Reliability of moisture related approaches in building design

SIMUREX, Aussois October 2018

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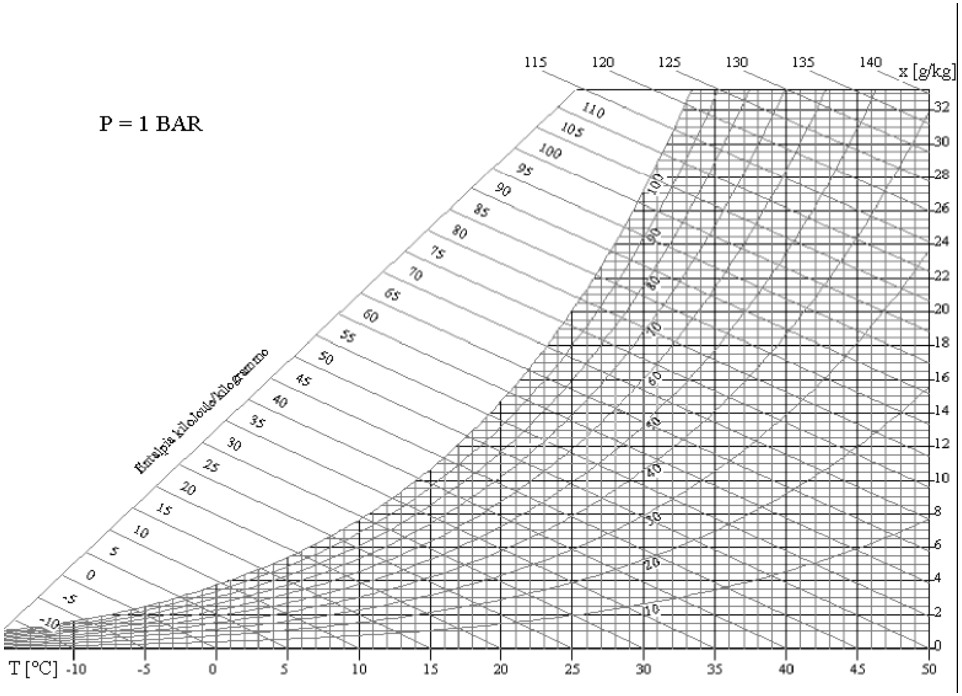
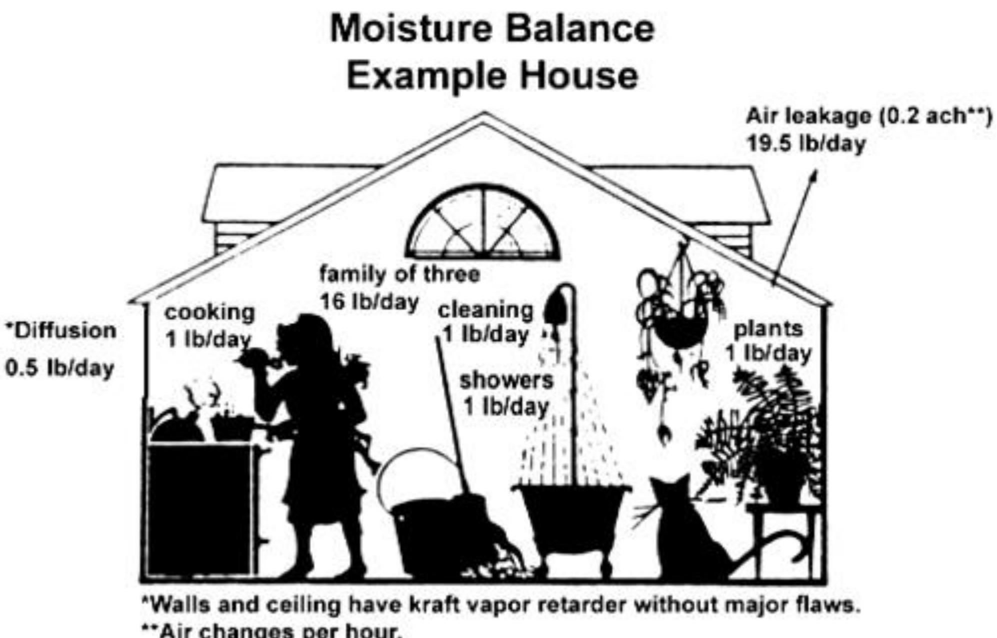
Air is not dry

- Air : a complex mix of many components.
- A lot of water vapour.
- The nightmare of many students in building physics



Moisture balance in buildings

- Many indoor activities generate water vapour.
- → There is more vapour inside than outside.
- → Permanent vapour transfer across the building envelope.



lb = pound

Condensation risk ?

Evaluation of the condensation risk

- For homogeneous walls, the risk is very low.
  - Surface condensation only.
- For insulated heterogeneous walls, the risk must be evaluated.

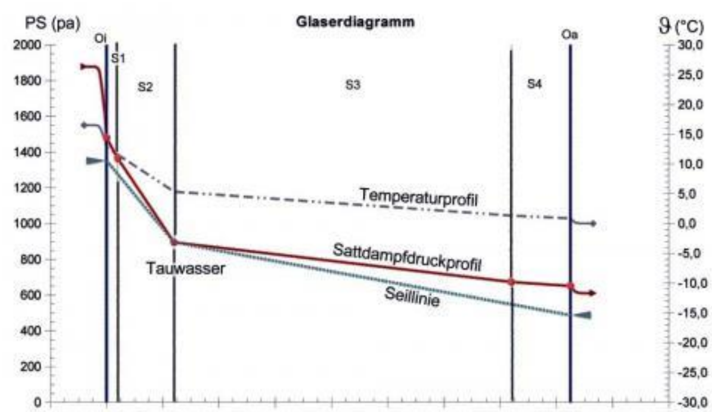
The GLASER Method

The GLASER Method (1958):

- Simple
- Efficient
- Clever
- Elegant

Fourier's Law	$\vec{g}_h = -\lambda \vec{\nabla} T$
Fick's Law	$\vec{g}_v = -\pi \vec{\nabla} p_v$

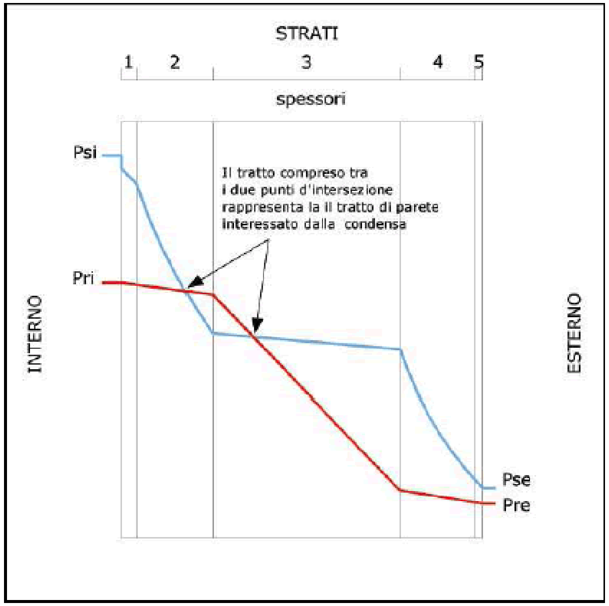
- Condensation or not? Where? How much? Vapour pressure distribution?

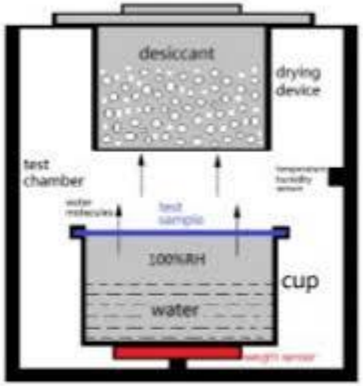


4ev lab

GLASER : the reference method

- Standardized method
  - CEN ISO 13788
- The most popular hydric method for the building community
- Standardized characterization methods refer to the GLASER method.
  - Cup test method





gravimetric method 1

Discussion about the GLASER Method

- Water vapour inside
- Water vapour outside

- → Only water vapour has to be considered

Discussion about the GLASER Method

- Water vapour inside
- Water vapour outside
- … vap… to be …

WRONG!

Discussion about the GLASER Method

- Water vapour inside
- Water vapour outside
- [illegible] vap[illegible] to be [illegible]

WRONG!

- Many construction materials (hygroscopic materials) convert water vapour into liquid water
- Liquid water into the wall

Consequences

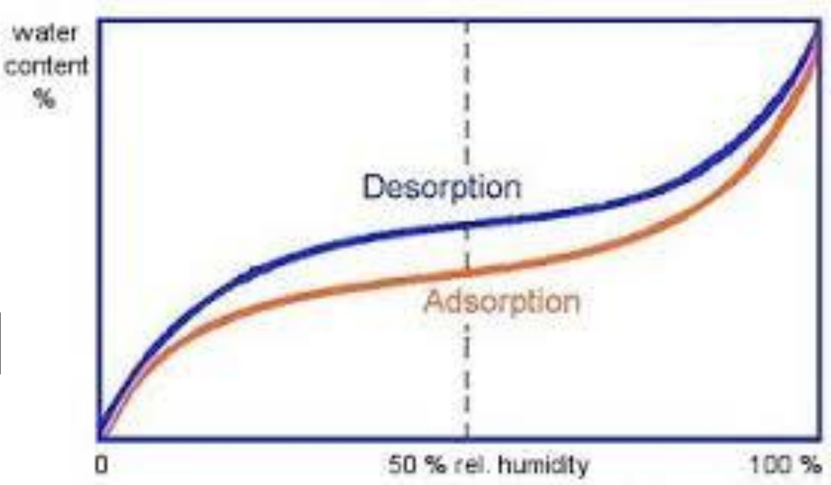
- Liquid/vapour equilibrium must be described → Sorption isotherms

- Vapour & Liquid flows must be considered → Fick's law
  Darcy's law

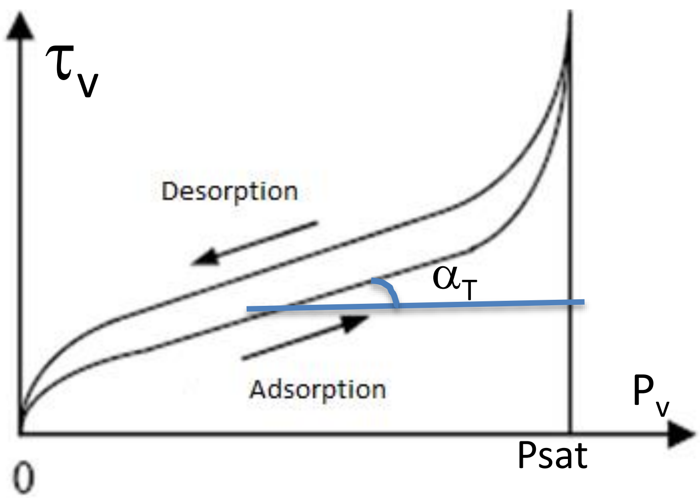
- Water phase change must be taken into account. → Heat transfer equation is affected

The sorption curves

- The fundamental characteristic of hygroscopic materials.
- The hysteresis is generally ignored
- Explains how adsorbed and vapour phases are split when a water mass change occurs.



Splitting the liquid and vapour phases of water



Adsorbed part

Vapour part

$$\frac{1}{V}dm_{H2O} = d\tau_v + \varepsilon d\rho_v$$

$$\frac{1}{V}dm_{H2O} = \alpha_T dp_v + \frac{\varepsilon}{r_v T}dp_v$$

The slope of the sorption curve reveals the « moisture buffering » capacity of the material.

α_T can be considered as the « hydric inertia » of the material.

Because of moisture sorption, buffering effects can be very significant → Dynamic approaches are necessary.

Vapour and Liquid flow description

- Fick's law for vapour $\vec{g}_v = -\pi \vec{\nabla} p_v$
- Darcy's law for liquid $\vec{g}_l = -K_l \vec{\nabla} p_l$
- Kelvin's law for coupling vapour and liquid potentials

$$p_l - p_t = \rho_l r_v T \ln\left(\frac{p_v}{p_{sat}(T)}\right)$$

- Coupling : Temperature gradient appears in the moisture transfer equation

$$\vec{\nabla} p_l = \rho_l r_v \left(\ln RH - \frac{L}{r_v T}\right)\vec{\nabla} T + \frac{\rho_l r_v T}{p_v}\vec{\nabla} p_v$$

Introduction of phase change

- Latent heat must be introduced in the enthalpy of vapour
- Coupling : vapour pressure gradient appears in the heat transfer equation

$$h_v = C_{pl}(T - T_0) + L$$

$$\vec{g}_h = -\lambda \vec{\nabla} T + L \vec{g}_v$$

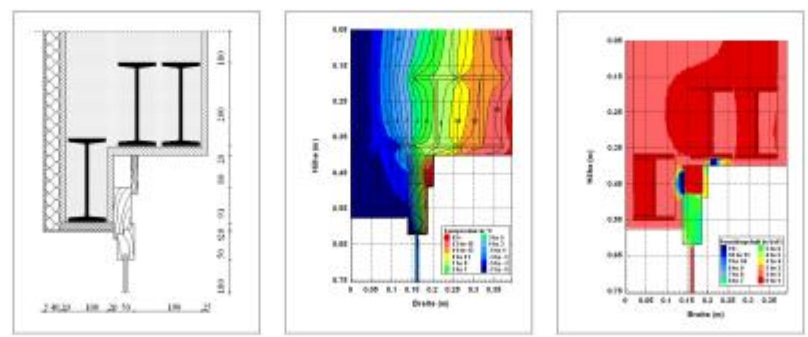
$$\vec{g}_h = -\lambda \vec{\nabla} T - L \pi \vec{\nabla} p_v$$

A new generation of coupled heat & moisture transfer models

- Dynamic and coupled models
- Integrating liquid and vapour transfers
- Coded for 2D/3D configurations
- Sometimes used by engineering consultants for envelope design

WUFI
https://wufi.de/en/

DELPHIN
http://bauklimatik-dresden.de/delphin/



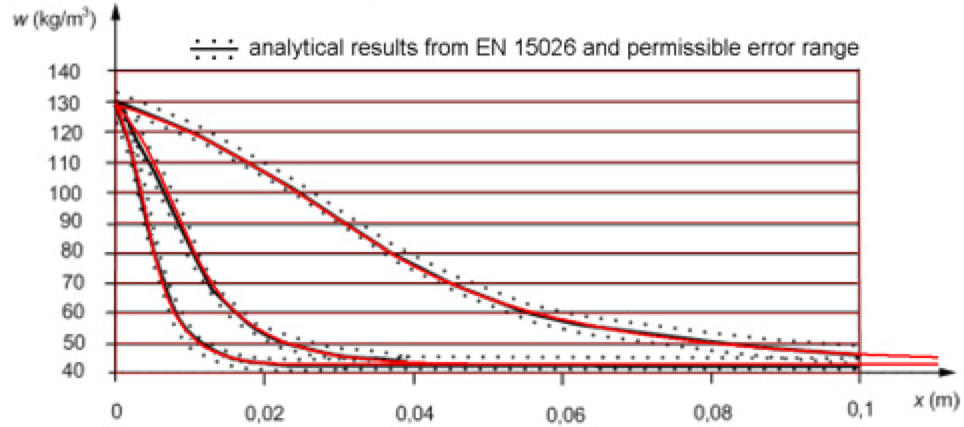
Benchmark test: EN 15026

Semi infinite slab

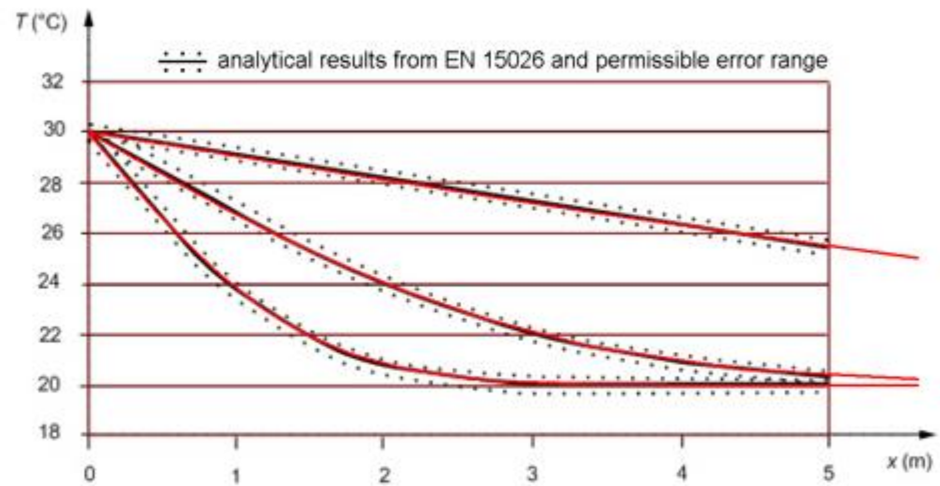
Initial conditions :
T=20°C
HR=50%

Boundary conditions :
T=30°C
HR=95%

Comparison of analytic and simulated solutions.



The moisture distribution at 7 days, 30 days and 365 days



The temperature distribution at 7 days, 30 days and 365 days
(background image: EN 15026)

Benchmark test: EN 15026

Semi infinite slab

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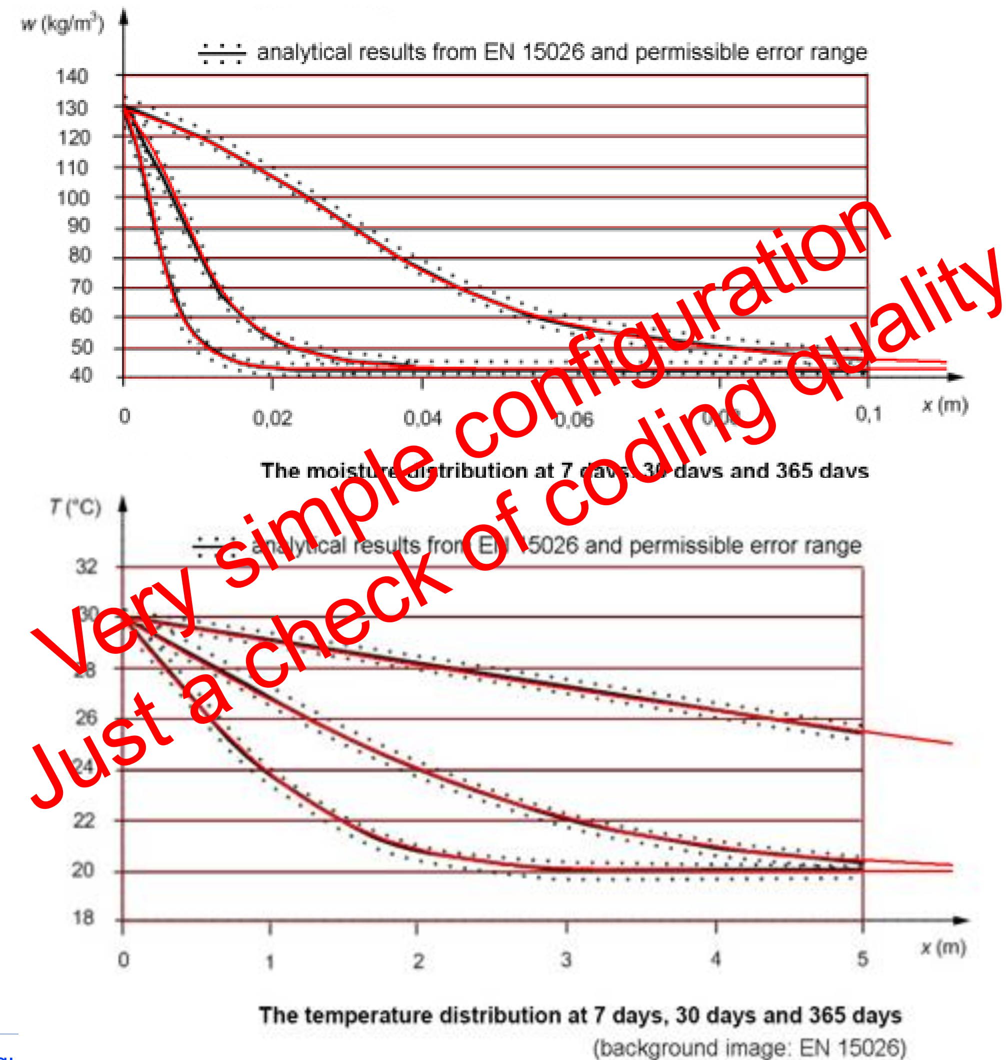
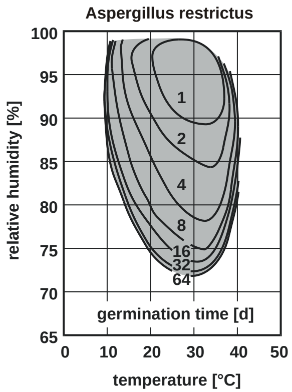


Very simple configuration
Just a check of coding quality

Moisture control issues

- New construction → Renovation
  - Reliability of retrofitting actions
- Evaluation of hydrothermal comfort & performance



- Biomaterials & mould growth
- Indoor Air Quality and moisture
- Specific processes using moisture
  - Thermochemical heat storage

- Moisture sensible technologies
  - Vacuum Insulation Panels

Moisture control issues

- Socio-economic
  - Excess of moisture first indicator of building troubles
  - 84 millions Europeans living in unhealthy housing (https://www.ibp.fraunhofer.de/en/Press/Press_releases/pm_16112016_literaturestudymould.html)
- Cultural
  - Exploitation and maintenance cost of cultural heritage buildings

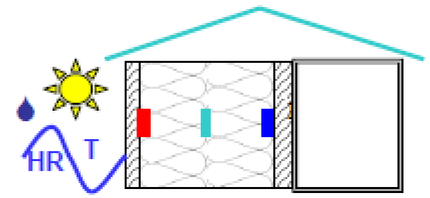
⇒ Heat and mass transfer simulations should be integrated in the design processes

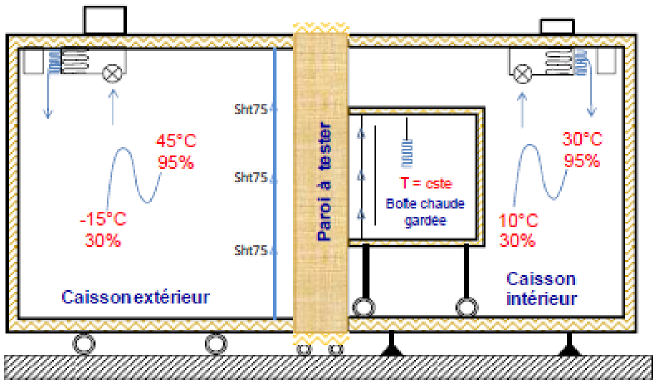
Reliability of these approaches?
Validation in complex configurations?

VALIDATION ATTEMPTS IN COMPLEX CONFIGURATIONS

The French project HYGROBAT

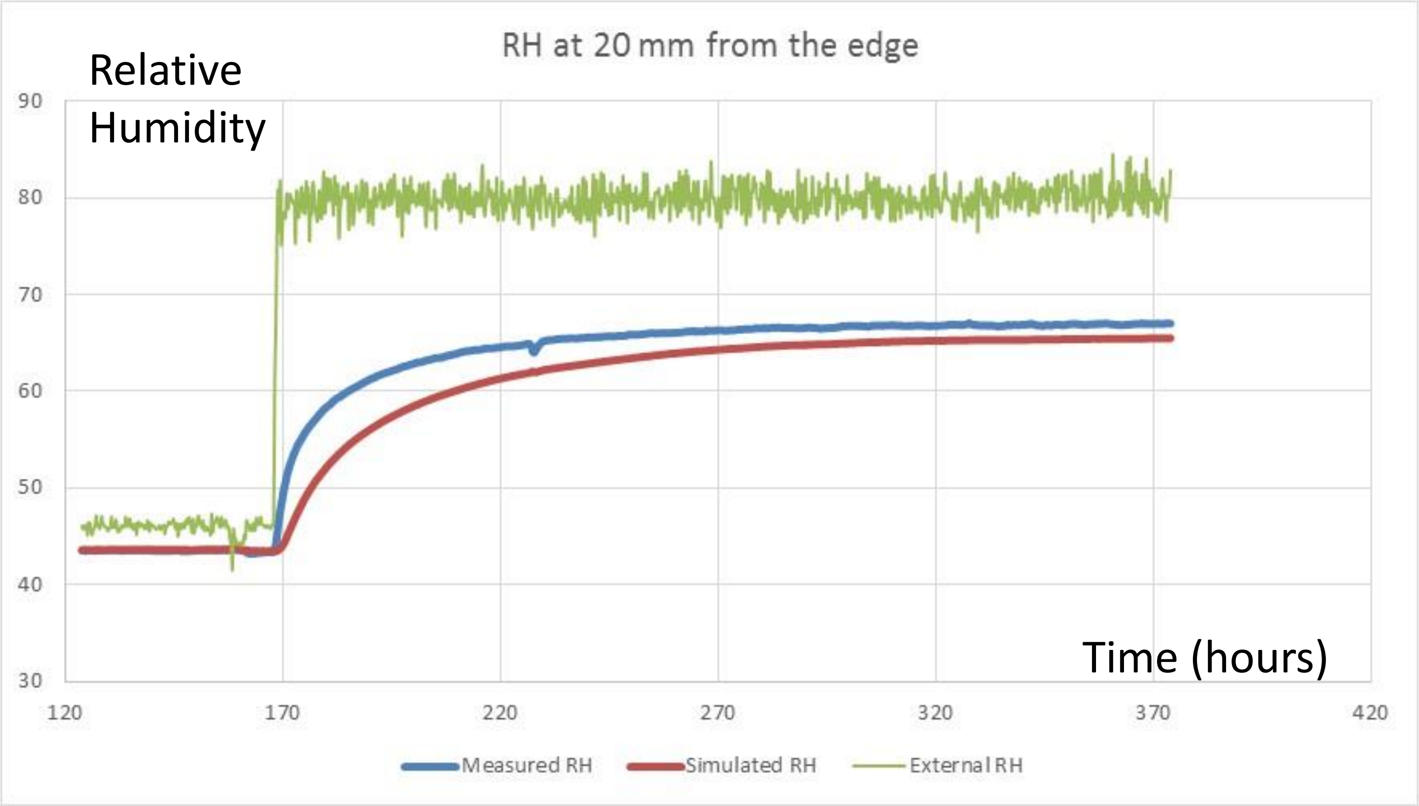
- 13 partners from research and industry
- Main objective : fill the gap between experimental and simulation results.
- High quality measurements in more and more complex configurations :
  - Walls composition (very reactive hygroscopic materials)
  - Solicitations (artificial and natural cyclic evolutions)





Validation attempt 1

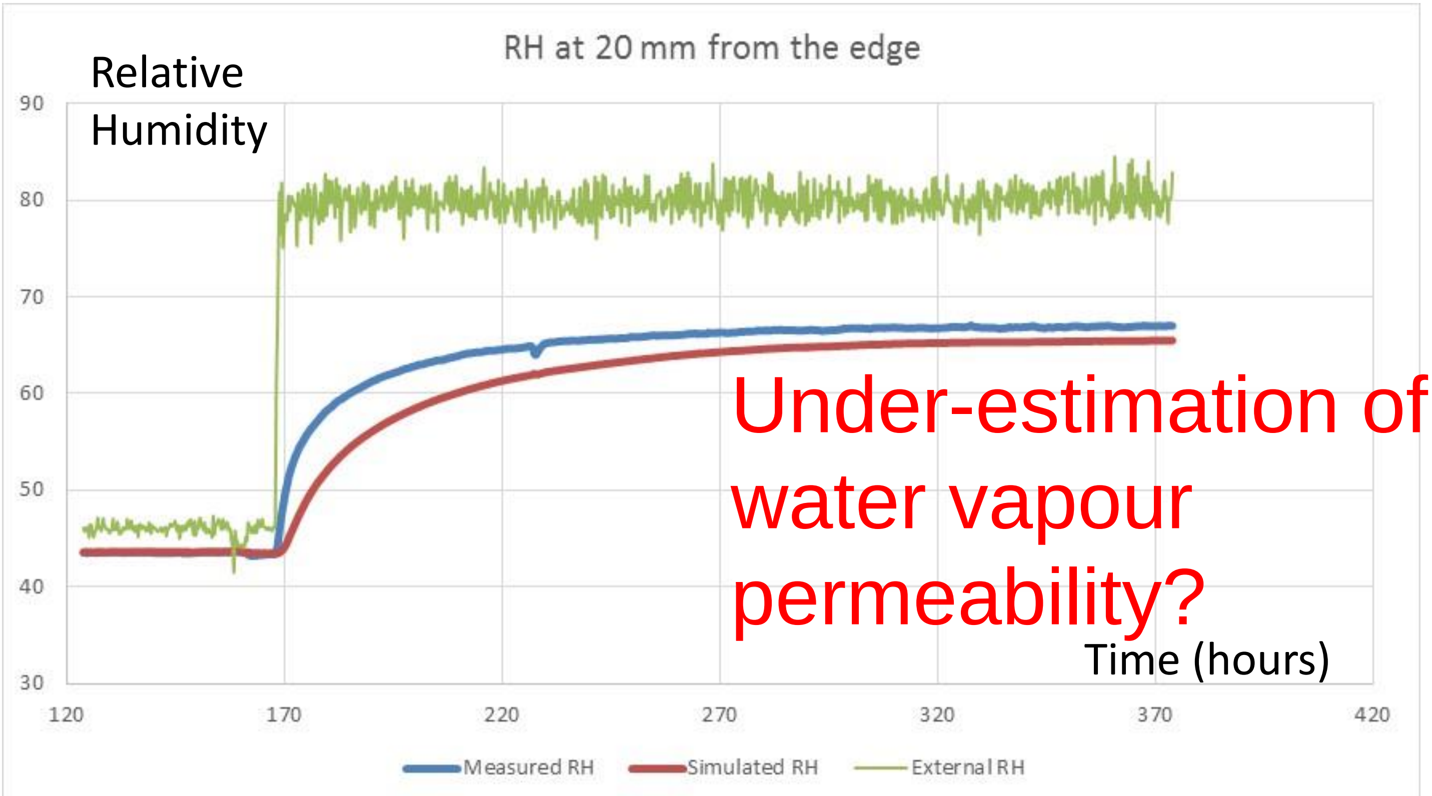
Moisture step



Lack of moisture transfer

Validation attempt 1

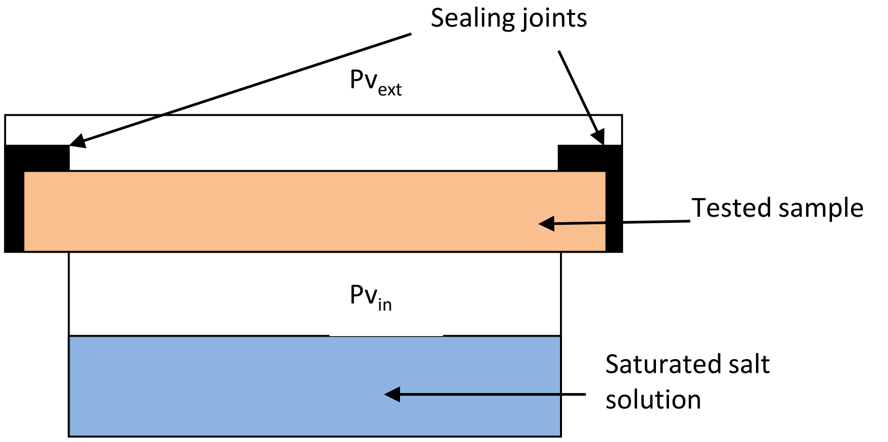
Moisture step

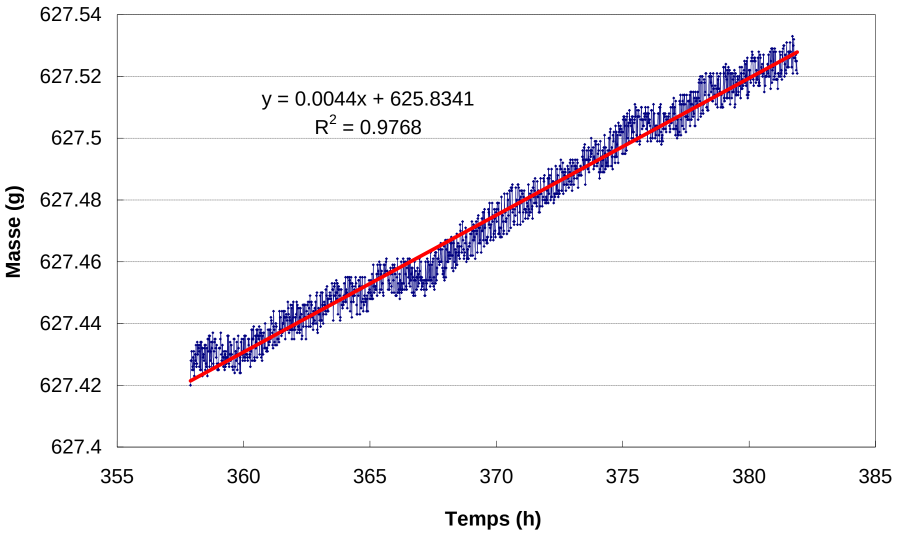


Lack of moisture transfer

Vapour permeability estimation through the cup test method

- A very simple experimental process
  - Controlled relative humity on both faces of the sample.
  - Uniform controlled temperature.
  - Regular weighing of the assembly.
  - Coefficient evaluation in steady state

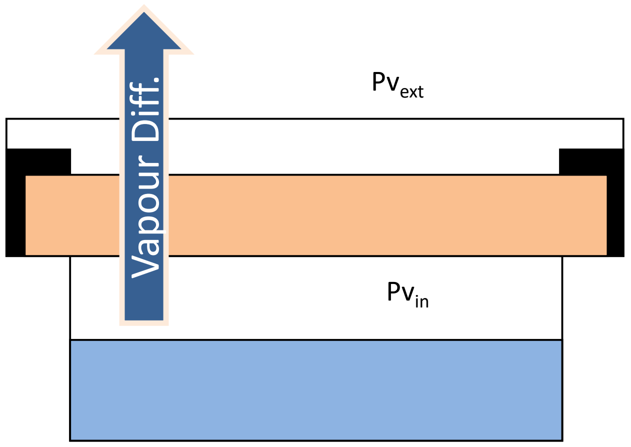




- Nevertheless, this measurement interpretation is more complex than expected.

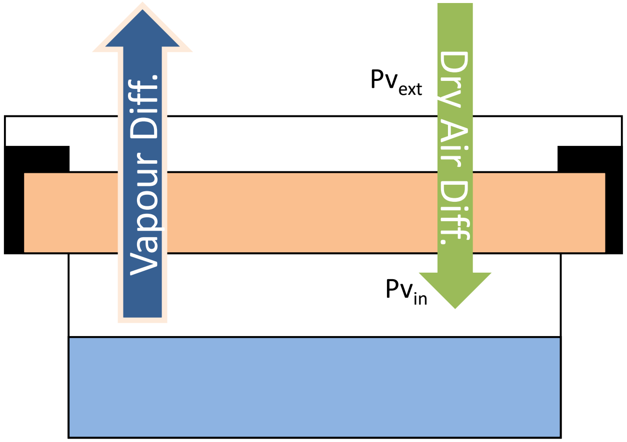
Description of gas transfers during a cup test

- Vapour diffusion takes place because of the P_v difference between the both faces of the sample.



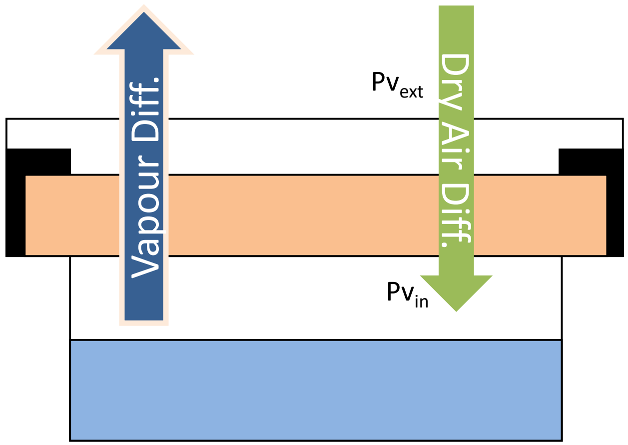
Description of gas transfers during a cup test

- Vapour diffusion takes place because of the P_v difference between the both faces of the sample.
- Dry air diffusion takes place in the opposite direction.



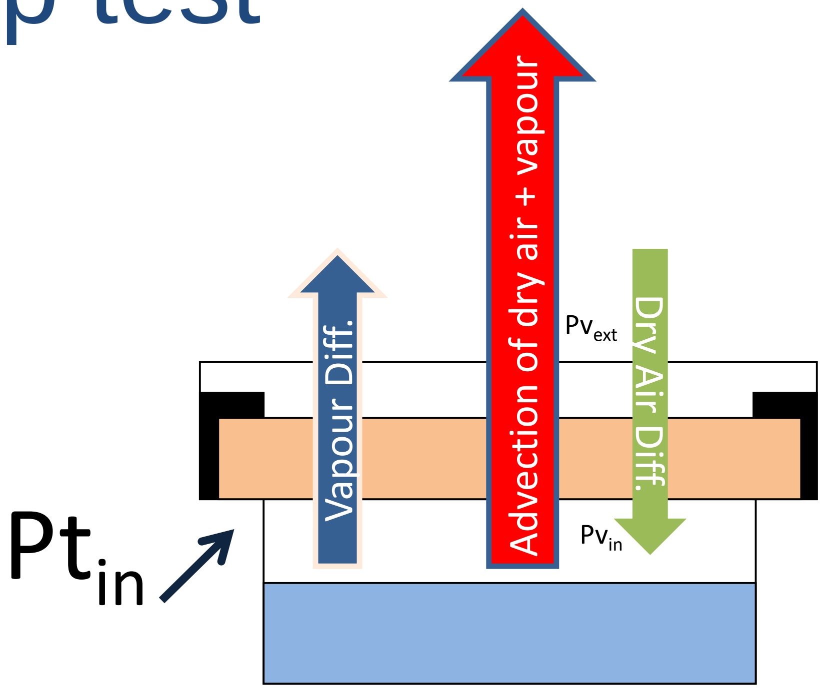
Description of gas transfers during a cup test

- Vapour diffusion takes place because of the P_v difference between the both faces of the sample.
- Dry air diffusion takes place in the opposite direction.
- In steady state, the overall dry air flow can only be zero (no source nor sink of dry air in the cup).



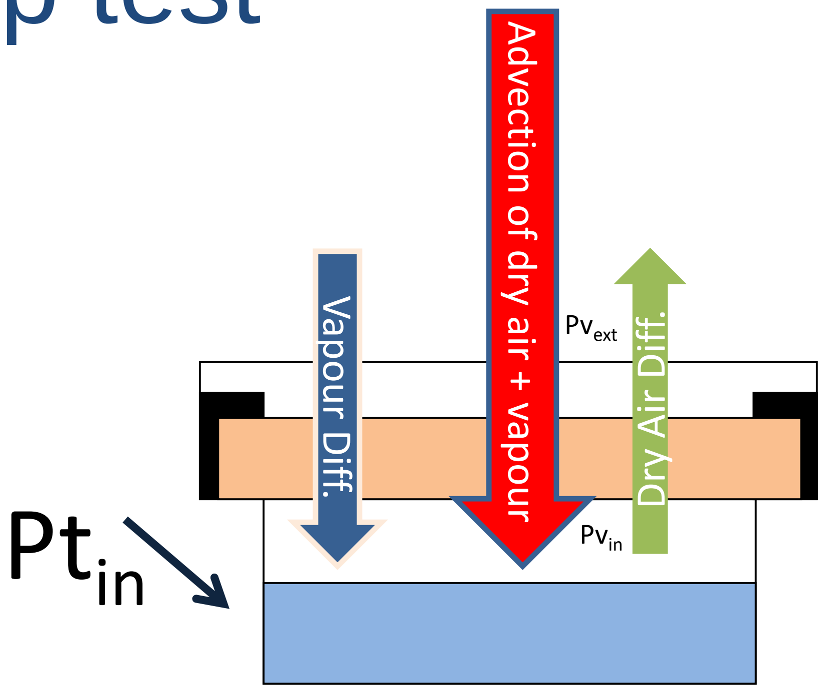
Description of gas transfers during a cup test

- Vapour diffusion takes place because of the P_v difference between the both faces of the sample.
- Dry air diffusion takes place in the opposite direction.
- For balancing the dry air flow, an internal overpressure appears which involves an advective gas flow



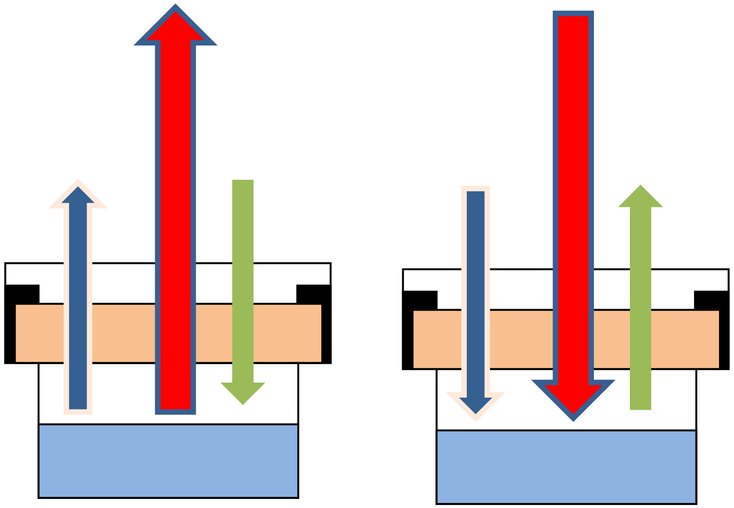
Description of gas transfers during a cup test

- Vapour diffusion takes place because of the P_v difference between the both faces of the sample.
- Dry air diffusion takes place in the opposite direction.
- When the vapour flow is in the opposite direction, gas pressure decreases in the cup.



Description of gas transfers during a cup test

- Vapour diffusion takes place because of the P_v difference between the both faces of the sample.
- Dry air diffusion takes place in the opposite direction.
- Gas overpressure or underpressure in the cup.

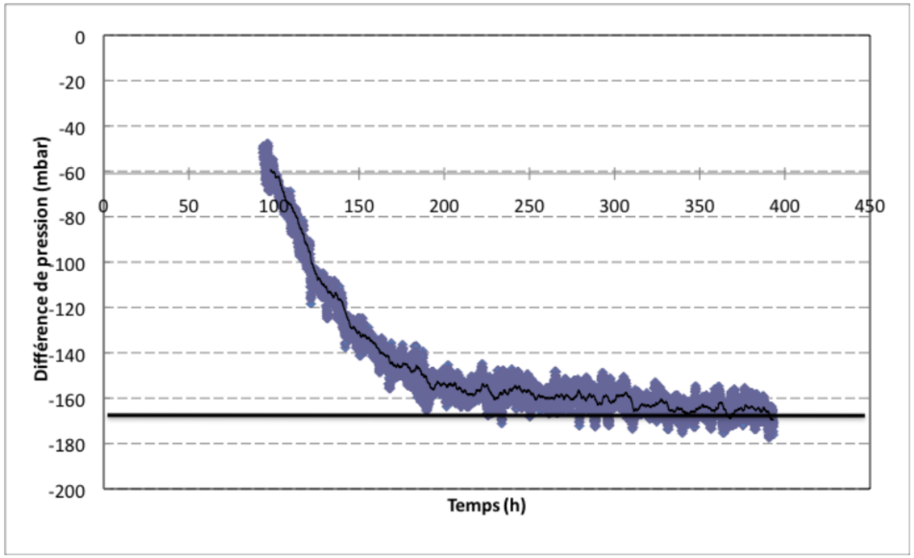


In steady state, the gas pressure can't be flat

P_t is higher where P_v is higher

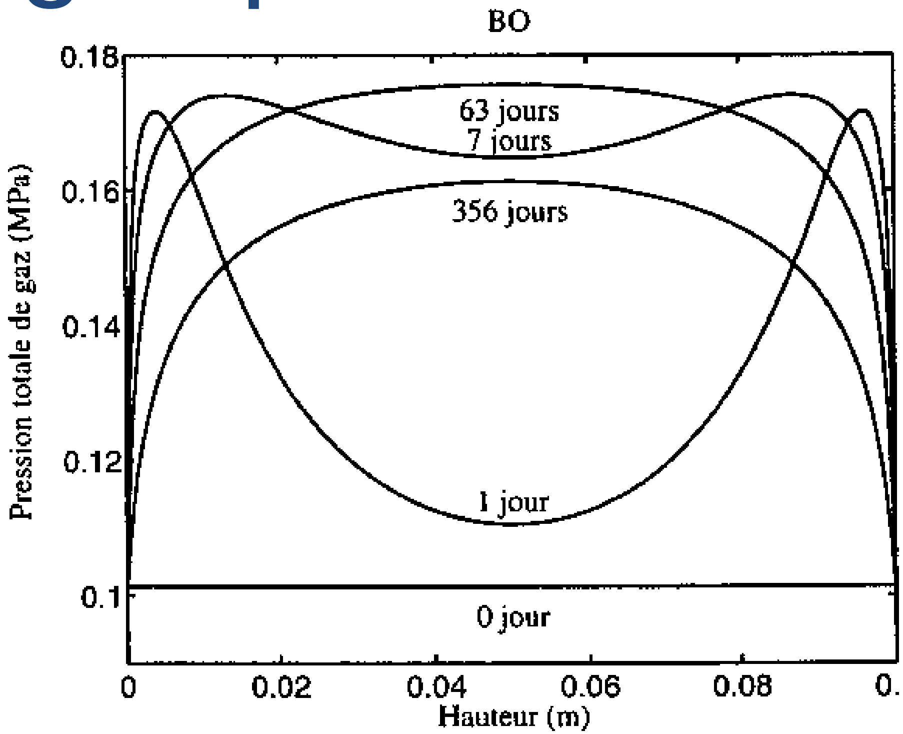
Experimental evidence

- Sample of oak.
- Testing temperature : 60°C.
- External RH : 50% (P_v=9866 Pa).
- Internal RH : 11% (P_v=2171 Pa).
- Under pressure in the cup : 16 800 Pa.



Impact of total gas pressure

- The uniformity of gas pressure is a common hypothesis of moisture transfer modelling.
- However, some configurations are obviously non-isobaric.



Marc Mainguy. Modèles de diffusion non linéaire en milieux poreux. Applications a la dissolution et au séchage des matériaux cimentaires. Ecole Nationale des Ponts et Chaussées, 1999. French.

- Vapour diffusion in non-isobaric conditions :

$$\vec{g}_v = -\pi \vec{\nabla} p_v \quad \Rightarrow \quad \vec{g}_v = -\pi_v^* \vec{\nabla} \frac{p_v}{p_t}$$

Consequence for the cup test

- In a cup test, both P_v and P_t gradients have the same orientation.
- But they have opposite signs in the expression of the vapour flow. → The pressure gradient tends to decrease the vapour flow.
- If it is not considered, the identified vapour permeability ($\pi = \frac{\pi_v^*}{p_t}$) is under-estimated

$$\vec{g}_v = -\pi_v^* \vec{\nabla} \frac{p_v}{p_t}$$

$$\Downarrow$$

$$\vec{g}_v = -\frac{\pi_v^*}{p_t} \vec{\nabla} p_v + \frac{\pi_v^* p_v}{p_t^2} \vec{\nabla} p_t$$

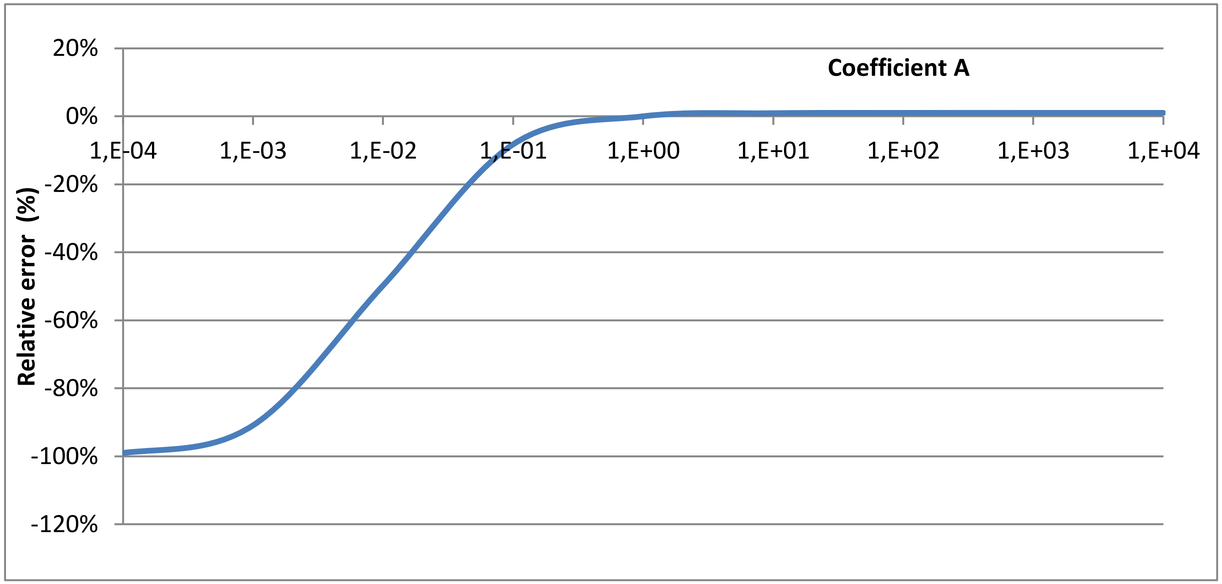
Error on the π evaluation

- The measurement error depends on the value of the ratio K_t/π

→ Small values lead to large underestimations of the vapour permeability

$$A = \frac{M_v}{M_t}\frac{K_t}{\pi}$$

$$\frac{\pi_{app} - \pi}{\pi}$$



New experimental process

- Measurement of total gas pressure on both sides of the sample.
- Simultaneous determination of gas permeability K_t and diffusion coefficient π_v^*

$$c_v = \frac{p_v}{p_t}$$

$$K_t = \frac{\left[\left(1-\bar{c}_v\right)M_{as} + \bar{c}_v M_v\right] g_v e}{M_v \Delta p_t}$$

$$\pi_v^* = \frac{g_v e}{\Delta c_v}\left(1-\bar{c}_v\right)$$

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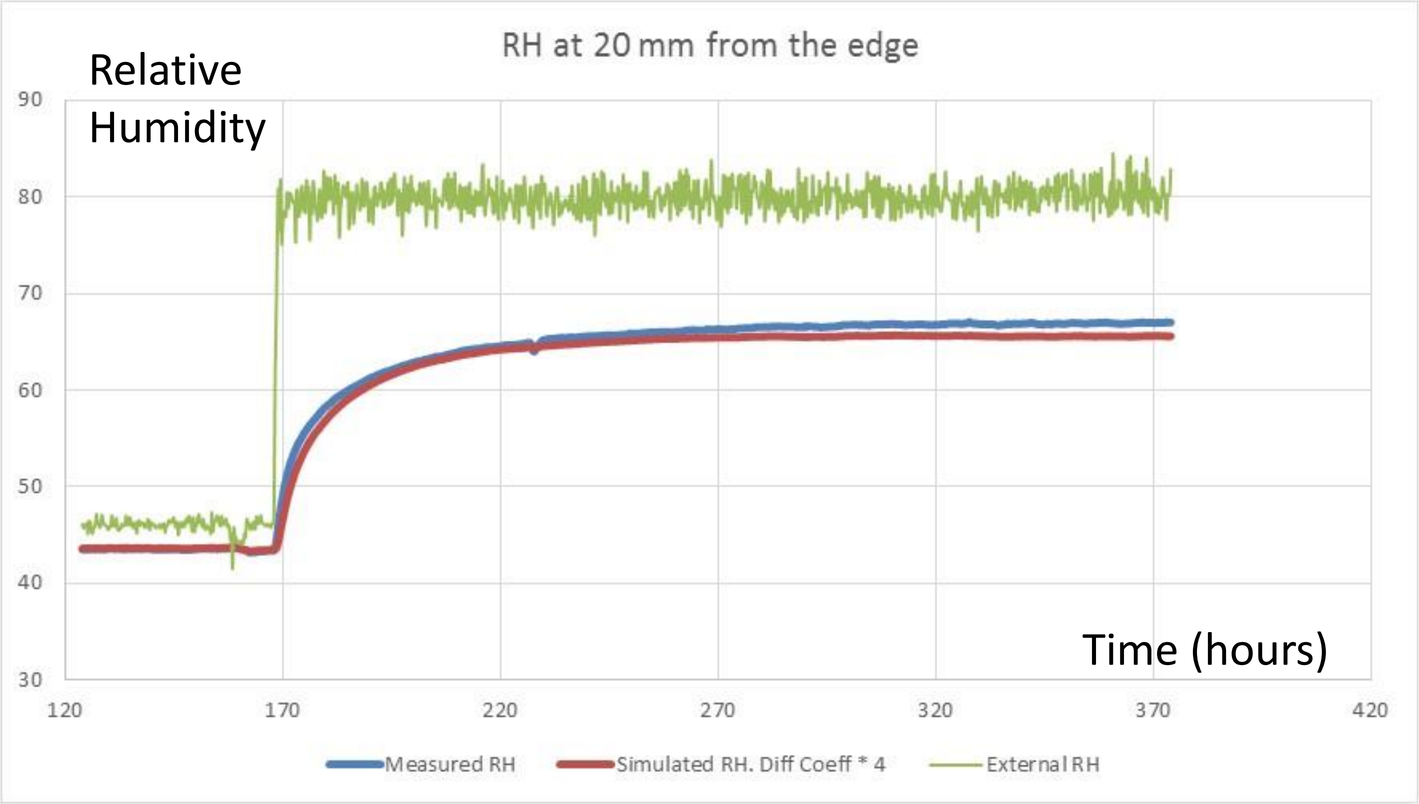
$$\bar{\pi}_v^* = \frac{g_v e}{\Delta c_v}\left(1-\bar{c}_v\right)$$

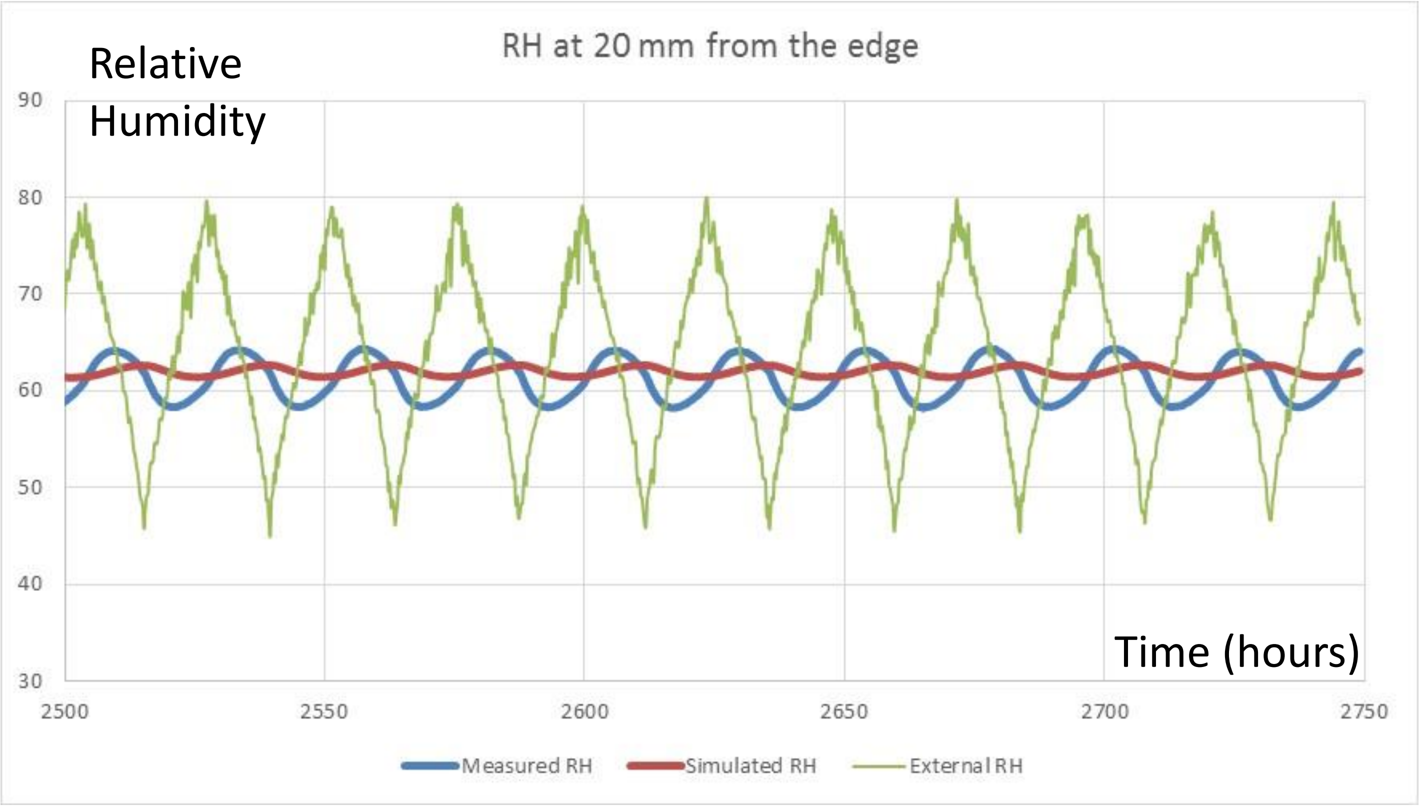
TO BE EVALUATED

Validation attempt with a corrected diffusion coefficient



Validation attempt 2

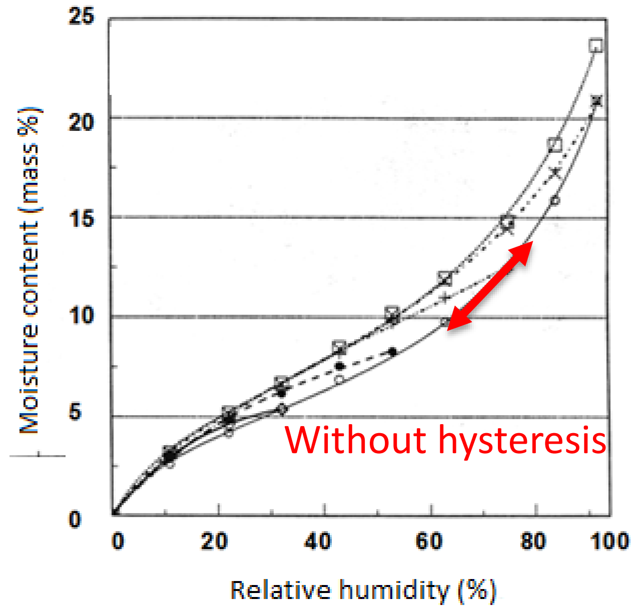
Moisture cycle



Excessive buffering of relative humidity

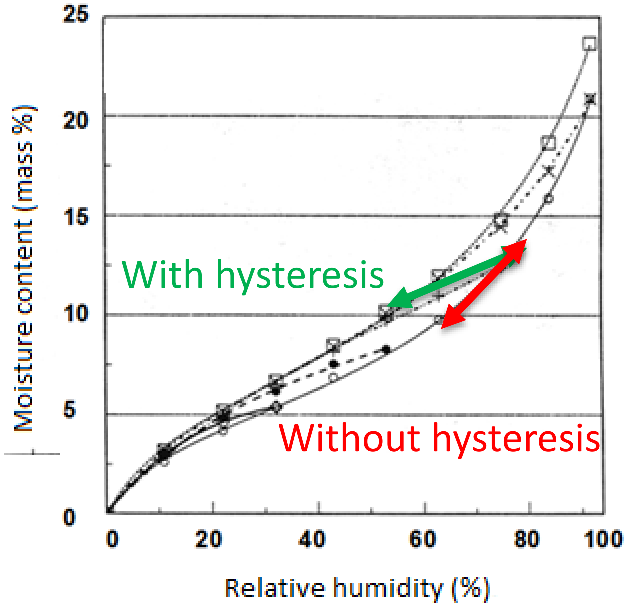
Impact of hysteresis for cyclic evolutions

- Without any account of hysteresis, cyclic evolutions occur along a single sorption curve.



Impact of hysteresis for cyclic evolutions

- When hysteresis is considered, cyclic evolutions occur between both sorption curves, with a weaker slope.



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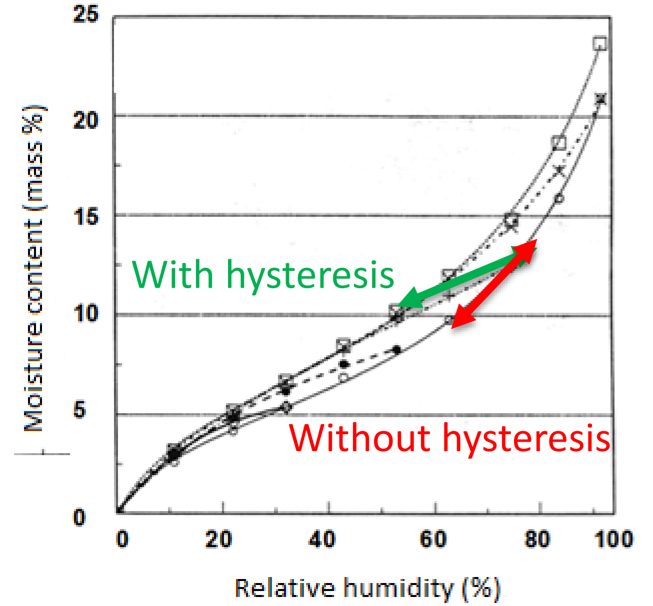
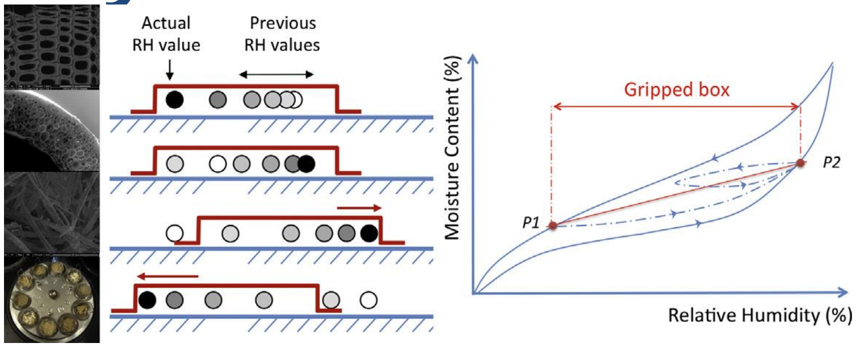


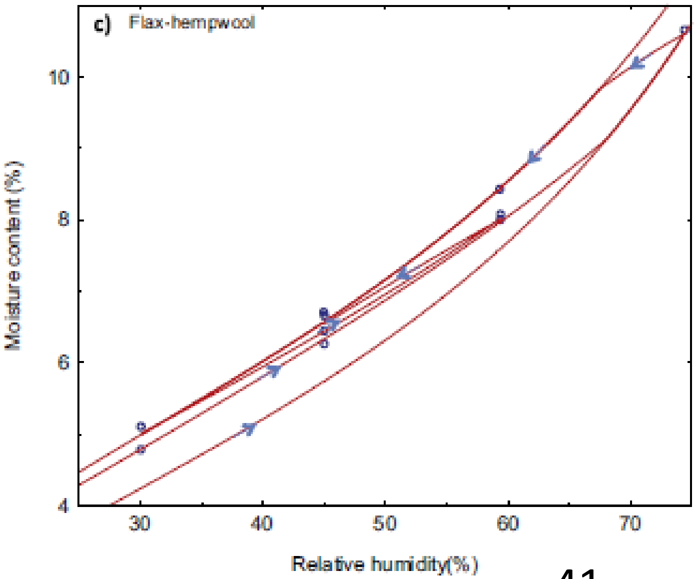
- When hysteresis is not considered, hygric inertia is overestimated, and relative humidity evolutions are significantly damped.

Modelling with hysteresis

- For modelling, hysteresis should be described by a formulation which is compatible with current heat and mass transfer models.
- Such an attempt already exists (P. Perré & al. 2018).
- Implementation in models is in progress.



Source : The gripped-box model: A simple and robust formulation of sorption hysteresis for lignocellulosic materials. Romain Rémond, Giana Almeida, Patrick Perré. Construction and Building Materials 170 (2018) 716–724

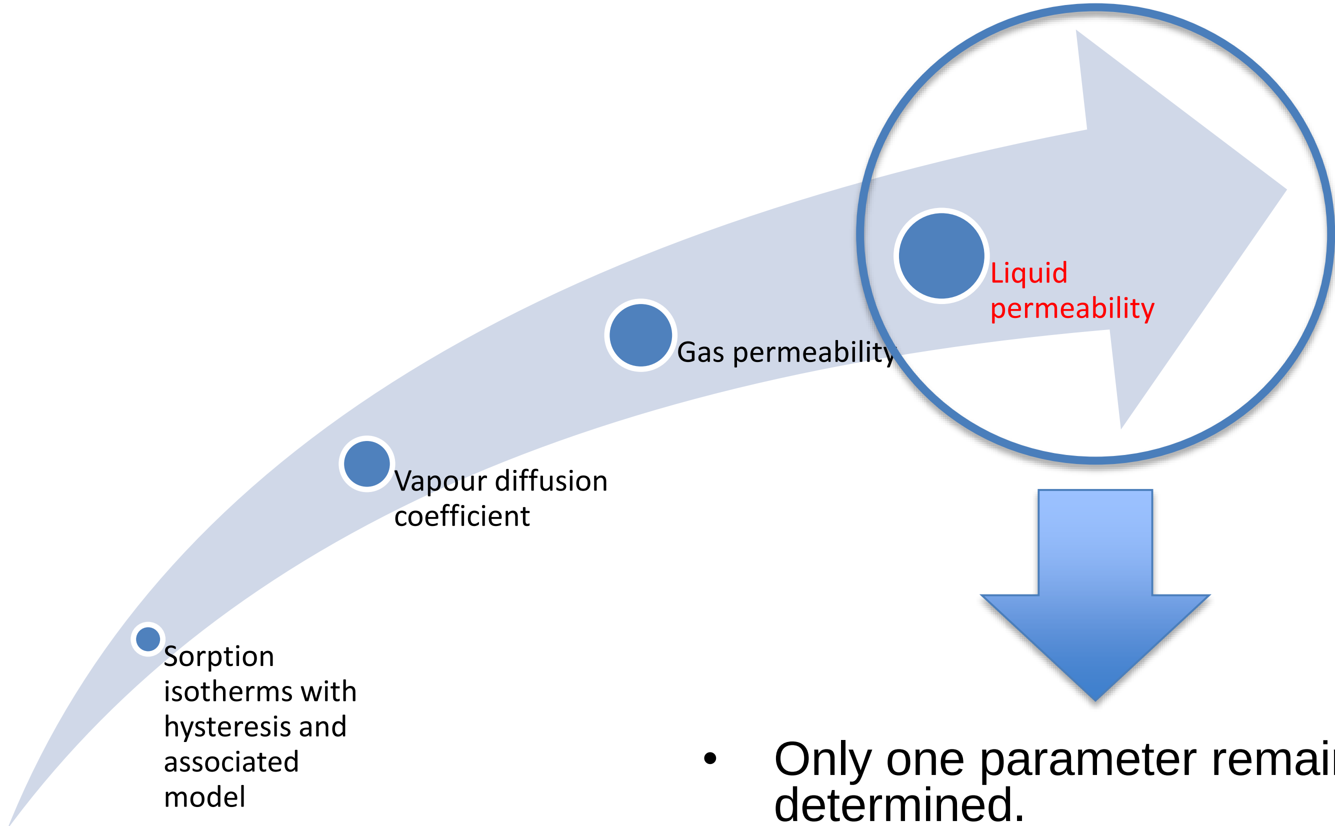


CONCLUSIONS AND OUTLOOKS

Conclusions

- Obvious technical, scientific, social & economic issues
- Present approaches, focused on condensation risk evaluation, fail to demonstrate their reliability in more complex situations
- Nevertheless, we are about to correct the main drawbacks of the scientific arsenal :
    - Gas pressure impact
    - Hysteresis impact
    - Reliable determination of materials characteristics

Toward a complete hydric characterization of all materials



- Only one parameter remains to be determined.

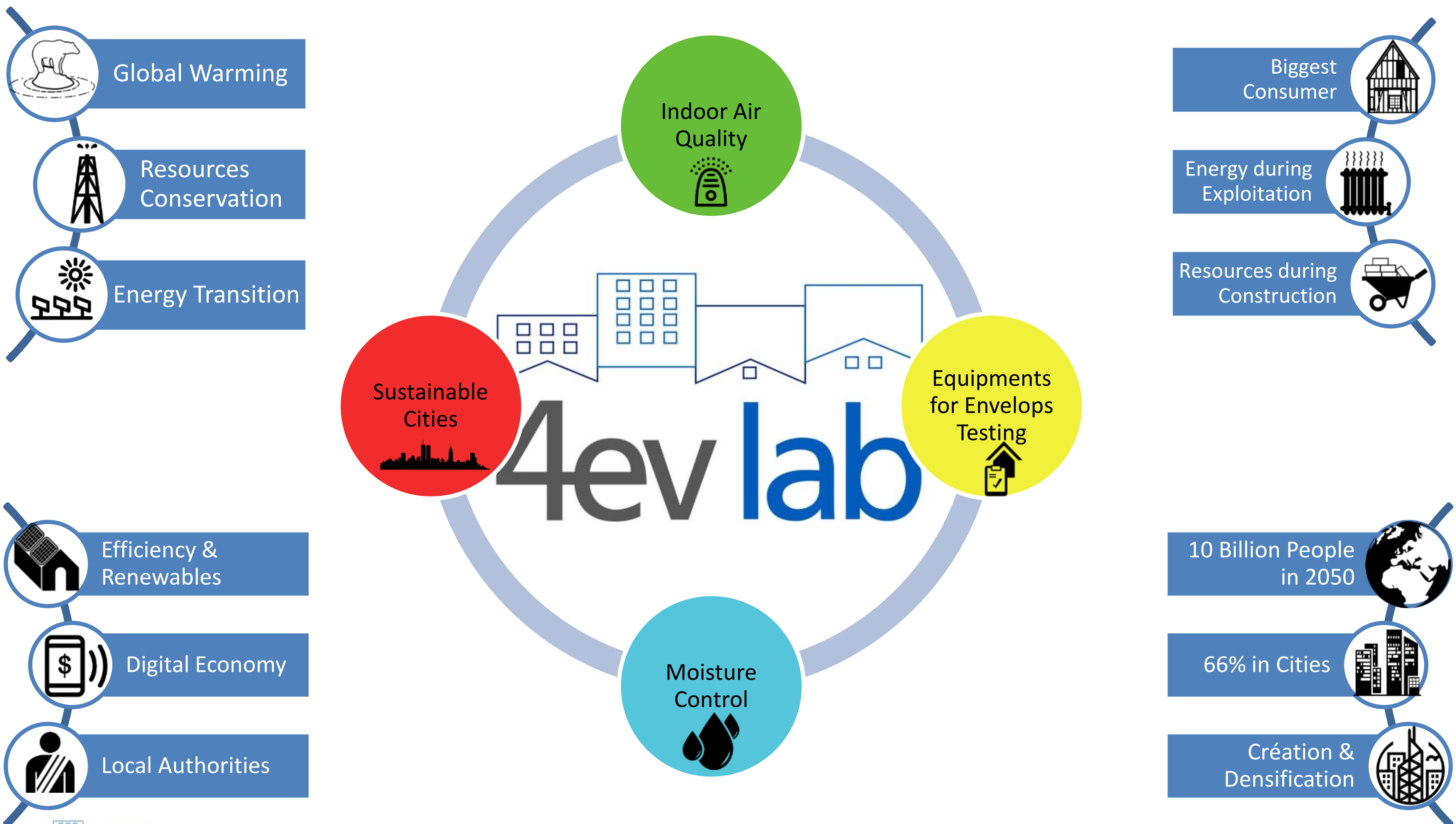
→ Liquid permeability identification through inverse methods becomes feasible.

Outlooks : Two main issues

- Prove the reliability of our scientific approaches.
  - Modelling
  - Materials characterization
- Install new hygrothermal approaches into the building design activity.
  - Adapted tools and methods
    - Updated standards and evaluation methods
    - Helpful tips (e.g. for the definition of initial & boundary conditions)
  - Relevant indicators for designers
    - Adapted to the concerned issues

THANK YOU FOR YOUR ATTENTION

Back-up



Global Warming
Resources Conservation
Energy Transition
Efficiency & Renewables
Digital Economy
Local Authorities
Indoor Air Quality
Sustainable Cities
4ev lab
Equipments for Envelops Testing
Moisture Control
Biggest Consumer
Energy during Exploitation
Resources during Construction
10 Billion People in 2050
66% in Cities
Création & Densification

4ev lab

The model developed at EDF R&D

Choice of potentials

Phenomenological equations

Energy conservation

$$\left(\rho_s C_s + \tau_v C_l - \tau_v h_p + \varepsilon \rho_v \left(C_l + \frac{dL(T)}{dT}\right) + \varepsilon \rho_{as} C_{pas} - (L(T) + h^m)\left(\frac{\beta_p p_v}{\rho_l r_v T} + \frac{\varepsilon p_v}{r_v T^2}\right) + \frac{p_t \beta_p}{\rho_l}\right)\frac{dT}{dt}$$

$$+\left(-\tau_v h_T + (L(T) + h^m)\left(-\frac{p_v \alpha_T}{\rho_l r_v T} + \frac{\varepsilon}{r_v T}\right) + \frac{p_t \alpha_T}{\rho_l}\right)\frac{dp_v}{dt}$$

$$-\varepsilon \frac{dp_t}{dt} =$$

$$\vec{\nabla}.\left(\lambda^* \vec{\nabla} T + (L(T) + h^m)\left(\frac{\pi_v^*}{p_t}\right)\vec{\nabla} p_v + (L(T) + h^m)\left(\omega_{mv} K_t - \frac{\pi_v^* p_v}{p_t^2}\right)\vec{\nabla} p_t\right)$$

Water conservation

$$\left(\beta_p - \frac{\varepsilon p_v}{r_v T^2}\right)\frac{dT}{dt} + \left(\alpha_T + \frac{\varepsilon}{r_v T}\right)\frac{dp_v}{dt} =$$

$$\vec{\nabla}.\left(K_l \rho_l \left(r_v \ln\left(\frac{p_v}{p_{sat}(T)}\right) - \frac{L(T)}{T}\right)\vec{\nabla} T + \left(\frac{\pi_v{}^*}{p_t} + K_l \frac{\rho_l r_v T}{p_v}\right)\vec{\nabla} p_v + \left(\omega_{mv} K_t - \frac{p_v \pi_v{}^*}{p_t^2}\right)\vec{\nabla} p_t\right)$$

Dry air conservation

$$-\frac{p_t - p_v}{r_{as} T}\left(\frac{\beta_p}{\rho_l} + \frac{\varepsilon}{T}\right)\frac{dT}{dt} - \frac{1}{r_{as} T}\left(\frac{\alpha_t (p_t - p_v)}{\rho_l} + \varepsilon\right)\frac{dp_v}{dt} + \frac{\varepsilon}{r_{as} T}\frac{dp_t}{dt} =$$

$$\nabla.\left[\left(-\frac{\pi_v^* M_{as}}{p_t M_v}\right)\vec{\nabla} p_v + \left(\rho_{as}\frac{Kk_{rg}}{\eta_t} + \frac{\pi_v^* p_v M_{as}}{p_t^2 M_v}\right)\vec{\nabla} p_t\right]$$