# TWO-PHASE FLOW IN A POROUS MEDIA

# TEST-CASES PERFORMED WITH TOUGH2

**Paris**
**23rd September 2010**

*E. Treille, J. Wendling*
*Andra*

# Tough2 – Overview (1/2)

- **Code for multi-phase and multi-component fluid flow and transport in porous media**
- **Developed at Lawrence Berkeley National Laboratory (LBNL)**
- **Thermophysical fluid properties for a wide range of pressures and temperatures**
- **Many capillary pressure and relative permeability relationships**
- **Available version with FORTRAN 77 files of source code =>adaptable for specific needs:**
  - additional relationships (Problem4)
  - additional outputs
- **Specific fluid property modules:**
  - EOS5 for water/hydrogen mixtures (Problems 1-2-3)
  - EOS3 for water/air mixtures (Problem 4)

# Tough2 – Overview (2/2)

- **Space discretization is made from the integral form of the basic conservation equations (IFDM: integral finite difference method)**
- **Time is discretized fully implicitly (first-order)**
- **Linear equation system is solved using a Newton-Raphson iteration process**
- **Automatic time step control**
- **Primary variables (isothermal conditions):**
  - single phase conditions: P, $X_{mass\ H2/air}$
  - two-phase conditions: $P_g$, $S_g$
  - primary variables are switched and re-initialized in response to a change of phase

# Tough2 modules EOS3/EOS5

- Components: water and hydrogen (EOS5) or air (EOS3)
- Phases: liquid and gas
- Ideal gas law for gas phase
- Dalton's law for partial pressures: $P_{gas}=P_{H2/air}+P_{vap}$
- Fluid advection described with a multiphase extension of Darcy's law
- Solubility of hydrogen according to Henry's law: $X_{mole}=H*P_{H2/air}$

# Main deviations from the test-cases specifications

- **Diffusion model:**
  - diffusive flux $j_\alpha^i$ of component i in fluid phase $\alpha$

$$j_\alpha^i = -\phi S_\alpha \rho_\alpha d_\alpha^i \nabla X_\alpha^i$$

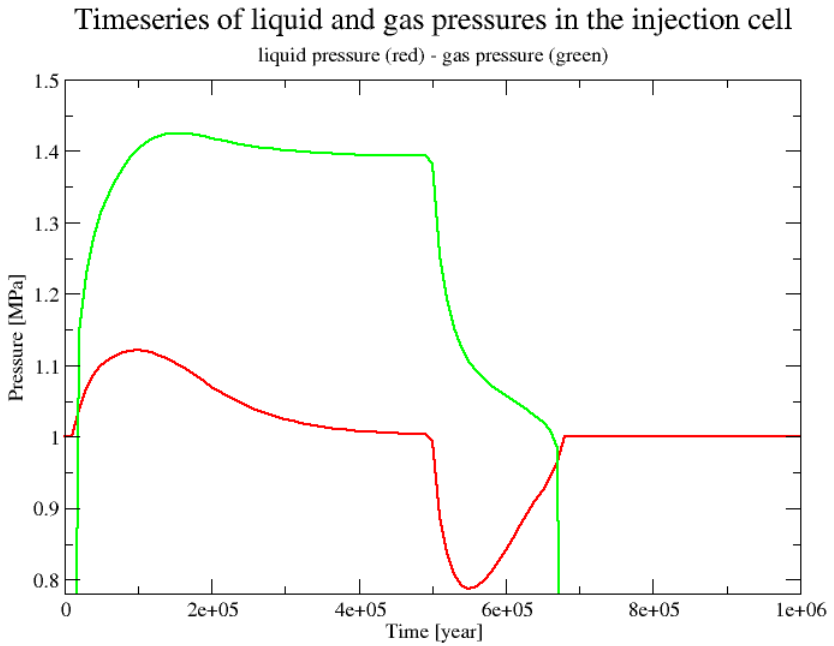
with $X_\alpha^i$ mass fraction of component i in phase $\alpha$

- **Vapor pressure is not neglected:**
  - At 300 K saturated vapor pressure is 3532 Pa
  - At 303 K saturated vapor pressure is 4205 Pa
- **Compressibility of liquid water**
- **Production term for hydrogen:**
  - applied on a thin specific volume instead of a boundary surface

# Problem 1: gas phase appearance/disappearance

- **Porous media initially fully saturated with pure water**

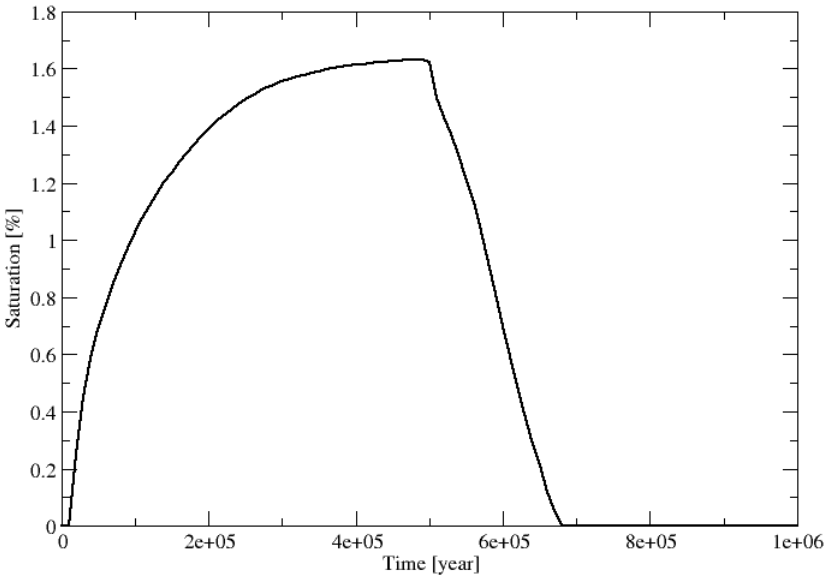
- **Regular spatial discretization: dx=1 m**
- **Time discretization:**
  - dtmin=1 s, dtmax = 1000 years
- **Relative convergence criterion: $10^{-5}$**



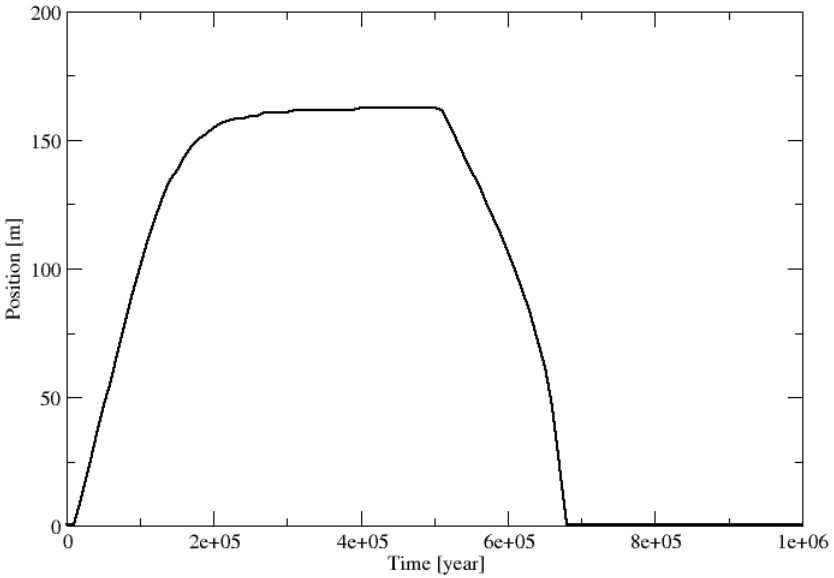
# Problem 1: gas phase appearance/disappearance

- **Porous media initially fully saturated with pure water**

Timeseries of gas saturation in the injection cell



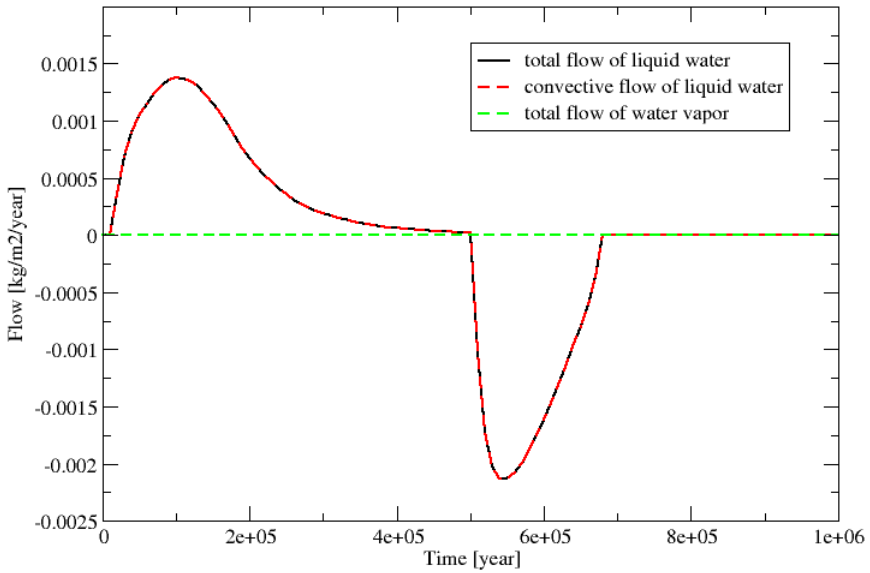

Timeseries of saturation front position



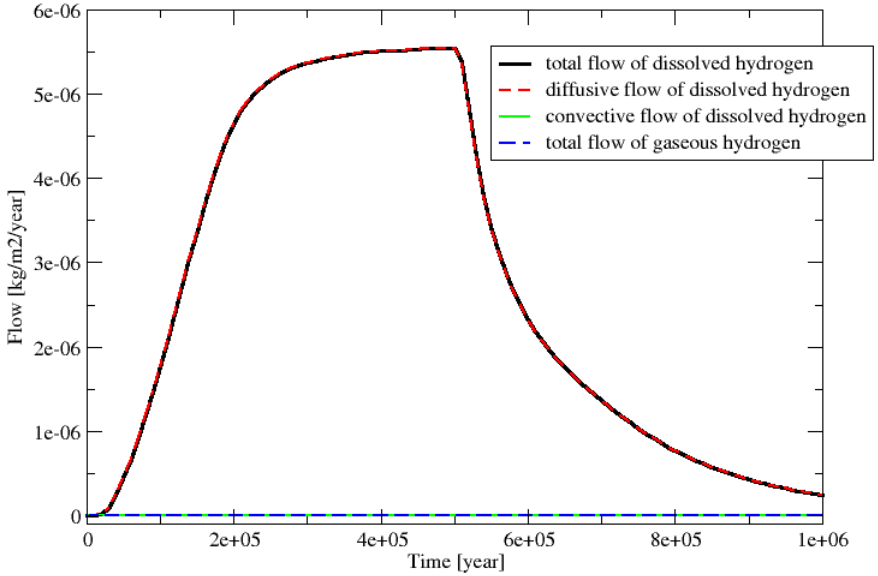
# Problem 1: gas phase appearance/disappearance

- **Porous media initially fully saturated with pure water**

Timeseries of water flow across exit boundary



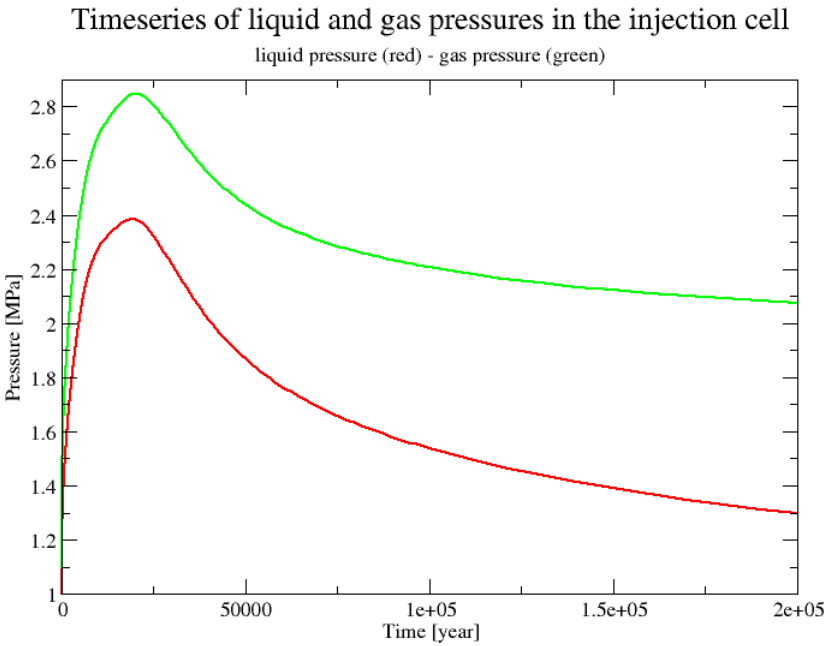

Timeseries of hydrogen flow across exit boundary



# Problem 1: gas phase appearance/disappearance

- **Porous media initially partially saturated with liquid**

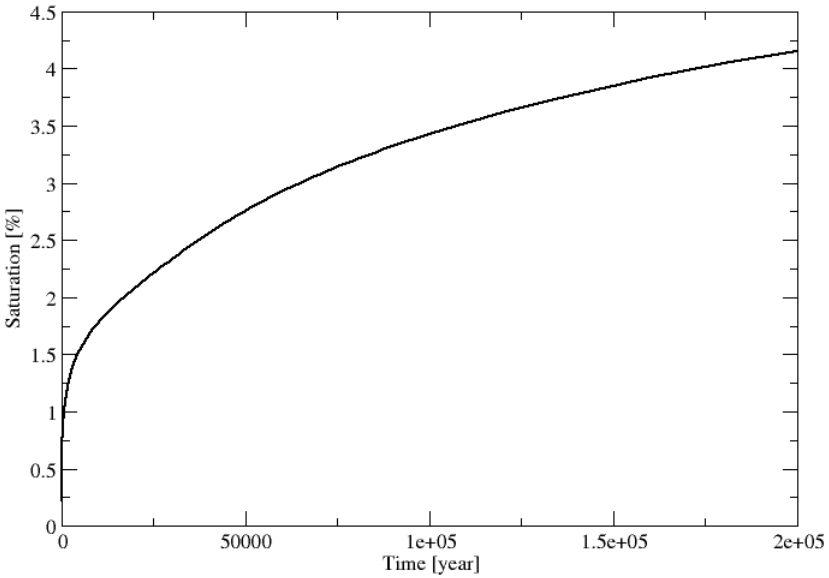
- **Regular spatial discretization: dx=1 m**
- **Time discretization:**
  - dtmin=1 s, dtmax = 1000 years
- **Relative convergence criterion: $10^{-5}$**



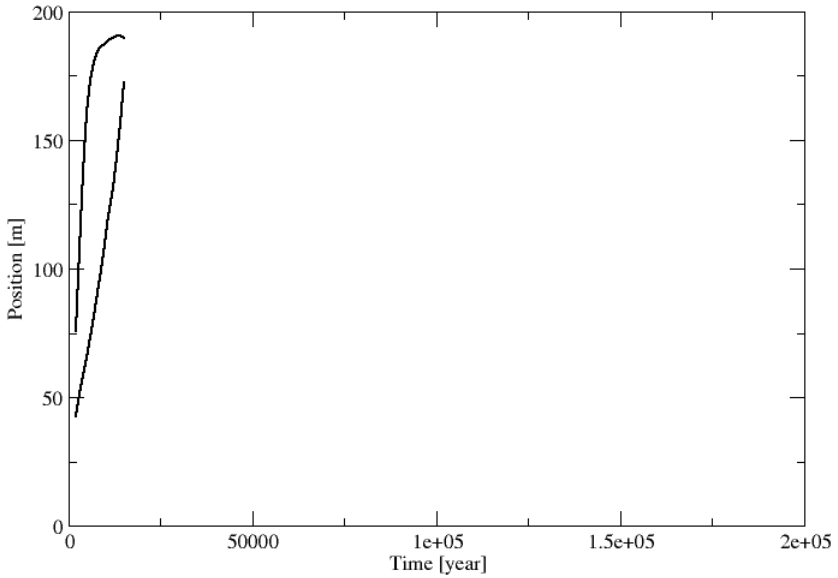
# Problem 1: gas phase appearance/disappearance

- **Porous media initially partially saturated with liquid**

Timeseries of gas saturation in the injection cell

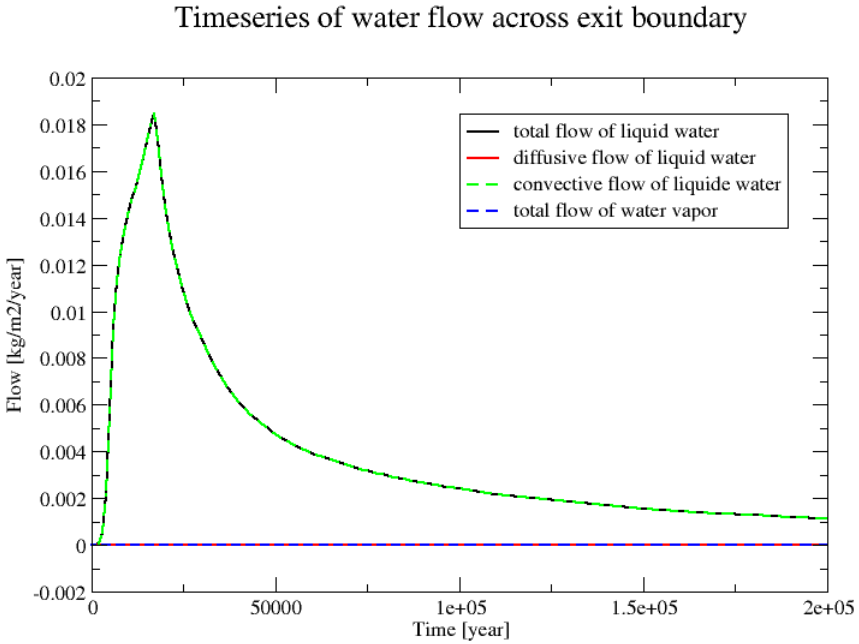


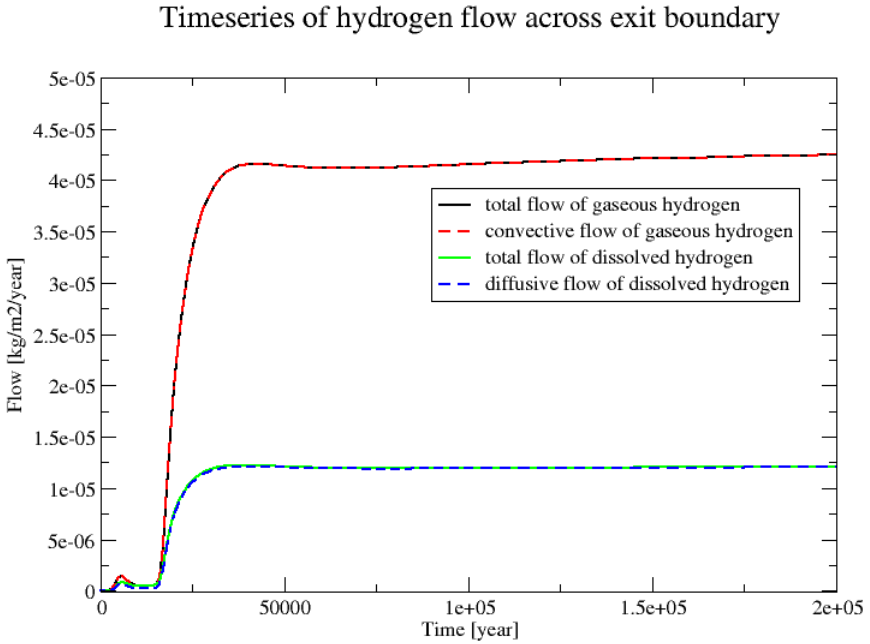

Timeseries of saturation front positions



# Problem 1: gas phase appearance/disappearance

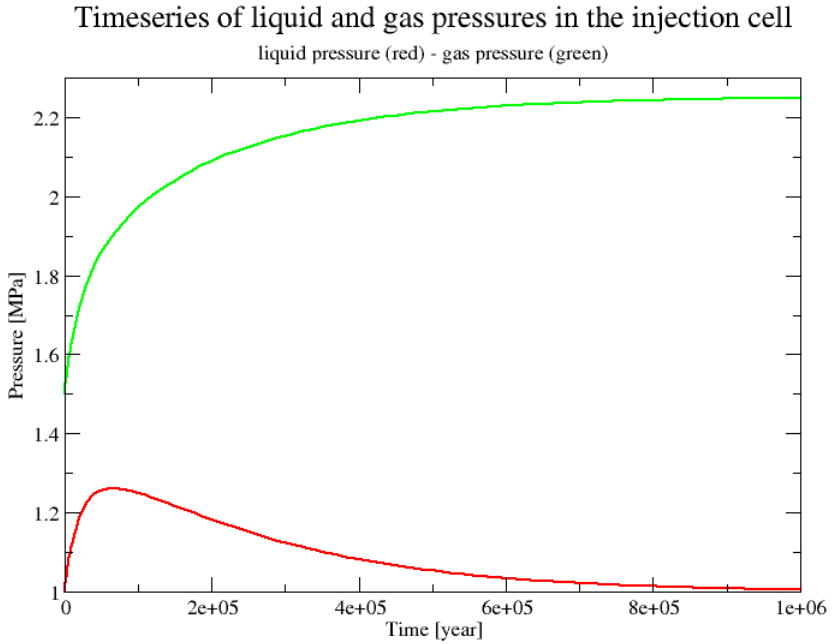
- **Porous media initially partially saturated with liquid**

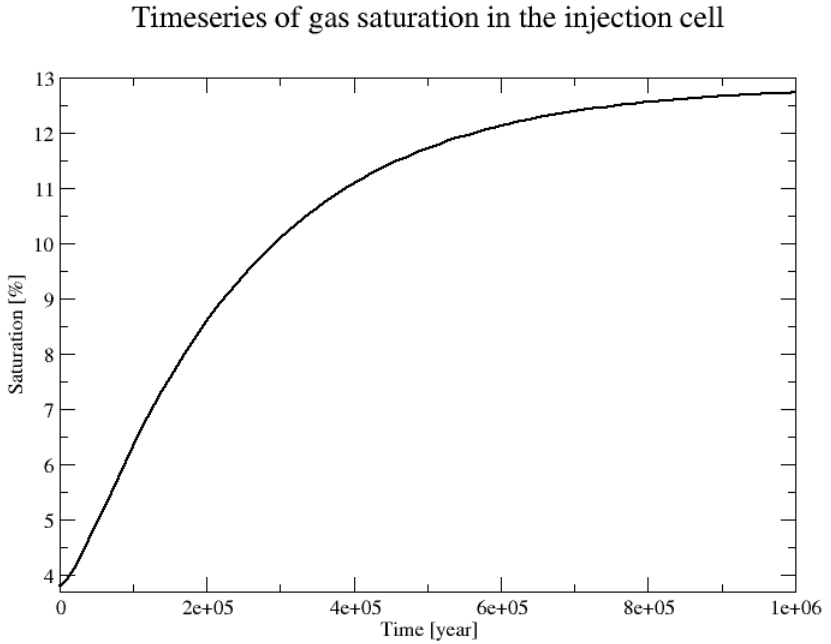


# Problem 2: two-phase flow in a non homogeneous porous media

- **Porous media initially partially saturated with liquid**

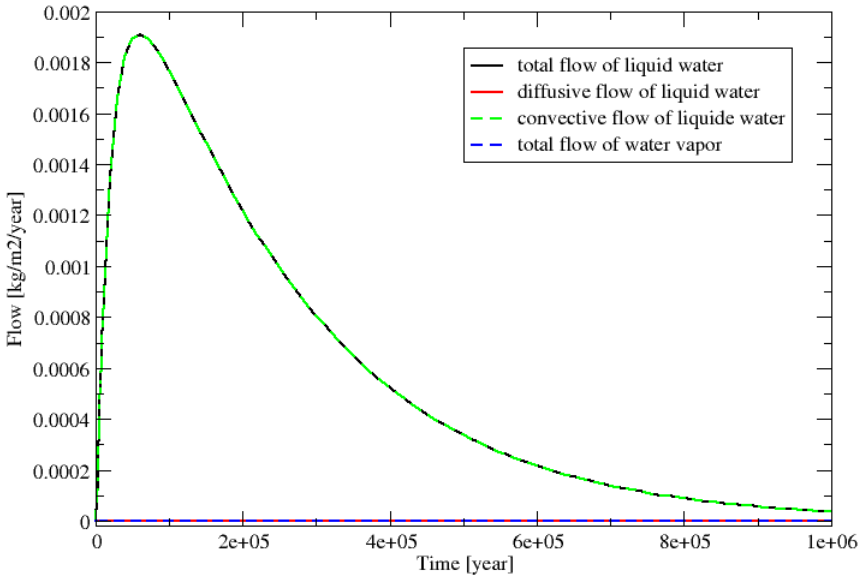


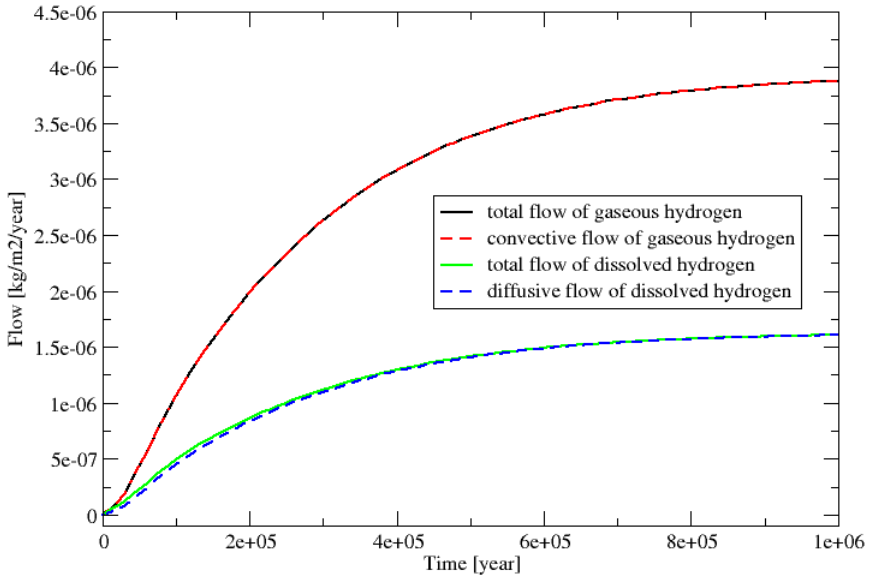
# Problem 2: two-phase flow in a non homogeneous porous media

- **Porous media initially partially saturated with liquid**

Timeseries of water flow across exit boundary



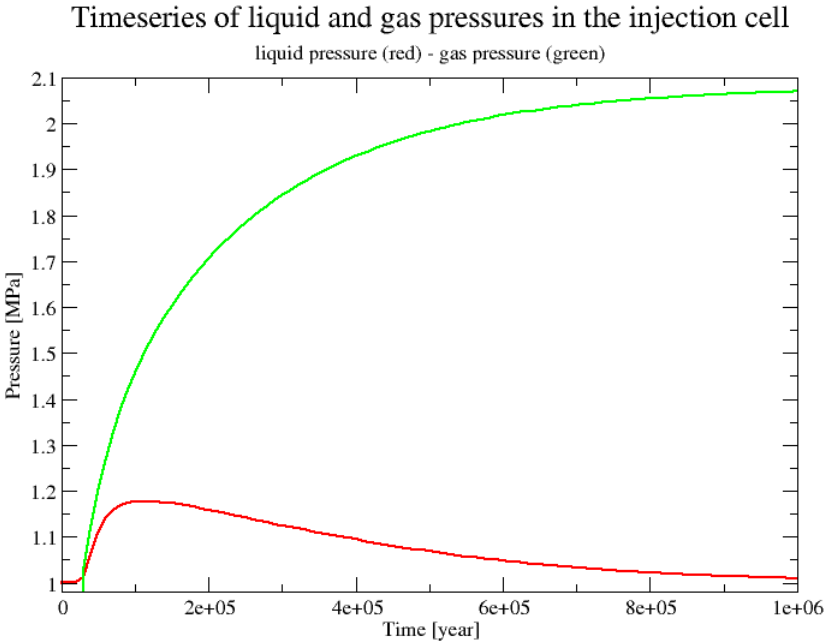

Timeseries of hydrogen flow across exit boundary



# Problem 2: two-phase flow in a non homogeneous porous media

- **Porous media initially fully saturated with pure water**

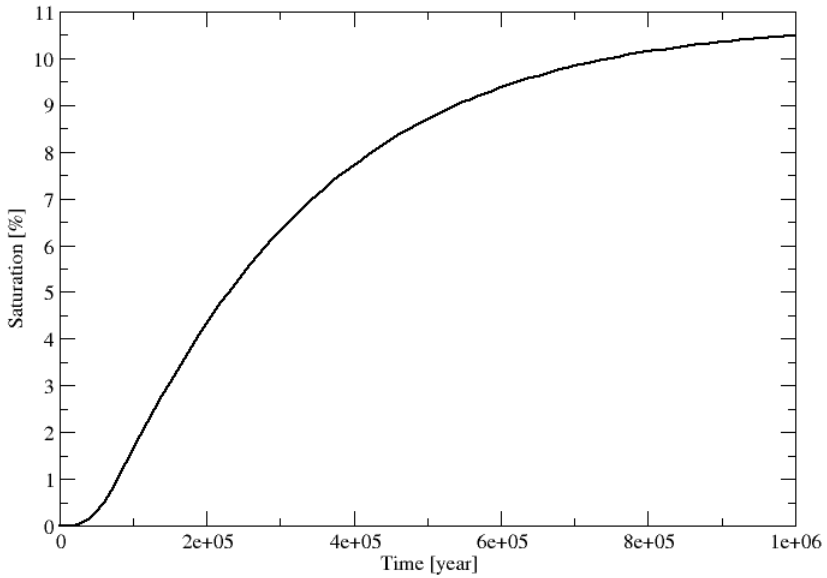
- **Regular spatial discretization: dx=1 m**
- **Time discretization:**
  - dtmin=1 s, dtmax = 1000 years
- **Relative convergence criterion: $10^{-5}$**



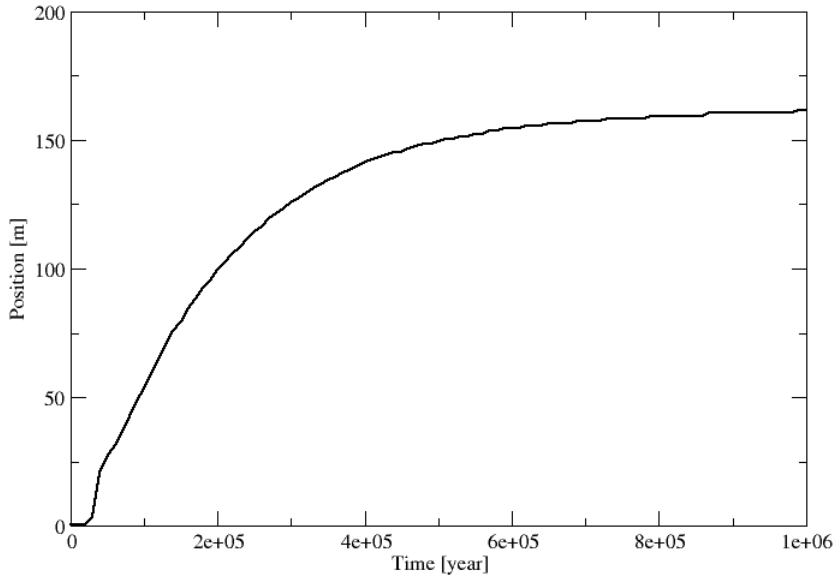
# Problem 2: two-phase flow in a non homogeneous porous media

- **Porous media initially fully saturated with pure water**

Timeseries of gas saturation in the injection cell



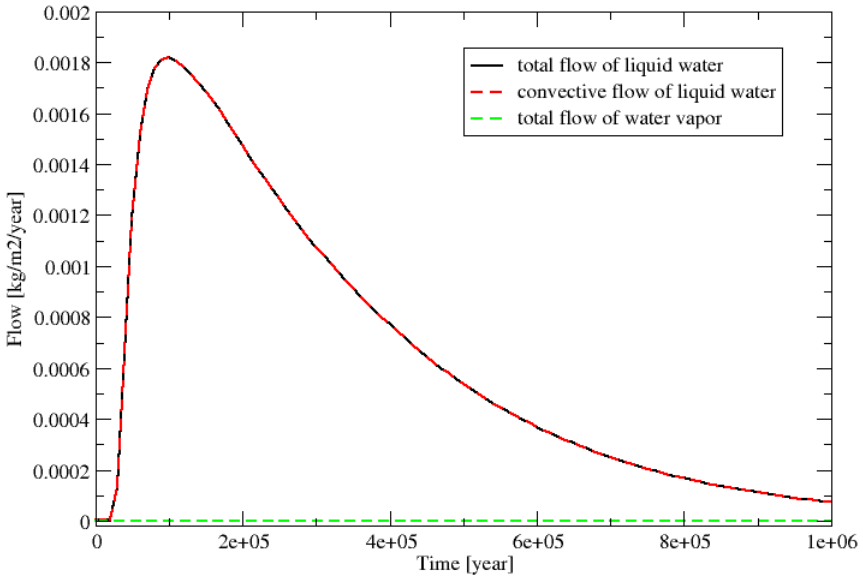

Timeseries of saturation front position



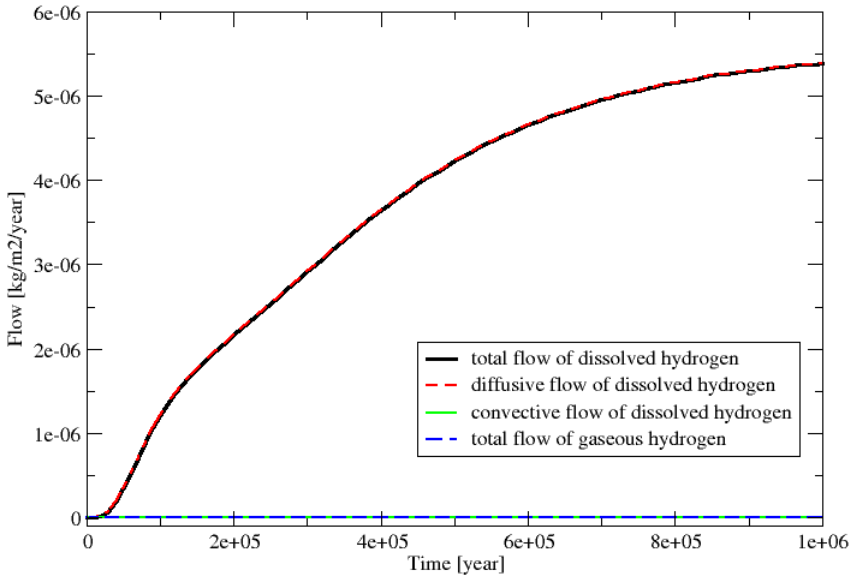
# Problem 2: two-phase flow in a non homogeneous porous media

- **Porous media initially fully saturated with pure water**

Timeseries of water flow across exit boundary




Timeseries of hydrogen flow across exit boundary

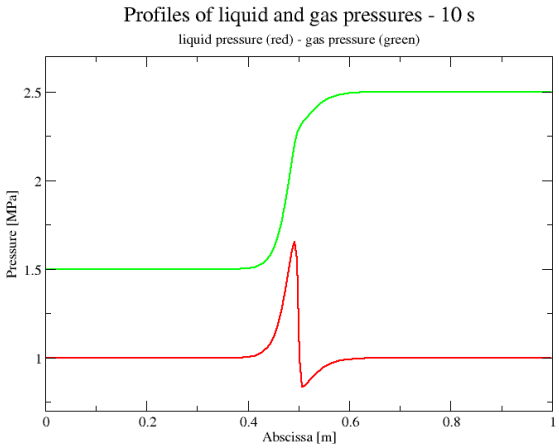


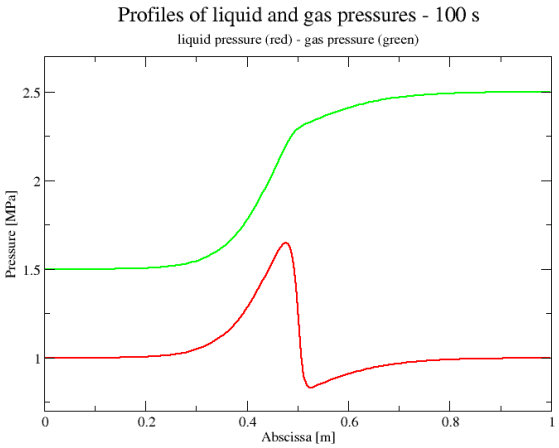
# Problem 3: two-phase flow with non equilibrium states at initial time

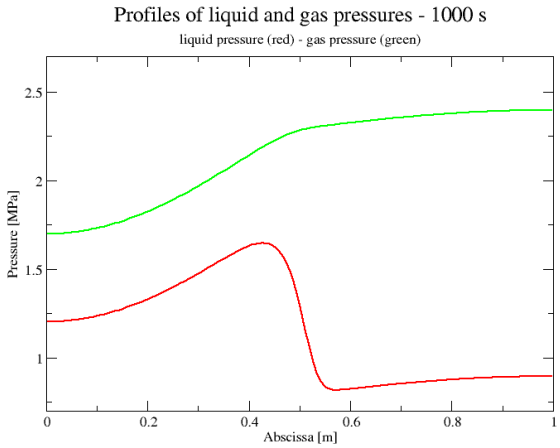
- **Regular spatial discretization: dx=0.005 m**
- **Time discretization:**
  - dtmin=1 s, dtmax = 1000 years
- **Relative convergence criterion: $10^{-5}$**

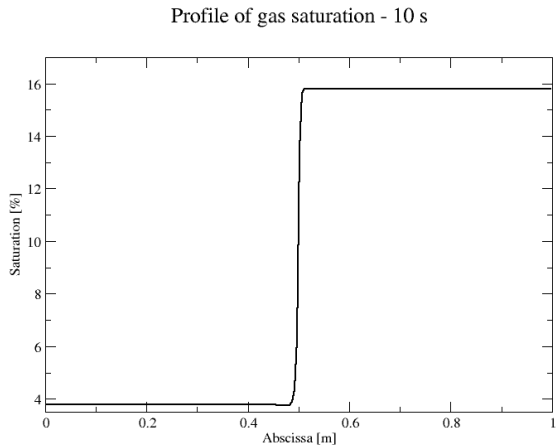
# Problem 3: two-phase flow with non equilibrium states at initial time

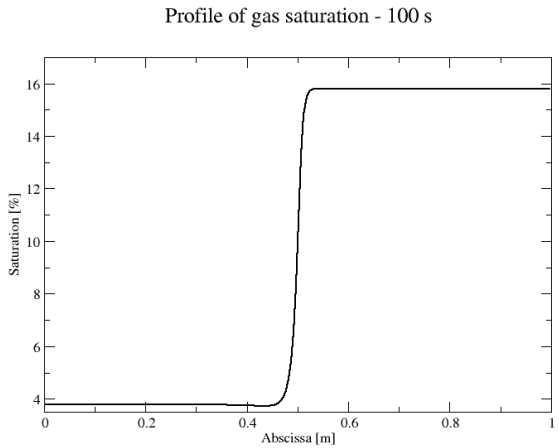
## ➢ Two adjacent partially saturated zones at initial time

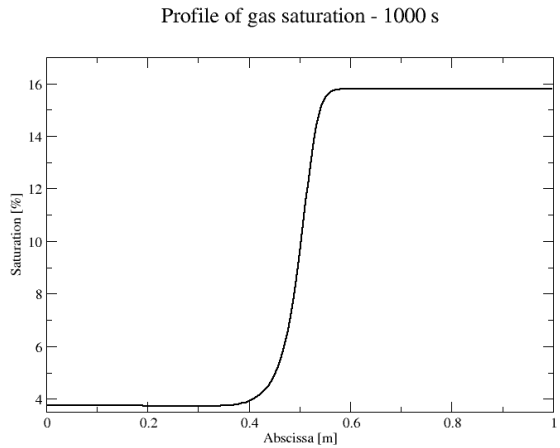


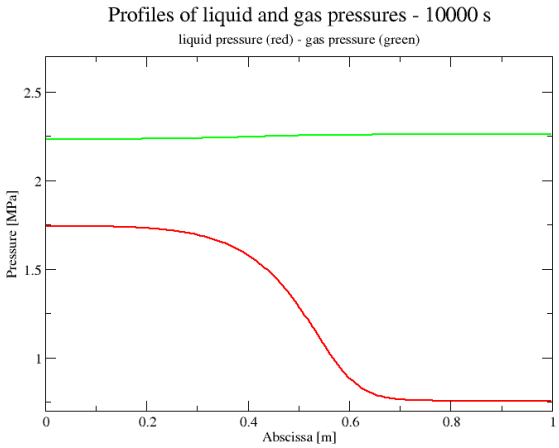



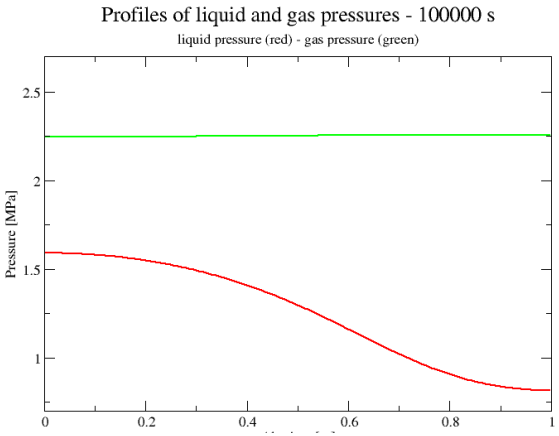



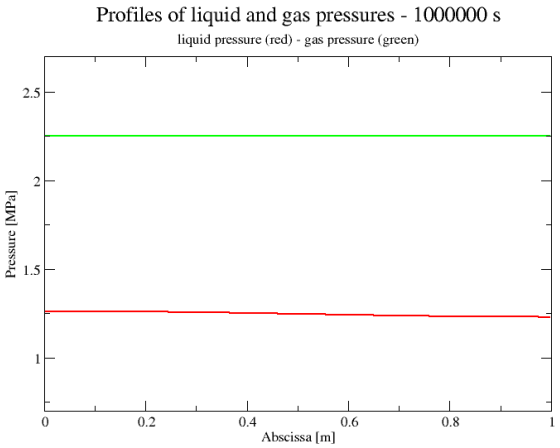



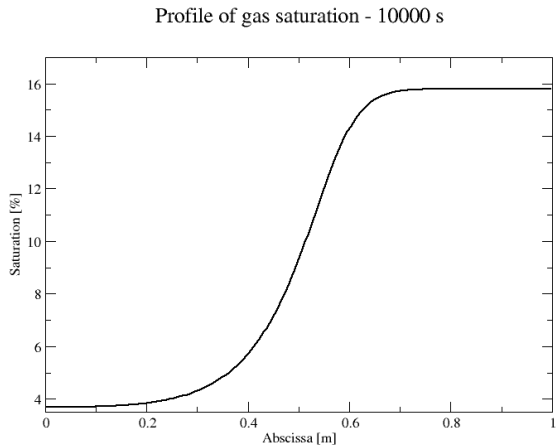
# Problem 3: two-phase flow with non equilibrium states at initial time

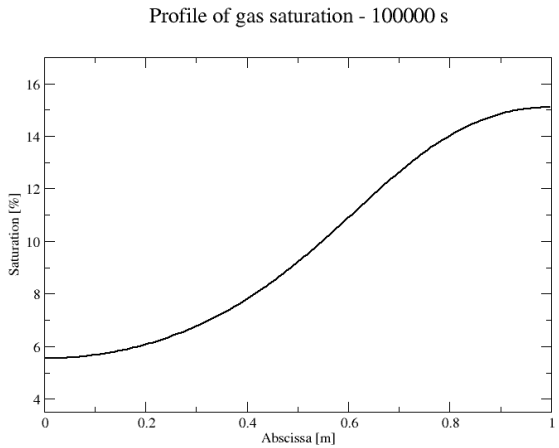
## ➢ Two adjacent partially saturated zones at initial time

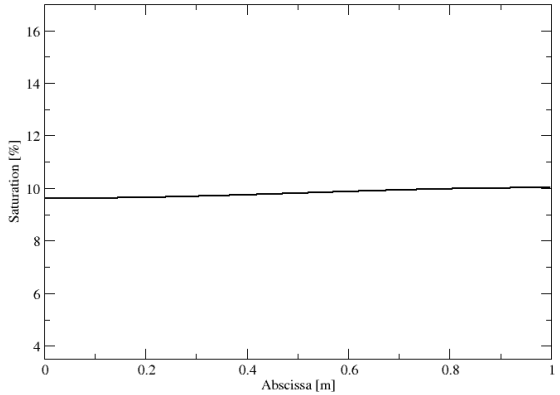


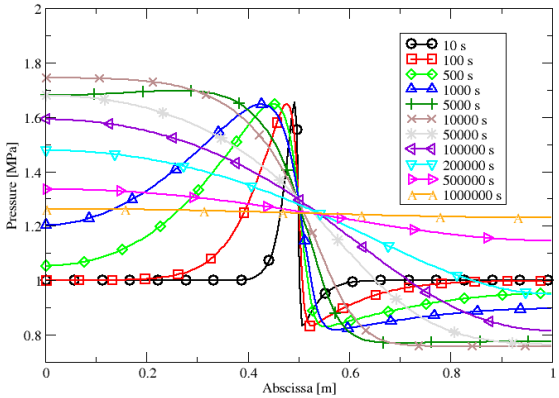



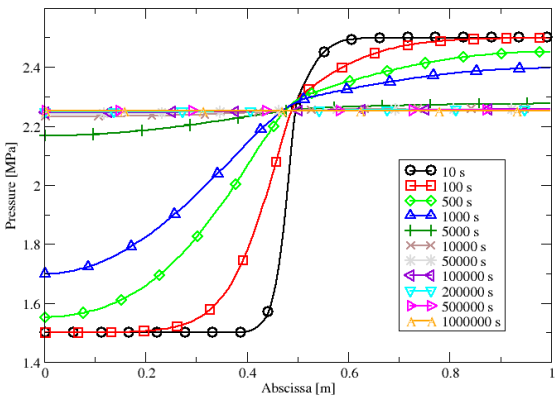
# Problem 3: two-phase flow with non equilibrium states at initial time

- **Two adjacent partially saturated zones at initial time**

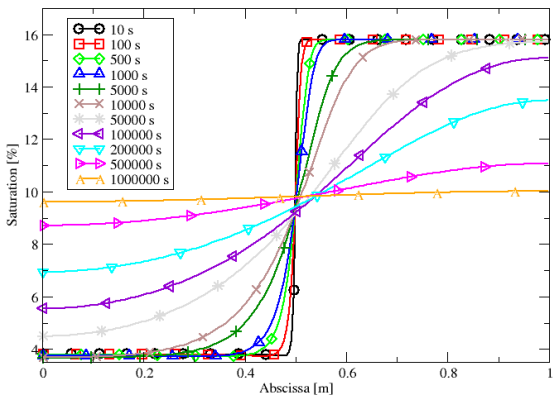
profiles of liquid pressure




profiles of gas pressure

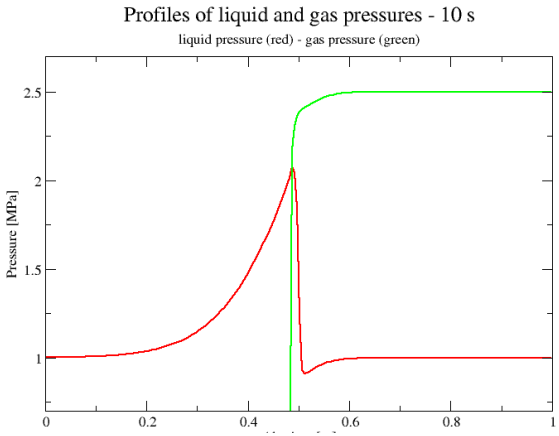


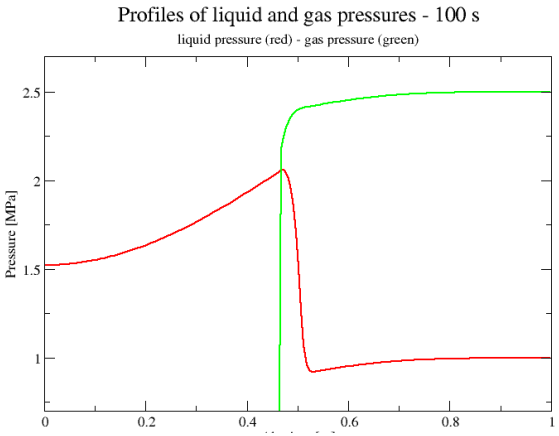

profiles of gas saturation

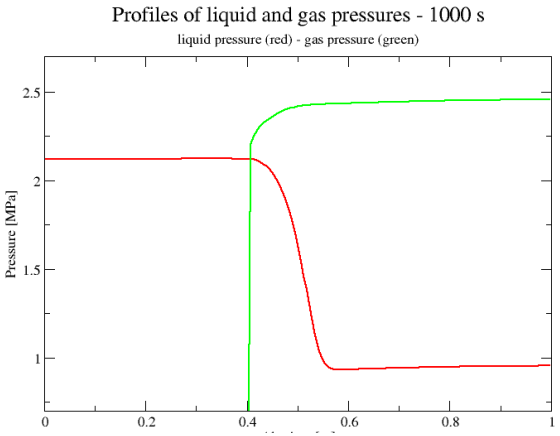


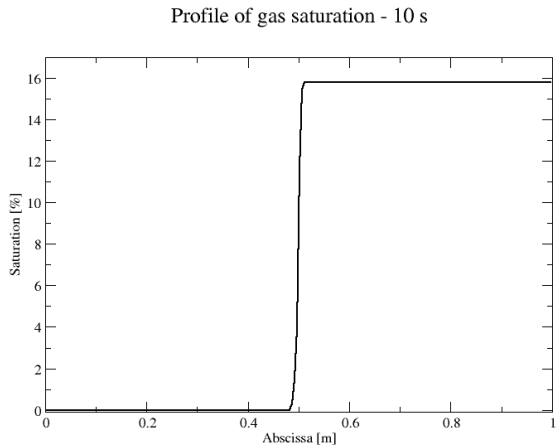
# Problem 3: two-phase flow with non equilibrium states at initial time

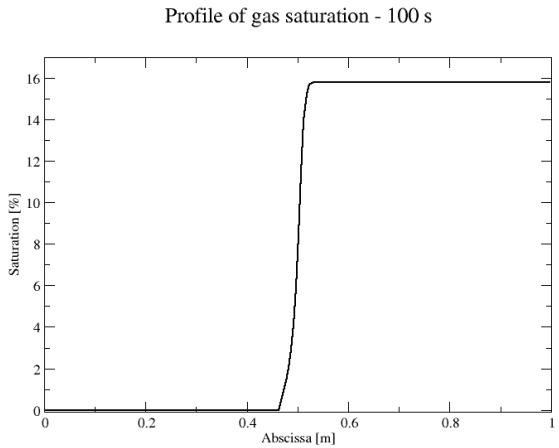
- **Left zone is fully liquid saturated at initial time**

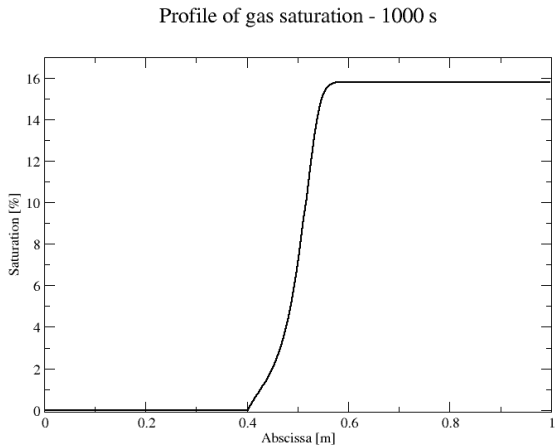


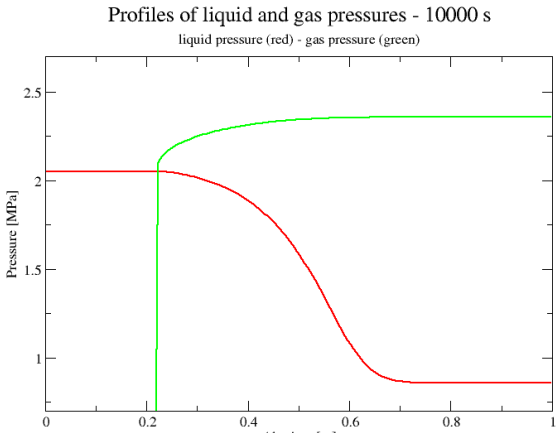



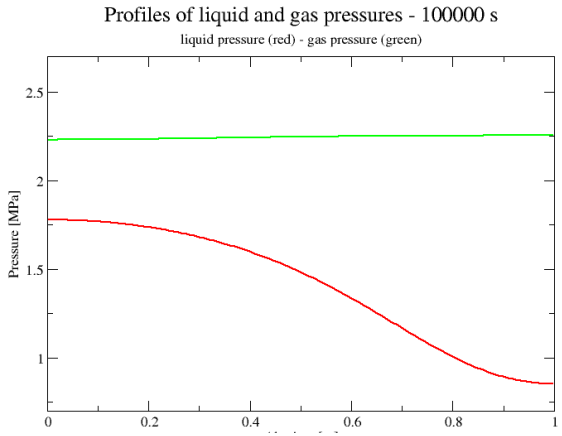



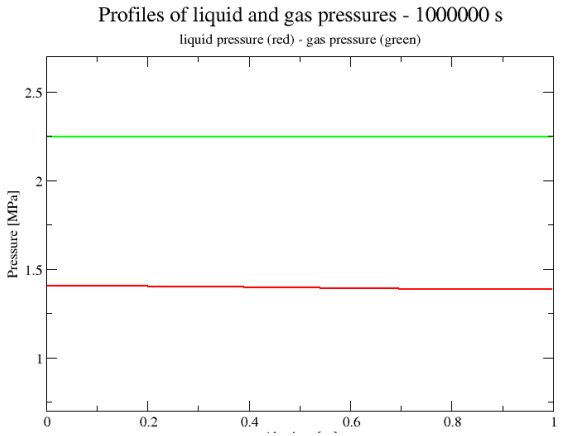



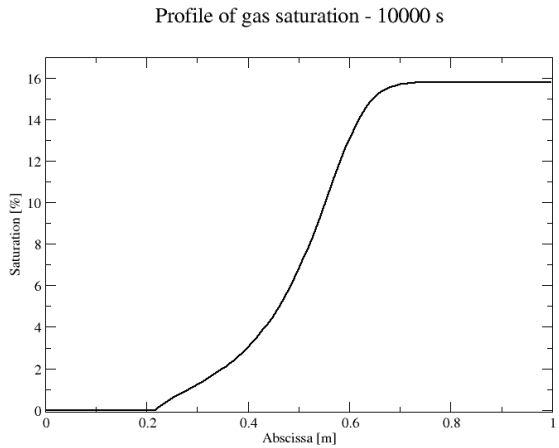
# Problem 3: two-phase flow with non equilibrium states at initial time

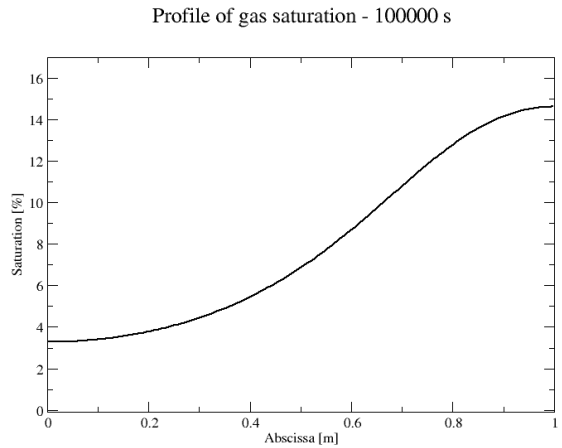
- **Left zone is fully liquid saturated at initial time**

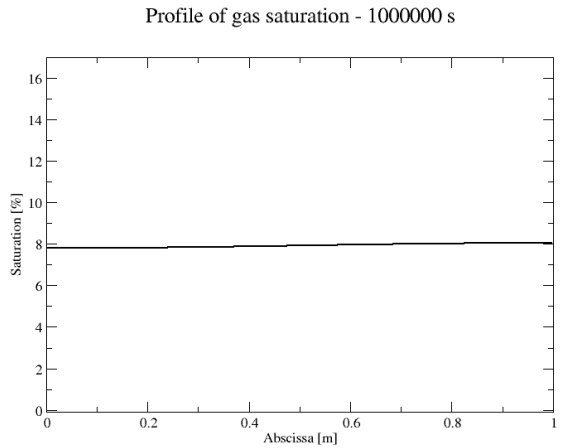


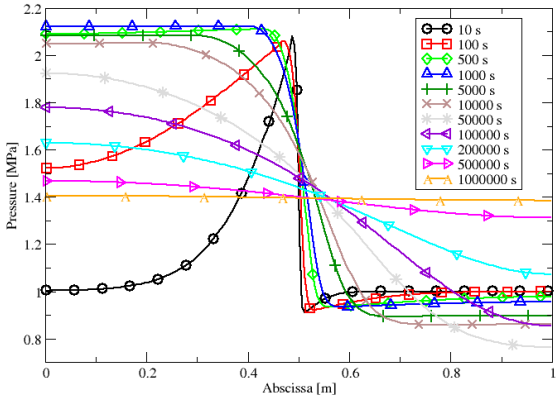



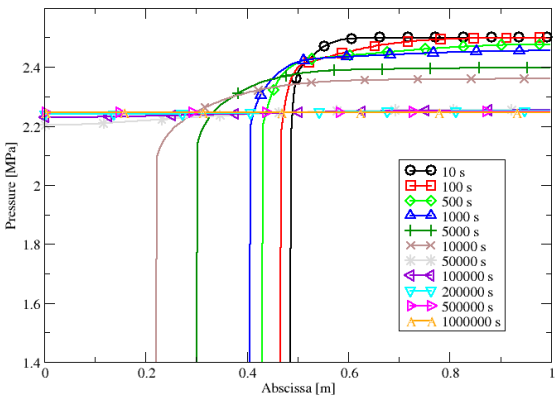
# Problem 3: two-phase flow with non equilibrium states at initial time

- **Left zone is fully liquid saturated at initial time**

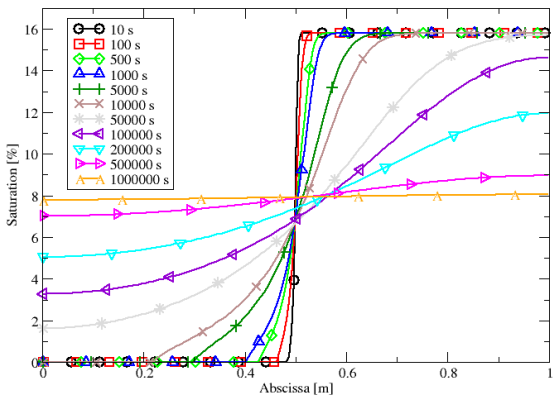
profiles of liquid pressure




profiles of gas pressure




profiles of gas saturation



# Problem 4: two-phase flow with non equilibrium states at initial time

- **Irregular spatial discretization:**
  - dxmax=2.25 cm, dxmin=0.02 cm
- **Time discretization:**
  - dtmin=10 s, dtmax = 100 s
- **Relative convergence criterion: $10^{-5}$**