some infrastructures now get built on spoil piles

The big issue is that coal is **auto-combustible**. So, putting fire out (water injection, capping layer) is often only **temporary** !

Ground and coal temperature must drop to below 85 degrees !

➔ Need to harvest the heat !

Objectives of the research project

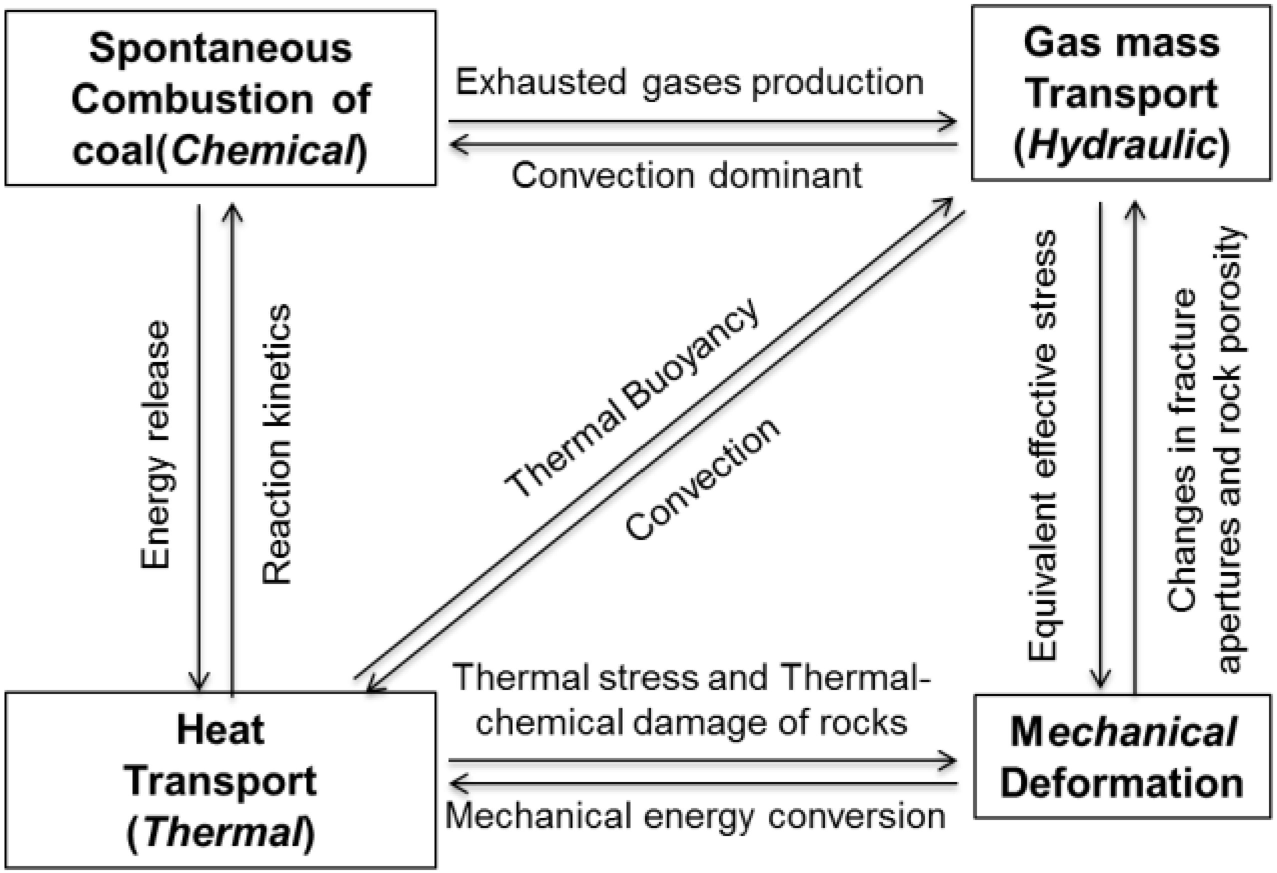
Objective of the research project is to assess whether it is possible to :

- Develop an array of heat collectors in the ground to lower temperature
- Re use the heat for an alternative use (energy, direct use)

Project revolves around:

- Thermo mechanical characterization of materials in the laboratory (rocks, spoil piles)
- Assessment of the fire situation and ground temperature in a spoil pile
- Design and implementation of heat collector in the ground (spoil pile)
- FEM modelling of underground coal fire (intact seam, spoil pile)

Physical-chemical model of UCSF

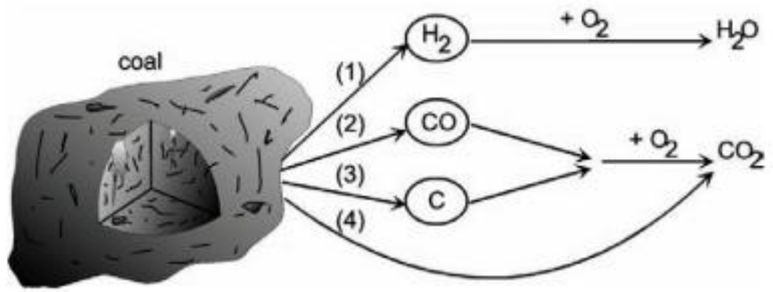


Coupled chemical, thermal, hydro, mechanical processes in UCF

(Modified from Wesling, 2007)

Reaction model of Coal Spontaneous Combustion

Rosema et al., 2001, Schmidt, 2001, Lohrer et al., 2005, Wesling, 2007



$$Coal + O_2 \rightarrow solid\ products + exhaust\ gases$$
$$(CO_2 + CO + H_2O + SO_2\,etc.) + \Delta H \uparrow$$

Mass conservation equations

$$\frac{\partial C_j}{\partial t} + S_j = 0$$ **j= coal (c) or solid product**

$$S_j = \left(\frac{v_j}{v_c}\right)\left(\frac{M_j}{M_c}\right) \cdot S_c$$

Stoichiometry: v_i- stoichiometric coeffici

M_i- molecular weight

Second-order Arrhenius-type reaction rate for coal

$$S_c = -C_c C_{O_2} k_0 \exp\left(-\frac{E}{RT}\right)$$ **E and K_0 determined experimentally**

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Numerical problems of coal spontaneous combustion

Different time scale with temperature

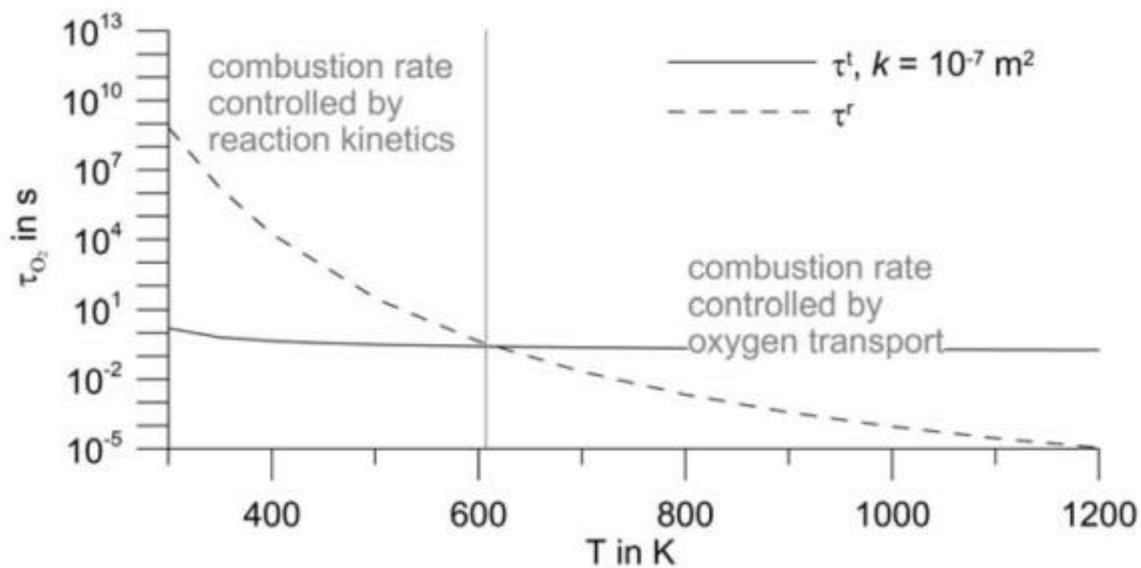
$$\frac{\partial \theta C_j}{\partial t} + \boldsymbol{q}\,\nabla C_j - \nabla\cdot\left(D_{ij}\nabla C_j\right) + S_j = 0\ (\mathrm{j} = \mathrm{O_2}\ \text{or gaseous product})$$

Transport part

Consumption part

$$\tau^r_{o_2} \cong \Delta t^t_{o_2} \sim \frac{\phi L_c^{o_2}}{\frac{k}{\mu}\rho_0^c \frac{\Delta T}{T}|g|}$$

$$\tau^r_{o_2} = C_{o_2} Q_{o_2}^{-1} = \frac{v_f}{v_{o_2}}\frac{M_f}{M_{o_2}}\left(C_f k_0 e^{-\frac{E}{RT}}\right)^{-1}$$



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Numerical problems of coal spontaneous combustion

Modelling reactive medium in a THM context

MWAT2D → Darcy velocities of gas → **ADVE2D**

NTECL

C_{O2}= C_{O2}+FIC(IN,IPI)*XY(6,KF)

REACT → Average O_2 concentration degradation rate in DELTAT → **ADVE2D**

New data transfer file: NTECF

Degradation term ↑ **ADVE2D**

Numerical Resolution of coal spontaneous combustion model

$\Delta t_{tr}, T_0$
C_0(coal)=C^t
$C_0(O_2)$=0.297 kg/m³

↓

Calculate O_2 consumption time scale: $\Delta t_{ch} = \alpha \cdot \tau^r_{o_2}$
Total time substeps: NSTEP= $\Delta t_{tr} / \Delta t_{ch}$

↓

Calculate coal consumption rate: $Q_C = C_C C_{O_2} k_0 \exp\left(-\frac{E}{RT}\right)$

O_2 consumption : $C_{O_2}^{t+\Delta t_{ch}} = C_{O_2}^{t} - \frac{\Delta t_{ch}}{\theta} \cdot \delta \cdot Q_c$

Coal consumption: $C_c^{t+\Delta t_{ch}} = C_c^t - \Delta t_{ch} \cdot Q_c$

$$\sum_{i=1}^{NSTEP} \Delta t_{ch} = \Delta t_{tr}$$

↓

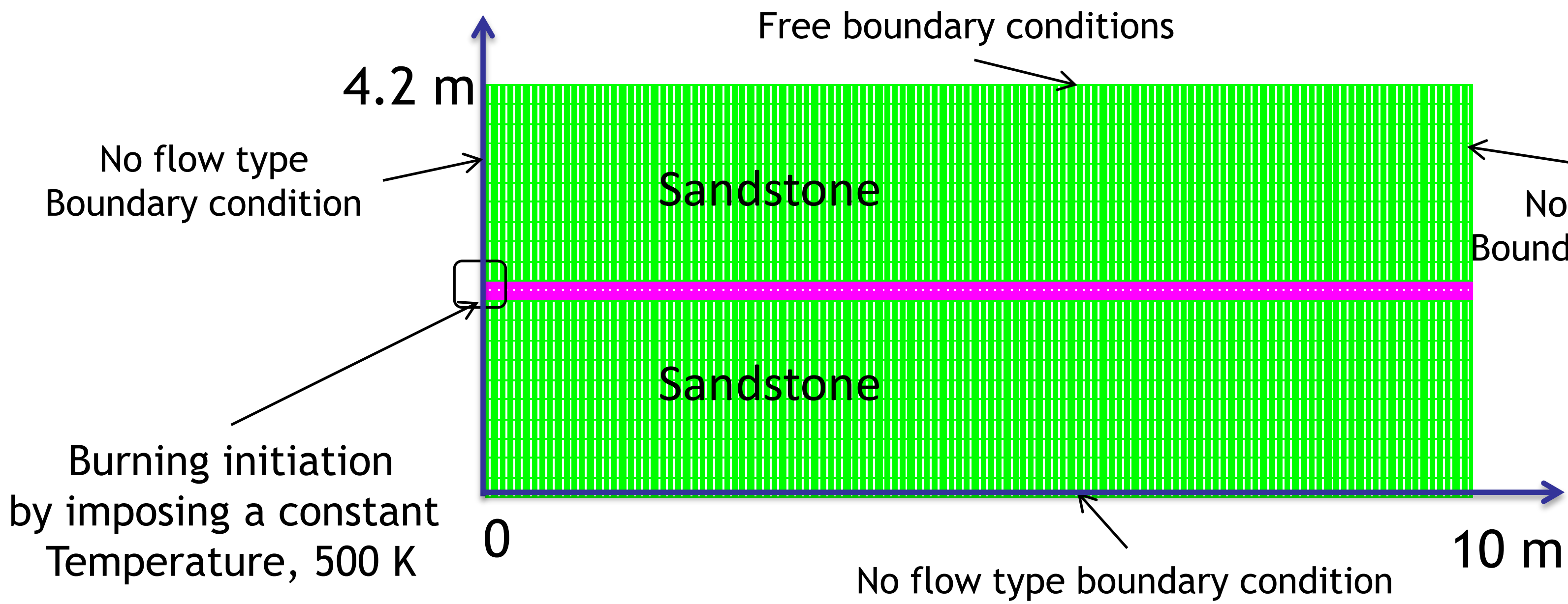
IF: ΔC_{O_2} > 1.0E-4
Calculate energy production rate:
$Q_t = \Delta H \cdot (C_c^{t+\Delta t_{tr}} - C_c^t)/\Delta t_{tr}$

(loop back to the first step)

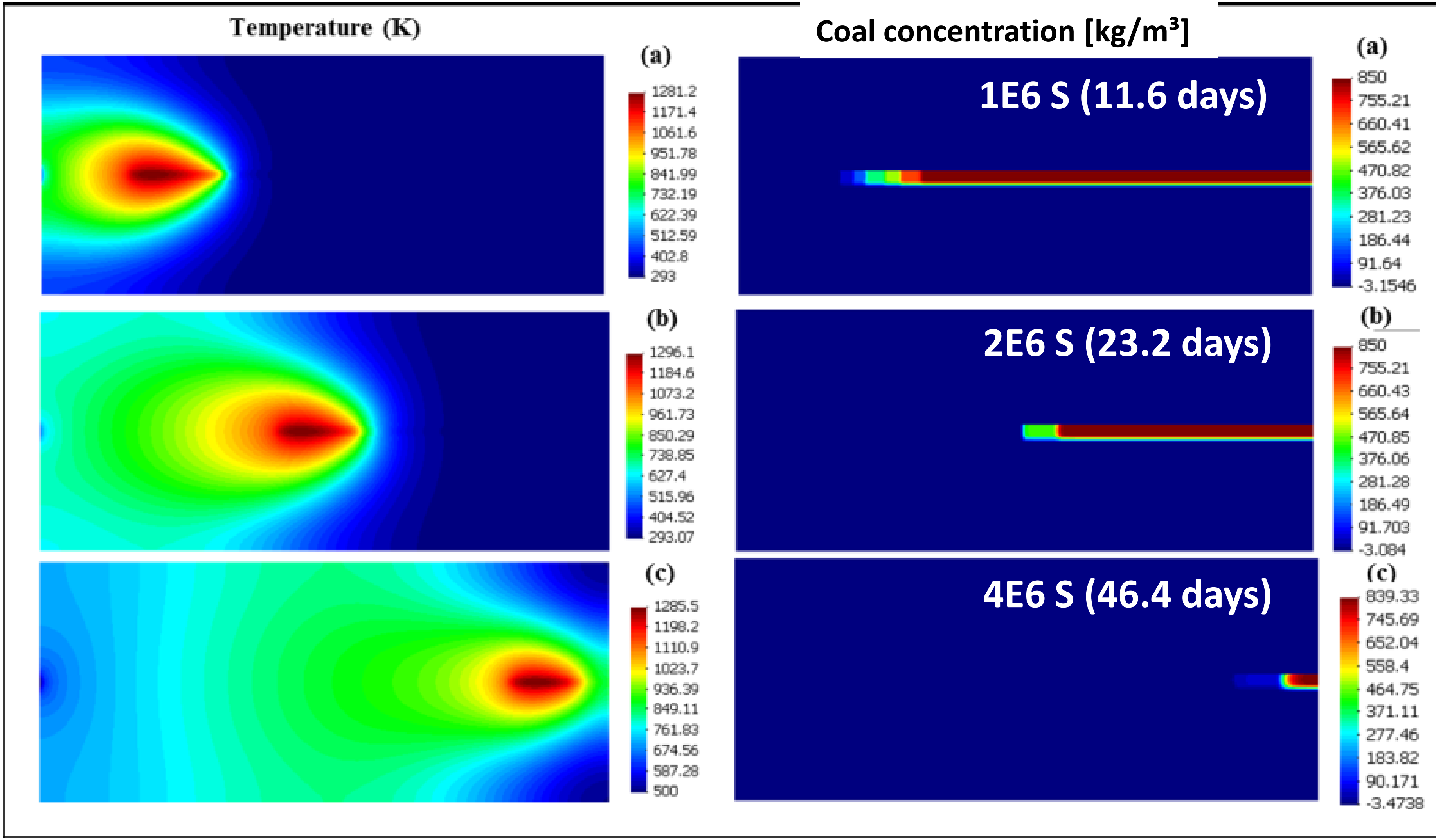
Reaction model coupled with Heat transport

Features modelled:

- Coal Spontaneous Combustion (not initiation)
- Heat transport: conductive transport + radiation part



Reaction model coupled with Heat transport



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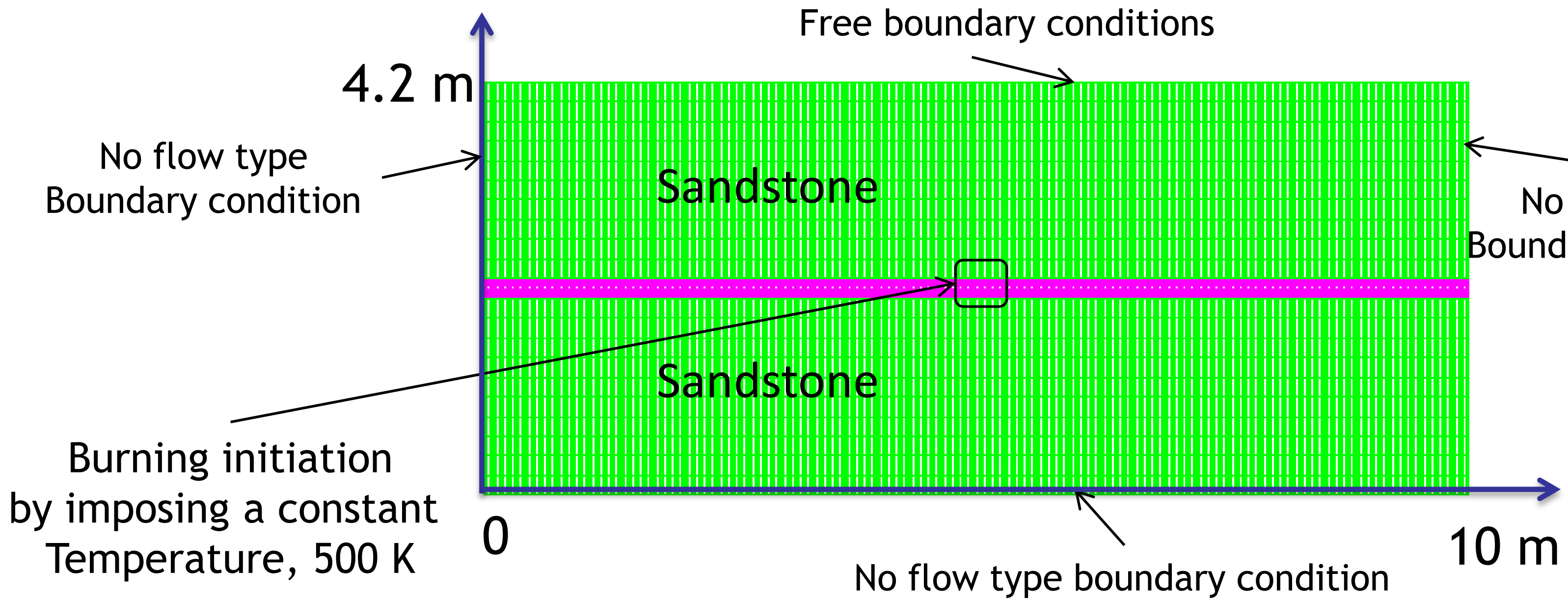
Reaction model coupled with Heat-gas transport

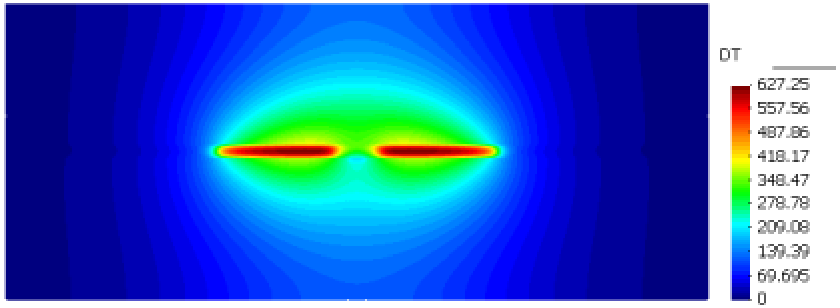
Features modelled:

- Coal Spontaneous Combustion (not initiation)
- Heat transport: conductive transport + convection by gas transport + radiation part
- Effect of temperatures on gas pressure

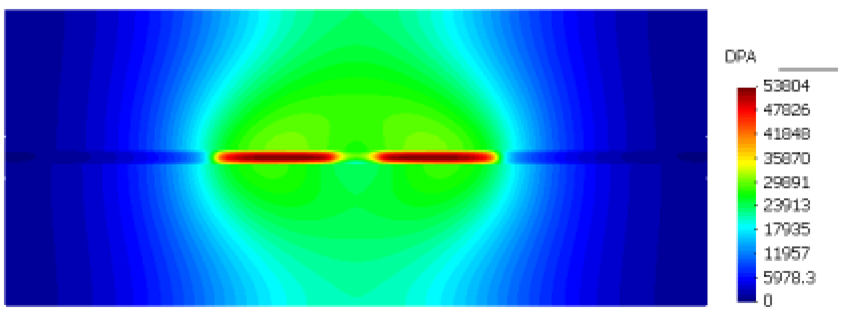


Reaction model coupled with Heat-gas transport

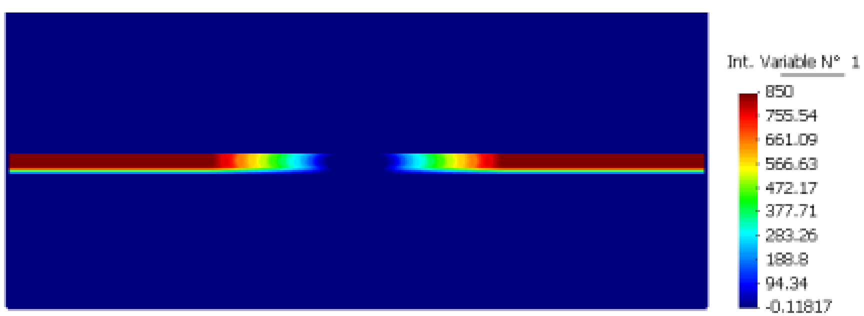
4E6 S (46.4 days)



Temperature variation

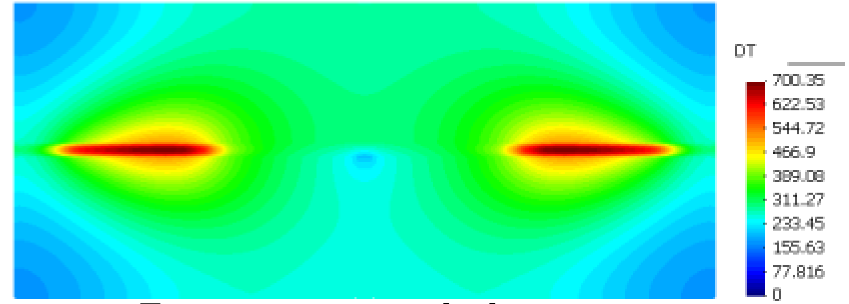


Gas pressure variation

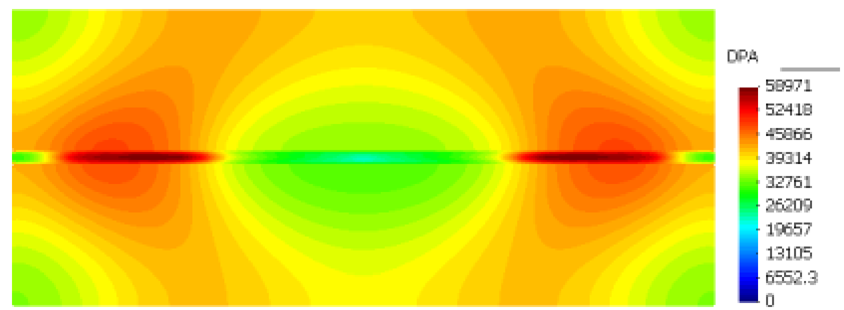


Coal concentration [kg/m³]

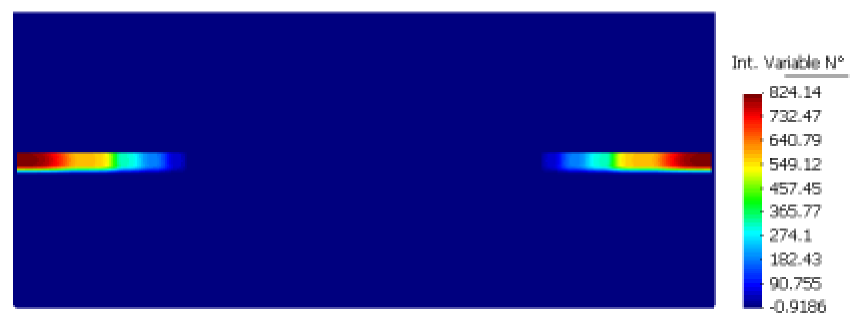
8E6 S (92.8 days)



Temperature variation



Gas pressure variation

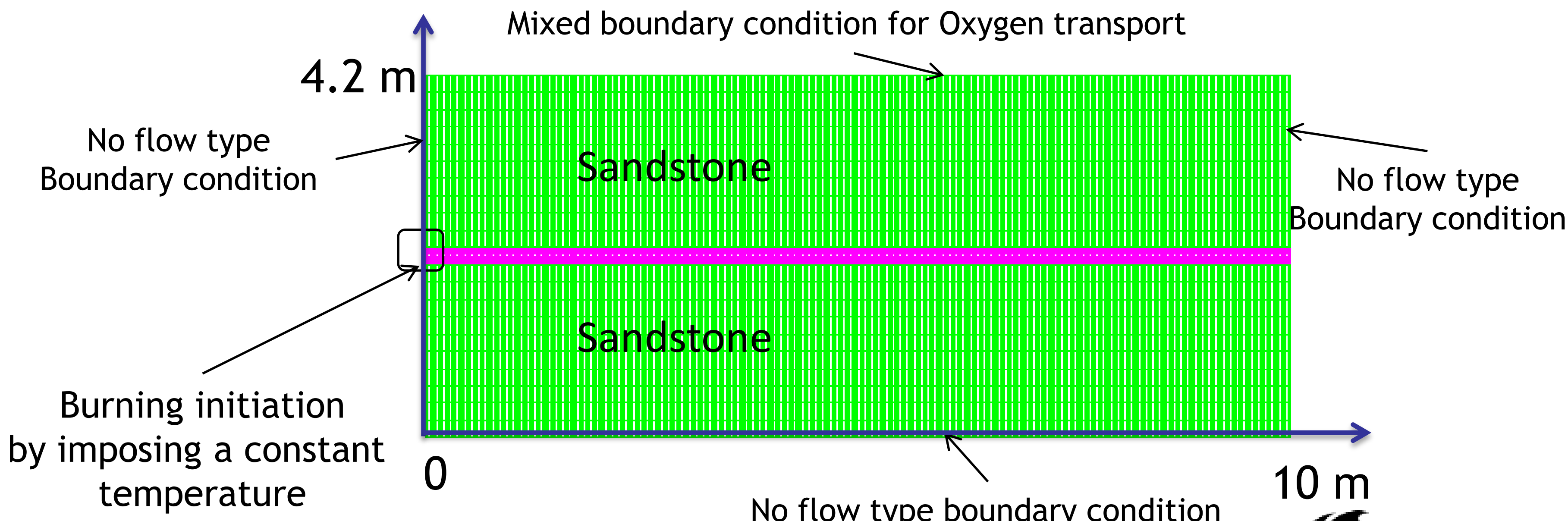


Coal concentration[kg/m³]

Reaction model coupled with Heat-Gas-Oxygen transport

Features modelled:

- Coal Spontaneous Combustion (not initiation)
- Heat transport: conductive transport + convection by gas transport + radiation part
- Effect of temperatures on gas pressure
- Surface thermal radiation (boundary condition on top)
- Oxygen transport (one of gas species)



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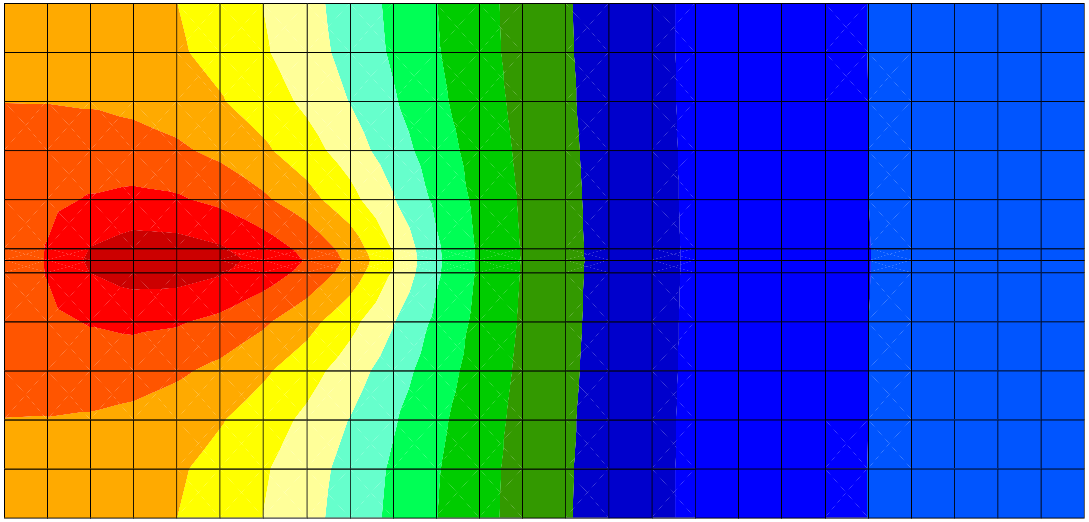
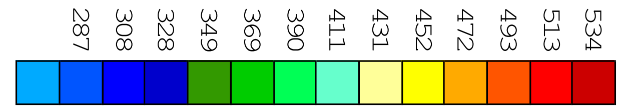
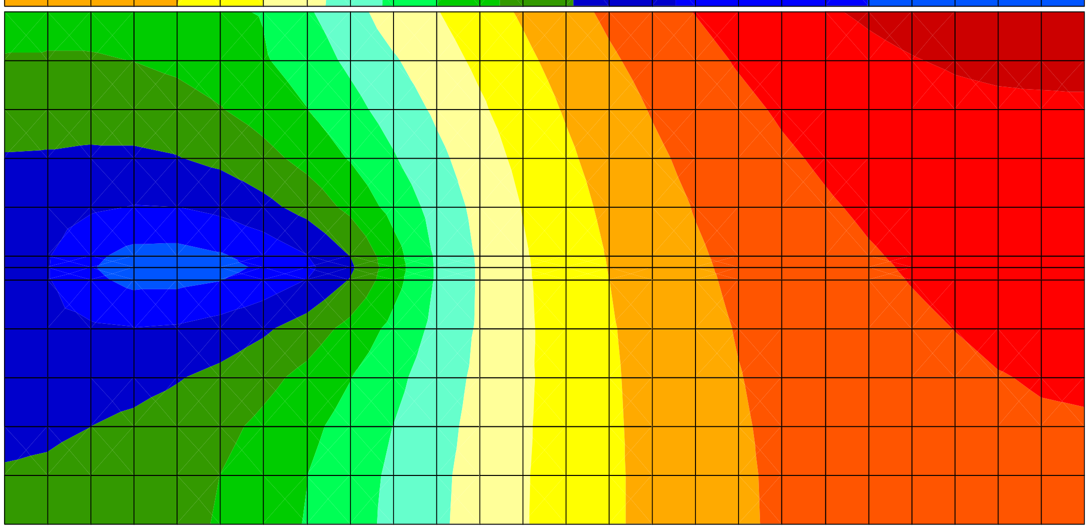
THC model coupled with *Oxygen Transport*

After a simulation time of 46.3 days

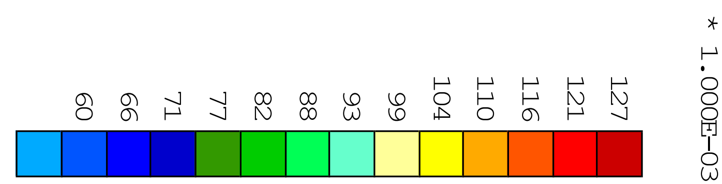


Temperature evolution (K)





Oxygen concentration evolution (kg/m^3)



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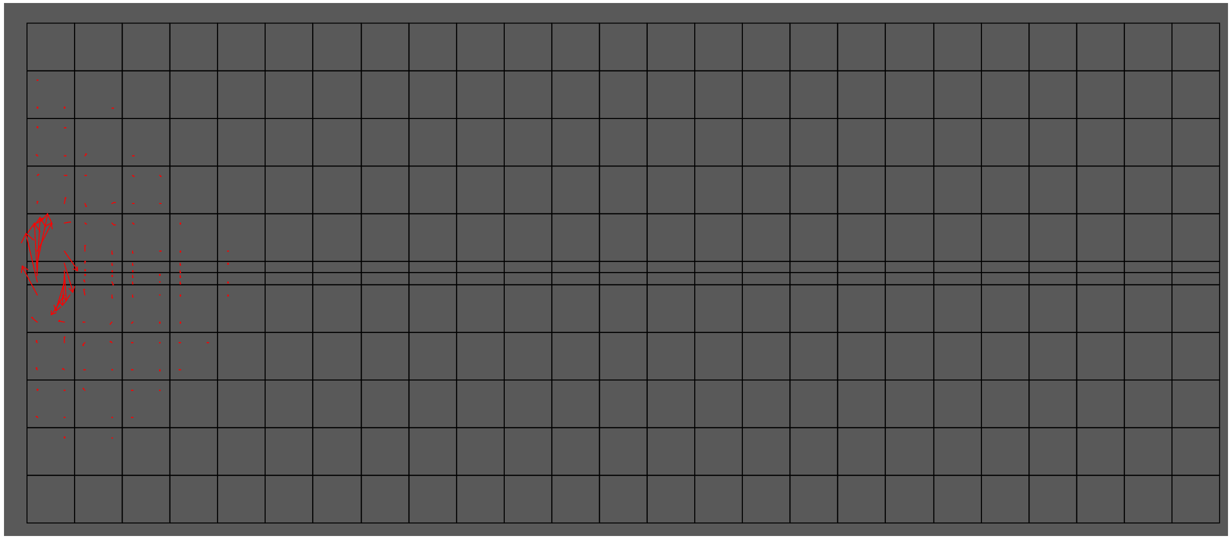
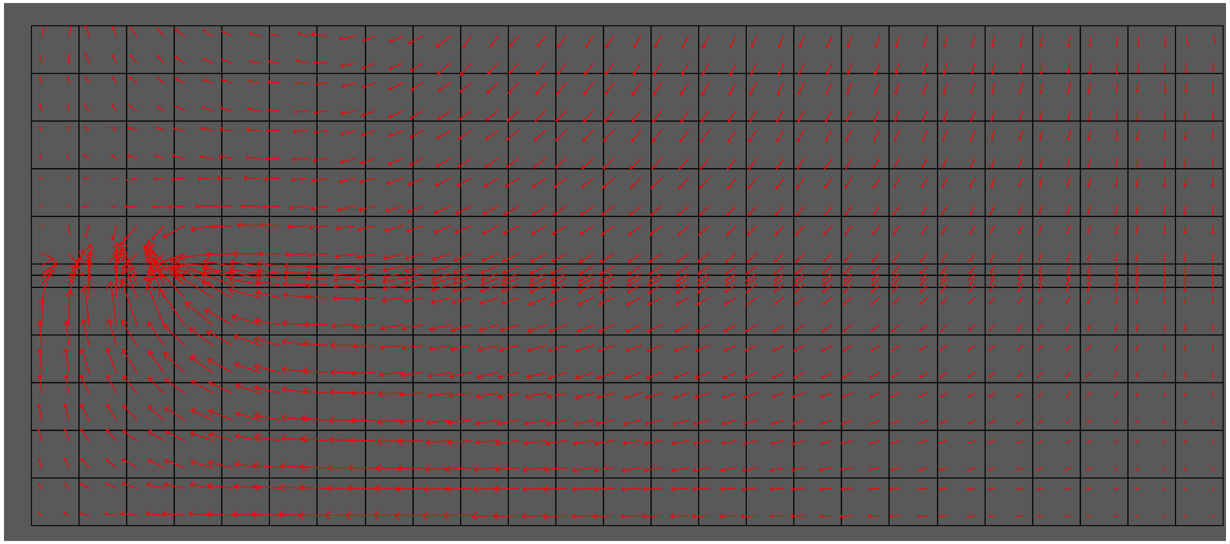
THC model coupled with *Oxygen Transport*

Oxygen flow field evolution



1E+3 s
(16 minutes)



2E+6 s
(23.14 days)

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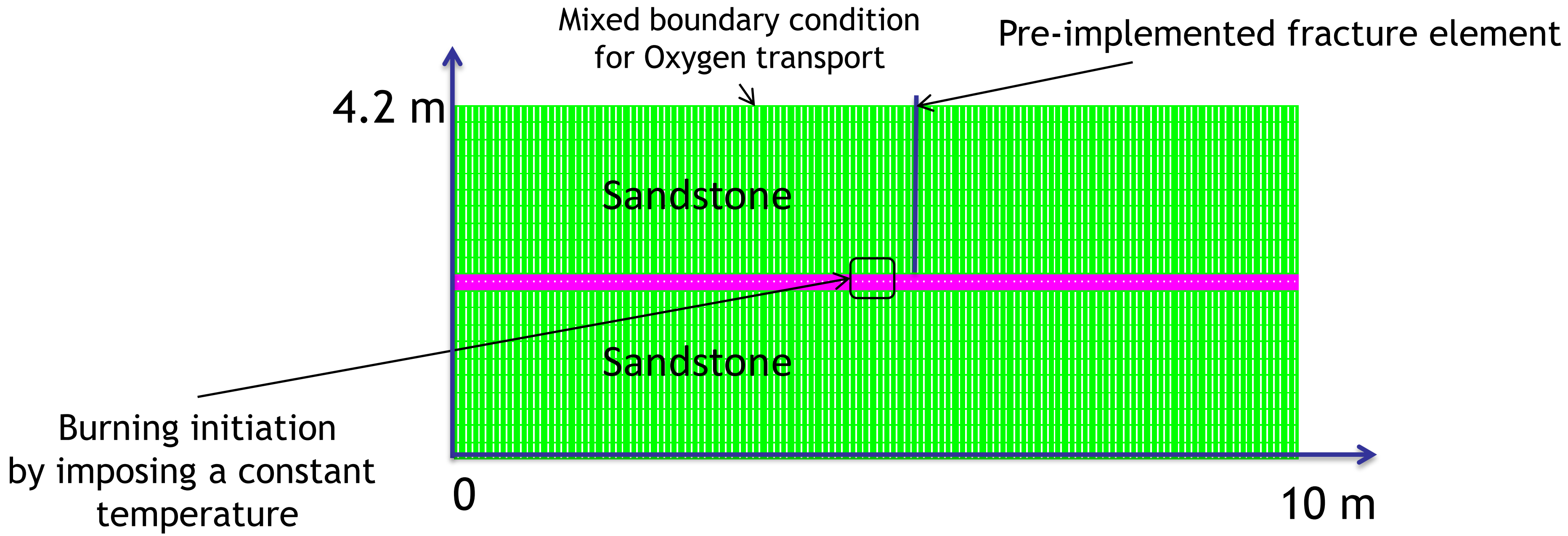
On-going development of THC model with fracture

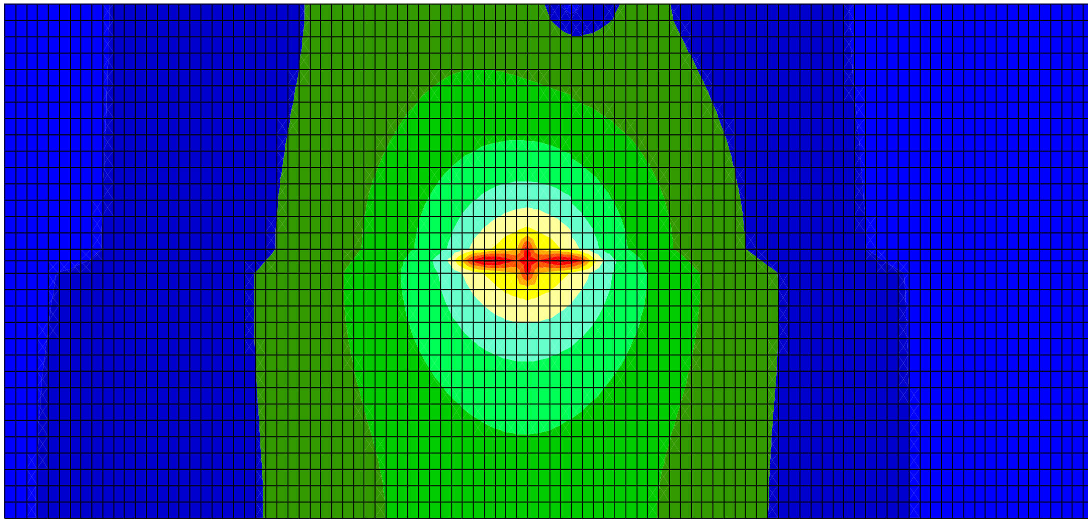
Improved features modelled:

- Improved mixed boundary condition for Oxygen depending on gas flow direction (in or outwards)
- Pre-implemented fracture element including 1-D Oxygen transport plus heat and gas transport
- Cracks of given permeability (variable with aperture)

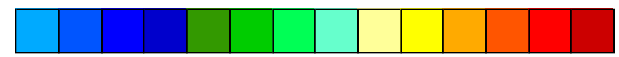


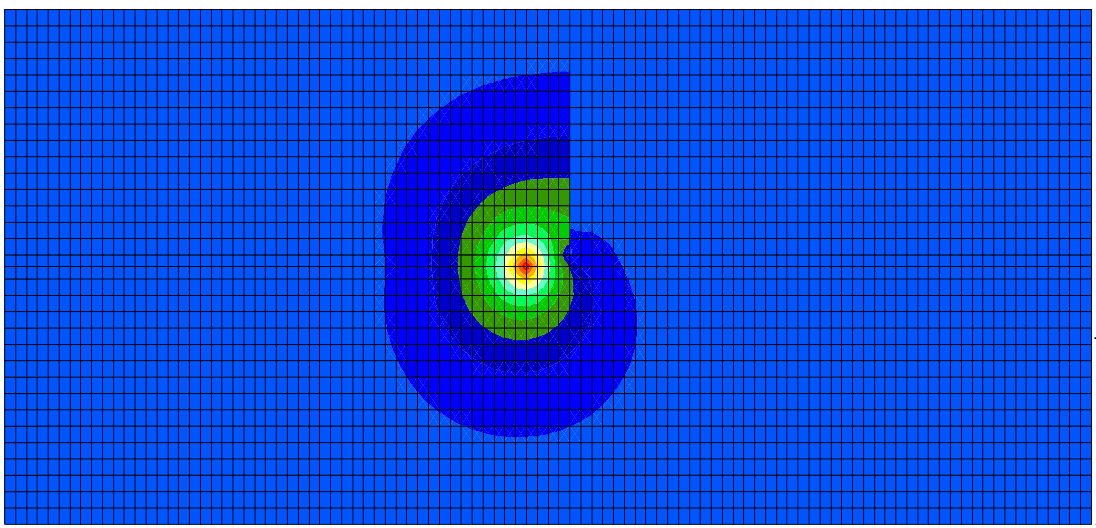
Preliminary results of improved model

After a simulation time of 46.3 days

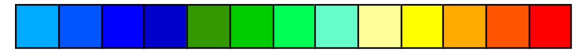


Temperature evolution (K)





Oxygen concentration evolution (kg/m^3)



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Future works

THMC modelling

- **Large scale simulation to characterize the features of UCSF**
- **Develop constitutive model of rock with coupling Mechanical-Chemical damage**
- **Numerical simulation of fracture initiation and propagation in UCSF**
- **Numerical simulation of multi-physics processes in case of multi-coal seam fires**

Experimental work

- **Hydro-mechanical properties of rock at high temperature**
- **Fracture propagation of rock subjected to heating treatment**

Thank you for your attention