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Rammed earth building: contribution of moisture transfer on indoor comfort

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Abstract: To date, only a few scientific articles have quantified by numerical calculation the impact that the hygroscopic character of raw earth, often cited as one of the main advantages of the material, can have on the comfort of the building's occupants. To better quantify this effect, simulations of a building with rammed earth walls subjected to realistic meteorological conditions are performed on the EnergyPlusTM building energy simulation software and its coupled hygrothermal transfer module: HAMT. The simulations output parameters likely to be impacted by moisture transfer and its coupling with heat transfer are studied: temperatures, humidity, and a standardised comfort indicator: the PMV (Predicted Mean Vote). In particular, the evolutions of the previously mentioned outputs are compared through a parametric study. The varying input parameter studied is the type of possible transfer between earthen walls and their surroundings. We examine two transfer possibilities: hygrothermal coupled transfers, involving thermal and hydric interactions between walls and their surroundings, and pure heat transfers with disabled hydric interactions. Both possibilities employ identical models and resolution algorithms. Pure heat transfer represents hygrothermal transfer devoid of water exchange coefficients. The parametric study is conducted by varying the number of earthen walls able to have hygrothermal exchanges with their surroundings. This paper concludes that consideration of moisture transfer and its coupling with heat transfer between earthen walls and their surroundings has little effect on temperatures and PMV, but contributes significantly to the regulation of indoor relative humidity.

Keywords: Rammed earth ; hygrothermal ; coupled model ; building scale ; EnergyPlus ; parametric study ; comfort ; Predicted Mean Vote

1 Introduction

Currently, the building sector is responsible for a significant proportion of the global greenhouse gas emissions and energy consumption [1]. Reducing the environmental impact of this sector has been shown to be one of the most important levers for reducing humanity's overall carbon footprint [2].

In this context, raw earth seems to be a well-suited material. Indeed, the few operations required for its production and usage result in a very low environmental footprint compared to conventional materials [3]. Furthermore, the material shows interesting hygrothermal regulation properties that can passively improve the comfort of building users and limit the energy needs to regulate the indoor climate [4].

The hygrothermal properties of raw earth for construction have recently been the subject of numerous scientific studies and knowledge at the material scale has progressed considerably [5–7]. Specific analysis of the coupled heat and mass transfer model input parameters for this material have recently been conducted [8,9]. However, to date, very few studies have evaluated numerically the impact of moisture transfer and its coupling with heat transfer in raw earth buildings on the indoor hygrothermal comfort [4,10,11]. These papers showed that considering both moisture and heat transfers helps to regulate indoor relative humidity and slightly contributes to reduce indoor overheating periods. However, the improvement in comfort in relation to the standardised hygrothermal comfort indicators is not directly addressed in these studies. The aim of this article is to undertake this gap.

To achieve this goal, simulations will be carried out on EnergyPlus™ [12], open-source BES (Building Energy Simulation) software, using the software's built-in HAMT module (coupled Heat And Moisture Transfer). This module has already proven its ability to reproduce real cases [13] and has been used for BES involving raw earth walls [4,11].

The investigation will focus on evaluating the effects of considering moisture transfer together with heat transfer between hygroscopic earthen walls and their surrounding atmospheres through a parametric study. Specifically, the parameter under examination will be the number of active earthen walls. In detail, thermal parameters of the walls will remain constant across all simulations, while the incorporation of hydric exchange parameters for each wall is used to consider hydric transfer and its coupling with thermal transfer exchanges between the wall and its surrounding atmospheres.

The building related output parameters likely to influence user comfort will be studied: temperature and relative humidity and PMV (Predicted Mean Vote - standardised comfort indicator [14]).

2 Methodology and case study

2.1 Description of tools for BES

The coupled heat and moisture transfer module is based on the Künzel model [15]. This model is solved by EnergyPlus™ using the 1D finite element method within a discretised wall [16].

The model enables heat and moisture exchanges between walls and the surrounding air using boundary conditions of the third kind with convective transfer coefficients for heat and water vapour, respectively h_c and h_m . These terms depend on the environmental conditions in contact with the wall. The transfers between the wall and the indoor air are denoted by subscript “i” while transfers between the wall and the outdoor air are denoted by subscript “o”.

2.2 Case study

A parametric study will be conducted to quantify the effect of considering moisture transfer together with heat transfer on indoor air temperature and relative humidity as well as on PMV.

Simulation parameters

For each case, simulation parameters are chosen based on literature to minimize the interaction between the building and its surrounding that are not involving the hygroscopic raw earth walls. These parameters are listed below:

- The simulation time is set to 10 full years to eliminate the effect of the initial conditions inside the wall as suggested in [4]. Only the last year is considered for discussions;
- Timestep is set to 3 minutes [16];
- The simulated building consists of a single cubic room (side length: 3 m; internal surface area: 9 m²; volume: 27 m³);
- The walls (60 cm wide) are made of rammed earth and have no insulation. They are in contact with the outside atmosphere. The properties of the rammed earth are obtained from Losini *et al.* [17]. The selected data correspond to the lighter specimens;
- The floor and ceiling are simulated with pure heat transfer and are perfectly insulated. Therefore, these surfaces are not involved in any transfer from or to the outside of the room, so that only transfers through the walls are considered;
- Air infiltration: 0.1 vol/h to guarantee a minimal air renewal in the building. It is the only parameter responsible for air exchange with the outside environment;
- No openings;
- Facades facing full axis and are not affected by any exterior solar mask;

- Weather file used is described in Figure 1. It is taken from Lyon St Exupery airport weather station [18];
- No setpoint temperature or humidity are defined, which means the building inside parameters are freely evolving without any active temperature or humidity regulation;
- The building is unoccupied (no internal heat or moisture gains).

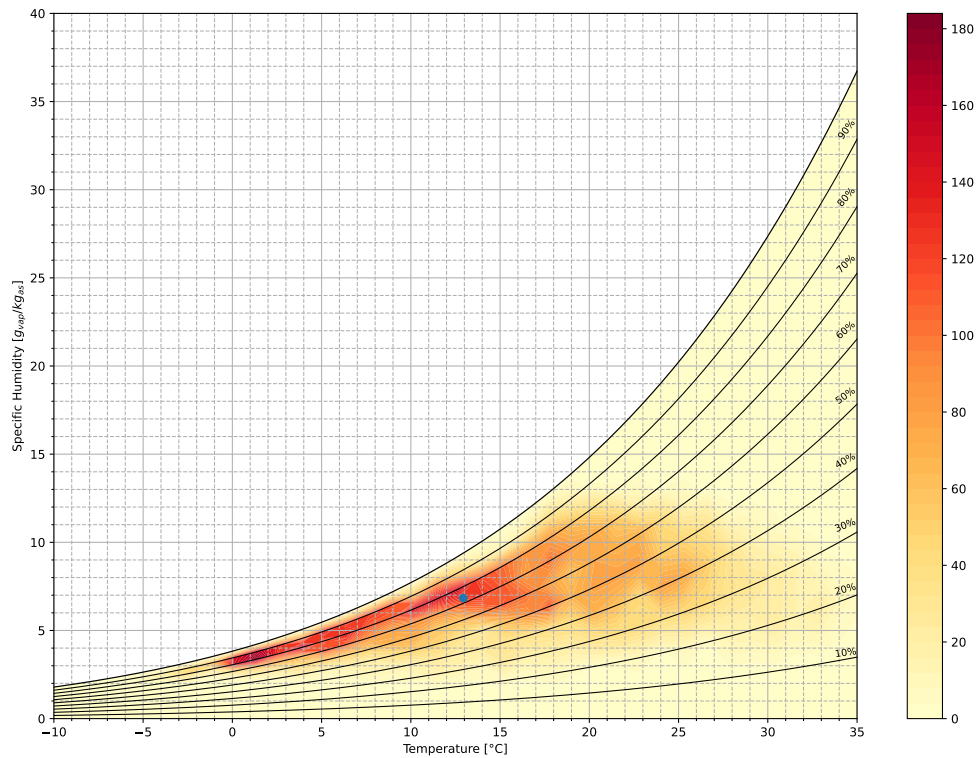


Figure 1. Graphical representation on the psychrometric diagram of the annual hourly distribution of the meteorological data used for Lyon Saint Exupery airport weather station (color bar represents the total time spent yearly in each area of the psychrometric diagram).

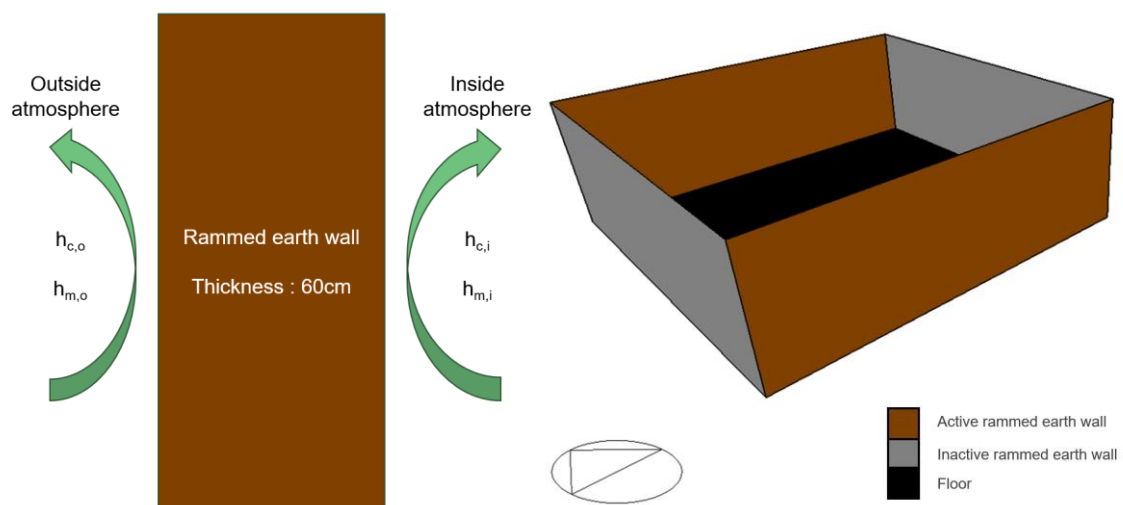


Figure 2. Left: Representation of the convective transfer coefficients through external earth wall. **Right:** Geometric view of the 2 active walls case-study.

Parametric input parameters

This paper will analyse the results of a parametric study. The only input simulation parameter that varies is the number of external walls that can have hygroscopic interactions with their surroundings. Two approaches will be considered to model the exchanges: 1) the first one involves walls that can only exchange heat with their surroundings 2) while the second one considers both moisture and heat transfers. The distinction will be determined by adjusting the convective transfer coefficients of the walls (see Figure 2).

The walls can exchange heat with their surrounding through the convective heat transfer coefficients, calculated through the dedicated basic algorithms in EnergyPlus™: the TARP algorithm for $h_{c,i}$ and the DOE-2 algorithm for $h_{c,o}$. These algorithms are described in [16].

The convective mass transfer coefficients for walls that can interact both thermally and hydrically with their surroundings are set to the default software values: 2×10^{-8} [kg/(Pa.s.m²)] for $h_{m,i}$ and 6.5×10^{-8} [kg/(Pa.s.m²)] for $h_{m,o}$. In order to obtain walls that cannot interact with their environment in a hygroscopic manner, both mass hydric transfer coefficients $h_{m,i}$ and $h_{m,o}$ of the surfaces are set to 0 [kg/(Pa.s.m²)].

To simplify, we will use the term "active wall" to describe a wall that is capable of exchanging moisture with its environment. In the case of an active wall, water vapour transfer takes place within the wall and with the internal and external atmospheres in contact with it. In the opposite case, water vapour transfer can still take place within the wall, but water exchange between the wall and its surroundings is impossible.

The number of active walls will increase from 0, *i.e.* a case with no water transfer between the external walls and their surroundings, to 4, *i.e.* a case with water transfer between all the external walls and their surroundings, passing through all the intermediate cases: 1, 2 and 3 active walls. The 2 active walls case study is represented in Figure 2.

2.3 Outputs

We will study the outputs related to hygrothermal comfort for building's users: temperature, humidity, and comfort indicator. The duration of each simulation is approximately 5 minutes and 30 seconds when executed on the 6 CPU cores "AMD Ryzen 5 PRO 5650U" processor.

Temperature: we will focus on the output data that have the greatest impact on users' comfort: the operative temperature [°C]. It is defined as the average of the inside air temperature [°C] and the inside face wall temperature [°C] weighted by their respective exchange coefficients.

Humidity: the most commonly used humidity output data is air relative humidity [%] [4,11,19].

Comfort indicator: we will study the Predicted Mean Vote (PMV). The PMV is currently the standard hygrothermal comfort indicator, which takes into account temperature, relative humidity, clothing, metabolic activity... It is described in ISO 7730 [14]. This indicator quantifies the theoretical average vote of a representative panel of people about the hygrothermal conditions they experience. A hygrothermal environment is considered comfortable if the PMV is between -1 and 1. Conversely, for a value outside these limits, the environment is considered uncomfortable.

The input values for the PMV calculation in this study are available in Table 1:

Table 1. Building users' input parameters for PMV calculation.

<i>M</i> : Metabolic ratio of the human body [W.m ⁻²]	<i>W</i> : Mechanical body work ratio [W.m ⁻²]	<i>f_{cl}</i> : Factor of clothed surface on the person [no unit]
120	0	Winter: 1; Summer :0.5

3 Results and Discussion

3.1 Global graphical analysis

The annual results of the 10th year obtained from the parametric study are presented in Figure 3. The selected format allows numerous statistical parameters to be studied. For each case study, at the top of the figure, the boxplot shows the median, represented by the central line of the box, the first and third quartiles, which delimit the box, as well as the ranges containing the minimum (or maximum) value reached in the 1st (or 3rd) quartile minus (or plus) 1.5 times the interquartile range for the left (or right) whisker. In parallel, at the bottom of the figure, values can be visualized through a graphical representation of their statistical distribution (arbitrary units).

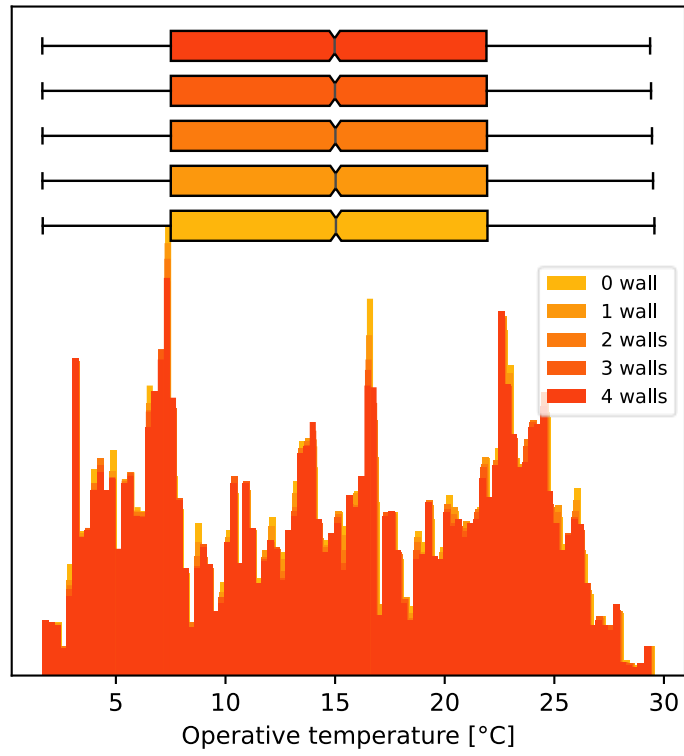


Figure 3. Boxplot diagram and statistical distribution representation of operative temperature [°C]

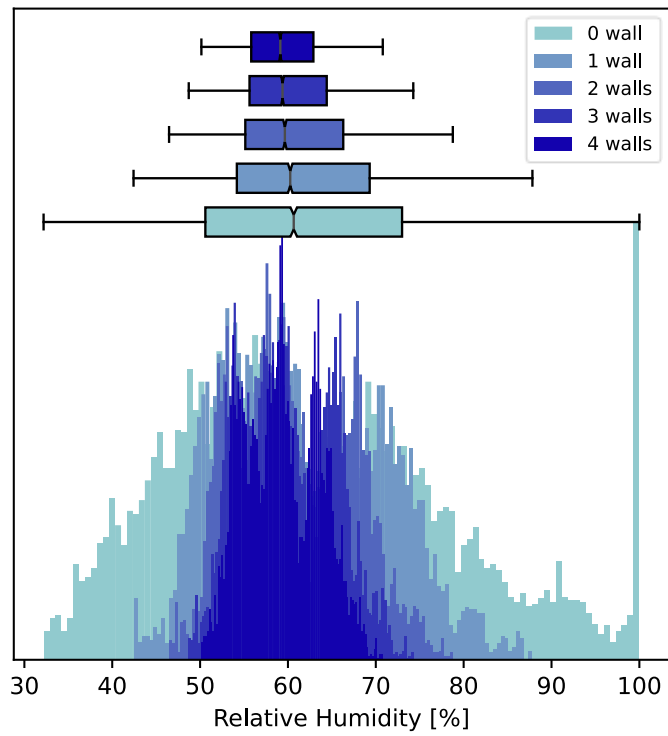


Figure 4. Boxplot diagram and statistical distribution representation of relative humidity [%]

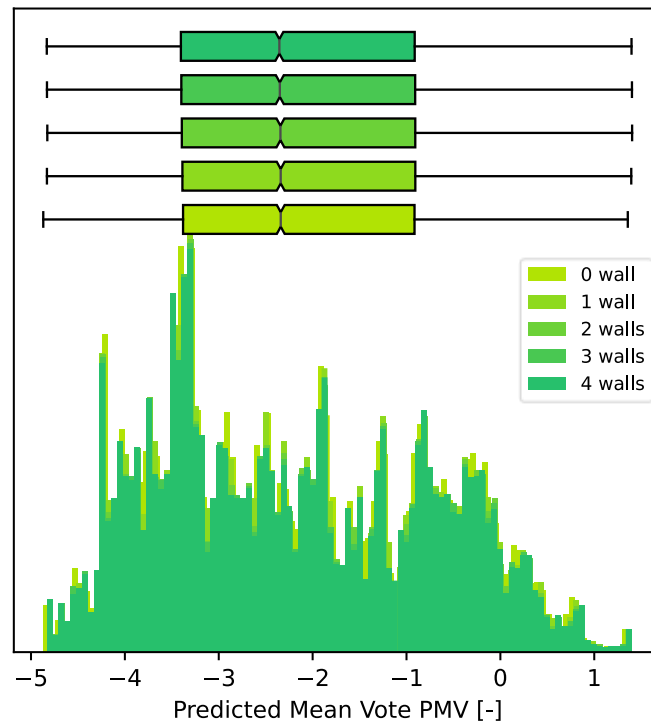


Figure 5. Boxplot diagram and statistical distribution representation of PMV [no unit].

Temperature (Figure 3): we observe minimal variation in operative temperatures between all cases throughout the analysed year. Although slight fluctuations can be discerned in the statistical distribution of values from one case to another, these changes do not manifest in visible modification within the boxplot diagrams; they appear consistent across all cases. Thus, considering both moisture and heat transfer between the wall and the room has no significant impact on the temperatures obtained.

Humidity (Figure 3): the addition of active walls has a significant impact on the relative humidity. Indeed, after each addition of active wall, we observe a decrease in the upper value of the whisker and the upper limit of the box, combined with an increase in the lower value of the whisker and the lower limit of the box. At the same time, the median value slightly decreases.

The impacts are most prominent when considering the maximum and minimum values, which vary greatly as soon as the first active wall is added to the simulation. In particular, the maximum value falls sharply: a reduction of more than 10% as soon as the first active wall is added, and a difference of close to 30% between the simulation without any active wall and

the one with 4 active walls. For the minimum value, the variation is also significant with an increase of more than 10% as soon as the first active wall is added and almost 20% difference between the simulation without any active wall and the one with 4 active walls. The median relative humidity decreases by around 1% at each addition of an active wall.

In particular, the first wall addition has the greatest impact on the relative humidity regulation. Indeed, after this addition, we note the most significant variations in both the minimum and maximum values observed across all case studies. Specifically, regarding the highest relative humidity values, a notable modification in the distribution occurs, characterized by the absence of a peak value previously observed at 100% relative humidity in the case study without any active wall which reflected a saturation of humidity in the room air. In each case, the influence of the addition of each supplementary active wall is smaller on all displayed parameters.

The regulating effect increases with each addition of active walls regardless of the initial number of active walls considered, even if the regulation due to the addition of the initial walls appears to be greater than that due to the addition of the subsequent walls.

Comfort indicator PMV (Figure 3): we observe minimal variation in PMV between all case studies throughout the analysed year. The observations that can be made are almost identical to those from the operative temperature analysis. The conclusion is the same as for the temperature: considering both the moisture and heat transfer between the wall and the room does not have a significant effect on the PMV values obtained. This observation was also made in a comprehensive literature review on hygrothermal comfort indicators [20], which indicates a minor influence of relative humidity on the PMV, with operative temperature being a predominant parameter influencing this indicator.

Synthesis: On the one hand, we notice that the operating temperature and the PMV are slightly affected by considering the moisture exchange between the walls and their surroundings.

On the other hand, we observe that the air relative humidity is significantly affected by considering the moisture exchange between the walls and their surroundings. With this consideration, the walls act as humidity regulators in the room: they reduce the variations in air relative humidity by increasing the minimum and the first quartile values and decreasing the maximum and third quartile values. We also found that each addition of active walls resulted

in better overall regulation, but the intensity of regulation seemed to decrease as the number of active walls added increased.

We will study numerically all these output parameters in detail to confirm the previously made statements.

3.2 Complementary numerical analysis

We present the numerical study of the annual hourly difference between the relative humidities of the air, simulation by simulation, hour by hour, during the 10th year of simulation. The results are displayed in (Table 2-4).

Concerning the operative temperature (Table 2) and the PMV value (Table 3), we observe very low values of hourly difference, averaging one-hundredth for mean values and not exceeding one-tenth for maximum values. These marginal variations confirm that the consideration of moisture transfer and its coupling with heat transfer is not affecting these parameters.

Concerning the relative humidity (Table 4), the addition of the first active wall implies a mean hourly relative humidity difference of 6.95% and a maximum hourly relative humidity difference of 24.72% compared to the case study without any active wall. The addition of the fourth and last active wall, on the other hand, only implies a variation of mean hourly relative humidity of 0.96% and a maximum hourly relative humidity difference of 3.48% compared to the three active wall case study. The current results confirm the observation derived from the comparison of prior numerical study: while each supplementary active wall addition contributes to improved overall regulation, their direct impact on air relative humidity is comparatively reduced.

Table 2. Annual hourly delta between the operative temperatures, simulation by simulation.

Number of active walls compared	0 and 1	1 and 2	2 and 3	3 and 4
Annual mean hourly delta Top [°C]	0.02	0.01	0.01	0.01
Annual maximum hourly delta Top [°C]	0.07	0.05	0.04	0.05

Table 3. Annual hourly delta between the PMV values, simulation by simulation.

Number of active walls compared	0 and 1	1 and 2	2 and 3	3 and 4
Annual mean hourly delta PMV [-]	0.02	0.01	0.00	0.00
Annual maximum hourly delta PMV [-]	0.09	0.03	0.01	0.01

Table 4. Annual hourly delta between the air relative humidities, simulation by simulation.

Number of active walls compared	0 and 1	1 and 2	2 and 3	3 and 4
Annual mean hourly delta RH [%]	6.95	2.42	1.30	0.96
Annual maximum hourly delta RH [%]	24.72	10.38	5.39	3.48

4 Conclusions

In this article, we examined how considering both moisture and heat transfers between hygroscopic raw earth walls and their surrounding atmospheres affects various BES output data. This objective was achieved through a parametric study with different scenarios which enabled to draw the following conclusions:

- The air relative humidity of the building's interior atmosphere is significantly affected by the moisture transfer and its coupling with thermal transfer consideration. The variations observed in HR clearly show that the use of hygroscopic materials helps to regulate the indoor air humidity.
- Each hygrothermal active wall addition contributes to a better overall humidity regulation, however, the greater the number of active walls already present, the less impact the addition of a further one will have.
- Nevertheless, the operative temperature is very slightly impacted by the moisture transfer and its coupling with heat transfer consideration.
- Thus, the standardised hygrothermal comfort indicator, PMV, is slightly impacted by the moisture transfer and its coupling with heat transfer consideration. Indeed, the relative humidity has a minor impact on PMV compared to temperature and the regulation brought by hygrothermal coupling consideration is not sufficient to make it vary significantly.

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