IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 7 Issue 6, June 2020
ISSN (Online) 2348 – 7968 | Impact Factor (2020) – 6.72
www.ijiset.com

Numerical study on heat and mass transfers on a CEB (compressed earth blocks) wall in a sahelian context.

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Abstract

Numerical modelling of coupled heat and mass transfer within a CEBs wall is presented. Based on Luikov's work, a mathematical modelling of the transfers mechanisms has been established. Temperature and moisture content were chosen as the main way of transfer. A numerical approach was applied (finite element method). The implementation of the mathematical model in COMSOL allowed us to obtain the results. These results allowed us to represent the spatiotemporal distribution of the temperature fields and the moisture content within the studied wall. The thermal inertia character of CEBs has been illustrated. The effect of temperature gradient on mass transfer has also been highlighted.

Keywords: *mass transfer, CEBs, coupled, main way of transfer, spatiotemporal, thermal inertia*.

Nomenclature :

Some notations used locally are no longer mentioned on the list below. They are specified as and when they appear in the text.

Latin characters:

$C_{p,a}$: specific heat of dry air (J/kg/K) ;

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

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

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

C_T : total specific heat of porous material (J/kg/K)

K : hydraulic conductivity (kg/Pa.m.s)

M : molar mass of water (kg/mol)

$\dot{m}$: flow density (kg/m^2.s) ;

n :normal vector at the exchange surface ;

$\dot{m}_l$: liquid flow density (kg/m^2.s) ;

$\dot{m}_v$: vapour flow density (kg/m^2.s);

$\dot{m}_T$: mass flow density under temperature gradient (kg/m^2.s);

P_v^{sat} : saturation vapour pressure(Pa) ;

P_c : capillary pressure (Pa) ;

P_v :partial water vapour pressure;

q : heat flux (W/m^2) ;

R_v : gas constant for water vapour (J/kg.K)

T_{ext} : ambient température (K);

T_{int} : temperature at the surface of the wall(K);

t : time (s) ;

v : air velocity (m/s).

Greek letters :

φ_{ext} : relative humidity outside (.);

φ_{int} : relative humidity inside(.);

β : mass transfer coefficient (kg/m^2.s.Pa);

δ_p : vapour permeability of the wet material (kg/m.s.Pa);

α : heat transfer coefficient (W/m^2.K).

ρ_v : density of vapour water (kg/m^3) ;

ρ_m : density of material (kg/m^3)

ρ_l : density of liquid water (kg/m^3)

ω : mass water content (kg/m^3) ;

Ω : moisture storage capacity (kg/m^3.Pa) ;

λ : thermal conductivity of the material (W/m.

Indice

a : air ;

c: capillary ;

l: liquid ;

m: material ;

p: permeability ;

T: temperature ;

1. Introduction

In the past decade, earthen construction has been gaining renewed interest [1], particularly using compressed earth blocks (CEBs). This recrudescence is explained in principle by their ease of implementation and their advantage certainly. CEBs used in construction constitute the interface between the indoor of the building and the outdoor environment. This interface is constituted by an assembly of porous material which is the seat of many coupled exchanges of heat and mass. These exchanges are due to temperature gradients T, moisture content φ, partial vapor temperature gradients T, moisture content φ, partial vapor pressure p_v pressure

p_v, capillary pressure p_c, total pressure p , water vapor concentration ρ_v, etc. They are established between the indoor and outdoor environments of the local through its constituent elements, especially within CEB material.

Depending on the climatic conditions and characteristics of CEBs material, a comfort level is difficult to reach for the room which wall is considered as a thermal filter. More often (Generally), this comfort is characterized inside the room by control parameters such as temperature and relative humidity In our sub-Saharan sub-region, it is desirable to live in room where temperatures and moisture content oscillate respectively between (26°C and 35°C) and (30% and 68%).

To evaluate the comfort sought in the room, only two of the forces (temperature gradients T, moisture content φ, partial vapor pressure p_v …) listed above are sufficient to describe the coupled of heat and mass exchanges [2]. Indeed the movement of moisture and heat transfer in building materials are strongly dependent and have a very important effect on the overall energy performance of buildings. Moreover, a perfect control of the climatic environment of a building always passes by a control of the exchanges within its interface (wall, roof…). Aware of this issue, many researchers have undertaken experimental and numerical studies to deepen the knowledge of the different coupled heat and mass transfers. The pioneers in the mathematical modelling of heat and mass transfer within the porous environment are Luikov in 1954 and J.R Phillip and D.A DE Vries in 1957. In 1962, another type of modelling based on the formalism of the thermodynamics of irreversible processes was introduced by Cary and Taylor [5,6]. Since then, a great many theoretical, numerical and experimental works have been devoted to solving the system of coupled equation governing these phenomena **[7,8,9,10,11]**. In the literature, few studies have been devoted to solving the problems of coupled heat and mass in 2D/3D under unsteady state of a building wall on the basis of local porous materials [12]. In this work we propose a 3D numerical study of coupled heat and mass transfer in order to understand the spatiotemporal of distribution moisture content and temperature within a wall made of compressed earth blocks (CEB). This study is made in unsteady mode according to temperature variations and moisture content of the air outside. The study is conducted under Comsol 5.2. The simulations are conducted over a remarkable climatic period (rainy period) in Burkina Faso to evaluate the hydrothermal performances of the model : August.

The present work will be conducted according to the plan indicated.

2. Modelling of coupled heat and mass transfers

2.1. Physical model

CEBs are hygroscopic and porous materials **[13]** in which numerous hygroscopic and/ or thermo-hygroscopic phenomena occur under the influence of temperature gradients and the moisture content in the air. These manifestations affect the thermophysical properties of CEBs **[14]** and the expected comfort when used for the construction of room. We propose in this study a physical model consisting of a wall made with CEBs assimilated to a rectangular parallelepiped of dimensions (Lxlxh) [29cm]x[14cm]x[9cm] joined by mortar thickness (1cm) made of sand, cement and water. The properties of the material are obtained experimentally from the work of Kabre et al **[14].** Figure 1 (a) illustrates the physical model in which the Representative Elemental Surface (SER) is isolated from which physical transfer phenomena are subjected (figure 1 (b)).

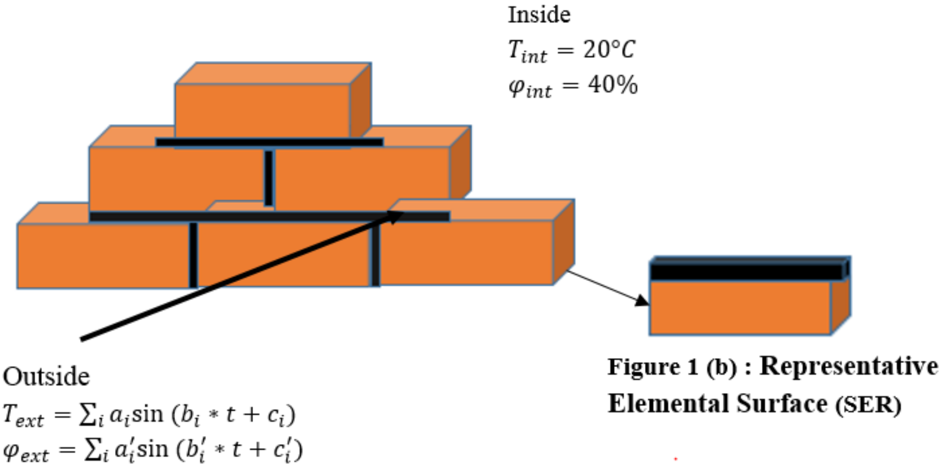


Figure 1 (b) : Representative Elemental Surface (SER)

Figure 1 (a) : Physical model

2.2. Simplifying hypotheses

We assume the following cases to solve the problem of coupled transfer of heat and mass

- The wall is made with CEBs of the same properties,
- The mortar is made of sand, cement and water,
- The environment studied is composed of three phases: solid phase, liquid phase (water) and gas phase (composed of water vapor and air),
- The solid phase is undeformable,
- The properties of gas phase are taken as those of a perfect gas,

- The driving force of the transfers are due the temperature T and the moisture content φ,
- The liquid water does not flow through the contact surface. Any water that flows to external surface is in vapour form.

2.3. mathematical model

The physical phenomena taken into account for the formulation of the mathematical model are :

- Conduction,
- Convection,
- Radiation,
- Phase change.

The equations governing the heat and mass transfers used in this work are based on the Luikov model **[9].**

The energy conservation and mass equations are respectively given by:

$$\nabla q = -\left(C_{p,m}\rho_m + C_{p,l}\omega\right)\left(\frac{\partial T}{\partial t}\right) \quad (1)$$

$$\frac{\partial \omega}{\partial t} + \nabla g = 0$$

(2)

Taking into account aforementioned hypotheses, equation (1) and (2) can respectively be in the form:

$$C_T\frac{\partial T}{\partial t} = \nabla.\left(C_{11}\nabla T + C_{12}\nabla\varphi\right) + v.\left(D_{11}\nabla T + D_{12}\nabla\varphi\right) \quad (3)$$

$$\Omega\frac{\partial \varphi}{\partial t} = \nabla.\left(C_{21}\nabla T + C_{22}\nabla\varphi\right) + v.\left(D_{21}\nabla T + D_{22}\nabla\varphi\right) \quad (4)$$

Where C_T is the total specific heat of the porous material (volume specific heat of the dry material and that of the liquid water), Ω is the moisture storage capacity.

The expressions of the different coefficients C_T, C_{ij}, Ω and D_{ij} with$1 \leq i \leq 2$ and $1 \leq j \leq 2$ are detailed in annex**.**

A matrix form representing these equations is given by:

$$d_a\begin{bmatrix}\frac{\partial T}{\partial t}\\ \frac{\partial \varphi}{\partial t}\end{bmatrix} = \nabla.\left(C\nabla\begin{bmatrix}T\\ \varphi\end{bmatrix}\right) + \beta.\nabla\begin{bmatrix}T\\ \varphi\end{bmatrix} \quad (5)$$

with:

$$d_a = \begin{bmatrix} C_T & 0 \\ 0 & \Omega \end{bmatrix} \quad (6)$$

$$C = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \quad (7)$$

$$\beta = v.\begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix}$$

(8)

The capillary pressure pc is related to the relative humidity by the Kelvin law **[15, 16]:**

$$\varphi = \exp\left(\frac{-p_c}{\rho_\omega RT}\right)$$

(9)

$$p_c = -Kln\varphi$$

(10)

with : $K = \rho_l RT$

2.4. Initial conditions

At the initial time, we suppose that:

- The values of parameters are those resulting from measurements [14] and according to the simulation period for thermal conductivity,
- On the inside, temperature and humidity are constant and fixed (figure 1).

2.5. Boundary conditions

The boundary conditions used for numerical simulation are:

Heat and mass exchanges following the normal to the contact surface. The other components of the flows are zero on the other surfaces [**17**]. These conditions take into account the physical phenomena mentioned above and verify the following equations:

$$\begin{bmatrix} (g_L + g_V).\boldsymbol{n} \\ (g_T - Lg_L).\boldsymbol{n} \end{bmatrix} = \begin{bmatrix} (\beta(p_v^{sat}(T_{ext})\varphi_{ext} - p_v^{sat}(T_{in})\varphi_{int} + \emptyset_{ray}).\boldsymbol{n} \\ (\alpha(T_{ext} - T_{int}) + \emptyset_{ray}).\boldsymbol{n} \end{bmatrix}$$

(11)

the outdoor ambient temperature $T_{ext}$and the outdoor moisture content φ_{ext},vary in time according to the simulation periods. Air temperature and humidity data for the month of August 2011, measured at the Somgandé station by National Meteorological Agency of Burkina Faso (ANAM). The external temperature and the external relative humidity were respectively modelled by the sinusoidal fonction T_{ext}(t) and φ_{ext}(t) as a fonction of time. Figures 2 and 3 show mean relative humidity and average temperature for August respectively. The modeled climatic parameters are given by:

$T_{ext} = \sum_i a_i \sin(b_i * t + c_i)$
(12)

$\varphi_{ext} = \sum_i a'_i \sin(b'_i * t + c'_i)$
(13)

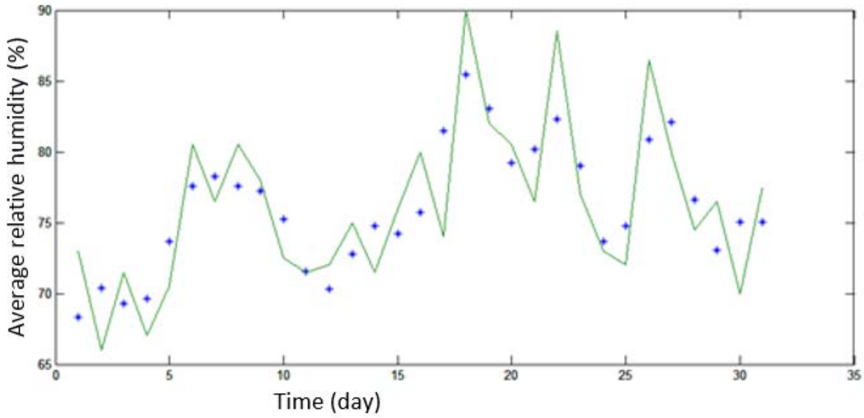


Fig. 2: Modelling the average relative humidity of August.

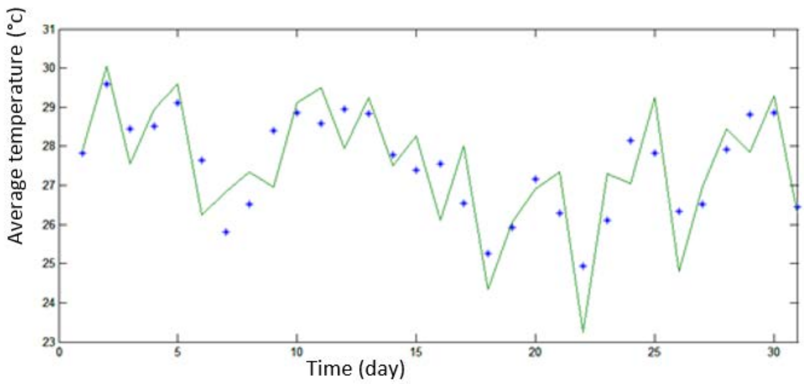


Fig. 3: Modelling the mean temperature of August

2.6. Numerical model

The numerical scheme used for solving equations is the finite elements implemented in COMSOL MultiPhysics ® version 5.2. For the resolution of the problem we chose the 3D geometry. The mesh used is that of "normal". The quality of elements of the model presented in figure 4.

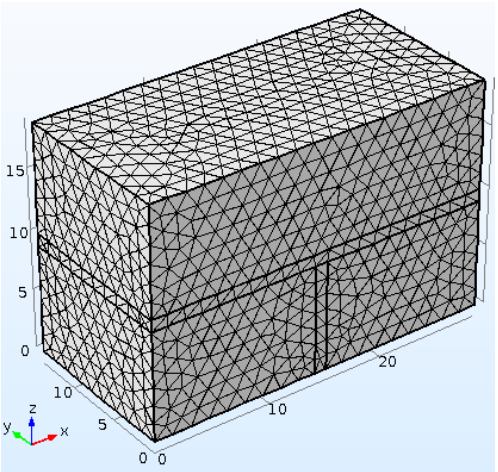
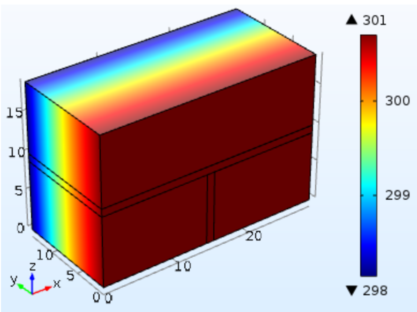


Fig. 4: maillage.

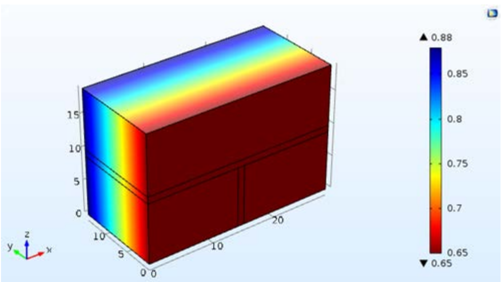
3.Results and discussion

The wall studies is that shown in figure 4. Temperature and moisture content profile were plotted. The surface temperature distribution and surface moisture content of the wall made with CEBs were also illustrated in figure 5.

3.1. Evolution of air temperature and humidity



a



b

Fig. 5: surface temperature (a) and moisture content (b) profile for the month of August.

Figure 5-a shows the temperature distribution of the CEB wall surface for the month of August. From outside to inside of wall, We notice a higher diffusion of the temperature for depth up to about 7.5 cm. On the other hand, diffusion is weak within the CEB wall for a depth higher than 7.5 cm. Note also that, for a duration of exposure beyond twelve hours (12h) the diffusion of the temperature does not evolve any more. The different colors indicate the different temperature. The direction of the arrows indicates the diffusion of the mass flow

within the block of CEB. This is the opposite of that of the diffusion of heat that always starts from warmest to the least hot.

Figures 6a and 6b respectively show the evolution of the temperature and the moisture content between solicited face (e=0), the middle of the block (e=L/2) and the unsolicited face (e=L). Sensors placed on the face exposed to climatic conditions (e=0), in the middle of the block (e=L/2) and the unsolicited face (e=L) make it possible to record the evolution of the temperature and moisture content over a period of twenty-four (24 h) hours. We can see if the thickness of the block increases the amplitude of the temperature decrease. This variation in temperature as a function of the thickness brings into play the role that thermal inertia plays in thermal regulation within a wall. However, we observe the opposite phenomenon for the moisture content. A. Oudrane and al. in their study on concrete blocks came to same conclusion

To better understand this phenomenon, we have shown simultaneously in Fig.7 the two profiles

We notice when the temperature decrease gradually the moisture content increase. The shape of the curve obtained for the temperature explains the character of thermal inertia of our blocks. The decreasing phase corresponds to the heat storage phase within the CEB blocks. The increasing part of the curve corresponds to the phase of the restitution of the heat. This phenomenon explain in addition the perspiring character of the material of CEBs.

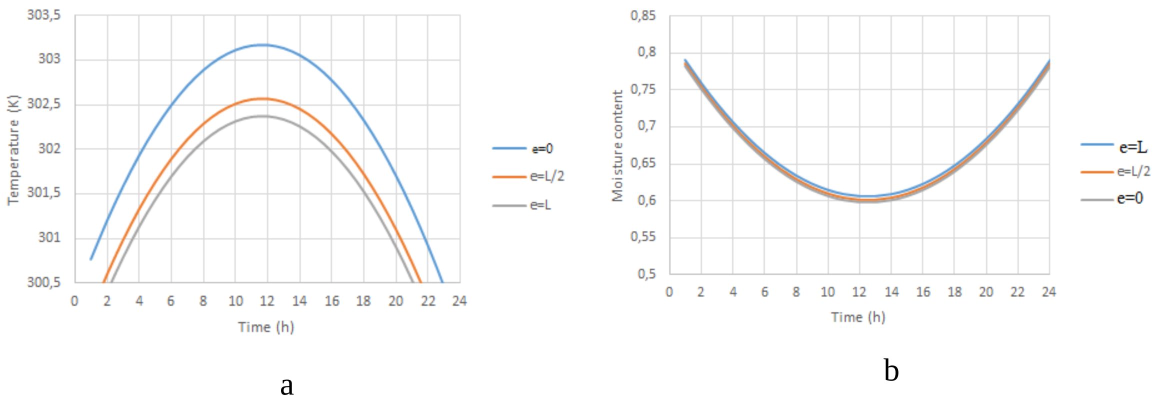


Fig. 6: Profile of temperature (a) and moisture content (b) for different thicknesses of the CEBs

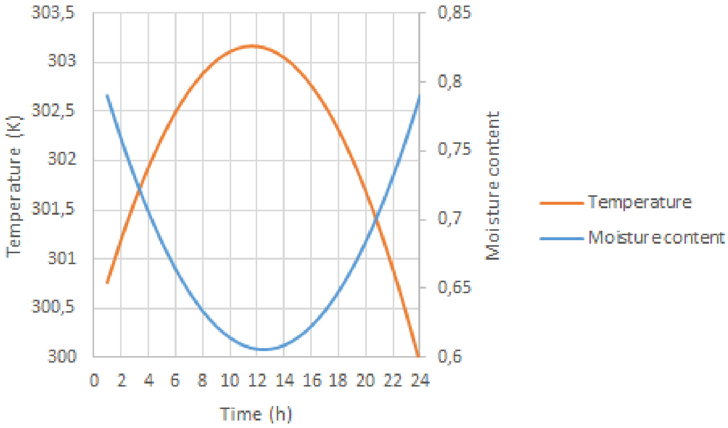


Fig.7 *Simultaneous evolution of temperature and moisture content*

Figure 8 illustrates the evolution of the temperature as a fonction of the duration of the stress on the wall. We note that these differences are very pronounced in the first three hours. Theses differences are illustrated in figure 8. These results corroborate the analysis of figure 5.

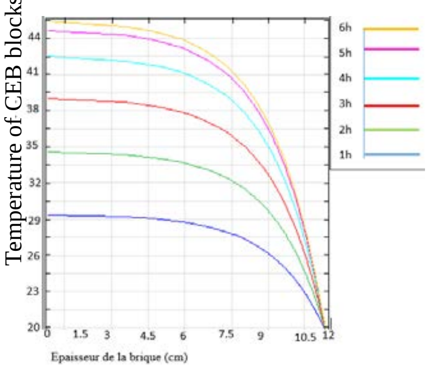


Fig 8 : the evolution of the temperature according to the duration of the solicitation

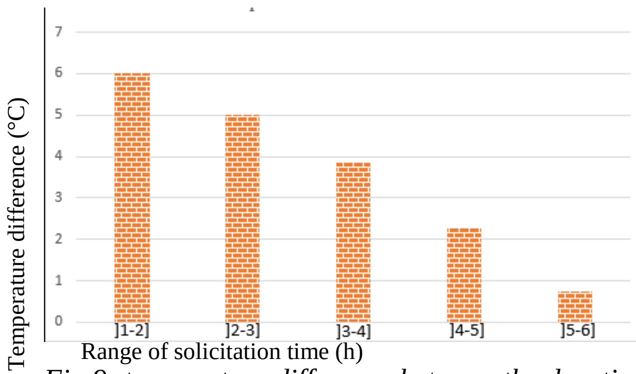


Fig 9: temperature difference between the duration of the solicitation.

3.2. Model sensitivity study

The fig.9 show the temperature profiles for the different thermal conductivity lamda values (W/m/K) of the BTC blocks. We notice the wall heats up with the thermal conductivity value for a given exposure time

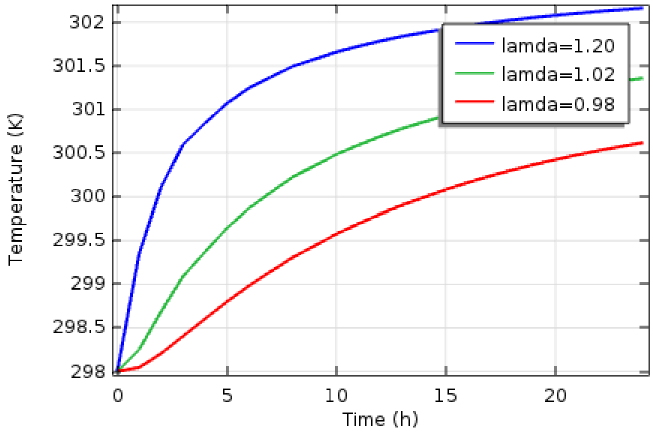


Fig.9: Temperature profile for the different values of thermal conductivities in August

4. Conclusion

In this work, we have modelled on the COMSOL software the thermal and mass exchanges that take place in a wall made with CEB blocks. The study supports the following:

- when CEB blocks are exposed to heat flow, part of the flow is stored for a given of periode of time. Over time, the storage phase stops in favor of the restitution phase.
- within the studied wall, the temperature field and the mass evolve concomitantly over time. Thus, the effect of the temperature gradient of the mass transfer has been demonstrated by the model,
- over time, the temperature difference between the different durations decrease gradually until 12 o'clock.

A study conducted on other months on the year under the same conditions could better complete this manuscript.

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