

Modeling of Coupled Heat and Mass Transfers in a Building Envelope Made with BTC

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Abstract With a view to reducing heat and mass transfer within the envelope of the building constructed with BTC, numerical modelling of coupled heat and mass transfer was carried out. The model is based on the work of Luikov. The mathematical model governing heat and mass transfer was established using temperature and moisture content as the main variables. The problem was tackled using a numerical approach based on the finite element method. Implementing the mathematical model in COMSOL Multiphysics enabled us to obtain very satisfactory results. These results enabled us to represent the spatiotemporal distribution of temperature fields and moisture content within the wall studied. Half a day's numerical simulation shows that the heat and humidity do not penetrate the entire wall.

Keywords: mass transfer, heat transfer, BTC, coupled, temperature, moisture content

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1. Introduction

Issue of saving energy is becoming increasingly worrying for developing countries, particularly those in sub-Saharan Africa. According to United Nations data, three billion people use traditional biomass and coal, and more than one and a half billion have no access to electricity in rural areas [1]. Depletion of fossil fuels and global warming predicted by energy and climate change experts between now and 2050 could lead to a rise in the Earth's temperature of around 2°C compared with pre-industrial levels [2]. Energy consumed in the building sector accounts for between 30% and 40% of global energy consumption [3]. Despite the thermal regulations in force, energy used for air conditioning and heating still accounts for 66% of the total energy consumed by buildings [4]. This energy consumption produces enormous greenhouse gas emissions for the environment [2]. Building envelope is still the main cause of energy consumption due to heat transfer [4,5]. In order to reduce this consumption, numerous efforts are being made both on materials and on the design of walls [6]. The earth material is an ideal choice because of its local availability, low energy consumption and recyclability. Conventional materials, because of the way they are synthesised, may contain chemicals that are harmful to humans and the

environment [7]. Rain, wind and solar radiation are atmospheric conditions to which the materials used in the building envelope are exposed. Moisture build-up in the wall affects thermal insulation [8]. These phenomena can be used to diagnose the choice of building materials. Previous work has shown that there are two types of models for studying the hygrothermal behavior of the building envelope. Nodal models and coupled transfer models, which are much more widely used [9]. The pioneers of this model, Luikov in 1954, then De Vries and Philip in 1957, took into account the coexistence of liquid and vapor phases within phase change materials [10,11]. In 1962, another type of modelling based on the formalism of the thermodynamics of irreversible processes was introduced by Cary and Taylor. Since then, a great deal of theoretical, numerical and experimental work has been devoted to solving the systems of coupled equations governing these phenomena [12,13,14]. In the literature, few studies have been devoted to solving coupled heat and mass transfer problems in 2D/3D under the unsteady regime of a phase change material. In this work we propose a 3D numerical study of coupled heat and mass transfer in order to understand the spatio-temporal distribution of moisture content and temperature within a wall made of compressed earth brick (BTC). This study was carried out in COMSOL 5.2, in an unsteady regime. Simulations were carried out over three remarkable climatic periods in Burkina Faso to assess the model's hydrothermal performance.

2. Formulation of the Problem

2.1. Physical Description of the Problem

BTC is a hygroscopic material and also materials that change phase under the influence of a temperature and/or humidity gradient [15]. These events affect the thermophysical properties of BTC and the comfort expected when it is used in the construction of a building. [16]. In this study, we propose a physical model consisting of a wall made of BTC joined by mortar (1 cm thick) consisting of sand, cement and water (Figure 1). The thermophysical properties of BTC were obtained experimentally from the work of [16]. The conservation equation for energy and mass is given by 1 and 2:

$$(c_{p,m}\rho_m + c_{p,l}\rho_l)\frac{\partial T}{\partial t} = \nabla(-\lambda\nabla T) + L_v\nabla(\dot{m}_v) \quad (1)$$

with:

$C_{p,m}$: Specific heat of dry material (J/kg/K);

ρ_m : Density of the material (kg/m³);

ρ_l : Density of liquid water (kg/m³);

$C_{p,l}$: Specific heat of liquid water (J/kg/K);

T: Temperature (K);

t: Time (s);

$\frac{\partial}{\partial t}$

$\frac{\partial}{\partial t}$: Partial derivative with respect to time

λ : Thermal conductivity of the material (W/m.K);

$\dot{m}_v$: Vapor flux density (kg/m².s);

L_v : Latent heat of change of state (J/kg)

$$\frac{\partial \omega}{\partial t} + \nabla(\dot{m}_l + \dot{m}_v) = 0 \quad (2)$$

with:

ω : water content by mass (kg/m³);

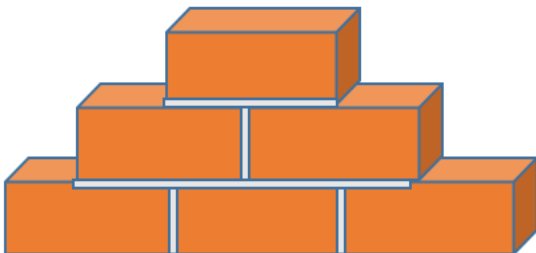
$\dot{m}_l$: Liquid flow density (kg/m².s);

∇ : nabla operator

2.2. Simplified Assumptions

For this study, we make the following assumptions:

- the wall is made of BTC with the same properties.
- the wall is assumed to be semi-infinite along (oz) and (oy).
- the liquid phase consists essentially of water.
- the gas phase is made up of air and water vapor considered as perfect gases.



a

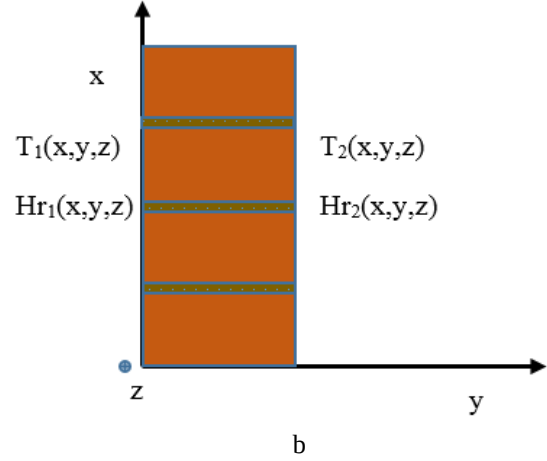


Figure 1. Physical model, front view (a) and side view (b)

2.3. Numerical Model Formulation

The equations governing the transfers involved in our model are based on those proposed by [10,11].

Taking into account the above assumptions, the development of equations (1) and (2) gives:

$$(c_{p,m}\rho_m + c_{p,l}\rho_l)\left(\frac{\partial T}{\partial t}\right) + \nabla(k_v\nabla\omega + \lambda^*\nabla T) = 0 \quad (3)$$

$$\frac{\partial \omega}{\partial t} + \nabla((k_v + k_l)\nabla\omega + (\delta_v + \delta_l)\nabla T) = 0 \quad (4)$$

$$\text{Posing } C_T = C_{p,m}\rho_m + C_{p,l}\rho_l, \quad \beta^\omega = k_v + k_l$$

$\beta^T = \delta_v + \delta_l$ the two equations (3) and (4) can be expressed as follows:

$$\begin{cases} c_T \frac{\partial T}{\partial t} + \nabla(k_v\nabla\omega + \lambda^*\nabla T) = 0 \\ \frac{\partial \omega}{\partial t} + \nabla(\beta^\omega\nabla\omega + \beta^T\nabla T) = 0 \end{cases} \quad (5)$$

with

k_v : hydraulic conductivity in the vapour state (kg/Pa.m.s);

k_l : hydraulic conductivity in the liquid state (kg/Pa.m.s);

δ_v : Vapour permeability (kg/Pa.m.s);

δ_l : Liquid state permeability (kg/Pa.m.s)

Equation (6) is obtained from equation (5) by changing the parameters

$$\begin{cases} \frac{\partial T}{\partial t} + \nabla(C_{11}\nabla T + C_{12}\nabla\omega) = 0 \\ \frac{\partial \omega}{\partial t} + \nabla(C_{21}\nabla T + C_{22}\nabla\omega) = 0 \end{cases} \quad (6)$$

2.4. Initial and Boundary Conditions

a. initial Conditions

The temperature and moisture initialized at time t_0 are such that:

$$T(x, y, z, t) = T(t = t_0) = T_0 \quad (7)$$

$$\omega(x, y, z, t) = \omega(t = t_0) = \omega_0 \quad (8)$$

where t_0 is the instant when the wall begins to interact with the surrounding environment.

b. boundary conditions

The boundary conditions used for the numerical simulation are:

- the wall being semi-infinite according to (ox) and (oz), the upper side ($x = L, y = l, z = h$), the underside ($x = L, y = l, z = 0$) and the sides ($x = 0, y = l, z = h$) et ($x = L, y = 0, z = h$) are adiabatic and isolated. The heat and mass flows are then zero, which translates into:

$$\left(\frac{\partial T}{\partial y}\right)_{x=0,z} + \left(\frac{\partial T}{\partial z}\right)_{x=0,y} = 0 \quad (9)$$

$$\left(\frac{\partial T}{\partial y}\right)_{x=L,z} + \left(\frac{\partial T}{\partial z}\right)_{x=L,y} = 0 \quad (10)$$

$$\left(\frac{\partial T}{\partial x}\right)_{y,z=0} + \left(\frac{\partial T}{\partial y}\right)_{x,z=0} = 0 \quad (11)$$

$$\left(\frac{\partial T}{\partial x}\right)_{z,y=0} + \left(\frac{\partial T}{\partial z}\right)_{x,y=0} = 0 \quad (12)$$

$$\left(\frac{\partial \omega}{\partial y}\right)_{x=0,z} + \left(\frac{\partial \omega}{\partial z}\right)_{x=0,y} = 0 \quad (13)$$

$$\left(\frac{\partial \omega}{\partial y}\right)_{x=L,z} + \left(\frac{\partial \omega}{\partial z}\right)_{x=L,y} = 0 \quad (14)$$

$$\left(\frac{\partial \omega}{\partial x}\right)_{y,z=0} + \left(\frac{\partial \omega}{\partial y}\right)_{x,z=0} = 0 \quad (15)$$

$$\left(\frac{\partial \omega}{\partial x}\right)_{z,y=0} + \left(\frac{\partial \omega}{\partial z}\right)_{x,y=0} = 0 \quad (16)$$

- At the material-air interface ($y = 0$ and $y = l$), the continuity of the liquid and vapor flows satisfies the following expressions:

$$\begin{bmatrix} \dot{m}_l + \dot{m}_v \\ \dot{m} - L_v \dot{m}_l \end{bmatrix} = \begin{bmatrix} \beta(p_v^{sat}(T_{ext})\omega_{ext} - p_v^{sat}(T_{int})\omega_{int}) \\ \alpha(T_{ext} - T_{int}) \end{bmatrix} \quad (17)$$

In this expression, T_{ext} is the outdoor temperature and Hr_{ext} is the outdoor humidity, which varies over time according to the simulation periods.

3. Numerical Resolution Method

The model was solved using COMSOL Multiphysics® numerical calculation software. For numerical simulation, the system is subdivided into two sub-domains (BTC block and air). We have chosen the "normal" mesh type for the complete 3D geometry. A triangular mesh with several elements was selected. The mesh diagram of the

wall studied is shown in Figure 2. As the study regime was unsteady, the time duration was set at 7 hours as the maximum exposure time for the wall of a building in the open air. The time step is set to one (01) hour and the relative tolerance to 0.001 for all parameters.

With reference to the coupled equations developed above, we have adapted them to the CSOMSOL Partial Derivative Equation (PDE) by (18):

$$e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} + \nabla(-c\nabla u - \alpha u + \gamma) + \beta \nabla u + \alpha' u = f \quad (18)$$

Where u can be a single or coupled state variable (temperature, moisture content water content, partial or total pressure, or in some cases chemical potential).

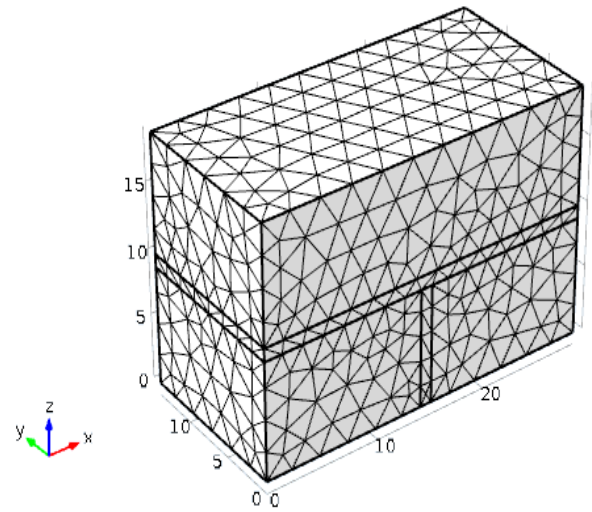


Figure 2. Mesh diagram

In our model u denotes the temperature-humidity coupling $u(T, w)$. Some coefficients have been chosen to be zero because of the form of the PDE to be solved. The final form adopted is that given by equation (19). To solve the problem in COMSOL, equation (6) was written in matrix form as follows:

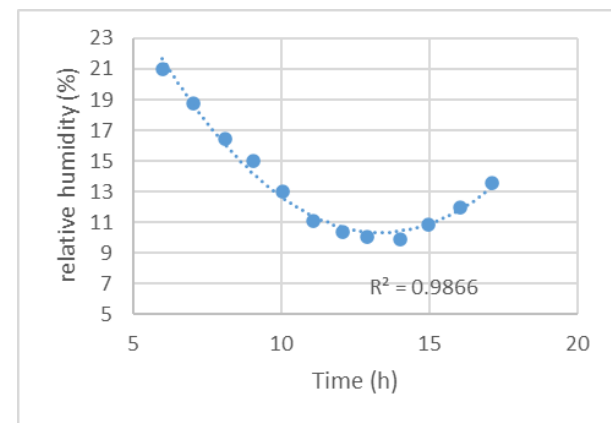
$$d_a \begin{bmatrix} \frac{\partial T}{\partial t} \\ \frac{\partial \omega}{\partial t} \end{bmatrix} = \nabla \cdot \left(C \nabla \begin{bmatrix} T \\ \omega \end{bmatrix} \right) + \beta \cdot \nabla \begin{bmatrix} T \\ \omega \end{bmatrix} \quad (19)$$

The discretization scheme is of the Lagrangian linear type (finite element method). The convergence criterion is of the order of 10^{-3} for all equations.

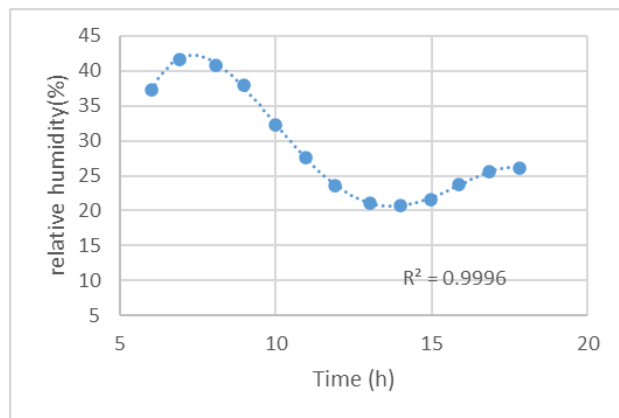
4. Results and Discussions

4.1. Representation of Input Parameters

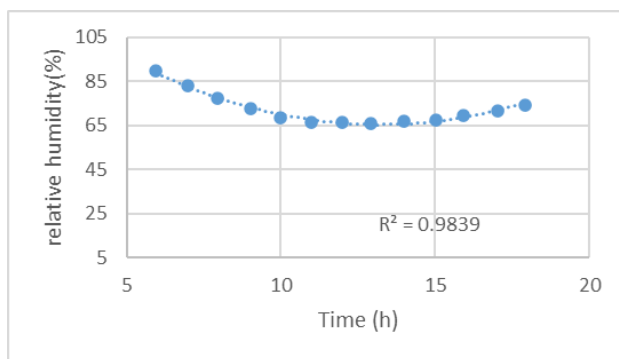
To carry out the modelling, we modelled the input parameters, i.e. the relative humidity and temperature for each month. Figure 4.a to Figure 4.c and Figure 5.a to Figure 5.c show the modelled relative humidity and temperature for each month, respectively.



a

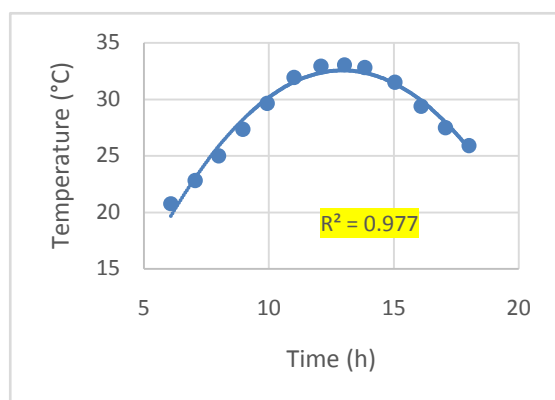


b

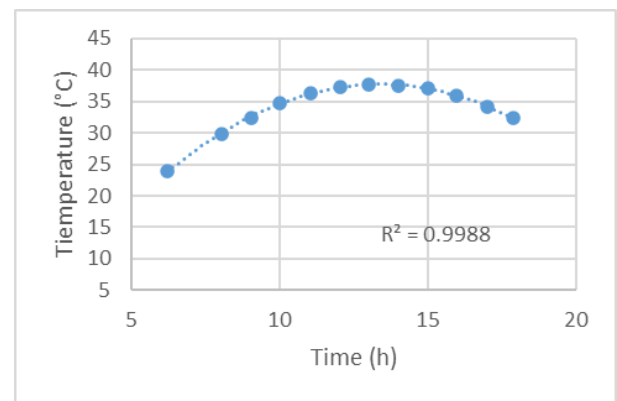


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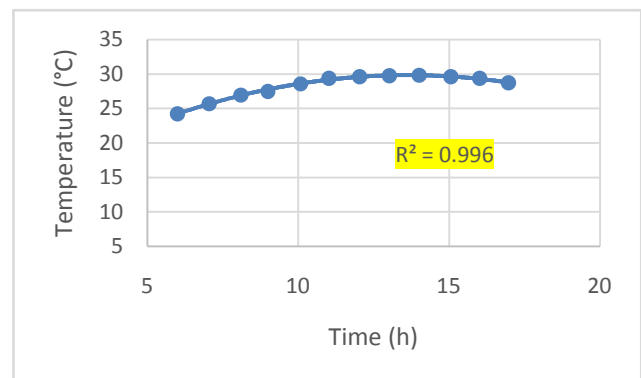
Figure 3. Modelled relative humidity in January (a), April (b) and August (c)



a



b

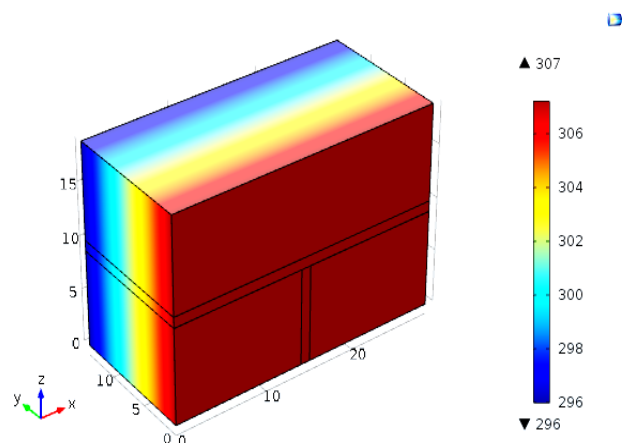


c

Figure 4. Modelled temperature in January (a), April (b), and August (c)

4.2. Temperature and Humidity Distribution with in the 3D BTC Block

The surface temperature and surface humidity distributions of the wall made of BTC for a maximum duration of seven (07) hours. Figures 6.a, 6.b and 6.c show the surface temperature distribution for January, August and April respectively. The different colours indicate the migration of heat from warmer to cooler within the wall. We note that the strong variation in temperature occurs between the outer face of the BTC blocks and the ambient air. This heat is exchanged with the air by convection.



a

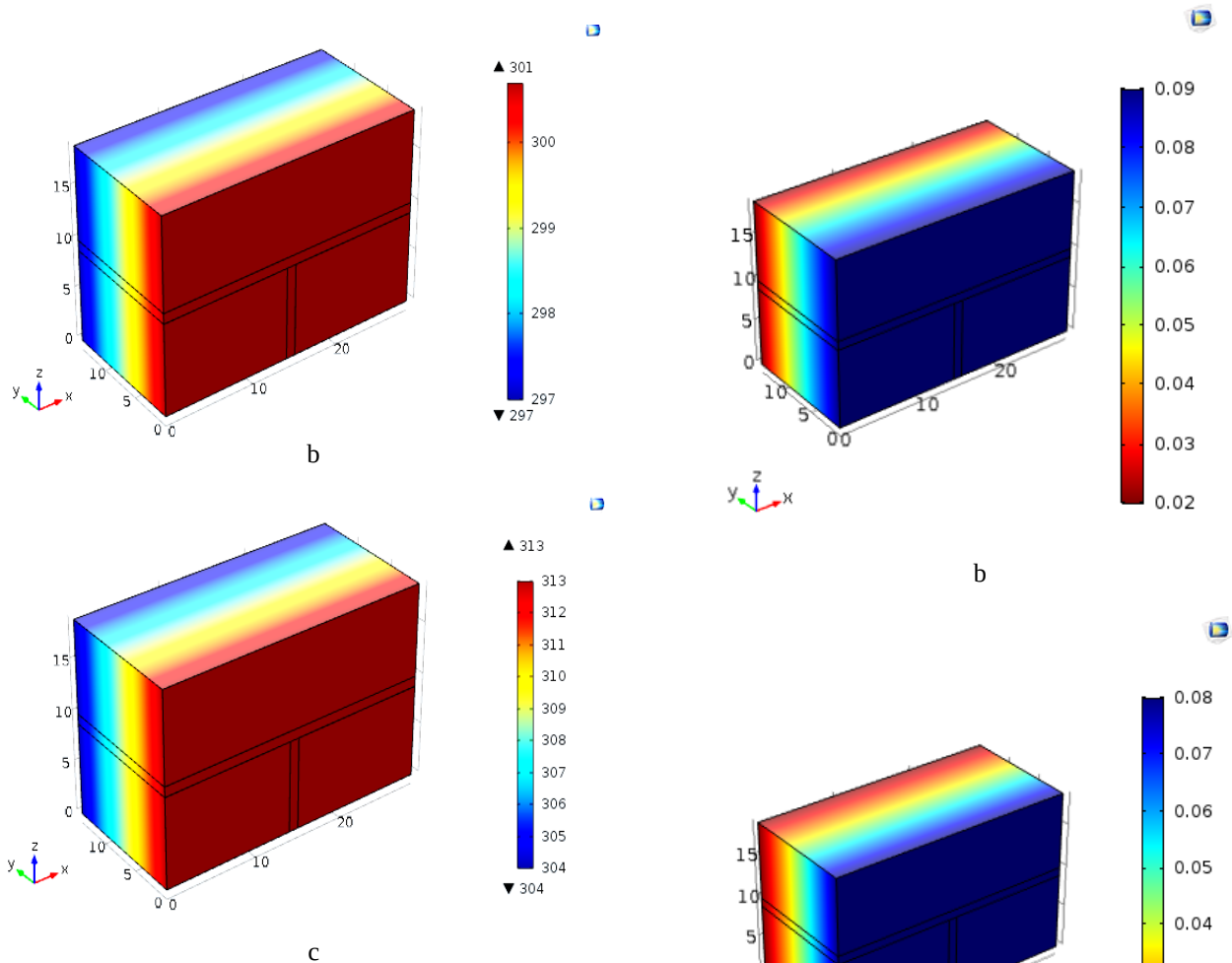


Figure 5. Temperature profile in the wall for a 7-hour exposure period: (a) January; (b) August; (c) April

Figure 7.a, Figure 7.b and Figure 7.c illustrate the diffusion of humidity on the wall during January, August and April respectively. The different colors indicate the migration of the humidity level from the highest to the lowest within the wall. We note that the strong variation in the humidity level occurs between the outside of the wall and the ambient air. Over time, water migrates from the exposed side to the unexposed side, as shown in Figures (7.a, 7.b and 7.c).

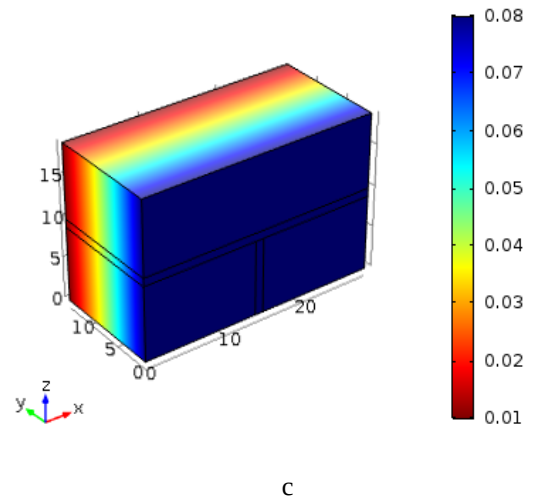


Figure 6. Temperature profile in the wall for a 7-hour exposure period: (a) August; (b) April and (c) January

5. Conclusion

The present work has numerically studied the coupled heat and mass transport within a wall made of BTC. The model considers temperature and water content as variables for heat and mass transfer respectively. The model was successfully calibrated by solving a coupled PDE (partial differential equation) in 3D using COMSOL. - Within the wall studied, the temperature and mass fields evolve along the exposed wall over time to a certain depth. Numerical results show a migration of heat and water content in the material.

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