Simurex 2018

On the Modeling of Heat, Air and Moisture in Buildings

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Simurex
2018

Heat, Air and Moisture (HAM) transfer in Buildings

- When did people become interested in HAM transfer in buildings?

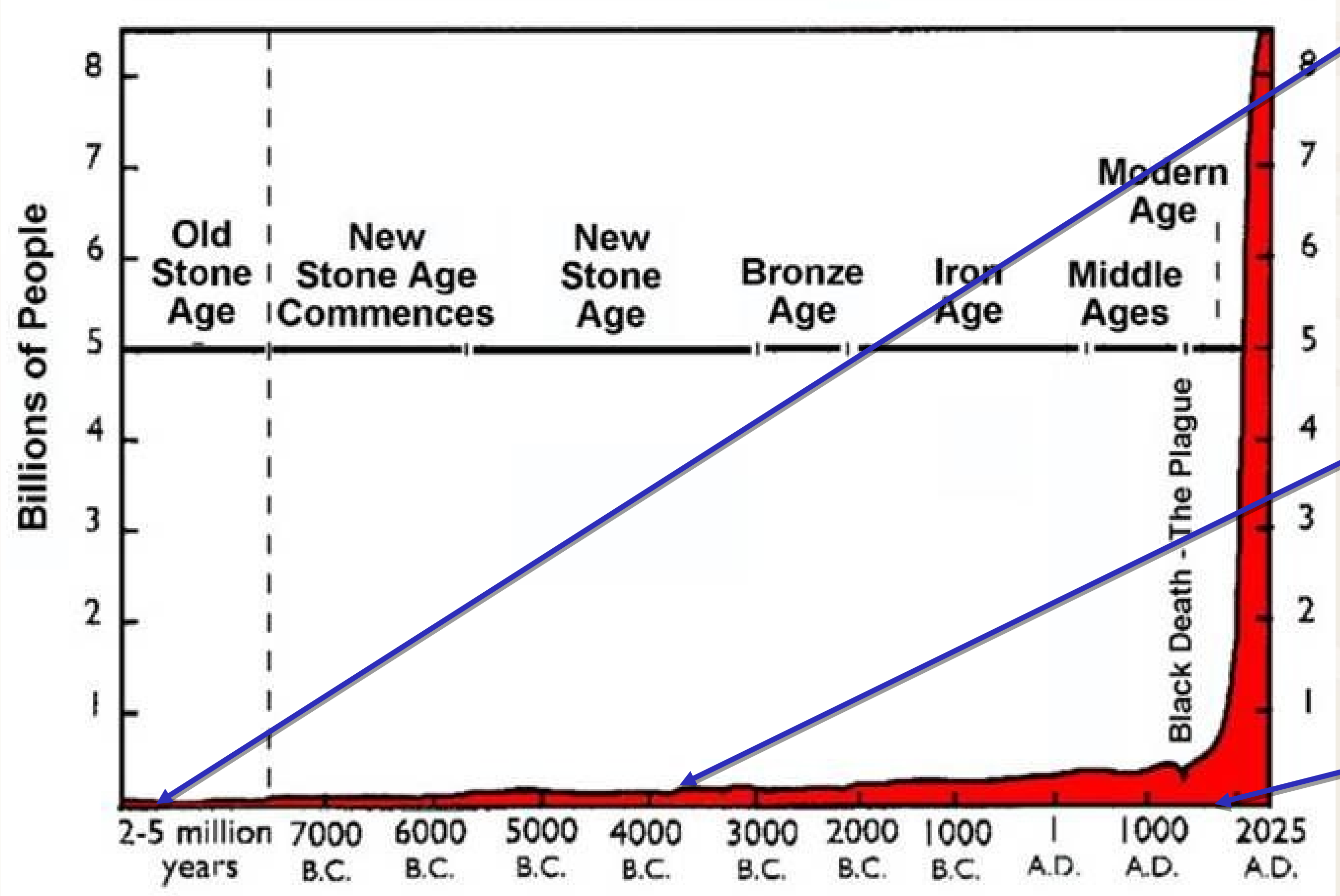
- When did people become interested in building energy simulation / energy efficiency?

- When did people start to think of energy conversion?

- What can we expect for the future in terms of HAM transfer prediction in buildings?

Population growth and some highlights on energy conversion

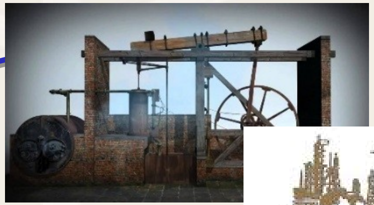
Pre-history – 18th

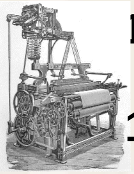


Population Reference Bureau, http://www.prb.org

2.000.000 years

4000 B.C.





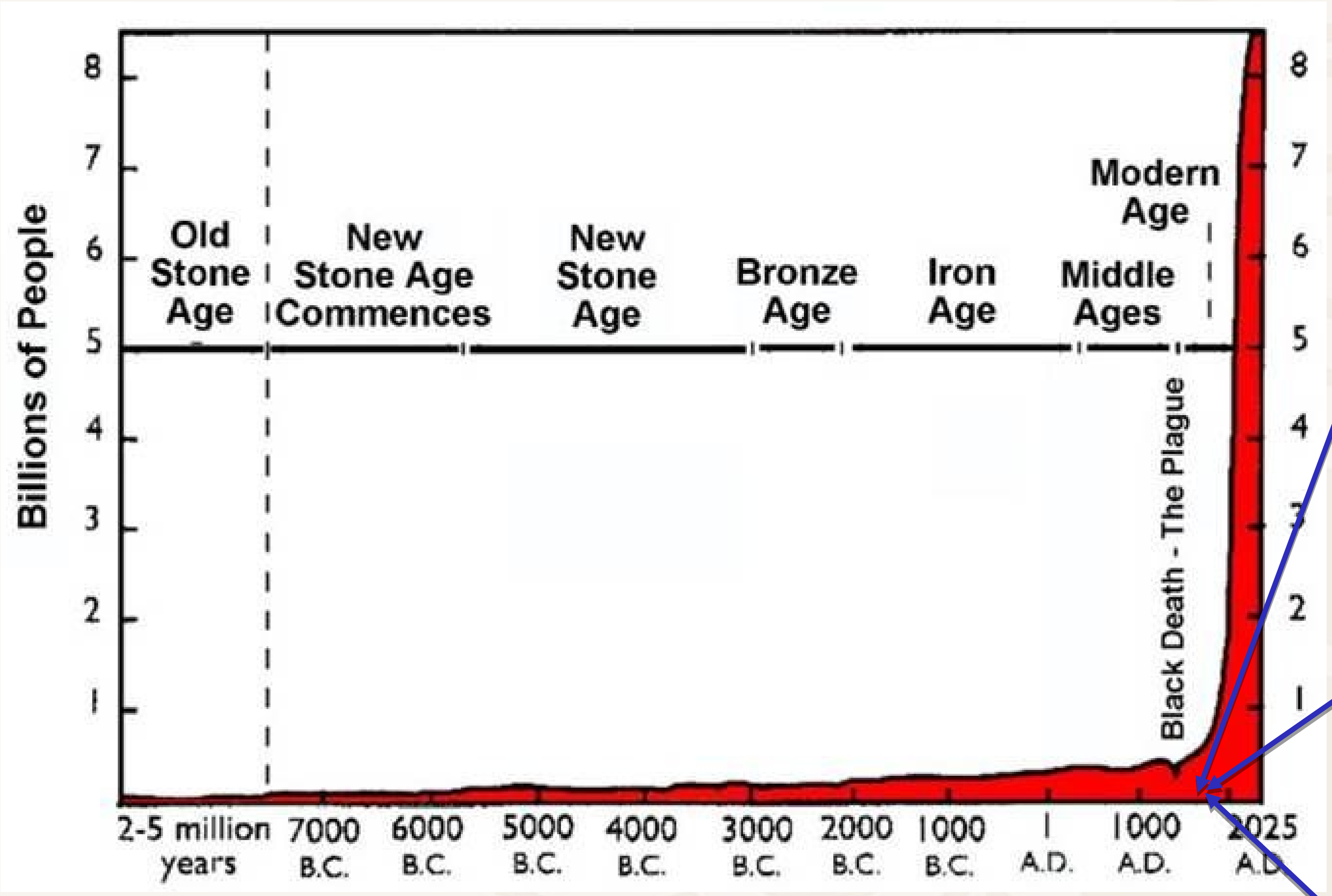
1769

1785

Population growth and some highlights on energy conversion

19th

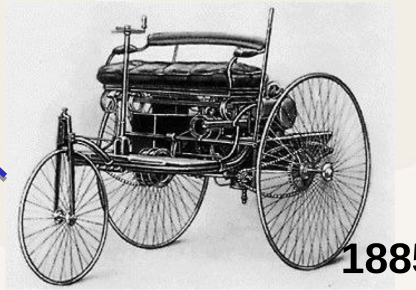
Principle of electric motor
1821



Population Reference Bureau, http://www.prb.org

1870

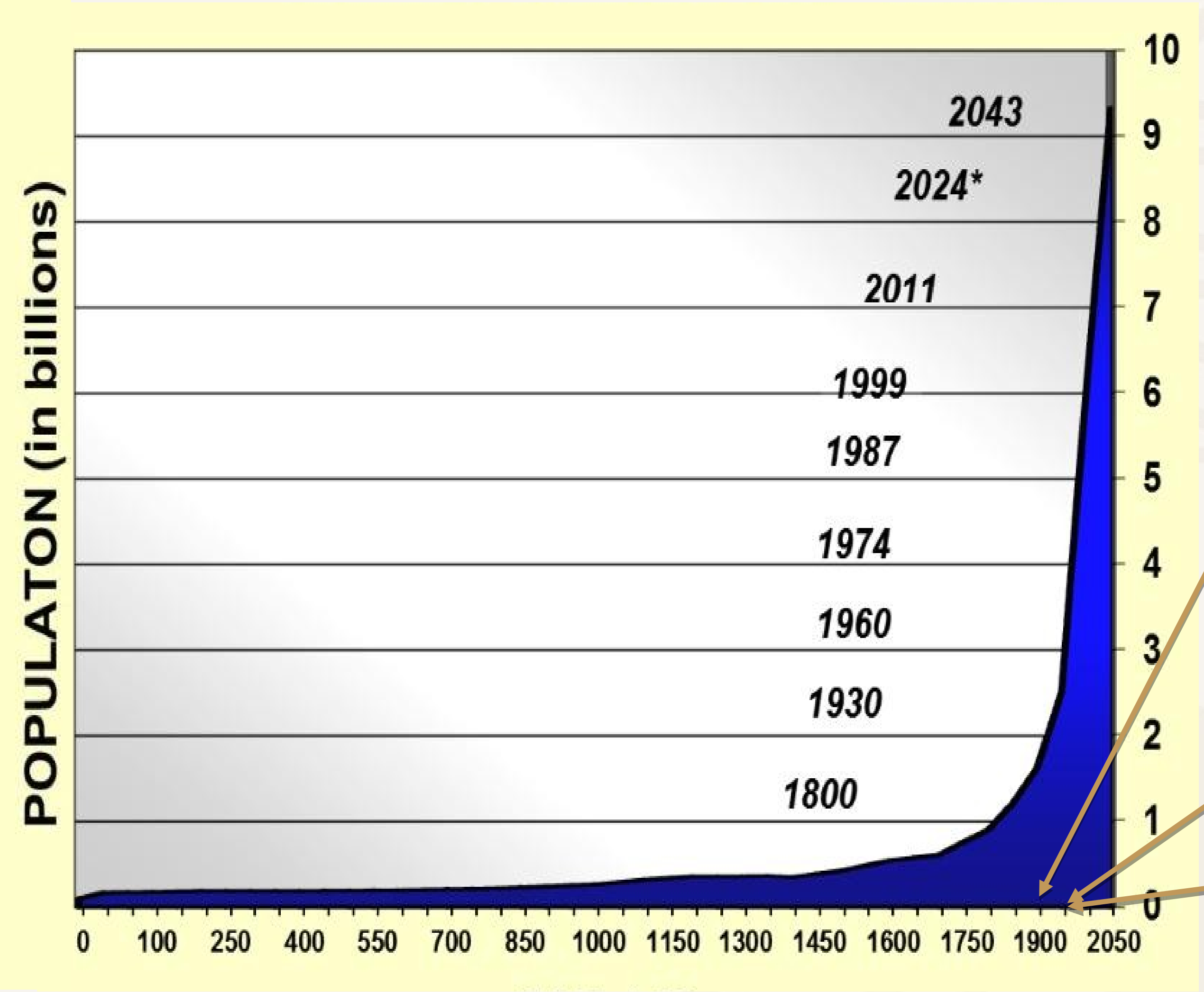
1878



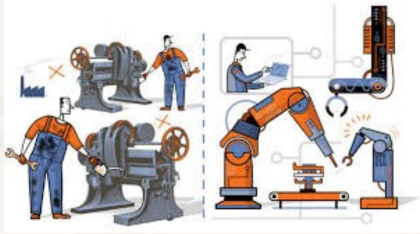
1885

Population growth and some highlights

20th



1903



1969
(Ethernet, PC, Floppy disk, automated production)

1970's Energy Crises

BES tools

http://mycicm.civdigital.net/content/population-information

Energy-efficient building envelope research is not recente !!!

Frobisher Bay on Baffin Island in the mid-19th century. | Source= ''Arctic Researches and Life Among the Esquimaux: Being the Narrative of an Expedition i

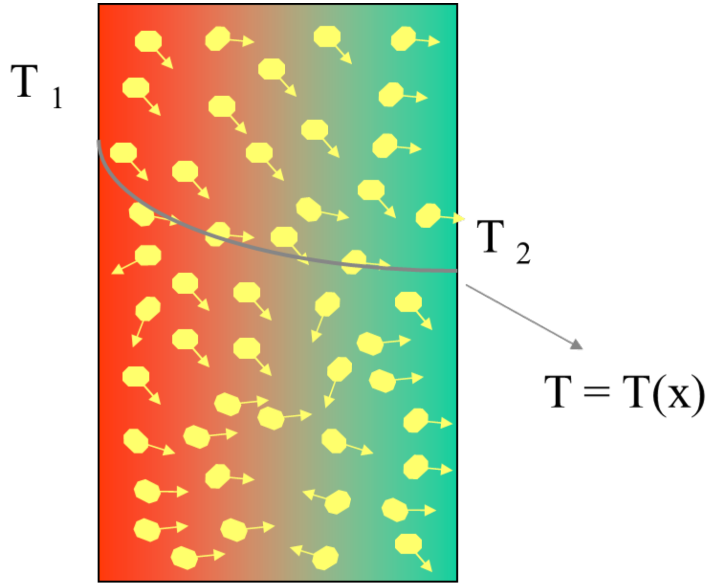
Building Envelope (Energy Efficiency)

Diffusion

$$\Psi \quad \alpha \quad -\nabla\phi$$

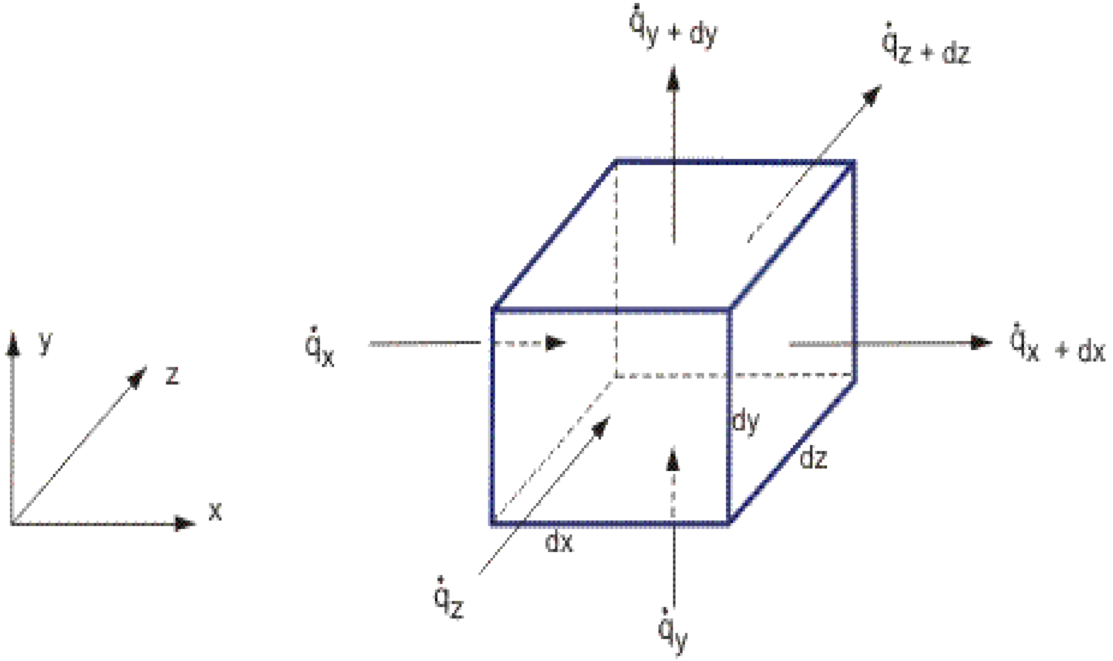
Conductive heat transfer
Fourier's Law

$$q = -\lambda \nabla T$$



Building Envelope

Diffusion in Building Physics



$$\frac{\partial u}{\partial t} = -\nabla.(\mathbf{q})$$

$$\frac{\partial u}{\partial t} = -\nabla.(-\lambda \nabla T)$$

Thermal diffusivity

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T$$

Diffusion in Building Physics

In 3D, with variable thermal conductivity:

$$\rho_0 c_m \frac{\partial T}{\partial t} = \nabla . (\lambda \ (T) \nabla T)$$

In building Physics, 1D hypothesis is normally assumed so that:

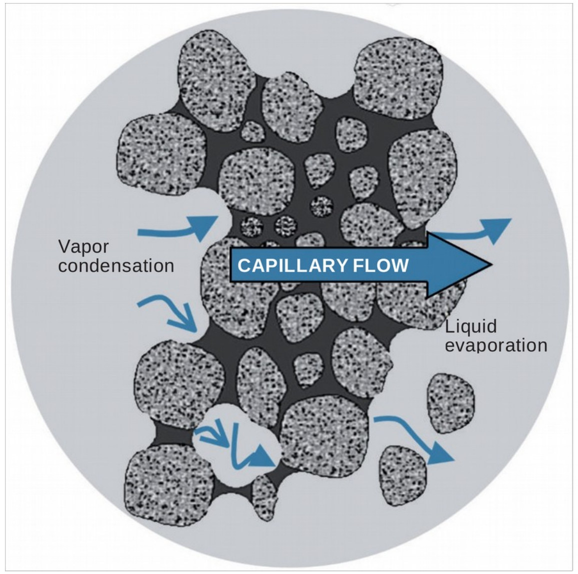
$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

Since 1970’s used in several worldwide BPS tools

Building Envelope

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

What about moisture?



Glaser method (1959), DIN 4108

- Steady-state based graphical method for risk assessment and design of moisture-safe constructions
- Major limitations: disregard of hygroscopic sorption, liquid transport, and transient effects

However, over the last 30 years, with significant progress in computer hardware, the Glaser method has inspired the development of detailed heat, air, and moisture (HAM) mathematical models and simulation tools for the analysis of a single porous building element or the whole building. The models have been progressively improved so that different models are available, and a very brief and non-complete overview will be presented.

Building Envelope – Moisture consideration in the 80’s

Silveira-Neto (1985) => analytical solutions (monolithic porous walls, constant properties)

Cunningham (1988) => electrical analogy for the vapor flow and an exponential approximation function with constant mass transport coefficients

Kerestecioglu and Gu (1988) applied the evaporation-condensation theory in the pendular state

Building Envelope – Moisture in 90's and 2000's

Burch and Thomas (1991) => MOIST, vapor transfer

Pedersen (1991) => MATCH, vapor and liquid transfer

Liesen (1994) => Evaporation-condensation theory and a response factor method => IBLAST

Künzel (1995) => WUFI

Mendes (1997) => UMIDUS

Grunewald (1997) => DIM1 => DIM 3 (HMT, 2003) => DELPHIN

Santos et al. (2003) => 3D SOLUM

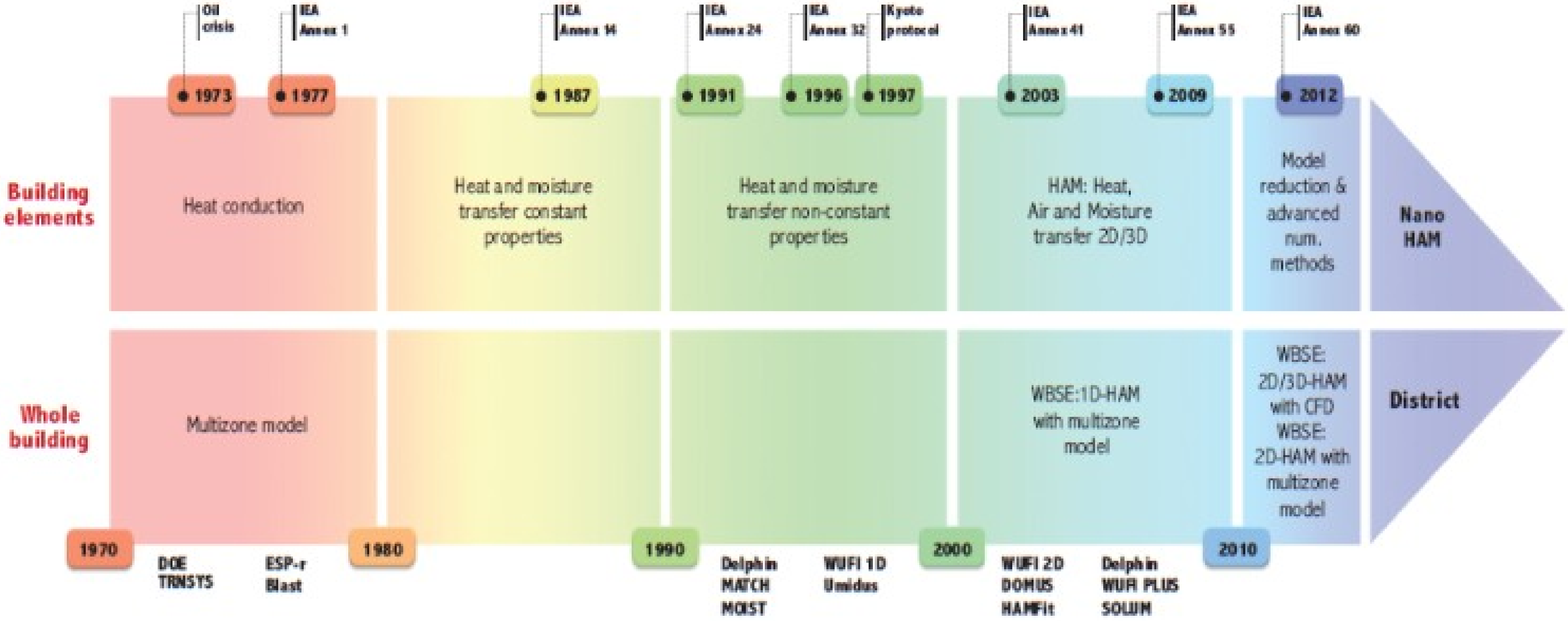
Karagiozis (2001) => MOISTURE-EXPERT

Hagentoft et al. (2004) => HAMSTAD

Kalagasidis (2004) => HAM-Tools

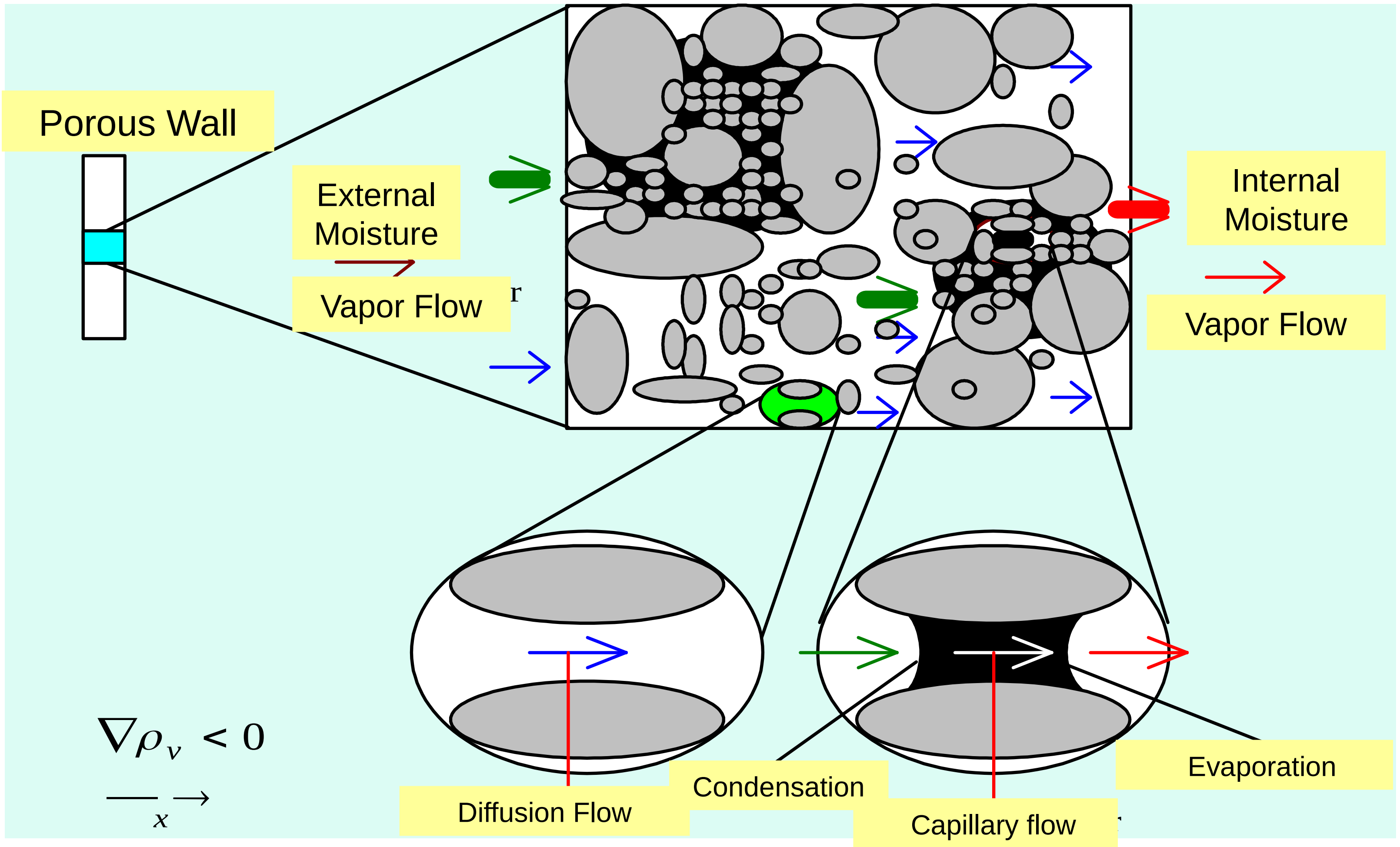
among others…

HAM/BPS Short History

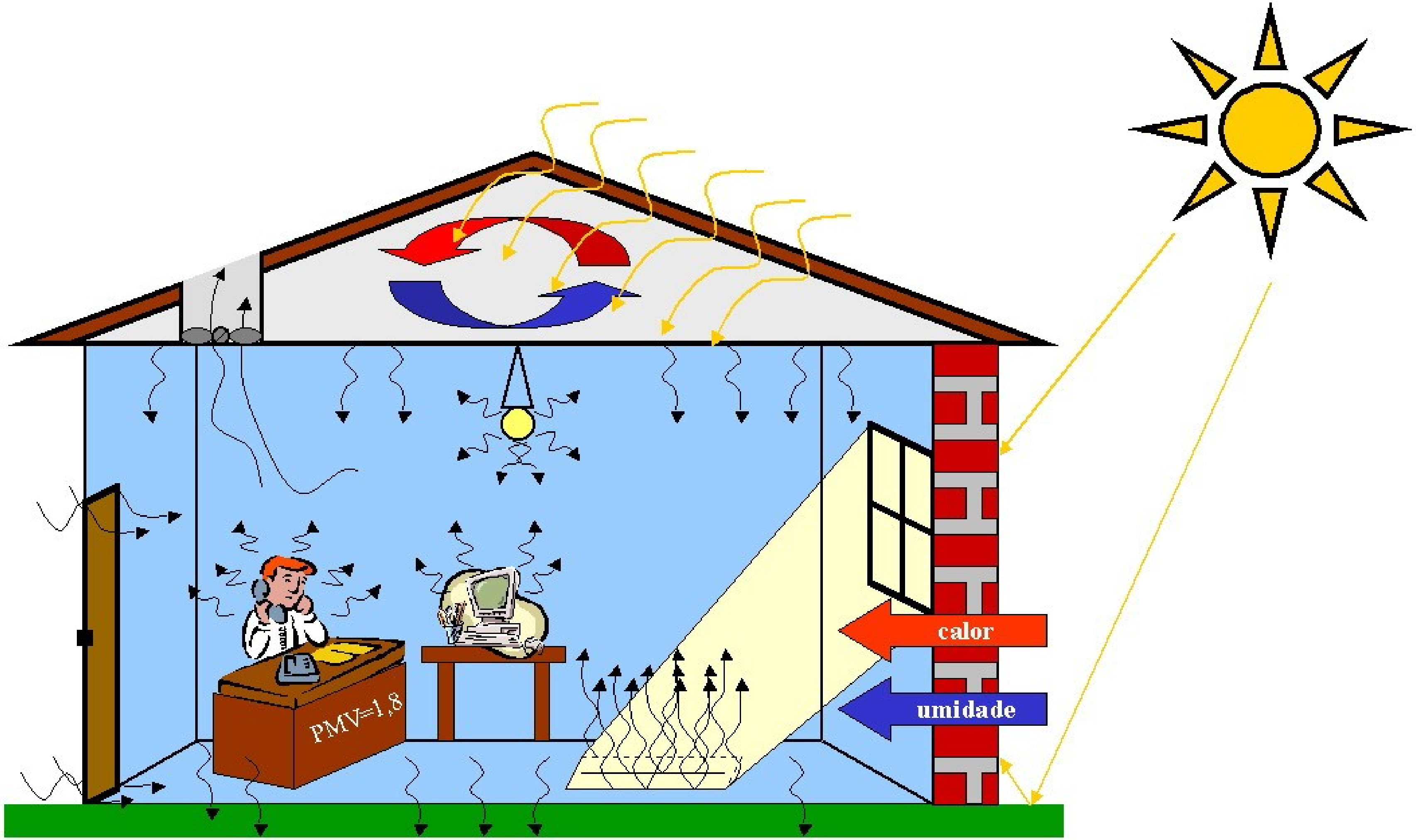


HAM Transfer and Room Air

Moisture Transport in Porous Envelopes



Balances



MATCH

- **Energy Balance**

$$\rho_0 \frac{\partial u}{\partial t} = -\frac{\partial q}{\partial x} - L\frac{\partial j_v}{\partial x}$$

- **Moisture Balance**

$$\rho_0 \frac{\partial \omega}{\partial t} = -\frac{\partial j_v}{\partial x} - \frac{\partial j_l}{\partial x}$$

$$j_v = -\delta_v\left(\phi\right)\frac{\partial P_v}{\partial x}$$

$$j_l = \delta_l\left(\phi\right)\frac{\partial P_c}{\partial x} \qquad j_l = \delta_l P_c \frac{\partial \ln P_c}{\partial x}$$

Umidus Envelope Model

Porous Elements

- **Energy Balance**

$$\rho_0 . c_m . \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + L \frac{\partial}{\partial x}\left(D_{TV} \frac{\partial T}{\partial x} + D_{\theta V} \frac{\partial \theta}{\partial x}\right)$$

- **Moisture Balance**

$$\frac{\partial \theta}{\partial t} = -\nabla . \left(\frac{\mathbf{j}}{\rho_l} \right) \qquad \frac{\partial}{\partial t}(\theta) = \frac{\partial}{\partial x}\left[D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x} \right]$$

Mathematical Model for Soil Simulation

Philip and De Vries model

- **Energy Balance**

$$\rho_0 c_m(T,\theta)\frac{\partial T}{\partial t} = \nabla.\left(\lambda\ (T,\theta)\nabla T\right) - L(T)\left(\nabla.\mathbf{j}\right)$$

- **Mass Conservation**

$$\frac{\partial \theta}{\partial t} = -\nabla.\left(\frac{\mathbf{j}}{\rho_l}\right)$$

Mathematical Model for Soil Simulation

Vapor and liquid flow:

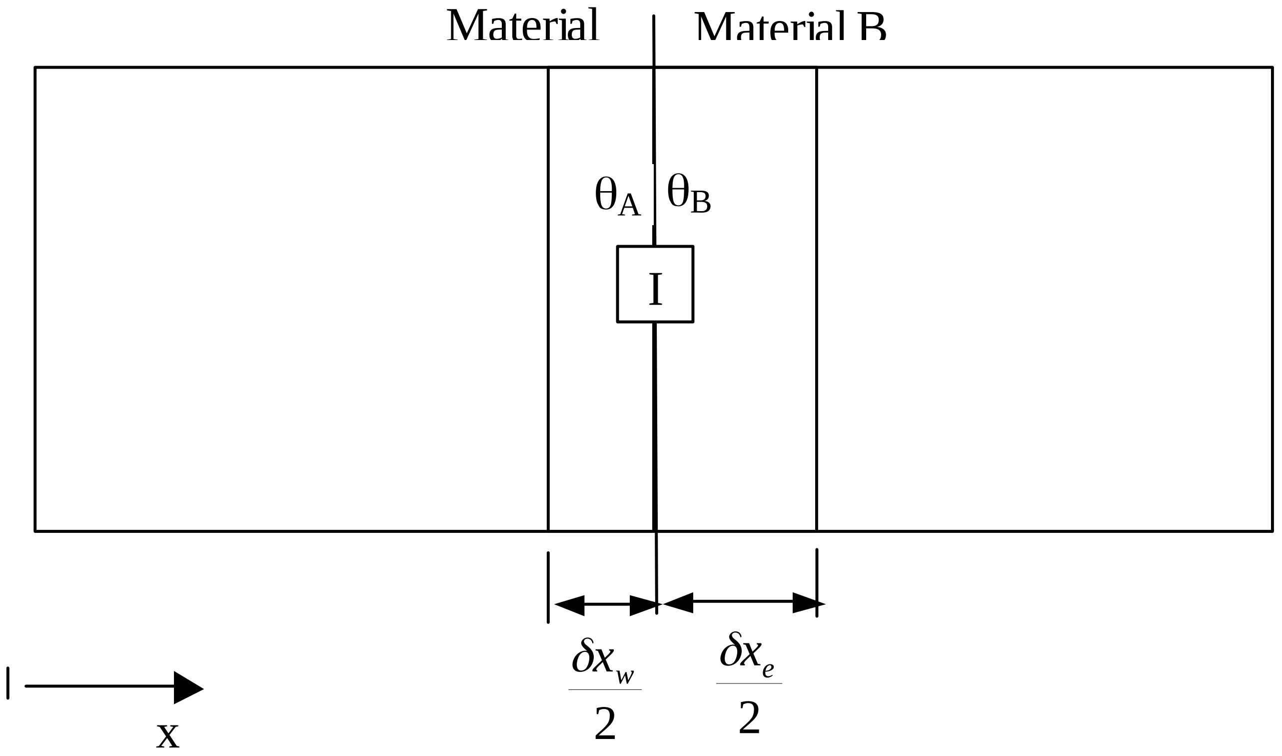
$$\frac{\mathbf{j}}{\rho_l} = -\left[D_T(T,\theta)\frac{\partial T}{\partial x} + D_\theta(T,\theta)\frac{\partial \theta}{\partial x} \right] \mathbf{i}$$

$$-\left[D_T(T,\theta)\frac{\partial T}{\partial y} + D_\theta(T,\theta)\frac{\partial \theta}{\partial y} \right] \mathbf{j}$$

$$-\left[D_T(T,\theta)\frac{\partial T}{\partial z} + D_\theta(T,\theta)\frac{\partial \theta}{\partial z} + \frac{\partial K_g}{\partial z} \right] \mathbf{k}$$

Moisture Content Profile Discontinuity

$$\begin{cases} (T)_A = (T)_B \\ (\psi)_A = (\psi)_B \end{cases}$$



$$\left(\frac{\partial\phi}{\partial\theta}\right)_A^{prev}\left(\theta_A(s) - \theta_A(s)^{prev}\right) = \left(\frac{\partial\phi}{\partial\theta}\right)_B^{prev}\left(\theta_B(s) - \theta_B(s)^{prev}\right)$$

JCR

Moisture Content Profile Discontinuity

ELSEVIER

International Journal of Heat and Mass Transfer

Volume 48, Issue 1, January 2005, Pages 37–51

A method for predicting heat and moisture transfer through multilayered walls based on temperature and moisture content gradients

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2004.08.011, How to Cite or Link Using DOI

WUFI

- **Energy Balance**

$$\rho_0(c_0 + c_1\omega_1 + c_v\omega_v)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + L\frac{\partial}{\partial x}\left(\delta_v \frac{\partial \phi P_s}{\partial x}\right)$$

- **Moisture Balance**

$$\frac{\partial \omega}{\partial \phi}\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x}\left(D_l \frac{\partial \omega}{\partial \phi}\frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial x}\left(\delta_v \frac{\partial \phi P_s}{\partial x}\right)$$

HAMSTAD Project

- **Energy Balance**

$$\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) - r_a \rho_a c_{p,a} \frac{\partial T}{\partial x} + \frac{\partial}{\partial x} l_{lv}(\delta_p \frac{\partial P_v}{\partial x}) - \frac{r_a l_{lv}}{R_v T} \frac{\partial P_V}{\partial x} = c\rho_0 \frac{\partial T}{\partial t}$$

- **Moisture Balance**

$$\frac{\partial}{\partial x}\left(\delta_p \frac{\partial P_v}{\partial x}\right) - \frac{r_a}{R_v T} \frac{\partial P_v}{\partial x} - \frac{\partial}{\partial x}(K \frac{\partial P_{suc}}{\partial x}) = \frac{\partial w}{\partial t}$$

HAM tools

- **Energy Balance**

$$\frac{1}{\rho_0}\frac{\partial \omega}{\partial t} = -\frac{\partial}{\partial x}\left(-\delta_l \frac{\partial P_c}{\partial x} - \delta_v \frac{\partial P_v}{\partial x} + \mathbf{j}_a \omega\right)$$

- **Moisture Balance**

$$\rho_0 c_m \frac{\partial T}{\partial t} = -\frac{\partial}{\partial x}\left(-\lambda \frac{\partial T}{\partial x} + \mathbf{j}_a c_a T + L \mathbf{j}_v\right)$$

GHAM

Three driving potential model

$$\nabla T, \nabla P_v, \nabla P_g$$

Santos, G.H., Mendes, N., Combined Heat, Air and Moisture (HAM) Transfer Model for Porous Building Materials. Journal of Building Physics, v. 32, p. 203-220, 2009.

Santos, G.H., Mendes, N.; Philippi P.C.. A building corner model for hygrothermal performance and mould growth risk analyses. International Journal of Heat and Mass Transfer, v. 52, p. 4862-4872, 2009.

Santos, G.H., Mendes, N., Heat, air and moisture transfer through hollow porous blocks. International Journal of Heat and Mass Transfer, v. 52, p. 2390-2398, 2009.

Three driving potential model for HAM transfer

Moisture Transport

$$\mathbf{j} = \mathbf{j_l} + \mathbf{j_v}$$

$$\mathbf{j_l} = K(\nabla P_{suc} - \rho_l \mathbf{g})$$

$$\mathbf{j_v} = -\underbrace{\delta_v \nabla P_v}_{Diffusion} - \underbrace{\rho_v \frac{kk_{rg}}{\mu_g} \nabla P_g}_{Convection}$$

$$\frac{\partial w}{\partial t} = \frac{\partial w}{\partial \phi}\frac{\partial \phi}{\partial P_v}\frac{\partial P_v}{\partial t} + \frac{\partial w}{\partial \phi}\frac{\partial \phi}{\partial T}\frac{\partial T}{\partial t} = \nabla.\left[-K\frac{\partial P_{suc}}{\partial T}\nabla T - \left(K\frac{\partial P_{suc}}{\partial P_v} - \delta_v\right)\nabla P_v + \rho_v \frac{kk_{rg}}{\mu_g}\nabla P_g + K\rho_l \mathbf{g}\right]$$

Three driving potential model for HAM transfer

Dry Air Transport

$$\mathbf{j}_a = \underbrace{\delta_v \nabla P_v}_{difus\tilde{a}o\ \text{do ar}} - \underbrace{\rho_a \frac{kk_{rg}}{\mu_g} \nabla P_g}_{convec\c{c}\tilde{a}o\ \text{do ar}}$$

$$\frac{\partial \rho_a}{\partial t} = \frac{\partial \rho_a}{\partial P_g}\frac{\partial P_g}{\partial t} + \frac{\partial \rho_a}{\partial P_v}\frac{\partial P_v}{\partial t} + \frac{\partial \rho_a}{\partial T}\frac{\partial T}{\partial t} = \nabla . \left(- \delta_v \nabla P_v + \rho_a \frac{kk_{rg}}{\mu_g} \nabla P_g \right)$$

Three driving potential model for HAM transfer

Heat Transport

$$c_m \rho_0 \frac{\partial T}{\partial t} = -\nabla.\mathbf{q} + S$$

$$\mathbf{q} = \mathbf{q}_{\mathbf{cond}} + \mathbf{q}_{\mathbf{conv}} \qquad \mathbf{q}_{\mathbf{cond}} = -\lambda \nabla T \qquad \mathbf{q}_{\mathbf{conv}} = \underbrace{\mathbf{j_l} c_{pl} T}_{\text{fluxo de líquido}} + \underbrace{\mathbf{j_a} c_{pa} T}_{\text{fluxo de ar seco}} + \underbrace{\mathbf{j_v} c_{pv} T}_{\text{fluxo de vapor}}$$

$$c_m \rho_0 \frac{\partial T}{\partial t} = \nabla.\left\{ \begin{array}{l} \left(\lambda - K \dfrac{\partial P_{suc}}{\partial T} c_{pl} T\right) \nabla T - \left(K \dfrac{\partial P_{suc}}{\partial P_v} c_{pl} T + \delta_v c_{pa} T - \delta_v c_{pv} T\right) \nabla P_v + \\ \left(\rho_a \dfrac{kk_{rg}}{\mu_g} c_{pa} T + \rho_v \dfrac{kk_{rg}}{\mu_g} c_{pv} T\right) \nabla P_g + K \rho_l c_{pl} T \mathbf{g} \end{array} \right\} - L(T) \nabla.\mathbf{j}_v$$

Three driving potential model for HAM transfer

Governing Conservation Equations

$$\frac{\partial \rho_a}{\partial t} = \frac{\partial \rho_a}{\partial P_g}\frac{\partial P_g}{\partial t} + \frac{\partial \rho_a}{\partial P_v}\frac{\partial P_v}{\partial t} + \frac{\partial \rho_a}{\partial T}\frac{\partial T}{\partial t} = \nabla . \left(-\delta_v \nabla P_v + \rho_a \frac{k k_{rg}}{\mu_g} \nabla P_g \right)$$

$$\frac{\partial w}{\partial t} = \frac{\partial w}{\partial \phi}\frac{\partial \phi}{\partial P_v}\frac{\partial P_v}{\partial t} + \frac{\partial w}{\partial \phi}\frac{\partial \phi}{\partial T}\frac{\partial T}{\partial t} = \nabla . \left[-K \frac{\partial P_{suc}}{\partial T} \nabla T - \left(K \frac{\partial P_{suc}}{\partial P_v} - \delta_v \right) \nabla P_v + \rho_v \frac{k k_{rg}}{\mu_g} \nabla P_g + K \rho_l \mathbf{g} \right]$$

$$c_m \rho_0 \frac{\partial T}{\partial t} = \nabla . \left[\begin{array}{l} \left(\lambda - K \frac{\partial P_{suc}}{\partial T} c_{pl} T \right) \nabla T - \left(K \frac{\partial P_{suc}}{\partial P_v} c_{pl} T + \delta_v c_{pa} T - \delta_v c_{pv} T \right) \nabla P_v + \\ \left(\rho_a \frac{k k_{rg}}{\mu_g} c_{pa} T + \rho_v \frac{k k_{rg}}{\mu_g} c_{pv} T \right) \nabla P_g + K \rho_l c_{pl} T \mathbf{g} \end{array} \right] - L(T) \nabla . \mathbf{j}_v$$

CAR-HAM

- **Energy Balance**

$$\frac{\partial\left(\left(\rho_0 c_0+\omega_l c_l+\omega_v c_v\right)T\right)}{\partial t}=-\nabla\cdot\left[-\left(\lambda+\delta_l\frac{\partial P_c}{\partial T}h_l\right)\nabla T\right]-\nabla\cdot\left[r_a\left(\frac{MP_v}{\rho_l RT}h_v+\rho_0 c_0 T\right)\right]$$

$$-\nabla\cdot\left[\left(\delta_l\frac{\partial P_c}{\partial P_v}h_l-\delta_v h_v\right)\nabla P_v\right]-\nabla\cdot\left[\delta_l\rho g h_l\right]+q_r$$

- **Moisture Balance**

$$\frac{\partial\omega}{\partial\phi}\frac{\partial\phi}{\partial P_v}\frac{\partial P_v}{\partial t}+\frac{\partial\omega}{\partial\phi}\frac{\partial\phi}{\partial P_s}\frac{\partial P_s}{\partial T}\frac{\partial T}{\partial t}=-\nabla\cdot\left(-\delta_v\nabla P_v+r_a\frac{P_v M}{\rho_l RT}+\delta_l\left(\frac{\partial P_c}{\partial P_v}\nabla P_v+\frac{\partial P_c}{\partial T}\nabla T-\rho g\right)\right)$$

Boundary Conditions (uniform)

$$-\left[\lambda(T,\theta)\frac{\partial T}{\partial x}-h_{LV}(T)\,j_v\right]_{x=0}=h(T_\infty-T_{x=0})+h_{LV}(T)h_m\left(\rho_{v,\infty}(T,\theta)-\rho_{v,x=0}(T,\theta)\right)+\alpha q_r+\sum_{i=1}^{m}f\varepsilon\sigma\left(T_{Sur}^4-T_{x=L}^4\right)$$

$$-\left[\frac{\partial}{\partial x}\left[\left(D_{\theta L}(T,\theta)+D_{\theta V}(T,\theta)\right)\frac{\partial\theta}{\partial x}+\left(D_{TL}(T,\theta)+D_{TV}(T,\theta)\right)\frac{\partial T}{\partial x}\right]\right]_{x=0}=\frac{h_m}{\rho_l}\left(\rho_{v,\infty}(T,\theta)-\rho_{v,x=0}(T,\theta)\right)$$

Air transport

$$r_a\rho_a c_{p,a}T_{ext}$$

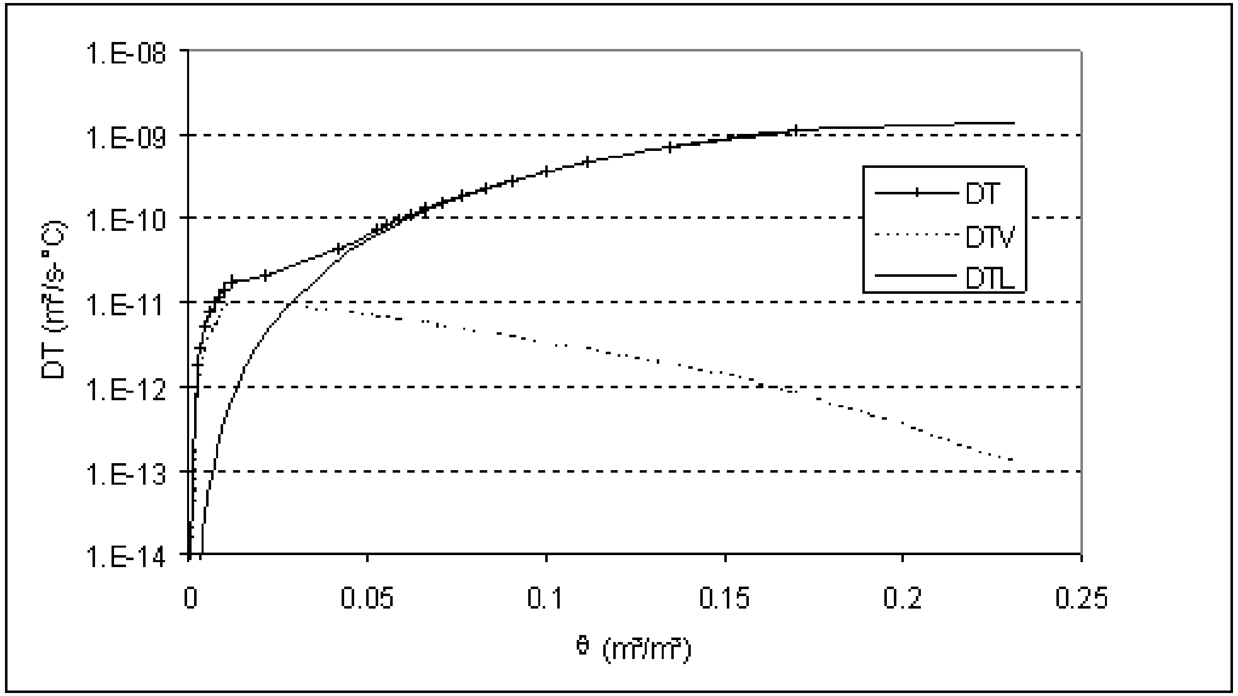
Rain

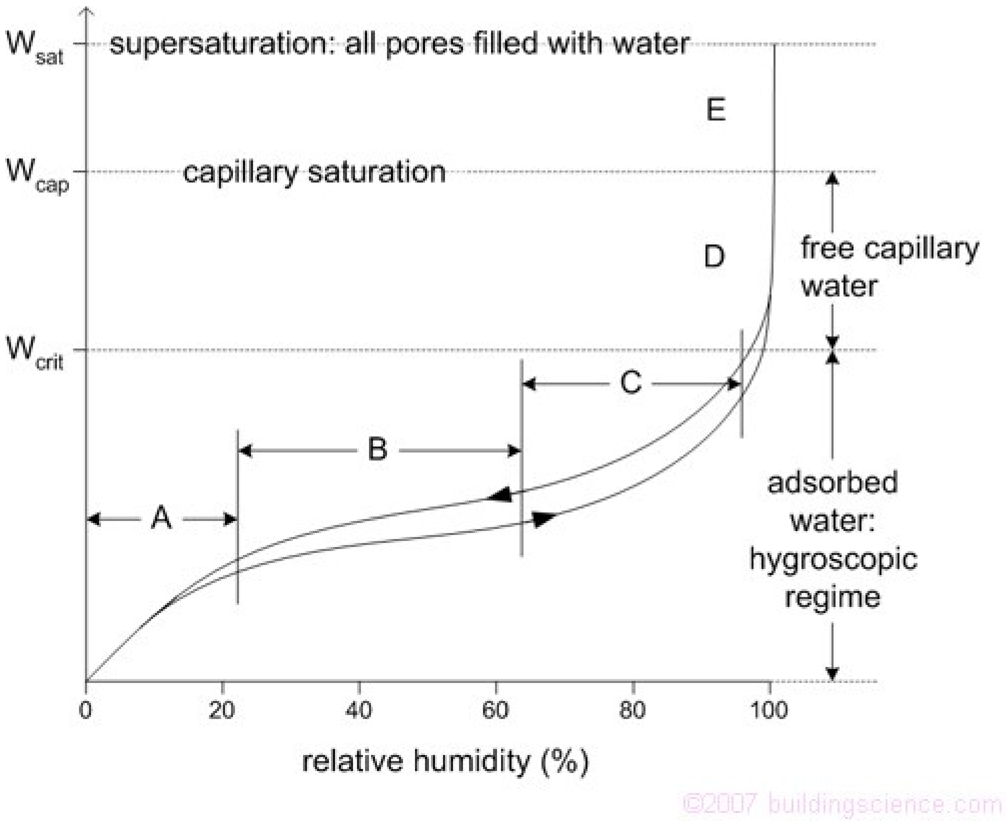
$$g_{liq}c_{p,l}T_{ext} \qquad j_{liq}=-K\left(\frac{\partial P_{suc}}{\partial x}\right)_{x=0}$$

$$j=\beta_v\left(p_{v,\infty}-p_{v,\sup}\right) \qquad P_{g,\infty}=P_{g,\sup}$$

$$h_{int}=\left[\left[a\left(\frac{\Delta T}{d}\right)^p\right]^m+\left[b(\Delta T)^q\right]^m\right]^{\frac{1}{m}} \qquad h_m=\frac{h}{\rho_{air}c_{air}Le^{2/3}}$$

Hygrothermal Properties





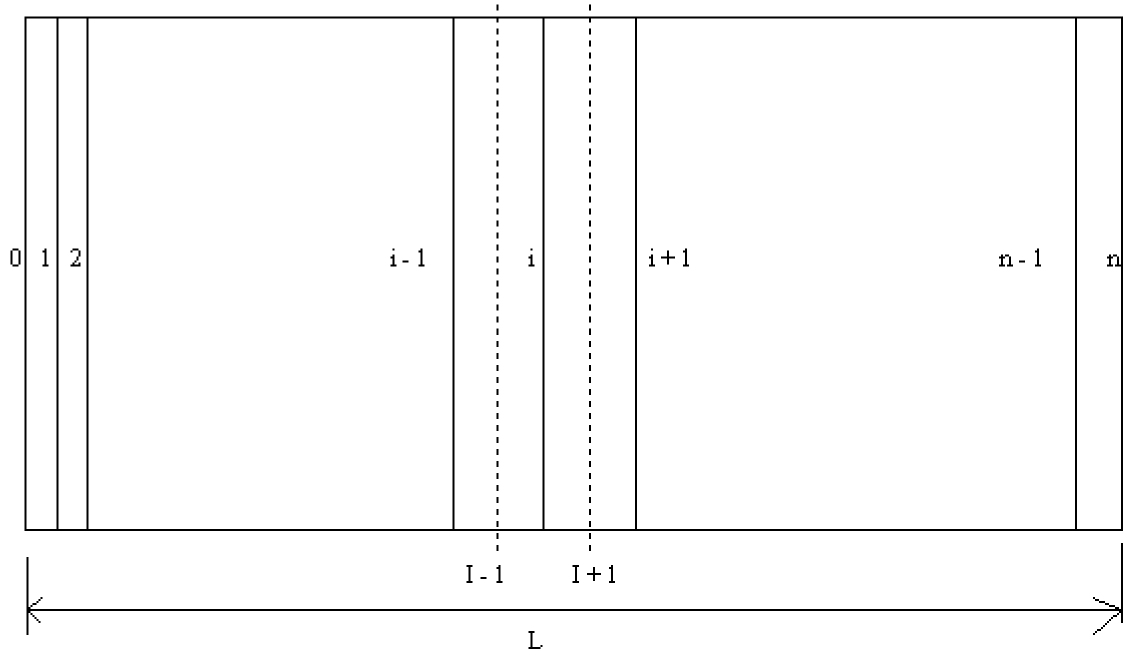
A: Single-layer of adsorbed molecules
B: Multiple layers of adsorbed molecules
C: Interconnected layers (internal capillary condensation
D: Free water in Pores, capillary suction
E: Supersaturated Regime

Discretization

$$\frac{\delta x_e}{D_e} = \frac{\delta x^-{}_e}{D_P} + \frac{\delta x^+{}_e}{D_E}$$

$$D_e = \frac{2}{\frac{1}{D_P} + \frac{1}{D_E}}$$

$$D_w = \frac{2}{\frac{1}{D_P} + \frac{1}{D_W}}$$



Indexation of control volume elements in the calculation domain

Schematic grid for the domain discretization

Discretization

Algebraic equations for the internal points of the physical 1-D domain

$$\left(\frac{\Delta x}{\Delta t}+\frac{D_{\theta e}}{\delta x_e}+\frac{D_{\theta w}}{\delta x_w}\right).\theta_p=\frac{D_{\theta e}}{\delta x_e}\theta_E+\frac{D_{\theta w}}{\delta x_w}\theta_W+\frac{\Delta x}{\Delta t}\theta_p^0+\frac{D_{Te}}{\delta x_e}T_E^0+\frac{D_{Tw}}{\delta x_w}T_W^0-\left(\frac{D_{Tw}}{\delta x_w}+\frac{D_{Te}}{\delta x_e}\right)T_P^0$$

$$\left(\rho_0.c_m.\frac{\Delta x}{\Delta t}+\frac{\lambda_e}{\delta x_e}+\frac{LD_{TVe}}{\delta x_e}+\frac{\lambda_w}{\delta x_w}+\frac{LD_{TVw}}{\delta x_w}\right)T_P=\left(\frac{\lambda_e}{\delta x_e}+\frac{LD_{TVe}}{\delta x_e}\right)T_E+\left(\frac{\lambda_w}{\delta x_w}+\frac{LD_{TVw}}{\delta x_w}\right)T_W+\rho_0 c_m\frac{\Delta x}{\Delta t}T_P^0+$$

$$L\rho_l\left(\frac{D_{\theta Ve}\left(\theta_E^0-\theta_P^0\right)}{\delta x_e}-\frac{D_{\theta Vw}\left(\theta_P^0-\theta_W^0\right)}{\delta x_w}\right).$$

Discretization

For the boundary conditions, with a half control volume, the following expressions are obtained at the external surface (x=0)

$$\left(\frac{\Delta x}{2\Delta t}+\frac{D_{\theta e}}{\delta x_e}\right)\theta(0)=\frac{D_{\theta e}}{\delta x_e}\theta(1)+\frac{\Delta x}{2\Delta t}\theta^0(0)+D_{Te}\left[\frac{T^0(1)-T^0(0)}{\delta x_e}\right]+\frac{h_{m,ext}}{\rho_l}\left(\rho_{v,ext}-\rho(0)\right)$$

$$\left[\rho_0 c_m\frac{\Delta x}{2\Delta t}+\frac{\lambda_e}{\delta x_e}+L\rho_l\frac{D_{TV\,e}}{\delta x_e}+h_{ext}\right]T(0)=\left[\frac{\lambda_e}{\delta x_e}+L\rho_l\frac{D_{TV\,e}}{\delta x_e}\right]T(1)+\rho_0 c_m\frac{\Delta x}{2\Delta t}T^0(0)+$$

$$L\rho_l D_{\theta V\,e}\left[\frac{\theta^0(1)-\theta^0(0)}{\delta x_e}\right]+h_{ext}T_{ext}+\alpha q_r-\varepsilon R_{ol}+Lh_{m,ext}(\rho_{v,ext}-\rho_v(0)).$$

TDMA (Tridiagonal Matrix Algorithm)

$$A_P\Phi_P = A_E\Phi_E + A_W\Phi_W + D$$

$$A_P = A_E + A_W + A_P^0 \qquad D = A_P^0\Phi_P^0 + F$$

Φ - dependent variable (T or θ).

Stability Conditions

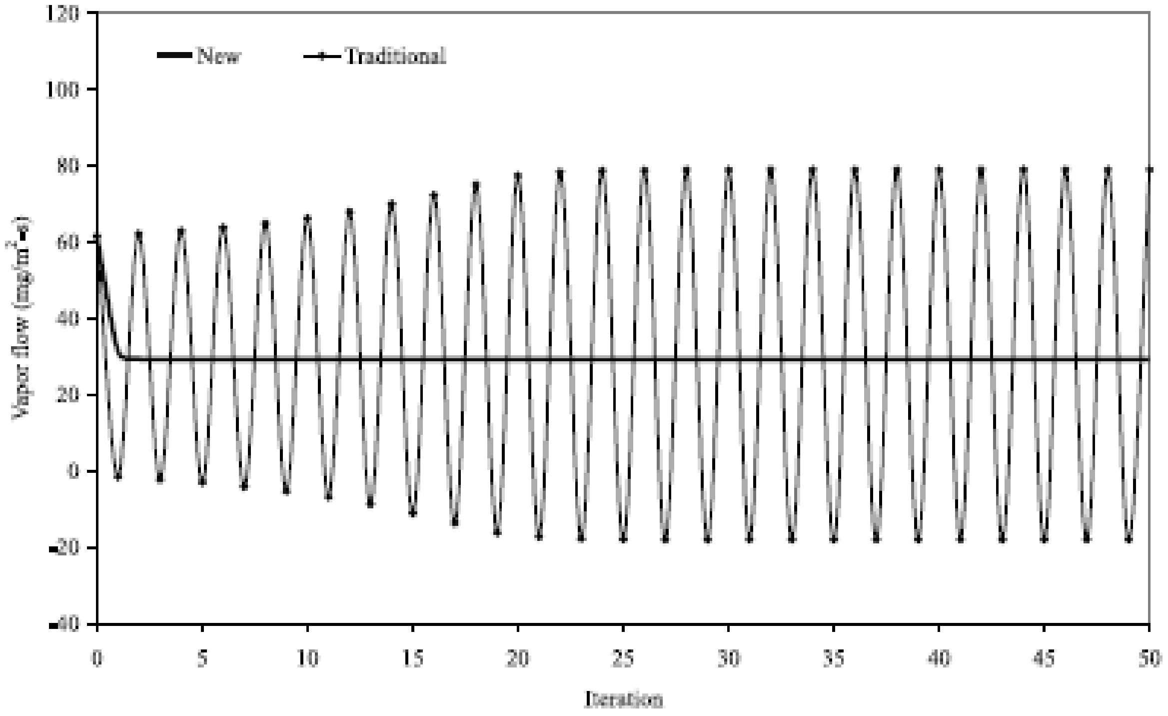


Fig. 5. Vapor flow at the surfaces of a 100-mm lime mortar wall for 1-h time step.

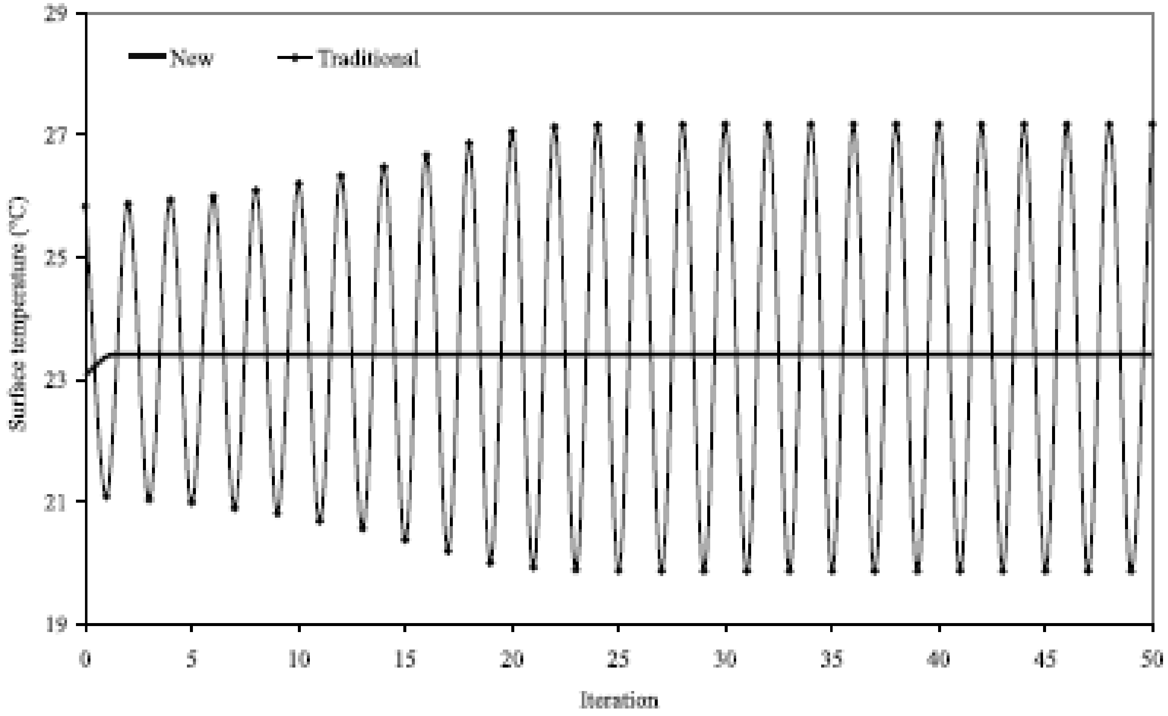


Fig. 7. Temperature at the surfaces of a 100-mm lime mortar wall for 1-h time step.

A new mathematical method to solve highly coupled equations of heat and mass transfer in porous media

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Linearization of the Source Term

$$\left(\rho_{v,ext} - \rho_{vo}\right) = M_{1,ext}\left(T_{ext} - T_0\right) + M_{2,ext}\left(\theta_{ext} - \theta_0\right) + M_{3,ext}$$

where:

$$M_{1,ext} = A_{ext}\frac{M}{R}h_{ext}$$

$$M_{2,ext} = \frac{M}{R}\left(\frac{P_s\left(T_0\right)}{T_0}\right)^0 \left(\frac{\partial h}{\partial \theta}\right)_0^0$$

$$M_{3,ext} = \frac{M}{R}\left[\left(\frac{P_s\left(T_0\right)}{T_0}\right)^0 R(\theta_0^0) + h_{ext}(R(T_{ext}) - R(T_0^0))\right]$$

Linearization of Boundary Conditions

$$\left[\rho_0 c_m \frac{\Delta x}{2\Delta t} + \frac{\lambda_e}{\delta x_e} + h_{LV}(T)\rho_l \frac{D_{TVe}}{\delta x_e} + h + h_{LV}(T) h_m C_1\right] T(S) = \left[\frac{\lambda_e}{\delta x_e} + h_{LV}\rho_l \frac{D_{TVe}}{\delta x_e}\right] T(n(S)) +$$

$$h_{LV}(T)\rho_l \frac{D_{\theta Ve}}{\delta x_e}\left(\theta^{prev}(n(S)) - \theta^{prev}(S)\right) + hT_\infty + h_{LV}(T) h_m \left(C_1 T_\infty + C_2\left(\theta_\infty - \theta^{prev}(S)\right) + C_3\right)$$

$$+ \rho_0 c_m \frac{\Delta x}{2\Delta t} T^0(S)$$

MTDMA for Solving the Strongly-Coupled Equations

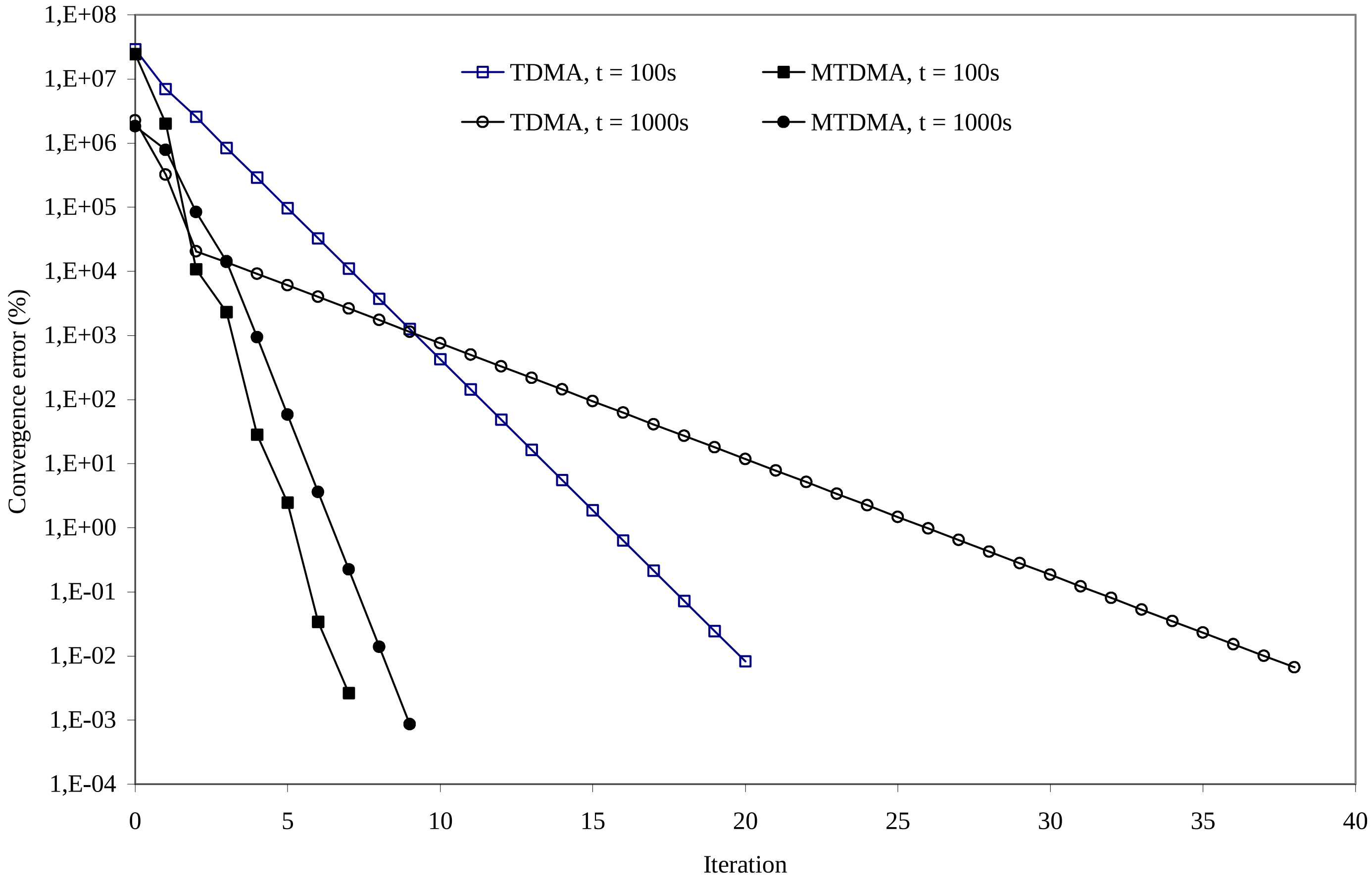
$$\underset{\approx}{A_i} \cdot \underset{\sim}{X_i} = \underset{\approx}{B_i} \cdot \underset{\sim}{X_{i+1}} + \underset{\approx}{C_i} \cdot \underset{\sim}{X_{i-1}} + \underset{\sim}{D_i}$$

$$\underset{\sim}{X_i} = \begin{bmatrix} \theta \\ T \end{bmatrix}$$

$$\underset{\approx}{P_i} = \left[\left[\underset{\approx}{A_i} - \underset{\approx}{C_i} \cdot \underset{\approx}{P_{i-1}} \right]^{-1} \cdot \underset{\approx}{B_i} \right]$$

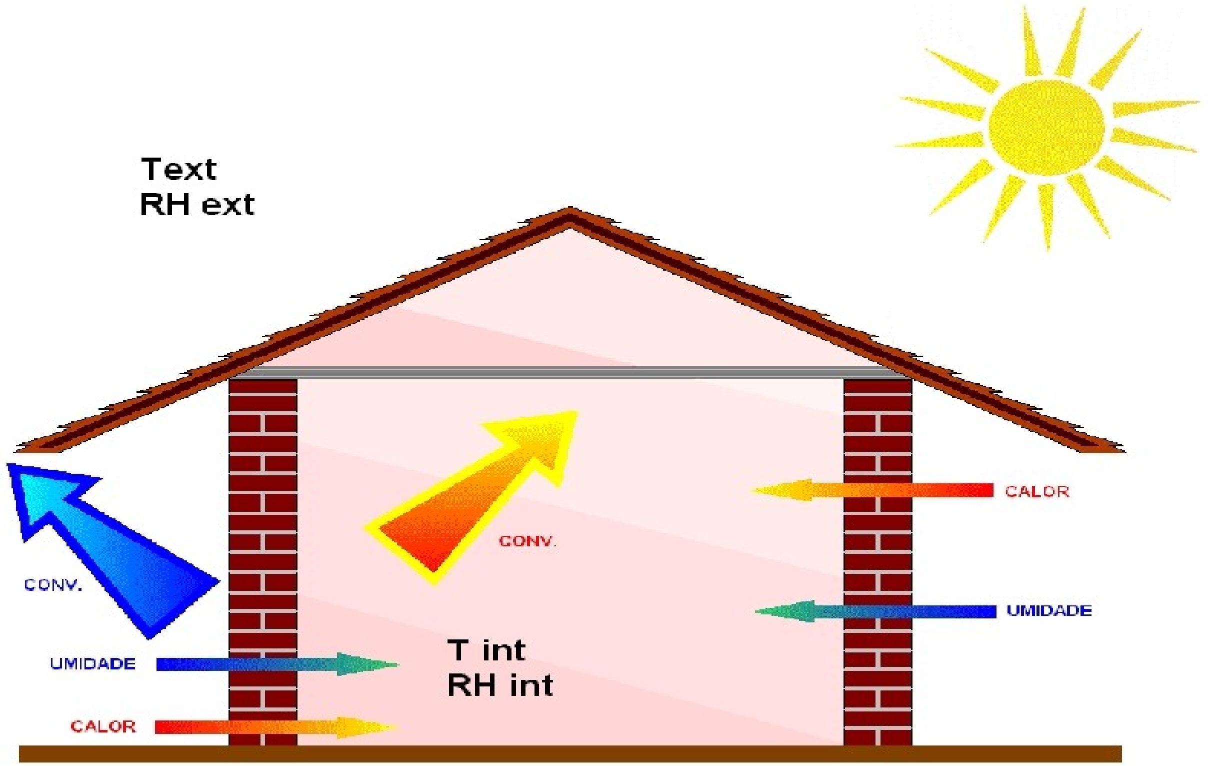
$$\underset{\sim}{Q_i} = \left[\underset{\approx}{A_i} - \underset{\approx}{C_i} \cdot \underset{\approx}{P_{i-1}} \right]^{-1} \cdot \left[\underset{\approx}{C_i}\, \underset{\sim}{Q_{i-1}} + \underset{\sim}{D_i} \right]$$

Comparison between TDMA and MTDMA

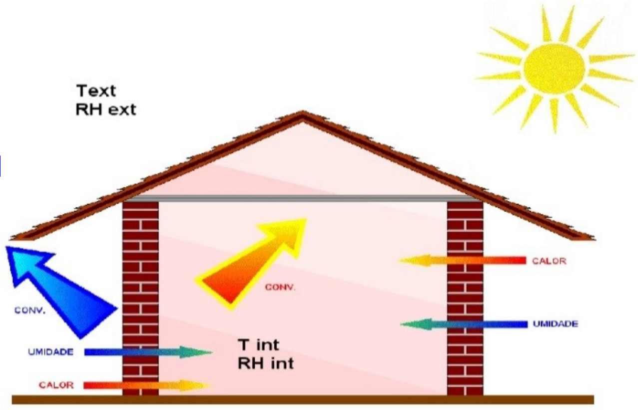


Comparison of convergence errors for a 20-node grid

Room air balance



Domus room air balance



- **Energy Balance**

$$\dot{E}_t + \dot{E}_g = \rho_{air} c_{air} V_{air} \frac{dT_{\mathrm{int}}}{dt}$$

- **Water Vapor Mass Balance**

$$(\dot{m}_{\mathrm{inf}} + \dot{m}_{vent})(W_{ext} - W_{\mathrm{int}}) + J_b + J_{ger} +$$

$$J_{porous\ surface} + J_{HVAC} = \rho_{air} V_{air} \frac{dW_{\mathrm{int}}}{dt}$$

$\dot{E}_t$ energy flow that crosses the room (W)

$\dot{E}_g$ internal energy generation rate (W)

ρ_{air} air density (kg/m^3)

c_{air} specific heat of air (J/kg-K)

V_{air} room volume (m^3)

T_{int} room air temperature (^{o}C)

Building Envelope HAM Models (1985 - 2008)

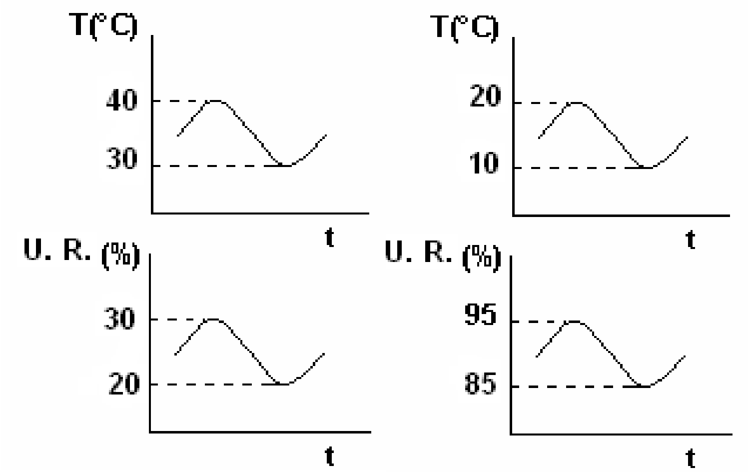
- The main difference are particular assumptions and the choice of driving potentials.
- Some of HAM (Heat, Air and Moisture) diffusive transfer tools have been developed in the last 25 years and some of them are commented in detail in IEA Annex 24 (1996) such as 1D-HAM, WUFIZ, MATCH, HYGRAN24, JOKE and LATENITE.
- During the IEA Annex 41 project (2004-2007), some HAM models were presented and compared (DELPHIN, BSim, Wufi+ and Domus among others).
- Woloszin and Rode (2008) presented in details those tools tested during the IEA Annex 41, which were mainly developed from 1-D building element to the whole-building.

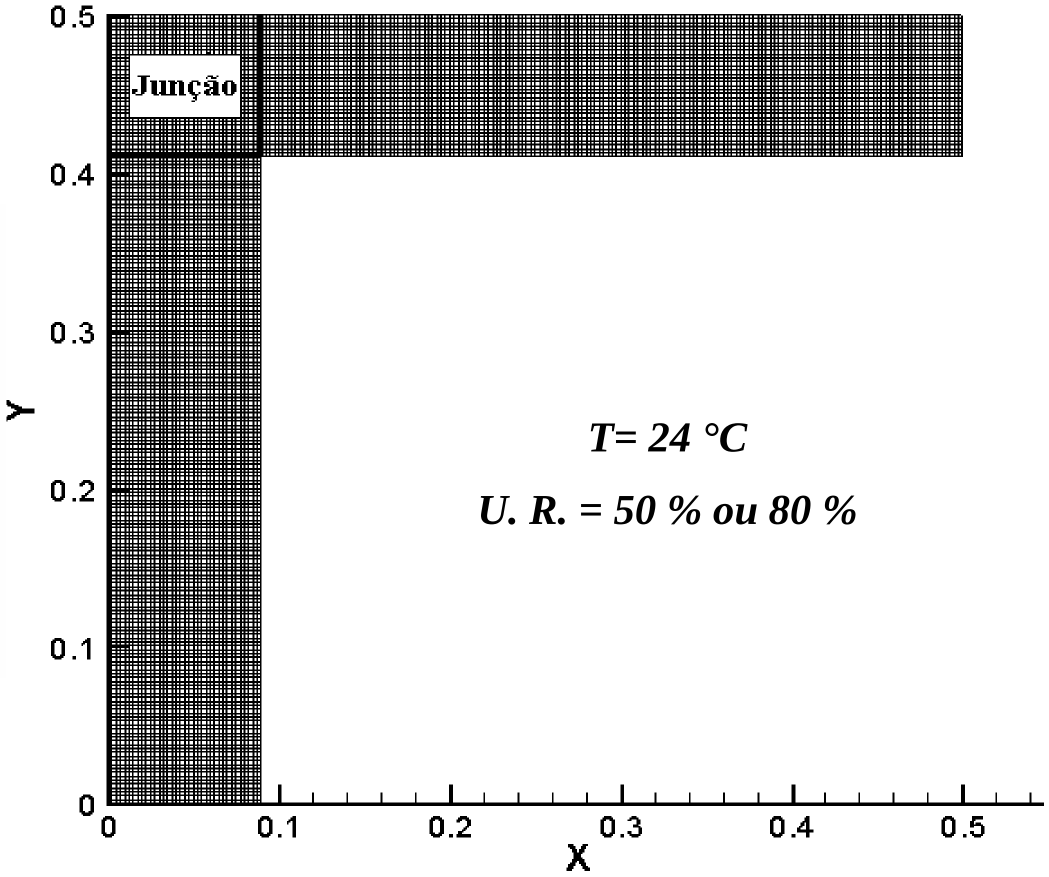
1D HAM Transfer in buildings?

Analysis of Mold Growth

Visualization of Mold Growth at upper corners

Hygrothermal Analysis of upper corners



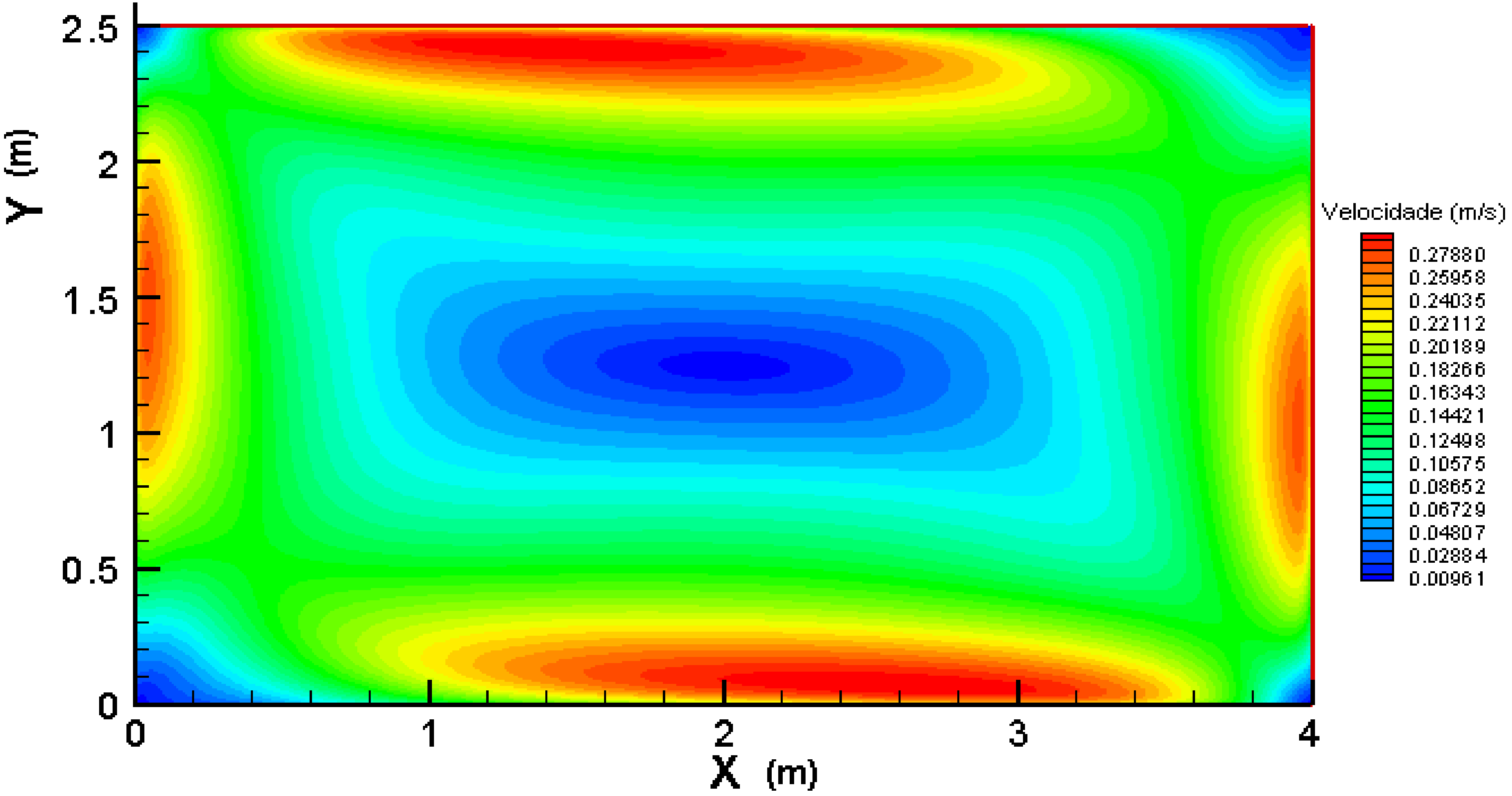


2.5-mm² regular grid

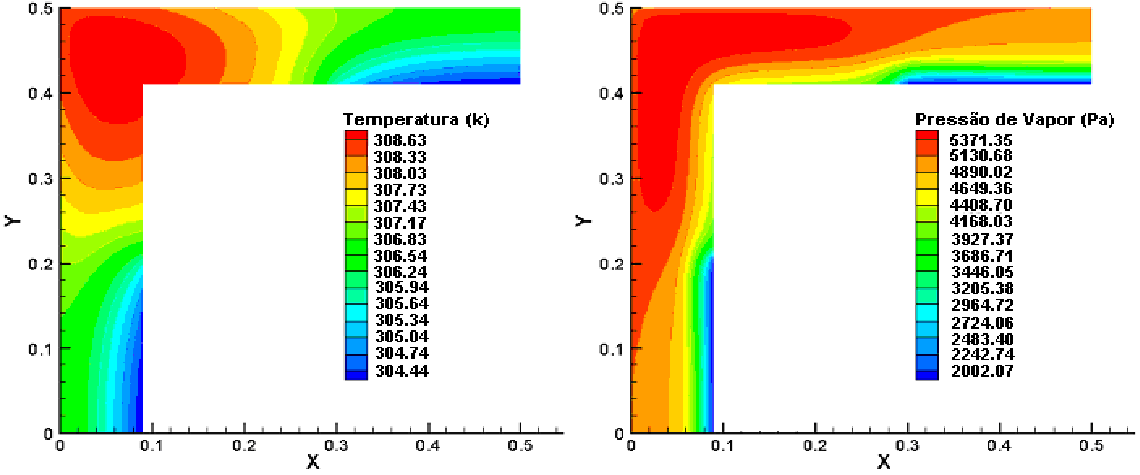
Δt = 120 s

Corner grid and size (m)

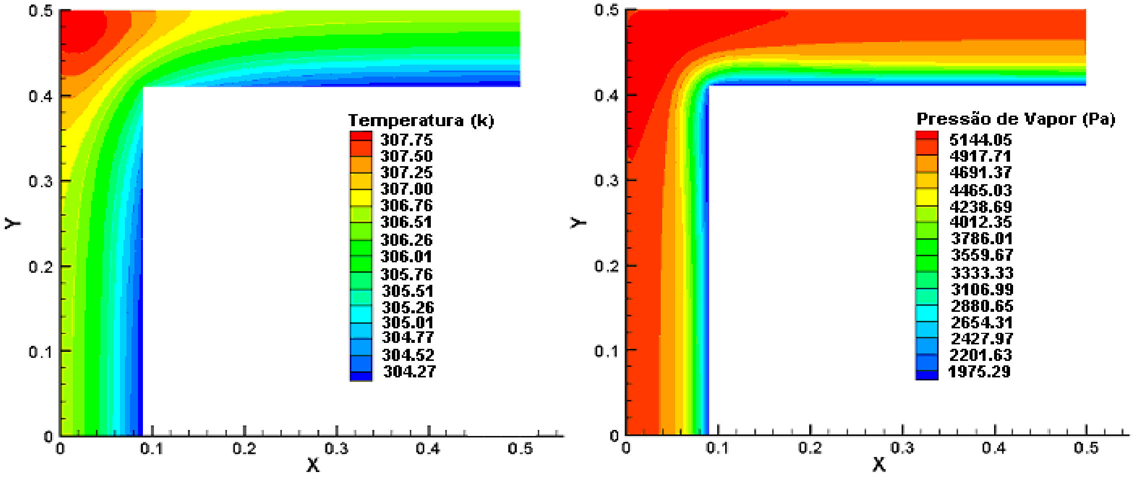
Hygrothermal Analysis of upper corners



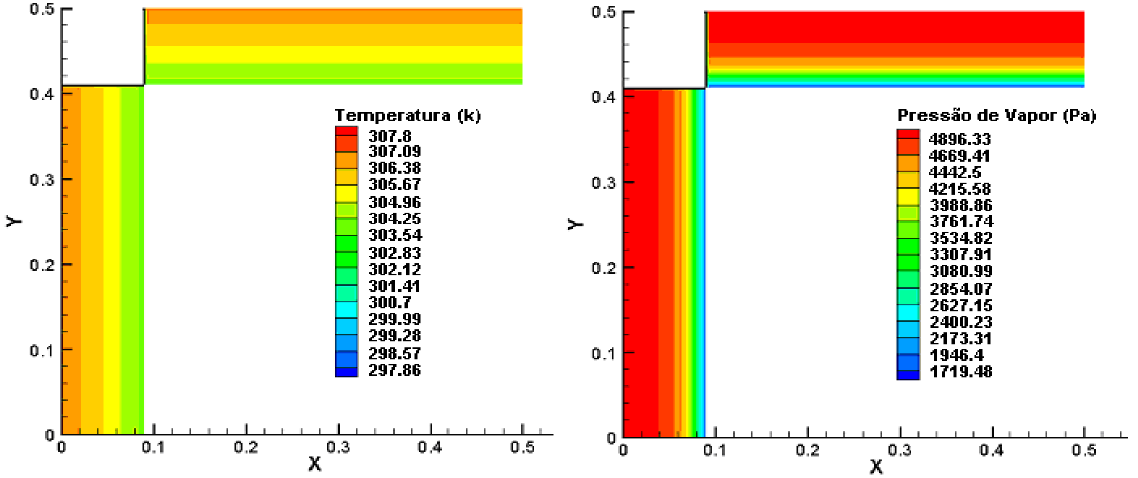
Upper Corner:



- *2-D and Non-uniform CHTC*



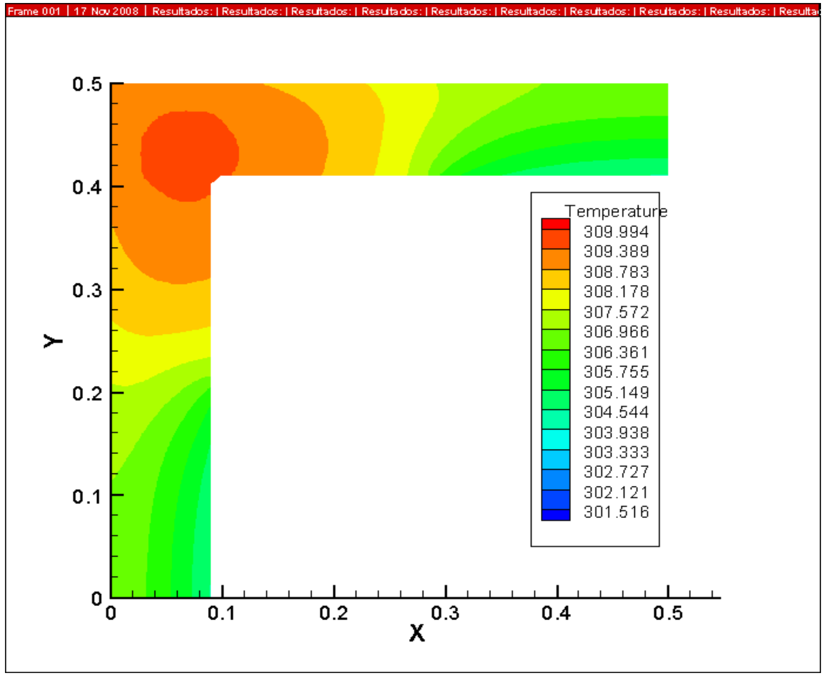
- *2-D and uniform CHTC*

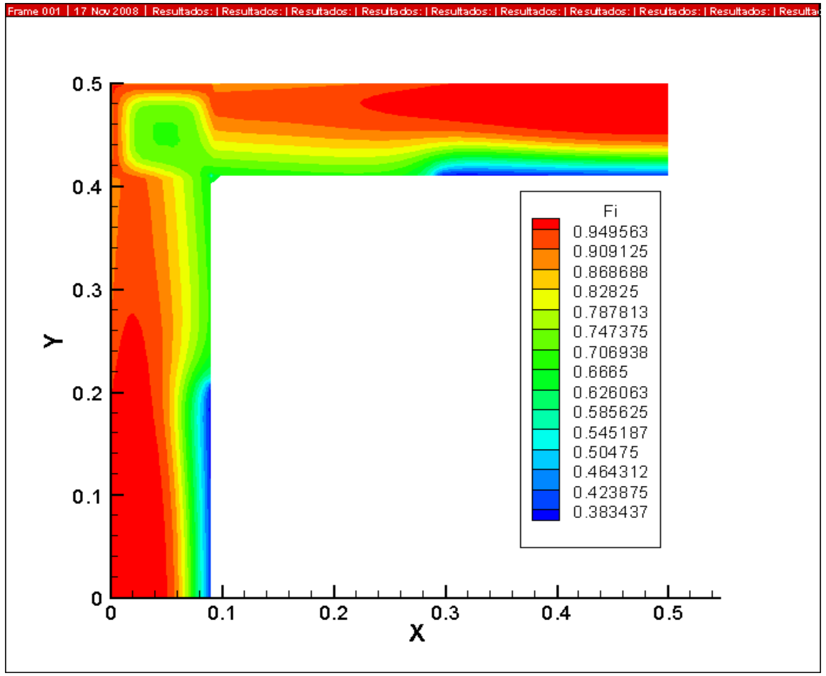


- *1-D and uniform CHTC*

Hot and humid weather

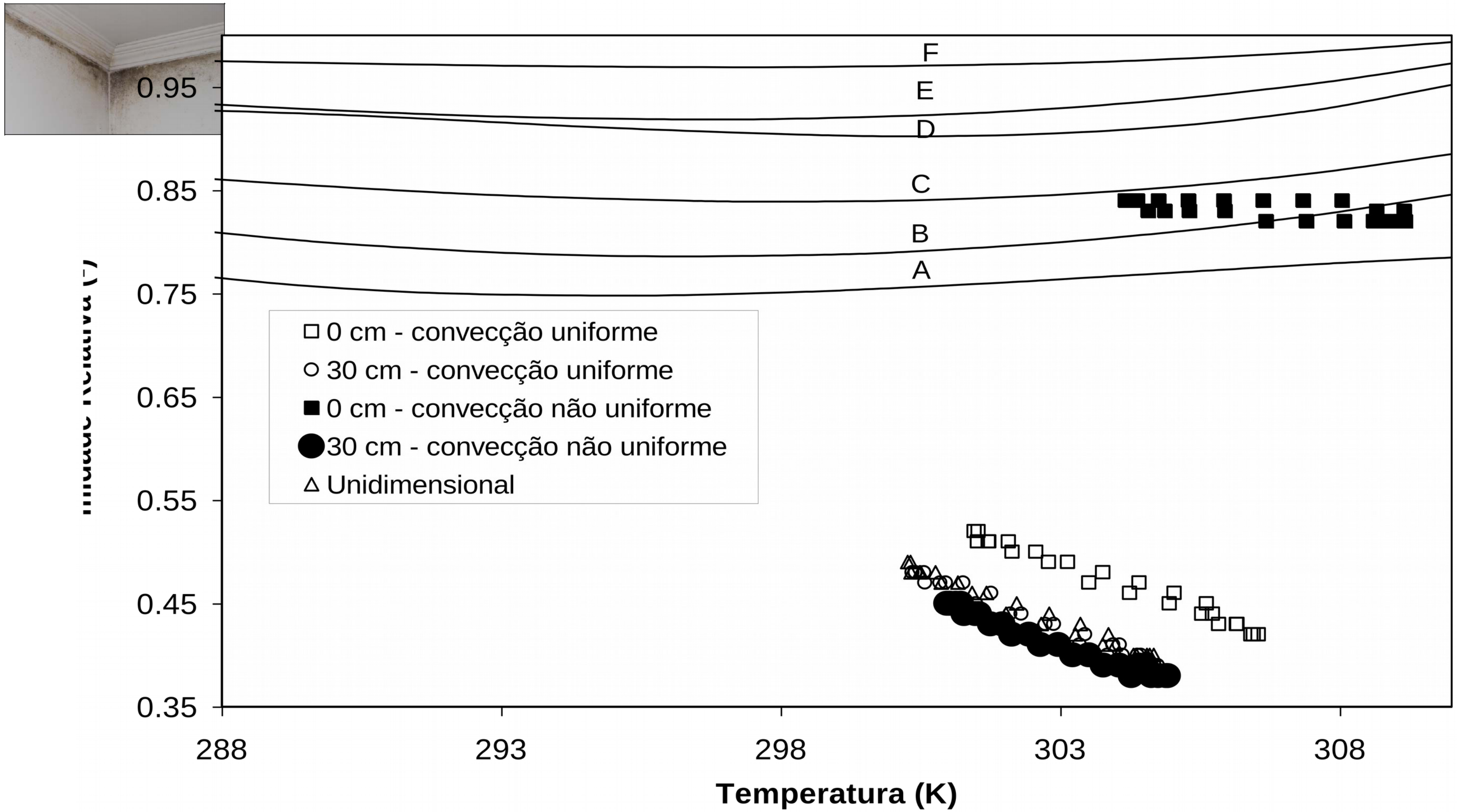
Hygrothermal Analysis of upper corners



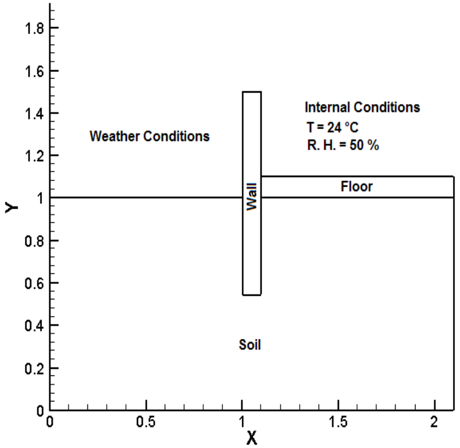


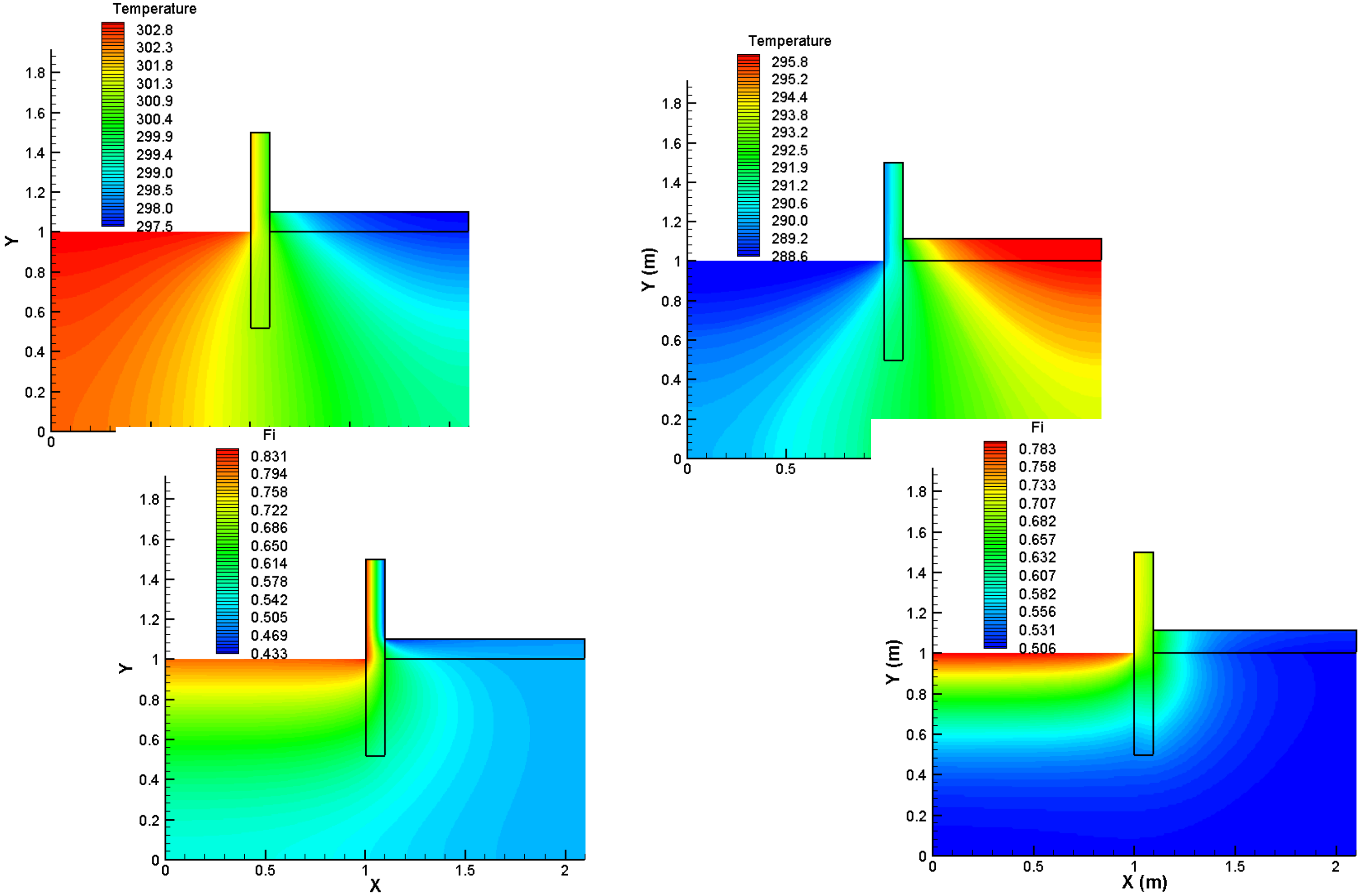
2-D and non-uniform CHTC - Concret Junction

Analysis of Mold Growth



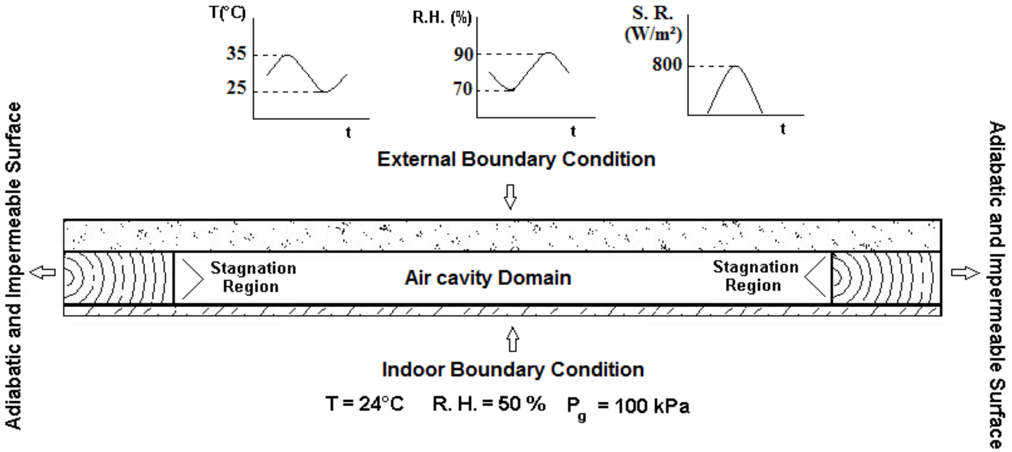
Lower Corners: Analysis of temperature and moisture

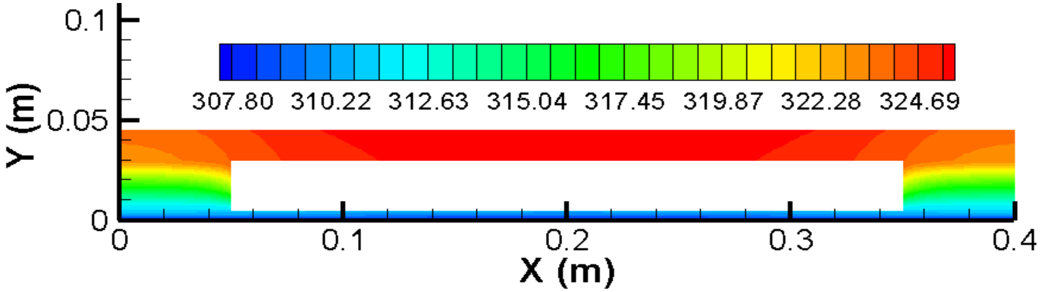


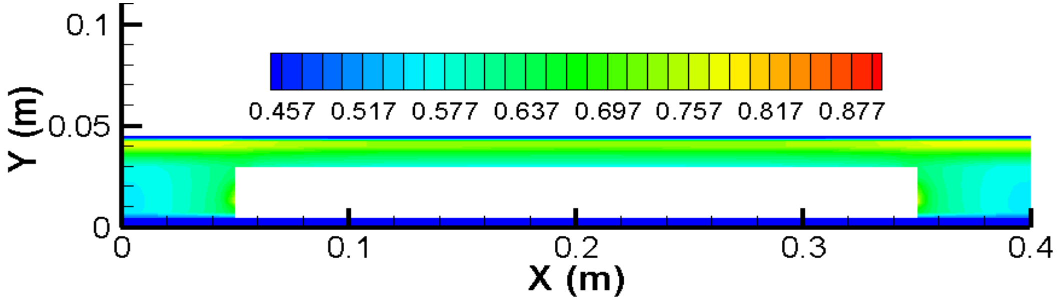


Temperature (K) and relative humidity profiles within the domain (summer and winter conditions).

HYGROTHERMAL PERFORMANCE OF REFLECTIVE INSULATED ROOF COATINGS







- 1D HAM transfer might not be enough.

- How might the HAM transfer simulations be in the short-term future?

- How can we make it better?

Evolution and Some Perspectives

3D HAM-CFD

Advanced Radiative Boundary Conditions

Co-Simulation, Intelligent Co-Simulation

District scale

Advanced Numerical Methods

Hardware-in-the-loop Simulation

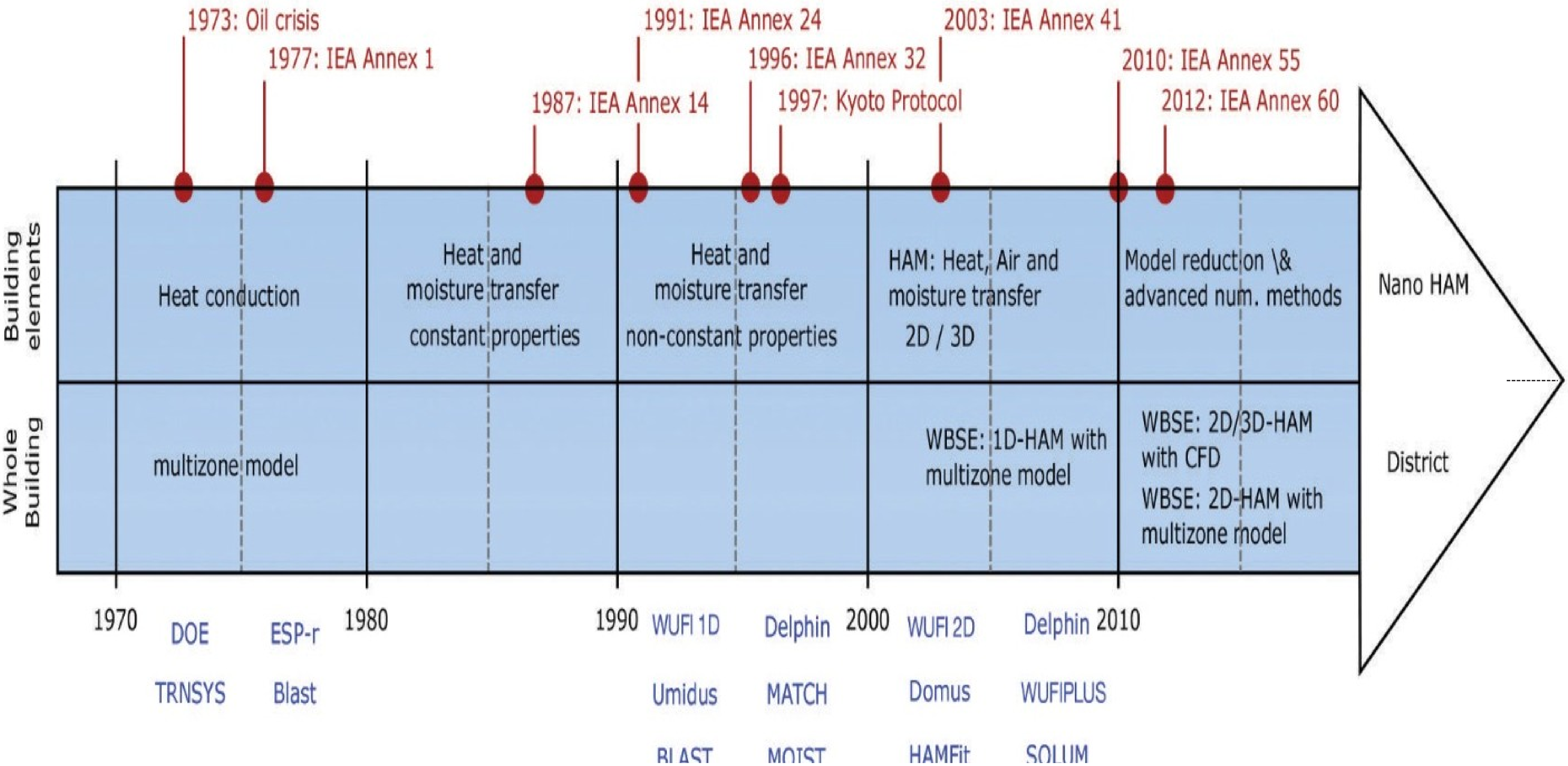
Pore scale

Nathan Mendes
PUCPR/PPGEM

Complex simulation demo

DOMUS-CFX Film

Energy and Moisture Modeling - Time line



Final remarks

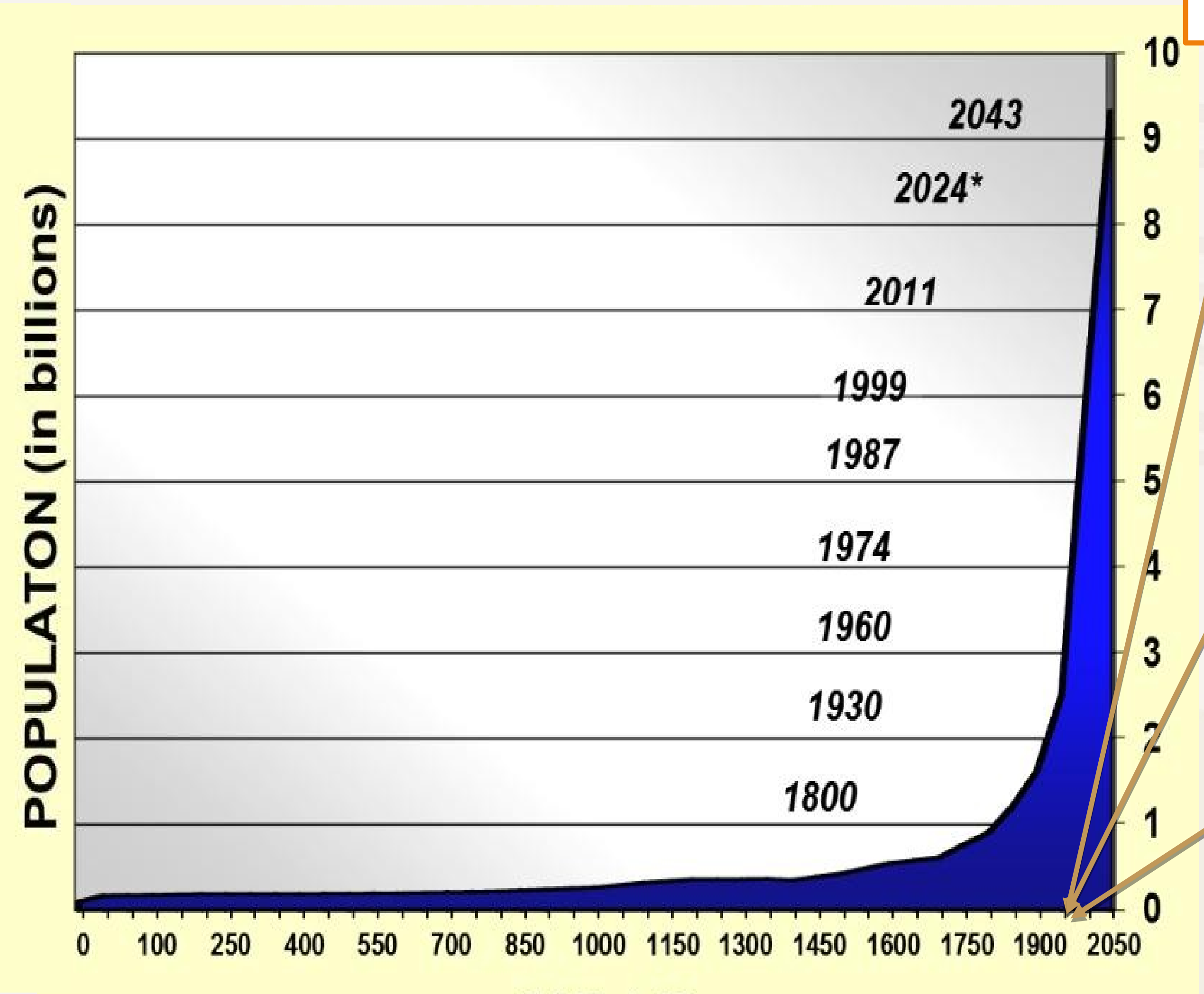
- Contributions to the state-of-the-art?
- Diffusion
- Moisture
- Convection
- Radiation
- Airflow

Final remarks

- Possibility to decrease the gap between reality and simulation;

- Intelligent co-simulation to provide a solution to the drawback associated to the high computational cost;

Population growth and highlights



1970's
Energy crises

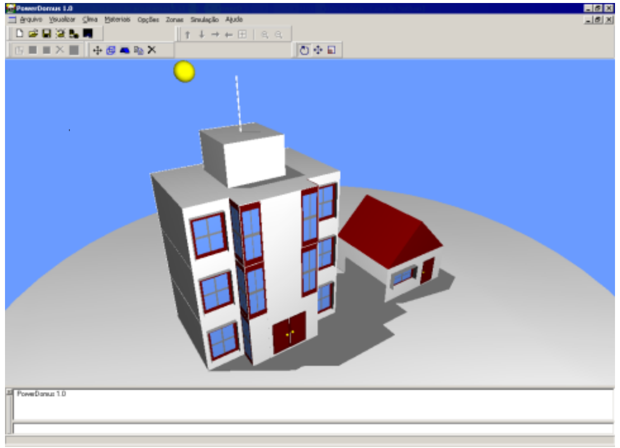
20th -21st

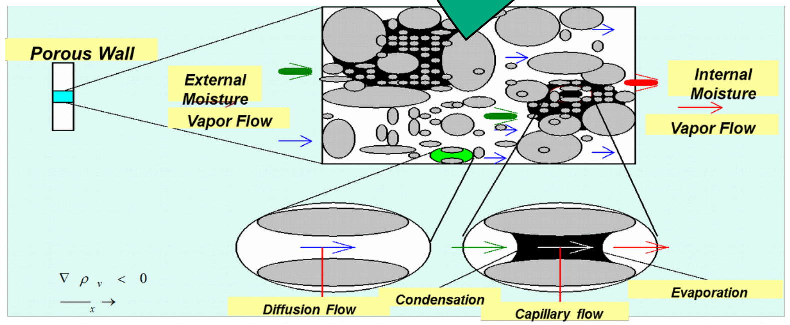
1990's
Internet Impact

2010's
Cloud computing
IoT
Cyber Physical Systems

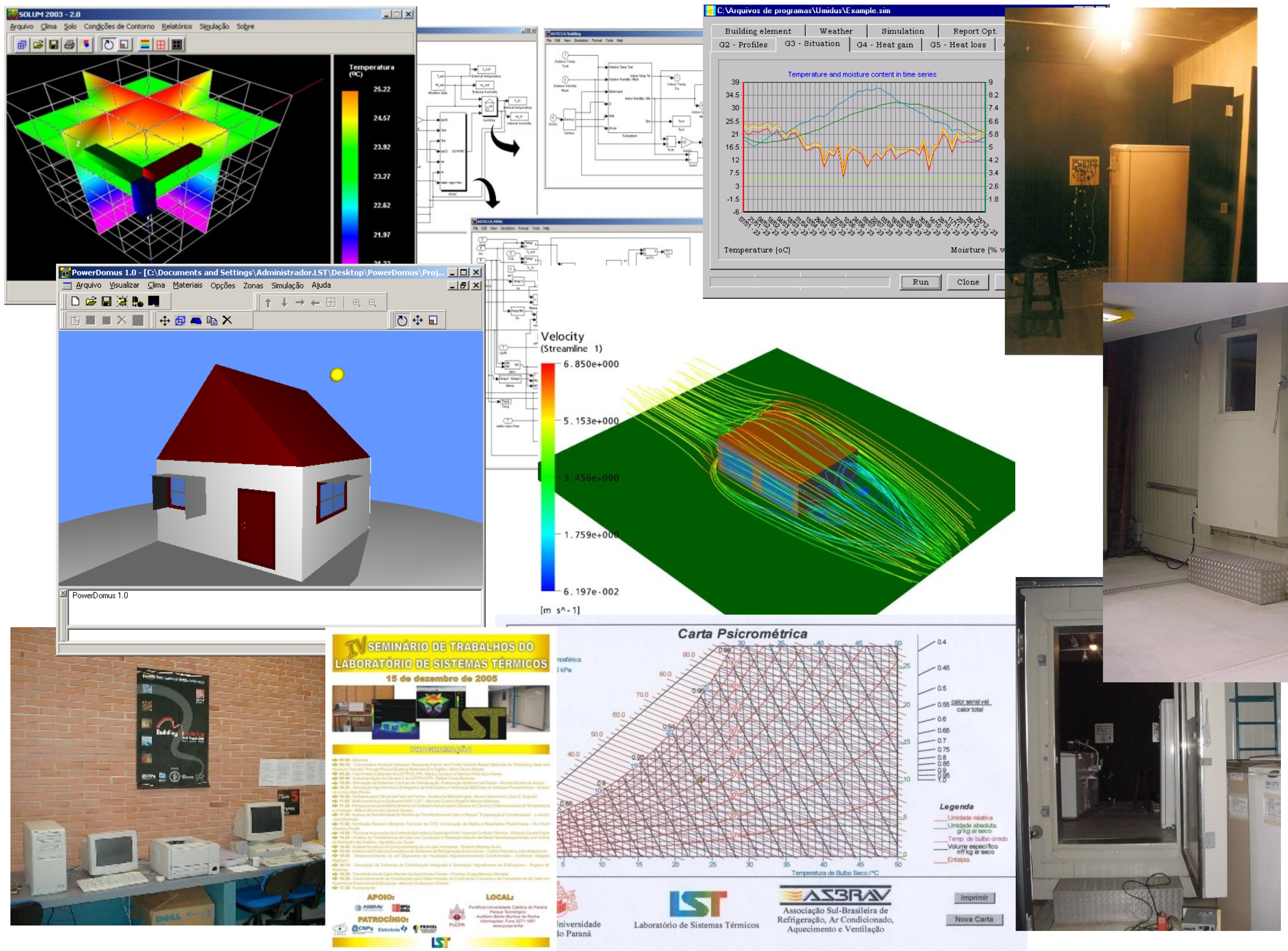
http://mycicm.civdigital.net/content/population-information

Multi-scale HAM transfer analysis





Thermal Systems Laboratory - PUCPR



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Merci !!!

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