Bio-Based and Recycled-Waste Materials in Buildings: A Study of Energy Performance of Hemp-Lime Concrete and Recycled-PET Façades for Office Facilities in France and Italy

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Abstract

Energy efficiency and Greenhouse Gases emission reduction are actual key issues in all the economic sectors and, in particular, in the building sector that is one of the most energy-consuming. This paper reports on the performance of sustainable materials produced from natural resources as hemp-concrete or from recycled-waste non-biodegradable materials including Recycled PolyEthylene Terephthalate (R-PET). Three façades employing three different materials (hemp-concrete, hemp-concrete with brick and R-PET) were investigated in three cities in France (Nancy and Carpentras) and in Italy (Perugia) with different climates. The energy performance of each façade was assessed in terms of cooling and heating demands, electrical consumptions and indoor thermal comfort including indoor temperature and relative humidity. The effects of two ventilation modes were tested using a constant airflow rate or humidity sensitive flow rate.

1. Introduction

Nowadays, the building sector is considered one of the most energy and resources consuming: buildings consume about 40 % of the world global energy, 25 % of the global water and 40 % of the global resources (United Nation Environment Program, 2016). Within the global aim of energy and resources saving, recent studies investigated buildings considering them as a fundamental part of the environment (Rossi et al., 2015), and also characterized innovative construction materials in detail (D'Alessandro et al., 2014). In this regard, the building sector has recently undergone a notable evolution towards sustainable materials (Asdrubali et al., 2015), thus contributing to both improving and promoting energy efficiency and renewable energy in sustainable development contexts. Also, climate changes are increasing as a result of growing atmospheric concentrations of carbon dioxide and other Greenhouse Gases (GHGs); this sets several challenges to be faced in the building sector. Therefore, it has become crucial to accelerate the shift from classical to environmentally friendly materials, in order to contribute to the transition to equitable, sustainable, post fossil-carbon societies. The use of bio-sourced materials as hemp-lime concrete or recycled-waste materials including Recycled PolyEthylene Terephthalate (R-PET) as insulating panels seems to be a promoting solution. In that context, this paper aims at performing a numerical assessment of the hygrothermal behaviours of three different walls. The latter incorporates hemp-lime concrete as shown in Fig. 1 (Elfordy et al., 2008; Arnaud and Gourlay, 2012; Collet et al., 2013; Ingrao et al., 2015) known as "hemp concrete" or "hempcrete", (Pretot et al., 2014; Ingrao et al., 2015) or R-PET which is PET, a thermoplastic polyester widely used for bottles and containers of food or pharmaceutical products (Massey et al., 2008). It can also be introduced in building applications in the form of insulating panels, with significant environmental benefits coming not only from the good thermal insulation performance but also, from the avoided use of virgin PET in the panel production phase (Ingrao et al., 2014; 2016).

The numerical study employs the simulation tool SPARK in which heat and moisture transfer equations are implemented. The annual electrical energy consumption values are also calculated through the simulations.

Fig. 1 – Hemp-lime concrete for building applications

2. Mathematical Model

This section is devoted to present the equations that were developed to assess the heating and cooling loads, on both the room and the air level.

The thermal performance of an envelope including the durability of the material highly depends on the moisture transport through the envelope. Thus, understanding the humidity transfers is crucial to improve performance and indoor thermal comfort especially when using a bio-sourced material like hemp-concrete (Lelievre et al., 2014; Tran Le et al., 2010). Along the years, several investigators have developed models of moisture transport in buildings and, in particular, in single building materials, among others: Künzel (1995), Pedersen (1992), and Mendes (1997).

Most of these models nearly have a similar physical basis: heat and mass equation, Philip and de Vries model (Philip and De Vries, 1957), and the laws of Fourier, Fick and Darcy. In contrast, the Umidus model (Mendes, 1997) which, as known, takes into account the liquid and vapour phase transfer is employed in this work. The wall thickness L is presented in Fig. 2 as well as the different transport phenomena, including mass and heat convections.

The governing partial equations to model heat and mass transfer are given as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(D_T \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_\theta \frac{\partial \theta}{\partial x}\right) \quad (1)$$

With the boundary conditions at the external surface (x = 0) and the internal surface (x = L):

$$\rho_l \left(D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x}\right)\Bigg|_{x=0,e} = h_{M,e}\left(\rho_{ve,a,e} - \rho_{ve,s,e}\right) \quad (2)$$

$$\rho_l \left(D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x}\right)\Bigg|_{x=L,i} = h_{M,i}\left(\rho_{ve,s,i} - \rho_{ve,a,i}\right) \quad (3)$$

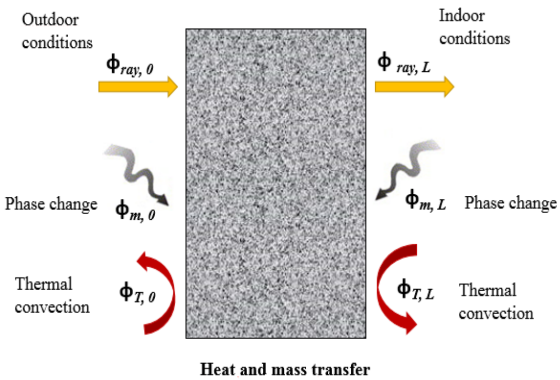


Fig. *2* - Heat and mass transfer through a material envelope

The energy conservation equation with coupled temperature and moisture for porous media is considered, and the effect of the absorption or desorption heat is added. This equation is written as follows:

$$\rho\, Cp_m \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda(T,\theta)\frac{\partial T}{\partial x}\right) + L_v \rho_l \left(\frac{\partial}{\partial x}\left(D_{T,v}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_{\theta,v}\frac{\partial \theta}{\partial x}\right)\right) \quad (4)$$

$$Cp_m = Cp_0 + Cp_l \frac{\rho_l}{\rho_\theta} \quad (5)$$

where Cpm is the average specific heat which takes into account the dry material specific heat and the contribution of the specific heat of liquid phase. λ is the thermal conductivity depending on moisture content. For a better understanding, it is underscored that the used boundary conditions take into account radiation, convection, and phase change.

$$-\lambda \frac{\partial T}{\partial x}\Big)_{x=0,e} - L_v \rho_l \left(D_{T,v} \frac{\partial T}{\partial x} + D_{\theta,v} \frac{\partial T}{\partial x}\right)_{x=0,e} = h_{T,e}\left(T_{a,e} - T_{s,e}\right) + L_v\, h_{M,e}\left(\rho_{ve,a,e} - \rho_{ve,s,e}\right) + \Phi_{ray,e} \quad (6)$$

$$-\lambda \frac{\partial T}{\partial x}\Big)_{x=L,i} - L_v \rho_l \left(D_{T,v} \frac{\partial T}{\partial x} + D_{\theta,v} \frac{\partial T}{\partial x}\right)_{x=L,i} = h_{T,i}\left(T_{s,i} - T_{a,i}\right) + L_v\, h_{M,i}\left(\rho_{ve,s,i} - \rho_{ve,a,i}\right) + \Phi_{ray,i} \quad (7)$$

Since the wall comprises several material layers, equations at the interface between layers are added. In this case study, the contact between layers is assumed perfect, moisture and thermal resistances at the interface are neglected, and the temperature and capillary pressure are considered continuous, according to Tran Le et al. (2009), Mendes and Philippi (2005).

$$(T)_A = (T)_B \qquad (\psi)_A = (\psi)_B \quad (8)$$

where T is the temperature and ψ is the capillary pressure.
According to Kelvin's law:

$$\phi = \exp(\psi g / R_v T) \quad (9)$$

Then, it can be deduced that:

$$\frac{R_v (T)_A}{g} \ln(\phi)_A = \frac{R_v (T)_B}{g} \ln(\phi)_B \quad (10)$$

where R_v is the constant of water vapour, ϕ is the relative humidity and g is the gravity acceleration. Because the temperatures for both materials are the same at the interface, the above equation can be written as:

$$(\phi)_A = (\phi)_B \quad (11)$$

which means that relative humidity is the same at the interface for both materials, whilst moisture content is discontinuous because of the different pore structures of those materials.

2.1 Air Model

The air in the zone is assumed to be well mixed respecting the perfect gas law. The net heat transferred into the zone across its faces must equal the heat stored in the volume of air in the cell. This involves heat fluxes through the envelope (transmission, long and short-wave radiation input), additional thermal loads, air exchange due to natural convection or 'Heating, Ventilating and Air Conditioning' (HVAC). The energy equation can be written as:

$$(\rho_i c_p V + I)\frac{\partial T}{\partial \tau} = \Phi_{West} - \Phi_{East} + \Phi_{South} - \Phi_{North} + \Phi_{Bottom} - \Phi_{Top} + \Phi_{Source} \quad (12)$$

where I is the room's thermal inertia.
The humidity condition in the room is due to moisture transfer from interior surfaces, moisture production rate, and the gains or losses due to air infiltration, natural and mechanical ventilation, as well as sources or sinks due to the room occupancy. This yields the following mass balance equation for room air:

$$V\frac{\partial \rho_i}{\partial \tau} = Q_{mWest} - Q_{mEast} + Q_{mSouth} - Q_{mNorth} + Q_{mBottom} - Q_{mTop} + Q_{mSource} \quad (13)$$

2.2 Radiation Exchange

For the short-wave radiation transmitted through the walls, it can be considered that radiant energy enters the room by pane window. However, the mean radiant temperature method is used to calculate long-wave radiation exchange between walls. A linear equation expressing the radiative flow between a wall and all the other walls of the room is written as:

$$\Phi^{int}_{rad,LW} = h_r S\left(T - T_m\right) \quad (14)$$

The value of h_r is expressed by:

$$h_r = 4\varepsilon\sigma_0 T_m^3 \quad (15)$$

where T_m is the mean radiant temperature of the walls and is given by:

$$T_m = \frac{\Sigma S_j T_{Sj}}{\Sigma S_j} \quad (16)$$

3. Study Conditions

The composition of the first façade includes an external hemp-concrete layer of 0.095 $W.m^{-1}.K^{-1}$ thermal conductivity associated with 20 cm hollow brick (HCB façade). The second comprises a 36 cm hemp-concrete wall with indoor lime plaster (HC façade). The third façade is based on a thermal block, a thermal insulation layer realised with R-PET mats of 0.036 $W.m^{-1}.K^{-1}$ thermal conductivity and a ventilated cavity associated with a cladding layer (PER façade). The characteristics of each façade are presented in Tables 1, 2, and 3.

The energy performances of the façades were compared through annual energy analyses; each façade is coupled with a virtual office considering different climatic conditions in two cities in France (Nancy and Carpentras) and one in Italy (Perugia). Two types of ventilation are compared: the constant flow rate (36 m^3/h) and the relative humidity sensitive rate (16 – 43 m^3/h).

With reference to the standard NF EN 12831, the air infiltration rate is estimated to 0.2 h^{-1}. An additional night free cooling of 2 h^{-1} is considered in the summer season (from 3 am to 8 am) to optimise cooling energy consumption. Because of lack of data for the hollow bricks, moisture transfer was neglected in this layer (for both HCB and R-PET façades). Room temperature was kept constant from October to late March and was allowed to float between 19 °C and 26 °C for the remaining period. Simulations were run for a period of 24 months, the results of the first twelve months were neglected and used to initialize the calculation, then the final results were presented for the last twelve months from January to December. The time step was set to 10 minutes.

The cooling and heating energy demands as well as the electrical energy consumptions were calculated taking into account the heat and moisture within the façade (especially for the hemp-concrete material).

Table 1 – Hemp-concrete brick façade (HCB) properties

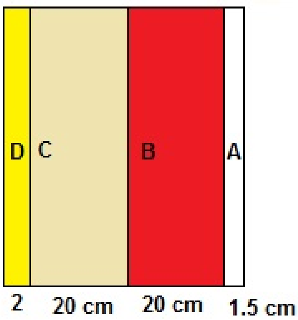
Façade (HCB)	Layers (from inside to outside)	Mass density (kg m^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Specific heat (J kg^{-1} °C^{-1})	Transmittance (W m^{-2} K^{-1})
	A - Gypsum plaster	900	0.25	850	
	B - Optibric PV3+ Imeris	700	0.187	850	0.3
	C - Sprayed hemp concrete	420	0.095	1000	
	D - Lime sand plaster (2cm)	1650	0.4	830	

Table 2 – Hemp-concrete façade (HC) properties

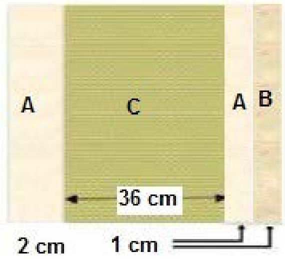
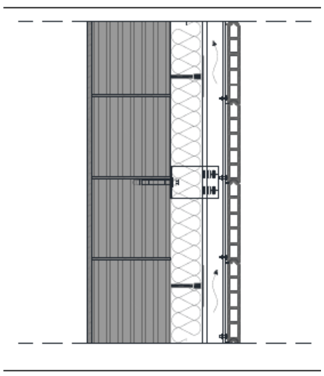
Façade (HC)	Layers (from inside to outside)	Mass density (kg m^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Specific heat (J kg^{-1} °C^{-1})	Transmittance (W m^{-2} K^{-1})
	B - Hemp-lime plaster	930	0.2	1000	**0.26**
	A - Lime sand plaster	1650	0.4	830	
	C - Sprayed hemp-concrete	420	0.095	1000	

Table 3 - R-PET façade properties

Façade (R-PET)	Layers (from inside to outside)	Mass density (kg m^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Specific heat (J kg^{-1} °C^{-1})	Transmittance (W m^{-2} K^{-1})
	Lime sand plaster (1.5 cm)	1650	0.4	830	0.22
	Thermal block (25 cm)	531	0.18	900	
	Thermal insulation (10 cm)	30	0.0365	240	
	Ventilated cavity				
	Cladding (4 cm)	750	0.3		

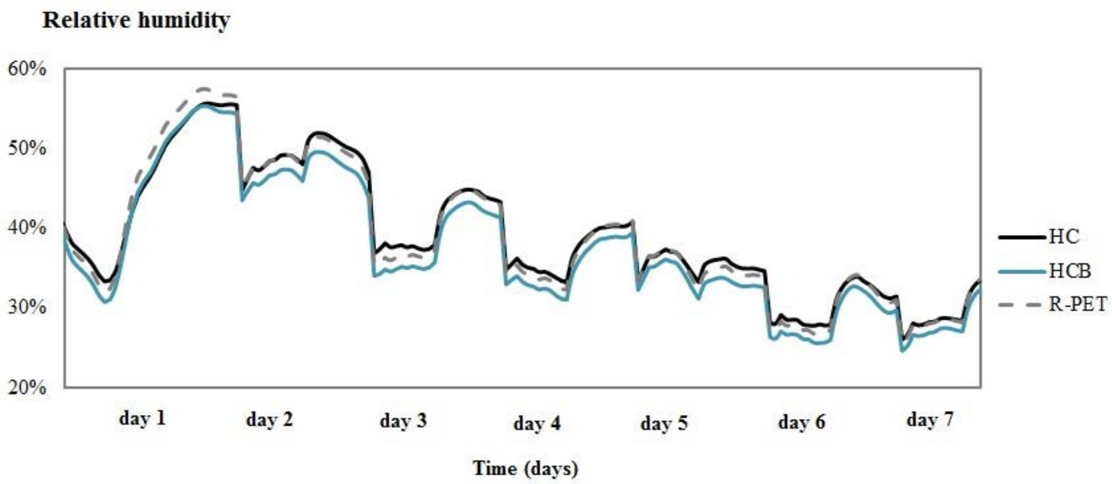


Fig. 3 - Indoor relative humidity variation during one week of December in Nancy using a constant flow rate ventilation mode

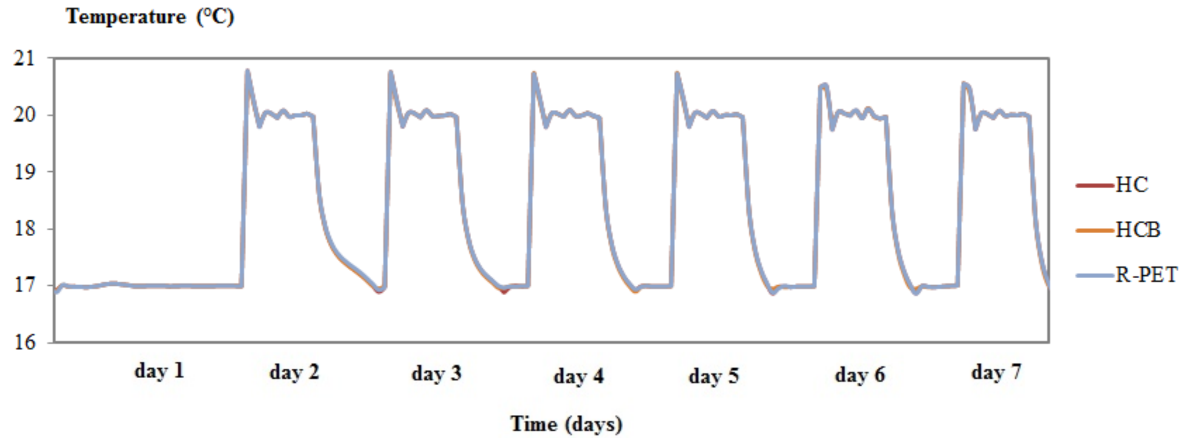


Fig. 4 - Indoor temperature variation of the PI controller during one week in Nancy using a constant flow rate ventilation mode

4. Results

4.1 Constant Air Flow Rate Case

Detailed analyses of the indoor air conditions in Nancy city, during the winter and in Carpentras city, during the summer, were developed and are discussed in this section on the constant air flow rate. For a better understanding, it needs to be clarified that Perugia's air conditions are not presented since the variations are close to Carpentras.

For Nancy, the indoor relative humidity profiles are depicted for a period of one week in the winter season (mid-December) and for the three façades. In Fig. 3 one can see that during occupancy hours, the indoor relative humidity varies between 27 % and 49 %. The relative humidity for HC and R-PET façades are close since the lime hemp and lime mortar plasters have close buffering moisture values higher than gypsum. In vacancy hours, the relative humidity increases since the indoor temperature setpoint decreases from 20 °C to 17 °C as depicted in Fig. 4. For the three cases, indoor relative humidity profiles are close and less affected by the façade material because of the air ventilation rate.

4.2 Heating and Cooling Energy Consumption

The yearly heating and cooling needs for each façade are calculated and presented in Fig. 5 and 6, or the constant flow rate ventilation mode and for relative humidity sensitive air flow rate, respectively. Based upon the findings one can see that, for Nancy city, (located in the North of France with semi-continental weather) the main energy demand comes from the heating phase, whereas for Carpentras and Perugia cities, the cooling energy demand is higher than the heating one, mainly because of their locations in the related regions. In addition, it can be noticed that the heating energy demands decrease sharply in the case of humidity sensitive flow rate ventilation with a slight increase in the cooling energy demands, independently of the considered façades. For Nancy, the heating demand decreases by about 28 %, whereas for Carpentras it decreases by 56 %, and for Perugia by 61 %.

Concerning the cooling demand, we can see an average increase by about 10 % in Nancy, 8.5 % in Carpentras, and 7.5 % in Perugia. These growths are similar for the three façades except for the HCB in Carpentras where the cooling need increase reaches 18.5 % due to the indoor high relative humidity.

In the light of this, it appears that cooling is not needed for Nancy and, so, other passive means are recommendable like day window opening for natural ventilation in summer.

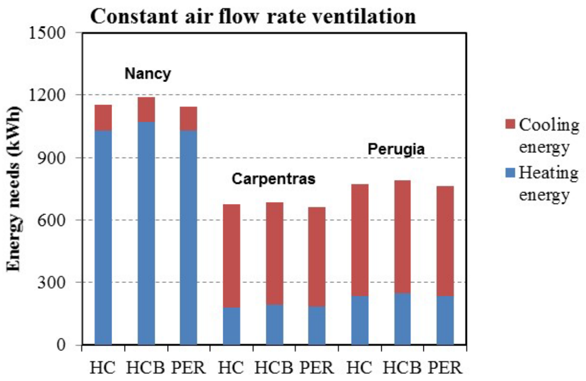


Fig. 5 - Annual heating and cooling energy consumption for the three studied building façades for the constant flow rate ventilation case in the cities of Nancy, Carpentras, and Perugia

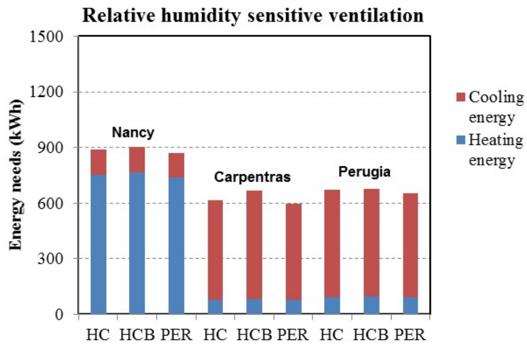


Fig.6 - Heating and cooling needs for the three façades using relative humidity sensitive ventilation

Table 4 - Total electrical energy consumption (kWh.y^{-1}) for the three building façades considered (constant air ventilation rate)

	HC	HCB	R-PET
Nancy, Fr	373.8	386.3	372.8
Carpentras, Fr	254.6	258.3	250.2
Perugia, It	286.9	293.2	284.5

Table 5 - Total electrical energy consumption (kWh.y^{-1}) for the three building façades considered (humidity sensitive flow rate ventilation)

	HC	HCB	R-PET
Nancy, Fr	281.0	285.0	276.3
Carpentras, Fr	234.8	252.3	229
Perugia, It	253.5	256.0	248.3

4.3 Electrical energy consumption

The annual electrical energy consumption for the aforementioned cities using the two air ventilation systems are shown in Table 4 and 5. There is evidence that the lowest values of overall electricity consumption were recorded in Carpentras, thanks to the three façades' thermal behaviour with the best performance in winter, and rather acceptable in summer (compared to the other two cities). Additionally, it can be clearly seen that the use of a humidity sensitive air ventilation rate decreases the annual energy consumption by about 24 % for Nancy, 7 % for Carpentras, and 11.6 % for Perugia with a hemp-concrete façade. The same observations are applied for the other façades. Moreover, the usage of R-PET mats allows for very good thermal behaviours of the related façade, which makes the latter the less electricity demanding one, with the lowest consumption rate recorded in Carpentras when using the humidity sensitive flow rate ventilation.

5. Conclusion

In this paper, a numerical study of the hygrothermal behaviour of three different walls was performed via the simulation tool SPARK. Three façades including hemp-concrete (HC), hemp-concrete with a brick layer (HCB), and Recycled PolyEthylene Terephthalate (R-PET) were tested for three cities (Nancy, Carpentras in France, and Perugia in Italy) with constant and relative humidity sensitive air flow rates. For each case, heating and cooling demands were computed and used to calculate the annual electrical energy consumption. Our results suggest that relative humidity sensitive ventilation reduces electrical energy consumption when compared to the constant air flow rate. For Nancy city, electrical consumption is reduced by about 24 % whereas for Carpentras and Perugia cities, the reduction is by about 7 % and 11.6 %, respectively. Besides, the thermal behaviour of the HC façade is close to that of the R-PET one in cold climates and its energy performance slightly decreases when summers get warmer as in Carpentras and Perugia, because of the low thermal inertia of the hemp-concrete.

Nomenclature

Symbols

w	Moisture content by mass	kg/kg
C	Specific heat	$J.kg^{-1}.K^{-1}$
C_0	Specific heat of dry material	$J.kg^{-1}.K^{-1}$
C_l	Specific heat of water	$J.kg^{-1}.K^{-1}$
D_T	Mass transport coefficient associated to a temperature gradient	$m^2.s^{-1}.K^{-1}$
$D_{T,v}$	Vapor transport coefficient associated to a temperature gradient	$m^2.s^{-1}.K^{-1}$
D_θ	Mass transport coefficient associated to a moisture content gradient	$m^2.s^{-1}$
$D_{\theta v}$	Vapor transport coefficient associated to a moisture content gradient	$m^2.s^{-1}$
h_M	Mass transfer convection coefficient	$kg.m^{-2}.s^{-1}$
h_T	Heat transfer convection coefficient	$W.K^{-1}.m^{-2}$
I	Room's thermal inertia	
L_v	Heat of vaporization	$J.kg^{-1}$
R_v	Constant of water vapor	$J.kg^{-1}.K^{-1}$
T	Temperature	K
Ta	Indoor air temperature	K
T_m	Mean radiant temperature of the walls	K
T_0	Operative temperature	K
τ	Time	s
θ	Moisture content	$m^3.m^{-3}$
λ	Thermal conductivity	$W.m^{-1}.K^{-1}$
ρ_0	Mass density of dry material	$kg.m^{-3}$
ρ_l	Mass density of water	$kg.m^{-3}$
ρ_v	Mass density of vapor water	$kg.m^{-3}$
ρ_i	Air density	$kg.m^{-3}$
ϕ	Relative humidity	%
φ	Time shift	h
Φ	Heat flux	W
Q_m	Air flow rate	$kg.s^{-1}$
Φ_{source}	Heat source power	W
ψ	Capillary pressure	Pa
ε	Wall emissivity (long wave)	
σ_0	Stephan-Boltzmann constant	$W.m^{-2}.T^{-4}$

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