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Review

Energy in buildings: A review of models on hygrothermal transfer through the porous materials for building envelope

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ABSTRACT

The hygrothermal transfer is very important for the design of a building envelope for thermal comfort, economic and energy analysis of the building envelope. The lack of reference materials on models of moisture and temperature behavior in the building, including wooden walls, is a challenge. This paper reviewed the hygrothermal transfer models for building walls. Energy and mass conservation equations with boundary and input conditions were presented in this paper for concrete, bricks, and wooden walls. The review showed the presence of mainly physical-based models, while there is a dearth of data-based models. The influence of the type of wall, orientation, thickness, the density of the material, and climatic variations on the temperature and moisture evolutions within the building materials influenced the model mechanisms. Future research gaps should include shrinkage influence on hygroscopic materials like wood due to their behavior under ambient conditions. Data-based models should be explored too.

1. Introduction

Heat and moisture transport has been studied simultaneously in building envelope. The relative humidity of the air indoors can affect the micro-climate of the building envelope and, by extension, the energy consumption. While there is a clamor for energy-efficient buildings [1], this should be achieved in consonance with the material that has high moisture buffering capacity to avoid moisture damage within the building. Some researchers have estimated that building alone consumes about 36 -70 % of global energy, generating close to 50 % of global greenhouse gas emissions [1-3]. This energy is expended right from the operational phase of a building, material extraction, production, construction, transportation, and the end of the life span of the building [1-9]. Therefore emphasis now is to cut down energy utilization in a building to reduce greenhouse generation on the environment, acidification of the environment, depletion of the ozone layer, global warming, abiotic resources reduction, eutrophication, etc [1,10,11]. Countries are adopting a different green strategy in building, hoping to cut down energy consumption by 20- 42 % by 2050 with a 35 % reduction in greenhouse emissions [12, 13]. While some have considered the entire structural envelope, others have looked at the materials for construction or various components of the structures ranging from the walls, the floor, or the roof envelope [9, 14, 15]. The adoption of hygroscopic materials throws up the issue of moisture adsorption for these hygroscopic materials. Condensations inside the building envelope are most common due to variations in temperature and humidity indoors and outdoors the building. The presence of moisture within the building envelope will cause thermal discomfort and can corrode the metallic structures within the building and also make the indoors moldy [16]. This can lead to structural degradation and failure. Therefore the study of heat and mass transfer between the porous materials interface is done to elucidate their thermal performance and strength. Understanding the physics of this physical process is important to be able to predict them. The discontinuous moisture profile of two porous materials at the interface, because of their hygroscopic characteristics, has been used to predict the temperature and moisture gradients. Therefore, it is obvious that the nature of the materials used in building construction affects the temperature and moisture variations within the building as a function of the ambient weather changes and, by extension, the energy required for cooling or heating satisfaction [9, 17]. This will determine the magnitude of humidity, heating, and cooling required [18, 19].

Materials like wood, metal, steel, concrete, pozzolan, glass, bricks, and other multi-layered composites have been adopted for building walls [20-25]. Osayintola et al. [26] and Lelievre et al. [17] classified building materials as classical and hygroscopic building materials. Lelievre et al. [17] further sub-classified the building materials as bio-based and non-bio-based materials. The authors stated that bio-based materials like hemp concrete have potential low carbon emission, good thermo-hydric properties, and moisture buffering properties [27-30]. In several cases, walls can be made of more than one material layer, considering building insulations and cement plasters in some walls. Insulated walls (Figure 1) will regulate the heat and moisture transfer within the building envelope. Therefore, experimental and numerical studies have been carried out to study the physics of heat and moisture transfer of various materials in response to variation in weather parameters, which includes solar radiation, temperature, moisture, and relative humidity. These models are developed and present as single or multidimensional cases in the literature [31-47]. These models are resolved using finite elements, finite control volume etc, in a steady and non-steady numerical scheme. They are majorly predictive models to determine the temperature, relative humidity, and moisture condition of the inside of the building as a variation to the ambient conditions [32-34, 36-43]. The various studies used the thermo-physical properties of these materials, the nature of airflow, the dimension of moisture transfer, and the meteorological data of each area to develop the simulation codes to make their predictions with good result. The vapor adsorption and desorption isotherm is controlled by the main adsorption isotherm with the occurrence of hysteresis in the sorption curves [17]. Although the nature of hysteresis is yet well established, some authors included it in their modeling approach, while others neglected it. Simo-Tagne et al. [9] stated that studies like this would help in the selection of materials to satisfy the desired heat load at minimum dissipation of energy with less environmental impact. Some researchers have tried to review these models, though they presented only computer-based model tools, like UMIDUS, Wuf, MATCH, DELPHIN etc [46, 47]. Prior to that, the Canadian mortgage and housing cooperation in 2003 reviewed and showed that about forty five hygrothermal transfer models were in existence, which increased to about 57 models by 2008 [47]. The use of a dynamic coupled co-simulation approach for forecasting the hygrothermal behavior of building envelopes was discussed by Ferroukhi et al. [46]. However, with the development of new material and the creation of different kinds of boundary conditions and different interactions with the environment considered, new numerical models on hygrothermal transfer are presented and validated with experimental data. Busser et al. [78] towed this line in presenting the recent trends in the experimental validation of hygrothermal transfer models, but the specific equations were lacking in their presentations.

Prior knowledge of energy behavior is important to design a building for optimum comfort, taking into consideration all the heat loads. Moisture and temperature changes in the building are coupled together to study this moisture and temperature gradient. This requires the development of modeling tools for optimal condition prediction for different kinds of walls. Due to the effect of greenhouse gas emissions generated from the production of non–bio–based walls, interest is shifting to environmentally friendly walls. Wooden walls are now of interest, especially in Africa, when the cost of non-biobased walls is also considered. This review is an updated review of hygrothermal transfers with the addition of research work on wooden walls lacking in other previous reviews. Therefore these will bring up to date various reviews conducted with the same theme. The review will single out each model and discuss its pros and cons.

2. Methodology

This review involves searching and requesting available open literature on hygrothermal behavior for different walls. Emphasis was on the literature on models that have not been reviewed, although where the models are based on existing models, the old models were presented, and the new models can be discussed under them. Subsequently, the models were separated into those developed and validated with concrete and bricks and those validated with wood. After reading and deducing the mechanisms governing the behavior of the hygrothermal transfer and important equations and results, this is presented and discussed. Figure 1 gives the flow chart of the review methodology.

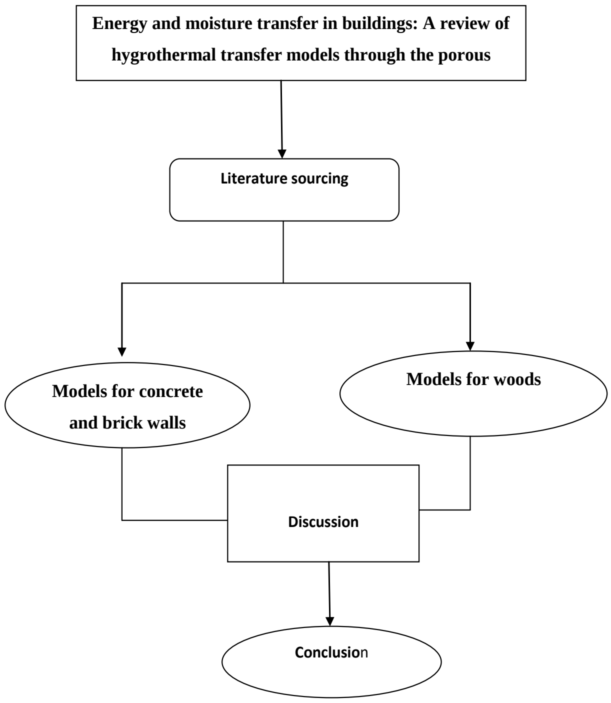

Figure 1. Schematics of the review process

3. Models for concrete and brick walls

Several modeling and simulation investigations exist with a different approach for concrete and bricks based walls in literature. To reduce energy consumption or improve hygrothermal transfer in buildings, researchers have developed different kinds of wall composite. Walls can be single, double or multilayer. A multilayer wall is a wall made up of more than one porous material. Concrete (bio-based and non-bio-based), bricks, cement plasters etc can be used to develop a multilayer wall. These walls have also been numerically simulated to obtain different varying conditions for indoor and outdoor conditions, and the results of the models were validated experimentally. The various models are as follows.

3.1 Xingguo models

Xingguo et al. [20] modeled a multi-layered porous wall made of cement mortar, red bricks, and cement plaster in the southern Chinese city of Hunan. The model developed was a modified one-dimensional transient hygrothermal model with temperature and humidity as the driving potential. Two key transport equations (1 and 3) for mass and heat transport, respectively, were solved using the finite element with established boundary conditions and the thermophysical properties of these materials. The maximum temperature and humidity difference obtained by the researchers were 1.87 °K and 11.4 % for indoor and outdoor conditions.

$$\frac{\partial W}{\partial t} = \frac{W_s}{\xi \rho_m}\left(D_v R_v T_m \rho_a + \frac{\xi \rho_m}{W_s} D_w\right)\frac{\partial^2 W}{\partial x^2} + \Phi \frac{\partial W_s}{\partial T}\frac{\partial T}{\partial t} \quad (1)$$

The resultant boundary conditions for the above equation were given as follows.

$$-D_v R_v T_m \rho_a \frac{\partial W}{\partial x} = h_m\left(W_\infty - W_{surf}\right) \quad (2)$$

For heat transport, the following governing equation was used.

$$(\rho_m C_{vm})\frac{\partial T}{\partial t} = K\frac{\partial^2 T}{\partial x^2} + h_{fg} D_v R_v T_m \rho_a \frac{\partial^2 W}{\partial x^2} \quad (3)$$

The resultant boundary conditions for the above equation were given as follows.

$$-K\frac{\partial T}{\partial x} = h_m\left(T_\infty - T_{surf}\right) + Q_{rad} + h_{fg} m_s \quad (4)$$

3.2 Lelievre model

Lelievre et al. [17] combined two sub-models of Pederson and a phenomenological model from Mualem II to develop a numerical simulation model for multilayer hemp concrete. Hemp concrete is usually coated with plasters of different levels of permeability inside and outside, and the thickness is non-homogenous. The model developed, which accounted for phase change and hysteresis, depended on the temperature and moisture transfer as a function of the hygrothermal properties of the hemp. They gave the energy and moisture conservation equations as follows.

$$\rho_s\left(C_{p,s} + wC_{p,l}\right)\frac{\partial T}{\partial t} = -\nabla \times (-\lambda \nabla T) + -\nabla \times \left(D_v^{\varphi}\nabla\varphi + D_v^T \nabla T\right) \times \left(l_v + \left(C_{p,s} - C_{p,l}\right)\left(T - T_{ref}\right)\right) \quad (5)$$

$$\rho_s \theta \frac{\partial \varphi}{\partial t} = -\nabla \times \left(-\left(D_l^{\varphi} + D_v^{\varphi}\nabla T\right)\nabla\varphi - D_v^T \nabla T\right) \quad (6)$$

The sorption capacity of equation 6 was deduced using two hysteresis models in sorption and desorption phases from Pederson (equations 7 and 8) and Mualem (equations 9 and 10) as follows.

$$\theta_{ad,hys} = \frac{B(w - w_{ad})^A \theta_{des} + (w - w_{des})^A \theta_{ad}}{(w_{des} - w_{ad})^A} \quad (7)$$

$$\theta_{ad,hys} = \frac{(w - w_{ad})^A \theta_{des} + C(w - w_{des})^A \theta_{ad}}{(w_{des} - w_{ad})^A} \quad (8)$$

Using Mualem models, the following sorption equations were deduced.

$$w_{des,hys}(\varphi) = w_j - \frac{p_d}{w_s}\left(w_s - w_{ad}(\varphi)\right)\left(w_{ad}(\varphi_j) - w_{ad}(\varphi)\right) \quad (9)$$

$$w_{ad,hys}(\varphi) = w_j - \frac{w_j - w_i}{\left(w_{ad}(\varphi_j) - w_{ad}(\varphi)\right)}\left(w_{ad}(\varphi_j) - w_{ad}(\varphi)\right) \quad (10)$$

Validation of the above models showed that using sorption isotherm from Mualem gave a good agreement between the experimental and predicted results, while the model of Pederson was off the mark.

3.3 Djongyang model

Djongyang et al. [40] presented a hygrothermal transfer model for porous building components, which they validated with earth bricks wall. They considered a plane geometrical shape and the influence of inter-tropical conditions with variations in latitude for the three cities of Cameroun. In solving the numerical equations, they considered the periodic solution approach and validated their model with two works of Menghao et al. [48, 49]. The model developed was one dimensional in which liquid water and air and water vapor as a single binary gas mixture was considered. The conservation equations for mass and heat transport were taken from the equation of Luikov, which has been used by other researchers [50] as follows.

$$\frac{\partial u(x,t)}{\partial x} = a_m \frac{\partial^2 u(x,t)}{\partial x^2} + a_m \delta \frac{\partial^2 T(x,t)}{\partial x^2} \quad (11)$$

$$\frac{\partial T(x,t)}{\partial t} = \alpha \frac{\partial^2 T(x,t)}{\partial x^2} + \varepsilon\beta \frac{\partial u(x,t)}{\partial t}, \qquad 0 < x < l \quad (12)$$

Te boundary conditions for the two equations above were defined as follows.

$$-k_{qout}\frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} + h_{out}(T_{x=0} - T_{out}) + \lambda_{out}(1 - \varepsilon_{out})(u_{x=0} - u_{out}) = 0 \quad (13)$$

$$k_{mout}\frac{\partial u(x,t)}{\partial x}\bigg|_{x=0} + k_{mout}\delta_{out}\frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} + \alpha_{out}(u_{x=0} - u_{out}) = 0 \quad (14)$$

$$-k_{qin}\frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} + h_{in}(T_{x=0} - T_{in}) + \lambda_{in}(1 - \varepsilon_{in})(u_{x=0} - u_{in}) = 0 \quad (15)$$

$$k_{min}\frac{\partial u(x,t)}{\partial x}\bigg|_{x=0} + k_{min}\delta_{in}\frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} + \alpha_{in}(u_{x=0} - u_{in}) = 0 \quad (16)$$

Equations 13 and 15 represent the heat balance with the three components of the quantity of heat exchanged for outdoor and indoor, the convective heat transfer and evaporative flux, while equations 14 and 16 represent the mass balance with the components of moisture gradient, temperature gradient and the convective flux exchanged between the ambient and the surface of the materials. Djongyang et al. [40], considering the length of the day and the declination of the sun, converted equations 11 and 12 to oscillatory (periodic) equations using the Fourier series method as presented in equations 17 and 18, which they used in their validation adopting a periodic approach

$$\frac{\partial^2 u_n(x)}{\partial x^2} - \frac{inw}{a_m} u_n + \delta \frac{\partial^2 T_n(x)}{\partial x^2} = 0 \quad (17)$$

$$\frac{\partial^2 T_n(x)}{\partial x^2} - \frac{inw}{\alpha} T_n + \varepsilon\beta \frac{inw}{\alpha} u_n = 0 \quad (18)$$

Using a numerical approach, they solved equations 17 and 18 to generate the temperature and moisture profile of the material under variable external conditions. Validation of the results using thermo-physical properties of earth bricks gave good results. They showed that latitudes affect hygrothermal transfer.

Menghao et al. [49] also used the same one-dimensional Lukoiv equation presented in equations 11 and 12 in the modeling of a hygrothermal transfer for a fibrous slab, but they added the effect of adsorption and desorption heat, which is also one of the source or sink terms in coupled heat and mass transfer equations. They assumed a localized thermodynamic equilibrium between the fluid and the porous matrix in presenting the equations as follows.

$$C_P \rho \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + C_m \rho (\epsilon h_{lv} + \gamma) \frac{\partial m}{\partial t} \quad (19)$$

$$C_m \rho \frac{\partial m}{\partial t} = D_m \frac{\partial^2 m}{\partial x^2} + D_m \delta \frac{\partial^2 T}{\partial x^2} \quad (20)$$

The latent heat of vaporization will be integrated as part of the energy balance at the building materials boundary, which will be affected by mass diffusion due to deviations in temperature and moisture content [40, 51]. The boundary equations were given as follows.

$$k \frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} = \alpha_1 (T(0,t) - T_1) + \beta_1 h_{lv} (1-\varepsilon)(m(0,t) - m_1) \quad (21)$$

$$-k \frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} = \alpha_2 (T(l,t) - T_2) + \beta_2 h_{lv} (1-\varepsilon)(m(l,t) - m_2) \quad (22)$$

$$D_m \frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} + k_m \delta \frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} = \beta_1 (m(0,t) - m_1) \quad (23)$$

$$-D_m \frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} - k_m \delta \frac{\partial T(x,t)}{\partial x}\bigg|_{x=0} = \beta_2 (m(l,t) - m_2) \quad (24)$$

In the resolution of the equations using Laplace transformations, dimensionless terms were introduced to equations 19-24 to change it to dimensionless form. Validation of the equations was done using the experimental setup in Figure 2. The porous material is a multilayer material whereby that one side is permeable and exposed to outdoor humid conditions while the other side of the wall, which is impermeable, is subjected to cold temperatures. Validations of the numerical simulation model, although showed the same trend as the experimental data looking at Figure 3 plotted by the authors it shows that there is still temperature variations which implies that there is still some omitted parameters like hysteresis, which is yet to be understood by researchers because of non-homogeneous nature of some porous materials; however, moisture profile was more accurately predicted.

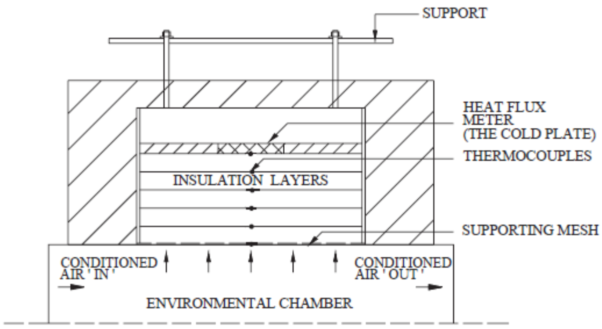

Figure 2. Experimental set of the testing rig for model evaluation [40, 51]

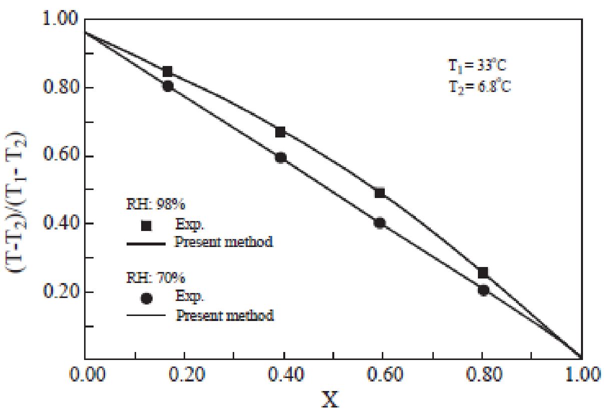

Figure 3. Comparison of the numerically simulated temperature profiles with the experimental result after quasi-steady state [40]

3.4 Simo-Tagne model

Simo-Tagne et al. [9] presented a numerical model for predicting the hygrothermal transfer for concrete walls for outdoor conditions in sub-Saharan Africa. The model took into account all kinds of bound and integrated the type of flow in the boundary conditions, which is not common in other established models. They also stated that all water type occurring in the material is modified during the moisture transfer; therefore, they presented the mass conservation equations for liquid water, bound water, and vapor phases in equation 25-27, respectively, as follows.

$$\frac{\partial(\alpha S \rho_l)}{\partial t} + \vec{\nabla}.\vec{J_l} = -K_l \quad (25)$$

$$\frac{\partial(X_b \rho_S)}{\partial t} + \vec{\nabla}.\vec{J_{as}} = -K_{as} \quad (26)$$

The contribution of water vapor to the mass balance equations is given by:

$$\frac{\partial(\alpha(1-S)\rho_g C_g)}{\partial t} + \vec{\nabla}.(\rho_g \vec{V_g} + \vec{J_g}) = K_{as} + K_l \quad (27)$$

$\rho_g \vec{V_g}$ is the flux characteristic of the movement of the vapour phase. The solution of equation 27 gave equation 28 as follows.

$$\frac{\partial(\rho_S H)}{\partial t} + \vec{\nabla}.(\rho_g \vec{V_g} + \vec{J_l} + \vec{J_{as}} + \vec{J_g}) = 0 \quad (28)$$

The heat energy balance was given by equation 29 as follows.

$$\left[\rho C_p \frac{\partial T}{\partial t} + \vec{\nabla}\vec{J}_T\right]_s + \left[\rho C_p \frac{\partial T}{\partial t} + \vec{V}.\vec{\nabla}T\right]_g + \left[\rho C_p \frac{\partial T}{\partial t} + \vec{V}.\vec{\nabla}T\right]_l + K_l L + K_{as}(L + E_b) = 0 \quad (29)$$

The boundary conditions are given in equations 30 and 31 as follows.

$$\left[-\rho_s(E_b + L)D_H \frac{\partial H}{\partial x} - (\lambda + \alpha_t \rho_s (E_b + L) D_H)\frac{\partial T}{\partial x}\right]\Big|_{x=0} = h_{c,ext}\left(T_{aext} - T(0,t)\right) + \rho_w L h_{m,ext}\left(X_{eq}(T_{aext}, HR_{aext}) - H(0,t)\right) + G_{gloi} \quad (30)$$

$$\left[-D_H \frac{\partial H}{\partial x} - \alpha_t D_H \frac{\partial T}{\partial x}\right]\Big|_{x=0} = h_{m,ext}\left(X_{eq}(T_{aext}, HR_{aext}) - H(0,t)\right) \quad (31)$$

The above equations were discretized with finite differences using the Crank-Nicolson scheme, and the solution is with the Gauss-Seidel relaxation iteration method using Fortran 90 language. Validation of the model was with hemp concrete with a low mean relative error.

3.5 Philip and De-Vries model

Philip and De-Vries proposed a model applied to study the heat and mass transfer through a porous medium using a building wall based on the thermodynamics of irreversible processes [78]. This model has been the bases for some other models, which will also be discussed in this section. This model took into consideration the effect of temperature and humidity gradients, and also, the altitude of the location was taken into account. The medium is assumed to be stable and homogenous. Kevin's law was applied at every point of the medium, and the hysteresis effect between adsorption and desorption phenomena is neglected. This model is given as follows.

$$\begin{cases} \frac{\partial X}{\partial t} + a\frac{\partial X}{\partial t} + c\frac{\partial T}{\partial t} = div\left(D_q \vec{grad}X + D_T \vec{grad}T\right) - \frac{\partial K}{\partial z} \\ \rho C_p \frac{\partial T}{\partial t} = div\left(\lambda \vec{grad}T\right) + \rho_l L div\left(D_{qv}\vec{grad}X + D_{Tv}\vec{grad}T - a\frac{\partial X}{\partial t} - c\frac{\partial T}{\partial t}\right) + \\ \rho_l C_l\left(D_{ql}\vec{grad}X + D_{Tl}\vec{grad}T - K\right)\vec{grad}T + \rho_l C_v\left(D_{qv}\vec{grad}X + D_{Tv}\vec{grad}T\right)\vec{grad}T \end{cases} \quad (32)$$

Where $K = \frac{k_l g}{g_l}, y = -\frac{P_c}{\rho_l g}, D_{ql} = K\left(\frac{\partial y}{\partial x}\right)_T$ (33)

$$D_{Tl} = K\left(\frac{\partial y}{\partial T}\right)_x, D_{qv} = fD\left(\frac{M_v}{RT}\right)^2 \frac{gP_{vs}}{\rho_l}\left(\frac{\partial y}{\partial x}\right)_T exp\left(\frac{M_v g y}{RT}\right), D_q = D_{ql} + D_{qv} \quad (34)$$

$$D_{Tv} = fD\frac{P}{P-P_v}\left(\frac{M_v}{RT}\right)^2 \frac{LP_{vs}}{T\rho_l} exp\left(\frac{M_v g y}{RT}\right) + fD\frac{P}{P-P_v}\left(\frac{M_v}{RT}\right)^2 \frac{gP_{vs}}{\rho_l}\left(\left(\frac{\partial y}{\partial T}\right)_x - \frac{y}{T}\right)HR \quad (35)$$

$$D_T = D_{Tl} + D_{Tv}, a = \frac{(J-q_l)D_{qv}}{fD\frac{P}{P-P_v}} - \frac{P_v M_v}{\rho_l RT}, c = \frac{(J-q_l)D_{Tv}}{fD\frac{P}{P-P_v}} - \frac{(J-q_l)P_v}{\rho_l RT} \quad (36)$$

Neglecting the heat transfer due to the mass transfer and the local temporal variation of the condensed water content in the vapor state, the simplified model of Philip and De-Vries is obtained, and it is well described by the experimental data obtained by Larbi in 1990 [78].

$$\begin{cases} \frac{\partial X}{\partial t} = div\left(D_{q_v}\vec{grad}X + D_{T_v}\vec{grad}T\right) - \frac{\partial K}{\partial z} \\ \rho C_p \frac{\partial T}{\partial t} = div\left(\lambda \vec{grad}T\right) + \rho_l L div\left(D_{q_v}\vec{grad}X + D_{Tv}\vec{grad}T\right) \end{cases} \quad (37)$$

The model of Umidus [79] assumed that the humidity is transferred through the wall only in vapor and liquid forms. The liquid form is transferred by capillary, and the vapor form is transferred due to the partial pressure of the vapor. Thus, the model in one dimension is as follows:

$$\begin{cases} \frac{\partial X}{\partial t} = \frac{\partial}{\partial x}\left(D_T\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_H\frac{\partial X}{\partial x}\right) \\ \rho_o\left(C_{po} + C_{pl}\frac{\rho_l}{\rho_o}X\right)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + L_v\rho_l\begin{pmatrix}\frac{\partial}{\partial x}\left(D_{Tv}\frac{\partial T}{\partial x}\right) + \\ \frac{\partial}{\partial x}\left(D_{Hv}\frac{\partial X}{\partial x}\right)\end{pmatrix} \end{cases} \quad (38)$$

The boundary equations are given by:
Humidity:

$$-\rho_l\left(D_T\frac{\partial T}{\partial x} + D_H\frac{\partial X}{\partial x}\right)\Big|_{x=0,e} = h_{M,e}\left(\rho_{ve,a,e} - \rho_{ve,s,e}\right) \quad (39)$$

$$-\rho_l\left(D_T\frac{\partial T}{\partial x} + D_H\frac{\partial X}{\partial x}\right)\Big|_{x=L,i} = h_{M,i}\left(\rho_{ve,a,i} - \rho_{ve,a,i}\right) \quad (40)$$

Temperature:

$$-\lambda\frac{\partial T}{\partial x} - L_v\rho_l\left(D_{Tv}\frac{\partial T}{\partial x} + D_{Hv}\frac{\partial X}{\partial x}\right)\Big|_{x=0,e} = h_{T,e}\left(T_{a,e} - T_{s,e}\right) + L_v h_{M,e}\left(\rho_{ve,a,e} - \rho_{ve,s,e}\right) \quad (41)$$

$$-\lambda\frac{\partial T}{\partial x} - L_v\rho_l\left(D_{Tv}\frac{\partial T}{\partial x} + D_{Hv}\frac{\partial X}{\partial x}\right)\Big|_{x=L,i} = h_{T,i}\left(T_{s,i} - T_{a,i}\right) + L_v h_{M,i}\left(\rho_{ve,a,i} - \rho_{ve,a,i}\right) \quad (42)$$

Using this model to study the heat mass transfer through the wall building with and without a perfect contact on a double-layer wall, Le [80] shows that the assumption with a perfect contact can produce some errors during the determination of the physical parameters influenced by the humidity. When the contact is real (not perfect), the model shows that the energy consumption is reduced by 10%. Using the experimental data taken from the literature, Le [80] validated this model. Using the same assumptions by Philip and De-Vries, the model of Duforestel is given by Simo-Tagne [78] as follows.

$$\begin{cases} a_T\frac{\partial p_v}{\partial t} - \frac{a_T p_v}{\rho_v T^2}(h_m + L)\frac{\partial T}{\partial t} = div\left(\left(\frac{p_v}{p_t} + K_n + \frac{\rho_l K_l \rho_v T}{p_v}\right)\vec{grad}p_v - \rho_l K_l\frac{L}{T}\vec{grad}T\right) \\ \left(-h_m a_T + h_m\frac{L}{\rho_v T}\right)\frac{\partial p_v}{\partial t} + \left(C' + \frac{a_T p_v}{\rho_v T^2}h_m(h_m + L)\right)\frac{\partial T}{\partial t} = div\begin{pmatrix}L\left(\frac{P}{P_t} + K_n\right)\vec{grad}p_v \\ +\lambda\vec{grad}T\end{pmatrix} \end{cases} \quad (43)$$

This model is easy to use than the one of Philip and De-Vries and can be applied to non-hygroscopic material of construction, but the fact it did not take into account the gradient of moisture content is often the reason for the difference between experimental data and numerical data. Based on the same assumptions of the model of Philip and De-Vries, Luikov presented his model with other parameters. This model gives satisfaction when the partial pressure of the gas phases is uniform during the heat mass transfer. Luikov's model is given by Simo-Tagne [78].

$$\begin{cases} \frac{\partial X}{\partial t} = div\left[a_m\left(\vec{gradX} + \delta\vec{gradT}\right)\right] \\ \rho C_p\frac{\partial T}{\partial t} = div\left(\lambda\vec{gradT}\right) + eL\frac{\partial X}{\partial t} \end{cases} \quad (44)$$

The difficulty faced in using this model is the difficulty in obtaining the conversion factor. Though it is mostly obtained using the inverse method, which is cumbersome. When the wall is constructed by the mortar slab, Saadani et al. [81] show that Luikov and Philip and De-Vries models can give similar values of temperature evolutions with some differences in the evolutions of moisture content, using the time steps between 0.1 and 1 s. Nitcheu et al. [82] used Luikov's model with satisfaction to estimate the numerical heat mass transfer through the wall building constructed in earth bricks stabilized with thatch fibers. They used the finite differences method and implicit scheme of Crank–Nicolson to generate the numerical results, but the thermophysical parameters of the medium were considered constant during the process.

3.6 Whitaker model

In 1977, Whitaker presented a model based on the morphology and the average thermophysical values of the building wall. The mass transfer of water in gas and liquid phases were separately written. This model is very difficult to use, but Thaï used it with satisfaction in 2006 [78]. This model is given by:

$$\begin{cases} \rho_w\frac{\partial \varepsilon_w}{\partial t} + \rho_w\vec{\nabla} < \vec{V_w} > + < \overset{*}{m} >= 0 \\ \frac{\partial}{\partial t}\left(\varepsilon_g < \rho_v >^g\right) + \vec{\nabla}\left(< \rho_a >^g < \vec{V_g} >\right) = \vec{\nabla}\left[< \rho_g >^g D_{eff}.\vec{\nabla}\left(\frac{<\rho_v>^g}{<\rho_{g}>^g}\right)\right] \\ < \rho > C_P\frac{\partial <T>}{\partial t} + \left[\rho_w C_{Pw} < \vec{V_w} > + < \rho_g >^g < C_P >^g < \vec{V_g} >\right]\vec{\nabla} < T > + \Delta h_v < \overset{*}{m} >= \vec{\nabla}\left(\lambda_{eff}\vec{\nabla} < T >\right) \end{cases} \quad (45)$$

In 1992, Nicolas proposed a model that took into account the capillary and hysteresis effects with the temperature gradient as a motor term. The Kevin's law has been modified, and the pressures of water in saturation state, respectively in porous medium and in the free medium, have been differently written. The model obtained is given by:

$$\begin{cases} \rho C_p\left(\frac{\partial T}{\partial t} + \vec{V}.\vec{gradT}\right) = div\left(\lambda\vec{gradT}\right) \\ \qquad -\left((C_l - C_v)T - L_o\right)\frac{RT}{kM_v}ln\left(\frac{p_v}{p_{vs}}\right) \\ \frac{\partial(b_a\rho_a)}{\partial t} + div\left(b_a\rho_a\vec{v}_a\right) = 0 \\ \frac{\partial(b_v\rho_v)}{\partial t} + div\left(\rho_v b_v\vec{v}_v\right) + \frac{\partial(b_l\rho_l)}{\partial t} + div\left(\rho_l b_l\vec{v}_l\right) = 0 \\ \frac{\partial(b_l\rho_l)}{\partial t} + div\left(b_l\rho_l\vec{v}_l\right) = \frac{RT}{kM_v}ln\left(\frac{p_v}{p_{vs}}\right) \end{cases} \quad (46)$$

With :

$$b_a\vec{v}_a = -\left(K_g + \frac{p_v}{p_a}K_{av}\right)\vec{grad}p_a - \left(K_g - K_{av}\right)\vec{grad}p_v \quad (47)$$

$$b_v\vec{v}_v = -\left(K_g - K_{av}\right)\vec{grad}p_a - \left(K_g + \frac{p_a}{p_v}K_{av}\right)\vec{grad}p_v \quad (48)$$

$$b_l\vec{v}_l = -K_l\vec{grad}\left(p_l + \frac{\rho_l RT}{M_v}h(b_l) + \rho_l g\right) \quad (49)$$

$$p_a = \frac{\rho_a RT}{M_a}, p_v = \frac{\rho_v RT}{M_v}, p_l = p_a + p_v + p_v\frac{dh(b_l)}{db_l} \quad (50)$$

Using his model, Nicolas studied the influence of the variation of the total pressure of the gas on the phenomenon of imbibition of cement. He obtained that the variation of the moisture content is influenced by the variation of the value of the total pressure of gas. The high pressure of the gas decreases the rate of transfer of humidity in the medium. This model permits the study of the effects of the hysteresis phenomenon during the heat mass transfer through the humid building wall [78].

4. Models for wooden walls

The impact of wood as a building material for walls has been explored greatly in literature. An investigation has been carried out on the effects of wood on thermal comfort in terms of relative humidity, temperature, background noise levels, and CO_2 concentrations [53-59]. Therefore, wood is energy efficient with lower CO_2 concentrations. Wood, as a hygroscopic material, absorbs moisture from the environment, which has a direct and indirect impact on room conditions and thermal comfort [60]. Therefore, the type of wood, thickness, moisture isotherm etc. has been factored in the predictive models to describe the hygrothermal behavior of wood for indoor and outdoor conditions.

4.1 Luikov models

Due to the flexibility of Luikov models, it has formed the basis for modeling the coupled heat and mass transfer for porous material independent of its hygroscopic nature. The model accounts for all the bonding water simplistically without restricting the water transfer mechanism [61]. Therefore, these models can be applied for one, two, or three-dimensional coupled heats and mass transfer in woods. Younis et al. [61] used this model to predict the temperature and moisture transfer in a wooden slab. After defining the entire dimensionless variables, they used the finite element method, which operates in MATLAB, to solve the partial differential equations in three dimensions. They concluded that different dimensionless numbers (Luikov, Kossovitch, Posnov, and Biot numbers) in the coupled heat and mass transfer equations affected the overall heat and mass transfer behavior of the wooden slab. Comparison of this model with analytical and experimental data showed closer agreement with the analytical model rather than experimental data.

4.2 Osayintola model

Osayintola et al. [26] used a combined Knudsen and Fickian diffusion and neglected thermal diffusion in the modeling of heat and mass transfer evolution in spruce wood. The energy and mass conservation equations were defined in equations 51-54 as follows:

$$\rho\ell\frac{\partial \varepsilon\ell}{\partial t} + \dot{m} = 0 \quad (51)$$

$$\frac{\partial(\rho_v \varepsilon_g)}{\partial t} - \dot{m} = \frac{\partial}{\partial x}\left(D_{eff}\frac{\partial \rho_v}{\partial x}\right) \quad (52)$$

$$\rho C_{peff}\frac{\partial T}{\partial t} + \dot{m}h_{fg} = \frac{\partial}{\partial x}\left(k_{eff}\frac{\partial \rho_v}{\partial x}\right) \quad (53)$$

$$\dot{m} = -\rho 0\frac{\partial u}{\partial t} \quad (54)$$

The above equations were discretely solved, and a stable solution was provided with a relaxed, Gauss-Seidel iteration method. Discretization was by finite difference method with 2nd order accuracy for the implicit scheme. Although the authors suggested that the presented diffusion model can be used to compare the experimental results and set benchmarks for similar materials, they did not show this with their experimental data. Rather they only fitted the sorption data with moisture content, thermal conductivity, and water vapor permeability with good results.

4.3 Simonson model

Simonson et al. [69] presented a numerical simulation model to predict the moisture transfer (indoor climate) between the indoor air and the structural materials for wooden buildings in Belgium, Germany, Finland, and Italy. The model was developed to predict the temperature and relative humidity and applied to measure the comfort thresholds of the occupants in the building. The analysis of the model showed that the permeable interior layer is more satisfactory than when the interior layer is made with a water-resistant layer. The model is presented following the Ficks law of diffusion as follows:

$$qM = -kd(u,T)\nabla p_v - \rho_0 D_w(u,T)\nabla u + v_a\rho_v + K\rho_w g \quad (55)$$

Equation 55 is adopted from IEA ECBCS Annex 24 ‘Heat, Air and Moisture Transfer in Insulated Envelope Parts presented in detail in Hens [62]. The model took into consideration all the energy components of the moisture transfer process for adsorption, desorption, condensation, evaporation, freezing, and thawing. The conservation equations were solved simultaneously to predict the variable indoor conditions under different experimental data obtained in the field [64-69].

4.4 Talukdar model

Talukdar et al. [70] used a numerical model to set a benchmark for 1-D transient heat and moisture transfer models of spruce wood as a building material. Although the partial differential equations presented in equations 25-28 was used to set the governing energy conservation equations, they used an analytical approach to set the moisture penetration depth through the woods using equation 56 and 57. For a semi-porous material, the analytical equation developed for vapor transport is given in equation 30 as follows.

$$\frac{(\rho_v-\rho_{vi})}{(\rho_\infty-\rho_{vi})} = erfc\left(\frac{x}{\sqrt[2]{\alpha_m eff^t}}\right) - \left[exp\left(\frac{D_m x}{D_{eff}} + k\frac{h_m^2\alpha_m eff^t}{D_{eff}^2}\right)\right] \times \left[erfc\left(\frac{x}{\sqrt[2]{\alpha_m eff^t}} + \frac{h_m\sqrt{\alpha_m eff^t}}{D_{eff}}\right)\right] \quad (56)$$

$$\frac{(\rho_{v\delta_m}-\rho_{vi})}{(\rho_\infty-\rho_{vi})} = 0.01 \quad (57)$$

The obtained results show that increasing the air velocity increases the temperature, relative humidity, and moisture accumulation within the plywood.

4.5 Watt model

Watt et al. [71] proposed a two-dimension model for a light timber wall with an air barrier with changes in air tightness in a Swedish. The model was used to predict the moisture accumulation and mold growth within the building envelop. The magnitude of moisture accumulation is higher behind the outdoor air-tight layer of the simulated wall with the interior of the wall unsealed when compared to the sealed inside.

4.6 Simo-Tagne model

Simo-Tagne et al. [9] numerical model presented in equations 25-31 above was also used to predict the hygrothermal transfer for different wooden walls for outdoor conditions in sub-Saharan Africa. In this case, the model took into account the bound water presents in the wood with the integration of the flow pattern in the boundary conditions. Validation of the model was with Norway Spruce wood with a low mean relative error. Further analysis of the model showed that less dense wood with increased thickness provided better thermal comfort. Therefore, the nature of the wood and climatic factors is an important consideration that affects the hygrothermal transfer in woods. Simo-Tagne et al. [72] also presented a numerical simulation model for building walls in Nancy, France. The same approach and solutions in Simo-Tagne et al. [72] were adopted, but they integrated the Dufour and Soret effect. The driving potential for the heat and mass transfer was temperature and moisture gradient. The model showed the negligible influence of the wooden structure, while thickness is important in canceling the effect of ambient conditions. Simo-Tagne et al. [74, 75] present a novel model of heat mass transfer through wooden material. The model-based initially on the description of each type of water (bound water, vapor, and free water); equations obtained are given by:

$$\begin{cases} \dfrac{\partial W}{\partial t} = \dfrac{\partial}{\partial x}\left(D_{HH}\dfrac{\partial W}{\partial x} + D_{HT}\dfrac{\partial T}{\partial x}\right) \\ \rho C\dfrac{\partial T}{\partial t} = \dfrac{\partial}{\partial x}\left(D_{TH}\dfrac{\partial W}{\partial x} + (\lambda + D_{TT})\dfrac{\partial T}{\partial x}\right) \end{cases} \quad (58)$$

With:

$$D_{HH} = D_H - \frac{\rho_l k}{\rho_s}\left(\frac{k_r}{\mu}\right)_l\frac{\partial P_c}{\partial W} + \frac{\rho_g D_g}{\rho_s(1-C_g)}\frac{\partial C_g}{\partial W} \quad (59)$$

$$D_{HT} = D_T - \frac{\rho_l k}{\rho_s}\left(\frac{k_r}{\mu}\right)_l\frac{\partial P_c}{\partial T} + \frac{\rho_g D_g}{\rho_s(1-C_g)}\frac{\partial C_g}{\partial T} \quad (60)$$

$$D_{TT} = \frac{(E+L)\rho_g D_g}{1-C_g}\frac{\partial C_g}{\partial T} - E\rho_l k\left(\frac{k_r}{\mu}\right)_l\frac{\partial P_c}{\partial T} \quad (61)$$

$$D_{TH} = \frac{(E+L)\rho_g D_g}{1-C_g}\frac{\partial C_g}{\partial W} - E\rho_l k\left(\frac{k_r}{\mu}\right)_l\frac{\partial P_c}{\partial W} \quad (62)$$

$$D_T = \frac{E_b HR}{RT^2}\frac{\partial X_e}{\partial HR}D_H \quad (63)$$

The boundary equations are given by:
If x=0, thus:

$$\frac{\partial W}{\partial x} = 0\,;\frac{\partial T}{\partial x} = 0 \quad (64)$$

If x=±e/2, thus:

$$-D_{HH}\frac{\partial W}{\partial x} = h_m(W - X_e) \quad (65)$$

$$-(\lambda + D_{TT})\frac{\partial T}{\partial x} = h_c(T - T_{air}) + \rho_s L D_{HH}\frac{\partial W}{\partial x} \quad (66)$$

Using the real variations in thermophysical parameters presented in equations 47-55, Simo-Tagne et al. [75] showed that the model is flexible and will allow taking into account all properties of the wood types and the movement of all types of water (bound water, free water, vapor of water). However, they suggested that to adopt the model, the hydric diffusivities have to be experimentally determined for each wood. Generally, to have an accurate model for all the heat and mass transfer model equations, the sorption and desorption isotherm for all the materials have to be accurately determined, and also the accurate boundary condition is defined [75-77]. These values and equations mainly differentiated most of the presented equations in this review from each other.

4.7 Berger model

Berger et al. [73] proposed a numerical model using Scharfetter-Gummel scheme combined with a two-step Runge-Kutta approach. Three phases were distinguished: water vapor, liquid water, and dry air. The moisture mass balance was given as follows:

$$\begin{cases} \frac{\partial}{\partial t}(w_v + w_l) = -\nabla.(J_{c,v} + J_{c,l}) \\ \frac{\partial}{\partial t}(w_v + w_{da}) = -\nabla.(J_{c,v} + J_{c,da}) + l_{c,v} \end{cases} \quad (67)$$

The energy balance was given as follows:

$$(c_o\rho_o + C_v w_v + C_l w_l + C_{da} w_{da})\frac{\partial T}{\partial t} = -\nabla.J_q - r_{vl} l_{c,v} - \nabla.(C_v T)J_{c,v} - \nabla.(C_l T)J_{c,l} - \nabla.(C_{da} T)J_{c,da} \quad (68)$$

Where the volumetric vapor source $l_{c,v}$ is given by:

$$l_{c,v} = \frac{\Pi(1-\sigma)P_v}{R_v T^2}\frac{\partial T}{\partial t} + -\nabla.J_{c,v} \quad (69)$$

The heat flux was expressed as:

$$J_q = -\lambda_q \nabla T + (C_v w_v + C_{da} w_{da})\frac{T}{\Pi(1-\sigma)}V \quad (70)$$

V is the vapor velocity taken equal to the air velocity and given by:

$$V = -\frac{k_{vda}}{\mu}\nabla P \quad (71)$$

The flux of water vapor was given by:

$$J_{c,v} = -k_v \nabla P_v + \frac{P_v}{R_v T}V \quad (72)$$

The flux of dry air was given by:

$$J_{c,da} = \frac{w_v + w_{da}}{\Pi(1-\sigma)}V - J_{c,v} \quad (73)$$

The flux of liquid water was given by:

$$J_{c,l} = -k_m \nabla P_v + \frac{P_v}{R_v T}V - J_{c,v} \quad (74)$$

Applying this model to the wood fiber using the constant properties (without influences of humidity and temperature), Berger et al. [73] used a program translated with MatlabTM to obtain the curves that defined well the experimental data presented. Based on Whitaker's model, Perré and Turner [83] presented a model applied to the wooden wall byRafidiarison [84]. The medium is supposed to be partially saturated, and mass transfers are applied in each phase. This model is given by Simo-Tagne [78].

$$\begin{cases} \rho_l \frac{\partial \varepsilon_l}{\partial t} + \vec{\nabla}(\rho_l \vec{u_l}) = -\overset{*}{m} \\ \frac{\partial \rho_v^g}{\partial t} + \vec{\nabla}(\rho_v^g \vec{u_g}) = \overset{*}{m} + \overset{*}{m}_b \\ \frac{\partial \rho_b}{\partial t} + \vec{\nabla}(\rho_v^g \vec{u_v}) = \overset{*}{m} + \overset{*}{m}_b \\ \frac{\partial \rho_b}{\partial t} + \vec{\nabla}(\rho_b \vec{u_b}) = -\overset{*}{m}_b \end{cases} \quad (75)$$

$$\begin{cases} \rho_v^g \vec{u_v} = \rho_v^g \vec{u_g} - \rho_g D_{eff} \vec{\nabla}\left(\frac{\rho_v}{\rho_g}\right) \\ \rho_b \vec{u_b} = -\rho_c D_b \vec{\nabla}\left(\frac{\rho_b}{\rho_c}\right) \\ \vec{u_g} = -\frac{K_g}{\mu_g}\vec{\nabla}(p_g) \\ \vec{u_l} = -\frac{K_l}{\mu_l}\vec{\nabla}(p_l) \end{cases} \quad (76)$$

$$p_l = p_g - p_c \quad (77)$$

$$\rho C_p \frac{\partial T}{\partial t} + \Delta h_v\left(\overset{*}{m} + \overset{*}{m}_b\right) + h_s \overset{*}{m}_b - \rho_b \vec{u_b}.\vec{\nabla}(h_s) + \left[\left(\rho_l \vec{u_l} + \rho_b \vec{u_b}\right) C_{pl} + \sum_{i=a,v}\left(\rho_i^g \vec{u_i} C_{pi}\right)\right].\vec{\nabla}T = \vec{\nabla}\left(\lambda_{eff}\vec{\nabla}T\right) \quad (78)$$

Using experimental data given by Rafidiarison [84] and Rafidiarison et al. [85], the literature shows that this model gives satisfaction to predicting relative humidity, temperature, and moisture content of the wooden building walls in a temperate climate.

5. Discussions

The comprehensive bibliography of old and more recent hygrothermal transfer models for various building walls is reviewed in this paper. The hygrothermal transfer is very important for the design of a building envelope for thermal comfort and economic and energy analysis of the building. Several numbers of energy and mass conservation equations with different boundary conditions and input considerations have been presented in this paper for soil-based and wooden building walls. Some of the models are easier to use than others, though this doesn't make them give better results because, in most cases, the validation with the experimental results has more errors. For example, the model of Lukoiv poses a lot of challenges because the conversion factor of water from a liquid state to a vapor state is located between 0 and 1 due to the fact, they require the conversion factor to be obtained through a cumbersome process of the inverse method. Again, Duforestel model is easier to use than the one of Philip and De-Vries and can be applied to non-hygroscopic material in building, but the fact it did not take into account the gradient of moisture content is often the reason for the difference between experimental data and numerical data. The accuracy or otherwise of this model depends on the establishment of the right boundary conditions. Most of the research ignored the effect of hysteresis in their models, while very few considered the flow pattern of fluid through the wall surfaces. A literature review shows that most models were linked to Luikov equations for heat and mass transfer, and solutions were mostly by finite difference methods and implicit scheme of Crank–Nicolson to generate the numerical results. The thermophysical parameters of the medium were always considered constant during the process, but it will be good to consider swelling and shrinkage over time in the model as the material is influenced by environmental conditions. For example, in a high moisture environment, certain wood absorbs moisture and expands if used as a wall, while some shrink during the winter period. According to Ndukwu et al. [86], materials like wood, concrete or bricks used as a base material in wall construction if subjected to outdoor condition, undergoes continuous drying under ambient conditions. These materials, because they are hygroscopic, desorb or absorb moisture unless an equilibrium condition is maintained between the indoor and outdoor air, or the wall material surface is impermeable [87]. The subjection of these materials to external heat load from solar radiation and other high-temperature-producing sources like industrial activities results in continued moisture modification. Thus, moisture desorption or adsorption of most materials is a continuous process for the lifetime of the walls. The repercussion is the continuous modification of the thermophysical properties of this material. These require consideration in modeling the hygrothermal transfer for building walls. Therefore, as suggested by Ndukwu et al. [86], long-term behavioral models that will incorporate the continuous moisture loss or gain from building materials during structural application require investigation. The model should consider the effect of seasonal variations (winter, spring, summer, and autumn) and long-term meteorological data. Validations of the models showed the influence of wall, thickness, the density of the material, and climatic variations on the temperature and moisture evolutions within the building materials. Imaging models using software like COMSOL multi-physics, CFD etc. are scarce in the review bearing in mind that microscopic imagery is now deployed to measure the heat and moisture evolution in materials. Future models should include shrinkage or expansion influence, especially in fibrous materials like wood, as they respond to ambient variations.

6. Conclusion

The applications of various materials in building structures have been studied extensively. The study presents different models applied for predicting hygrothermal transfer for various building walls. Energy and mass conservation equations were applied with different boundary conditions, and thermophysical properties were presented in this paper for concrete, bricks, and wooden walls. Luikov models formed the basis of most models for porous materials. The parameters considered in most models were the nature of the materials of the wall, building orientation, variation in climate, the thickness of the wall, temperature, moisture changes, and the density of the material. Literature presenting imaging models using imagery software like COMSOL multi-physics, CFD etc. were scarce, considering that microscopic imagery is now deployed to measure the heat and moisture evolution in materials. Future models should include shrinkage or expansion influence on the fibrous material like wood due to their behavior under environmental conditions.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

References

[1] Jang M, T. Hong, C. Ji (2015). Hybrid LCA model for assessing the embodied environmental impacts of buildings in South Korea. Environmental Impact Assessment Review 50 (2015) 143–155

[2] ONU-environnement, Vers un secteur des batiments et de la construction a emission zero, efficace, et resilient, Bilan mondial (2017) 48pp 2017.

[3] A.M.E.A. Akata, D. Njomo, B. Agrawal, Assessment of building integrated photovoltaic (BIPV) for sustainable energy performance in tropical regions of Cameroon, Renew. Sustain. Energy Rev. 80 (2017) 1138–1152.

[4] Chang Y, Ries RJ, Wang Y. Life-cycle energy of residential buildings in China. Energy Policy 2013;62:656–64. http://dx.doi.org/10.1016/j.enpol.2013.07.053.

[5] Sartori I, Hestnes AG. Energy use in the life cycle of conventional and low-energy buildings: a review article. Energy Build 2007;39(3):249–57. http://dx.doi.org/10.1016/j.enbuild.2006.07.001.

[6] El-dessouky, H.T., Ettouney, H.M., Bouhamra, W.: A novel air conditioning system membrane air drying and evaporative cooling. Trans IChemE 78(Part A), 999–1009 (2000)

[7] M. C. Ndukwu · S. I. Manuwa · L. Bennamoun3 · O. J. Olukunle · F. I. Abam. In-Situ Evolution of Heat and Mass Transfer Phenomena and Evaporative Water Losses of Three Agro-Waste Evaporative Cooling Pads: An Experimental and Modeling Study. Waste and Biomass Valorization (2019) 10:3185–3195

[8] S. Braungardt, V. Burger, J. Zieger, T. Kenkmann, Contribution of Renewable Cooling to the Renewable Energy Target of the EU, Netherlands Enterprise Agency, July 2018 Publication number: RVO-088-1801/RP-DUZA (59p).

[9] Simo-Tagne M, M C Ndukwu, Y Rogoume (2019). Modelling and numerical simulation of hygrothermal transfer through a building wall for locations subjected to outdoor conditions in Sub-Saharan Africa. Journal of Building Engineering 26 (2019) 100901

[10] Hong T, Ji C, Park H. Integrated model for assessing the cost and CO2 emission (IMACC) for sustainable structural design in ready-mix concrete. J Environ Manage 2012;103:1–8. http://dx.doi.org/10.1016/j.jenvman.2012.02.034.

[11] Hong T, Ji C, Jang M, Park H. Assessment model for energy consumption and greenhouse gas emissions during the construction phase. J Manag Eng 2013;30(2):226–35.http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000199.

[12] European Commission, Feuille de route pour une Europe efficace dans l'utilisation des ressources, (2011), p. 31pp.

[13] L. Benahmed, F.Z. Ben-Mostefa, Integration d'un systeme de rafraichissement solaire au batiment. Faisabilite technico-economique, Master Thesis University of Abou Baker Belkaid Tlemcem (Algeria), 2013, p. 103.

[14] Shin S, Tae S, Woo J, Roh S. The development of environmental load evaluation system of a standard

Korean apartment house. Renew Sust Energ Rev 2011;15(2):1239–49. http://dx.doi.org/10.1016/j.rser.2010.09.036.
[15] Tae S, Shin S, Woo J, Roh S. The development of apartment house life cycle CO2 simple assessment system using standard apartment houses of South Korea. Renew Sust Energ Rev 2011;15(3):1454–67. http://dx.doi.org/10.1016/j.rser.2010.09.053.
[16] C. James, C.J. Simonson, P. Talukdar, S. Roels, Numerical and experimental dataset for benchmarking hygroscopic buffering models, International Journal of Heat and Mass Transfer 53 (2010) 3638–3654
[17] Lelievre D, T. Colinart∗, P. Glouannec . Hygrothermal behavior of bio-based building materials includinghysteresis effects: Experimental and numerical analyses. Energy and Buildings 84 (2014) 617–627
[18] P. Taylor, R.J. Fuller, M.B. Luther, Energy use and thermal comfort in a rammed earth office building, Energy Build. 40 (2008) 793–800.
[19] J.C. Damfeu, P. Meukam, Y. Jannot, Modeling and estimation of the thermal properties of clusters aggregates for construction materials: the case of clusters aggregates of lateritic soil, sand, and pouzzolan, Int. J. Heat Mass Transf. 102 (2016) 407–416.
[20] G. Xingguo, C. Youming, D. Yongqiang, Development and experimental validation of a one-dimensional dynamic hygrothermal modeling based on air humidity ratio, J. Cent. South Univ. 19 (2012) 703–708.
[21] J.C. Damfeu, P. Meukam, Y. Jannot, Modeling and estimation of the thermal properties of clusters aggregates for construction materials: the case of clusters aggregates of lateritic soil, sand, and pouzzolan, Int. J. Heat Mass Transf. 102 (2016) 407–416.
[22] W. Simpson, A. TenWolde, Physical Properties and Moisture Relations of Wood, Chapter 3, Forest Products Laboratory, 1999, p. 463 3.1-3.25.
[23] H. Jafarian, M.H. Demers-Claude, P. Blanchet, V. Laundry, Impact of indoor use of wood on the quality of interior ambiances under overcast and clear skies: case study of the Eugene H. Kruger building, Quebec City. BioResources 11 (1) (2016) 1647–1663.
[24] M. Watchman, A. Potvin, M.H. Demers-Claude, Wood, and comfort: a comparative case study of two multifunctional rooms, BioResources 12 (1) (2017) 168–182.
[25] G. Pajchrowski, A. Noskowiak, A. Lewandowska, W. Strykowski, Wood as a building material in the light of environmental assessment of full life cycle of four buildings, Constr. Build. Mater. 52 (2014) 428–436.
[26] O.F. Osanyintola, C.J. Simonson, Moisture buffering capacity of hygroscopicbuilding materials: experimental facilities and energy impact, Energy andBuilding 38 (2006) 1270–1282.
[27] Bevan, T. Woolley, Hemp Lime Construction: A Guide to Building with HempLime Composites, IHS/BRE Press, Bracknell, Berkshire, UK, 2008.
[28] T. Woolley, H. Thompson, T. McGrogan, M. Alexander, The role of low impactbuilding materials in sustainable construction: the potential for hemp, in:Proceeding of Sustainable Building Conference, 13–18 September 2004, Stel-lenbosch, South Africa, 2004.
[29] T. Pierre, T. Colinart, P. Glouannec, Measurement of thermal properties ofbiosourced building materials, International Journal of Thermophysics (2013),http://dx.doi.org/10.1007/s10765-013-1477-0.
[30] S. Prétot, F. Collet, C. Garnier, Life cycle assessment of a hemp concrete wall:impact of thickness and coating, Building and Environment 71 (2013) 223–231.
[31] J. Hildebrandt, N. Hagemann, D. Thran, The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe, Sustainable Cities and Society 34 (2017) 405–418.
[32] J. Le Dreau, P. Heiselberg, R.J. Lund, A full-scale experimental set-up for assessing the energy performance of radiant wall and active chilled beam for cooling buildings, BUILD SIMUL (2014) 1–13, https://doi.org/10.1007/s12273-014-0190-7.
[33] T. Busser, A. Piot, M. Pailha, S. Rouchier, M. Woloszyn, Experimental and numerical study of wood-based materials: from material to room scale, Energy Procedia 132 (2017) 747–752.
[34] D.P. Chen, C.X. Qian, C.L. Liu, A numerical simulation approach to calculating hygrothermal deformation of concrete based on heat and moisture transfer in porous medium, International Journal of Civil Engineerng 8 (4) (2010) 287–291.
[35] A. Ruuska, T. Hakkinen, Efficiency in the delivery of multi-storey timber buildings, Energy Procedia 96 (2016) 190–201
[36] N. Mendes, P.C. Philippi, A method for predicting heat and moisture transfer through multilayered walls based on temperature and moisture content gradients, Int. J. Heat Mass Transf. 48 (2005) 37–51.
[37] Z. Pasztory, P.N. Peralta, S. Molnar, I. Peszlen, Modeling the hygrothermal performance of selected North American and comparable European wood-frame house walls, Energy Build. 49 (2012) 142–147.
[38] Z. Bing, C. Zhongqing, Z. Liang, Numerical simulation for coupled heat and moisture transfer in building material, 3rd International Conference on Material, Mechanical and Manufacturing Engineering (IC3ME, 2015, pp. 216–221.
[39] A. Holm, M. Kunzel-Hartwig, Non-isothermal moisture transfer in porous building materials, Materialsweek, Munich, 2000, pp. 1–9 https://www.ibp.fraunhofer.de/ content/dam/ibp/de/documents/non-isothermal_tcm45-35019.pdf , Accessed date:18 August 2018.
[40] N. Djongyang, R. Tchinda, D. Njomo, A study of coupled heat and mass transfer across a porous building component in intertropical conditions, Energy Build. 41(2009) 461–469.
[41] A.D. Tran Le, D. Samri, M. Rahim, O. Douzane, G. Promis, T. Langlet, Effect of temperature-dependent sorption characteristics on the hygrothermal behavior of hemp concrete, Energy Procedia 78 (2015) 1449–1454.

[42] I. Bonefacic, I. Wolf, B. Frankovic, Numerical modeling of thermal comfort conditions in an indoor space with solar radiation sources, J. Mech. Eng. 61 (11) (2015) 641–650.
[43] Q. Menghao, R. Belarbi, A. Aıt-Mokhtar, A. Seigneurin, An analytical method to calculate the coupled heat and moisture transfer in building materials, Int. Commun. Heat Mass Transf. 33 (2006) 39–48.
[44] J. Kwiatkowski, M. Woloszyn, J.J. Roux, Modelling of hysteresis influence onmass transfer in building materials, Building and Environment 44 (2009)633–642.
[45] H. Steeman, M. Van Belleghem, A. Janssens, M. De Paepe, Coupled simulationof heat and moisture transport in air and porous materials for the assessmentof moisture related damage, Building and Environment 44 (2009) 2176–2184.
[46] P. Talukdar, O.F. Osanyintola, S.O. Olutimayin, C.J. Simonson, An experimentaldata set for benchmarking 1-D, transient heat and moisture transfer modelsof hygroscopic building materials. Part II: Experimental, numerical and ana-lytical data, International Journal of Heat and Mass Transfer 50 (2007) (2007)4915–4926.
[47] A. Janssens, M. Woloszyn, C. Rode, A. Sasic-Kalagasidis, M. De Paepe, From EMPDto CFD: overview of different approaches for heat air and moisture modeling,in: C. Rode, H. Hens, H. Janssen (Eds.), Proceedings of the IEA ECBCS Annex 41Closing Seminar, Dept. of Civil Engineering, Technical University of Denmark,Copenhagen, Denmark, 2008, pp. 9–20
[48] Q.Menghao, R. Belarbi, Development of an analytical method for simultaneous heat and moisture transfer in building materials utilizing transfer function method,Journal of Materials in Civil Engineering 17 (5) (2005) 492–497.
[49] Q. Menghao, R. Belarbi, A. Aı¨t-Mokhtar, A. Seigneurin, An analytical method to calculate the coupled heat and moisture transfer in building materials, International Communications in Heat and Mass Transfer 33 (2006) 39–48
[50] D. Kulasiri, I. Woodhead, On modelling the drying of porous materials: analytical solutions to coupled partial differential equations governing heat and moisture transfer, Mathematical Problems in Engineering 3 (2005) 275–291.
[51] W.J. Chang, C.I. Weng, An analysis solution to coupled heat and mass diffusion transfer in porous materials, Int. J. Heat Mass Transfer 43(2000) 3621–3632
[52] N.E. Wijeysundera, M.N.A. Hawlader, Effect of condensation and liquid transport on the thermal performance of fibrous insulation, Int. J. Heat Mass Transfer 35 (1992) 2605– 2616
[53] N.E. Wijeysundera, B.F. Zheng, Numerical simulation of the transient moisture transfer through porous insulation, Int. J. Heat Mass Transfer 39 (1995) 995–1003..
[54] Hildebrandta Jakob, Hagemann Nina, Thrän Daniela, The contribution of wood-based construction materials for leveraging a low carbon building sector in europe. Sustainable Cities and Society 34 (2017) 405–418.
[55] Watchman Mélanie, Potvin André, Demers Claude M. H., Wood and comfort: a comparative case study of two multifunctional rooms. BioResources 12(1), (2017)168-182.
[56] Poirier Geneviève, Demers Claude M. H., Potvin André, Experiencing wooden ambiences with nordic light : scale model comparative studies under real skies. BioResources 12(1), (2017) 1924-1942.
[57] Yuan Jihui, Farnham Craig, Emura Kazuo, Optimum insulation thickness for building exterior walls in 32 regions of China to save energy and reduce CO2 emissions. Sustainability (2017), 9, 1711 :1-13; doi:10.3390/su9101711.
[58] Ramage Michael H., Burridge Henry, Busse-Wicher Marta, Fereday George, Reynolds Thomas, Shah Darshil U., Wu Guanglu, Yu Li, Fleming Patrick, Densley-Tingleye Danielle, Allwood Julian, Dupree Paul, Linden P.F., Scherman Oren, The wood from the trees: The use of timber in construction. Renewable and Sustainable Energy Reviews 68 (2017) 333–359.
[59] Pajchrowski Grzegorz, Noskowiak Andrzej, Lewandowska Anna, Strykowski Wladyslaw, Wood as a building material in the light of environmental assessment of full life cycle of four buildings. Construction and Building Materials 52 (2014) 428–436.
[60] C. Rode, A. Holm, T. Padfield, A review of humidity buffering in the interior spaces, Journal of Thermal Envelope and Building Science 27 (3) (2004) 221–226
[61] R. Younsi , D. Kocaefe, Y. Kocaefe. Three-dimensional simulation of heat and moisture transfer in wood. Applied Thermal Engineering 26 (2006) 1274–1285
[62] C. J. Simonson, M. Salonvaara,T. Ojanen The effect of structures on indoor humidity – possibility to improve comfort and perceived air quality. Indoor Air 2002; 12: 243–251
[63] Hens, H. (1996) Modelling, Final Report, IEA ECBCS Annex 24, KU Leuven, Belgium.
[64] Simonson, C.J., Salonvaara, M. and Ojanen, T. (2001a) ImprovingIndoor Climate and Comfort with Wooden Structures, Espoo,Finland, VTT Publications, 431, 192 pages + App. 91 pages.
[65] Simonson, C.J., Salonvaara, M. and Ojanen, T. (2001b)Moisture content of indoor air and structures in buildings with vapour permeable envelopes. In: Proceedings (CD) of Performance of Exterior Envelopes of Whole Buildings VIII: Integration of BuildingEnvelopes , Clearwater Beach, Florida. ASHRAE.
[66] Simonson, C.J. and Ojanen, T. (2000) Moisture performance of buildings with, no plastic vapour retarder in cold climates.In: Seppa¨ nen, O. and Sa¨ teri, J.(eds) Proceedings of Healthy Buildings 2000, Finnish Society of Indoor Air Quality and Climate, Vol. 3, 477–482.
[67] Salonvaara, M. and Karagiozis, A. (1994)Moisture transport in building envelopes using an approximate factorization solution method. In: Gottlieb, J.and Ethier, C. (eds) Proceedings of the Second Annual Conference of the CFD Society of Canada, Toronto, Canada, June, 317–326.

[68] Salonvaara, M. and Kokko, E. (1999) Heat and Mass Transfer in Cellulose Fibre Insulation Structures Sellukuiturakenteiden la¨mmo¨ nja aineensiirtotekninen toiminta), Espoo, Finland, VTT Research Notes, 1946, ISBN 951-38-5650-X, 951- 38-5651-8, http://www.inf.vtt.fi/pdf/tiedotteet/1999/T1946.pdf (in Finnish).

[69] Salonvaara, M.H. (1998)Prediction of hygrothermal performance of building envelope parts coupled with indoor climate, ASHRAE Transactions, 104, 908–918.

[70] Talukdar P, O F. Osanyintola b, S O. Olutimayin , C J. Simonson. An experimental data set for benchmarking 1-D, transient heat and moisture transfer models of hygroscopic building materials. Part II: Experimental, numerical and analytical data. International Journal of Heat and Mass Transfer 50 (2007) 4915–4926

[71] Watt D, S. Sjöberg, P. Wahlgren. Hygrothermal performance of a light weight timber wall assembly with an exterior air barrier. Energy Procedia 78 (2015) 1419 – 1424

[72] Simo-Tagne M, R. Remond , R. Kharchi , L Bennamoun, M C Ndukwu, Y Rogaume. Modeling, numerical simulation and validation of the hygrothermal transfer through a wooden building wall in Nancy, France. Thermal Science and Engineering Progress 22 (2021) 100808

[73] Berger J, Dutykh D, Mendes N, Rysbaiuly B. A new model for simulating heat, air and moisture transport in porous building materials. International Journal of Heat and Mass Transfer 134 (2019) 1041-1060.

[74] Simo-Tagne, M.; Remond, R.; Rogaume, Y.; Zoulalian, A.; Beguide, B.Modeling of coupled heat and mass transfer during drying of tropical woods.International Journal of Thermal Sciences2016, 109, 299-308.

[75] Simo-Tagne, M.; Bennamoun, L.; Léonard, A.; Rogaume, Y. Modeling, numerical simulation and validation of a convective dryer in steady conditions: case study of tropical woods. International Journal of Modelling and Simulation 2020, 40:2, 143-161.

[76] Simo-Tagne, M.; Rémond, R.; Rogaume, Y.; Zoulalian, A.; Perré, P.Characterization of sorption behaviour and mass transfer properties of four central Africa tropical woods: ayous, sapele, frake, lotofa. Maderas. Ciencia y tecnología2016, 18(1): 207 – 226.

[77] Simo-Tagne, M.; Ndukwu, M.C.; Azese, M.N. Experimental Modelling of a Solar Dryer for Wood Fuel in Epinal (France). Modelling 2020, 1, 39-52. doi: 10.3390/modelling1010003

[78] Simo-Tagne, M. Contribution à l'étude du séchage des bois tropicaux au Cameroun : Aspects caractérisation, modélisation multi-échelle et simulation. Le cas des bois d'ayous (triplochiton scleroxylon) et d'ébène (diospyros crassiflora). PhD thesis, University of Yaoundé I (Cameroon), 2011.

[79] Mendes N. Models for prediction of heat and moisture transfer through porous building element, Thèse de Doctorat, 225, Federal University of Santa Catarina, Florianopolis, SC, Brésil, 1997 (en portugais).

[80] Le, A.D.T. 2010. Etude des transferts hygrothermiques avec et sans prise en compte de la résistance de contact dans une paroi double couche. XVIIIème Rencontres de l'AUGCAt: La Bourboule, France.

[81] Saadani R., S. Ou ben moh, M. Rahmoune, A. Sbaibi, 2015. Numerical Solutions of Luikov and Philip and De-Vries Equations of Heat and Mass Transfer in Porous Media. IJSR 4 (3) 516-520. https://www.ijsr.net/archive/v4i3/SUB152038.pdf

[82] Nitcheu M., D. Njomo, P. Meukam, C. Fotsing Talla. Modeling of Coupled Heat and Mass Transfers in a Stabilized Earthen Building Envelope with Thatched Fibers. Fibers 2018, 6, 75; doi:10.3390/fib6040075, 1-9.

[83] Perre, P.; Turner, I.W. A 3-D version of TransPore: A comprehensive heat and mass transfer computational model for simulating the drying of porous media. InternationalJournal of Heat and Mass Transfer 1999, 42, 4501–4521.

[84] Rafidiarison H.M., Etudes expérimentales des transferts de masse et de chaleur dans les parois des constructions en bois en vue de leur modélisation. Application aux économies d'énergies et au confort dans l'habitat. Doctorat thesis, Lorraine University, 204p (2012).

[85] Rafidiarison H., R. Rémond, E. Mougel.Dataset for validating 1-D heat and mass transfer models within building walls with hygroscopic materials. Building and Environment 89 (2015) 356-368. http://dx.doi.org/10.1016/j.buildenv.2015.03.008

[86] Ndukwu M. C. , · L. Bennamoun · M. Simo-Tagne · M. I. Ibeh · U. C. Abada · I. E. Ekop (2021). Influence of drying applications on wood, brick and concrete used as building materials: a review. Journal of Building Pathology and Rehabilitation (2021) 6:24. https://doi.org/10.1007/s41024-021-00119-0

[87] Busser T, Piot A, Pailha M, Rouchier S, Woloszyn M (2017) Experimental and numerical study of wood-based materials: frommaterial to room scale. Energy Procedia 132:747–752