Hygrothermal behaviour of hemp concrete

Experimental evidences and modelling

Antonin FABBRI, Fionn McGregor, Tania Simoes,
Frederic SALLET, Emmanuel GOURDON

Context

Lime

Water

Hemp shiv

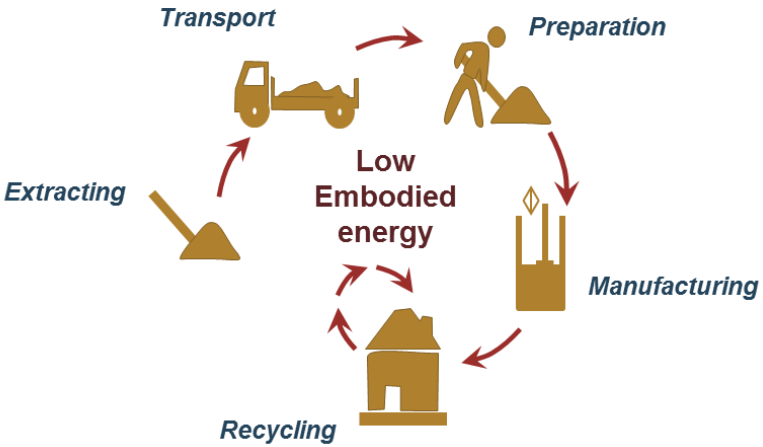
Context

Lime

Water

Hemp shiv

Bio-based material



Material particularities :

- Low embodied energy

Context

Lime

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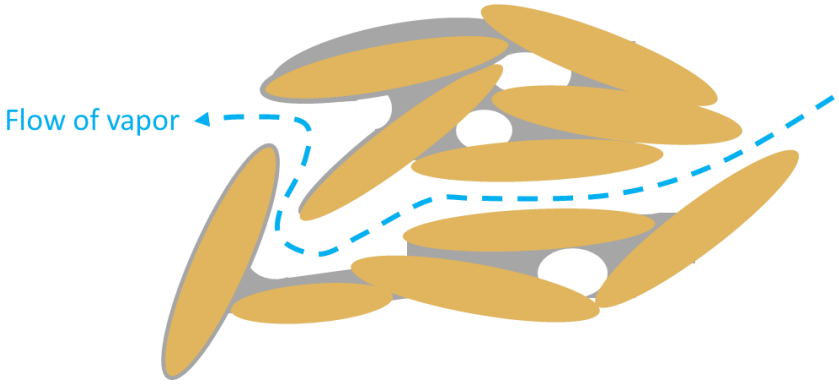
Hemp shiv



Material particularities :

- Low embodied energy
- Vapor permeancy

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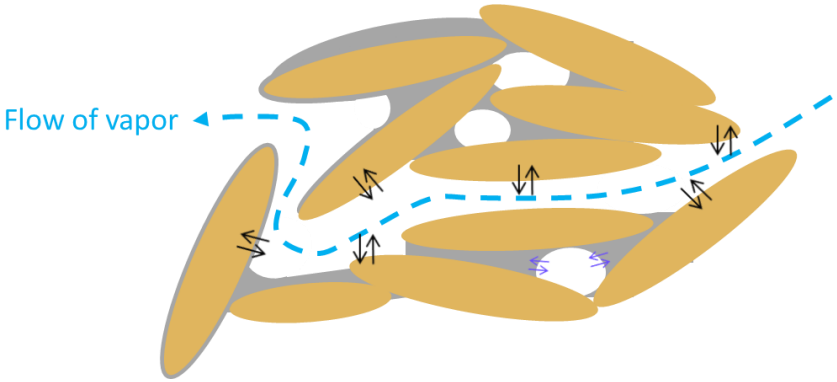
Hemp shiv



Material particularities :

- Low embodied energy
- Vapor permeancy
- Moisture buffering abilities
- Hygrothermal abilities

06/2013 – 07/2016

Leader

PAREXGROUP
Building expertise, together

Partners

ENTPE

ésitpa École d'Ingénieurs en Agriculture

Karibati L'expertise des filières du bâtiment biosourcé

The old buildings are a major source of energy loss . The IBIS project aims to develop bio-sourced sustainable solutions , economical and low environmental impact , for the renovation and the thermal insulation of buildings which are constructed prior to 1950 .

Goals

- To develop at an industrial scale and until its application, sustainable insulation composite bio-based mortars with accurate energy and acoustic performance
- To reduce the energy consumption and CO_2 emissions of old buildings , while improving the comfort of the inhabitants thanks to the properties of bio-based insulation
- To develop the theoretical tools and tests in order to properly assess the performance of these bio-based mortar.

06/2013 – 07/2016

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Outline

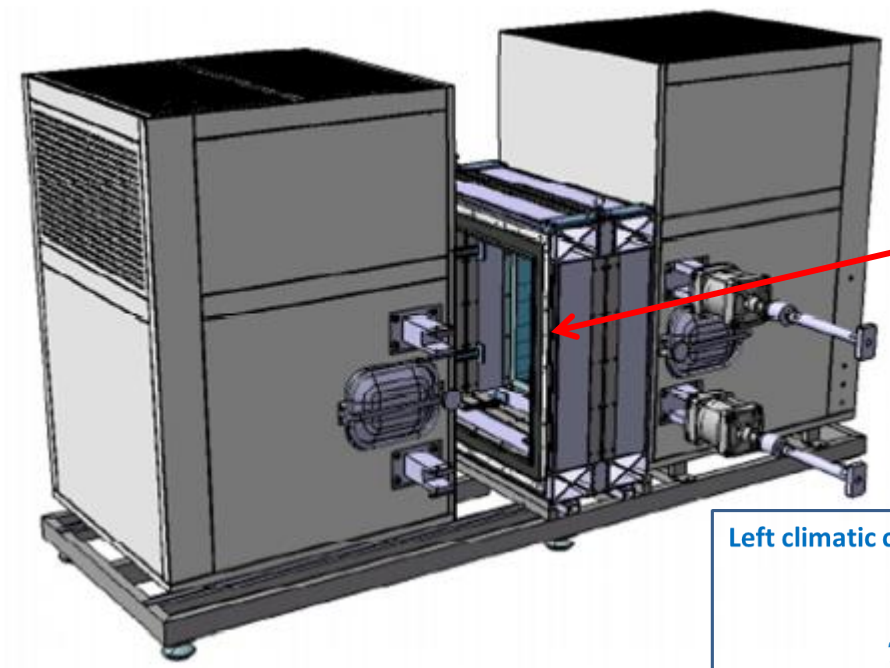
I. Experimental identification of HT processes

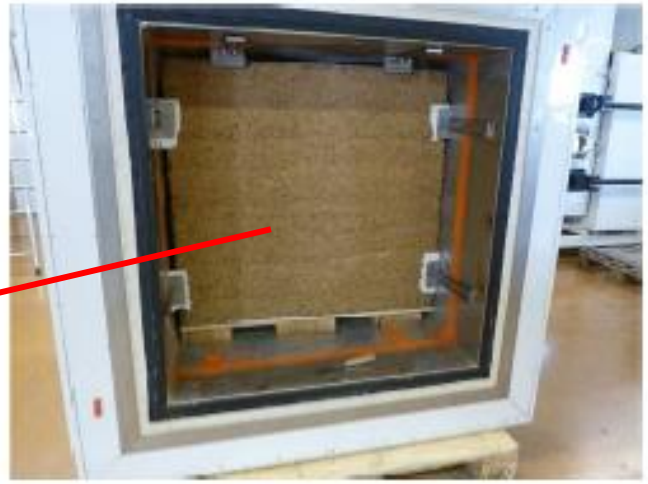
II. Modelling
   - Equilibrium model
   - Kinetic model

III. Conclusion

Experimental identification

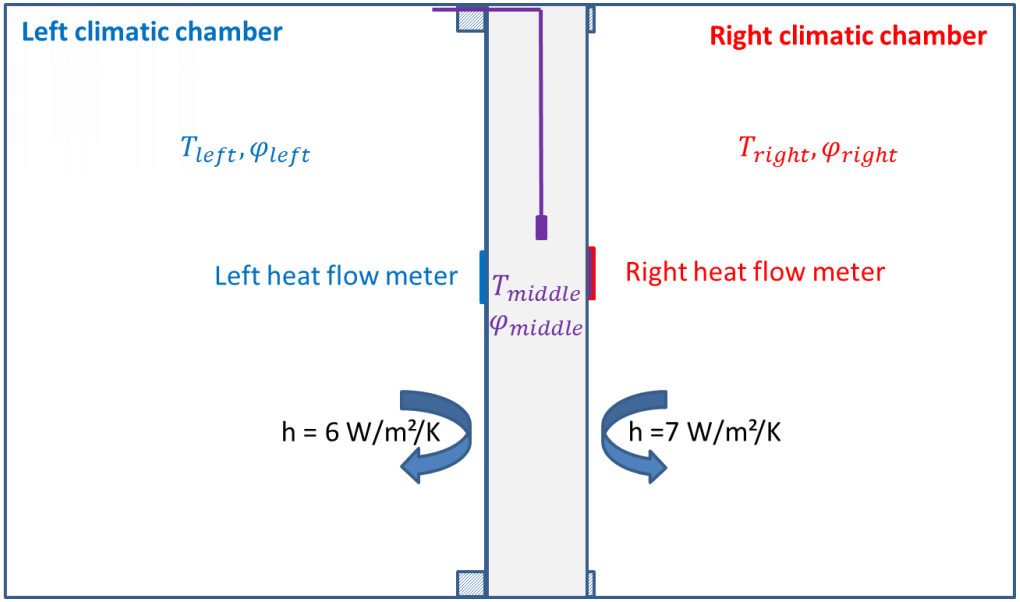
➢ Double climatic chamber DUO



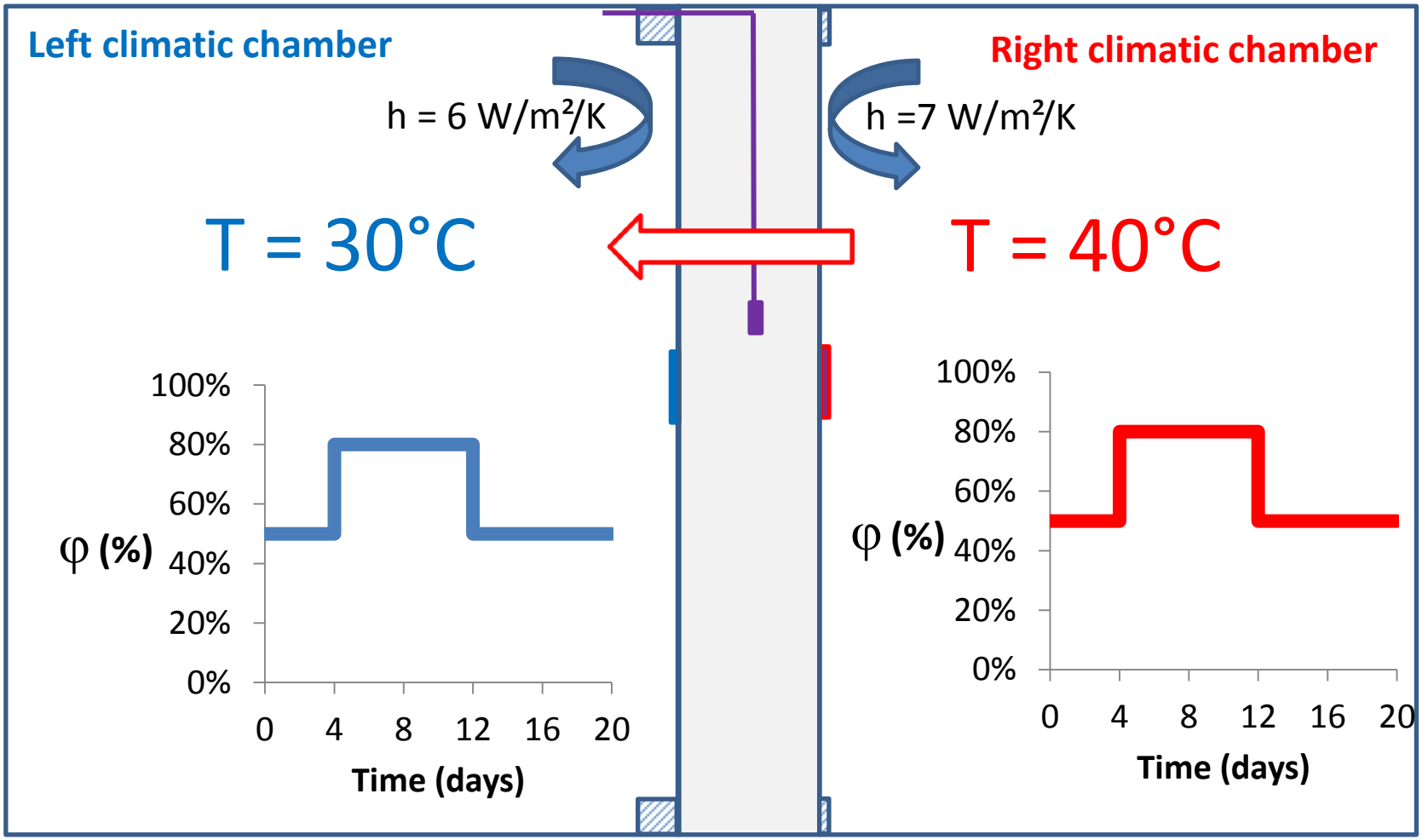


Samples : 90 x 90 x 10 [cm^3].

Instrumentation plan :



Experimental identification



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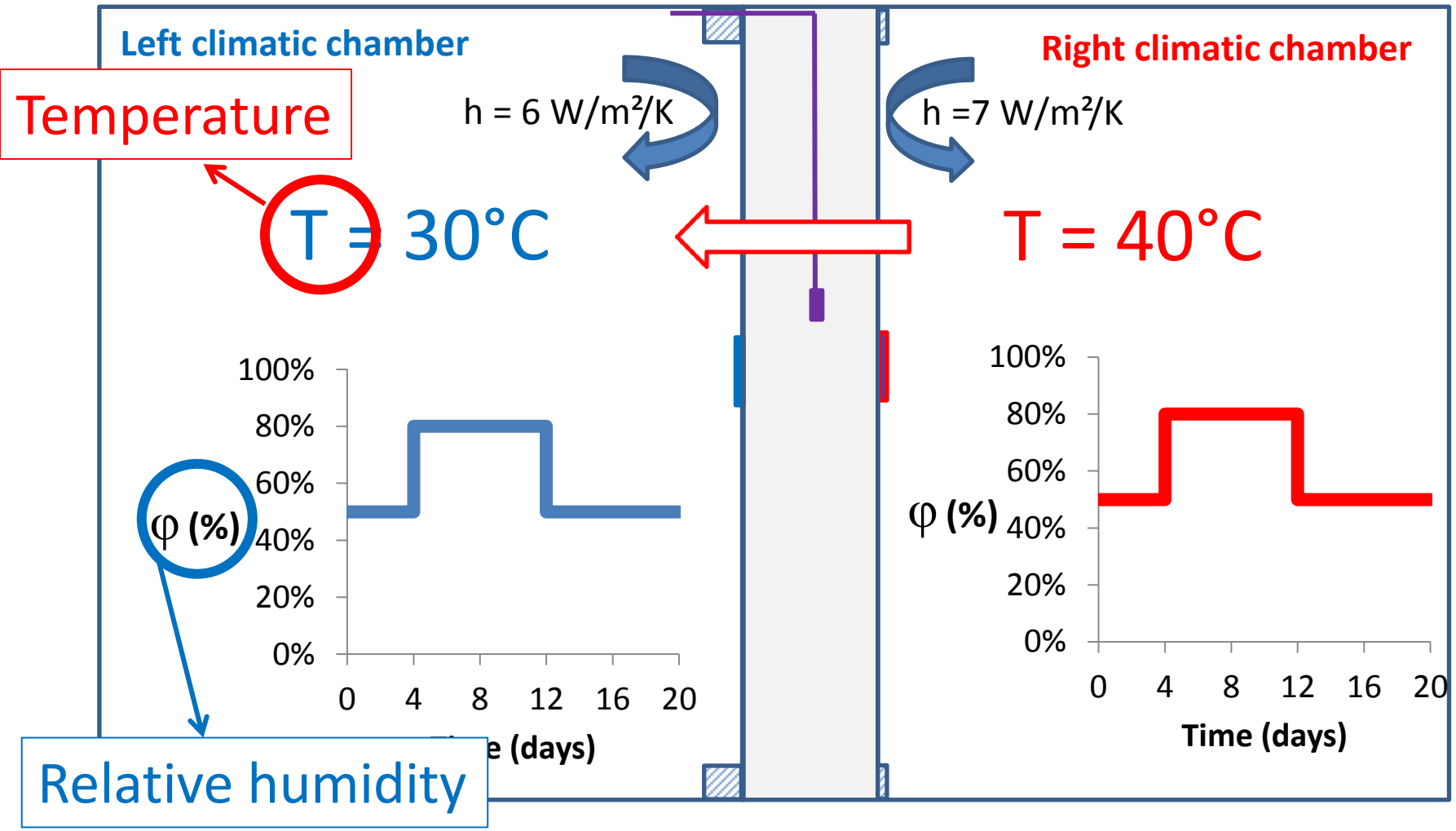


Experimental identification

2 tested walls :

Hemp concrete

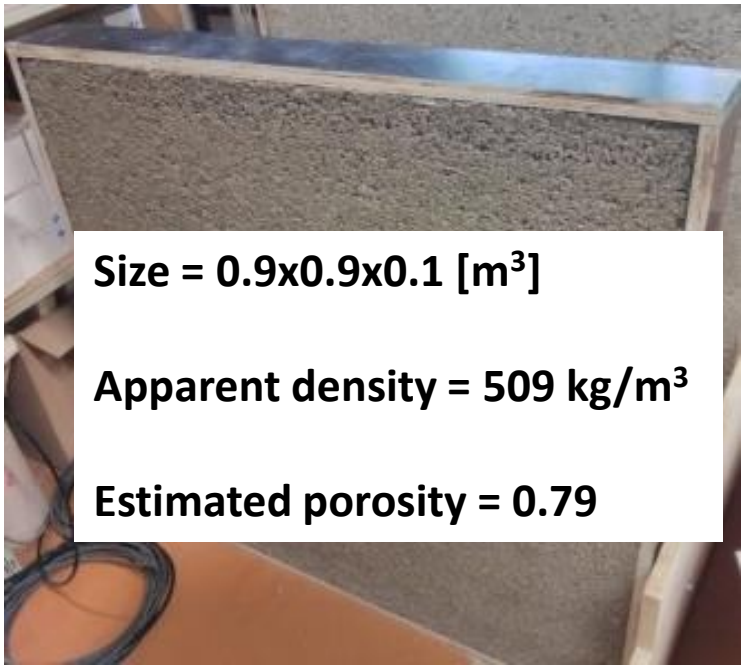
Pure hemp

Same volume – Almost same porosity

Experimental identification

2 tested walls :

Hemp concrete

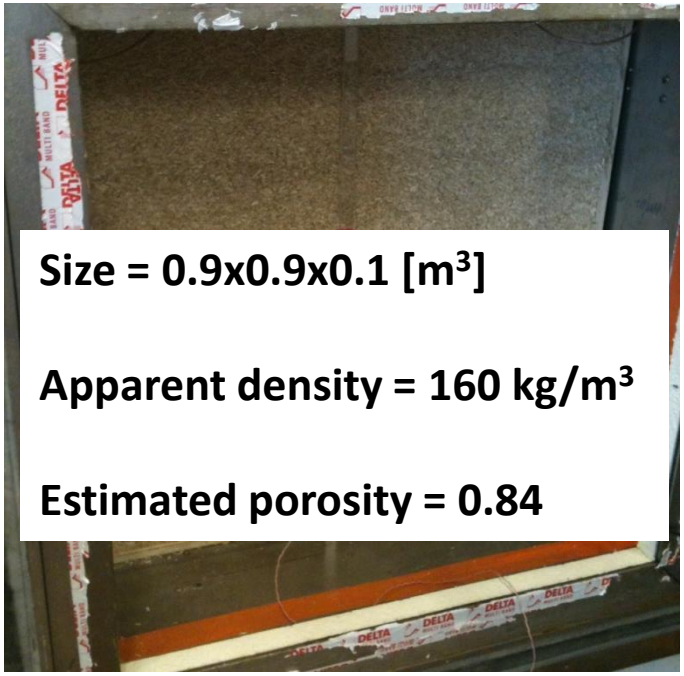


Size = 0.9x0.9x0.1 [m³]

Apparent density = 509 kg/m³

Estimated porosity = 0.79

Pure hemp



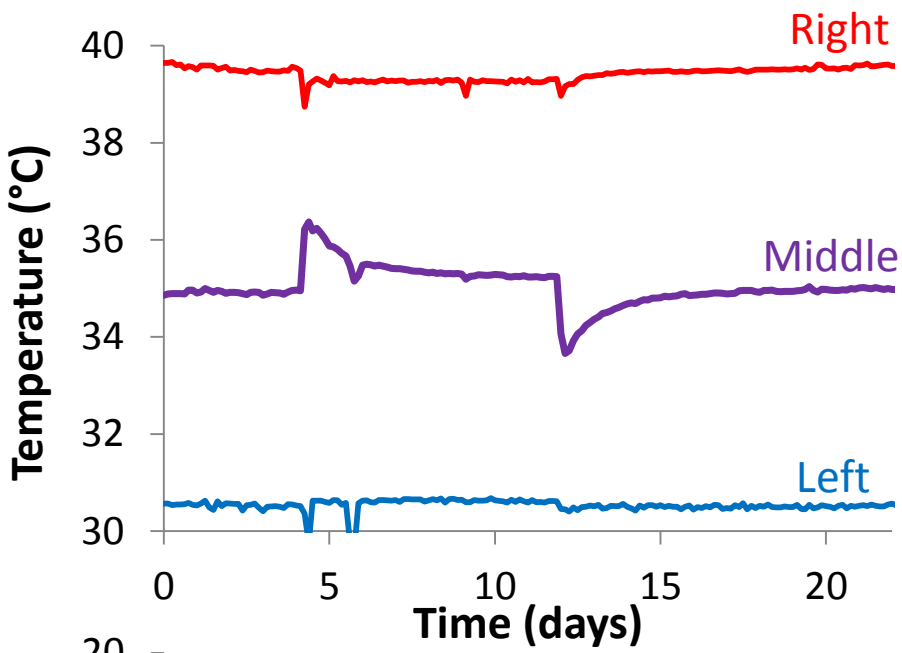
Size = 0.9x0.9x0.1 [m³]

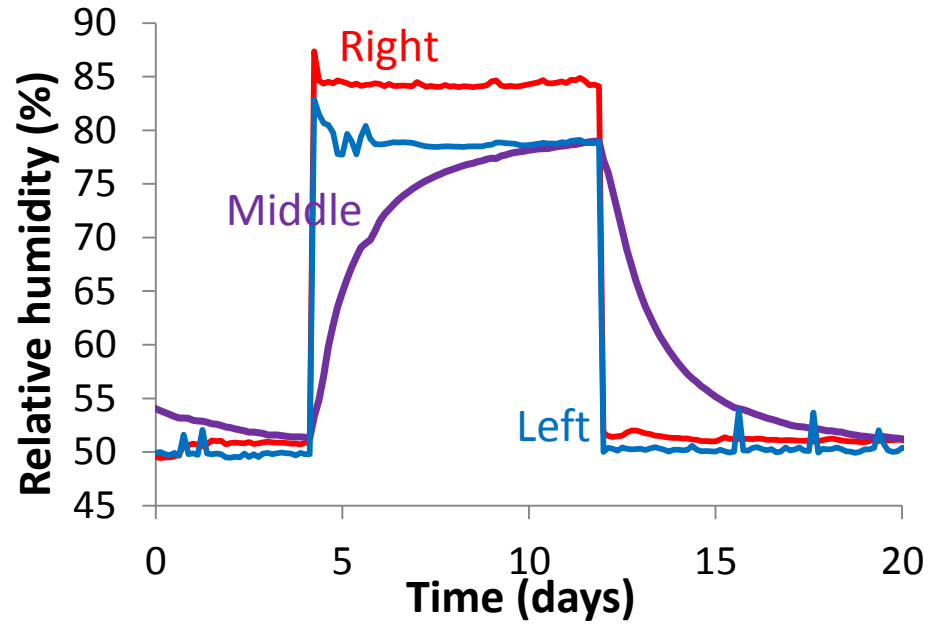
Apparent density = 160 kg/m³

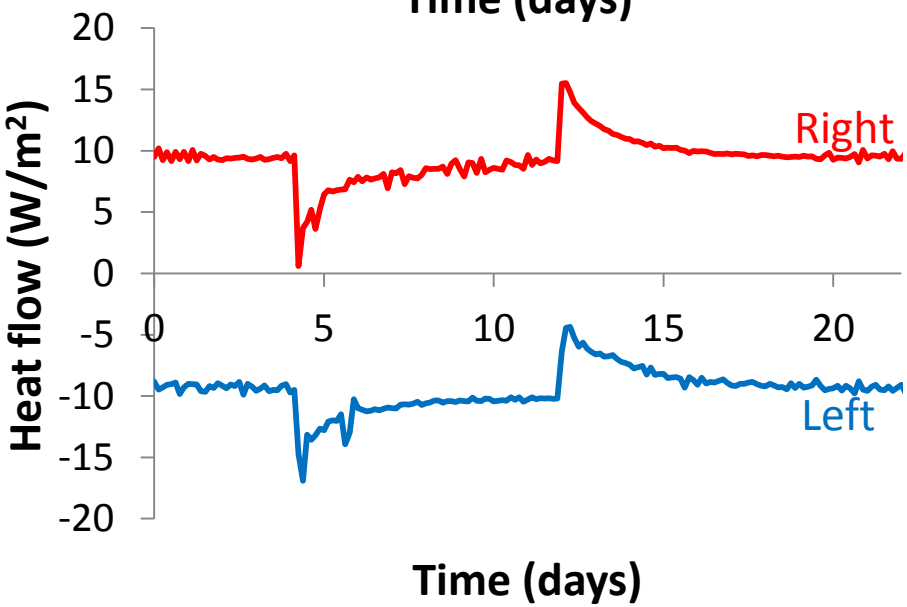
Estimated porosity = 0.84

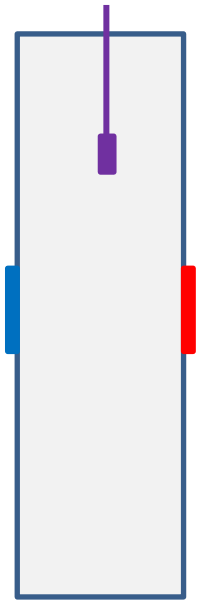
Same volume – Almost same porosity

Hemp concrete **results**

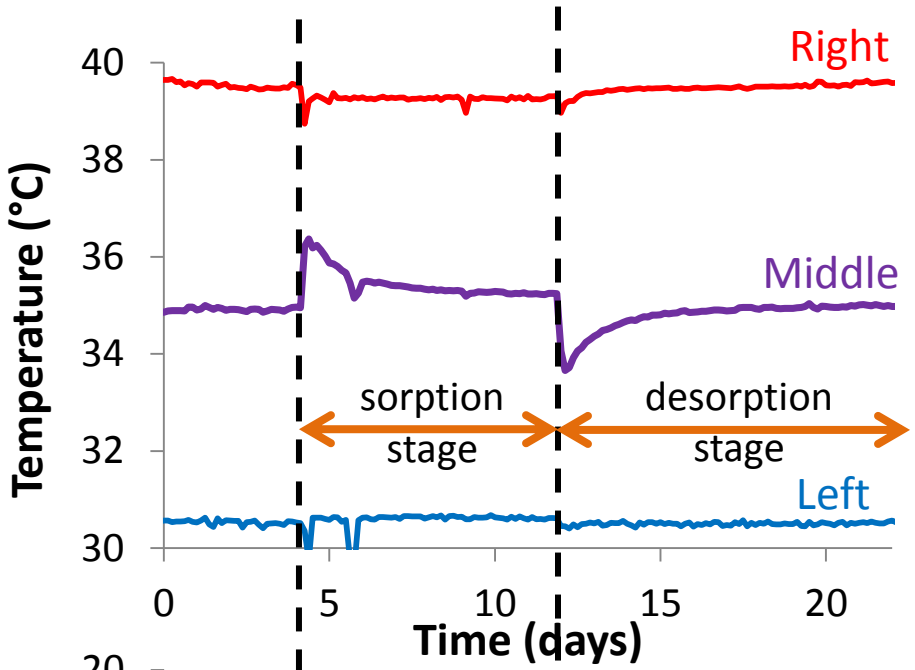


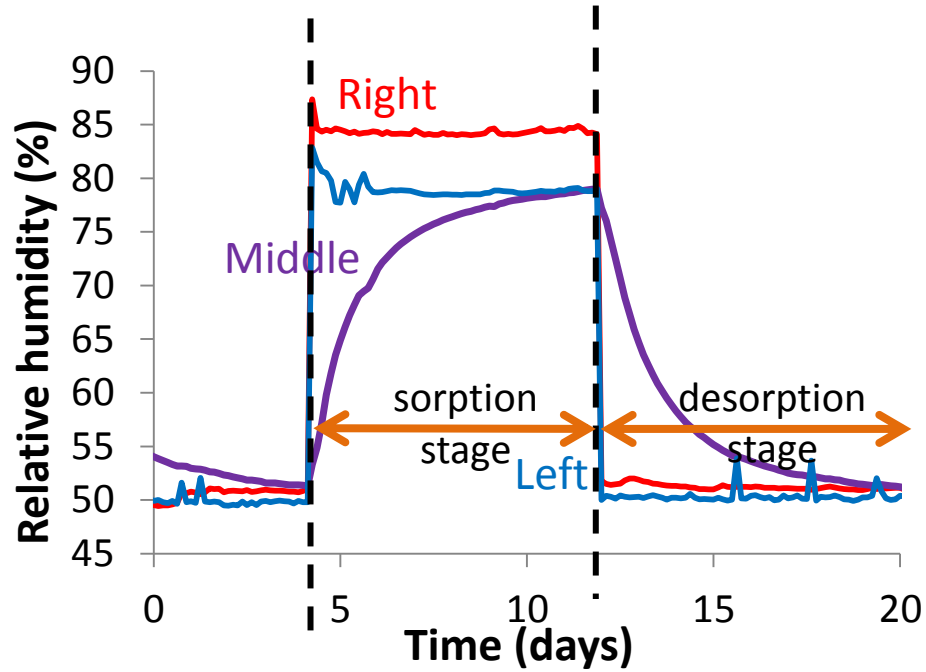


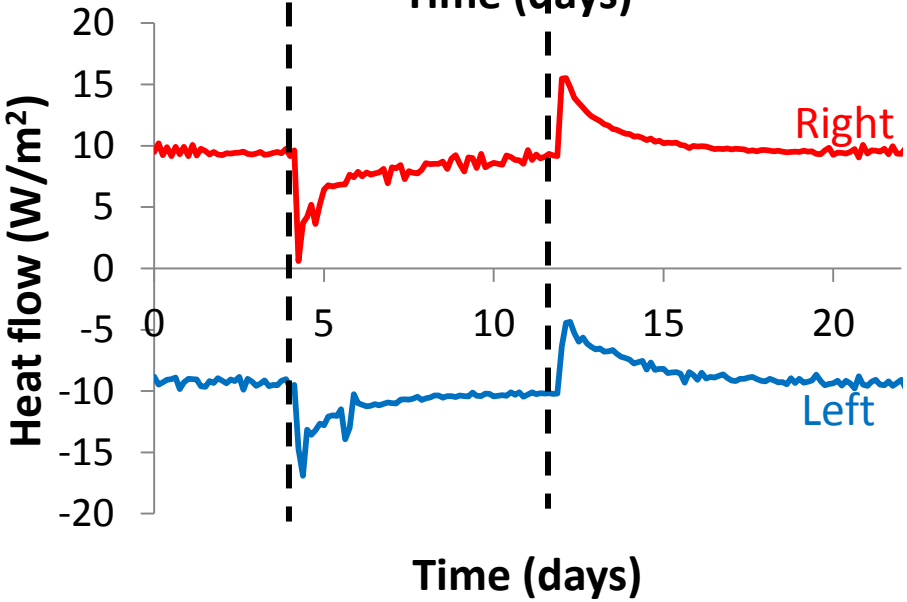


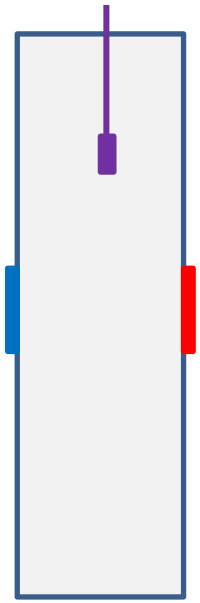


Hemp concrete results









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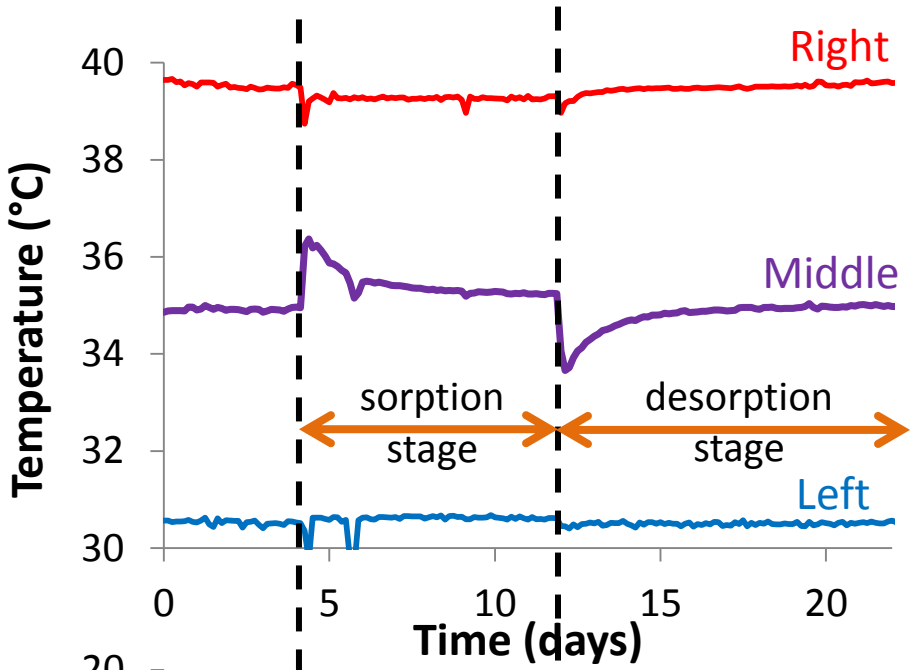

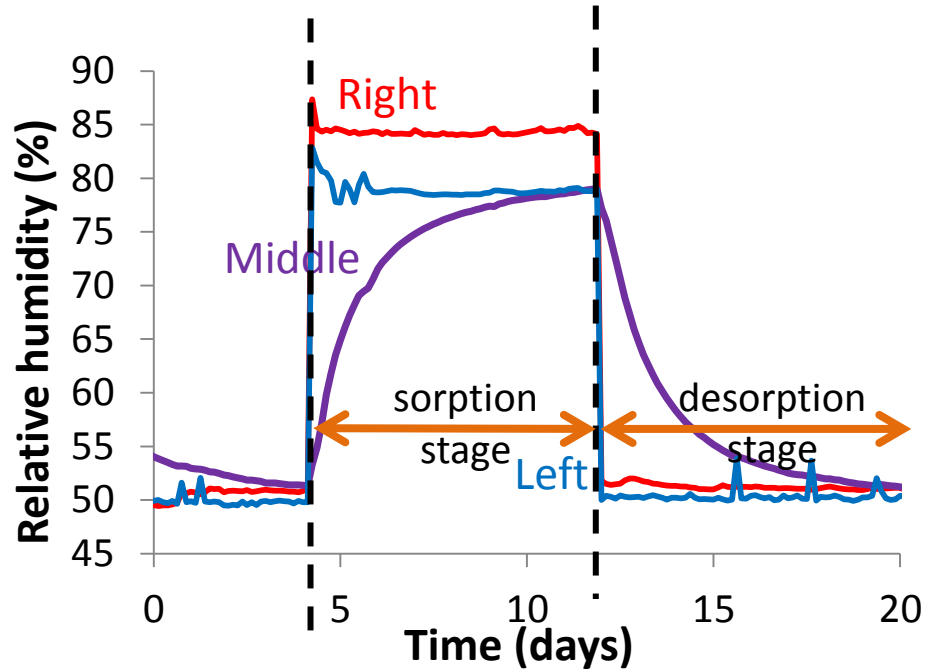

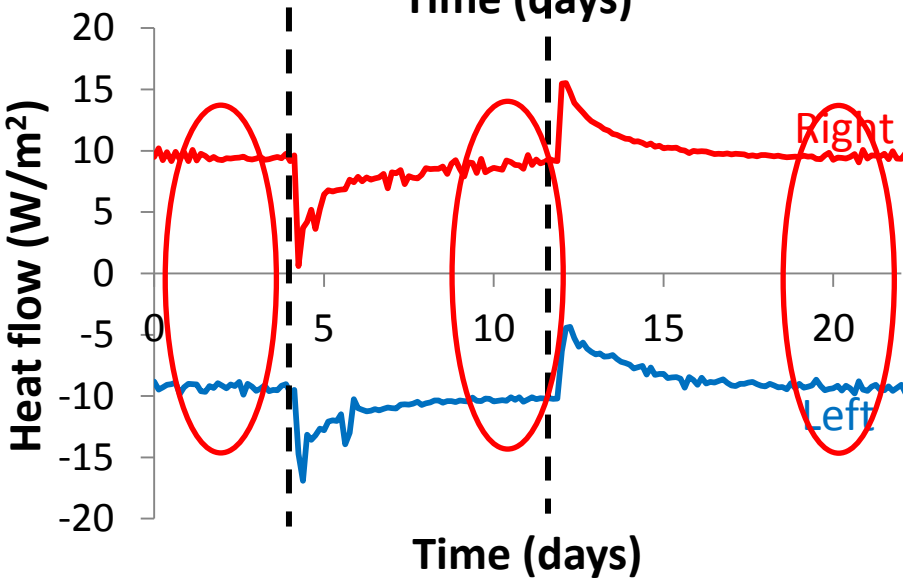

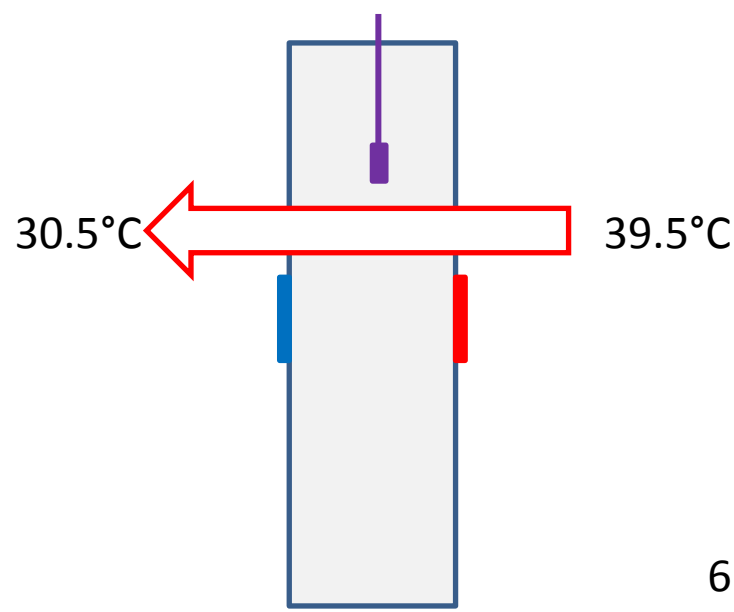

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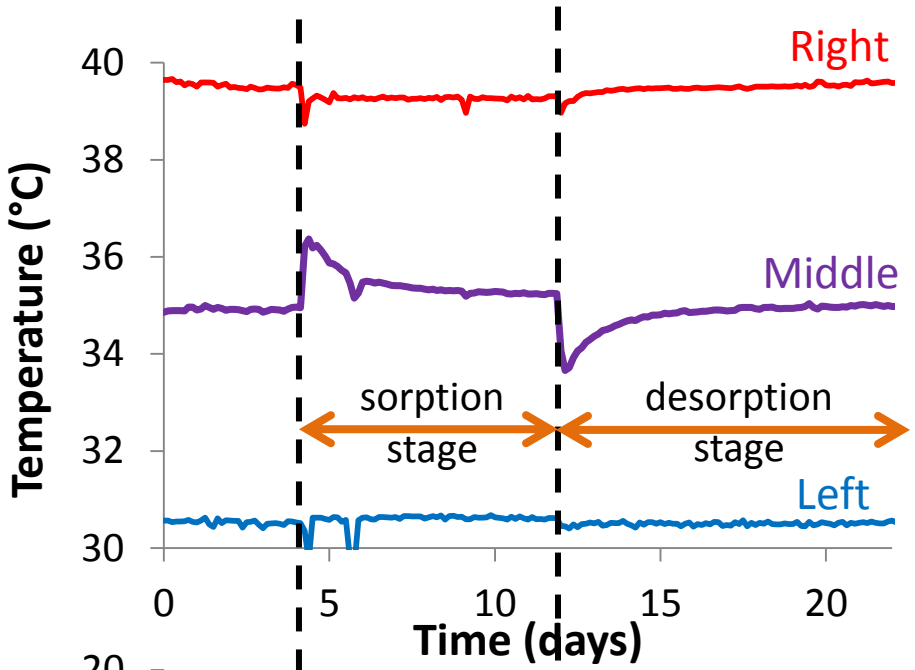

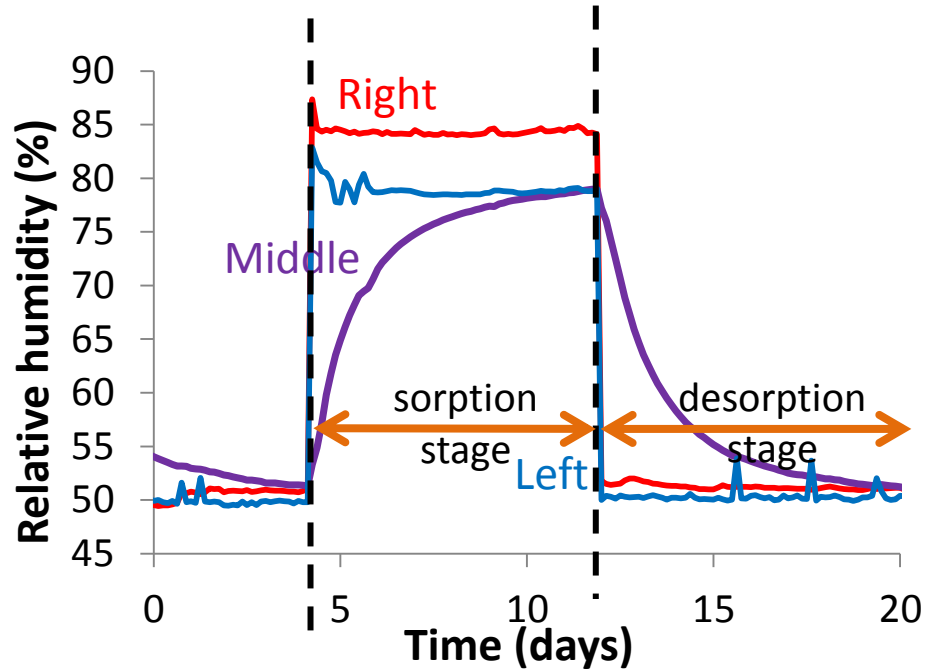

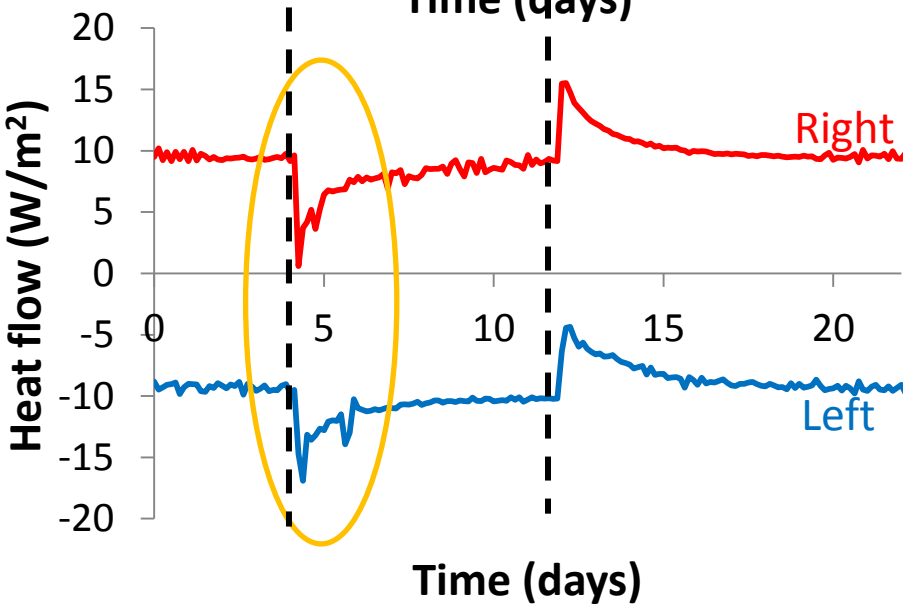

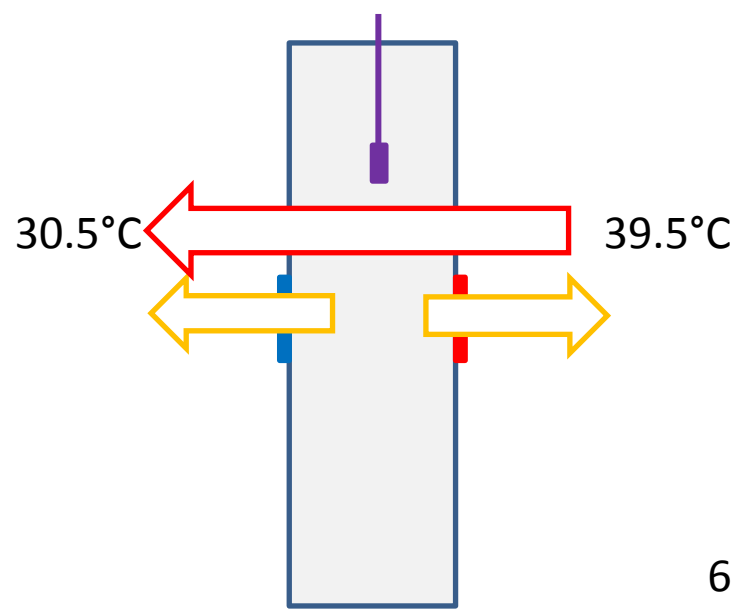

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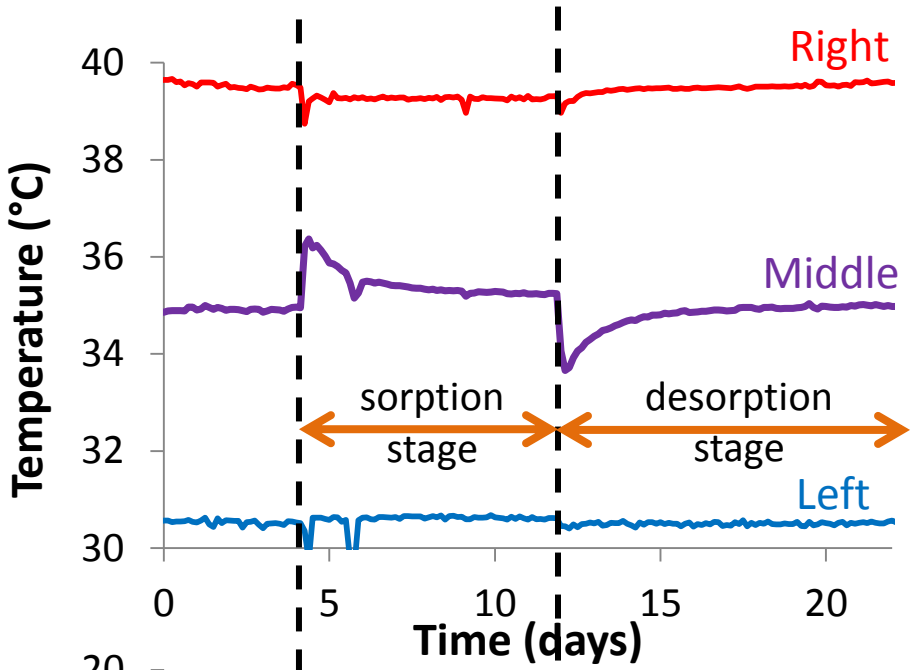

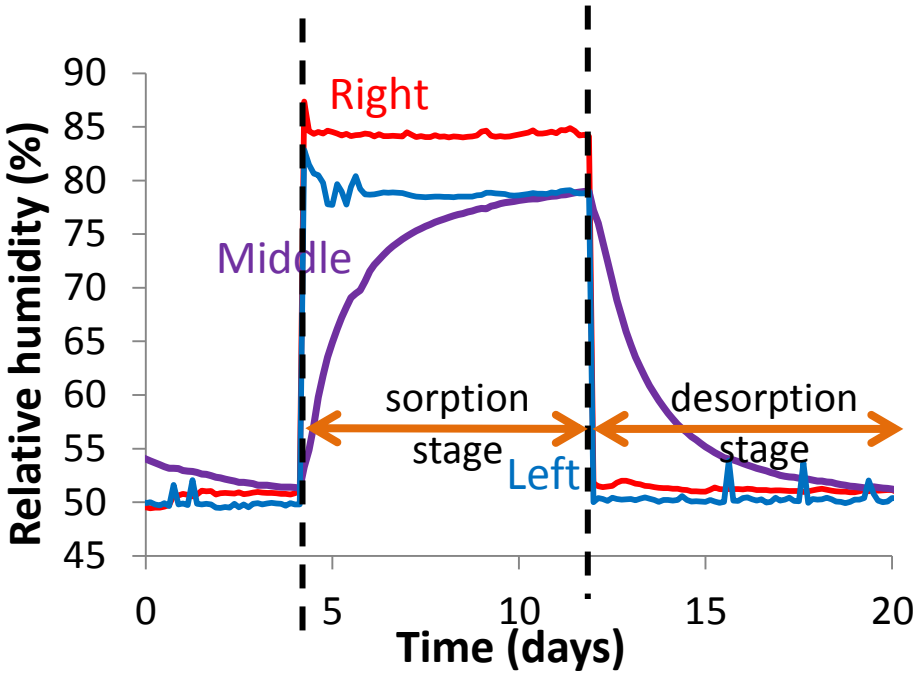

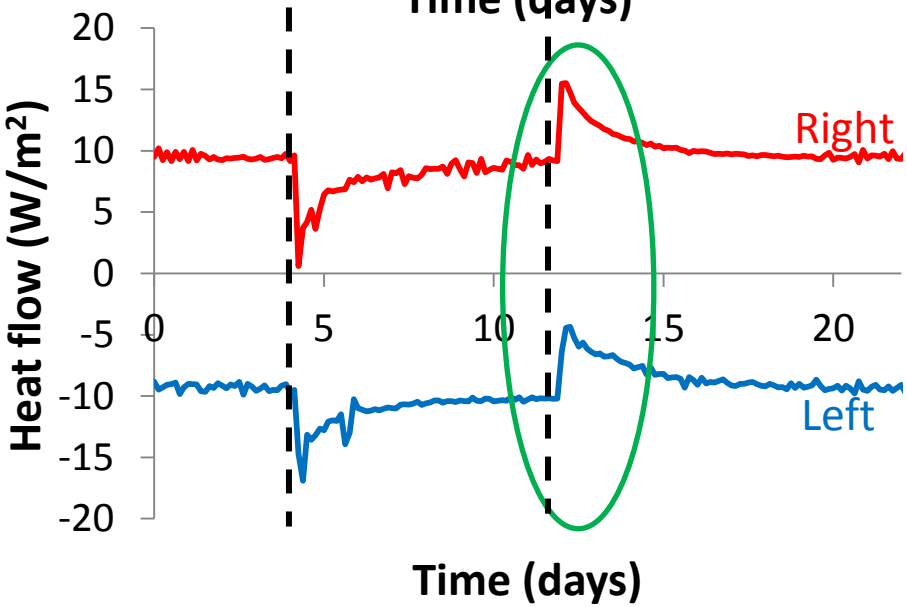

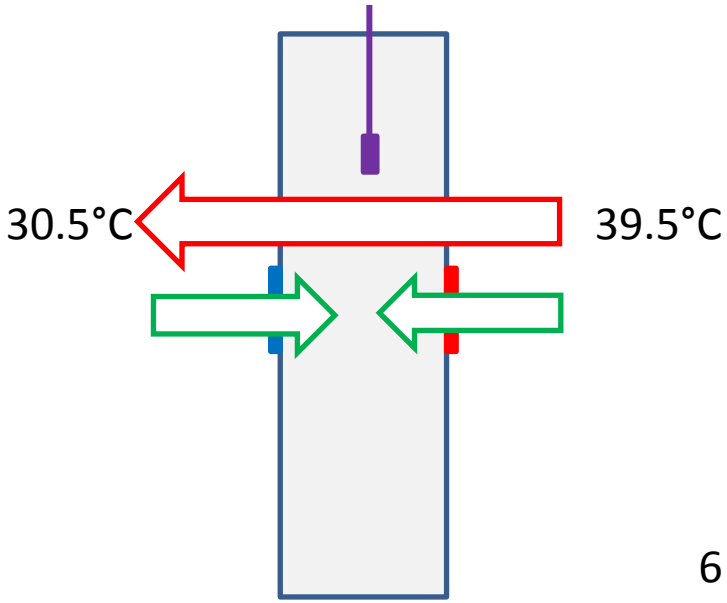

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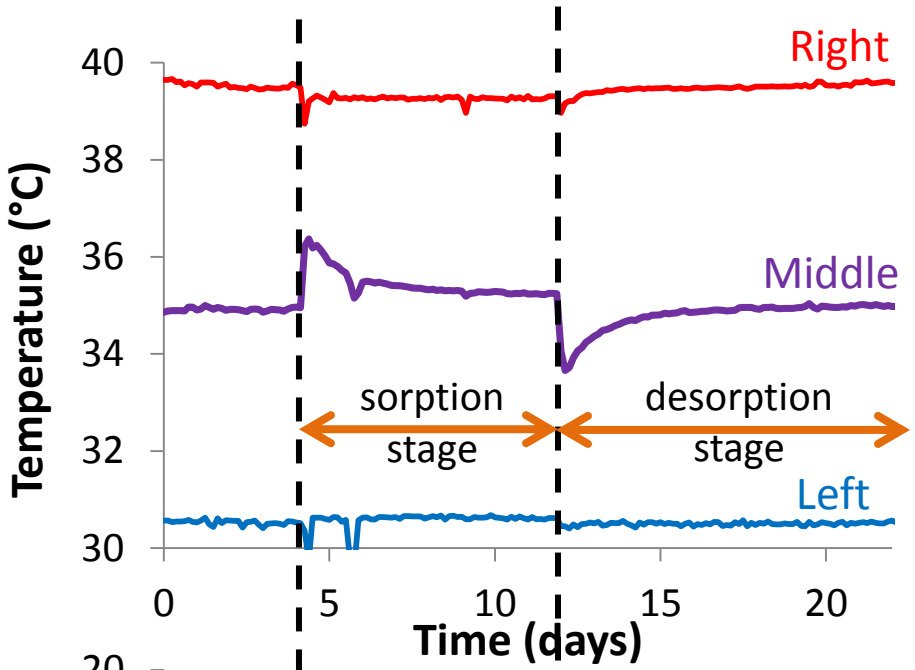
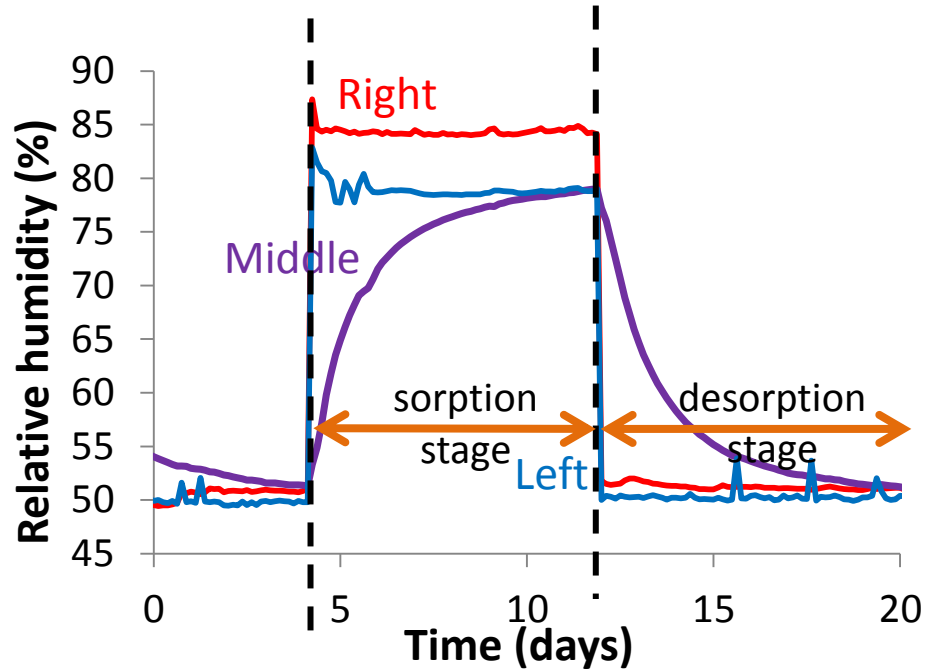
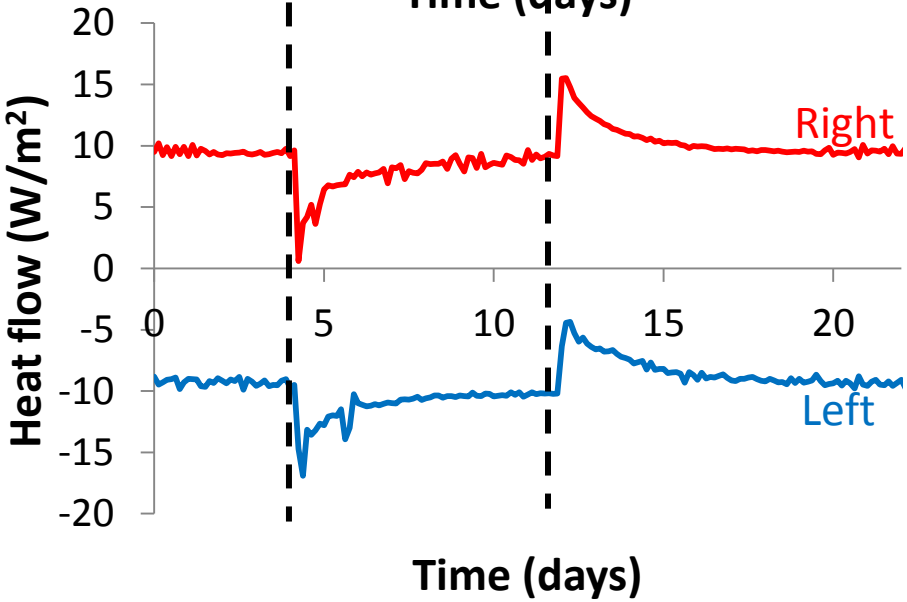
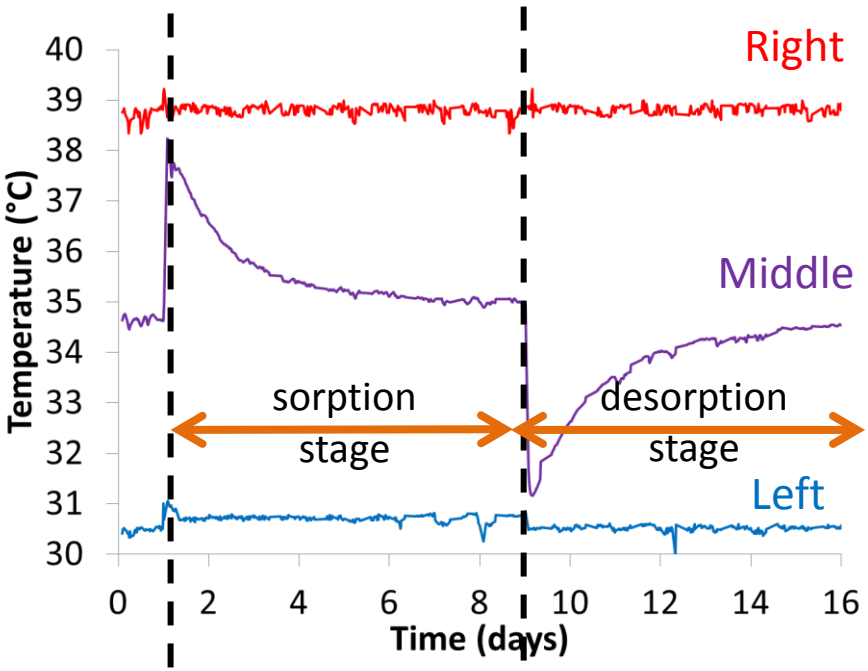


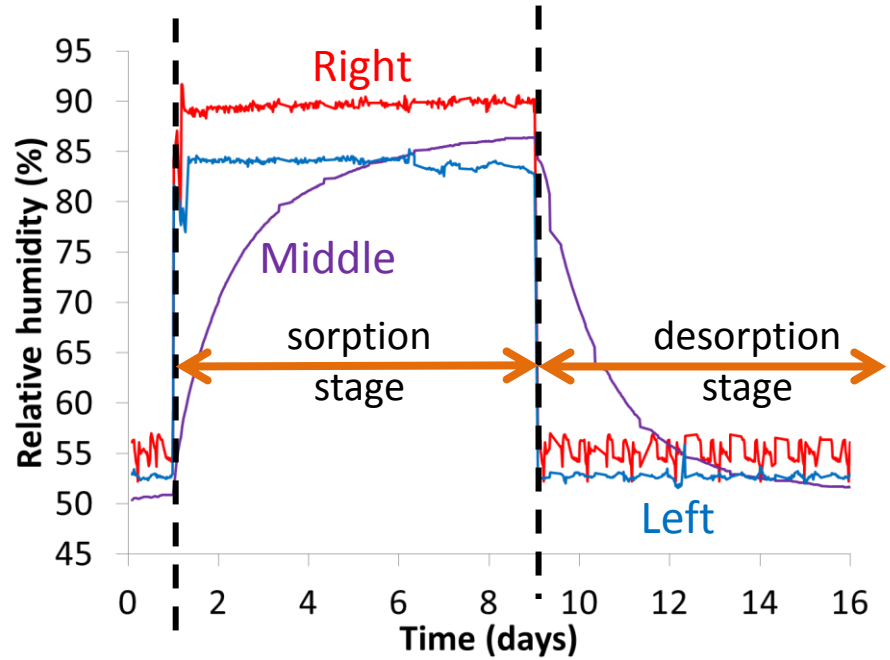


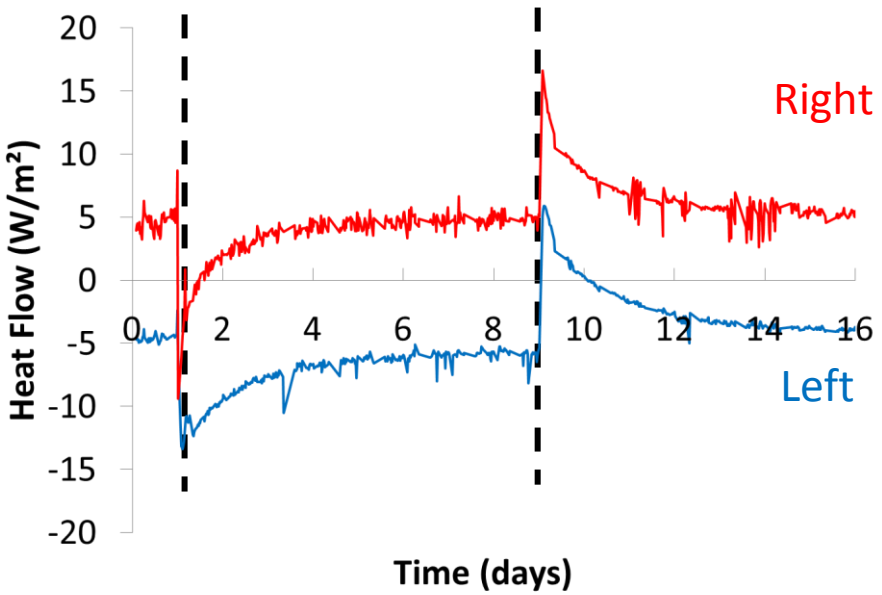


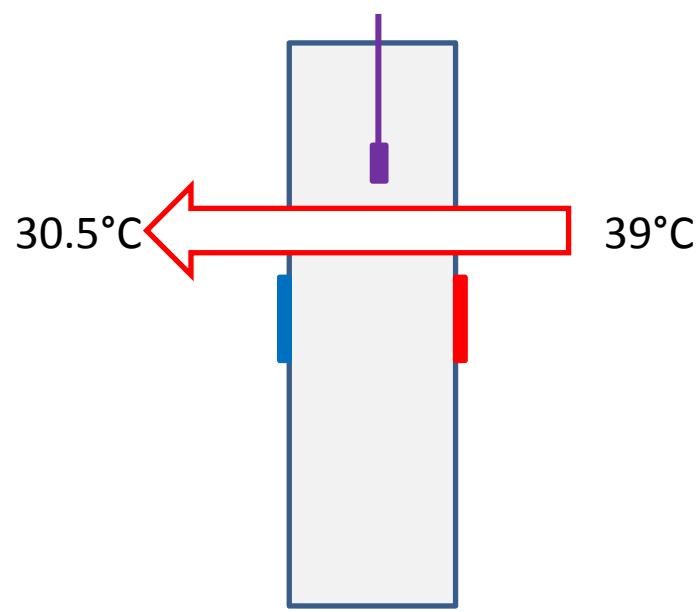
- **Sorption** = > Reduction of the incoming heat flow at the hot surface (=> reduction of the looses at the evening)
- **Desorption** => Reduction of the outgoing heat flow at the cold surface (=> keep the freshness during the day in summer)

Pure hemp results









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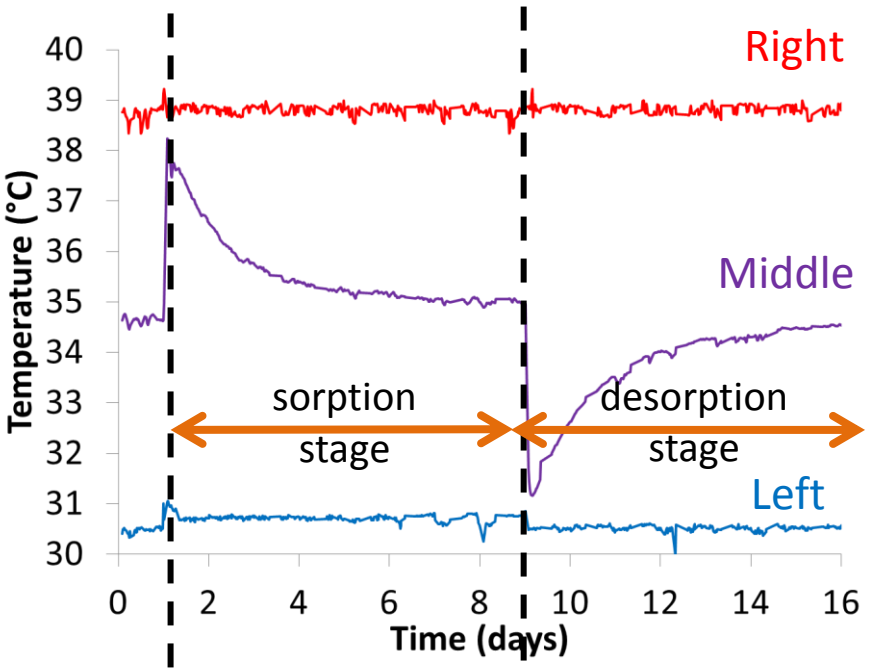

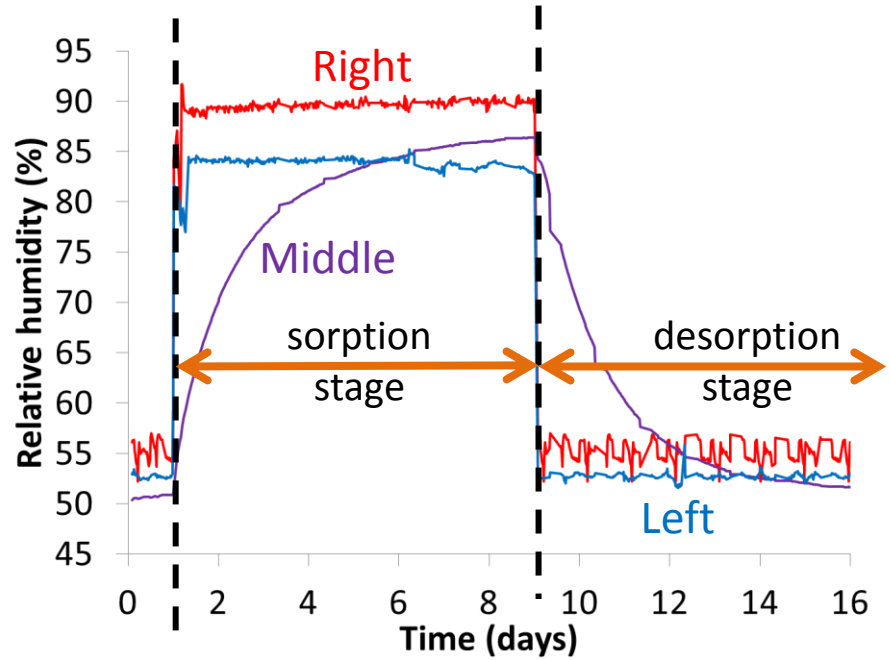

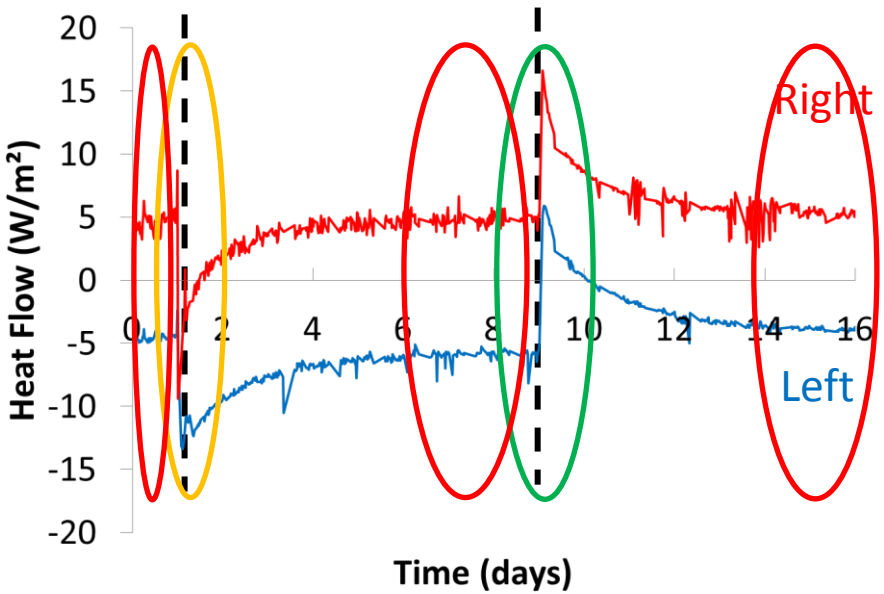

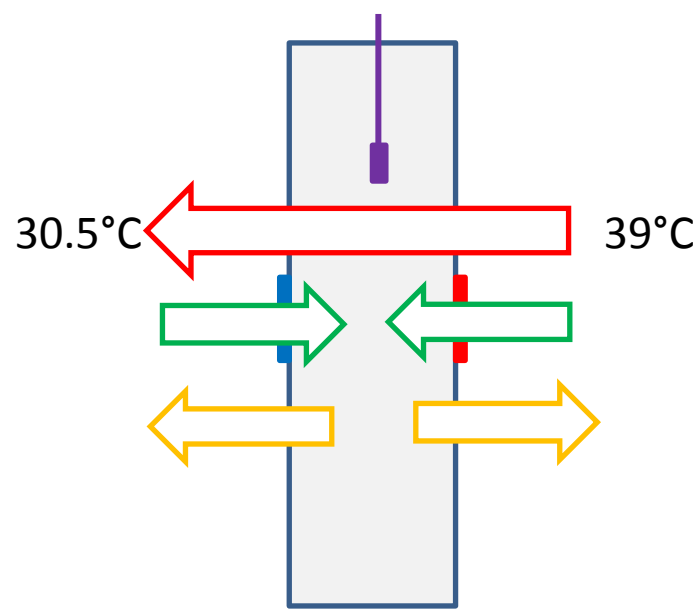

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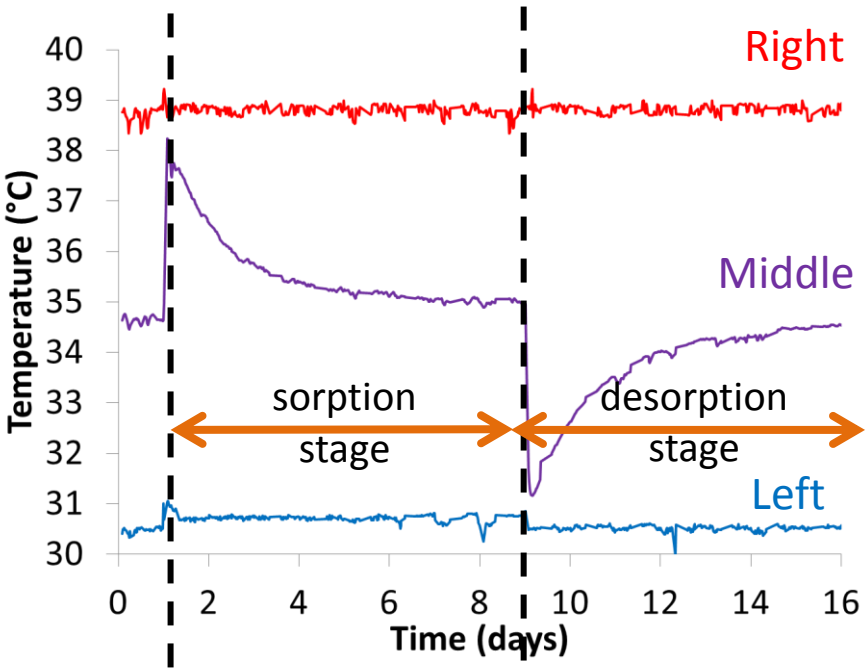
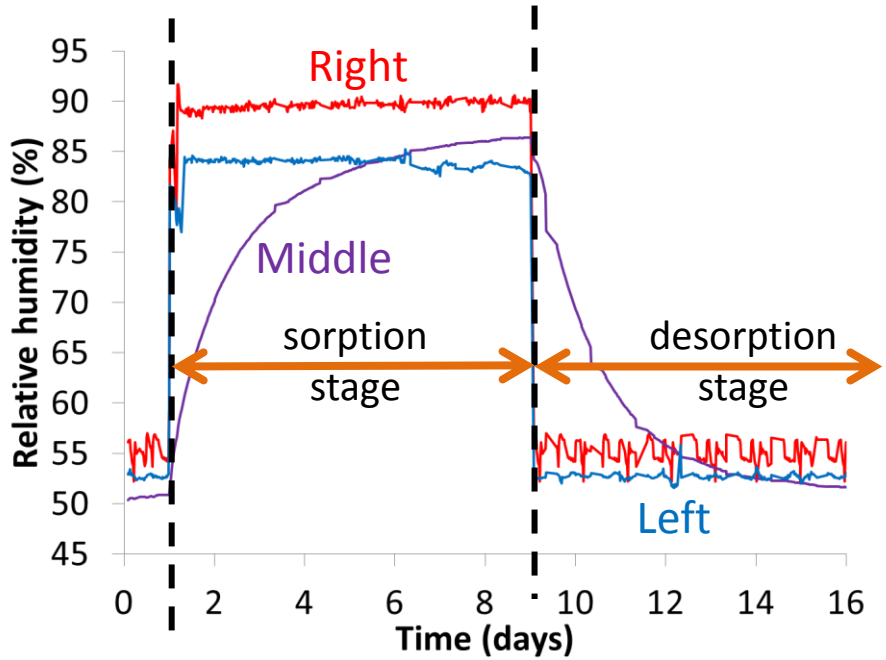
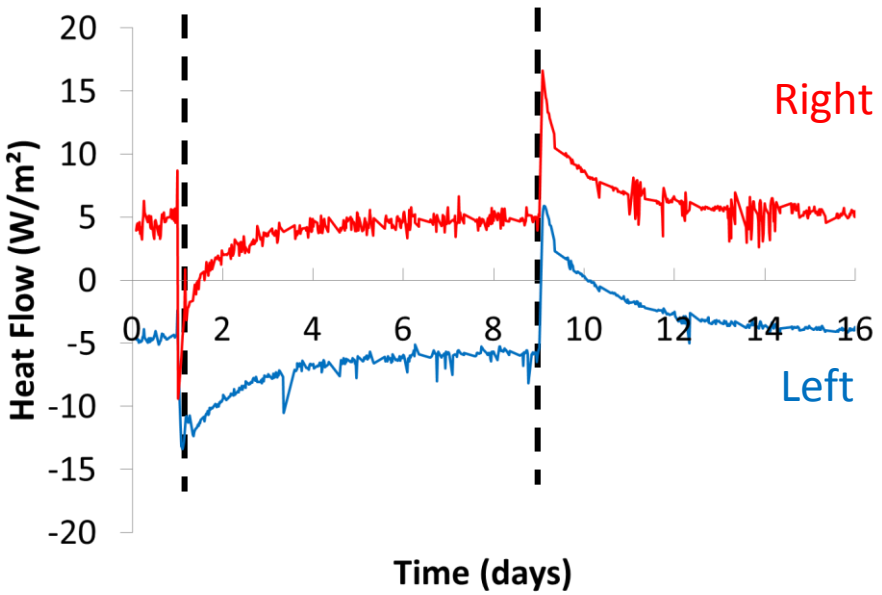


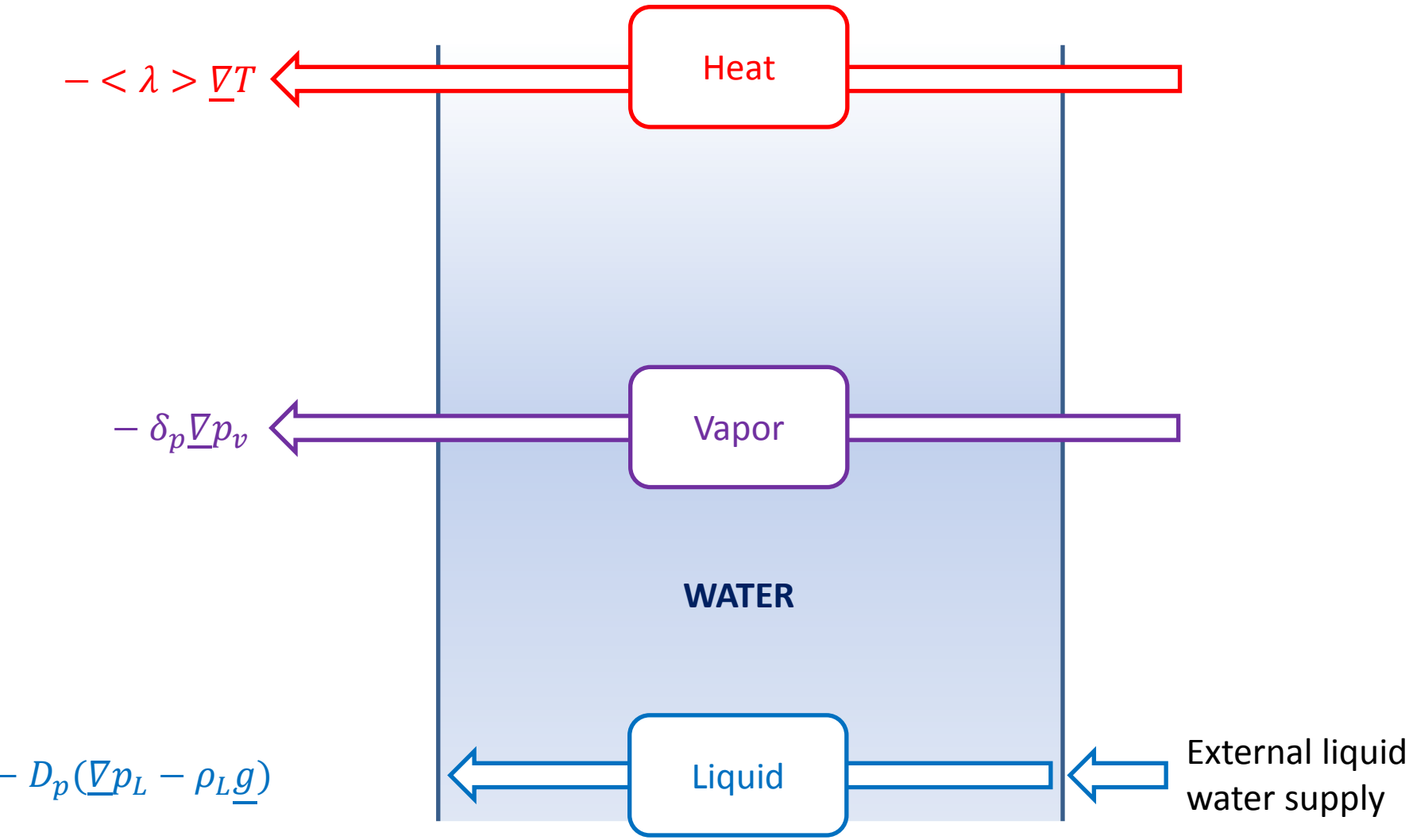




- Enhanced hygrothermal properties while the porosity is almost the same

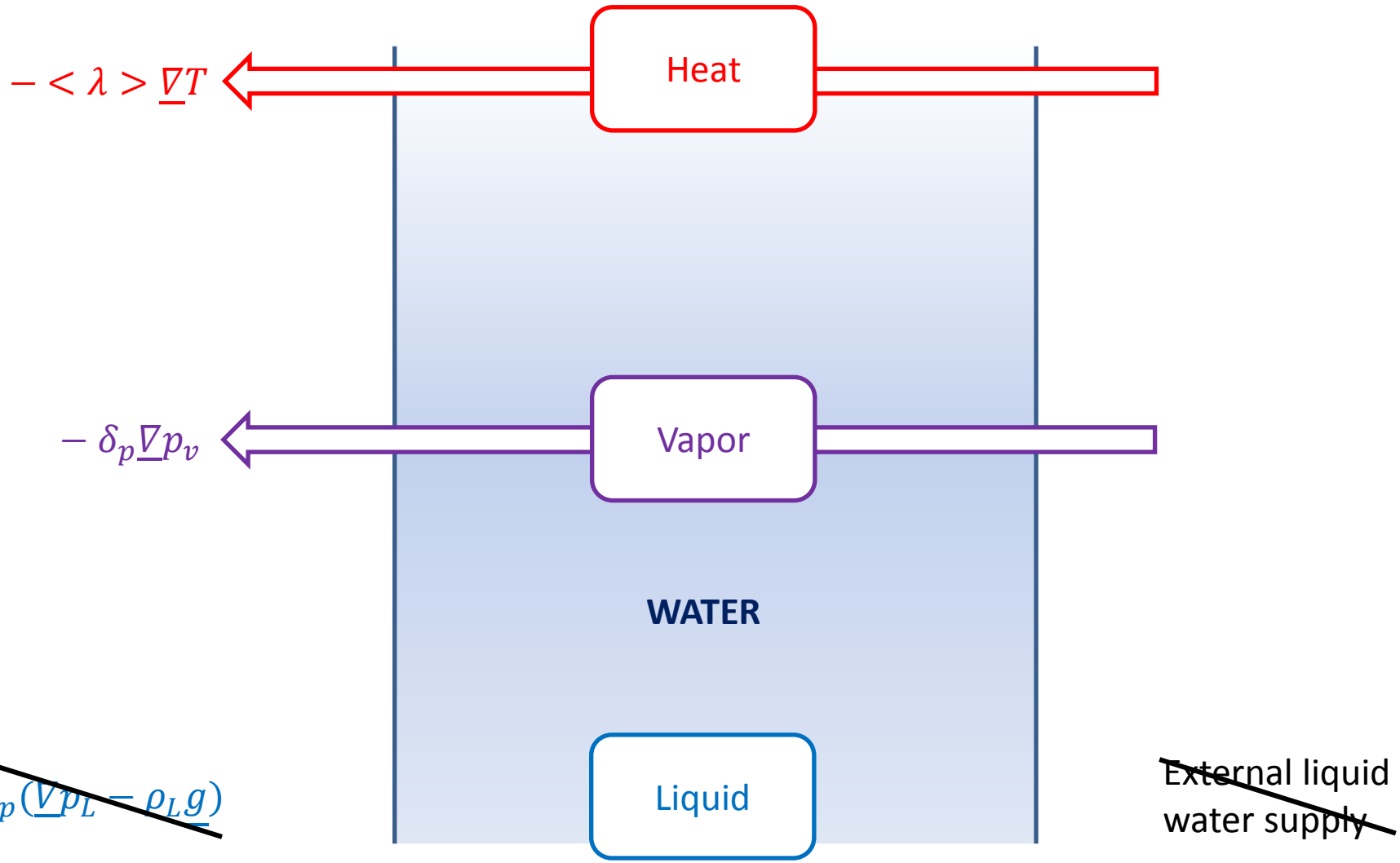
HT Modelling

Physical principles



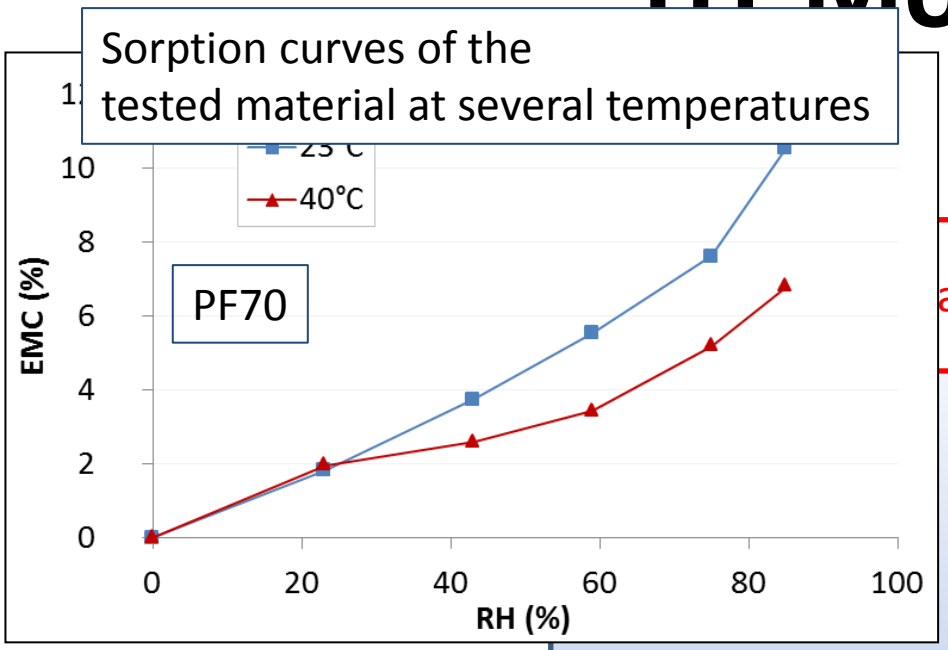
HT Modelling

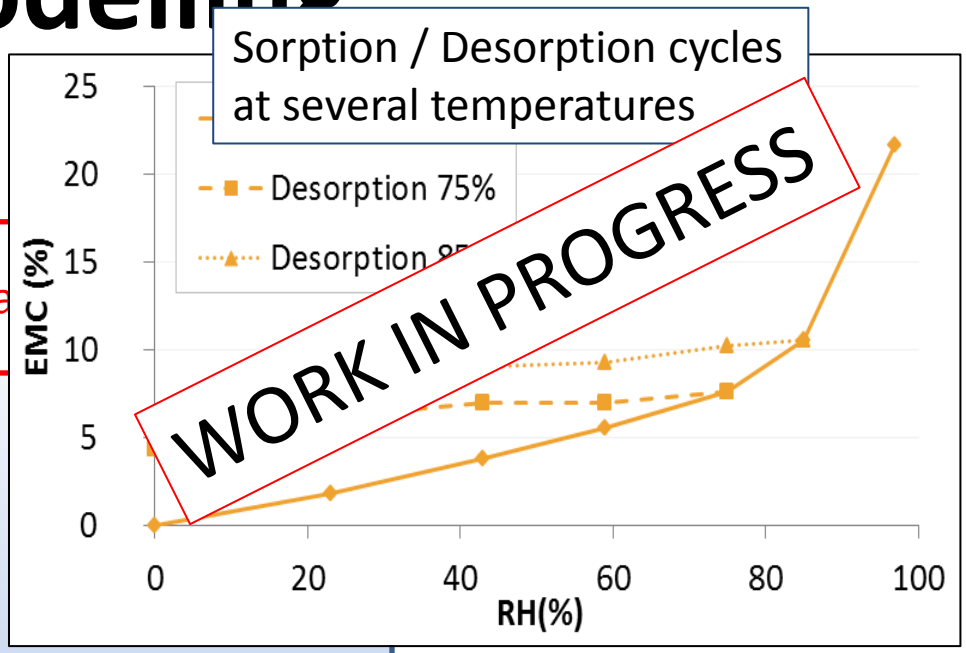
Physical principles

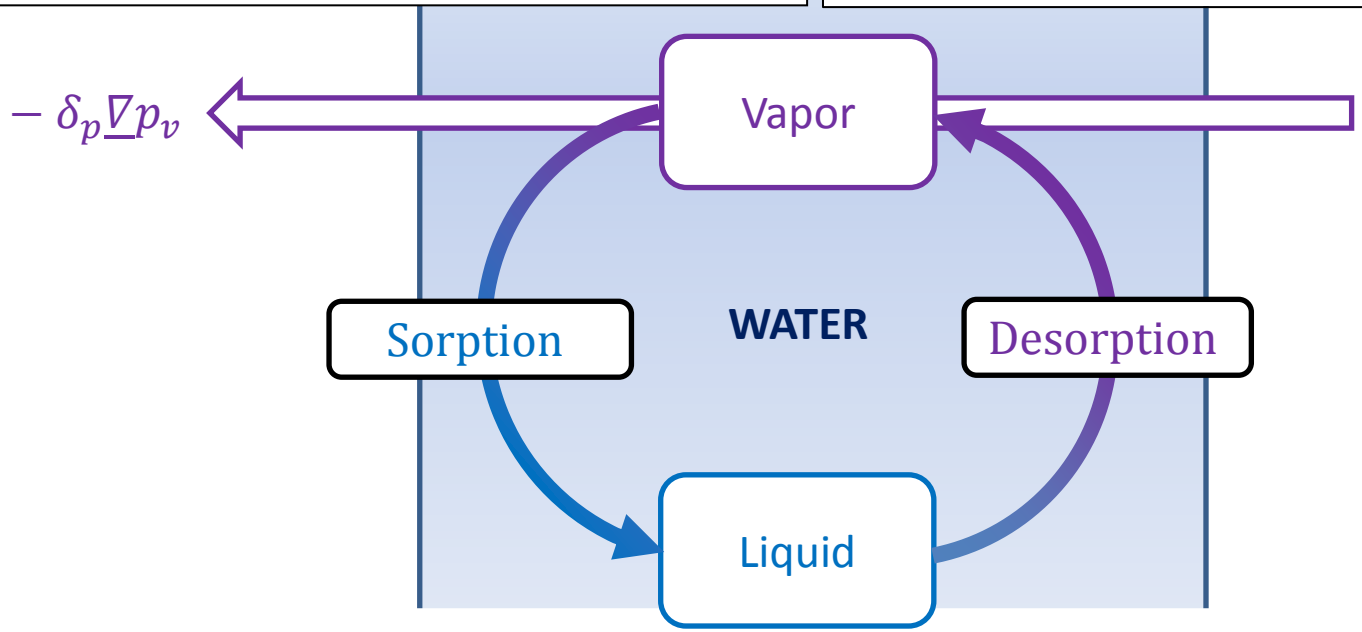


$D_p \approx 0$ for hemp concrete in the hygroscopic regime

HT Modelling







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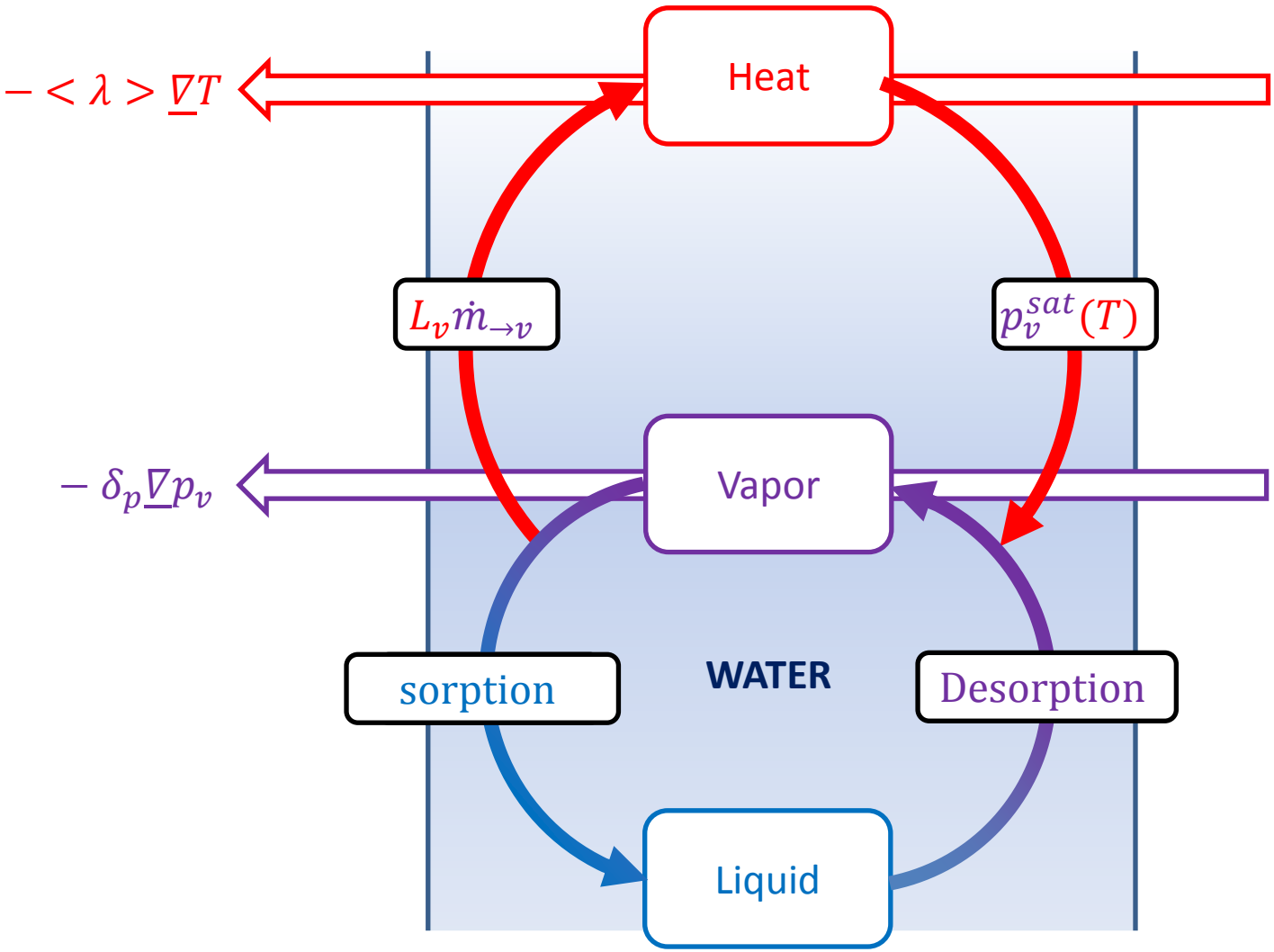

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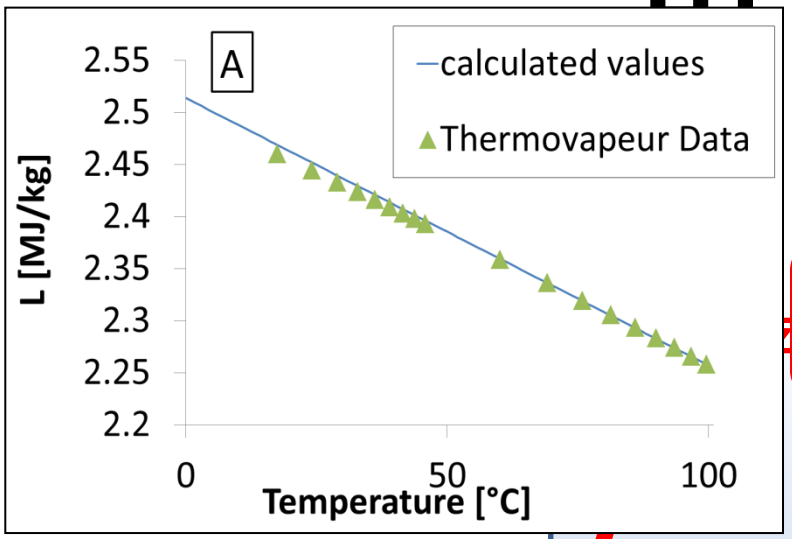

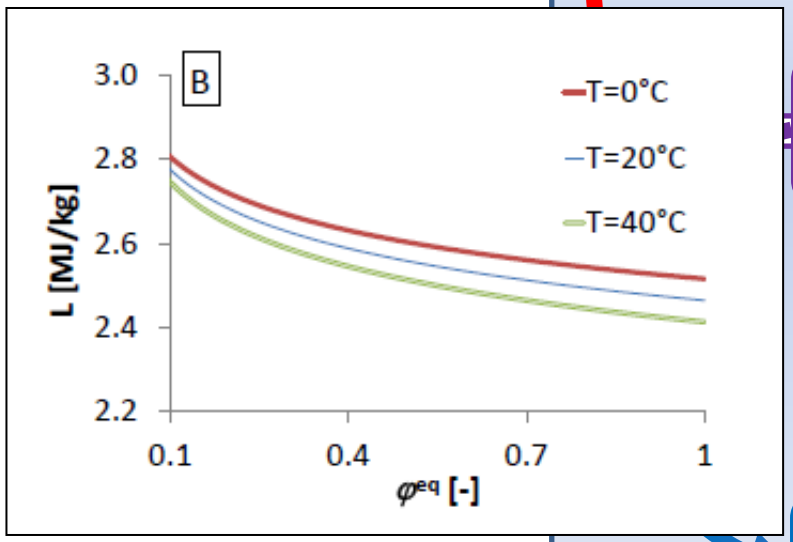

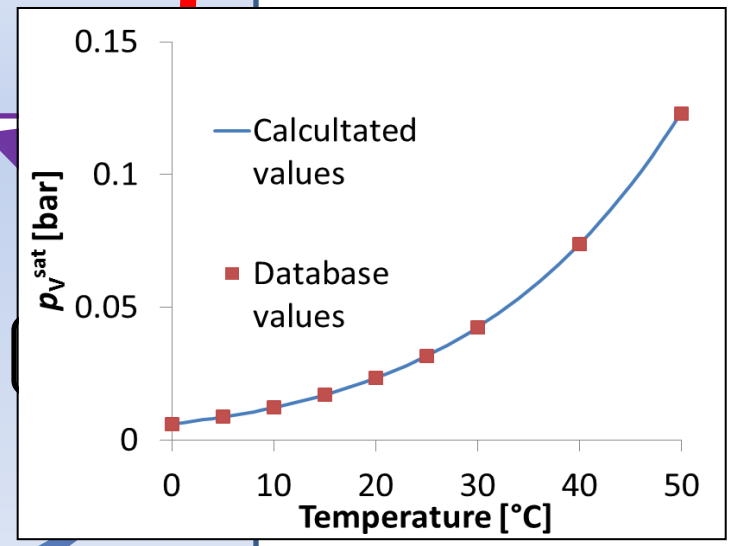

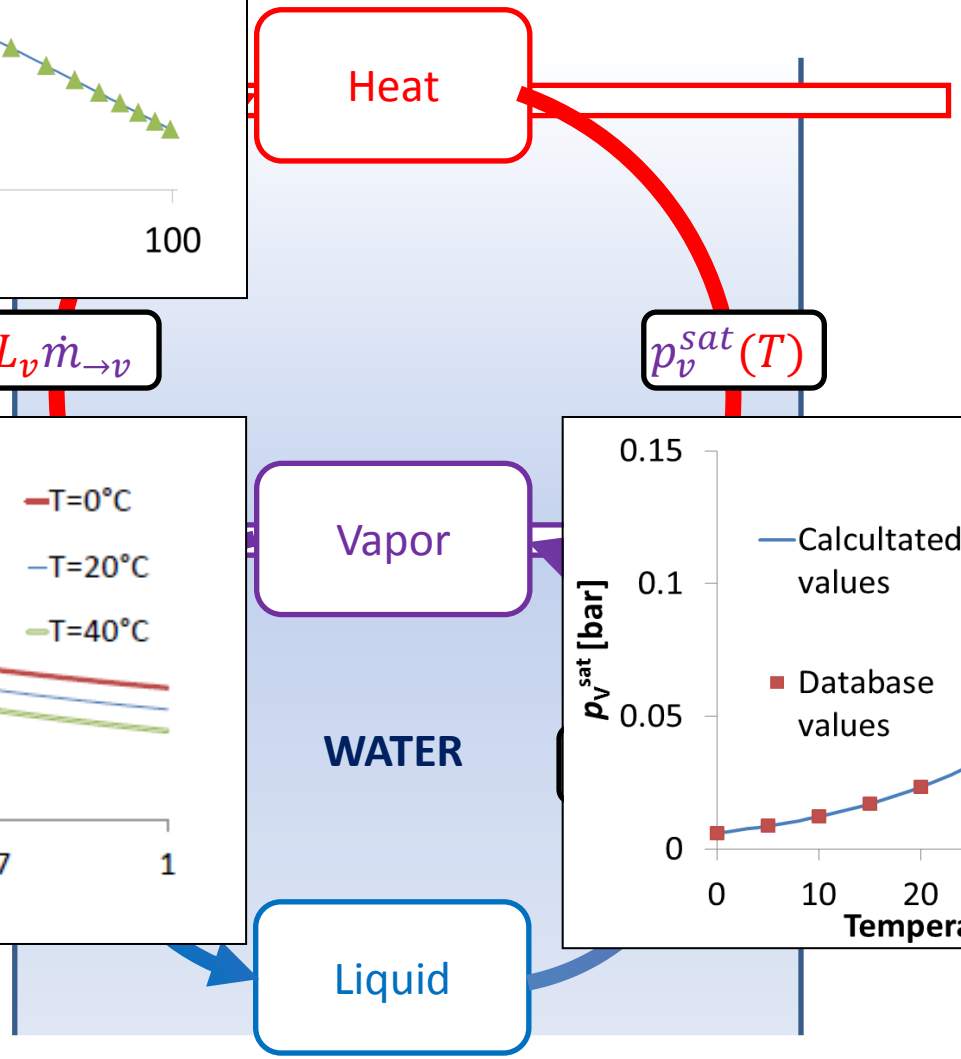

HT Modelling

Continuity equations

Heat balance :

$$< \rho C > \frac{\partial T}{\partial t} = \underline{\nabla} \cdot \left(< \lambda > \underline{\nabla} T \right) - L_v \dot{m}_{\rightarrow v}$$

Vapor mass balance :

$$m_{vs} \left(\frac{\partial \varphi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \underline{\nabla} \cdot \left(\delta_p \underline{\nabla} p_v \right) + \dot{m}_{\rightarrow v}$$

Water mass balance :

$$\rho_d \frac{\mathrm{d}\omega}{\mathrm{d}t} + m_{vs} \left(\frac{\partial \varphi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \underline{\nabla} \cdot \left(\delta_p \underline{\nabla} p_v + \cancel{D_p \underline{\nabla} p_l} \right)$$

<u>*Notations :*</u>

$< \rho C >$ **: average heat capacity at constant pressure**

$< \lambda >$ **: average thermal conductivity**

δ_p**: vapor diffusif transport coefficient**

$m_{vs} = \left(\phi - \frac{\rho_d}{\rho_l} \right) \frac{M_w p_{vs}}{R\,T}$ **: Mass of vapor at saturation with the RVE**

$\alpha_p = \varphi \left(\frac{1}{pvs} \frac{\mathrm{d}p_{vs}}{\mathrm{d}T} - \frac{1}{T} \right)$ **: Apparent thermal dilatation of vapor at constant hygrometry**

$D_p = \rho_L \frac{\kappa}{\eta}$ **: Transport coefficient of liquid water $\approx$ 0 for hemp concrete**

HT Modelling : common assumptions

Continuity equations

Heat balance :

$$< \rho C > \frac{\partial T}{\partial t} = \underline{\nabla} \cdot \left(< \lambda > \underline{\nabla} T \right) - L_v \dot{m}_{\rightarrow v}$$

$$\dot{m}_{\rightarrow v} \approx -\underline{\nabla} \cdot \left(\delta_p \underline{\nabla} p_v \right)$$

Vapor mass balance :

$$m_{vs} \left(\frac{\partial \varphi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \underline{\nabla} \cdot \left(\delta_p \underline{\nabla} p_v \right) + \dot{m}_{\rightarrow v}$$

Water mass balance :

$$\rho_d \frac{\mathrm{d}\omega}{\mathrm{d}t} + m_{vs} \left(\frac{\partial \varphi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \underline{\nabla} \cdot \left(\delta_p \underline{\nabla} p_v + D_p \underline{\nabla} p_l \right)$$

H1 : Variation of mass of vapor negligible

HT Modelling : common assumptions

Continuity equations

Heat balance :

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$$p_l = p_0 + \rho_l \frac{RT}{M_l} \ln \varphi \quad \Rightarrow \quad \frac{\partial \omega}{\partial t} = \frac{\partial \omega}{\partial \varphi} \frac{\partial \varphi}{\partial t} + \frac{\partial \omega}{\partial T} \frac{\partial T}{\partial t}$$

H1 : Variation of mass of vapor negligible

H2 : Equilibrium between the liquid water and the vapor within the pores

HT Modelling : common assumptions

Continuity equations

Heat balance :

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H1 : Variation of mass of vapor negligible

H2 : Equilibrium between the liquid water and the vapor within the pores

H3 : Influence of *T* on water content at constant φ négligible

HT Modelling : Equilibrium model

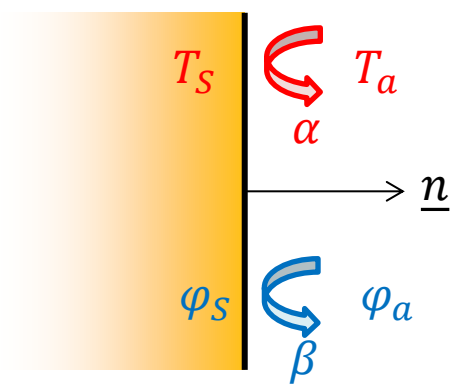
Final set of equations

$$< \rho C > \frac{\partial T}{\partial t} = \underline{\nabla} \cdot \left(< \lambda > \underline{\nabla} T \right) + L_v \underline{\nabla} \cdot \left(\delta_p \underline{\nabla} p_v \right)$$

$$\rho_d \frac{\partial \omega}{\partial \varphi} \frac{\partial \varphi}{\partial t} = \underline{\nabla} \cdot \left(\delta_p \underline{\nabla} p_v \right) \quad \text{where} \quad p_v = \varphi \, p_v^{sat}(T)$$

Boundary conditions

$$\begin{bmatrix} \left(\underline{q} + L \underline{g_v} \right) \cdot \underline{n} \\ \left(\underline{g_v} + \underline{g_l} \right) \cdot \underline{n} \end{bmatrix} = \begin{bmatrix} -\left(\lambda \underline{\nabla T} + \delta_p \underline{\nabla} p_v \right) \cdot \underline{n} \\ -\left(\delta_p \underline{\nabla} p_v + \cancel{D_p \underline{\nabla} p_l} \right) \cdot \underline{n} \end{bmatrix} = \begin{bmatrix} \alpha (T_a - T_s) + L_v \beta \left(p_v^{sat}(T_a) \, \varphi_a - p_v^{sat}(T_s) \varphi_S \right) \\ \beta \left(p_v^{sat}(T_a) \, \varphi_a - p_v^{sat}(T_s) \varphi_S \right) \end{bmatrix}$$



HT Modelling : Equilibrium model

Final set of equations

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$$\rho_d \frac{\partial \omega}{\partial \varphi} \frac{\partial \varphi}{\partial t} = \underline{\nabla} \cdot \left(\delta_p \underline{\nabla} p_v \right) \quad \text{where} \quad p_v = \varphi \, p_v^{sat}(T)$$

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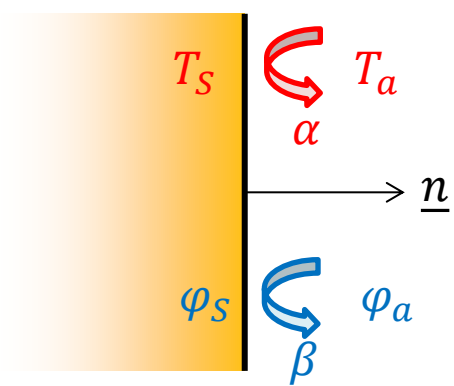
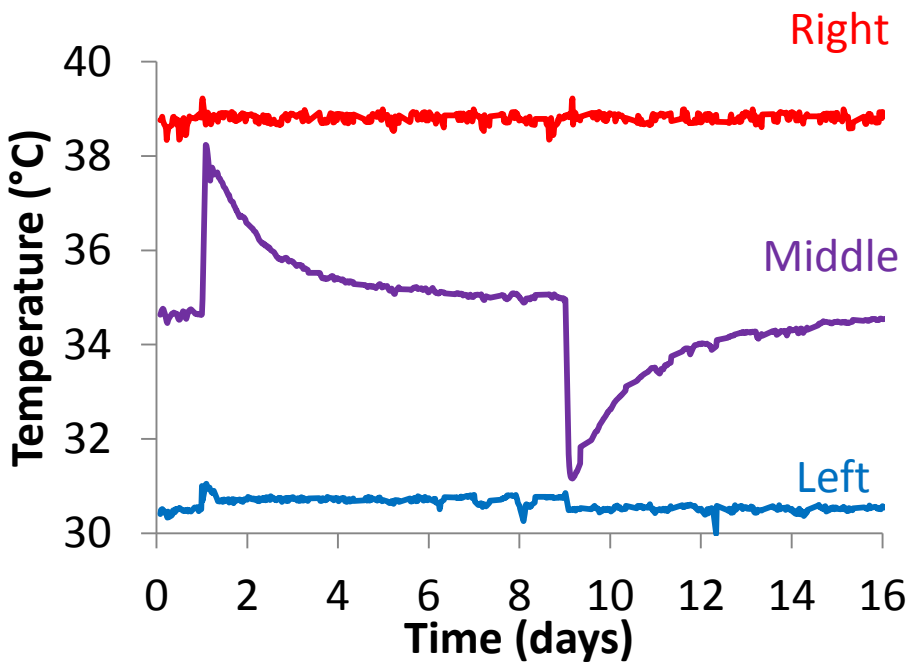
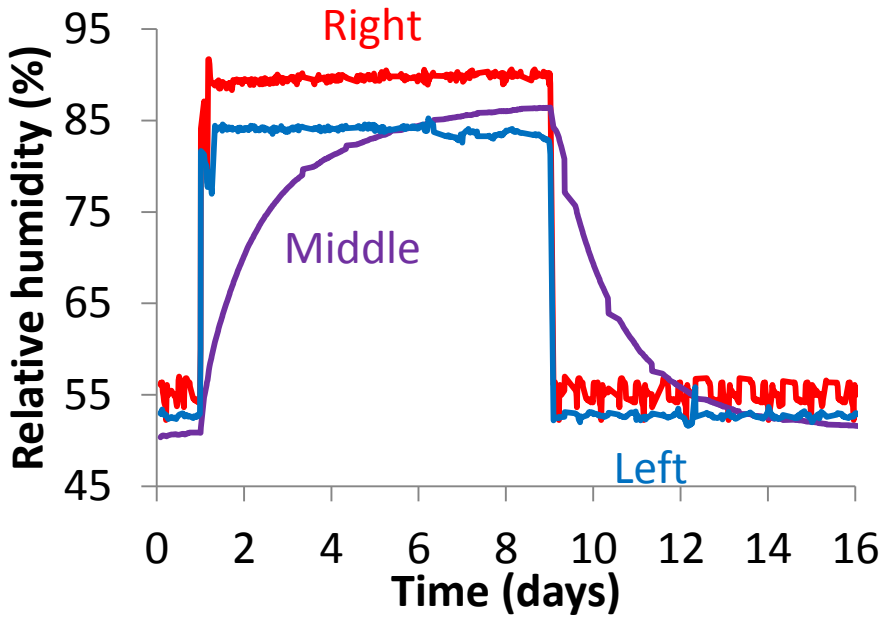
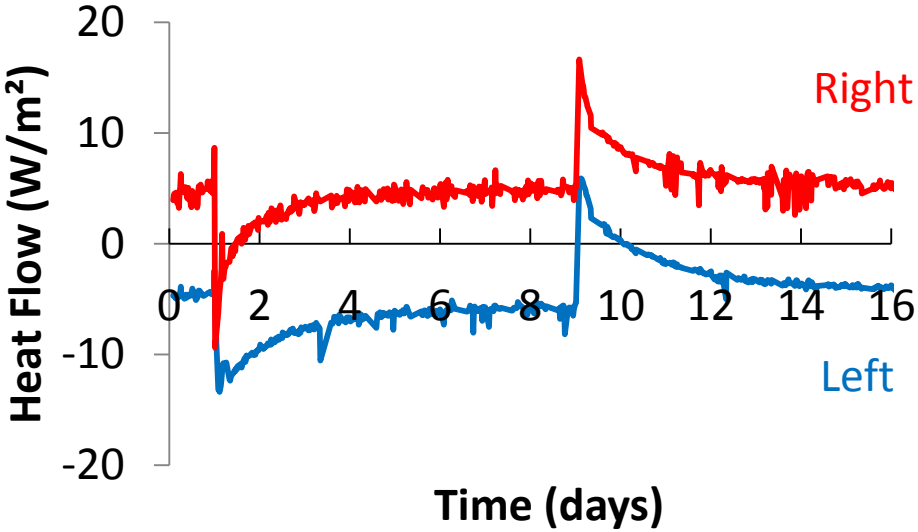
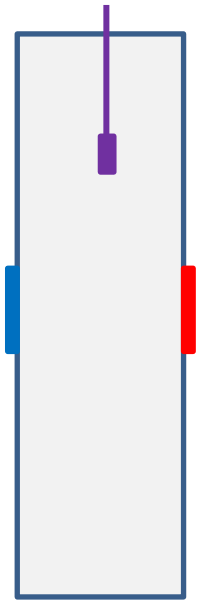


Model *VS* experiment : Pure Hemp

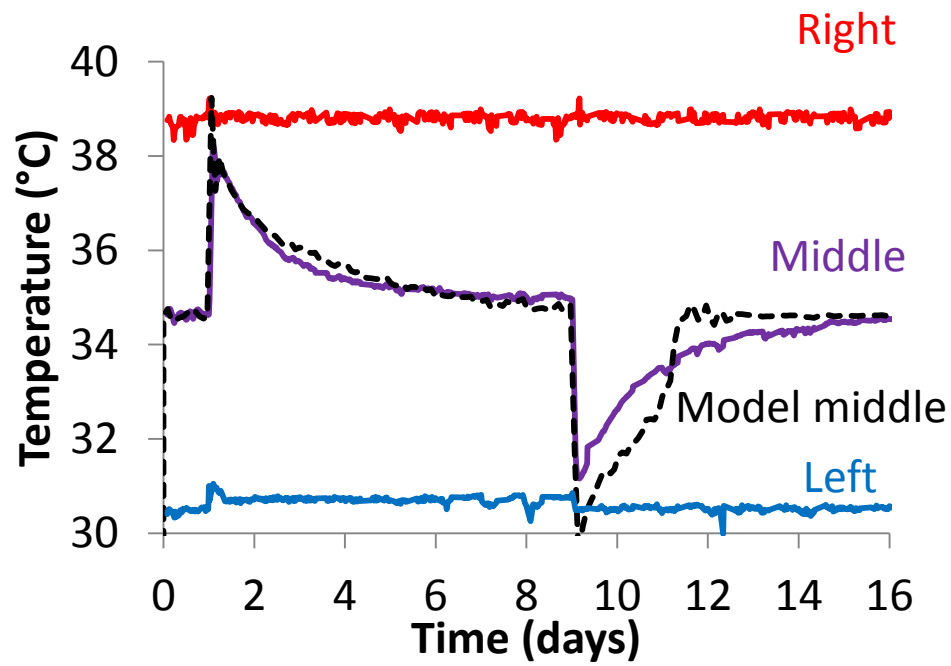


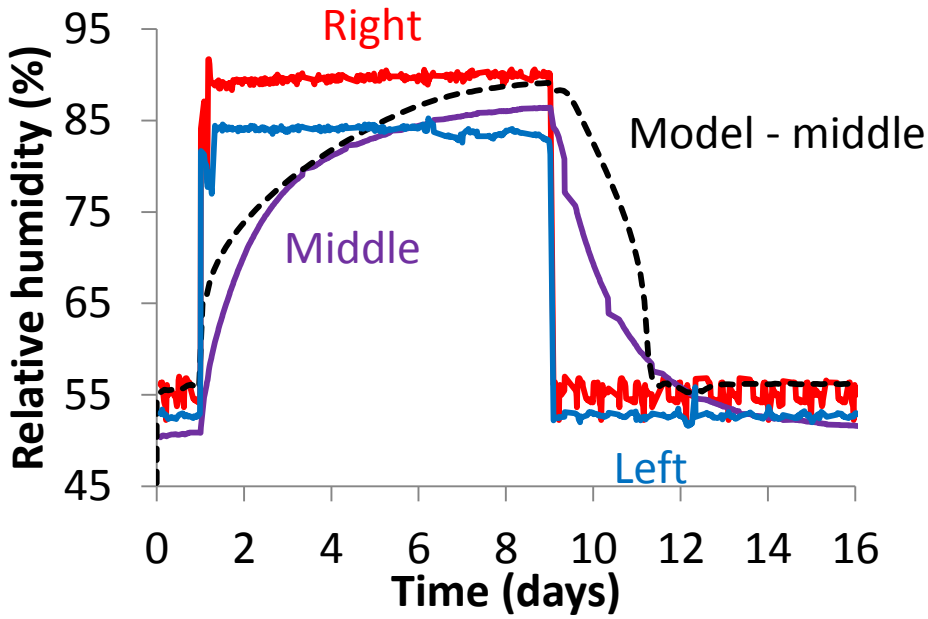


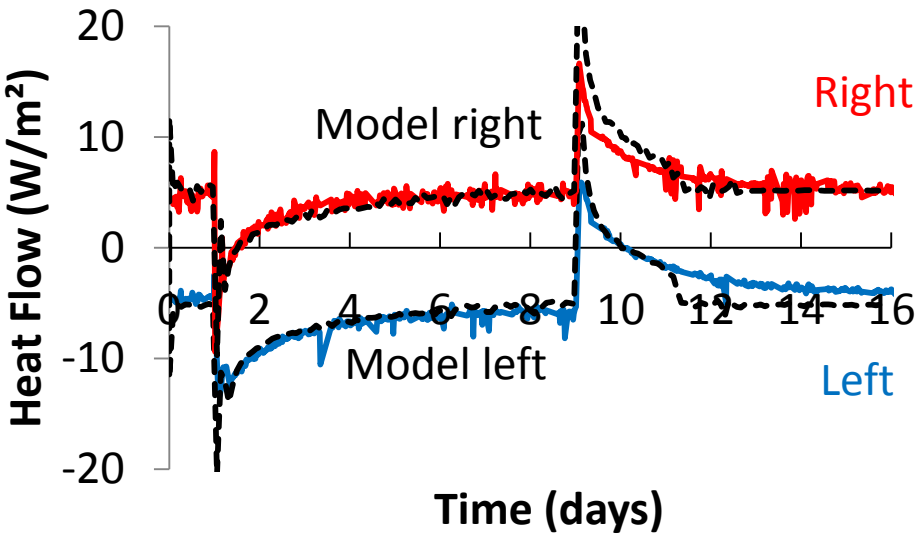


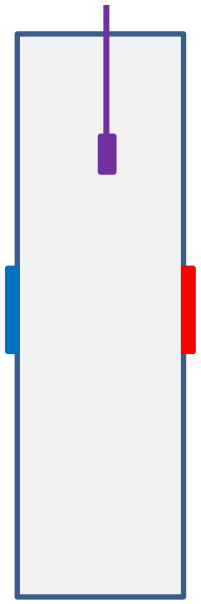


Model *VS* experiment : Pure Hemp

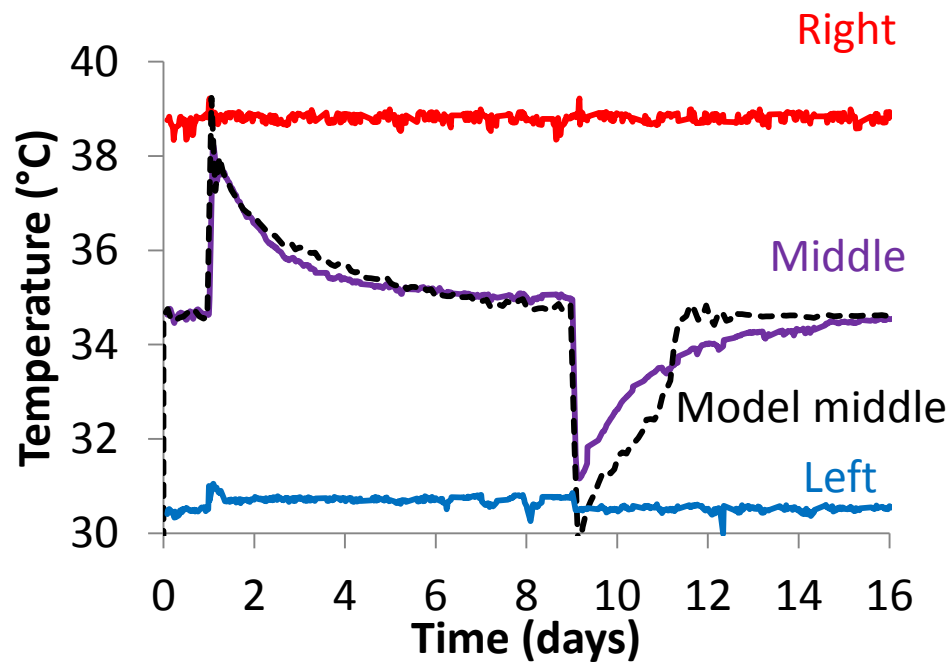


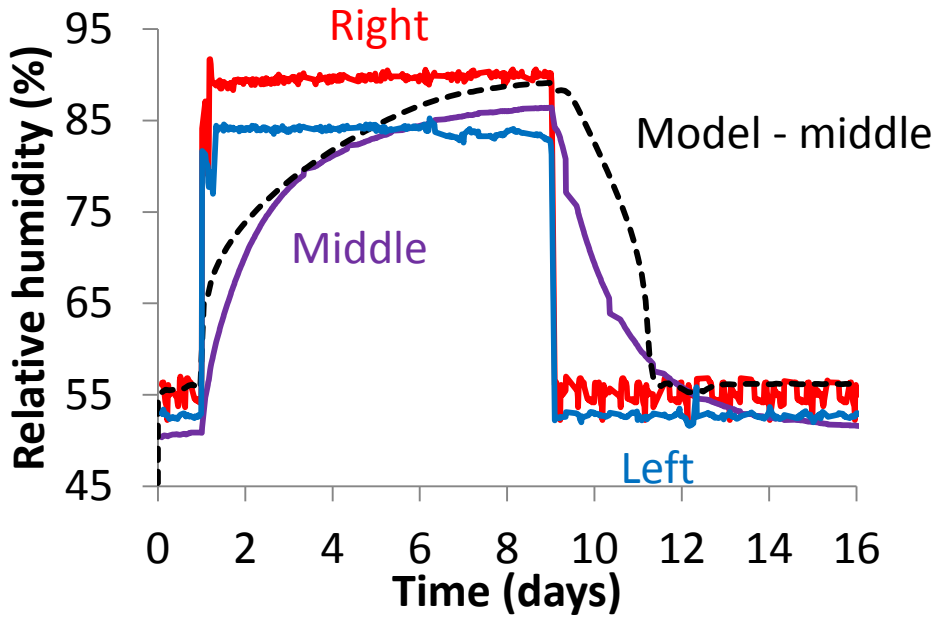


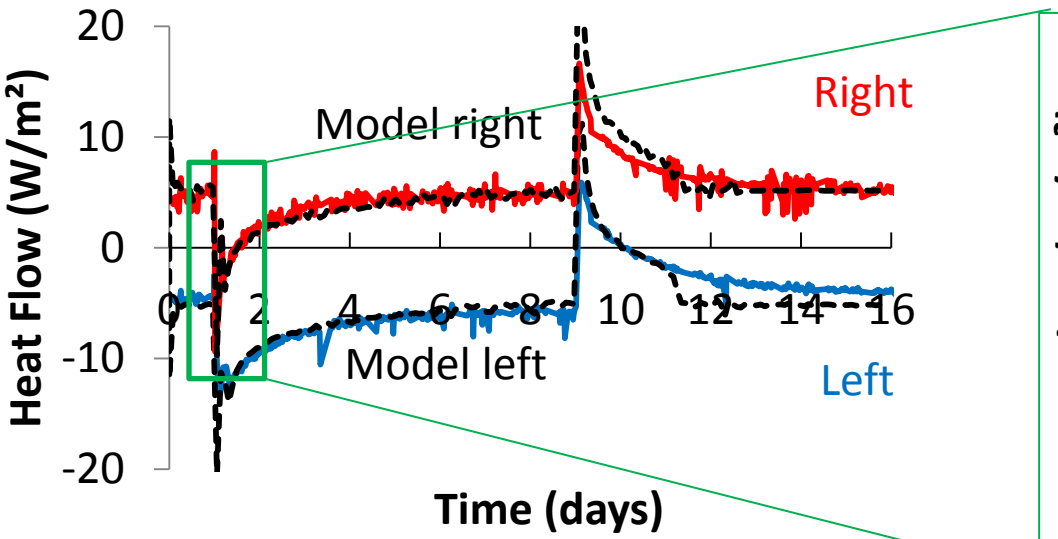


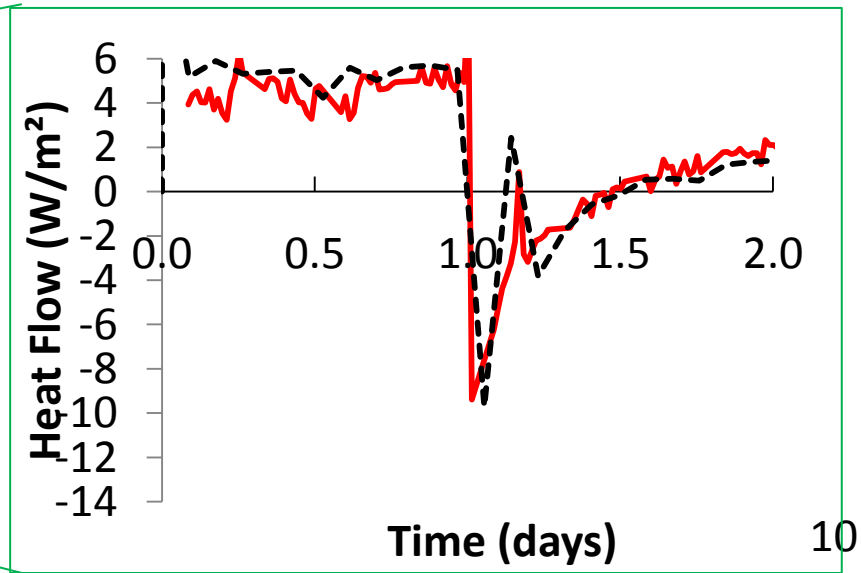


Model *VS* experiment : Pure Hemp

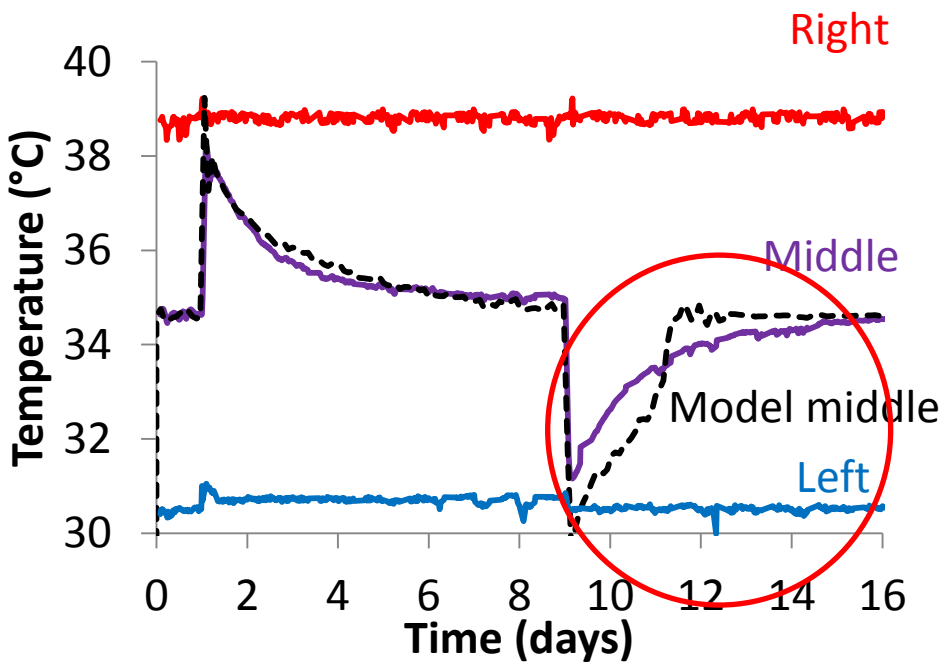


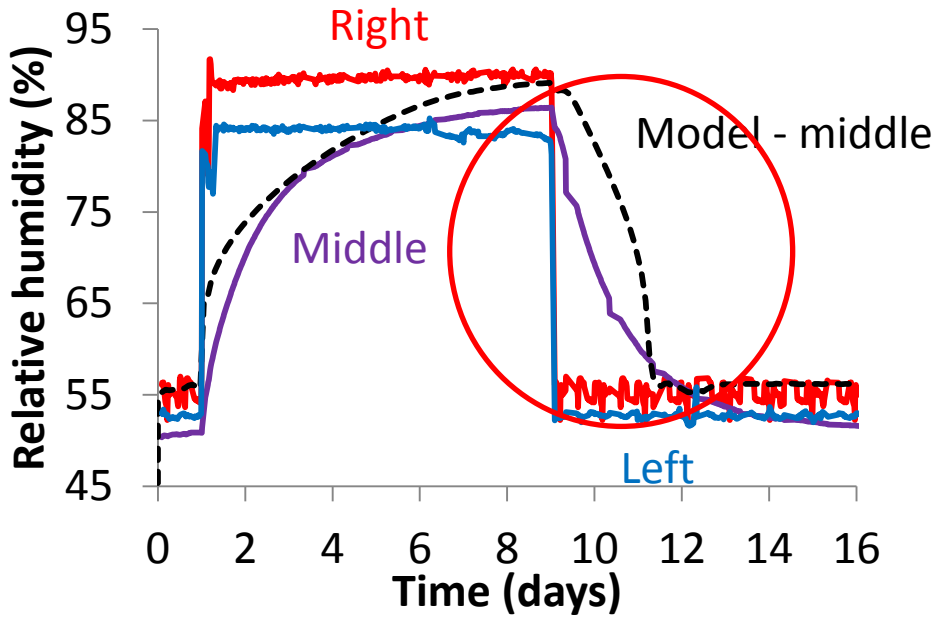


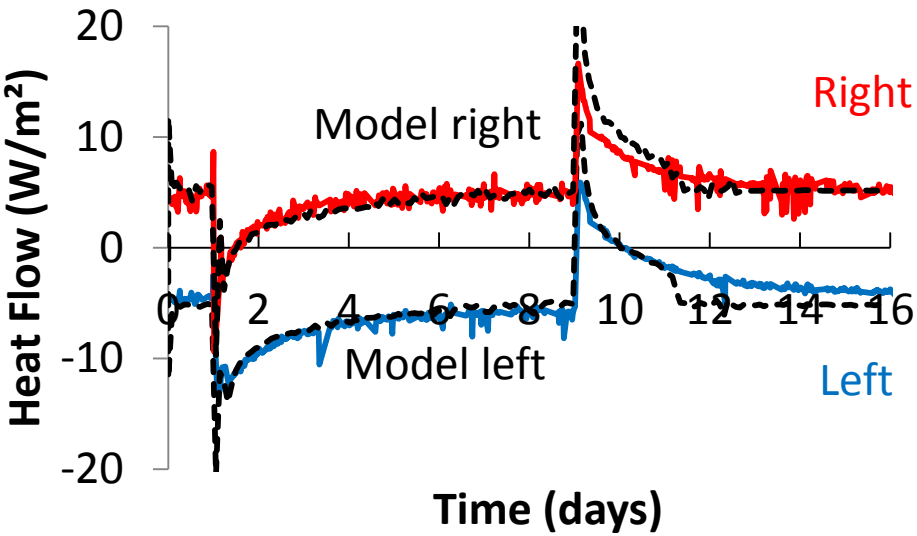




Model *VS* experiment : Pure Hemp

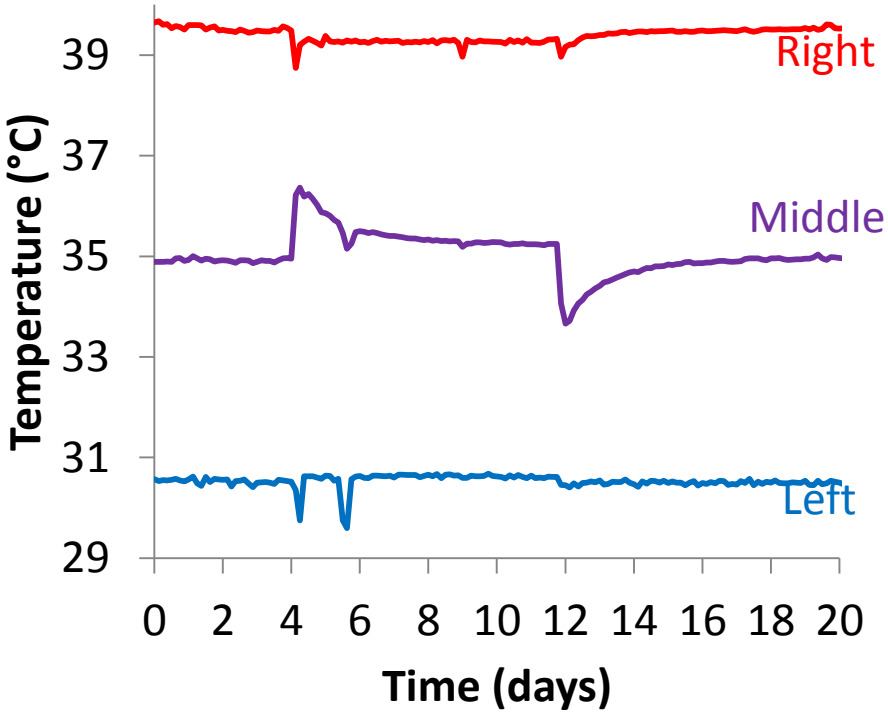


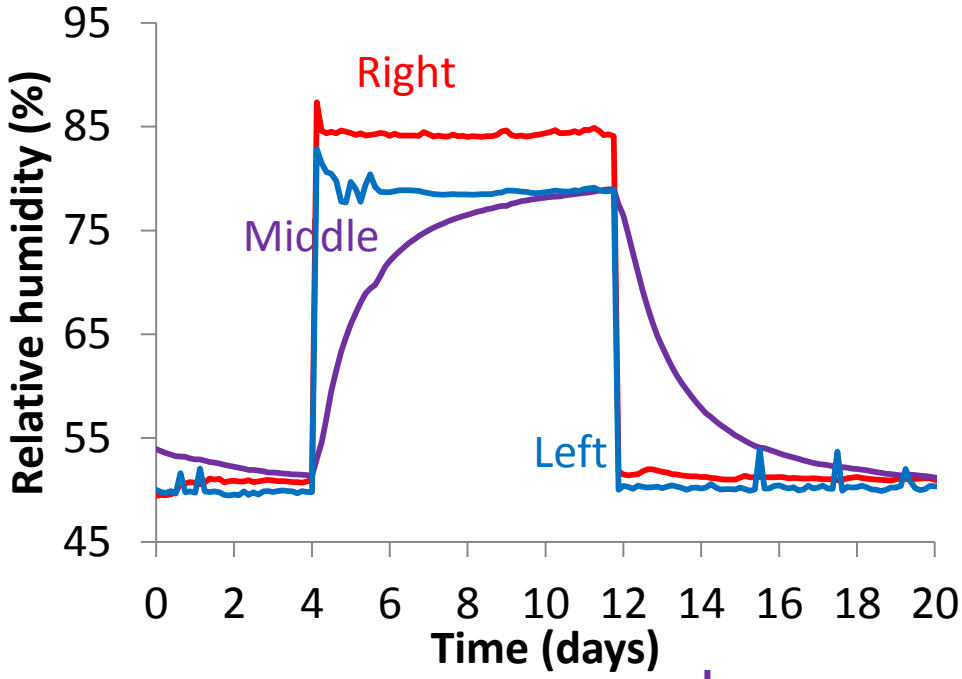


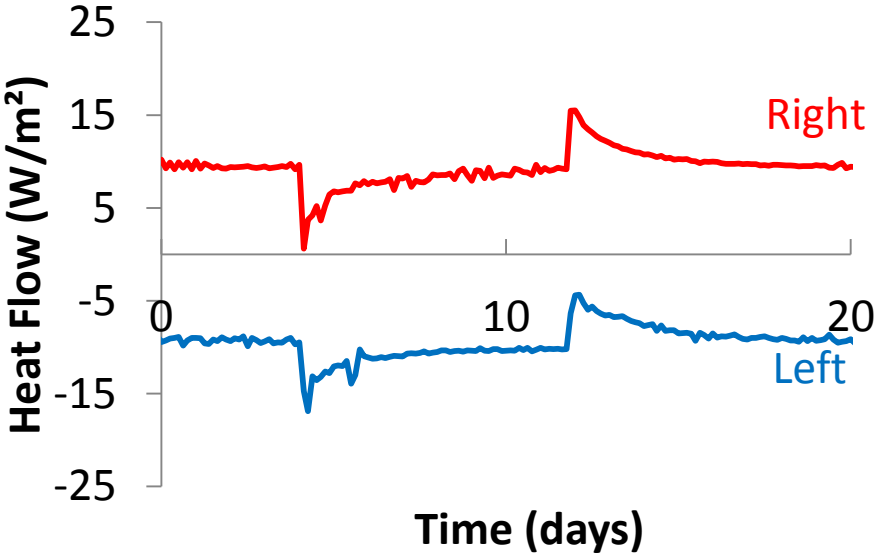


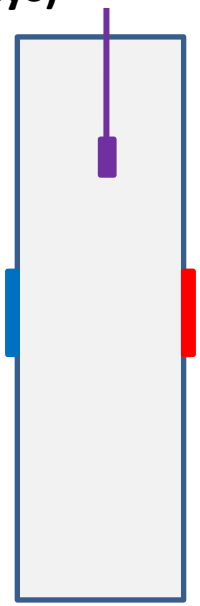
- Good agreement between experimental data and model in sorption
- Important differences in desorption => need to use the desorption curve

Model *VS* experiment : Hemp Concrete

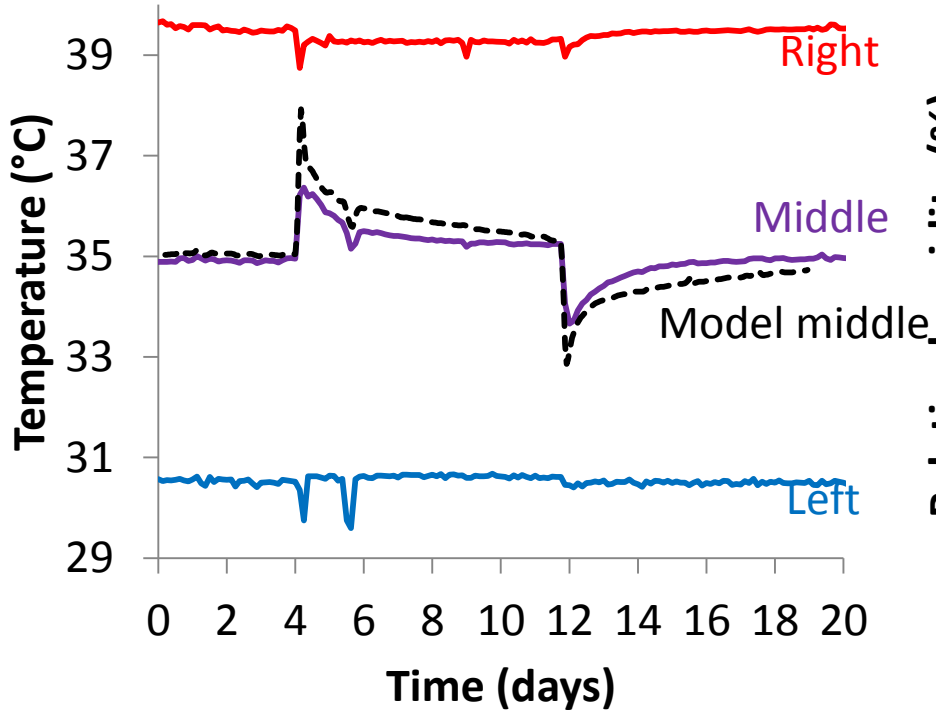


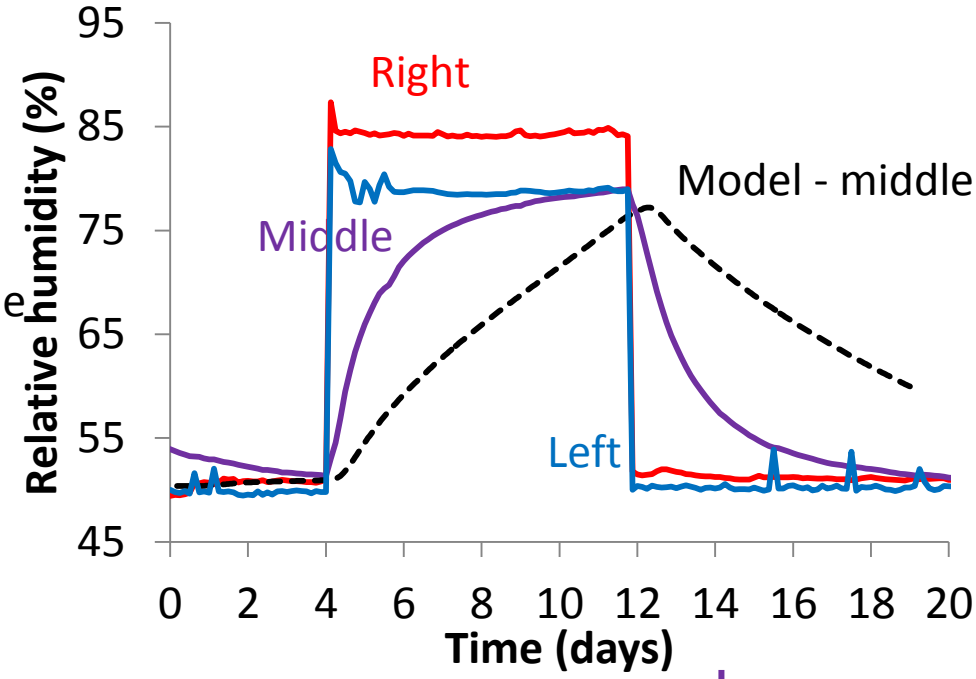


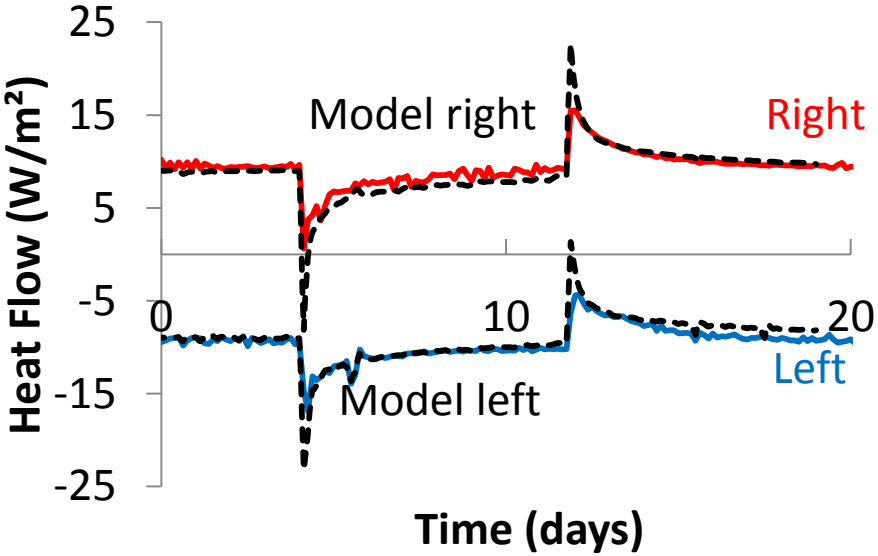


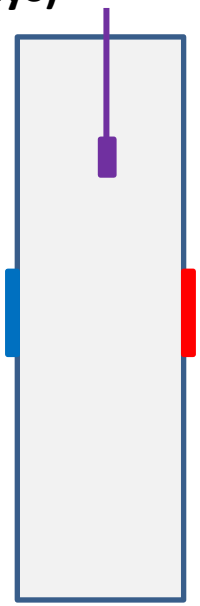


Model *VS* experiment : Hemp Concrete









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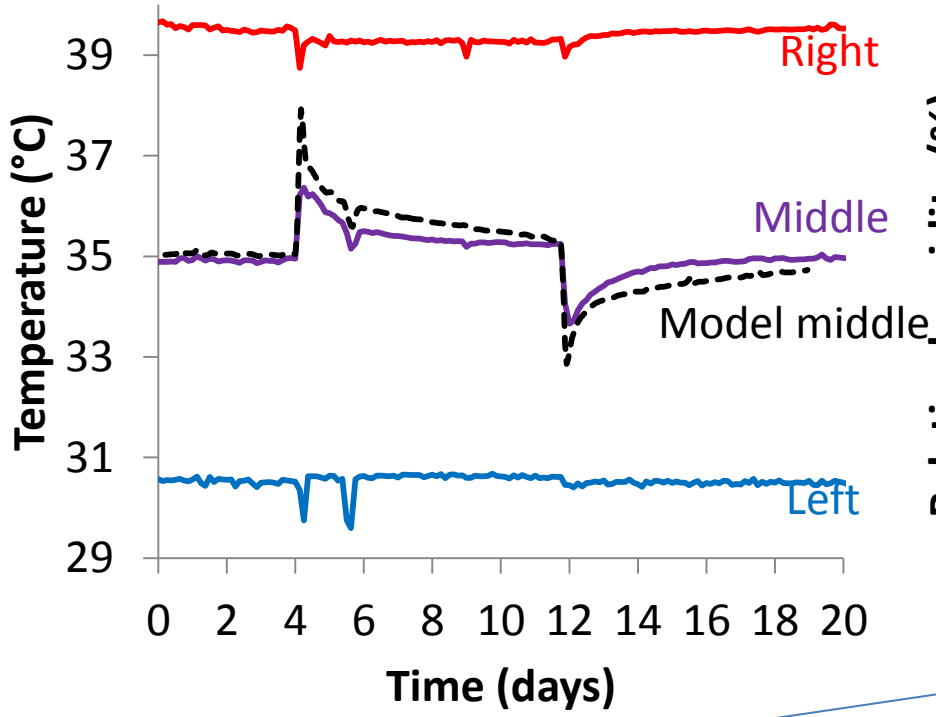
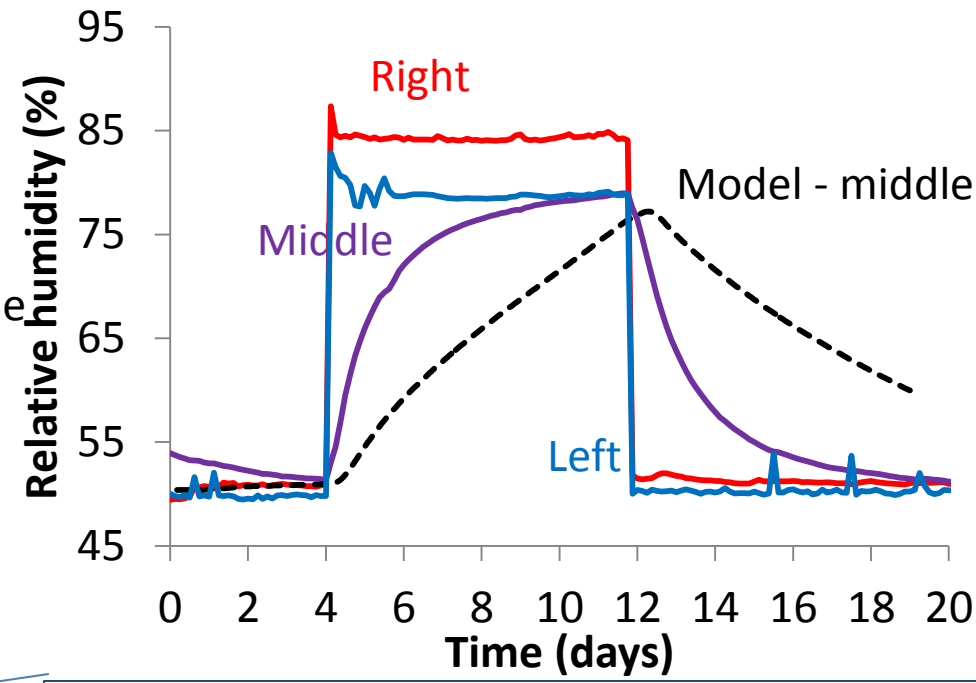
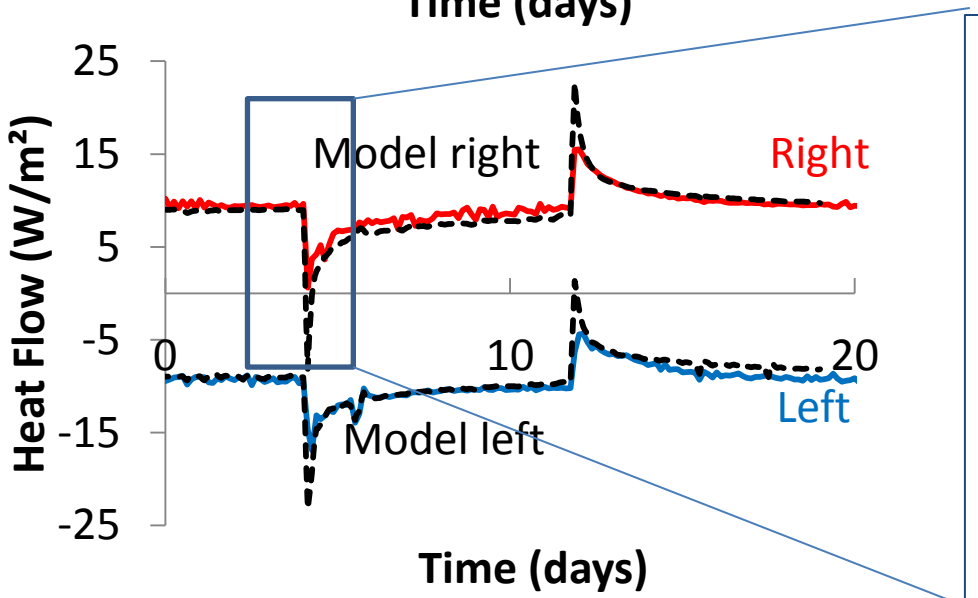
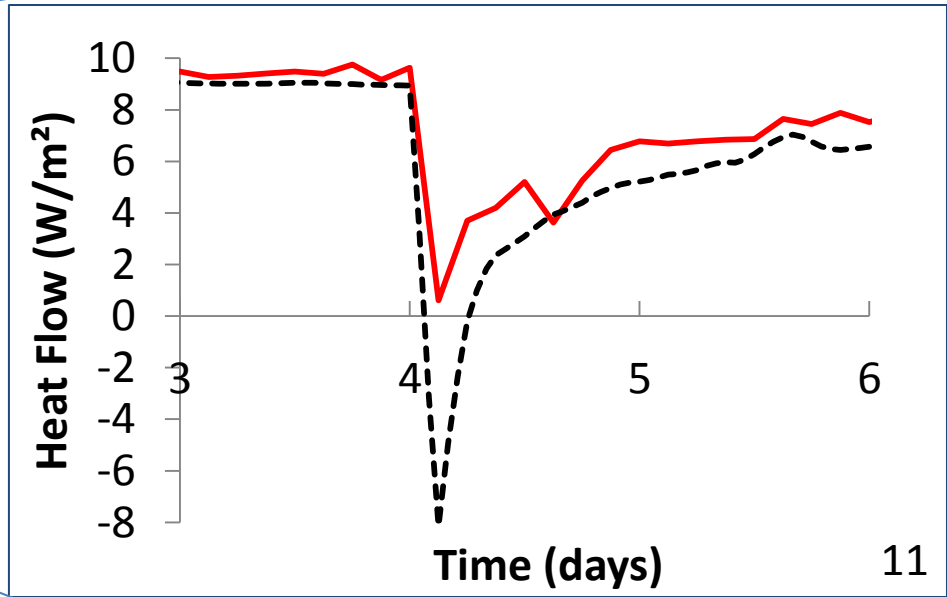
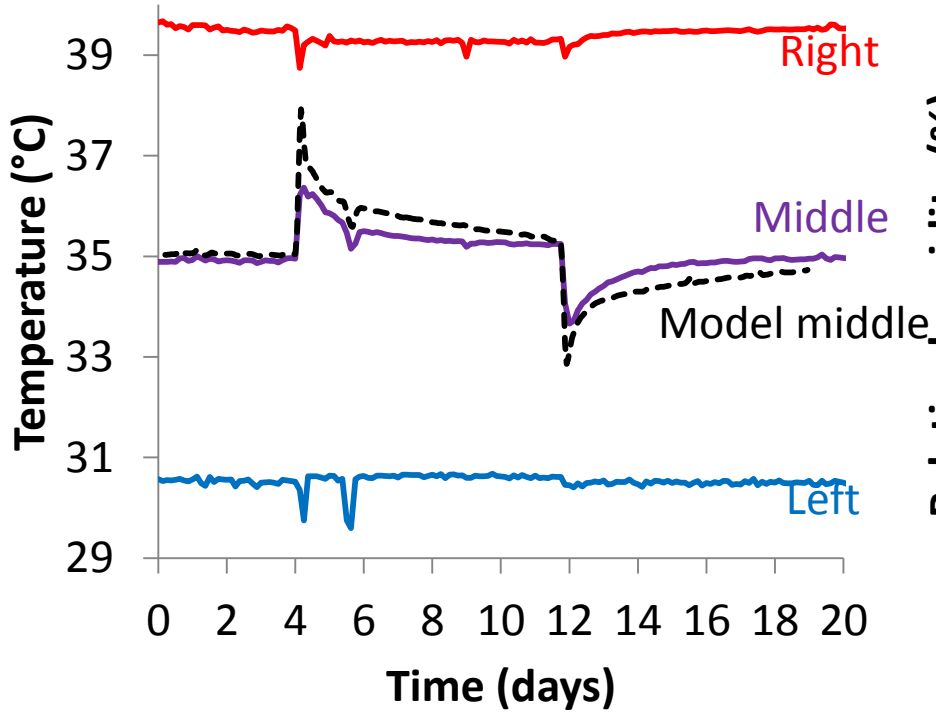


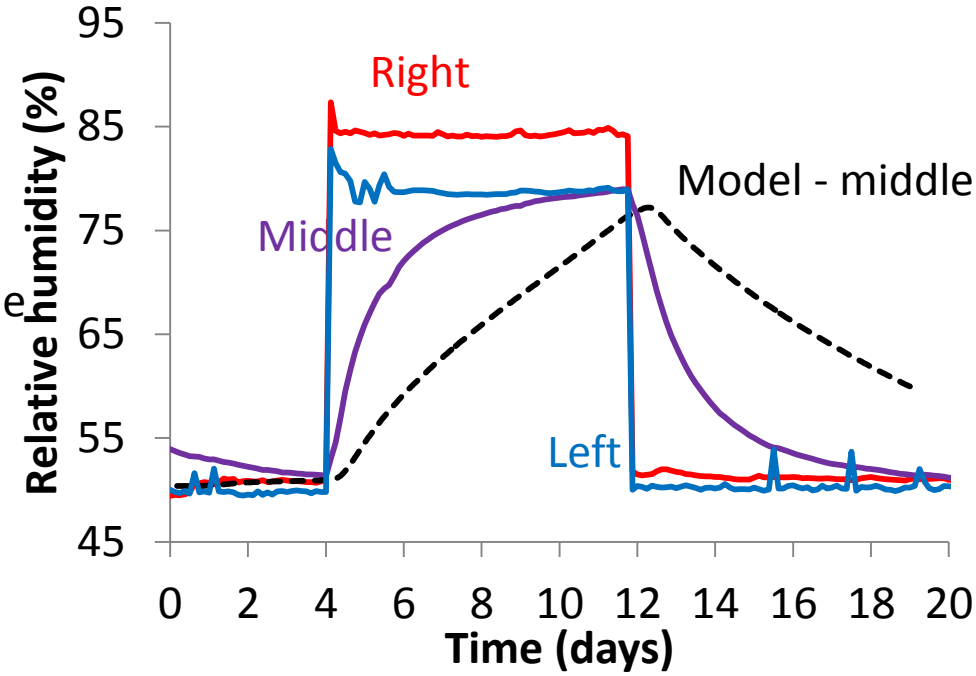


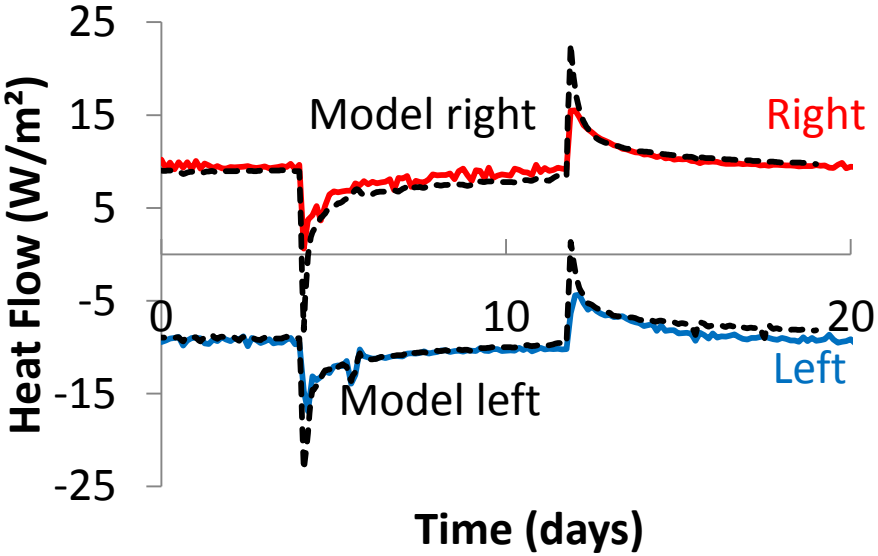




Model *VS* experiment : Hemp Concrete

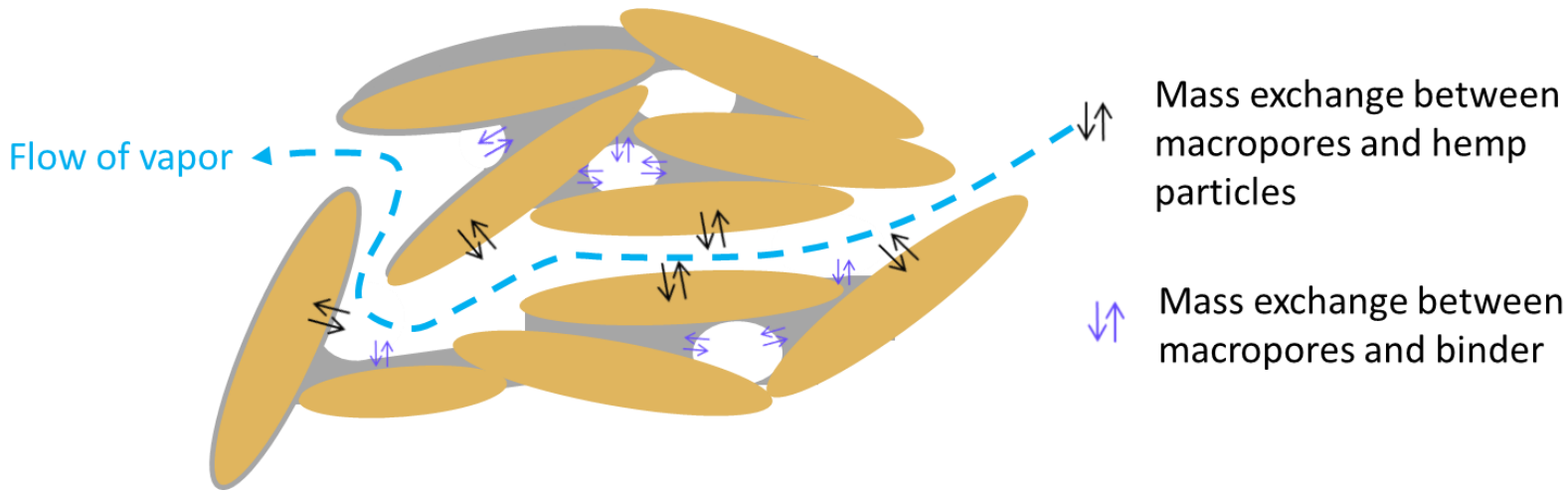






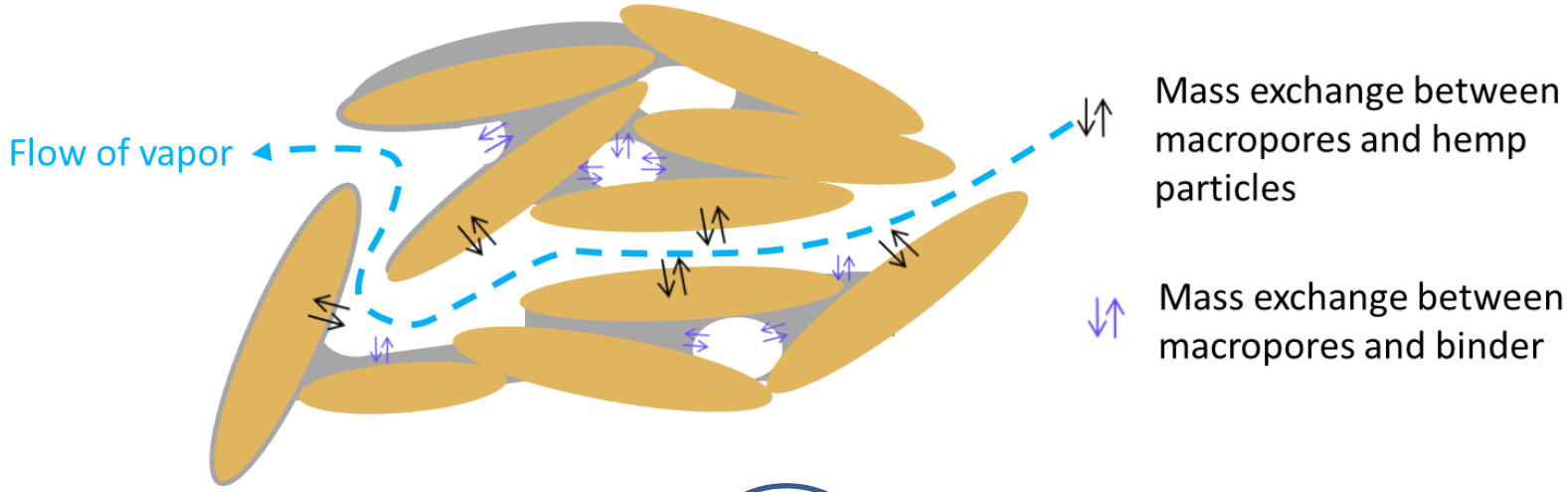
- **Overestimation** of the phase change effect on both heat and mass balances
- The « classic » HT-model need to be improved to simulate the behavior of hemp concrete

HT Modelling : double porosity model

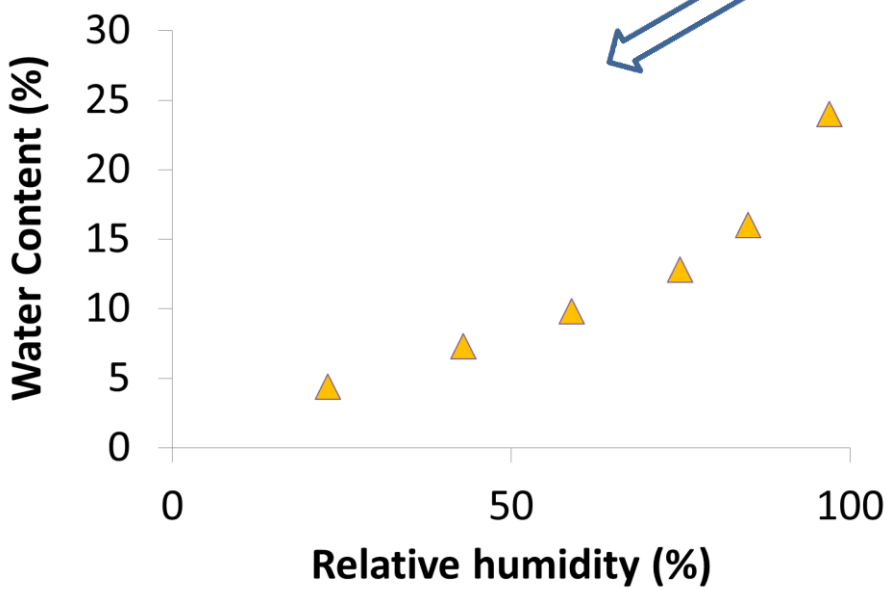


$$\omega = \frac{m_{hemp}}{m_s}\tilde{\omega}_{hemp} + \omega_{binder}$$

HT Modelling : double porosity model



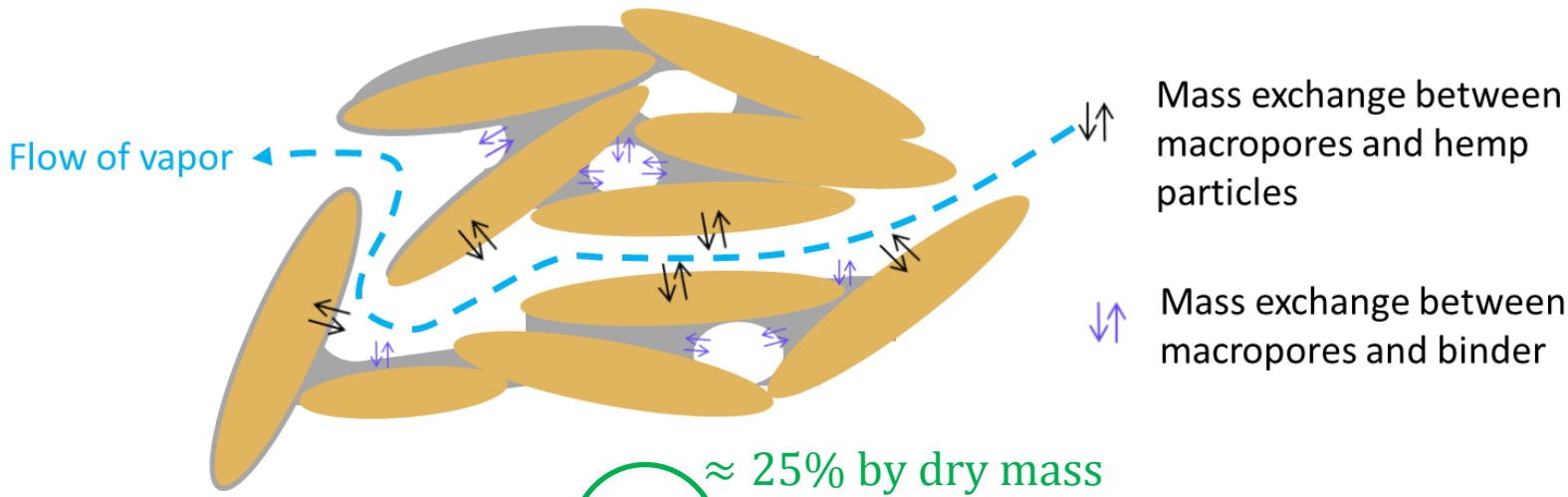
$$\omega = \frac{m_{hemp}}{m_s}\tilde{\omega}_{hemp} + \omega_{binder}$$



Instantaneous phase change

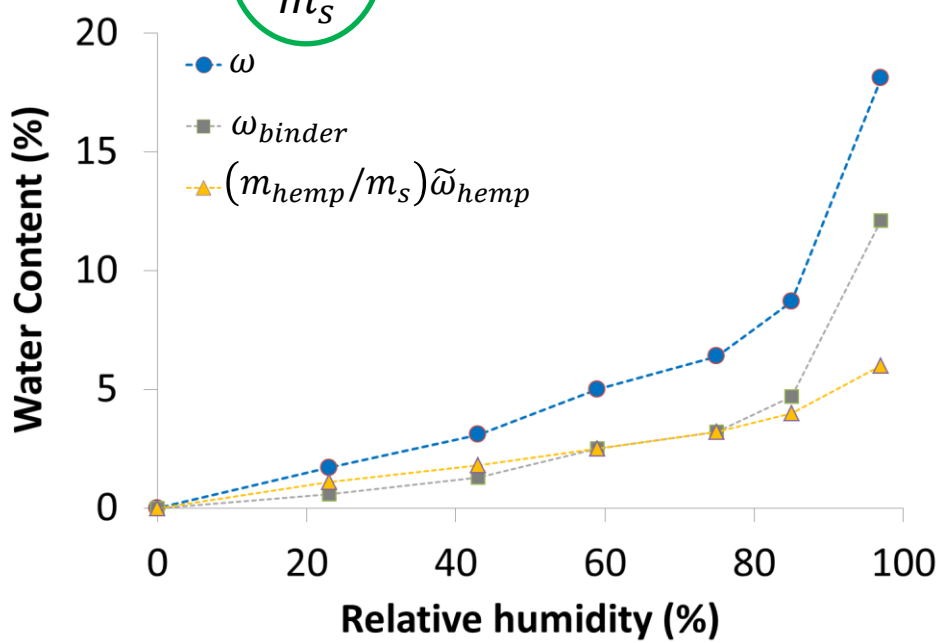
$$\frac{\partial \tilde{\omega}_{hemp}}{\partial t} = \frac{\partial \tilde{\omega}_{hemp}}{\partial \varphi}\frac{\partial \varphi}{\partial t}$$

HT Modelling : double porosity model

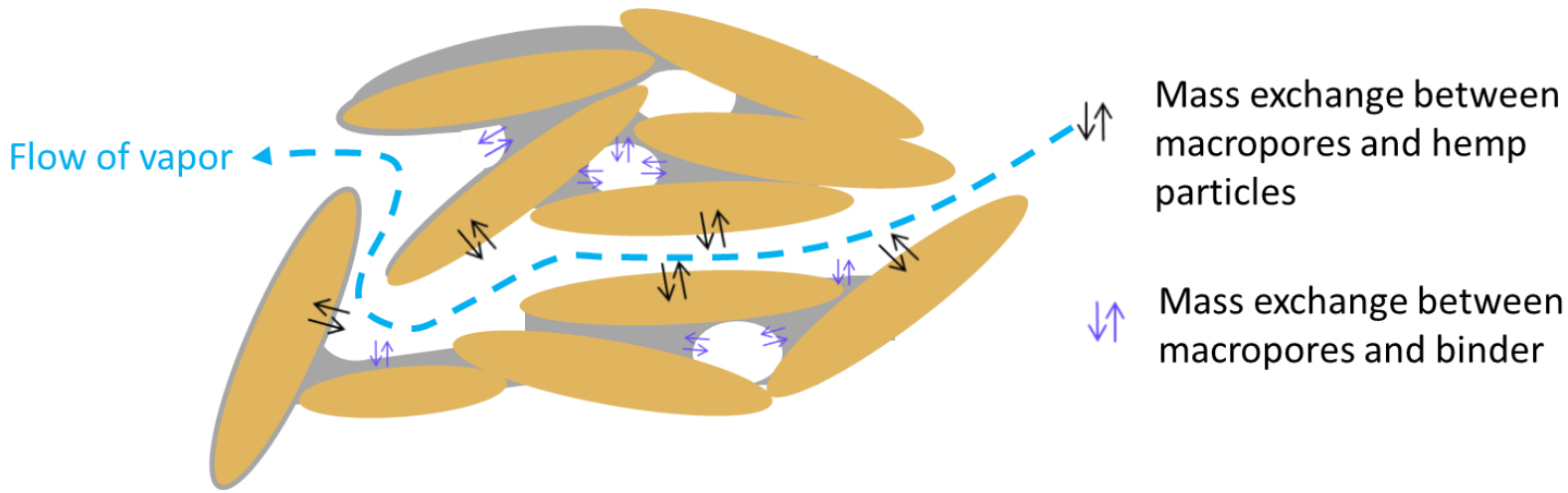


$$\omega = \frac{m_{hemp}}{m_s}\tilde{\omega}_{hemp} + \omega_{binder}$$

$\approx$ 25% by dry mass



HT Modelling : double porosity model



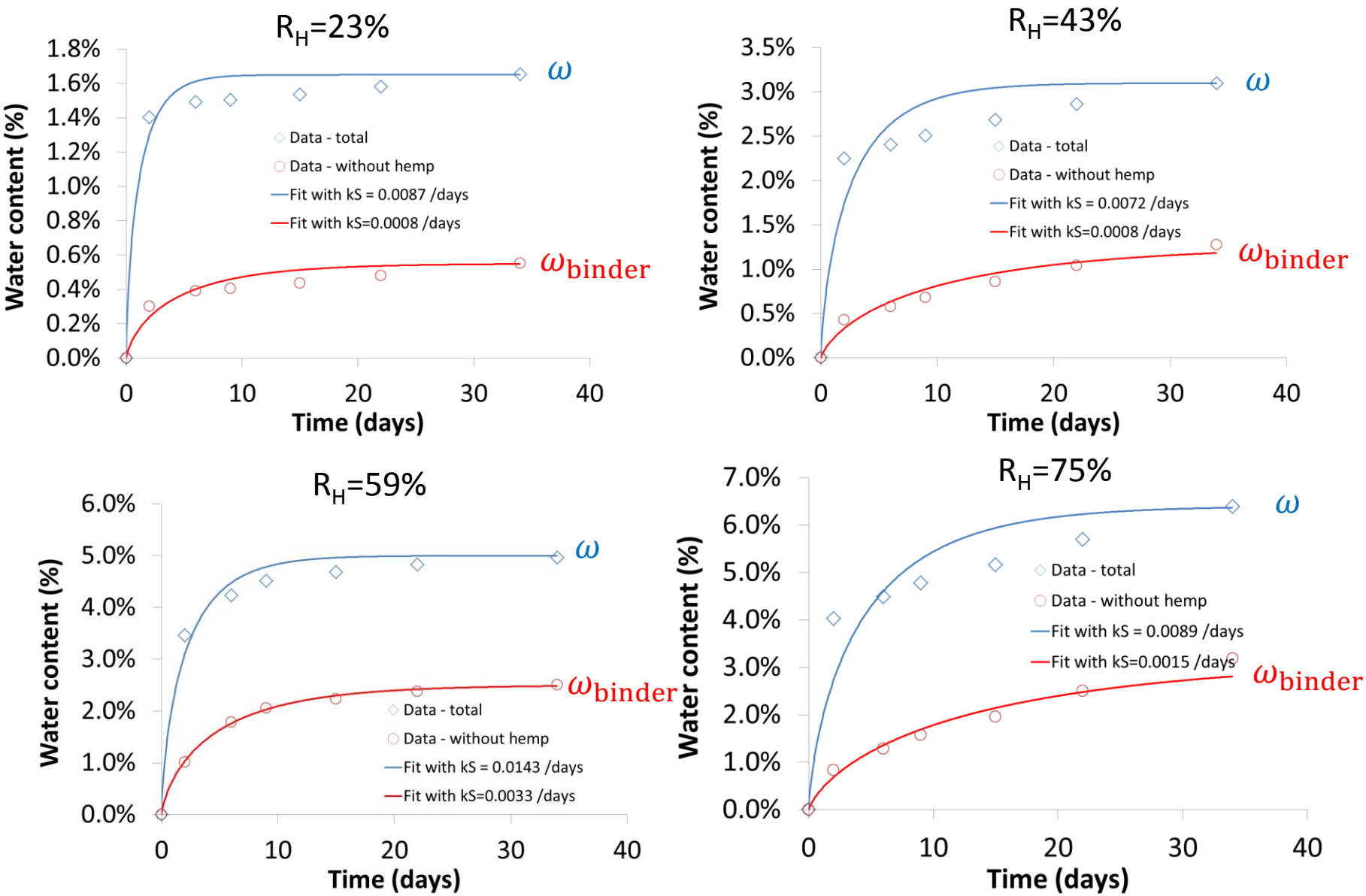
$$\omega = \frac{m_{hemp}}{m_s}\tilde{\omega}_{hemp} + \omega_{binder}$$

Mass echange law between the two porous systems

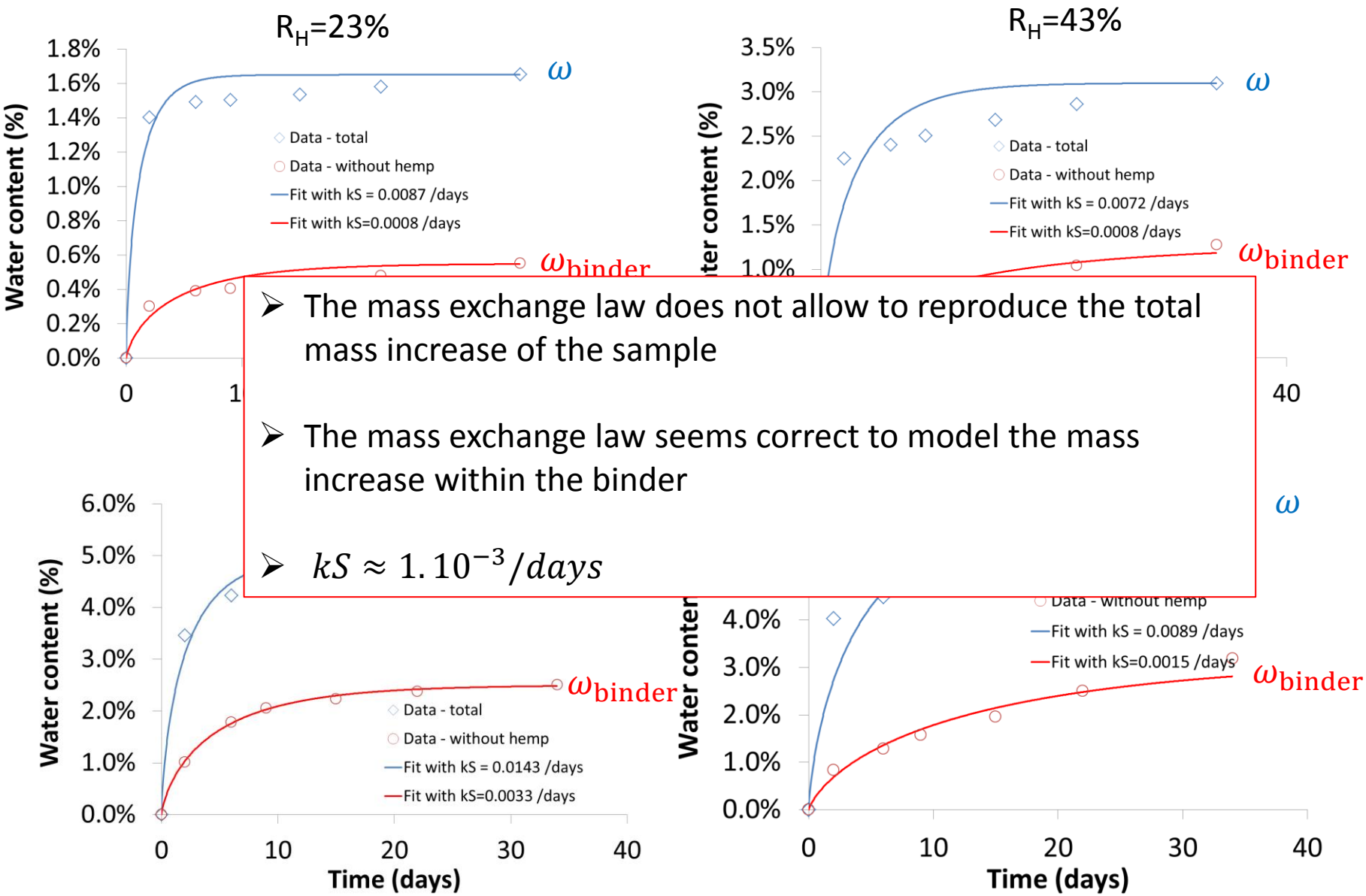
$$\frac{\partial \omega_{binder}}{\partial t} = KS\,\rho_d(\mu_v - \mu_l) = -KS\frac{\rho_l RT}{M_w}\left(\ln\left(\frac{\varphi^*(\omega_{binder})}{\varphi}\right)\right) \approx -kS\ln\left(\frac{\varphi^*(\omega_{binder})}{\varphi}\right)$$

where $\varphi^*(\omega_{binder}) = \exp\left[-\frac{\gamma}{f(\omega_{binder})}\frac{M_l}{\rho_l RT}\right]$ = Relative humidity in equilibrium with the in-pore water of the lime binder

HT Modelling : double porosity model



HT Modelling : double porosity model



- The mass exchange law does not allow to reproduce the total mass increase of the sample
- The mass exchange law seems correct to model the mass increase within the binder
- $kS \approx 1.10^{-3}/days$

HT Modelling : double porosity model

Continuity equations with phase change kinetic

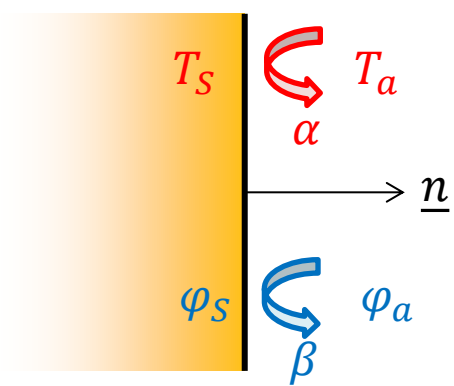
$$< \rho C > \frac{\partial T}{\partial t} = \underline{\nabla} \cdot \left(< \lambda > \underline{\nabla} T \right) + L_v \underline{\nabla} \cdot \left[\delta_p \underline{\nabla} \left(\varphi p_v^{sat}(T) \right) \right]$$

$$\rho_d \left(\frac{m_{hemp}}{m_s} \frac{\partial \widetilde{\omega}_{hemp}}{\partial \varphi} \frac{\partial \varphi}{\partial t} + \frac{\partial \omega_{binder}}{\partial t} \right) = \underline{\nabla} \cdot \left[\delta_p \underline{\nabla} \left(\varphi p_v^{sat}(T) \right) \right]$$

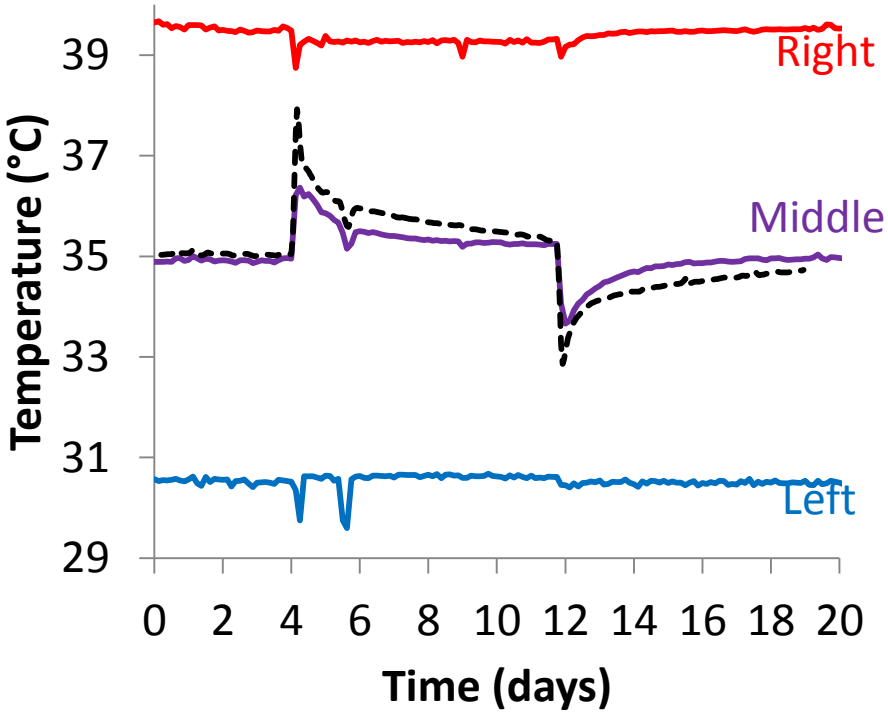
with $$\frac{\partial \omega_{binder}}{\partial t} = -kS \ln \left(\frac{\varphi^*(\omega_{binder})}{\varphi} \right)$$

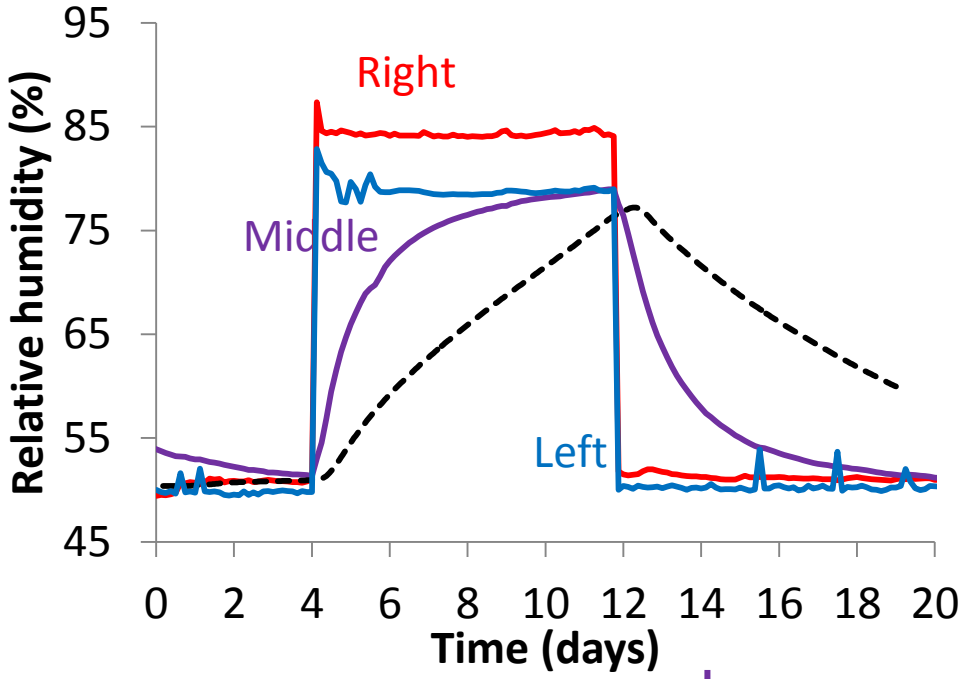
Boundary conditions

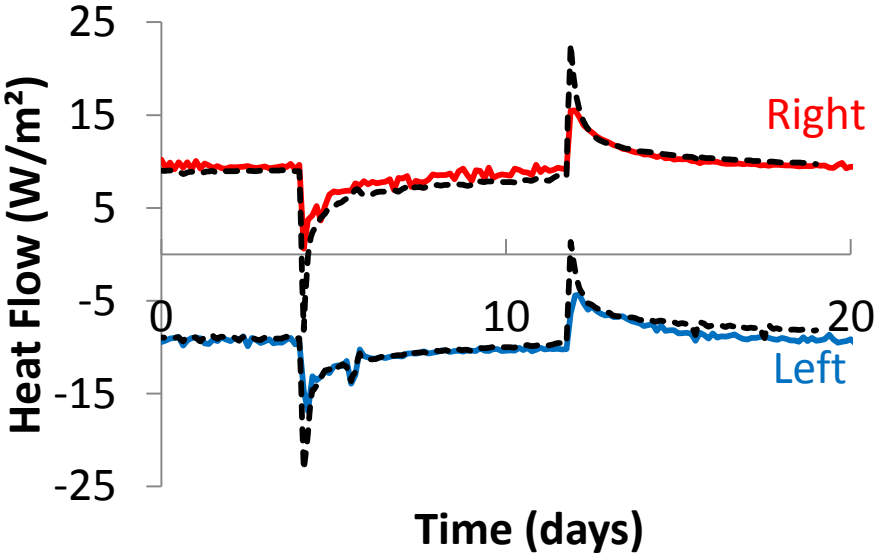
$$\begin{bmatrix} \left(\underline{q} + L \underline{g_v} \right) \cdot \underline{n} \\ g_v \cdot \underline{n} \end{bmatrix} = \begin{bmatrix} -\left(\lambda \underline{\nabla T} + \delta_p \underline{\nabla} p_v \right) \cdot \underline{n} \\ -\left(\delta_p \underline{\nabla} p_v \right) \cdot \underline{n} \end{bmatrix} = \begin{bmatrix} \alpha (T_a - T_s) + L_v \beta \left(p_v^{sat}(T_a)\, \varphi_a - p_v^{sat}(T_s) \varphi_S \right) \\ \beta \left(p_v^{sat}(T_a)\, \varphi_a - p_v^{sat}(T_s) \varphi_S \right) \end{bmatrix}$$



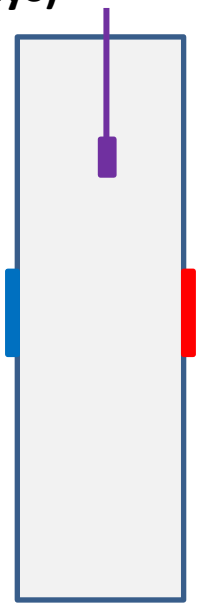
HT Modelling : Model VS Experiment



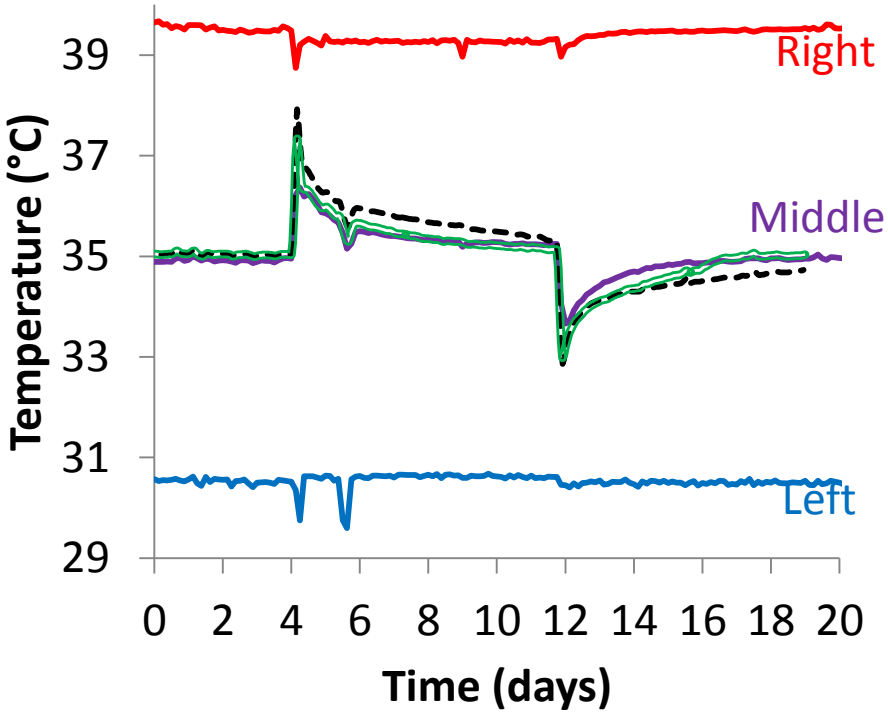


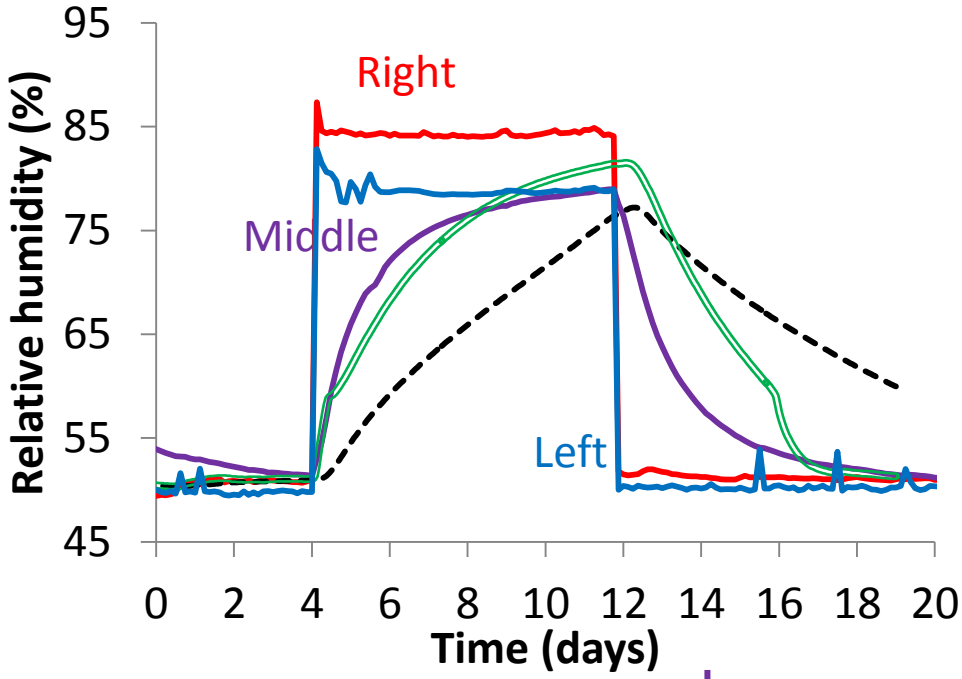


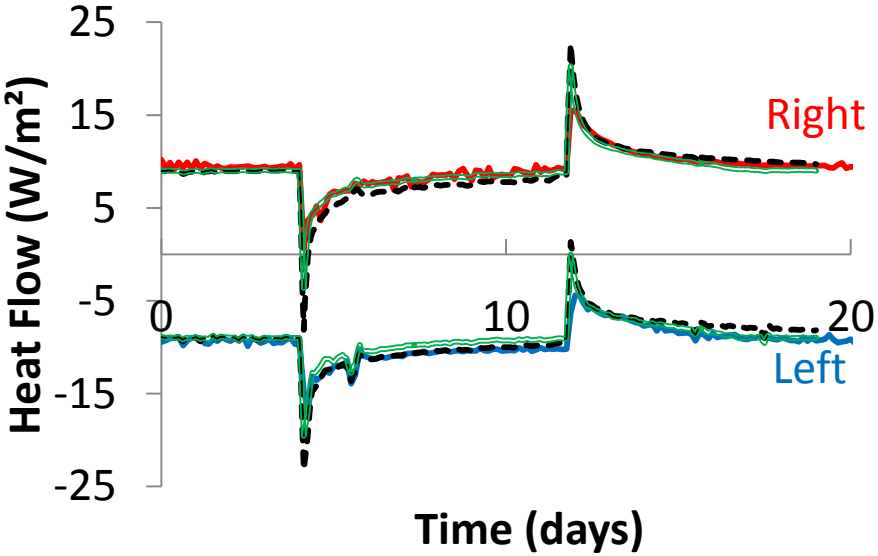
----- Calculation with equibrium model



HT Modelling : Model VS Experiment

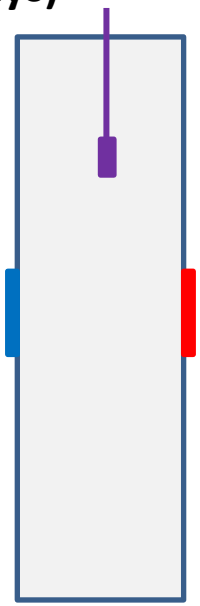




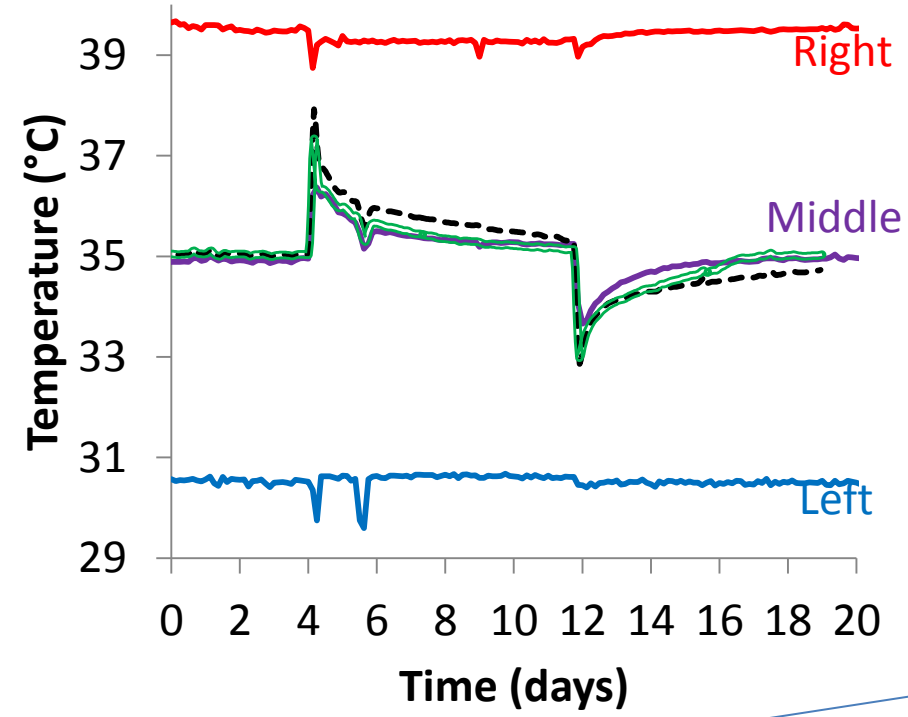


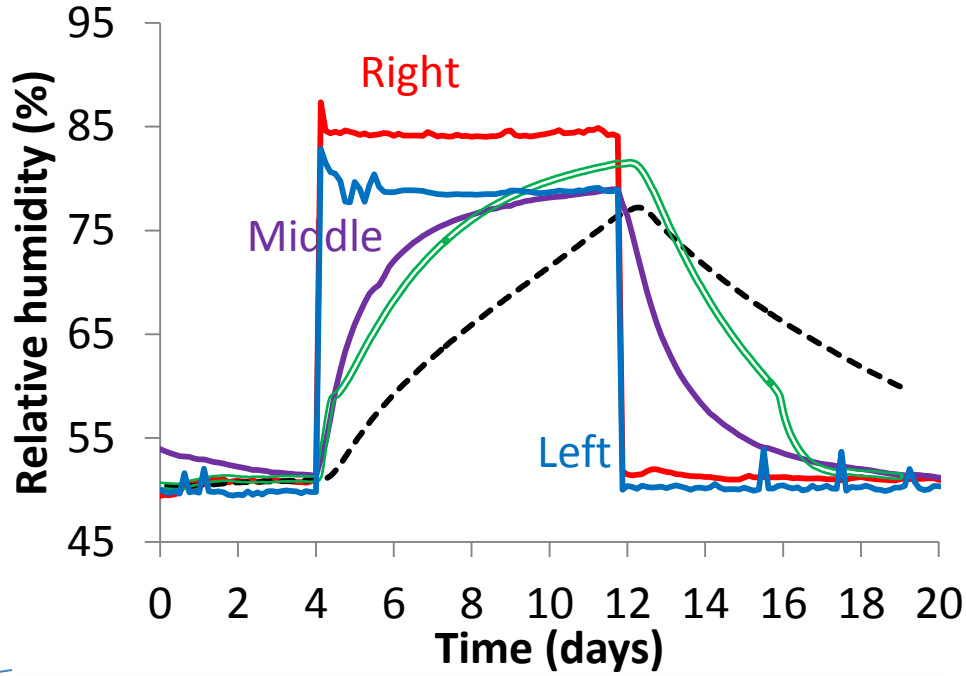
----- Calculation with equibrium model

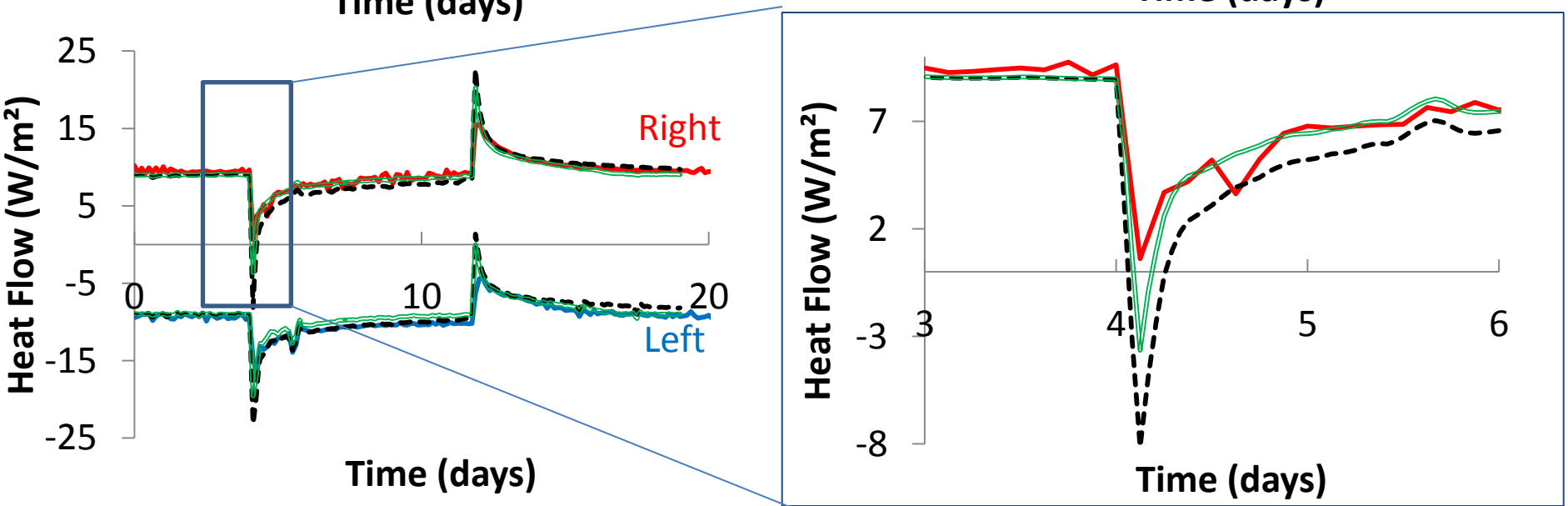
Calculation with kinetic model



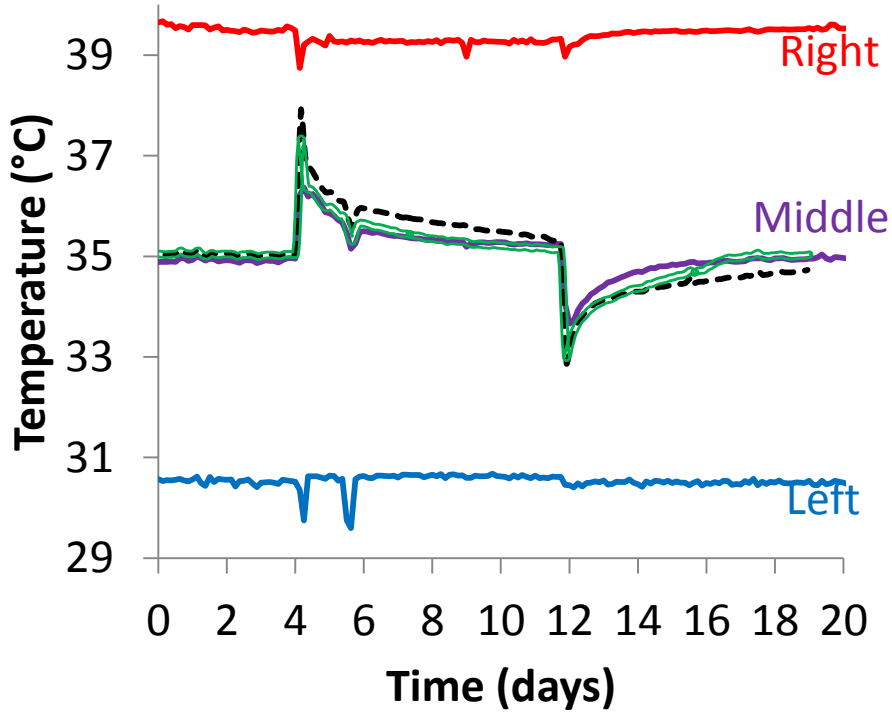
HT Modelling : Model VS Experiment

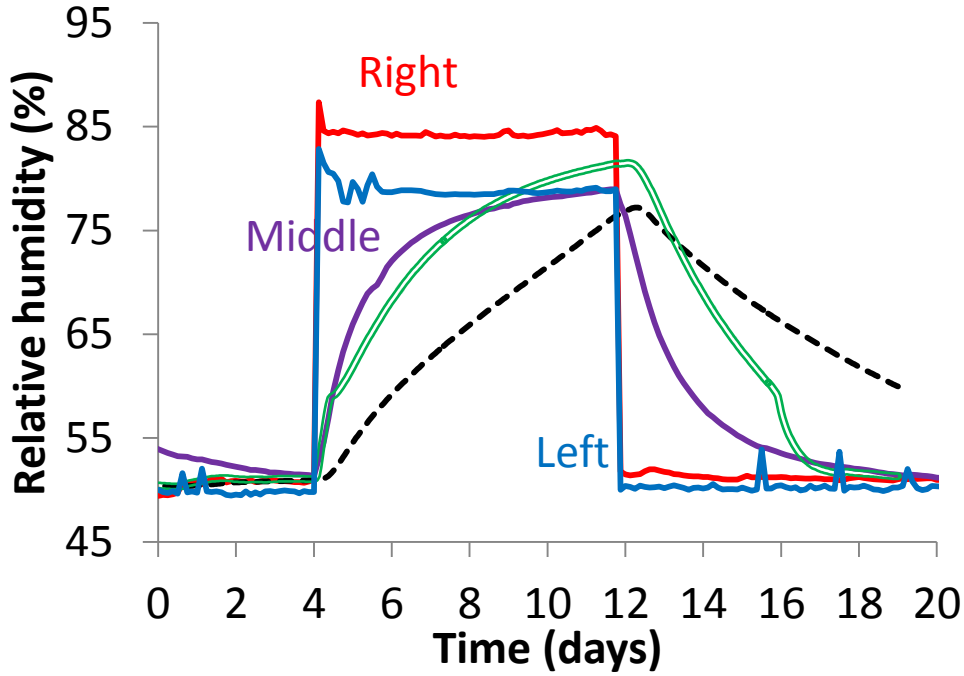


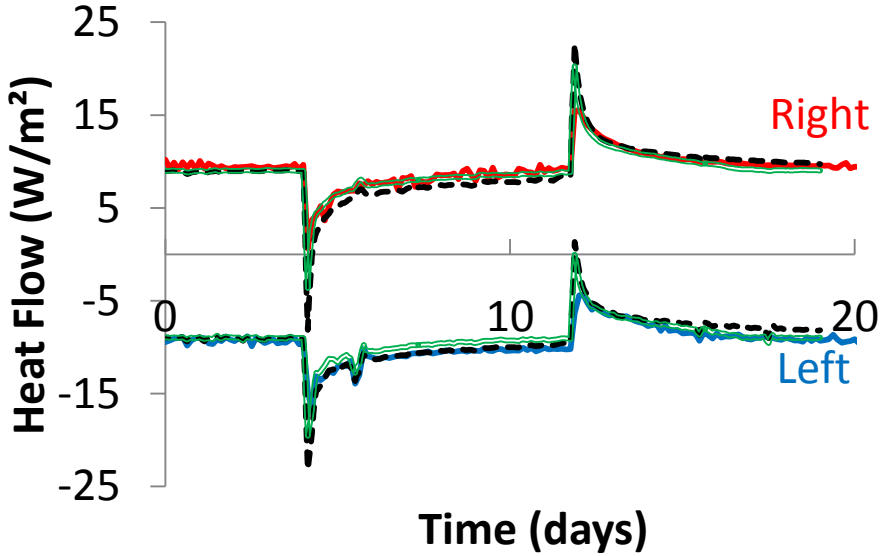




HT Modelling : Model VS Experiment







- **Better estimation** than equilibrium model
- It remains **some differencies** between model and experiments **in desorption** (effect of the hysteresis?)

Conclusions and perspectives

- **Experimental identification** of the hygrothermal behavior of hemp concrete
- This effect is non negligible and **is higher than 6W/m^2 for more than 1 day** in the experiment reported in this study
- A hygrothermal model that distingish the effect of water in hemp particules and water in binder is developped
- This model leads to first promising results. It suggests that **all the water does not have the same impact on the hygrothermal behavior** of the material
- More studies on **effect of temperature** and **on sorption-desorption hysteresis** are in progress to improve the model

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