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# Sensitivity analysis of transient heat and moisture transfer in a bio-based date palm concrete wall

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## Abstract

Hygrothermal mathematical models are commonly used to describe heat and moisture transfer in porous and bio-based building construction materials. This allows to evaluate their thermal insulation capacity, as well as their ability to regulate external climatic conditions and ensure indoor comfort for inhabitants. In this paper, a sensitivity analysis is performed on Kunzel's model, while it is applied to simulate the hygrothermal behavior of a wall structure made of a new bio-based building material (cement composite including date palm fibers). In a first part, the effects of finite variations of material properties/boundary conditions on the model's outcome are investigated. In a second step, specific transfer modes are neglected in the model, in order to study their influence on the numerical predictions. The results of this parametric study show that special attention should be paid to few parameters (heat capacity and density for heat transfer, sorption isotherm and water vapor resistance factors for moisture transfer) at the expense of others. Uncertainties on these influent parameters may result in large error accumulation, especially when modeling the moisture transfer process. Furthermore, initial boundary conditions and sensors position appear to be possible sources of discrepancies in the calculated RH profiles. Finally, the pure conduction model is found to provide good estimation of the temperature profiles compared to the full model, whereas liquid transfer must always be taken into account in the model to ensure accurate RH predictions through a bio-based date palm concrete wall.

**Key words:** heat and moisture transfer, sensitivity analysis, uncertainties, bio-based building materials, date palm concrete.

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## 1 Nomenclature

2	$A_c$	water absorption coefficient ( $\text{kg m}^{-2} \text{s}^{-1/2}$ )
3	$b$	moisture supplement of thermal conductivity (-)
4	$C_p$	material's heat capacity ( $\text{J kg}^{-1} \text{K}^{-1}$ )
5	$D_l$	liquid conduction coefficient under relative humidity gradient ( $\text{kg m}^{-1} \text{s}^{-1}$ )
6	$D_{l,ws}$	capillary transport coefficient for suction process ( $\text{kg m}^{-1} \text{s}^{-1}$ )
7	$D_{l,\varphi}$	liquid conduction coefficient in hygroscopic region ( $\text{kg m}^{-1} \text{s}^{-1}$ )
8	$G_\Omega$	vapor flux at the boundary surface ( $\text{kg m}^{-2} \text{s}^{-1}$ )
9	$h$	exterior heat transfer coefficient ( $\text{W m}^{-2} \text{K}^{-1}$ )
10	$l_v$	latent heat of vaporization ( $\text{J kg}^{-1}$ )
11	$p_{sat}$	vapor saturation pressure (Pa)
12	$p_v$	vapor pressure (Pa)
13	$Q_\Omega$	heat flux at the boundary surface ( $\text{W m}^{-2}$ )
14	$S$	relative sensitivity (%)
15	$t$	time (s)
16	$T$	temperature (K)
17	$w$	water content ( $\text{kg m}^{-3}$ )
18	$W$	water content given by sorption isotherm ( $\text{kg m}^{-3}$ )
19	$W_f$	water content at free saturation ( $\text{kg m}^{-3}$ )
20	$x$	model's parameter
21	$Y$	model's solution ( $T$ or $\varphi$ )
22	$\beta$	water vapor transfer coefficient at boundaries ( $\text{kg m}^{-2} \text{s}^{-1} \text{Pa}^{-1}$ )
23	$\delta$	water vapor permeability of the material ( $\text{kg m}^{-1} \text{s}^{-1} \text{Pa}^{-1}$ )
24	$\delta_a$	water vapor permeability of air ( $\text{kg m}^{-1} \text{s}^{-1} \text{Pa}^{-1}$ )
25	$\xi_\varphi$	sorption capacity ( $\text{kg m}^{-3}$ )
26	$\lambda$	thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ )
27	$\mu$	vapor diffusion resistance factor in dry conditions (-)
28	$\mu^*$	vapor diffusion resistance factor at higher humidity (-)
29	$\rho$	density ( $\text{kg m}^{-3}$ )
30	$\varphi$	relative humidity (-)
31	Scripts:	

1	0	at dry state or reference value
2	<i>amb</i>	ambient
3	<i>c</i>	convection
4	<i>l</i>	liquid
5	<i>r</i>	radiation
6	<i>v</i>	vapor
7	$\Omega$	at boundaries
8		
9		

# 1 **1 Introduction**

2 Bio-composites based on vegetal fibers are still an extensive field of research in the construction  
3 sector, as they can contribute to reduce energy consumption in buildings thanks to their low  
4 thermal conductivity and high thermal inertia [1]. Besides, these materials have the capacity to  
5 regulate both temperature and relative humidity (RH) of the indoor environment, offering in  
6 most cases an improved hygrothermal comfort for inhabitants [2].

7 So far, most studies dedicated to bio-based building materials were conducted at the sample  
8 scale and focused on the determination of various material characteristics, such as mechanical  
9 strength or heat/moisture storage and transmissibility properties (*i.e.* thermal conductivity,  
10 water vapor permeability, sorption isotherm, etc.). These works considered natural wastes of  
11 about 25 different kinds of plants, which were introduced/mixed in conventional construction  
12 materials [3]. Examples of well-known fibrous wastes from the biomass and used in this field  
13 are hemp [4], straw [5], date palm [6], wood [7] and flax [8]. These studies highlighted the good  
14 insulating properties of bio-based materials, as well as their ability to mitigate temperature and  
15 RH variations.

16 Since they obtained interesting results at the material level, researchers started to investigate  
17 the performance of these bio-based building materials under more realistic conditions at larger  
18 scales. Nevertheless, as experimental studies at the wall and building scales require huge  
19 equipment and can be very expensive, many researchers focused on the development of  
20 theoretical approaches. Since classical heat transfer models have shown limits when applied  
21 to bio-based materials [9], this work is focused on models considering coupled heat and mass  
22 transfer processes, which were proven effective in the case of building materials, even for  
23 those including natural fibers. Mathematical modeling of heat and mass transfer in porous  
24 materials was first carried out by Phillip and De Vries in the case of soil structures [10],  
25 and their work served as a solid basis for the development of subsequent models. In 1995,  
26 Kunzel [11] developed his own model based on a thorough investigation of heat and mass  
27 transport mechanisms in porous building materials. Since then, Kunzel's model has been  
28 widely used by researchers in the field of bio-based building materials, and has also been  
29 validated by comparison with experimental evidences in several works [12, 13].

30 Hygrothermal models are commonly used to describe heat and mass transfer in building  
31 envelopes (walls, roofs, floors ...etc.). At the building scale, these models are usually combined  
32 with heat and mass balances of the indoor air environment. They rely on a system consisting at

1 least of two equations that describe heat and moisture transfer processes, and involve two  
2 unknowns (i.e., temperature for heat transfer and RH or moisture content for moisture transfer).  
3 In specific cases, air transfer is also considered in the problem, and a third equation is thus  
4 added to the previous system. The coefficients of these equations are generally defined in  
5 relation to actual experimental parameters. Some of these parameters are represented by single  
6 constant values, while others may depend on other material properties or on the system's  
7 unknowns themselves. The experimental determination of these parameters represents a source  
8 of errors, which may strongly influence or introduce bias in the final solution of the system [14,  
9 15]. This issue has prompted some researchers to study the sensitivity of the hygrothermal  
10 models to variations of the different parameters, in order to improve as much as possible, the  
11 numerical estimations of both temperature and RH.

12 Sensitivity analyses are very often adopted in almost all fields of research. The Global  
13 Sensitivity Analysis (GSA) is used to determine the sensitivity of model outputs to different  
14 inputs variations, and sensitivity indices are generally determined with the Monte Carlo method  
15 [16]. Differently, the Local Sensitivity Analysis (LSA) is used to assess the sensitivity of a  
16 model with respect to a given parameter [17]. In the field of hygroscopic building materials, the  
17 simulations are simply rerun for different parameter values/conditions, and the resulting new  
18 profiles are compared with the reference case. At the wall scale, Mendes *et al.* [18] carried out  
19 a sensitivity analysis on their model which is based on Phillip and De Vries theory. They defined  
20 different simplified sub-models in which they neglected or set constant specific transport  
21 coefficients, in order to evaluate their influence on the numerical results. The authors  
22 highlighted that neglecting moisture transfer in the model may lead to an underestimation of up  
23 to 59% of the yearly integrated heat flux, hence resulting in an underestimation of the overall  
24 energy consumption. Another work conducted by Bart *et al.* [14] studied the sensitivity of  
25 Kunzel's model to variations of the material density, thermal conductivity, heat capacity, vapor  
26 diffusion resistance factor, sorption curve and sensors position for the case of a hemp concrete  
27 wall. Results showed that theoretical RH profiles are mostly influenced by two parameters, *i.e.*,  
28 the sorption isotherm and the vapor resistance factor. Kunzel's model was also studied by  
29 Oumeziane *et al.* [19], who investigated the effects of the material density and the initial  
30 conditions on the numerical results of a hemp concrete wall. It was concluded from this work,  
31 that these parameters influence both the theoretical temperature and RH profiles, which was  
32 explained by the coupling effects of heat and moisture transfer processes. Othmen *et al.* [15]  
33 carried out a sensitivity analysis on Kunzel's model at the wall scale as well using the LSA

1 method. These authors studied the effect of several material properties, as well as the influence  
2 of boundary and initial conditions in the case of two walls made of tuffeau and hemp concrete.  
3 It was concluded from this analysis, that convective heat transfer coefficients influence both  
4 temperature and water content profiles, in addition to the adsorption isotherm that affects  
5 directly the water content distribution in the wall. At the building scale, Le *et al.* [2] performed  
6 another sensitivity analysis on Mendes model. They studied the impact of changes in the  
7 transport coefficients, sorption isotherm, ventilation rate and inhabitant's existence, on both  
8 indoor conditions and energy consumption. Once again, considering moisture transfer in the  
9 calculations had a significant effect on energy consumption, and this latter was also highly  
10 influenced by the ventilation rate.

11 Each of these works studied the sensitivity of hygrothermal models to various parameters or  
12 conditions, by considering a certain percentage of variation of these parameters/conditions with  
13 respect to their reference values. Moreover, some properties were considered constant, such as  
14 the thermal conductivity and sorption capacity. On the other hand, it was noticed that the results  
15 of the sensitivity analyses were sometimes different or contradictory if the models were applied  
16 to different materials under some specific experimental conditions [15]. This could be explained  
17 by the changes in material properties and conditions which may affect the kinetics of  
18 heat/moisture transfer. As a consequence, conclusions drawn from a sensitivity analysis should  
19 be restricted to the material under study.

20 In the present work, a comprehensive sensitivity analysis is carried out on Kunzel's  
21 hygrothermal model, while this latter is applied to Date Palm Concrete (DPC). To our very  
22 best knowledge, it is the first time this analysis is performed for this peculiar building material  
23 at the wall scale. The study is based on previous results obtained from an experimental  
24 campaign on a DPC at material and wall scales. DPC properties measured at material scale  
25 are used as reference input parameters in the model, while temperature and RH profiles  
26 collected from the DPC wall were used to validate the model's outcome that will be used in  
27 the sensitivity analysis as the reference solution. In this approach, the influence of a wide  
28 range of parameters (heat capacity  $C_p$ , exterior heat transfer coefficient  $h$ , thermal  
29 conductivity  $\lambda$ , vapor diffusion resistance factors  $\mu$ , density  $\rho$  and sorption isotherm  $W$ ),  
30 conditions and variation percentages are explored. A local sensitivity analysis (LSA) method  
31 is used to capture separately the influence of each parameter on the model outcome, and the  
32 global influence of the whole set of parameters is then evaluated as well. The effects of initial/  
boundary conditions and sensors



1 positions on the values of temperature/RH calculated at different depths of the DPC wall are  
2 also investigated. Finally, some terms of the hygrothermal model related to specific  
3 heat/moisture transfer modes were neglected in order to investigate the possibility of  
4 simplifying the model without affecting its accuracy.

5

## 6 **2 Materials and methods**

### 7 *2.1 DPC properties*

8 The material considered in this study is a new bio-based composite incorporating 15 wt. % date  
9 palm fibers in a classical mortar (cement + sand + water), and commonly referred to as Date  
10 Palm Concrete (DPC). This composite formulation was designed in previous studies [20-22],  
11 and was found to provide a good compromise between mechanical, thermo-physical and hygric  
12 properties. This DPC material offers both good thermal insulation/moisture buffering capacity,  
13 and also meets RILEM requirements for structural and insulating autoclaved aerated concretes  
14 ( $R_c > 2.5$  MPa,  $\lambda < 0.75$  W m<sup>-1</sup> K<sup>-1</sup>) [21]. The main hygrothermal properties of this new DPC  
15 bio-composite were experimentally measured in our previous works and are reported in Table  
16 1; these data will serve as reference inputs of the mathematical Kunzel's model in the  
17 framework of the sensitivity analysis.

18 The following sub-sections provide a brief description of the experimental methods used to  
19 determine these hygrothermal properties at the material scale.

#### 20 *2.1.1 Vapor resistance factors*

21 Water vapor diffusion resistance factors  $\mu$  and  $\mu^*$  characterize the ability of the material to  
22 oppose vapor transfer at different ranges of relative humidity. In the case of DPC, typical values  
23 were obtained using the dry and wet cup test method (EN ISO 12572 [23]).

#### 24 *2.1.2 Capillary suction and free saturation*

25 Capillary suction is a liquid transfer mode which occurs mainly in the capillary region (95% >  
26 RH > 100%). This process can be taken into account in the Kunzel's model through a water  
27 absorption coefficient ( $A_c$ ), whose value can be determined experimentally by suction process  
28 (EN ISO 15148 [24]). Free saturation defines the maximum liquid water storage capacity of a  
29 material after a total immersion, and is noted  $W_f$ .

1 **2.1.3 Thermal conductivity, heat capacity and dry density**

2 Thermal conductivity ( $\lambda$ ) is an important property with regard to the insulation capacity of  
 3 building materials, as it defines the ability of the medium to transmit a heat flux by conduction.  
 4 In this work, it is taken dependent on the moisture content ( $w$ ) according to [11]:

$$5 \quad \lambda(w) = \lambda_0 \left( 1 + b \cdot \frac{w}{\rho_0} \right) \quad (1)$$

6 Where  $\lambda_0$  is the thermal conductivity at dry state and  $b$  is the moisture supplement of thermal  
 7 conductivity. In the case of DPC, values of these coefficients were calculated from thermal  
 8 conductivity measurements. DPC density at dry state ( $\rho_0$ ) was also determined.

9 Heat capacity  $C_p$  defines the amount of heat needed to change a material's temperature. It was  
 10 determined experimentally for DPC.

11 Values collected for all these coefficients/properties in the case of DPC material are reported  
 12 in Table 1, along with the references from which they are taken. They will be considered as  
 13 reference values in the sensitivity analysis.

14 **2.1.4 Sorption isotherm**

15 Sorption isotherm represents the water retention evolution inside a material, during adsorption  
 16 or desorption processes, as a function of relative humidity at a known temperature. For DPC,  
 17 adsorption isotherm  $W$  was obtained experimentally (EN ISO 12571 [24]) by Chennouf *et al.*  
 18 [22] at 23 °C and fitted with the GAB model (Guggenheim-Anderson-de Boer [26]).

19 **Table 1:** Reference values of the DPC properties

Property	Value	Reference	Property	Value	Reference
Dry density ( $\rho_0$ ) [kg.m <sup>-3</sup> ]	954	[20]	Dry specific heat ( $C_{p0}$ ) [J.kg <sup>-1</sup> K <sup>-1</sup> ]	1500	[21]
Dry thermal conductivity ( $\lambda_0$ ) [W.m <sup>-1</sup> K <sup>-1</sup> ]	0.185	[20]	Moisture supplement of thermal conductivity ( $b$ ) [-]	10.190	[20]
Vapor resistance factor (dry cup) ( $\mu$ ) [-]	6.310	[22]	Vapor resistance factor (wet cup) ( $\mu^*$ ) [-]	5.570	[22]

Water absorption coefficient ( $A_c$ ) [kg.m <sup>-2</sup> s <sup>-0.5</sup> ]	0.165	[20]	Water content at free saturation ( $W_f$ ) [kg.m <sup>-3</sup> ]	429	[20]
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1

## 2 2.2 *Experimental test at the wall scale*

3 For more realistic tests, boundary conditions to be used in the sensitivity analysis were imported  
4 from an actual experimental campaign. A DPC wall of dimensions 50×40×15cm<sup>3</sup> (Fig. 1a) was  
5 fabricated and then insulated from lateral surfaces using polystyrene panels and plastic film in  
6 order prevent heat/moisture transfer through these surfaces and get a one-dimensional transfer  
7 across the thickness of the wall. Polystyrene panels were used to create a passive cell at the  
8 right side of the DPC wall, which represents the indoor environment (Fig. 1b). Three  
9 humidity/temperature sensors model DKRF400 from Driesen + Kern, Germany (measurement  
10 range of RH: 0-100% with an accuracy of ±1.8 %, and measurement range of T: -40°C to +45°C  
11 with an accuracy of ± 0.5°C) were inserted at three different depths of the wall for data  
12 acquisition (at 3 cm, 7.5 cm and 12.5 cm from the outer surface). The reason behind choosing  
13 these specific depths was to enable measurements of temperature and RH close to the inner /  
14 outer environments and at the middle of the wall as well, in order to evaluate the response of  
15 the material at these locations. The overall setup was placed in a climatic chamber that  
16 represents the outdoor environment and enables to apply dynamic boundary conditions to the  
17 external side of the wall (Fig. 1.b). Two additional sensors were used to monitor both  
18 temperature and RH values in the indoor and outdoor environments.

19 Hygrothermal scenarios applied to the DPC wall using the regulation system of the climatic  
20 chamber are described as follows:

21 1) An initial step change of temperature from 23°C to 40°C, followed by 4 repeated temperature  
22 cycles of 24 hours (hot/cold periods of 12 hours with step changes of temperature between 40°C  
23 and 18°C) at constant humidity level of 50% RH. This scenario simulates the daily temperature  
24 variation during summertime,

25 2) An initial step change of RH from 23% to 75% followed by a prolonged exposure to 75%  
26 RH for 9 days at constant temperature (23°C). Afterwards, another step RH change was applied  
27 from 75% to 33%, and this latter level was maintained for another 9 days, still at constant  
28 temperature of 23°C. The total duration of this scenario is 18 days.

1 These scenarios were applied as outdoor conditions using the climatic chamber, while indoor  
 2 conditions were left uncontrolled. After every test, the wall was reconditioned at relative  
 3 humidity  $\varphi = 50\%$  and  $T = 23\text{ }^{\circ}\text{C}$  which represent the initial conditions for the next test.

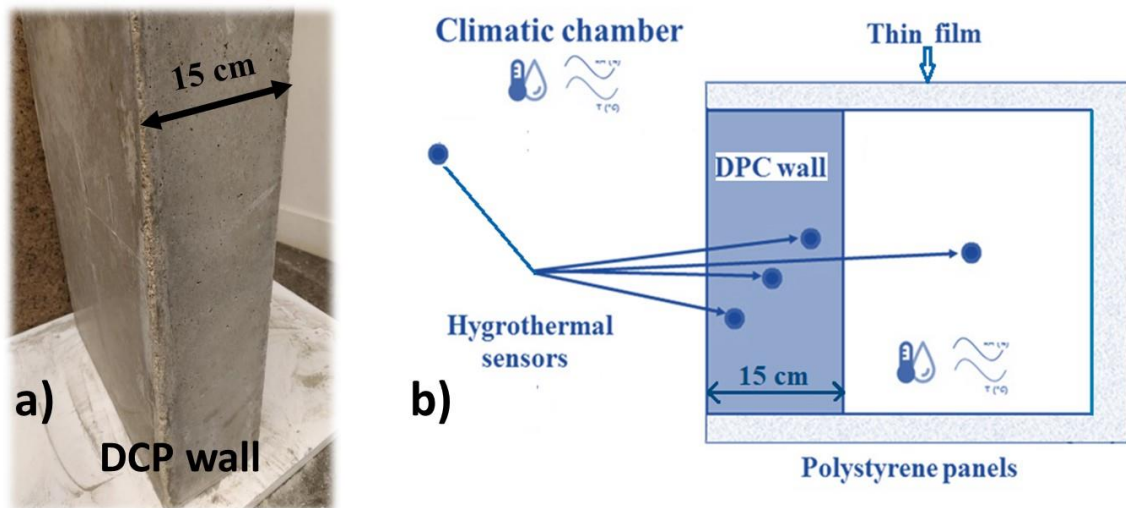
4 Details of the used scenarios are displayed in Table 2. Additional details regarding the  
 5 experimental setup and the protocols can be found in [27, 28].

6

7 **Table 2:** Outdoor conditions (values in brackets correspond to the initial conditions at the beginning  
 8 of the experiment, *i.e.*  $23\text{ }^{\circ}\text{C}$  and  $50\%$  HR)

Scenarios	Outdoor conditions		Duration
	T [ $^{\circ}\text{C}$ ]	$\varphi$ [%]	
<i>Scenario 1</i>	(23) $\rightarrow$ 40 $\rightarrow$ 18	50	4 cycles of 24 hours (12 h at $40\text{ }^{\circ}\text{C}$ , 12 h at $18\text{ }^{\circ}\text{C}$ )
<i>Scenario 2</i>	23	(50) $\rightarrow$ 75 $\rightarrow$ 33	18 days (9 days at 75% RH, 9 days at 33% RH)

9



10

11 **Fig. 1:** The DCP wall (a) and schematic view of the experimental setup (b)

# 1 **3 Mathematical formulation**

## 2 *3.1 Mathematical model*

3 All mathematical models describing heat and mass transfer in porous material are derived from  
4 basic conservation equations. In porous media, some hypotheses are usually applied in order to  
5 simplify the models [29], such as:

- 6     ▪ The studied material is considered isotropic,
- 7     ▪ The local thermodynamic equilibrium is reached between the different phases,
- 8     ▪ Air and vapor are considered as ideal gases,
- 9     ▪ Radiative heat transfer and chemical reactions are neglected inside the studied material,

10 The mathematical model describing heat and moisture transfer in porous building materials and  
11 used in this study refers to Kunzel [11]. Based on the previous assumptions, the model is written  
12 as follows:

13 Moisture transfer

$$14 \quad \xi_{\varphi} \frac{d\varphi}{dt} = \frac{\partial}{\partial x} \left( \delta \frac{\partial(p_{sat}\varphi)}{\partial x} + D_l \frac{\partial\varphi}{\partial x} \right) \quad (2)$$

15 Heat transfer

$$16 \quad \left( \rho_0 C_{p0} + C_{pl} w \right) \frac{dT}{dt} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + l_v \frac{\partial}{\partial x} \left( \delta \frac{\partial p_{sat}\varphi}{\partial x} \right) \quad (3)$$

17 The transfer modes considered in this model are: diffusion of liquid water and vapor in the case  
18 of mass transfer, heat conduction and phase change heat for heat transfer. This model neglects  
19 air transfer because of the small variations of the total pressure in the case of building  
20 components [11].

21 The liquid water transport takes place according to several processes that are expressed in the  
22 model by the following coefficients [11]:

- 23 a) The liquid conduction coefficient (acts mainly in the hygroscopic region), defined as  
24 follows:

$$25 \quad D_{l,\varphi} = P_{sat} \delta_a \left( \frac{1}{\mu^*(\varphi)} - \frac{1}{\mu} \right) \quad (4)$$

26 Where  $\mu$  and  $\mu^*(\varphi)$  are vapor resistance factors obtained from dry and wet cup tests  
27 respectively.

1 b) The capillary transport coefficient for suction process (acts mainly in capillary region):

$$2 \quad D_{l,ws} = \left( 3.8 \left( \frac{A_c}{W_f} \right)^2 \cdot 1000^{\frac{w}{w_f}-1} \right) \xi_\varphi \quad (5)$$

3  $A_c$  and  $W_f$  are measured experimentally (cf. section 2.1).

4 c) Liquid transport coefficient of redistribution; it is estimated as one decimal power below  
5 the capillary transport coefficient  $D_{l,ws}$ .

### 6 3.1.1 Boundary conditions

7 Experimental boundary conditions were defined and simulated according to Kunzel's work  
8 [11]. Heat and mass fluxes are equal to:

$$9 \quad Q_\Omega = h(T_\Omega - T_{amb}) \quad (6)$$

$$10 \quad G_\Omega = \beta(P_{v,\Omega} - P_{v,amb}) \quad (7)$$

11  $h$  takes into account both convection and radiation through the following relation:

$$12 \quad h = h_r + h_c \quad (8)$$

13 And  $\beta$  is the water vapor transfer coefficient at boundaries, defined as:

$$14 \quad \beta = 7 \cdot 10^{-9} \cdot h_c \quad (9)$$

### 15 3.2 Model validation

16 Kunzel's model was widely used and compared with experimental data in previous studies from  
17 the literature. The Fraunhofer Institute for Building Physics has developed a software (Wufi) to  
18 describe the hygrothermal behavior of building envelopes based on Kunzel's, which was  
19 validated by comparison with experimental evidences. A good agreement was reported between  
20 theoretical/experimental data for both temperature and RH profiles [13].

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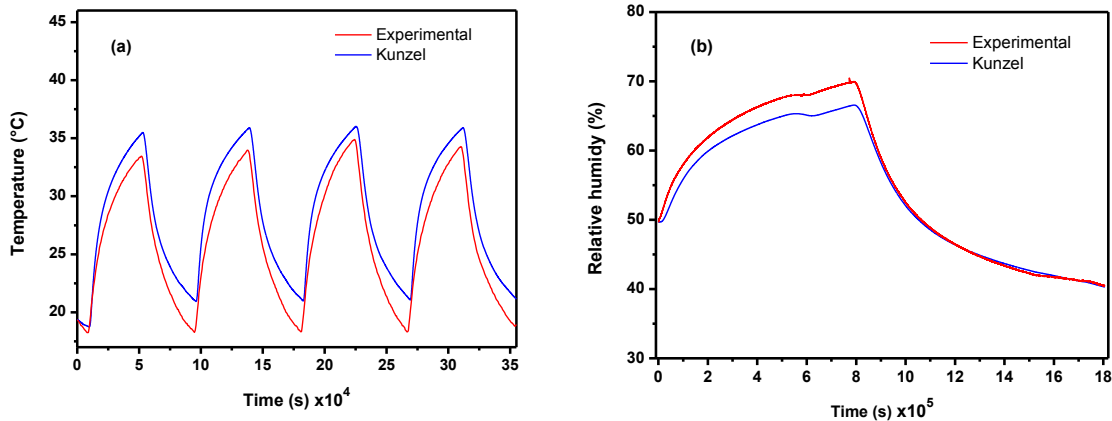
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1 **Fig. 2:** Kunzel's model validation: comparison of experimental and numerical profiles at 3 cm  
2 depth inside the DPC wall, for temperature (a) and relative humidity (b)

3  
4 Recently, we carried out a detailed validation of Kunzel's model using COMSOL Multiphysics  
5 software in the case of a DPC wall, using the same setup and scenarios described in section 2.2  
6 [12]. As an illustration, theoretical and experimental profiles obtained at a depth of 3cm in the  
7 DPC wall for temperature (scenario 1) and RH variations (scenario 2), are presented in Fig. 2.a  
8 and 2.b, respectively. A relatively good agreement was obtained between Kunzel's theory and  
9 experimental data in both cases. Nevertheless, slight differences were noticed between  
10 numerical/experimental curves, which could relate to various sources of errors: uncertainties  
11 on test conditions, accuracy/position of the sensors or values of input parameters that were  
12 injected into the model.

#### 14 **4 Assumptions and sensitivity analysis**

15 The goal of this work is to assess the influence of a wide range parameters and conditions on  
16 the response of the hygrothermal Kunzel's model. In this line, the impact of finite variations of  
17 several material parameters on the numerical results was evaluated (considering different  
18 percentages of variations of these inputs with respect to their reference values), as well as the  
19 effects of time, depth location inside the wall, initial conditions, sensors position, liquid transfer,  
20 phase change heat, etc. This is done for the case of a date palm concrete wall.

##### 21 *4.1 Uncertainties on the supposed known model parameters*

22 The first part of the study deals with the influence of input material parameters on the model's  
23 outcome. Significant errors are usually present on these parameters, due to measurement  
24 uncertainties at the material scale, or to the use of these parameters at higher scales as mentioned  
25 earlier (wall and building scales). This latter reason (transition from the material to the wall  
26 scale) may be responsible for much higher uncertainties on input values, because manufacturing  
27 several blocks or a sample of large dimensions can probably generate a wider range of  
28 uncertainties on the materials properties and on the homogeneity of the system [19]. As  
29 mentioned before, different sensitivity analysis methods are available depending on the number  
30 of variables set to change together, such as the Global Sensitivity Analysis (GSA) and the Local  
31 Sensitivity Analysis (LSA). The GSA consists in determining the sensitivity of output quantities  
32 to the variations of different input parameters, while the LSA evaluates the sensitivity of an

1 output quantity to the variation of a given input. In the field of hygroscopic building materials,  
 2 we are mainly interested in local methods where the simulations are simply rerun for different  
 3 parameters values and conditions, and the new profiles are compared with the reference case.  
 4 In the present work, to evaluate the influence of a varying parameter on the resulting  
 5 temperature and RH profiles, the relative sensitivity index is calculated as follows [30]:

$$6 \quad \mathbf{S}(\%) = \frac{|Y_{x-\Delta x} - Y_{x+\Delta x}|}{2Y_0} \cdot 100 \quad (10)$$

7 Where  $\mathbf{Y}$  is the solution of the model ( $\mathbf{T}$  or  $\boldsymbol{\varphi}$ ),  $\mathbf{Y}_0$  is the reference solution obtained when no  
 8 parameter is changed (all parameters are set to their reference values),  $\mathbf{x}$  indicates the variable  
 9 parameter and  $\Delta \mathbf{x}$  the variation range.

10 This relative sensitivity index is calculated considering different percentages of variation of  
 11 input parameters with respect to their reference values, ranging from 5% to 25% [2, 14, 19].  
 12 Low percentages represent errors that may occur at the material scale, while high percentages  
 13 are related to errors at higher scales due to the accumulation of small errors. The evolution of  
 14 the sensitivity index will be discussed as a function of: time, depth location and percentage of  
 15 variation of the parameters compared to their reference values.

16 The sensitivity of Kunzel's model has been investigated with respect to the following  
 17 parameters: heat capacity  $C_p$ , exterior heat transfer coefficient  $h$ , thermal conductivity  $\lambda$ , vapor  
 18 diffusion resistance factors  $\mu$ , density  $\rho$  and sorption isotherm  $W$  that is used to define the water  
 19 content  $w$  in the hygrothermal model (Eq. 3) under the thermodynamic equilibrium hypothesis.

20 In a first step, each parameter was changed separately considering different percentages of  
 21 variation ( $\Delta \mathbf{x}$ : -5%, +5%, -15%, +15%, -25% and +25% of the reference value), while the other  
 22 parameters were kept constant at their initial values. In a second stage, all the parameters were  
 23 changed simultaneously using the same percentages of variation, and the sensitivity index was  
 24 calculated for the variation of all these parameters together in order to reveal possible  
 25 interactions between parameters. For example, for this last case, all parameters were varied with  
 26 -5% relating to their initial value, to obtain  $\mathbf{Y}_{x-\Delta x}$  that is defined in Eq. 10. Then, all parameters  
 27 were also varied with +5% to obtain  $\mathbf{Y}_{x+\Delta x}$ , Finally, these two last results allow to obtain the  
 28 corresponding sensitivity index  $\mathbf{S}$ . This procedure was performed as well for the rest of  
 29 percentages variation  $\pm 15\%$  and  $\pm 25\%$ .



1 The different configurations of this sensitivity analysis are summarized in Table 3 (including  
 2 the reference case). Calculations were carried out for the two scenarios previously described in  
 3 section 2.2 (cycles of temperature and RH, respectively). 43 different simulations were run for  
 4 each scenario, representing a total of 86 simulations for the overall study.

5 Some of these parameters represent independent coefficients ( $C_p$ ,  $h$ ,  $\mu$  and  $\rho$ ) while other  
 6 parameters are defined as functions ( $\lambda$  defined by Eq. 1 and  $W$  defined by the GAB model) and  
 7 depend on other parameters or/and on the system's unknowns (temperature and relative  
 8 humidity RH). It is worth to mention that changing some parameters may imply the change of  
 9 others, *i.e.* changing the adsorption isotherm  $W$  implies a systematical recalculation of  $\xi_\varphi$ , the  
 10 sorption capacity that represents the derivative of the sorption isotherm. Moreover, the vapor  
 11 resistance factors obtained from wet and dry cup tests ( $\mu^*$  and  $\mu$ ), are both changed  
 12 simultaneously with the same percentages and are used to calculate liquid conduction  
 13 coefficient ( $D_l$ ) according to Eq. (4). In the same way, varying the heat exchange coefficient  $h$   
 14 with a certain percentage leads to a variation with the same percentage of the convective heat  
 15 transfer coefficient  $h_c$ , which is used to calculate the water vapor transfer coefficient at  
 16 boundaries  $\beta$  (see Eq. 9).

17 Besides, real boundary conditions imported from the actual experiment will be introduced in  
 18 the model (instead of creating uniform functions numerically), in order to perform the  
 19 sensitivity analysis under more realistic conditions. This choice will also facilitate future  
 20 comparisons between numerical simulations and experimental measurements.

21 **Table 3:** Study cases of the sensitivity analysis (for each case, 6 different percentages of  
 22 variations and two scenarios were considered)

Case	Varying parameters	Variation percentage	Unchanged parameters (set to their reference values indicated in Table 1)
<i>Reference case</i>	--	--	$C_p, h, \lambda, \mu, \rho, W$
<i>Case 1</i>	$C_p$	$\pm 5\%, \pm 15\%, \pm 25\%$	$h, \lambda, \mu, \rho, W$
<i>Case 2</i>	$h$	$\pm 5\%, \pm 15\%, \pm 25\%$	$C_p, \lambda, \mu, \rho, W$
<i>Case 3</i>	$\lambda$	$\pm 5\%, \pm 15\%, \pm 25\%$	$C_p, h, \mu, \rho, W$
<i>Case 4</i>	$\mu$	$\pm 5\%, \pm 15\%, \pm 25\%$	$C_p, h, \lambda, \rho, W$
<i>Case 5</i>	$\rho$	$\pm 5\%, \pm 15\%, \pm 25\%$	$C_p, h, \lambda, \mu, W$

<b>Case 6</b>	$W$	$\pm 5\%, \pm 15\%, \pm 25\%$	$C_p, h, \lambda, \mu, \rho$
<b>Case 7</b> <b>(simultaneous variation)</b>	$C_p, h, \lambda, \mu, \rho,$ $W$	$\pm 5\%, \pm 15\%, \pm 25\%$	--

1

## 2 4.2 Effect of initial conditions and sensors position

3 Another common possible source of errors in numerical calculations is related to the initial  
4 conditions. In the present case, initial values of temperature and RH are imported from the  
5 experiment. Consequently, the sensors accuracy may be responsible for some uncertainties on  
6 the measured values. The hygrothermal sensors (model DKRF400 from Driesen + Kern,  
7 Germany) present an accuracy of  $\pm 0.5$  °C on temperature and  $\pm 1.8\%$  on RH. It should be noted  
8 that these sensors have a higher accuracy compared those usually used in other works.

9 Besides, insertion of the hygrothermal sensors into the DPC wall requires drillings holes in  
10 view of positioning the sensor's probe at a given depth. This is a rather tough operation, which  
11 may result in significant errors on the sensor position. In order to evaluate the bias caused on  
12 theoretical temperature and RH profiles, the effect of a deviation of the sensor location (up to  
13  $\pm 1$  cm away from its reference position) on numerical results was investigated.

## 14 4.3 Simplification of heat and moisture transfer models

15 In the next part of the work, the possibility of simplifying the description of the transfer  
16 processes in the model was also investigated. In this line, some terms of the model related to  
17 specific transfer modes were neglected, and the effects of these modifications on the numerical  
18 outcomes were then evaluated by comparison with the reference case.

19 Such an investigation was already proposed in the literature [31]. Heat transfer was modeled  
20 by taking into account the conduction process only, and this simplified model proved to give  
21 good results in terms of temperature predictions.

22 In this part of the study, we explored the same hypothesis by neglecting the phase change term  
23 in the heat equation of the hygrothermal model (Eq. 3) and keeping only the heat conduction  
24 term. This leads to the following equation for heat transfer:

$$25 \quad \left( \rho_0 C_{p_0} + C_{p_l} W \right) \frac{dT}{dt} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) \quad (11)$$

26 This new model was solved for scenario 1, and the results obtained at different depth of  
27 the DPC wall were then compared to reference solutions provided by the complete model.

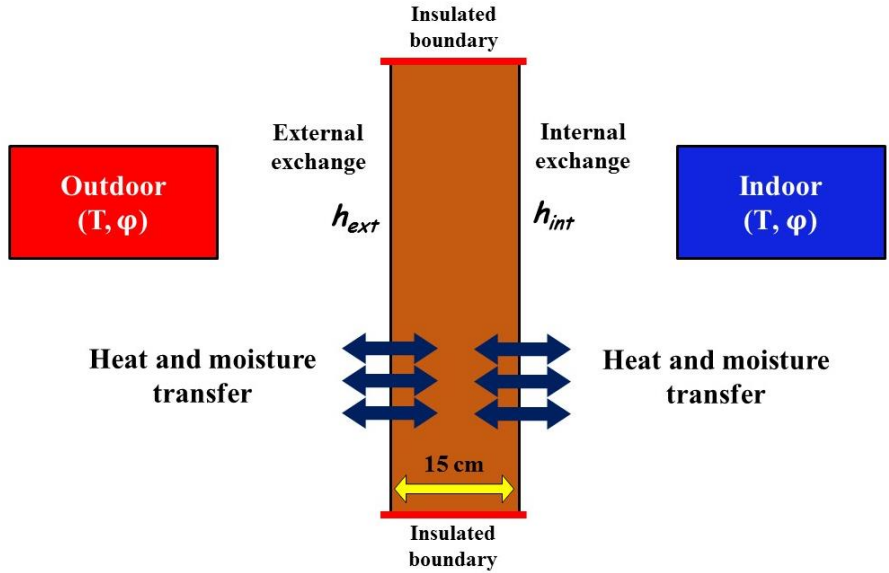
1 Likewise, as far as porous building materials are concerned, huge importance is usually given  
 2 to vapor transfer at the expense of liquid water transfer while modelling transfer phenomena  
 3 and RH variations. In order to estimate the contribution of liquid water diffusion to the overall  
 4 moisture transfer process, this specific mode was neglected in the model by setting to zero the  
 5 liquid transfer coefficients (cf. section 3.1) of the mass transfer equation (Eq. 4), hence leading  
 6 to the following expression:

$$7 \quad \xi_{\varphi} \frac{d\varphi}{dt} = \frac{\partial}{\partial x} \left( \delta \frac{\partial(p_{sat}\varphi)}{\partial x} \right) \quad (12)$$

8 This simplified model, based on vapor diffusion only, was solved using conditions of scenario  
 9 2, and numerical results obtained at various depth of the DPC wall were again compared to  
 10 those provided by the full model.

11 *4.4 Boundary conditions*

12 To resolve the problem, Kunzel’s model was implemented in COMSOL Multiphysics, a  
 13 simulation software and partial differential equations solver based on the finite element (FE)  
 14 method [32]. The wall presented in section 2.2 was simulated and discretized following the  
 15 same procedure as in [12]. A schematic view of the simulated wall and boundary conditions is  
 16 presented in Fig. 3.



17 **Fig. 3:** Model of the simulated wall

18 The global heat transfer coefficients at boundaries were estimated as follows, according to  
 19 Kunzel’s approximations [11]:

- 20 -  $8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ , with a convective contribution of  $3.57 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$  for the interior surface,

1 -  $17 \text{ W.m}^{-2}.\text{K}^{-1}$ , with a convective contribution of  $10 \text{ W.m}^{-2}.\text{K}^{-1}$  for the exterior surface.

## 2 **5 Results and discussion**

### 3 *5.1 Uncertainties on supposed known model parameters*

#### 4 *5.1.1 Reference solutions*

5 Reference solutions obtained at various depth of the DPC wall for scenarios 1 and 2 (heat and  
6 moisture transfers) are respectively presented in Figs. 4 and 5. These results were obtained by  
7 introducing into the model the reference values of input parameters (i.e., measured material  
8 properties or estimated value in the case of the heat transfer coefficient  $h$ ). These temperature  
9 and RH profiles will be used as a reference curves for the sensitivity analysis.

10

11

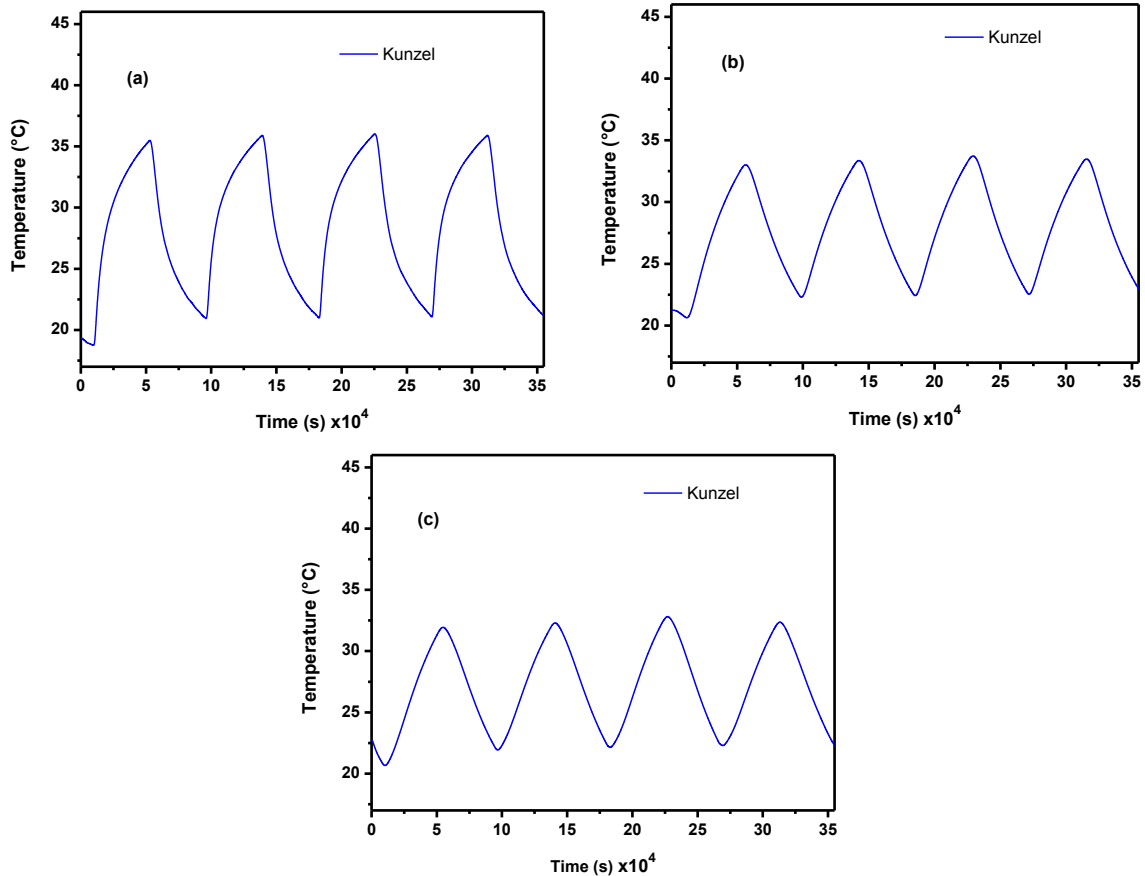
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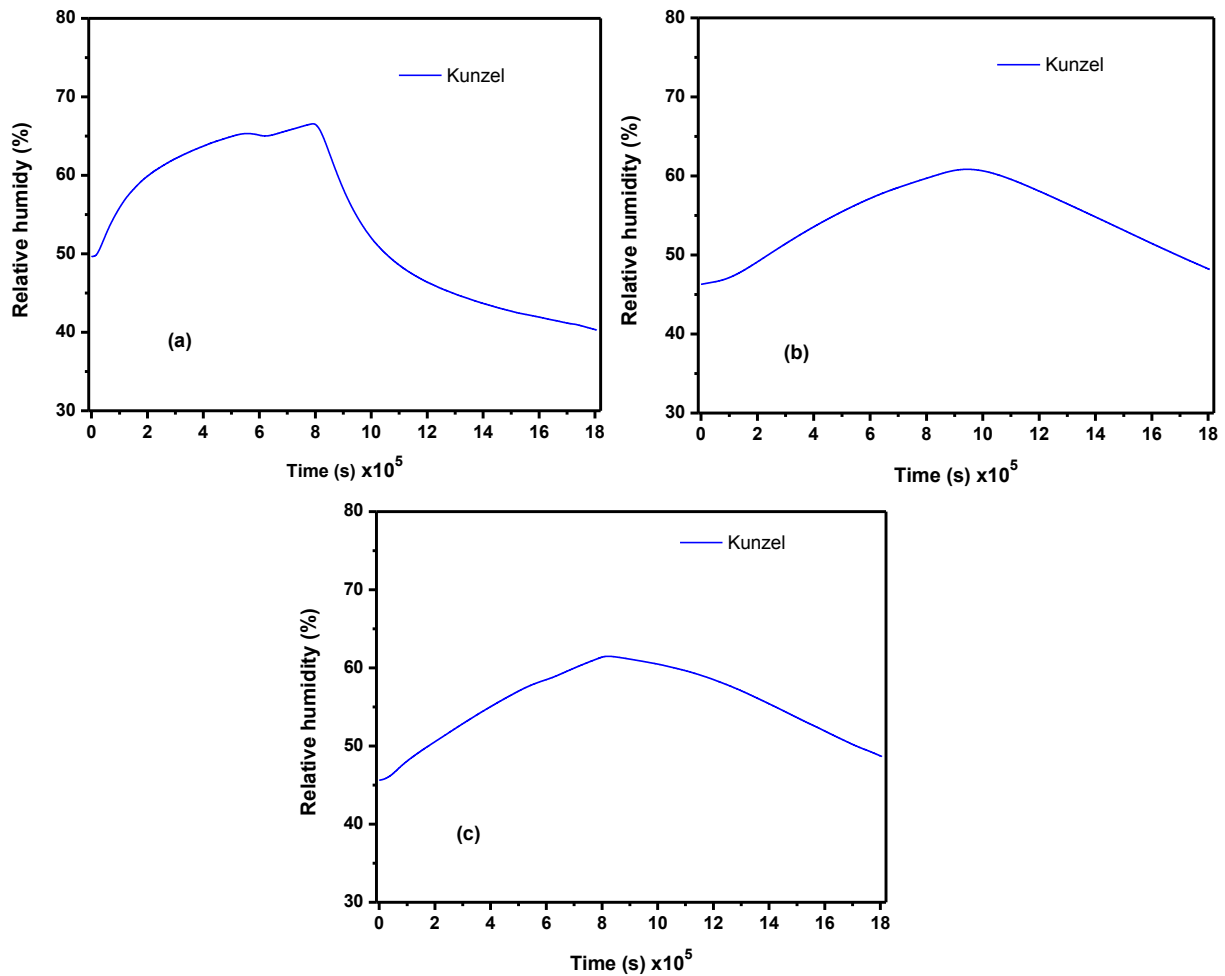
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23

24

**Fig. 4:** Reference solutions of the temperature profiles at various depths of the DPC wall subjected to scenario 1 (origin = outdoor side of the wall): 3 cm (a), 7.5 cm (b), 12.5 cm (c).



1 **Fig. 5:** Reference solutions of RH profiles at different depths of the DPC wall subjected to  
 2 scenario 2 (origin at the outdoor side of the wall): 3 cm (a), 7.5 cm (b) and 12.5 cm (c).

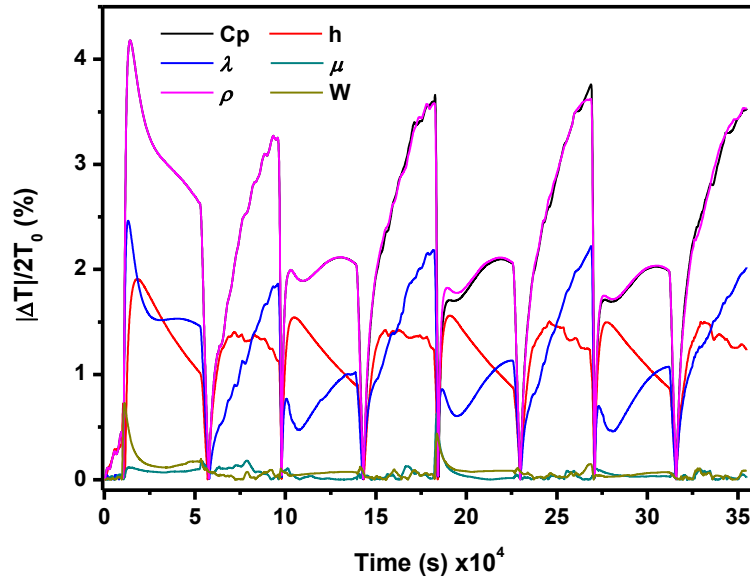
3

#### 4 **5.1.2 Sensitivity as a function of time**

5 In the current study, different factors may influence simultaneously the model's sensitivity for  
 6 the different input parameters: the percentage of variation of input parameters, time and depth  
 7 location. Therefore, we propose a methodology in which two of these factors are fixed, so that  
 8 the sensitivity evolution for the third factor can be assessed. In a first stage, the effect of time  
 9 evolution on the model's sensitivity to different input parameters is investigated for each  
 10 scenario. At first the effect of all parameters over time is displayed for a 25% variation  
 11 percentage at 3 cm depth (the effect at other depths is also presented below). This percentage  
 12 was chosen in order to show the extreme case of errors.

#### 13 **Heat transfer (scenario 1)**

1 Fig. 6 shows the evolution over time of the relative sensitivity of the model to the various input  
 2 parameters, at a depth of 3 cm in the DPC wall and considering 25% variation on parameters  
 3 with respect to their reference values.



11  
 12 **Fig. 6:** Evolution over time of the relative sensitivity of the model to various input parameters,  
 13 at 3 cm depth in the DPC wall and considering 25% of variation on parameters with respect to  
 14 their reference values (case of scenario 1)

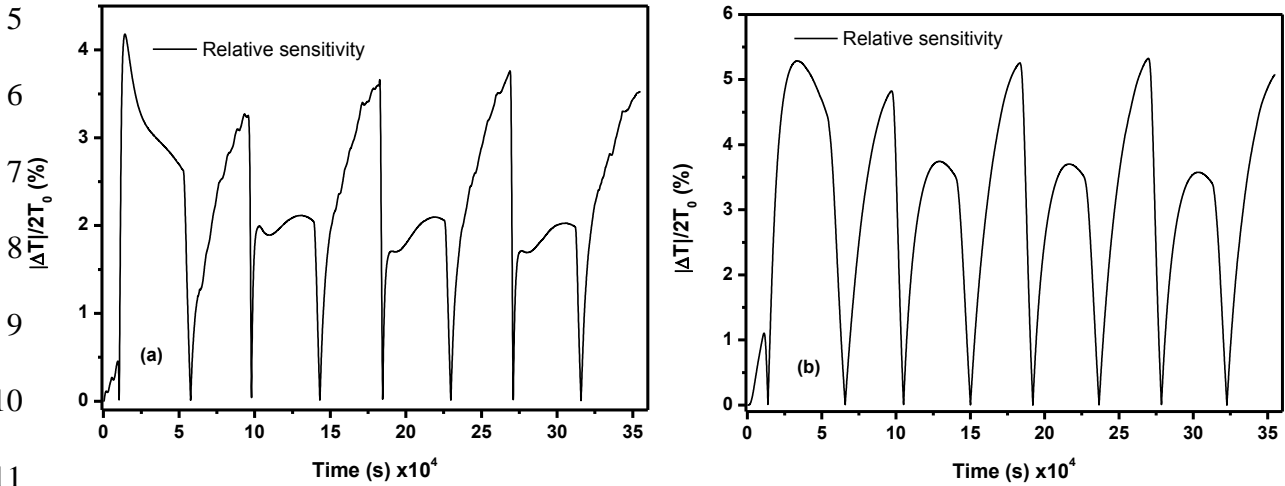
15 It can be observed that the various parameters do not have the same influence on the evolution  
 16 curves of the temperature relative sensitivity. The most influencing parameters are respectively  
 17  $C_p$  and  $\rho$ , followed by  $h$  and  $\lambda$ , and finally  $\mu$ . Likewise, it seems obvious that the sorption  
 18 isotherm  $W$  and the water vapor resistance factor  $\mu$  have a negligible impact in this case.

19 Besides, the curve obtained for the relative sensitivity to  $h$  shows a very different trend (and  
 20 even a reverse evolution) compared to the other curves: when the relative sensitivity to  $h$   
 21 increases, the sensitivities to the other parameters are found to decrease, and vice versa.  
 22 Moreover, sensitivities to  $C_p$  and  $\rho$  have almost the same evolutions. The same results were  
 23 obtained by Le *et al.* [33] for a hemp concrete wall and the same variation percentage (25%).  
 24 These two parameters are usually linked together but we plotted each of them separately  
 25 because their experimental values can be measured separately, and thus measurement errors  
 26 can be made on both properties.

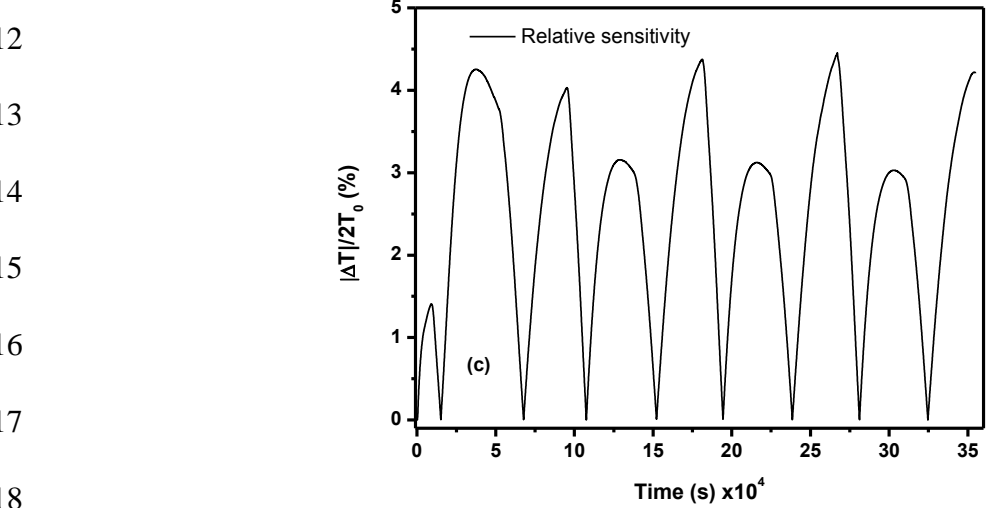
27 Fig. 7 displays the evolution versus time of the relative sensitivity to  $C_p$  (this parameter has  
 28 previously been identified as the most influencing parameter on heat transfer). Evolution curves

1 are plotted for different depths of the DPC wall, at 3 cm, 7.5 cm and 12.5cm away from the  
 2 outdoor side of the wall. It can be seen that the sensitivity index goes up and down  
 3 simultaneously at all depths.

4



11



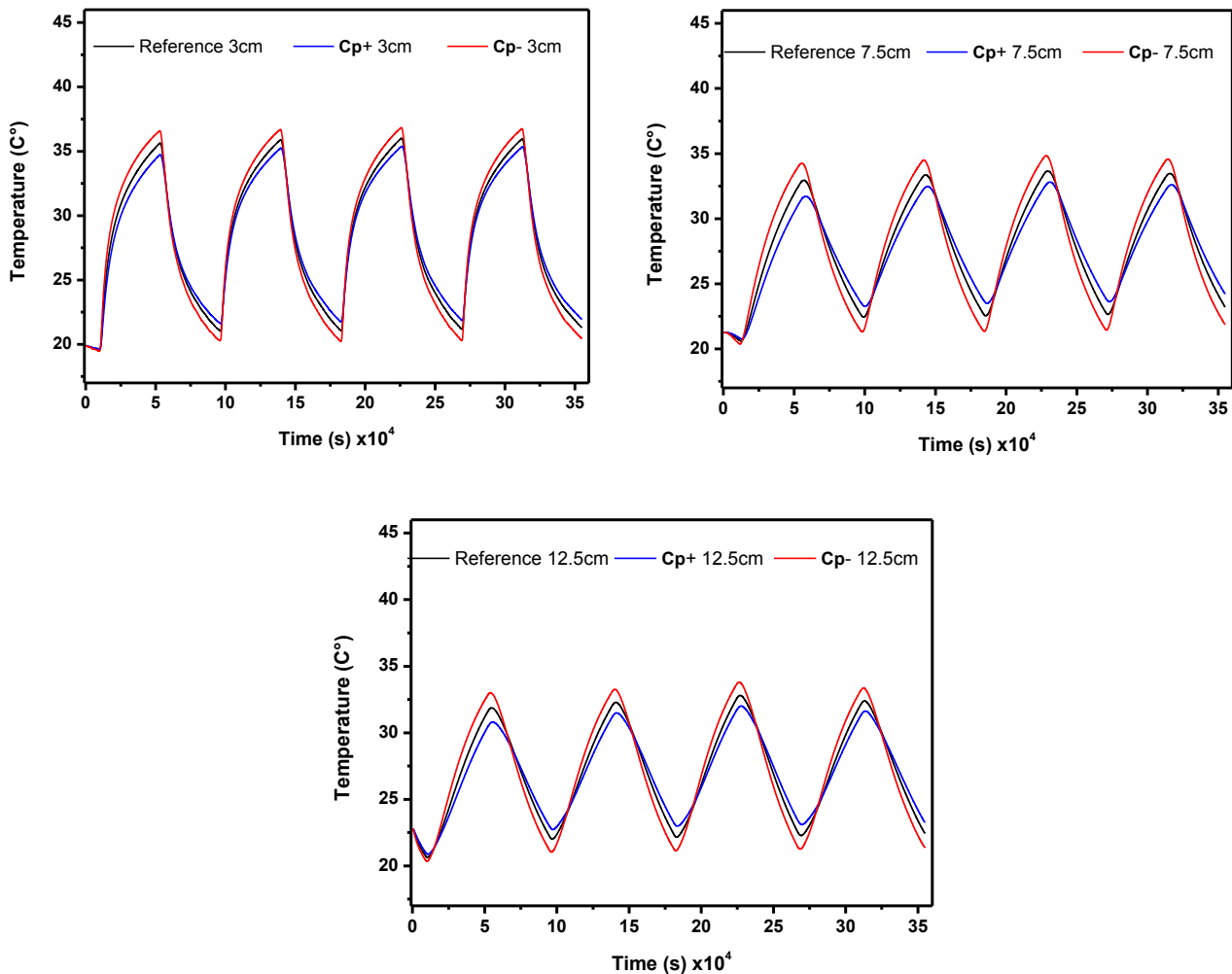
19 **Fig. 7:** Evolution versus time of the temperature relative sensitivity to a change of 25% in the  
 20 heat capacity ( $C_p$ ) with respect to the reference value, and at different depths of the DPC wall:  
 21 3 cm (a), 7.5 cm (b) and 12.5 cm (c)

22

23 Fig. 8 shows the evolutions of the new temperature profiles at different depths, which were  
 24 calculated considering variations of  $\pm 25\%$  on  $C_p$  with respect to the reference value  
 25 (reference curves are displayed on this graph as well). We can observe that the wall reacts in  
 26 the same way as external variations but with different amplitudes decreasing as a function of  
 depth. This is

1 due to the fact that we are moving away from the external surface where the outdoor  
 2 conditions (scenarios) are applied. By comparing Figs. 7 and 8, it is found that maximum  
 3 values of sensitivity are reached at the same time as the outdoor temperature reaches its  
 4 minimum during the imposed temperature cycle. Indeed, the quantity  $|Y_{x-\Delta x} - Y_{x+\Delta x}|$  is  
 5 maximal at this point, and when divided by the minimum reference temperature, it gives  
 6 maximum values of the relative sensitivity (Eq. 9). This was the case for all depths.

7 We can also notice that the sensitivity curves (Fig. 7) are smoother at 7.5 cm and 12.5 cm depths,  
 8 compared to 3 cm. This is due to temperature reference and new profiles which show also  
 9 smoother curves at 7.5 cm and 12.5 cm depths. Note that the first cycle was ignored in the result  
 10 analysis to avoid any possible effect of initial conditions.



11



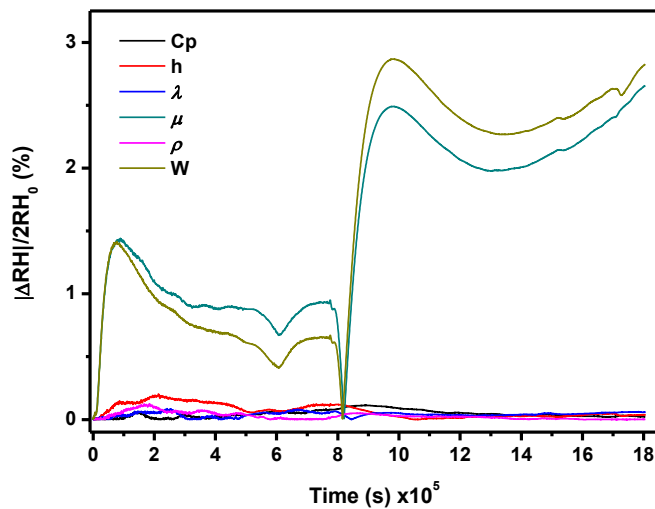
1 **Fig. 8:** New temperature profiles simulated at different depths of the DPC wall, considering  
 2 variations of the heat capacity by +25% ( $C_{p+}$ ) or -25% ( $C_{p-}$ ) compared to the reference value

3

4 **Moisture transfer (scenario 2)**

5 Regarding moisture transfer (scenario 2), the most influencing parameters are the sorption  
 6 isotherm  $W$  and vapor resistance factors ( $\mu$ ) whereas the other parameters have negligible  
 7 effects, as shown in Fig. 9.

8



15

16 **Fig. 9:** Evolution over time of the relative sensitivity of the model to various input  
 17 parameters, at 3 cm depth in the DPC wall and considering 25% of variation on  
 18 parameters with respect to their reference values (for scenario 2).

19

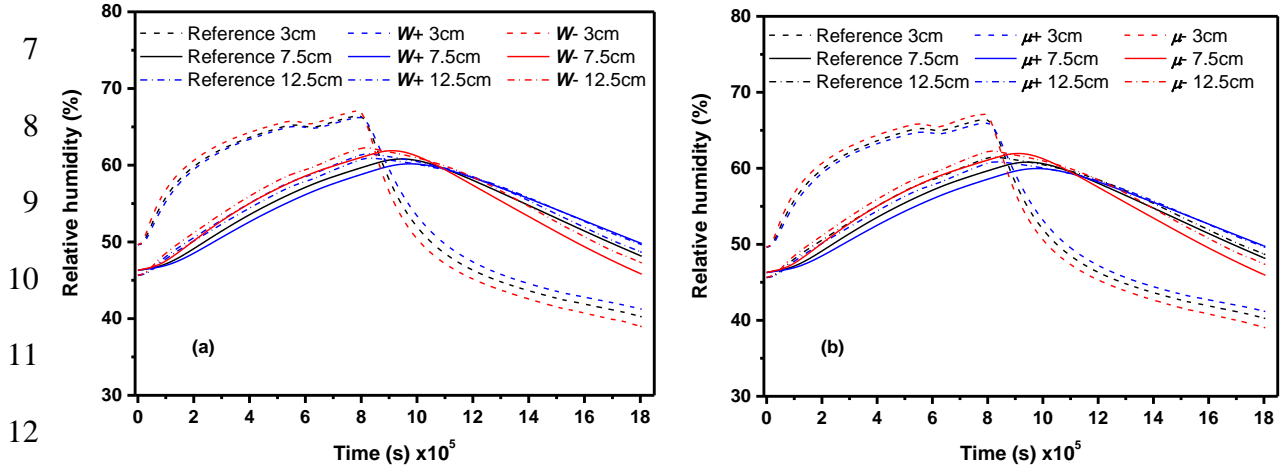
20 Fig. 10 depicts the new RH profiles simulated considering variations of +25% or -25% on these  
 21 two influent parameters, and at different depths of the wall. It was noted that lower values of  
 22  $W$  and  $\mu$  lead to higher RH curves during adsorption phase (*i.e.* max RH differences during  
 23 adsorption phase for a -25% sorption isotherm  $W$  read: 0.63%, 1.29% and 0.85% at 3 cm, 7.5  
 24 cm and 12.5 cm depth respectively) and lower curves during desorption phase (*i.e.* max RH  
 25 differences during desorption phase for a -25% sorption isotherm  $W$  read: 1.28%, 2.31% and  
 26 1.39% at 3 cm, 7.5 cm and 12.5 cm depth respectively). A lower sorption isotherm corresponds  
 27 to lower moisture storage in the material for the same RH value, this means that at a given water  
 28 content, we get a higher RH with the new sorption isotherm. Thus, a decrease in water content

1 resulted in slowing down the moisture transfer and storage in the material, as maximum and  
 2 minimum levels of RH were obtained with a time delay on the new profiles.

3 In the same way, a reduction of the vapor resistance factor  $\mu$  implies more vapor diffusion in  
 4 the material, hence higher RH levels during adsorption phase and lower ones during desorption.

5 The same observations and conclusions were also reported by [14, 34].

6



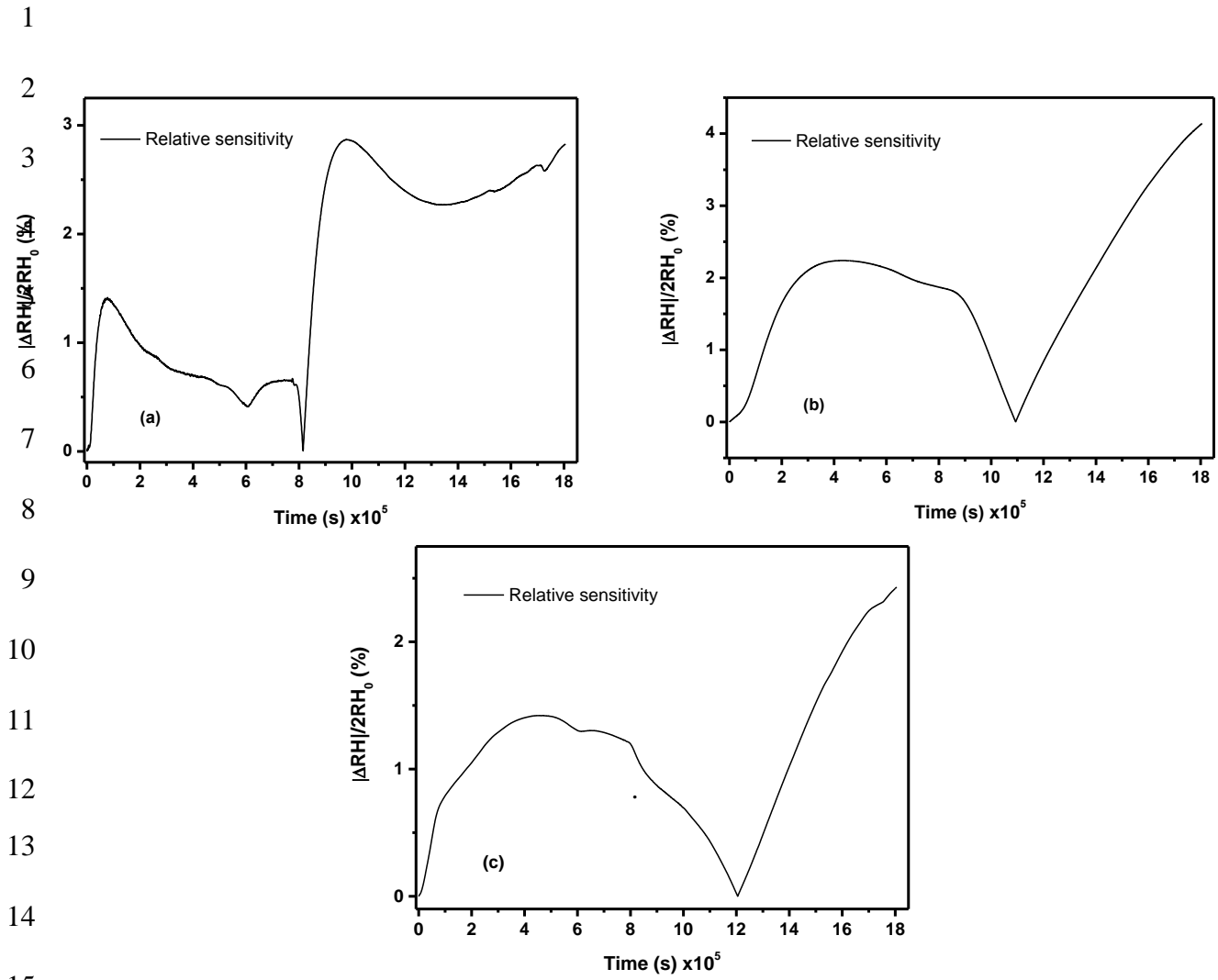
13

14 **Fig. 10:** New RH profiles simulated at different depths of the DPC wall, considering  $\pm 25\%$   
 15 variations on (a) the sorption isotherm  $W$  and on (b) the vapor resistance factor  $\mu$  compared to  
 16 their reference values

17

18 Fig. 11 represents the evolution over time of the relative sensitivity of the model to a 25%  
 19 variation on the sorption isotherm  $W$ , which was previously identified as the most influencing  
 20 parameter on moisture transfer. Numerical curves obtained at different depths of the DPC wall  
 21 are displayed. Larger variations can be observed at 3 cm depth compared to 7.5 cm and 12.5  
 22 cm depths (this is very similar to what was observed for the temperature relative sensitivity  
 23 **obtained in the case** scenario 1). The relative sensitivity reaches minimum values (zero) at the  
 24 points of the curves reversing shown on Fig. 10 (the points where the higher curve becomes  
 25 lower and the lower one becomes higher). This is because the new curves intersect and  $|Y_{x-\Delta x} -$   
 26  $Y_{x+\Delta x}|$  is equal to zero. Almost at all depths the highest relative sensitivity values were obtained  
 27 at the end of the test. At these points,  $|Y_{x-\Delta x} - Y_{x+\Delta x}|$  is maximum and  $RH_0$  is minimum.

28



**Fig. 11:** Evolution over time of the RH relative sensitivity to a change of 25% in the sorption isotherm ( $W$ ) with respect to the reference value, and at different depths of the DPC wall: 3 cm (a), 7.5 cm (b) and 12.5 cm (c).

### 5.1.3 Comparison of sensitivities to different parameters

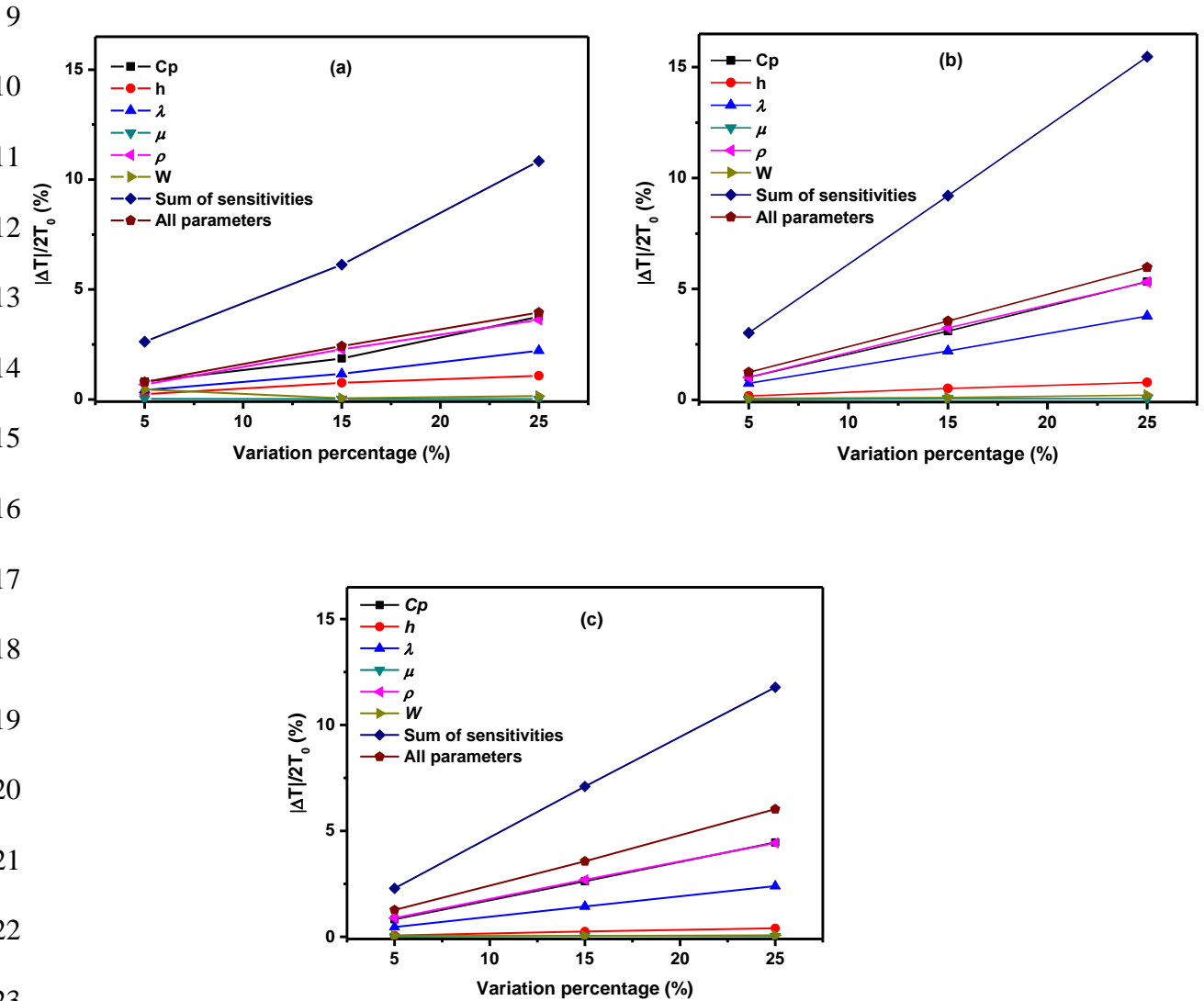
In a second stage, we compared the relative sensitivity of the model to each parameter at a fixed time, and considering different variation percentages of the model inputs. Simulations were carried out at different depths of the DPC wall. The time instants were chosen according to the analysis reported in section 5.1.2. The principle was to choose instants where the relative sensitivity reaches maximum values, so that the maximal influences of the various parameters can be compared. Different time instants were selected, depending on the scenario and the depth position considered.

## 1 Heat transfer (scenario 1)

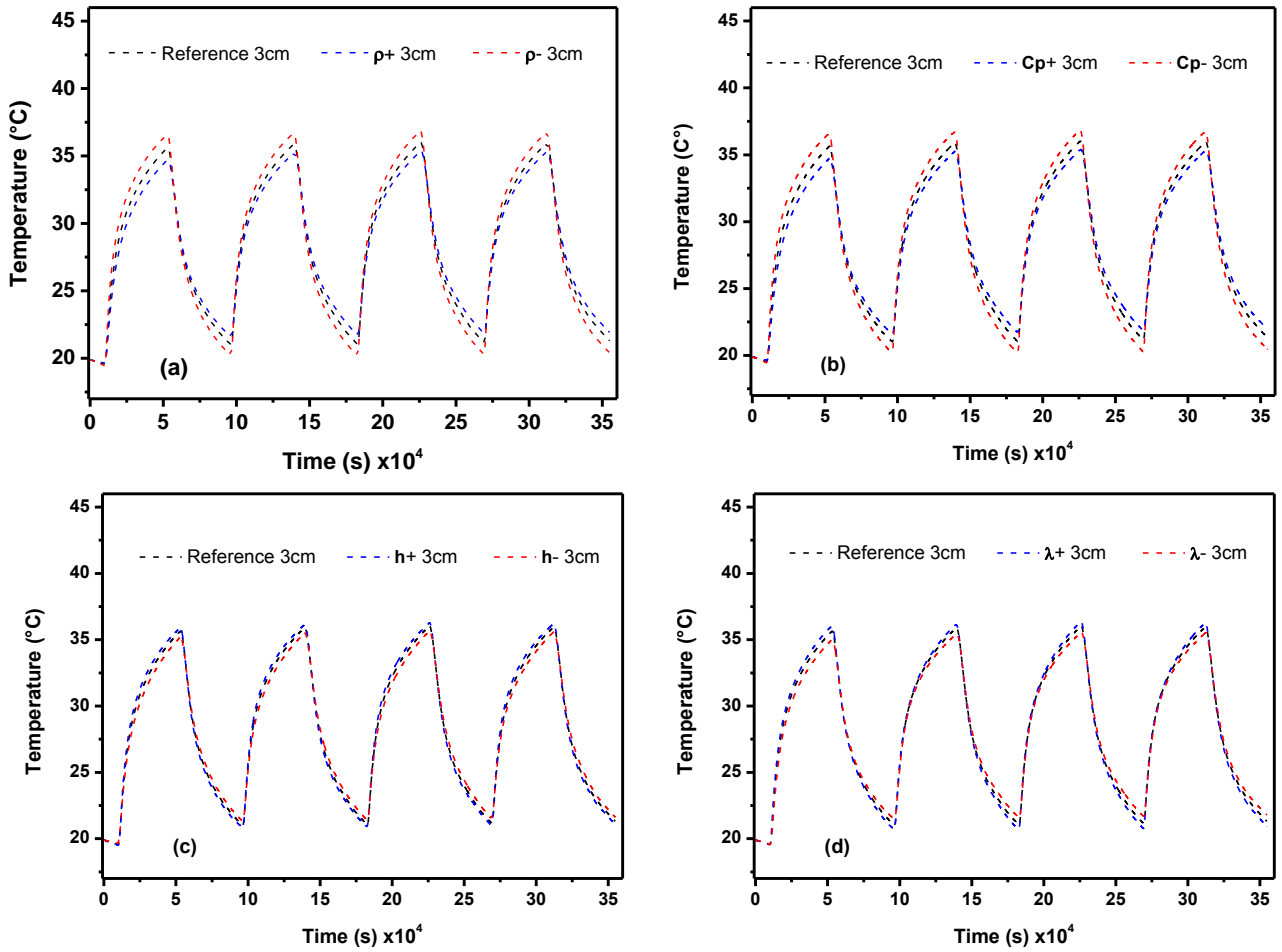
2 As already mentioned, the first cycle was not considered in this analysis. The instants chosen  
3 for the comparison are  $t_1=268920s$ ,  $t_2=269760s$  and  $t_3=267120s$  for 3 cm, 7.5 cm and 12.5  
4 cm depth respectively. They represent the instants where the sensitivity to  $C_p$ , the most  
5 influencing parameter on heat transfer reach a maximum value. At these times and using the  
6 relative sensitivity expression (Eq. 9), the evolution of the sensitivity as a function of the  
7 variation percentage of each parameter was plotted in Fig.12. This figure displays the graphs  
8 determined at different depths of the DPC wall. In agreement with previous results of section  
9 5.1.2, the most influencing parameters on the heat transfer were  $C_p$  and  $\rho$ , then  $h$  and  $\lambda$ , and  
10 finally  $\mu$  and  $W$ . A similar ranking was observed at all depths. Similar results were obtained by  
11 Van Belleghem *et al.* [34], who studied the sensitivity of heat and mass transfer to moderate  
12 changes (5%) in initial material properties, in the case of in gypsum boards. It can be noted that  
13 the sensitivity of the model to the external heat transfer coefficient ( $h$ ), decreases as a function  
14 of depth. This result was expected, due to the increasing distance from the outdoor surface of  
15 the wall.

16 Besides, the sensitivity of the model to a simultaneous change in the whole set of parameters  
17 (using the same variation percentage for all parameters) was found much lower compared to  
18 the sum of individual sensitivities. This result suggests that errors on input parameters don't  
19 accumulate and don't influence each other, or that they compensate each other in some way. In  
20 order to clear this up, the new temperature profiles simulated at 3 cm depth in the DPC wall  
21 considering a 25% variation on the most influencing parameters ( $C_p$ ,  $\rho$ ,  $h$  and  $\lambda$ , varied one by  
22 one while keeping the other parameters constant at their initial value) are represented in Fig.  
23 13. One can notice that  $C_p$  and  $\rho$  influence the temperature profiles in an opposite way compared  
24 to  $h$  and  $\lambda$ : increasing the values of  $C_p$  or  $\rho$  in the model results in a larger amplitude of the  
25 simulated profiles, whereas higher values of  $h$  and  $\lambda$  tend to decrease this amplitude. This  
26 opposite trend confirms that, when parameters are changed simultaneously, compensation  
27 phenomena occurs and lower the resulting sensitivity of the model in comparison to the sum of  
28 individual sensitivities. However, since variations of  $C_p$  and  $\rho$  have similar effects, errors on  
29 these two parameters may accumulate and emphasize the difference of the model outcome  
30 compared to the reference response. The same comment can be made regarding accumulation  
31 of errors on  $h$  and  $\lambda$ .

1 It should be noticed that some of the cases considered in this sensitivity analysis may not be  
 2 representative of actual experimental configurations, because varying a specific parameter may  
 3 in reality imply changing one or several other parameters. For instance, Collet *et al.* [35]  
 4 reported that thermal conductivity of hemp concrete blocks is highly dependent on the material  
 5 density ( $\lambda$  increases as a function of  $\rho$ ). Nevertheless, the present mathematical sensitivity  
 6 analysis remains relevant for parameters on which experimental errors can be made during  
 7 characterization. In other words, as long as a parameter can be measured independently,  
 8 experimental errors can be made on this specific parameter.



25 **Fig. 12:** Evolution of the temperature sensitivity versus the variation percentage of input  
 26 parameters (with respect to their reference values), at different depths of the DPC wall: 3 cm  
 27 (a), 7.5 cm (b) and 12.5 cm (c)



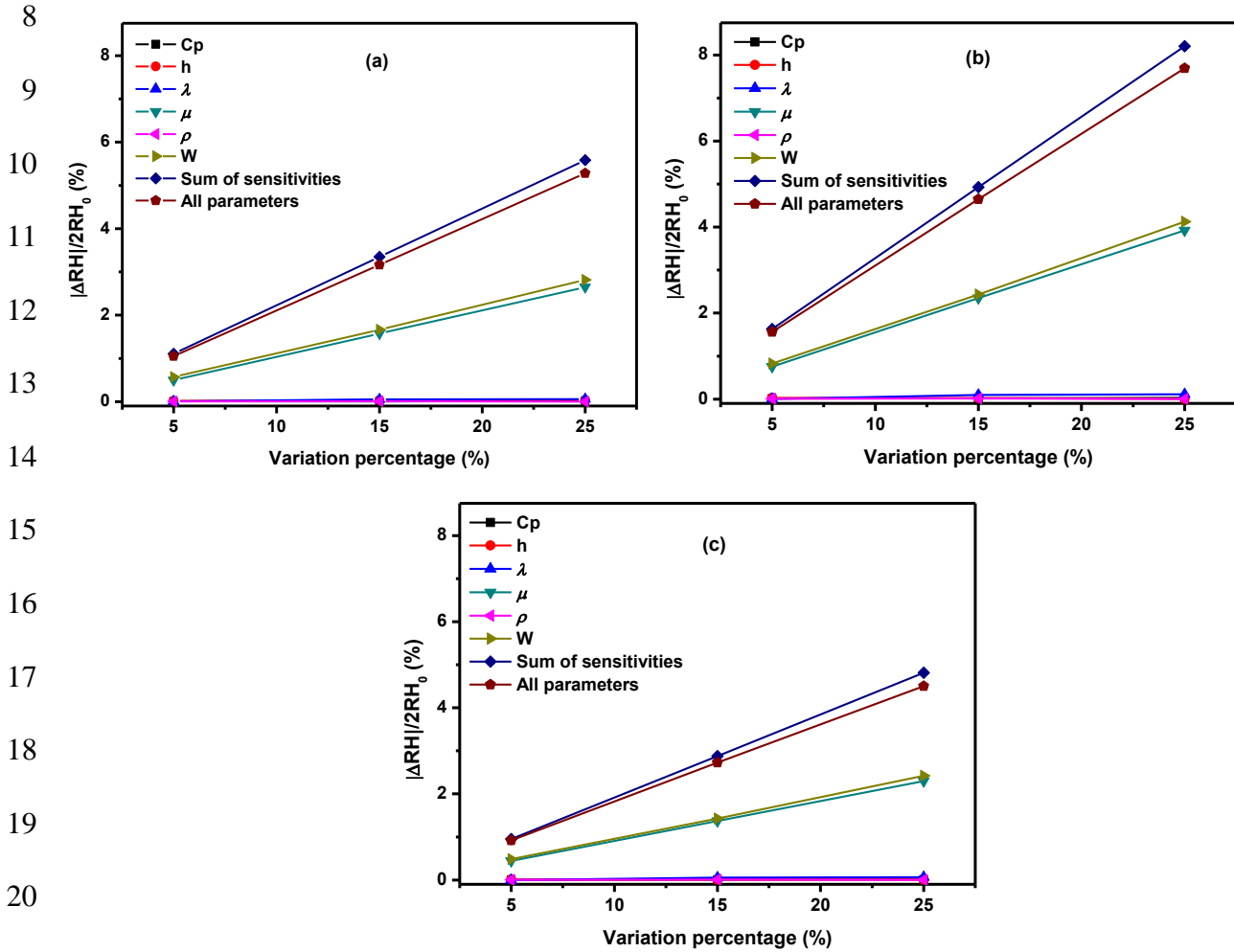
1 **Fig. 13:** New temperature profiles simulated at 3 cm depth in the DPC wall,  
 2 considering  $\pm 25\%$  variations on (a) the material density  $\rho$ , (b) heat capacity  $C_p$ , (c)  
 3 heat transfer coefficient  $h$  and (d) thermal conductivity  $\lambda$ , compared to their reference values

4 **Moisture transfer (scenario 2)**

5 Regarding the simulation of RH profiles (corresponding to scenario 2), the instant chosen for  
 6 comparison of parametric sensitivities is  $t=18 \times 10^5$  s for all depths. Fig. 14 shows the evolution  
 7 of the relative sensitivity versus the variation percentage of the model inputs. The graphs are  
 8 displayed for different depths of the DPC wall.

9 As previously noted in section 5.1.2,  $\mu$  and  $W$  are the most influencing parameters on moisture  
 10 transfer, while the impact of the rest of parameters is negligible. This was expected, because  
 11 these two parameters describe respectively the moisture transfer and storage in the model. The  
 12 same result was obtained by Bart *et al.* [14] and Van Belleghem *et al.* [34].

1 It is important to note that porosity does not explicitly appear in the transfer equations.  
 2 However, it is implicitly taken into account through the measured reference properties, which  
 3 are determined assuming homogeneity of the DPC material. This may be the reason behind the  
 4 low effect of density  $\rho$  on moisture transfer observed in this theoretical analysis. In reality, this  
 5 effect should be remarkable since porosity facilitates moisture diffusion. For instance, it was  
 6 shown that vapor permeability of hemp concrete blocks is influenced by the material density  $\rho$   
 7 [19, 35].



22 **Fig. 14:** Evolution of RH sensitivity versus the variation percentage of input parameters (with  
 23 respect to reference values) at different depths of the wall: 3 cm (a), 7.5 cm (b) and 12.5 cm (c)

25 Besides, varying all the parameters together provides high values of relative sensitivity on Fig.  
 26 14, which are also very close to the sum of individual sensitivities. This result means that these  
 27 material properties influence each other and that their uncertainties can accumulate and affect

1 the model outcome to a large extent. It was previously shown on Fig. 10, that 25% variation  
 2 on the two main influencing parameters ( $\mu$  and  $W$ ) have similar effects on theoretical profiles,  
 3 which explains the accumulation of errors observed in case 7 (simultaneous change in all  
 4 parameters).

5 **Table 4:** Comparison of sensitivity values for each case and each scenario at 7.5 cm depth  
 6 and considering 25% variation on the parameters

<b>Sensitivity per case</b>	<b>Varying parameters</b>	<b>Scenario 1: heat transfer</b>	<b>Scenario 2: moisture transfer</b>
<i>Reference case</i>	--	--	--
<i>Case 1</i>	$C_p$	5.33%	0.03%
<i>Case 2</i>	$h$	0.79%	0.01%
<i>Case 3</i>	$\lambda$	3.77%	0.11%
<i>Case 4</i>	$\mu$	0.05%	3.92%
<i>Case 5</i>	$\rho$	5.31%	0.01%
<i>Case 6</i>	$W$	0.21%	4.13%
<i>Case 7 (simultaneous variation)</i>	$C_p, h, \lambda, \mu, \rho, W$	5.97%	7.69%
<i>Sum of individual sensitivities</i>	$C_p, h, \lambda, \mu, \rho, W$	15.47%	8.21%

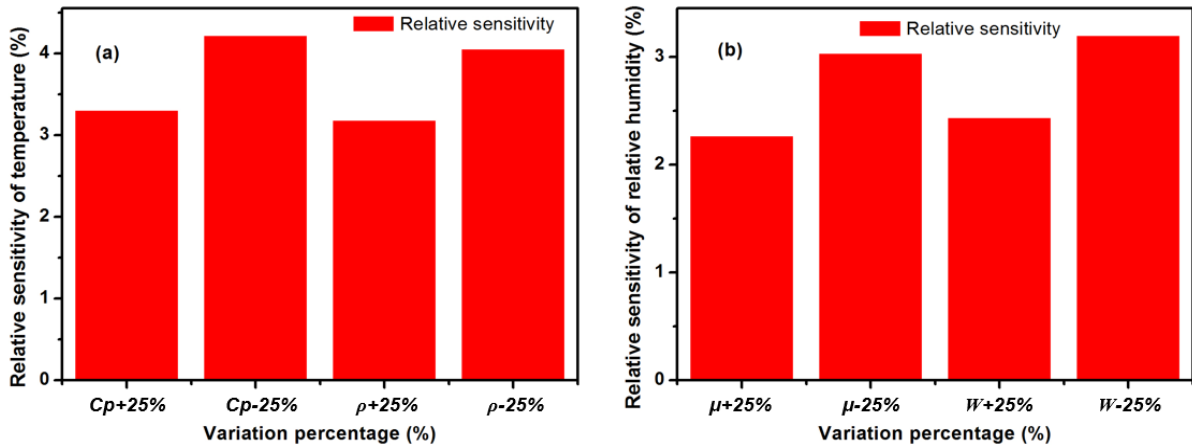
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8 Table 4 shows the sensitivity values obtained for the different cases of scenario 1 compared  
 9 with scenario 2 at 7.5 cm depth and 25% of variation. We notice that the global model's  
 10 sensitivity to heat transfer problems is higher than the sensitivity to moisture transfer ones, as  
 11 a higher error accumulation risk is obtained.

12 A major reason behind these uncertainties, both in the scenarios of heat and moisture transfer,  
 13 relates to the material homogeneity assumption which is usually adopted at all scales in  
 14 experimental/numerical approaches. As a matter of facts, procedures used for material  
 15 preparation may represent a source of heterogeneity, especially at large scale (wall or building).  
 16 This can induce variations on measured material properties, and thus on the model inputs.



1 Fig. 15 shows the effects of positive/negative changes in the values of  $C_p$  and  $\rho$  (one parameter  
 2 is varied while the other is kept constant at the reference value) on the relative temperature  
 3 sensitivity, as well as the influence of changing the values of  $W$  and  $\mu$  on RH sensitivity. The  
 4 effects of positive variations are found lower compared to those of negative changes. This was  
 5 also observed but not discussed in previous studies of the literature [2, 14, 34]. To our  
 6 knowledge, this is probably due to the nonlinear nature of the mathematical model, as the  
 7 coupled system involve several coefficients that depend on the system's unknowns and their  
 8 derivatives. Moreover, our study takes place in a transient state where the system is in a  
 9 continuous perturbation and varies over time. This is very different from a steady state study,  
 10 where the system is in equilibrium and the sensitivities usually tends to constant values.



11  
 12 **Fig. 15:** Effects of variations ( $\pm 25\%$ ) of selected parameters on the relative sensibility of the  
 13 model: (a) influence of  $C_p$  and  $\rho$  on the temperature sensibility, and (b) influence of  $W$  and  $\mu$   
 14 on RH sensibility

15 *5.2 Effect of initial conditions and sensors position*

16 *5.2.1 Effect of initial conditions*

17 Figs. 16 and 17 show the effect of changing initial conditions on simulated profiles of  
 18 temperature/RH at different depths. Regarding temperature profiles, and whatever the  
 19 considered depth, these effects are mainly observed during the first heating phase and then  
 20 rapidly vanish; the new profiles become very similar to the reference curve after a half cycle  
 21 (about 82000s after the beginning of the test). Regarding RH profiles, these effects are more  
 22 durable and can be observed throughout the test, but with lower influence at the end (deviation  
 23 of about 0.55% on RH value compared to the reference curve at  $t=18 \times 10^5$ s). This result was

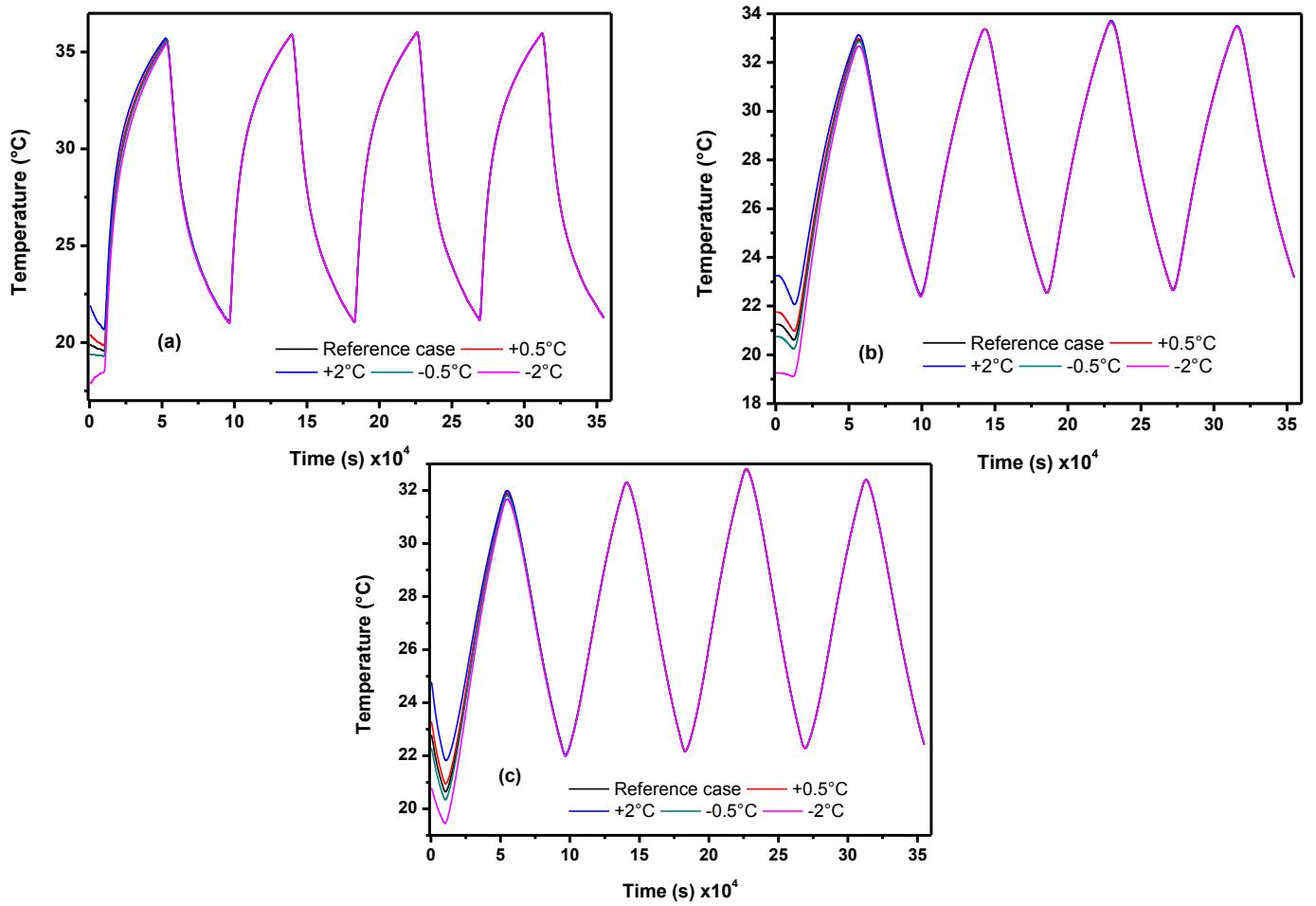
1 expected, because of the slow kinetics of moisture transfer compared to heat transfer. It was  
2 also reported by Oumeziane *et al.* [36], who studied the influence of initial moisture content  
3 and relative humidity on the MBV tests; the authors concluded that the initial hygric state has  
4 a strong impact on moisture transfer prediction, especially when hysteresis effect is taken into  
5 account. Globally, one must keep in mind that uncertainties on initial temperature conditions  
6 are relatively tolerated for long tests. Differently, uncertainties on RH conditions should be  
7 carefully evaluated, since errors as low as  $\pm 2\%$  can have a significant impact on numerical  
8 results.

### 9 **5.2.2 Effect of sensors position**

10 Fig. 18 shows the effect of changing the sensors position on simulated temperature profiles at  
11 different depths of the DPC wall. The largest deviation from the reference curve is obtained at  
12 3 cm of depth and equals to 0.92 °C, while at 7.5 cm and 12.5 cm of depths the maximum  
13 differences are 0.34 °C and 0.56 °C respectively. The effect of sensors position on numerical  
14 RH profiles at different depths is also shown in Fig. 19. Differences caused by a variation of  $\pm$   
15 1 cm from the reference position are more remarkable in this **scenario** (compared to scenario  
16 1). The largest deviation on RH is also obtained at 3 cm depth (5.36%), while smaller deviations  
17 of 1.66% and 1.65% are respectively found at 7.5 cm and 12.5 cm depths.

18 The accuracy of the sensors should also be taken into account in this analysis. In our case, the  
19 sensor accuracy specified by the manufacturer is  $\pm 0.5$  °C on temperature and  $\pm 1.8$  % on RH  
20 measurements. Temperature uncertainties are thus of the same order than temperature  
21 deviations resulting from the variation of sensors position, whereas RH uncertainties are much  
22 lower compared to RH deviations caused by errors on sensors position. Therefore, meticulous  
23 care should be taken while positioning the sensors on the experimental setup, especially for  
24 locations close to the outdoor surface of the wall where small errors may cause large data  
25 discrepancies. Similar conclusions were reported by Bart *et al.* [14], who studied the effect of  
26 sensors position on measured hygrothermal properties in the case of a 30 cm thick hemp  
27 concrete wall.

28

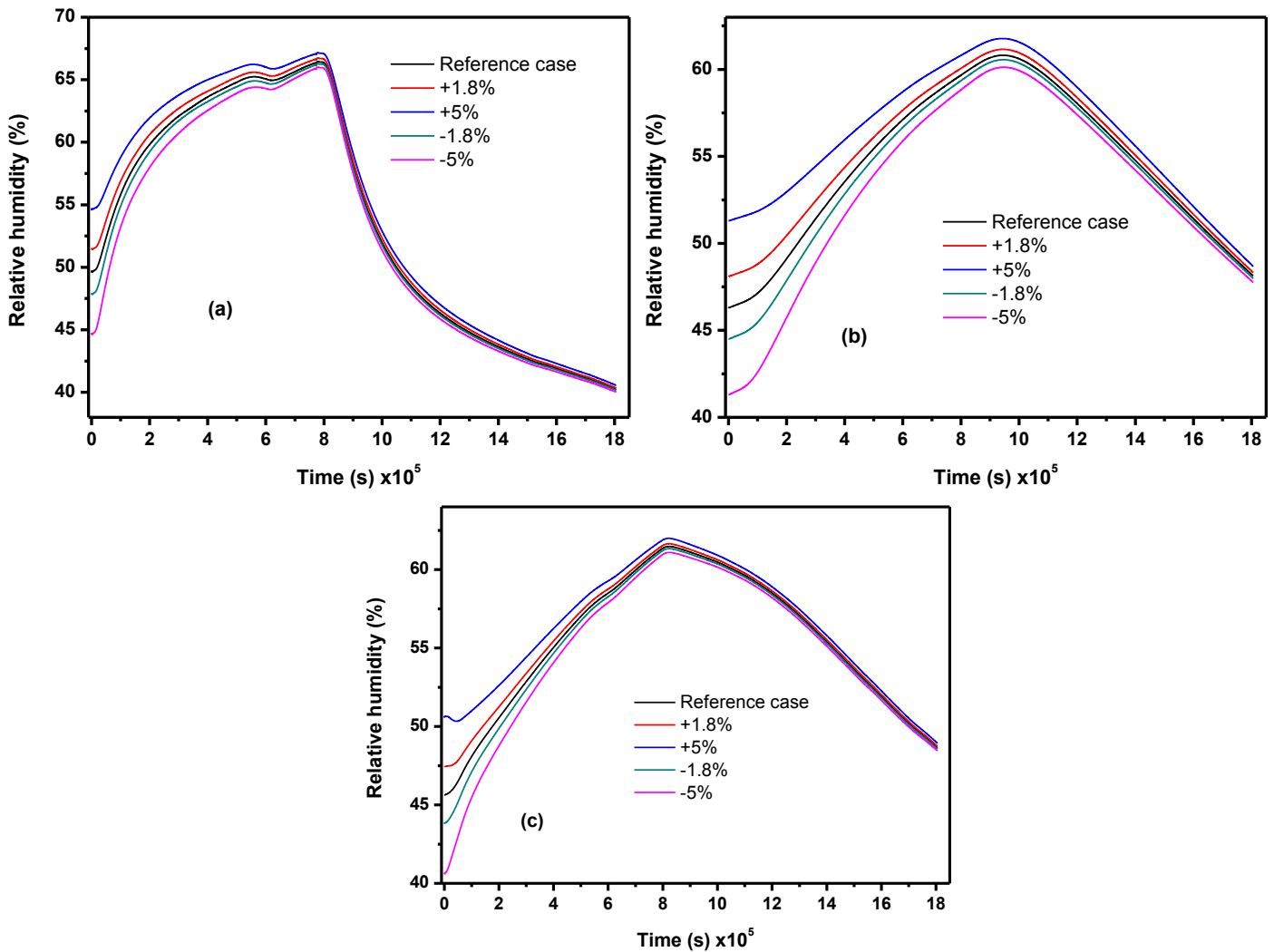


1 **Fig. 16:** Effect of changing initial temperature conditions on numerical temperature profiles  
 2 obtained at different depths: 3 cm (a), 7.5 cm (b) and 12.5 cm (c)

3

4

5



1 **Fig. 17:** Effect of changing initial RH conditions on numerical RH profiles obtained at  
 2 different depths: 3 cm (a), 7.5 cm (b) and 12.5 cm (c)

3

#### 4 **5.3 simplified models**

##### 5 **5.3.1 Pure conduction model**

6 Fig. 20 displays the numerical temperature profiles provided by the model based on pure  
 7 conduction transfer only, and by the full Kunzel model (reference case), at different depths of  
 8 the DPC wall. Differences between the numerical outcomes of the pure conduction and full  
 9 models did not exceed 0.25 °C, whatever the considered depth. This result shows that heat  
 10 conduction is the main transfer mode involved in the case of the DPC wall subjected to  
 11 conditions of scenario 1. This is also validated by the fact that RH boundary conditions were

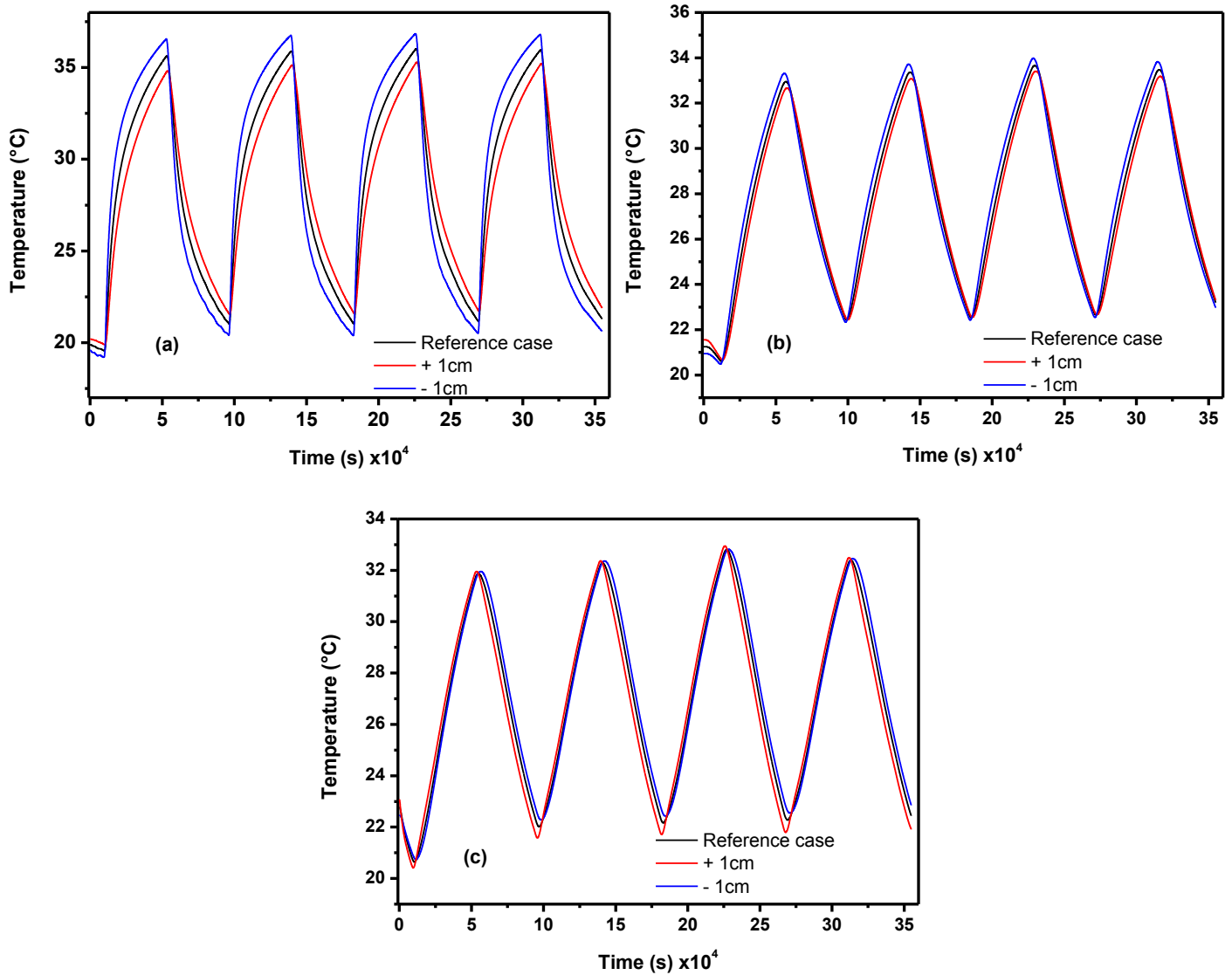
1 kept unchanged, and hence any moisture motion was the result of heat transfer due to the  
2 coupling effects between heat and moisture transfers (very small effect). This is translated  
3 mathematically by the phase change term in the right-hand side of Eq. 3, where the heat of  
4 phase change is related to vapor flux. In other words, this phase change term, which represents  
5 the only difference between the pure conduction and the full models, didn't play an important  
6 role in the studied case since the relative humidity was unchanged. Similar observations were  
7 noted by other authors on temperature profiles in the absence of phase change phenomena inside  
8 the material [31]. In such cases where only temperature changes are observed, one can conclude  
9 that the pure conduction model is sufficient to predict temperature profiles through a bio-based  
10 date palm concrete wall. This simplification provides a substantial gain of about 30% in  
11 calculation time.

### 12 **5.3.2 *Neglecting liquid transfer***

13 Fig. 21 compares the numerical RH profiles obtained with the full Kunzel model (reference  
14 case) with those obtained with a simplified model neglecting liquid transfer. It can be noticed  
15 that the two models provide very different outcomes whatever the considered depth. Deviations  
16 on RH values increase during the adsorption phase, with differences up to 3.8%, 4% and 2.3%  
17 at 3 cm, 7.5 cm and 12.5 cm respectively. Conversely, the gap between the two models is less  
18 important during desorption phase and becomes even negligible at 3 cm depth. This result can  
19 be explained by the fact that liquid and vapor transfers play both important roles during the  
20 adsorption phase, while liquid transfer is less influent during the desorption phase. Liquid  
21 transfer is naturally present in the adsorption phase, mainly through a surface diffusion process  
22 that starts to appear earlier in the hygroscopic region [11]. This process contributes to moisture  
23 transfer and accelerates its kinetics. Therefore, the full model provides numerical RH profiles  
24 that rise faster during adsorption phase and decrease faster during desorption phase, compared  
25 to the simplified model. Consequently, it is recommended not to neglect liquid transfer when  
26 modeling moisture transfer in porous building materials.

27

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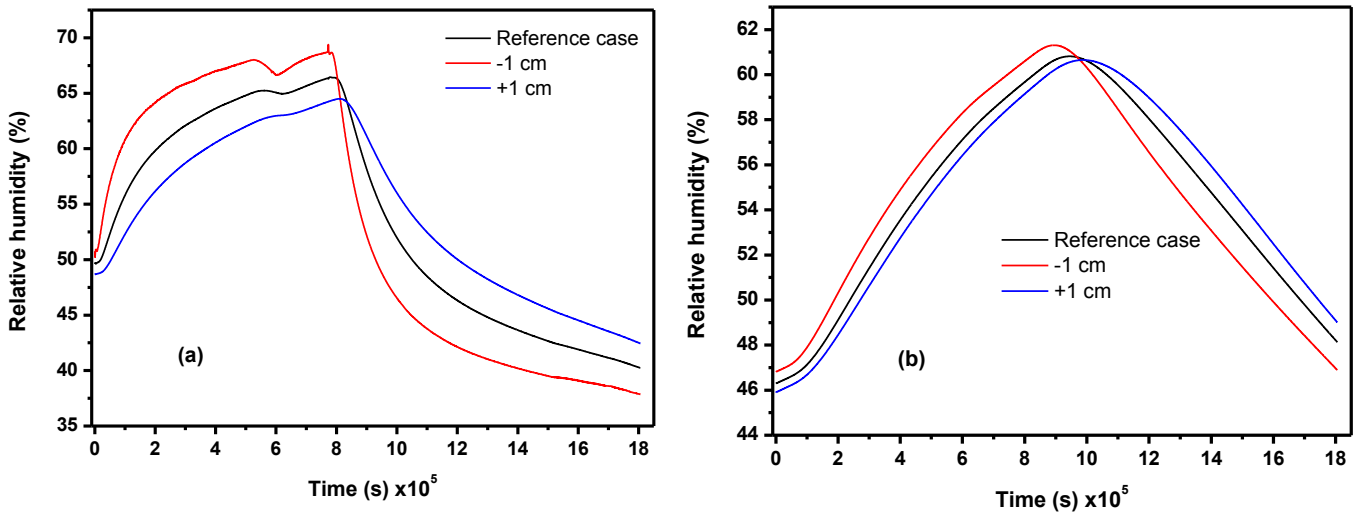
2 **Fig. 18:** Effect of changing sensors position on numerical temperature profiles determined at  
3 different depths of the DPC wall: 3 cm (a), 7.5 cm (b) and 12.5 cm (c)

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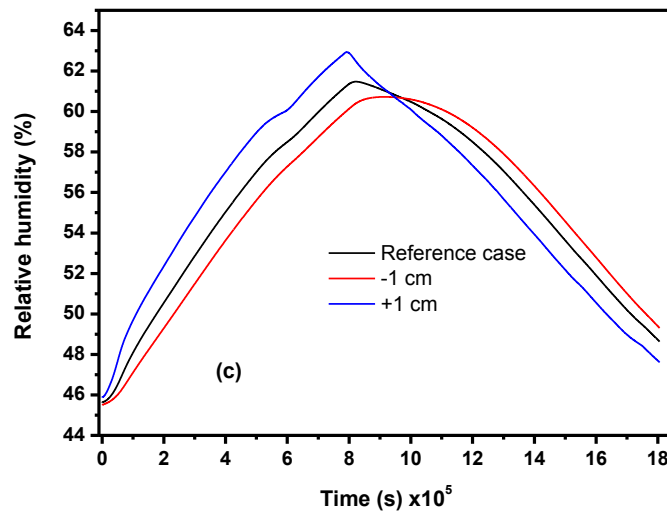
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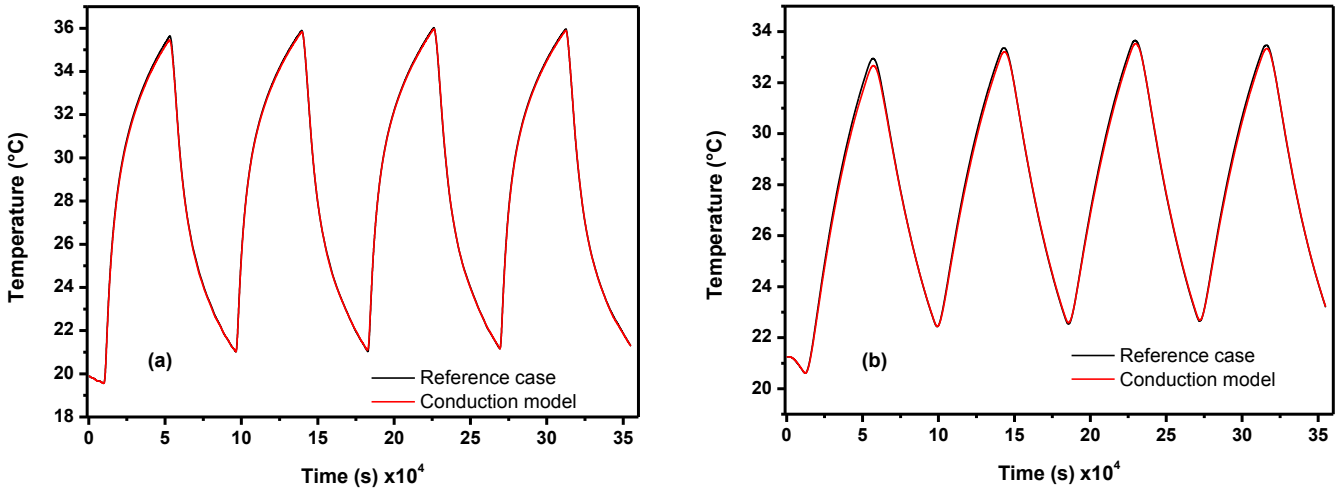
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4 **Fig. 19:** Effect of changing sensors position on numerical RH profiles determined at different  
5 depths of the DPC wall: 3 cm (a), 7.5 cm (b) and 12.5 cm (c)

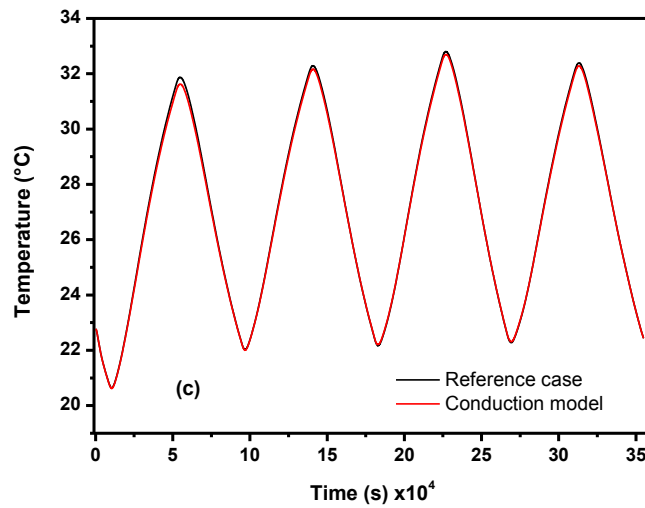
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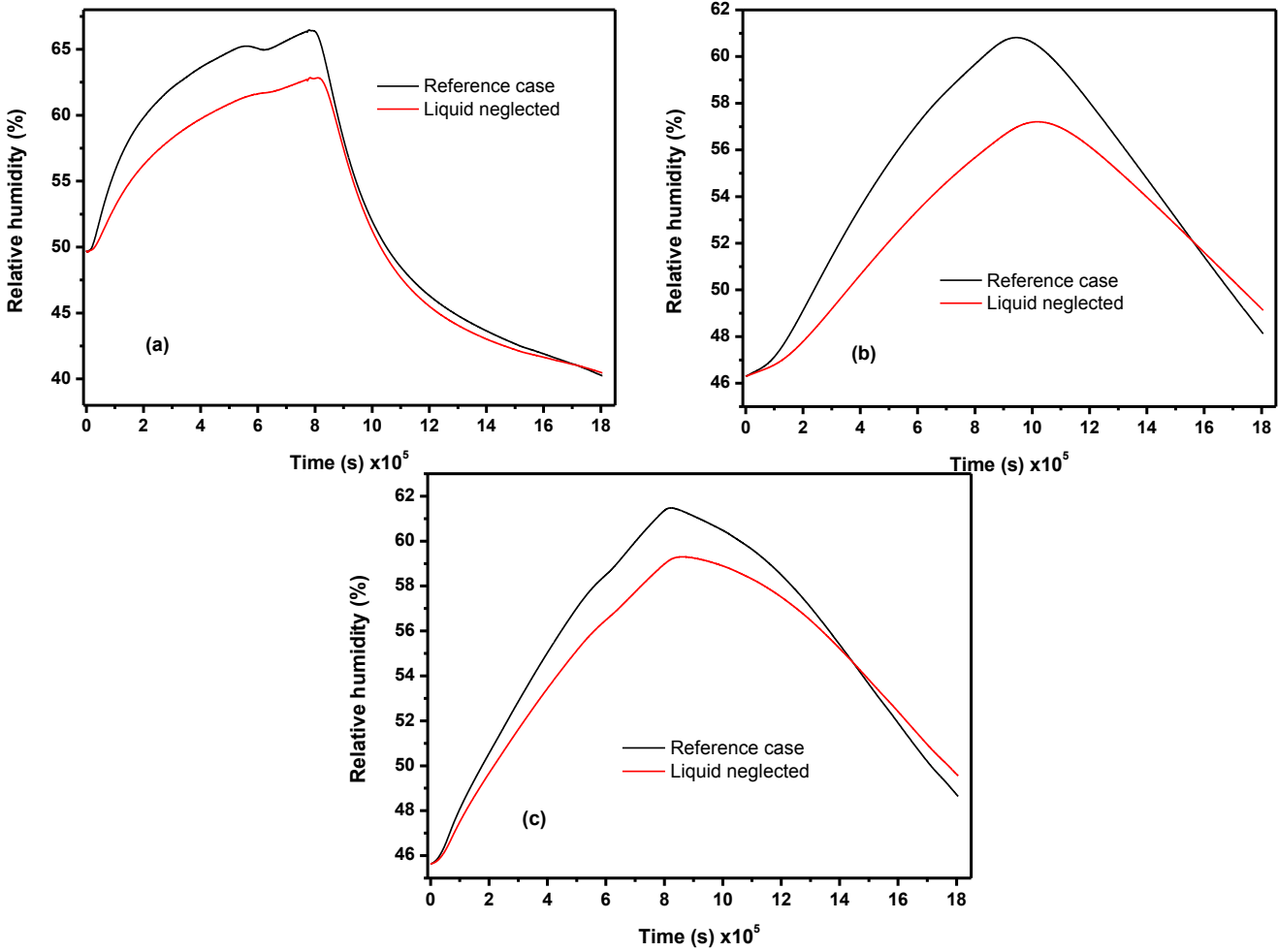
5 **Fig. 20:** Comparison of numerical temperature profiles provided by the pure conduction  
6 model and by the full Kunzel model (reference case), at different depths of the DPC wall: 3  
7 cm (a), 7.5 cm (b) and 12.5 cm (c)

8



1

2



3

**Fig. 21:** Comparison of numerical RH profiles provided by the model neglecting liquid transfer mode and by the full Kunzel model (reference case), at different depths of the DPC wall: 3 cm (a), 7.5 cm (b) and 12.5 cm (c)

6

## 1 **6 Conclusion**

2 In this work, a parametric sensitivity analysis was carried out on the transient heat and moisture  
3 transfer response of Kunzel's model. This model was applied to simulate the hygrothermal  
4 behavior a wall made of Date Palm Concrete (DPC), and boundary conditions for heat and  
5 moisture transfer scenarios were imported from real experiments. The effects of finite variations  
6 of the model inputs (reference material parameters and initial conditions) on the numerical  
7 outcome were investigated.

8 The results showed that the theoretical description of heat transfer is very influenced by  
9 changes in the heat capacity  $C_p$  and density  $\rho$ , which generates errors on temperature profiles  
10 reaching about 5.3% in terms of relative sensitivity. On the other hand, parameters  
11 influencing moisture transfer are mainly the sorption isotherm  $W$  and the vapor resistance  
12 factors  $\mu$ , which are responsible for a relative sensitivity of 4% on RH profiles. Therefore, a  
13 particular attention should be paid to the experimental determination of these reference  
14 properties at the material scale, and their validity at higher scales (wall or building) should be  
15 verified as well. It was also noted that moisture transfer is very sensitive to any errors in the  
16 initial conditions and sensors position. Uncertainties on initial RH values may influence the  
17 results even in the case of long tests (18 days' test in our case). Furthermore, uncertainties of  
18  $\pm 1$  cm on the sensors position may lead to 5.36% deviation on RH profiles.

19 Finally, some terms were neglected in the model, such as the heat of phase change and liquid  
20 diffusion, in order to explore the possibility of simplifying the model. It was shown that a pure  
21 conduction model is able to accurately describe the heat transfer process, whereas neglecting  
22 liquid diffusion leads to significant underestimations in RH profiles during the adsorption phase  
23 and should thus be proscribed.

24

### 25 **Acknowledgements:**

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27

## 1 7 References

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- [1] M. Haddadi, B. Agoudjil, N. Benmansour, A. Boudenne and B. Garnier, "Experimental and modeling study of effective thermal conductivity of polymer filled with date palm fibers", *Polymer Composites*, vol. 38, p. 1712–1719, 2015.
- [2] A. T. Le, C. Maalouf, T. H. Mai, E. Wurtz and F. Collet, "Transient hygrothermal behaviour of a hemp concrete building envelope", *Energy and buildings*, vol. 42, pp. 1797-1806, 2010.
- [3] L. Liu, H. Li, A. Lazzaretto, G. Manente, C. Tong, Q. Liu and N. Li, "The development history and prospects of biomass-based insulation materials for buildings", *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 912-932, 2017.
- [4] M. Rahim, O. Douzane, A. T. Le, G. Promis, B. Laidoudi, A. Crigny, B. Dupre and T. Langlet, "Characterization of flax lime and hemp lime concretes: Hygric properties and moisture buffer capacity", *Energy and Buildings*, vol. 88, p. 91–99, 2015.
- [5] M. Labat, C. Magniont, N. Oudhof and J. E. Aubert, "From the experimental characterization of the hygrothermal properties of straw-clay mixtures to the numerical assessment of their buffering potential", *Building and Environment*, vol. 97, pp. 69-81, 2016.
- [6] B. Agoudjil, A. Benchabane, A. Boudenne, L. Ibos and M. Fois, "Renewable materials to reduce building heat loss: Characterization of date palm wood", *Energy and Buildings*, vol. 43, p. 491–497, 2011.
- [7] M. Barletta, S. Guarino, G. Rubino, F. Trovalusci and V. Tagliaferri, "Environmentally friendly wooden-based coatings for thermal insulation: Design, manufacturing and performances", *Progress in Organic Coatings*, vol. 77, pp. 701-711, 2014.
- [8] J. Lazko, B. Dupré, R. M. Dheilily and M. Quéneudec, "Biocomposites based on flax short fibres and linseed oil", *Industrial crops and products*, vol. 33, pp. 317-324, 2011.
- [9] M. Caniato, L. Cozzarini, C. Schmid and A. Gasparella, "Acoustic and thermal characterization of a novel sustainable material incorporating recycled microplastic waste", *Sustainable Materials and Technologies*, vol. 28, no. e00274, 2021.
- [10] J. R. Philip and D. A. De Vries, "Moisture Movement in Porous Materials under Temperature Gradients", *Transactions American Geophysical Union*, vol. 38, pp. 222-232, 1957.
- [11] H. M. Künzler, Simultaneous heat and moisture transport in building components. One- and two-dimensional calculation using simple parameters, Stuttgart: IRB-Verlag, 1995.
- [12] T. Alioua, B. Agoudjil, N. Chennouf, A. Boudenne and K. Benzarti, "Investigation on heat and moisture transfer in bio-based building wall with consideration of the hysteresis effect", *Building and Environment*, vol. 163, no. 106333, 2019.
- [13] WUFI®, WUFI®, [Online]. Available: <https://wufi.de/en/software/validation/>.

- [14] M. Bart, S. Moissette, Y. Ait Oumeziane and C. Lanos, "Transient hygrothermal modelling of coated hemp-concrete walls", *Journal of Environmental and Civil Engineering*, vol. 18, pp. 927-944, 2014.
- [15] I. Othmen, P. Poullain and N. Leklou, "Sensitivity analysis of the transient heat and moisture transfer in a single layer wall", *European Journal of Environmental and Civil Engineering*, vol. 24, no. 13, pp. 1-19, 2018.
- [16] J. Morio, "Global and local sensitivity analysis methods for a physical system", *European journal of physics*, vol. 32, no. 1577, 2011.
- [17] H. M. Wainwright, S. Finsterle, Y. Jung, Q. Zhou and J. T. Birkholzer, "Making sense of global sensitivity analyses", *Computers & Geosciences*, vol. 65, pp. 84-94, 2014.
- [18] N. Mendes, F. Winkelmann, R. Lamberts and P. Philippi, "Moisture effects on conduction loads", *Energy and Buildings*, vol. 35, p. 631–644, 2003.
- [19] Y. Aït Oumeziane, S. Moissette, M. Bart, F. Collet, S. Pretot and C. Lanos, "Influence of hysteresis on the transient hygrothermal response of a hemp concrete wall", *Journal of Building Performance Simulation*, vol. 10, pp. 256-271, 2017.
- [20] B. Haba, B. Agoudjil, A. Boudenne and K. Benzarti, "Hygric properties and thermal conductivity of a new insulation material", *Construction and Building Materials*, vol. 154, p. 963–971, 2017.
- [21] N. Benmansour, B. Agoudjil, A. Gherabli, A. Kareche and A. Boudenne, "Thermal and mechanical performance of natural mortar reinforced with date palm fibers for use as insulating materials in building", *Energy and Buildings*, vol. 81, p. 98–104, 2014.
- [22] N. Chennouf, B. Agoudjil, A. Boudenne, K. Benzarti and F. Bouras, "Hygrothermal characterization of a new bio-based construction material: Concrete reinforced with date palm fibers", *Construction and Building Materials*, vol. 192, pp. 348-356, 2018.
- [23] E. I. 12572, "Hygrothermal performance of building materials and products - Détermination of water vapour transmission properties - Cup method", BS EN ISO 12572, 2016.
- [24] E. I. 15148, "Hygrothermal performance of building materials and products – Determination of water absorption coefficient by partial immersion", EN ISO, 2002.
- [25] E. I. 12571, "Hygrothermal performance of building materials and products - Détermination of hygroscopic sorption properties", BS EN ISO, 2013.
- [26] S. Brunauer, P. H. Emmett and E. Teller, "Adsorption of gases in multimolecular layers", *Journal of the American chemical society*, vol. 60, no. 2, pp. 309-319, 1938.
- [27] N. Chennouf, B. Agoudjil, T. Alioua, A. Boudenne and K. Benzarti, "Experimental investigation on hygrothermal performance of a bio-based wall made of cement mortar filled with date palm fibers", *Energy and Buildings*, vol. 202, no. 109413, 2019.

- [28] T. Alioua, B. Agoudjil, N. Chennouf, A. Boudenne and K. Benzarti, "Dataset on the hygrothermal performance of a date palm concrete wall", *Data in brief*, vol. 27, no. 104590, 2019.
- [29] T. Colinart, D. Lelièvre and P. Glouannec, "Experimental and numerical analysis of the transient hygrothermal behavior of multilayered hemp concrete wall", *Energy and Buildings*, vol. 112, pp. 1-11, 2016.
- [30] A. Boudenne, L. Ibos and Y. Candau, "Analysis of uncertainties in thermophysical parameters of materials obtained from a periodic method", *Measurement Science and Technology*, vol. 17, no. 1870, 2006.
- [31] Y. A. Oumeziane, Evaluation des performances hygrothermiques d'une paroi par simulation numérique: application aux parois en béton de chanvre, Rennes: Doctoral dissertation, 2013. <https://hal.archives-ouvertes.fr/tel-00871004/>
- [32] COMSOL Multiphysics user's guide, COMSOL Multiphysics, 2008.
- [33] A. T. Le, Etude des transferts hygrothermiques dans le béton de chanvre et leur application au bâtiment, Reims: Doctoral dissertation, 2010. <https://tel.archives-ouvertes.fr/tel-00590819/>
- [34] M. Van Belleghem, H. J. Steeman, M. Steeman, A. Janssens and M. De Paepe, "Sensitivity analysis of CFD coupled non-isothermal heat and moisture modelling", *Building and Environment*, vol. 45, pp. 2485-2496, 2010.
- [35] F. Collet and S. Prétot, "Thermal conductivity of hemp concretes: Variation with formulation, density and water content", *Construction and building materials*, vol. 65, pp. 612-619, 2014.
- [36] Y. A. Oumeziane, M. Bart, S. Moissette and C. Lanos, "Hysteretic behaviour and moisture buffering of hemp concrete", *Transport in porous media*, vol. 103, pp. 515-533, 2014.

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