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Heat and Mass Transfer in a Gypsum Board Subjected to Fire

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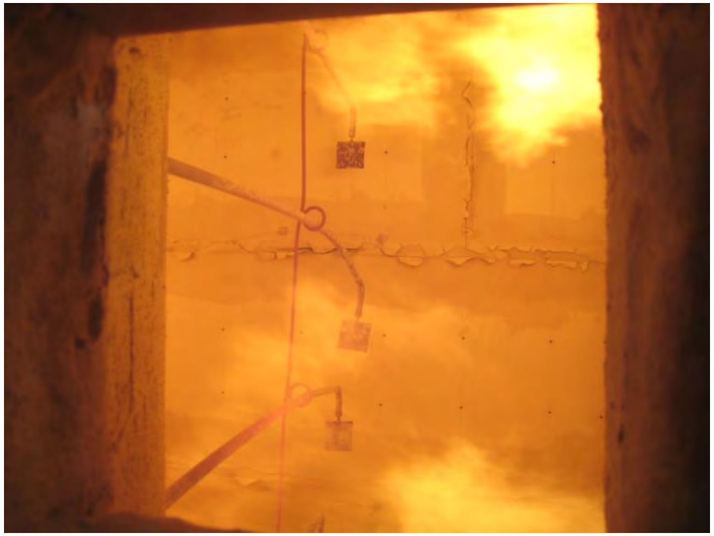
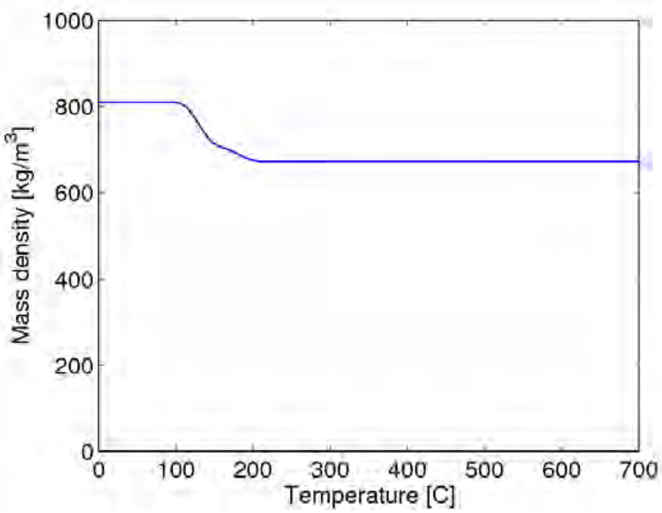


Excerpt from the Proceedings of the 2011 COMSOL Conference in Stuttgart

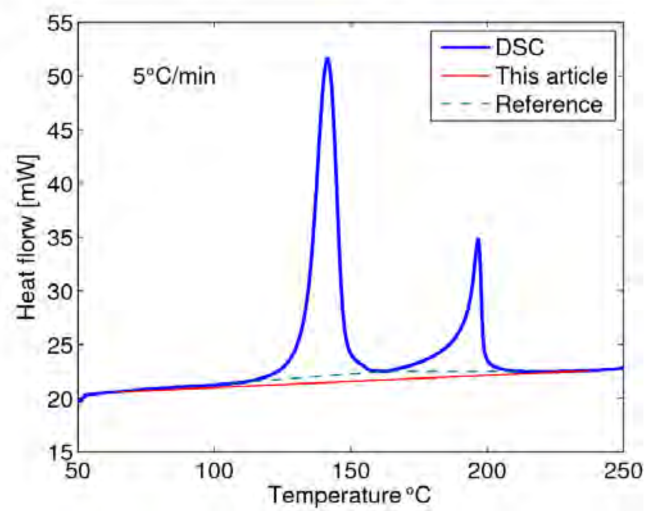
Motivation, dehydration

- Gypsum boards are widely used in construction for partition walls
- Resistance to fire
- Heat barrier due to dehydration (chemical reaction)
  - Vapour release (pure gypsum 21%, actual board 17%)
  - Endothermic reaction (consumes energy)

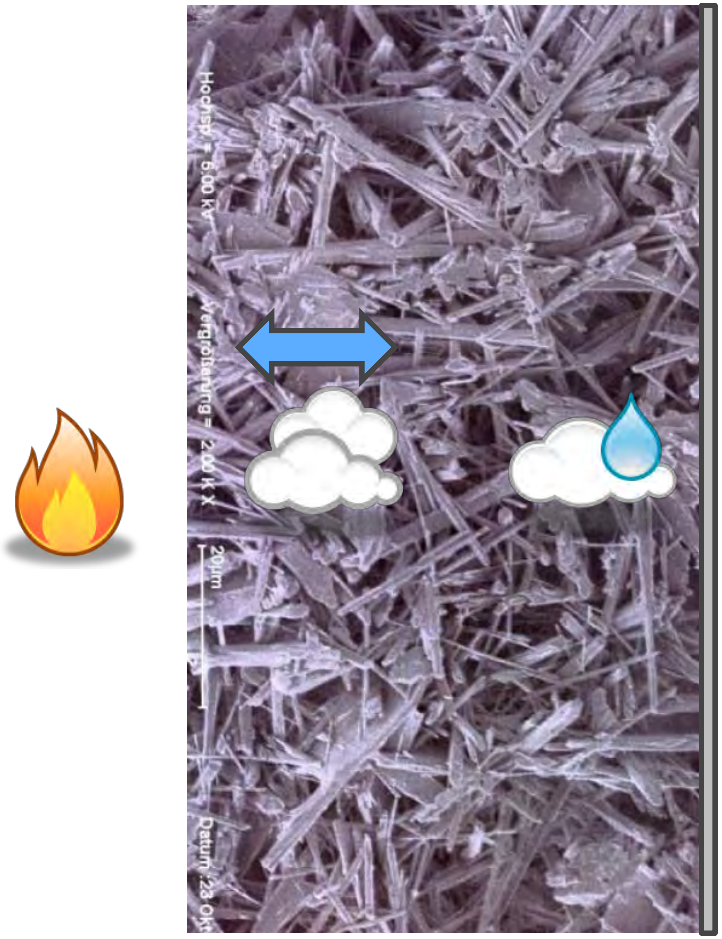
TGA: Thermographic analysis



DSC: Differential scanning calorimetry



Physical model



- Porous medium
- Heat conduction
- Dehydration front
  - Heat sink
  - Vapour source
- Gaseous mixture of dry air and vapour
  - Darcy’s law
  - Fick’s law
  - Paper liner
- Condensation / evaporation (heat of phase change)
- 1-D behavior

Main equations

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- Heat equation (porous media)

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot \left(-k_{\text{eff}} \nabla T\right) + \rho_g C_{pg} \mathbf{v}_g \cdot \nabla T = -\left(C_{pa} \mathbf{j}_a + C_{pv} \mathbf{j}_v\right) \cdot \nabla T - \dot{m}_{\text{dehyd}} \Delta H_{\text{dehyd}} - \dot{m}_{\text{evap}} \Delta H_{\text{evap}}$$

Modified source:
Energy transport
by interdiffusion

- Conservation of gaseous mixture (Darcy)

$$\frac{\partial}{\partial t}\left(\phi(1-S)\rho_g\right) + \nabla \cdot \left(\rho_g \mathbf{v}_g\right) = \dot{m}_{\text{dehyd}} + \dot{m}_{\text{evap}} \qquad \mathbf{v}_g = -\frac{\kappa_g}{\mu_g} \nabla p_g$$

- Conservation of vapour (Concentrated Species)

$$\phi(1-S)\rho_g \frac{\partial \omega_v}{\partial t} + \rho_g \mathbf{v}_g \cdot \nabla \omega_v + \nabla \cdot \mathbf{j}_v = (1-\omega_v)(\dot{m}_{\text{dehyd}} + \dot{m}_{\text{evap}}) \qquad \mathbf{j}_v = -\rho_g D_{eff} \nabla \omega_v$$

Change in weak form:
Porosity ϕ

Modified source:
Source from other phases
(V4.2 in interface)

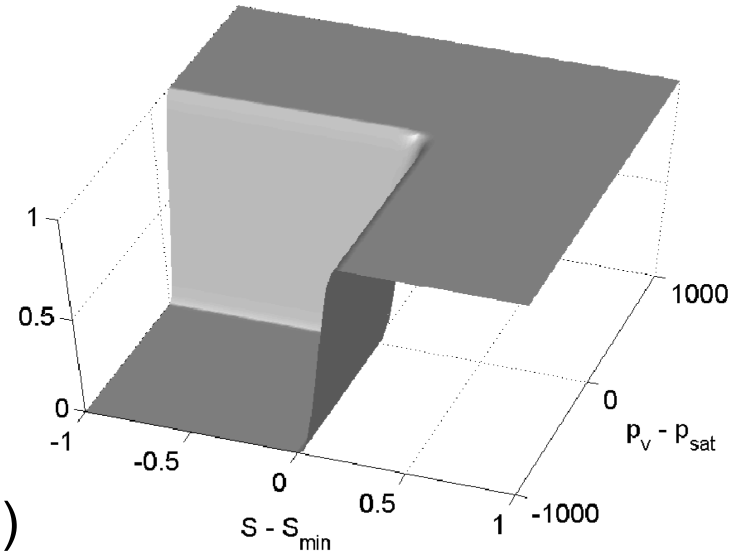
Condensation and evaporation

- Non-equilibrium formulation (penalty formulation)

$$\dot{m}_{\text{evap}} = K \frac{M_w}{RT}\left(p_{\text{sat}} - p_v\right)$$

- Avoid evaporation for $S \leq S_{\min}$

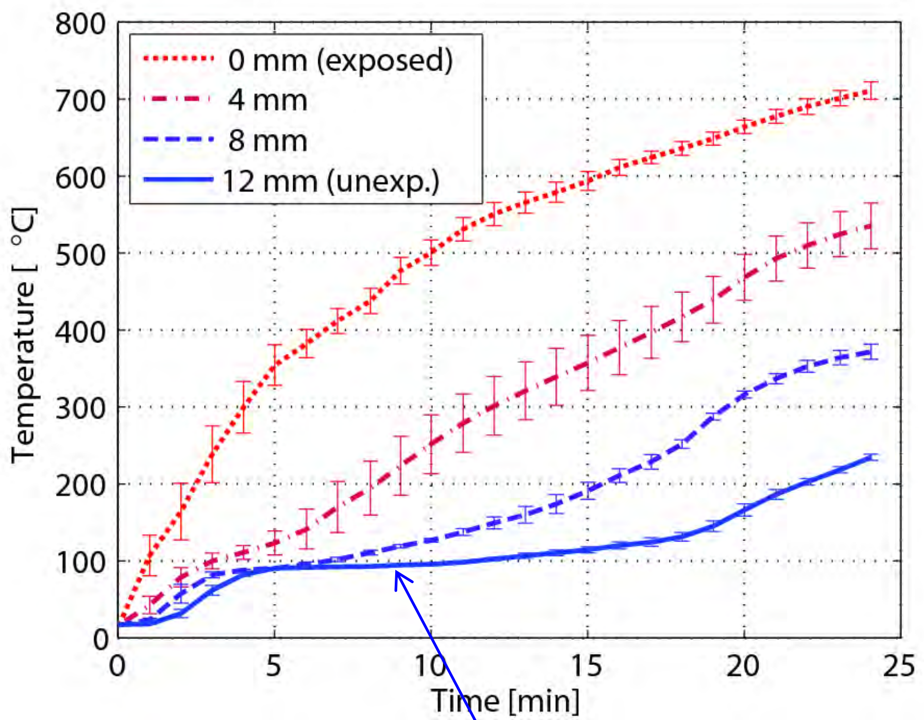
$$K = K_0\left[1 - H(S_{\min} - S)\cdot H(p_{\text{sat}} - p_v)\right]$$



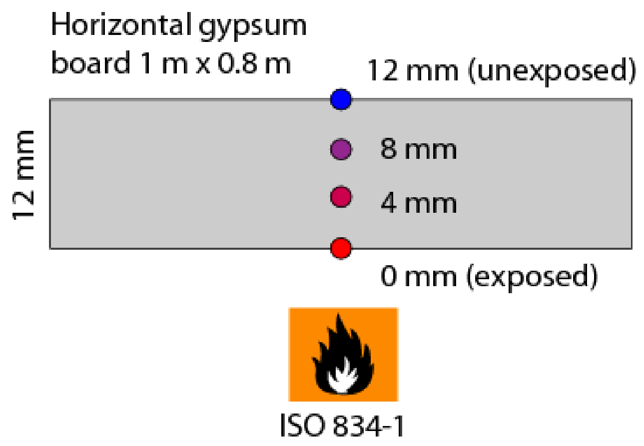
- Conservation of liquid water (immobile)

$$\frac{\partial}{\partial t}\left(\phi S \rho_w\right) = -\dot{m}_{\text{evap}}$$

Fire test

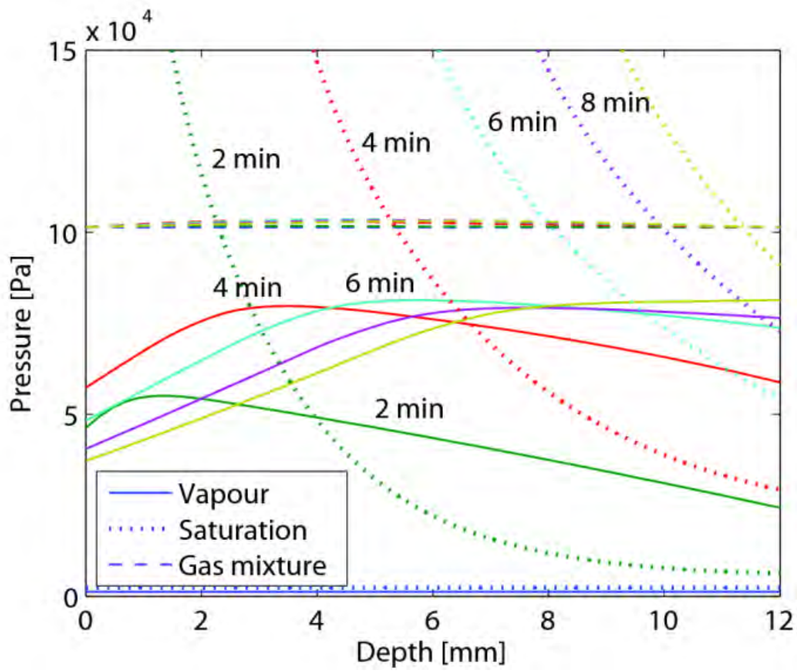


Temperature plateau



Results without condensation – Pressure

- Small gas pressure built-up
- Humidity less than 100% (partial vapor pressure < saturation press.)
- Paper liner prevents vapor from leaving the board
- Condensation expected 2 – 8 min (only indication)

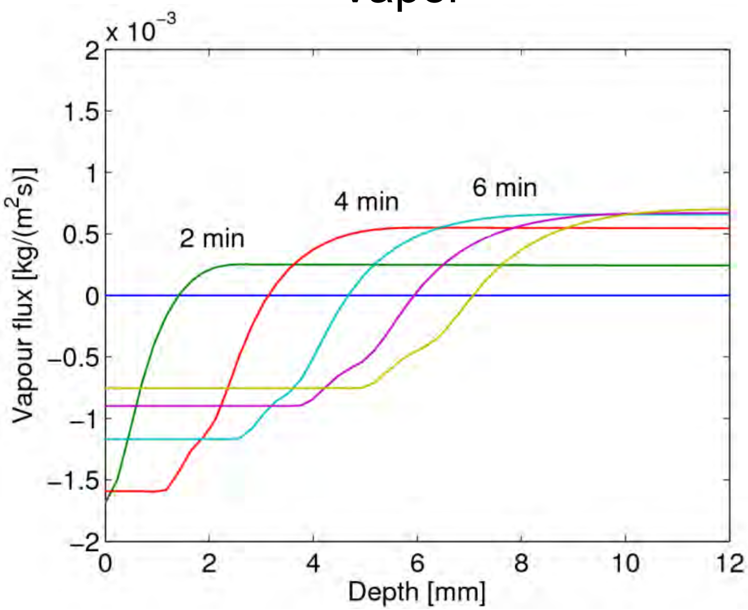


Cold side with
paper liner
(low mass transfer)

Results without condensation – Mass flux

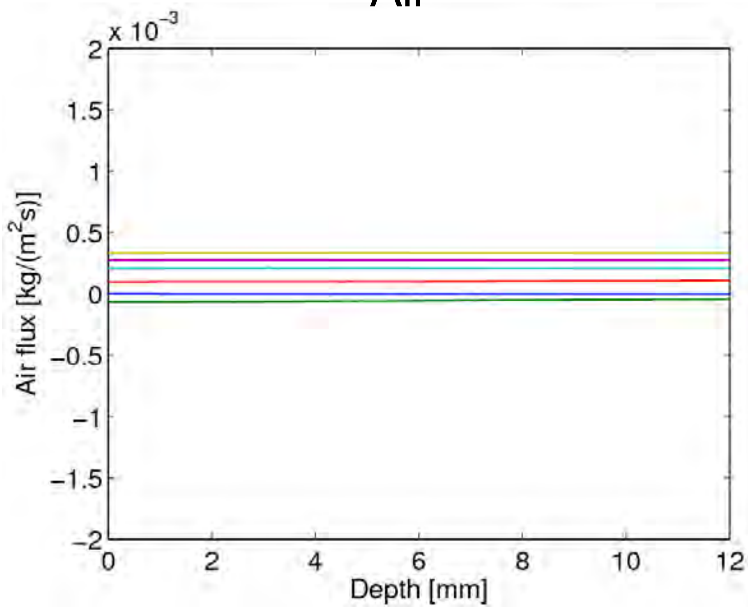
- Vapor produced at dehydration front, mode in both directions
- Negligible air flux
- Vapor flux in quiescent air (diffusion dominated)

Vapor



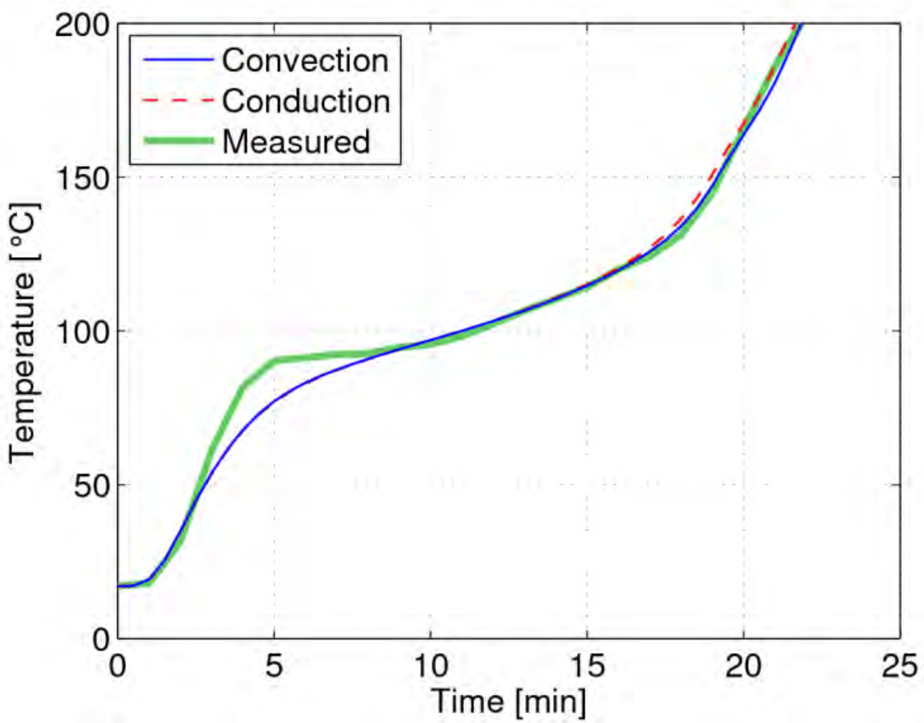
hot cold

Air



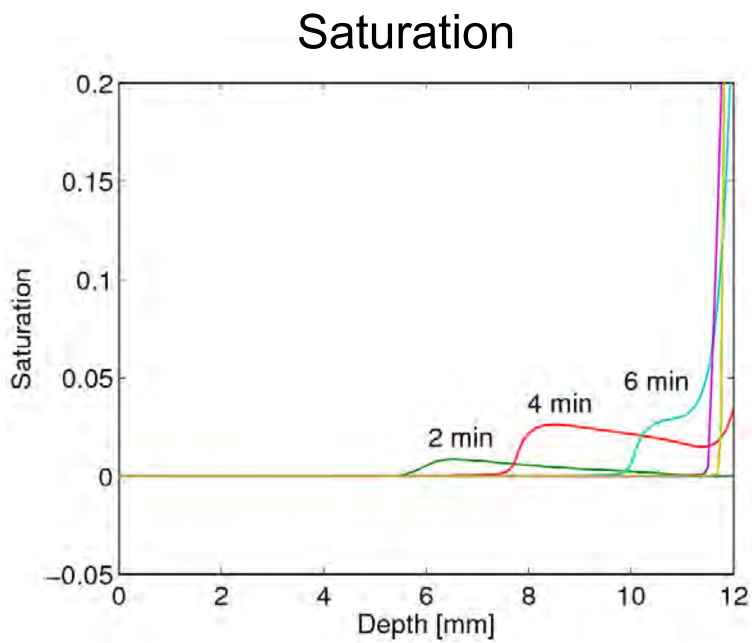
Results without condensation – Temperature at cold face

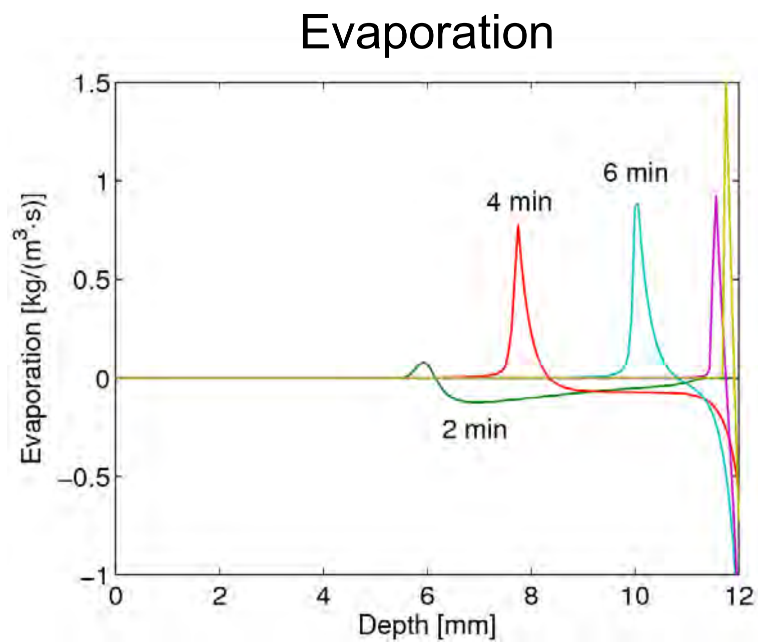
- Vapor transport has no influence on temperature (compared to conduction)
- Temperature plateau not captured



Results with condensation – Saturation and evaporation

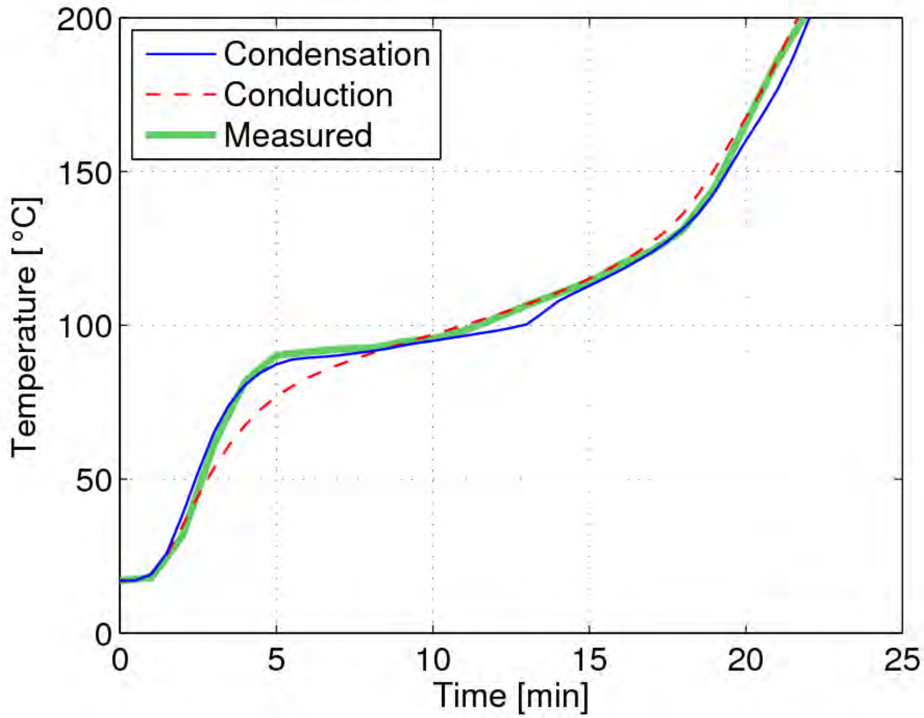
- Water accumulated near cold face (saturation)
- Water pushed to cold face by successive evaporation and condensation





Results with condensation – Temperature

- Temperature plateau well captured



Conclusions

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- Gypsum board modeled as porous material
  - Heat conduction
  - Dehydration with heat sink and vapor source
  - Mass transfer, mainly diffusion
  - Condensation and evaporation produces temperature plateau
- COMSOL very versatile
  - Derive differential equations
  - Some adjustments needed in standard equations
  - Relatively easy to try out various models

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Thank you for your attention!