Hygrothermal Modeling: a Numerical and Experimental Study on Drying

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COMSOL CONFERENCE
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Is Comsol really adequate for hygrothermal simulation in porous building materials?

Advantages

Limitations

Contents

Model

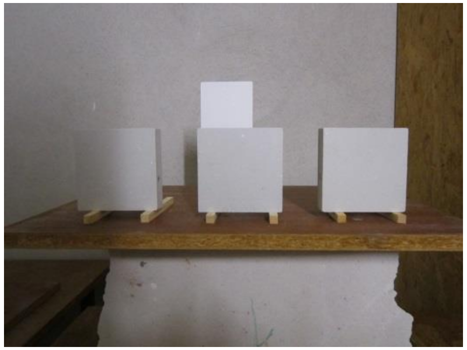
- Drying test
- Mathematical model

Results

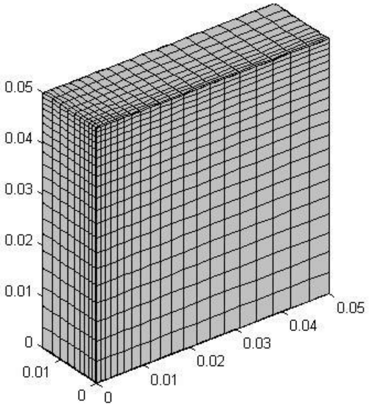
- Comparison with experimental data
- Numerical quality (mass conservation)

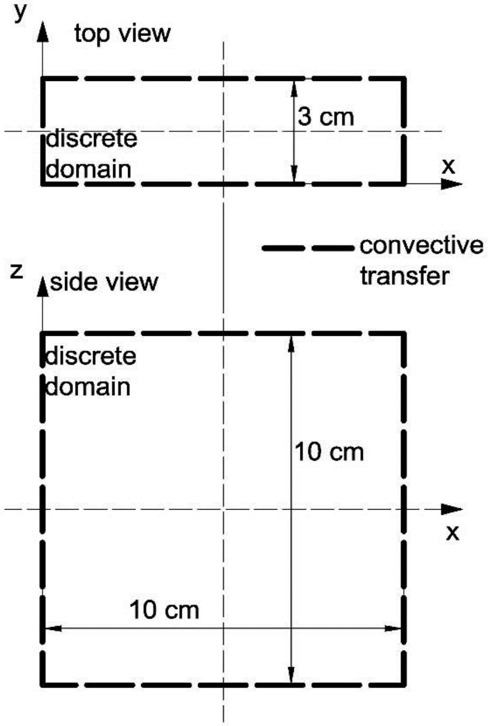
Drying test

Specimens (calcium silicate)



Mesh

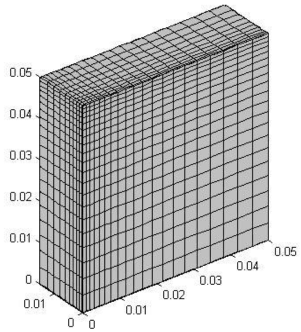




Boundary conditions

case	θ∞ [°C]	φ∞ [-]	α [W/m2K]	β [s/m]
bc1	23.5	0.52	9.32	$2.86 \cdot 10^{-8}$
bc2	25.0	0.40	11.84	$4.51 \cdot 10^{-8}$
bc3	30.0	0.35	12.60	$8.31 \cdot 10^{-8}$

Mathematical model



Driving equations (coefficient form PDE)

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial t} + \frac{\partial H}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla \cdot (K_{11}\nabla T + K_{12}\nabla \varphi) \quad \textbf{energy}$$

$$\frac{\partial u}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla \cdot (K_{21}\nabla T + K_{22}\nabla \varphi) \quad \textbf{moisture}$$

u…water content

Dependent variables:
φ…relative humidity
T…temperature

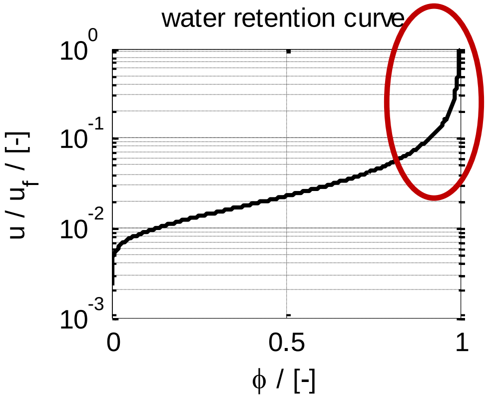
Transport coefficients

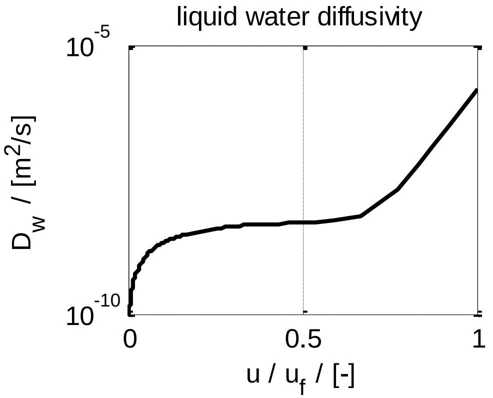
$$K_{11} = -\lambda - \left(h_{lv} + c_{p,v}\theta\right)\frac{\varphi D_v}{\mu R_v T}\frac{dp_s}{dT}$$

$$K_{12} = -\left(h_{lv} + c_{p,v}\theta\right)\frac{p_s D_v}{\mu R_v T} - c_w \theta D_w \frac{\partial u}{\partial \varphi}$$

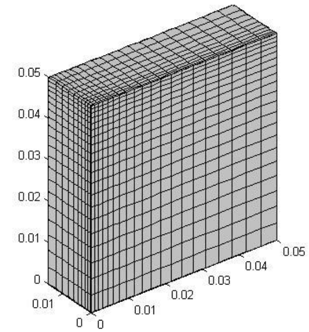
$$K_{21} = -\frac{\varphi D_v}{\mu R_v T}\frac{dp_s}{dT}$$

$$K_{22} = -\frac{p_s D_v}{\mu R_v T} - D_w \frac{\partial u}{\partial \varphi}$$





Mathematical model



Driving equations (coefficient form PDE)

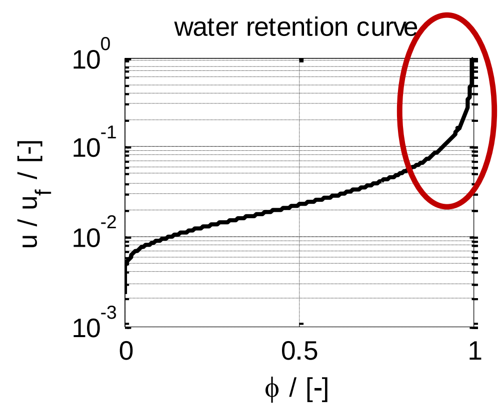
$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial t} + \frac{\partial H}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla \cdot (K_{11}\nabla T + K_{12}\nabla \varphi)$$ **energy**

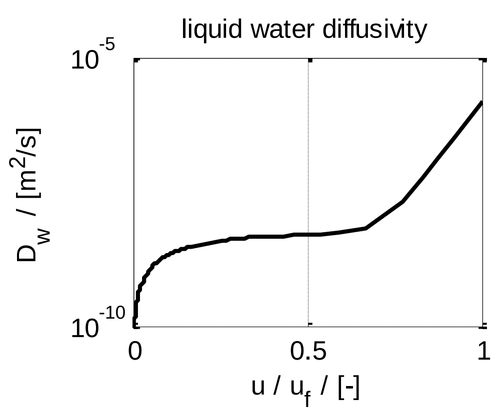
$$\frac{\partial u}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla \cdot (K_{21}\nabla T + K_{22}\nabla \varphi)$$ **moisture**

u…Water content

Dependent variables:
φ…Relative humidity
T…temperature

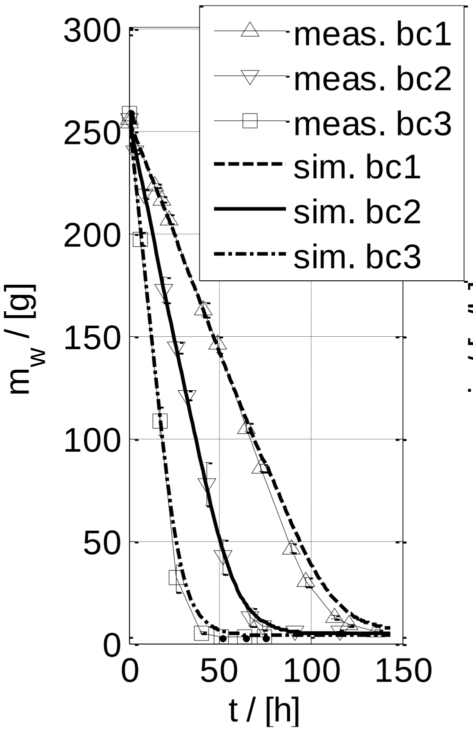
Damping coefficient



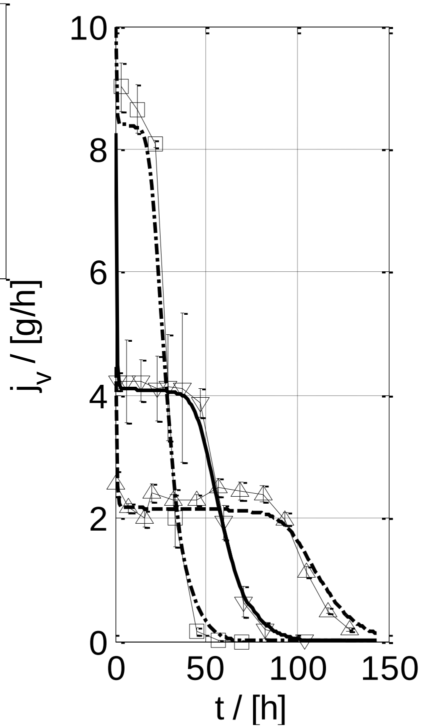


Gravimetric analysis

Water content



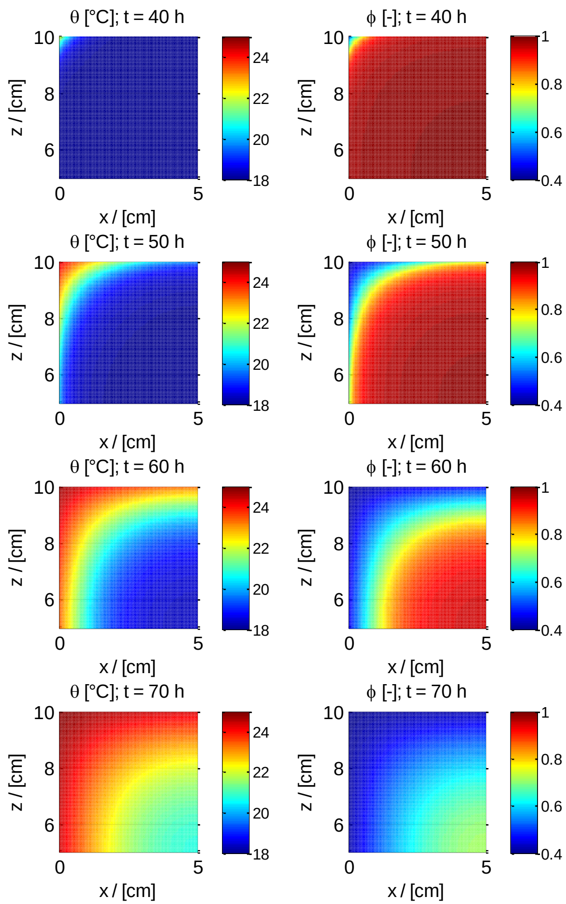
Drying rate



Weighing at different times

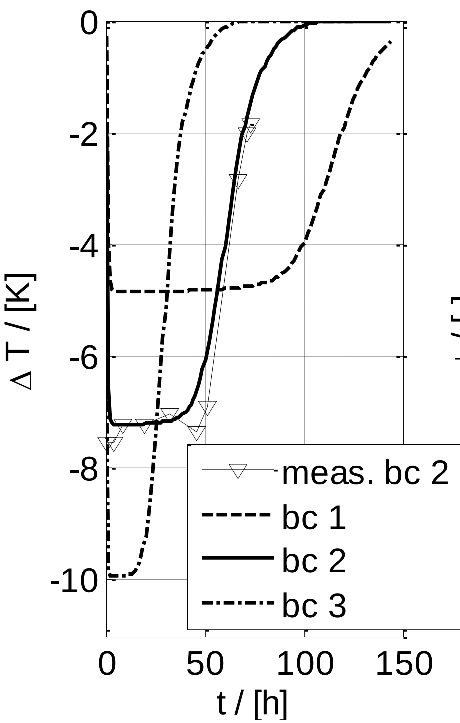
Surface distributions

temperature | Rel. humidity

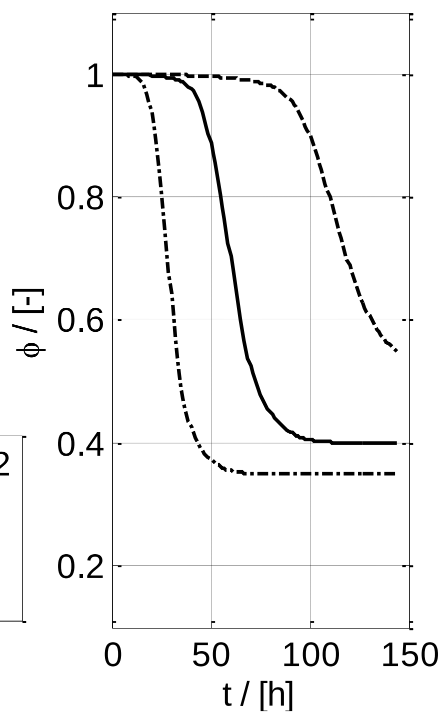


Mean surface temperature

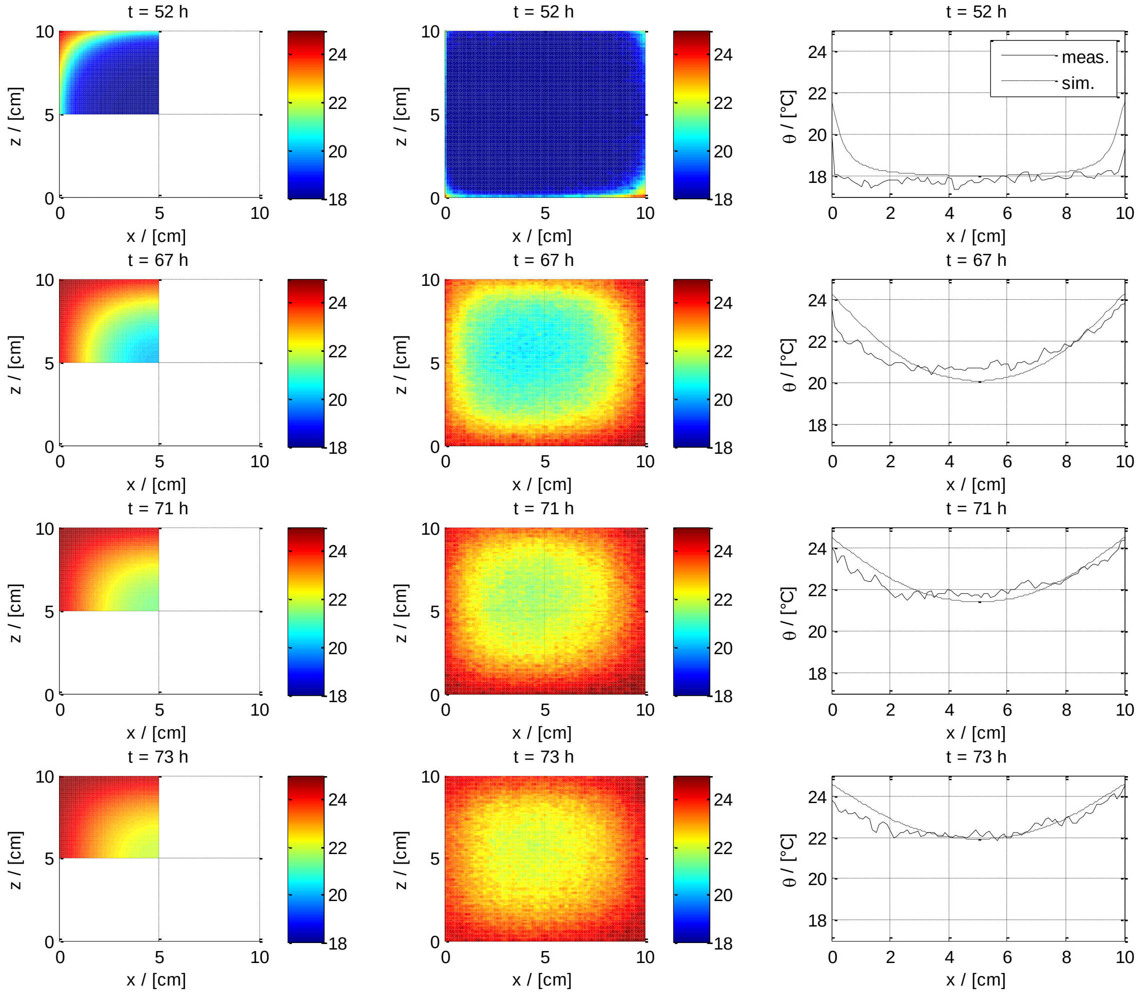
$\Delta T = T_{surf} - T_{\infty}$



Mean surface rel. humidity



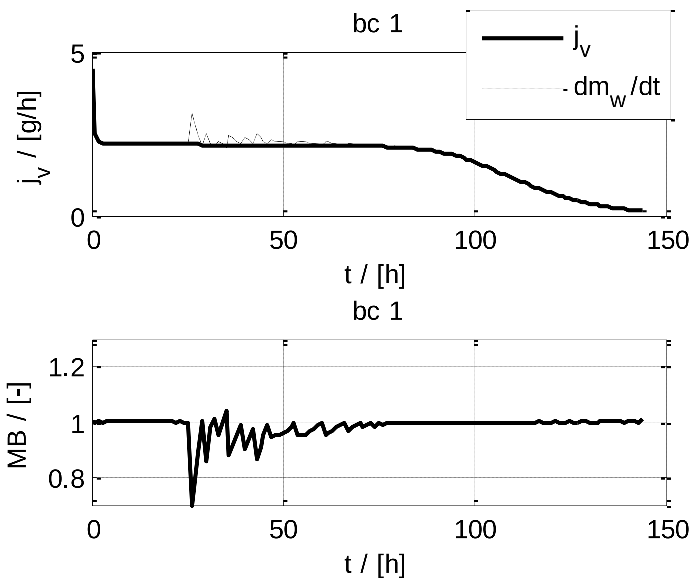
Infrared thermography

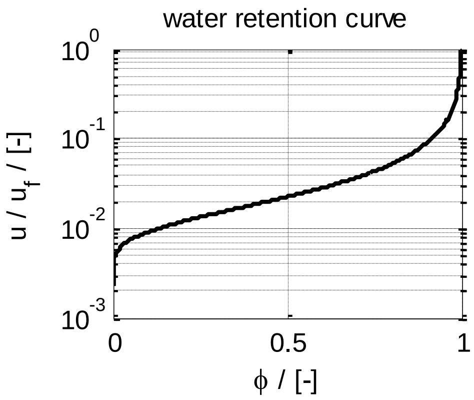


Simulated temperature **Mesured temperature**

Mass balance ratio

$$MB(t) = \frac{\iiint_{\Omega} du/dt \; dV}{\iint_{\partial\Omega} j_v \, dA} = \frac{total\ mass\ loss}{total\ net\ flux\ from\ the\ domain}$$



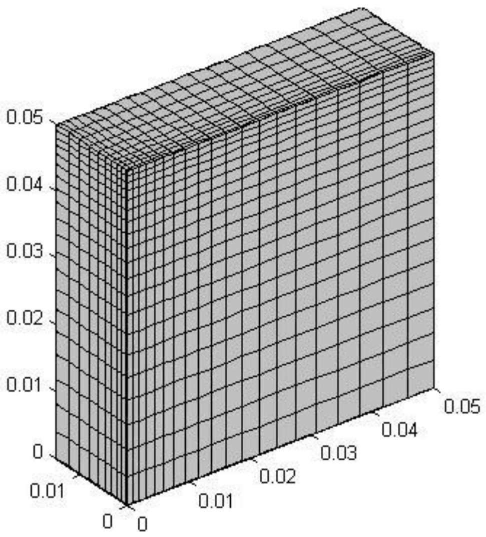


Mass balance

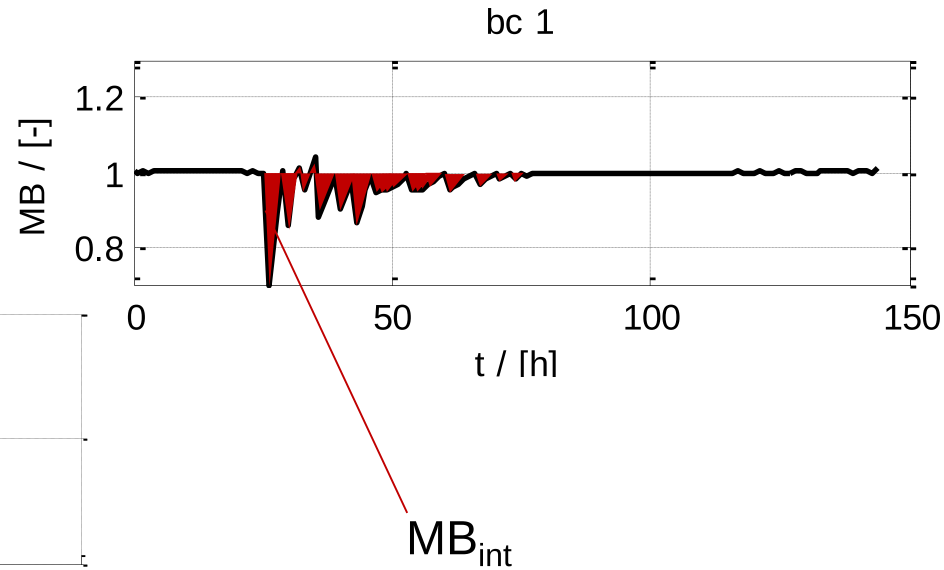
$$\frac{\partial u}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla \cdot (K_{21}\nabla T + K_{22}\nabla\varphi)$$

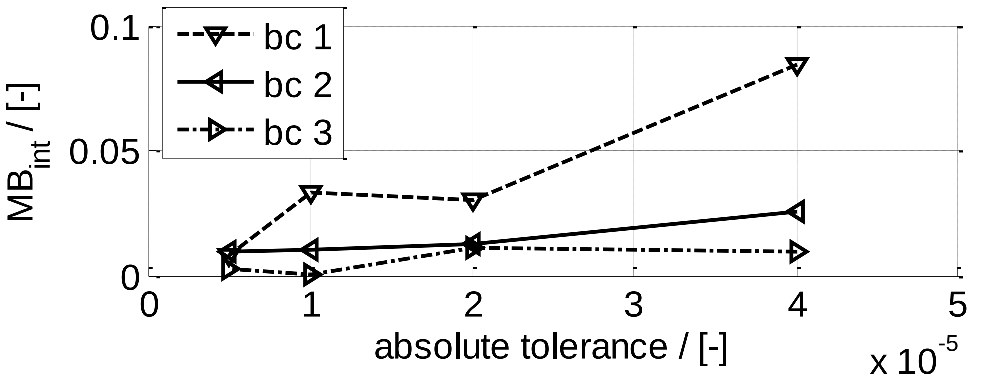
Numerical setup

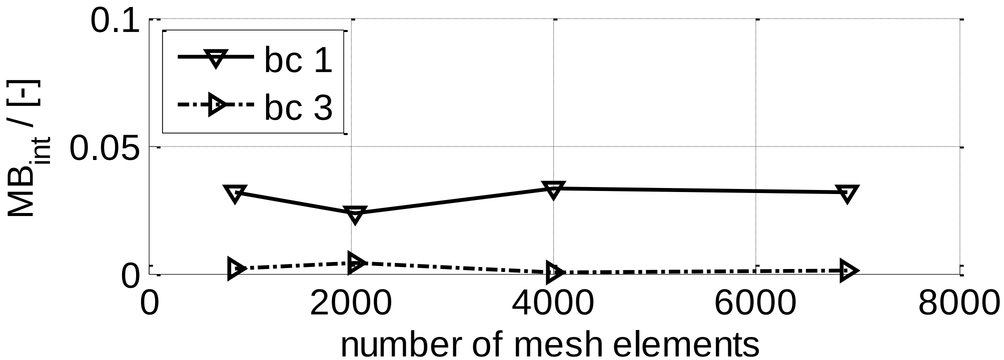
Parameter	Value / Setup
Mesh elements	4000
Element ratio	5
Shape function	Lagrange
Element order	linear
Absolute tolerance	10^{-5}
Relative tolerance	10^{-4}
Time step	variable
Time s. method	BDF
Max. BDF order	5



Influence of absolute tolerance and mesh







Conclusions

- Good agreement with the experimental data
- No mass conservative solutions
- Mass error negligible with a proper numerical setup

Outlook

Is a mass conservative solution possible with Comsol?

Mass balance: water content *u* as dependent variable

$$\frac{\partial u}{\partial t} = \nabla \cdot \left(K_{21} \nabla T + K_{22}{}^{*} \nabla u \right)$$

Outlook

Is a mass conservative solution possible with Comsol?

Mass balance: water content *u* as dependent variable

$$1\frac{\partial u}{\partial t} = \nabla \cdot \left(K_{21} \nabla T + K_{22}^{*} \nabla u \right)$$

Damping coefficient = 1