Intermediate Master Project

Study of moisture content's impact on heat transfer according to vapour migration on porous media as a building component material

Thatchanon Samerpop

Student Number 336300

WYDZIAŁ MECHANICZNY ENERGETYKI I LOTNICTWA
POLITECHNIKA WARSZAWSKA

FACULTY OF POWER AND AERONAUTICAL ENGINEERING
WARSAW UNIVERSITY OF TECHNOLOGY

Chapter 1 Introduction

Building performance and energy efficiency are critical considerations from an engineering point of view. Many research studies are continually investigated to optimize thermal comfort, sustainability, and cost-effectiveness. One fundamental aspect of building performance is the vital role of thermal management under varying environmental conditions. It encompasses the control of heat flow within a structure, affecting both occupant comfort and energy consumption. The core of thermal management relies on thermal conductivity, which quantifies a building material's ability to conduct heat. Materials with high thermal conductivity efficiently transfer heat, while those with low conductivity act as insulators. Therefore, selecting materials based on their thermal properties is crucial to achieve the desired energy performance. However, there is one component that has a significant impact on thermal behavior, which is moisture contained by the material.

Moisture absorbed in a building's material influences its thermal properties greatly, especially in thermal conductivity and heat transport. Wet materials conduct heat differently compared to dry ones. Consequently, water vapour movement, so-called advection, interacts with heat conduction, affecting overall heat flow. Demonstration of moisture transfers significantly impacts the sensitivity of building envelopes and their latent conduction loads [1]. These moisture dynamics play a crucial role in daily indoor moisture variations. Understanding and managing this phenomenon between moisture and thermal behavior is essential as it directly and indirectly affects historical and modern buildings [2]. The practical implication of moisture management is to ensure optimal building performance, prevent other moisture-related issues, and leverage energy-efficient buildings.

Hygrothermal is the material behavior that refers to the combination of heat and moisture transfer study within the material. As this phenomenon occurs through moisture absorption, the study introduces porous media. It is essential to investigate hygrothermal properties because they affect thermal properties and performance, resulting in building energy efficiency design analyses when using porous media as a building component. According to the overlap influence of these properties, hygrothermal can be analyzed by advanced calculation methods to interpret other properties such as hygrothermal stress [2]. Moreover, classic simulation tools can predict the hygrothermal fluctuation of building material in building envelopes using the assumption of relative humidity and validation of experimental data [1].

Chapter 2 Literature Review and Theoretical Framework

1. Hygrothermal Property on Porous Media

Hygrothermal property must be studied, especially in buildings with hygroscopic materials such as bio-based porous material. To understand this phenomenon, the hysteresis model is introduced. The hysteresis effect refers to the non-linear relationship between moisture content and relative humidity during the adsorption and desorption processes. When relative humidity changes, the material's moisture content doesn't respond immediately. However, during adsorption (moisture uptake), the material retains moisture even when humidity decreases, and vice versa during desorption. It affects the hygrothermal behavior of material, such as thermal conductivity, vapour diffusion, and heat storage. Therefore, much research on mathematical and experimental approaches to this phenomenon is carried out.

Reuge et al. [3] studies utilize a theoretical background on the hygrothermal effects of bio-based multi-layered walls by conducting 1D simulations using simulation tools that assume instantaneous equilibrium between local relative humidity φ and water content w. Collet et al. [4] described the necessary properties to perform a simula0tion of hygrothermal, which are the bulk densities at dry state ρ_0, the porosities ε_0, the vapour diffusion resistance factors at dry state μ_0, the thermal conductivities at dry state λ_0 and the specific heat capacities at dry state Cp_0. The hysteresis model is accounted for its dependency on hygrothermal property and can be evaluated by experiment. Y. Mualem [5] introduced the model of moisture content in the sorption and desorption phase as follows:

$$w_{des,hys}(\varphi) = w_j - \frac{P_D}{w_s}(w_s - w_{ad}(\varphi))(w_{ad}(\varphi_j) - w_{ad}(\varphi)) \tag{1}$$

$$w_{ad,hys}(\varphi) = w_j - \frac{w_j - w_i}{(w_{ad}(\varphi_j) - w_{ad}(\varphi))}(w_{ad}(\varphi_j) - w_{ad}(\varphi)) \tag{2}$$

where w_{ad} and w_{des} are the moisture contents of adsorption and desorption isotherms for a given relative humidity. (φ_i, w_i) and (φ_j, w_j) are the minimal and maximal values of the relative humidity and moisture content in a sorption–desorption cycle. P_d is the function of pore water blockage against air entry. The model was validated by an experiment by D. Lelievre [6] in bio-based building material within a wall. and the result is roughly compatible with the relative humidity and temperature measurement for the adsorption and desorption stages. Furthermore, after fitting in with the GAB (Guggenheim-Anderson-de Boer) model, which is commonly used to describe moisture sorption isotherms by assuming both mono- and multi-layer moisture adsorption at the pore surface, the experimental data can be well described by this model. The equation is known as.

$$w = \frac{w_m\, C\, K\, \varphi}{(1 - K\varphi)(1 + K(C-1)\varphi)} \tag{3}$$

where w_m , C, and K are fitting coefficients that can be obtained experimentally.

2. Mass and Heat Transport

Moisture transport in porous media is a critical aspect of understanding the hygrothermal performance of building materials. It involves moisture movement through a material, which can occur in liquid and vapour forms. This process is influenced by temperature gradients, relative humidity, and the material's intrinsic properties, including porosity and permeability. The expression of vapour can be described by the following expression, which includes the convection term, diffusion term, and moisture content over time. [11]

$$\frac{\partial(\rho Y)}{\partial t} + \nabla(\bar{v}\rho Y) = -\nabla(\bar{g}) \tag{4}$$

$$-\nabla(\bar{g}) = \nabla(\rho D \nabla Y) \tag{5}$$

where ρ [kg/m^3] is local density. D [m^2/s] is water vapour diffusivity. Y [$kg_{moisture}/kg_{air}$] is mass fraction. $\bar{g}$ [kg/m^{2}s] is moisture diffusion flux. $\bar{v}$ [m^2/s] is velocity.

The following equations can obtain the species mass fraction of the multicomponent, which is assumed to be the ideal gas for simplification.

$$Y_i = \frac{\rho_i}{\rho} \tag{6}$$

$$\rho_i = \frac{p_i}{R_i T} \tag{7}$$

$$p_i = p_{sat}\varphi \tag{8}$$

$$p_{sat} = e^{\propto T^{-1}} + b + cT + dT^2 + eT^3 + flnT \tag{9}$$

Where Y_i, is species's mass fraction. ρ_i [kg/m^3] is the species's density. R_i [kg/m^3] is the species's gas constant. p_i and p_{sat} [kPa] are the species's partial pressure and saturated pressure, respectively. φ [%] is relative humidity.

Saturated pressure is a function of temperature and can be obtained experimentally. The value for a mixture of air and vapour between 0 -100 is calculated using the equation provided by the ASHRAE standard, shown in equation (9). a, b, c, d, e, and f are the constant.

$$a = -\,5800.2206$$

$$b = 1.3914993$$

$$c = -\,0.048640239$$

$$d = 0.41764768 \times 10^{-4}$$

$$e = -\,0.14452096 \times 10^{-7}$$

$$f = 6.5459673$$

In the case of heat transport, the phenomena are illustrated in the following expression, which includes three different phenomena regarding heat flux due to heat conduction in the porous material, a heat flux due to vapour diffusion through the porous material, and a heat flux due to liquid moisture transport.

$$\frac{\partial E}{\partial t} = \nabla(\bar{q}_h) \tag{10}$$

$$\bar{q}_h = \nabla(k_{mat}\nabla\mathrm{T} - C_{liq}\mathrm{T}\bar{g}_{liq} - (C_{vap}\mathrm{T} + \mathrm{L})\bar{g}_{vap}) \tag{11}$$

Where $\bar{q}_h$ [W/m²] is the total heat flux. E [J] is the sum of the energy stored. $k_{mat}$is thermal conductivity of material. C_{liq} and C_{vap} [J/kgK] is specific heat capacity of liquid and vapour. $\bar{g}_{liq}$ and $\bar{g}_{vap}$ [kg/m²s] is moisture diffusion flux of liquid and vapour. L is latent heat of evaporation [J/kg]

3. Effect on Heat Conductivity

Moisture content directly impacts heat conductivity because water has a significantly higher thermal conductivity than stationary air, leading to higher overall conductivity when moisture is present. The relationship between moisture content and thermal conductivity is often linear, meaning that as moisture content increases, thermal conductivity increases proportionally. Building porous materials, for example, hemp, cotton, and rice straw, have a coefficient of thermal conductivity ranging from 0.2 to 0.08 W/(mK), and their high porosity enhances moisture absorbance under high humidity conditions, resulting in a large increase in thermal conductivity. W. Zhu [7] reported that when the building materials are moistened, wet material can increase the maximum thermal conductivity ratio between the dry and wet samples by 3.51 with a maximum moisture content of 15.1% in the ambient temperature ranging from 24.9℃ to 38.6 ℃. The moisture content of a building material is calculated based on the weight of absorbed moisture to the dry weight of the material. According to the ASTM C1616, the moisture content of organic and inorganic materials by mass is calculated from the following equation:

$$w = \frac{m - m_d}{m_d} \tag{12}$$

where *w* is the moisture content [%], m_d is the mass of the dried sample [kg], and *m* is the damped sample [kg].

The impact of moisture content on materials' thermal conductivity can also be explained through the material's structure, particularly density. High material density leads to a higher solid content within the material, making thermal conductivity of the solid parts more dominant, which means thermal conductivity reaches a minimal value when considering moisture. A. Lakatos [8] study found that the thermal conductivity of polystyrene insulation decreases with increasing density in the range of 10 and 25 kg/m^3, and a linear function expressed the relationship. In hemp concrete, density affects its thermal conductivity significantly more than water content. The thermal conductivity of sprayed hemp concrete (SHC) walls is studied, and the range in density is from 374 to 416 kg/m^3, varying from 0.116 to 0.125 W/mK [9]. Based on the experiment, the linear relation between the thermal conductivity of hemp concrete and density is:

$$k = 0.4228\rho - 42.281 \tag{13}$$

When considering moisture, the moisture-dependent thermal conductivity *k(w)* is introduced [2]:

$$k(w) = k_0(1 + b\frac{w}{\rho_s}) \tag{14}$$

where $k(w)$ [W/mK] is thermal conductivity of moist building material, k_0 [W/mK] is thermal conductivity of dry building material. ρ_s [kg/m^3], is bulk density of dry building material. b [%/M.-%] is thermal conductivity supplement, and supplement b indicates how much the thermal conductivity increases per mass percent of moisture, mainly independent of bulk density.

T. Pierre [10] evaluated the thermal conductivity of hemp concrete using the transient hot-strip technique at temperatures T ranging between −3 °C and 30 °C and relative humidities (RH) ranging between 0% and 95%. Temperature and relative humidity dependence were evaluated as follows:

$$k = 0.00818 + 2.76 \times 10^{-4} T + 0.0024 w \tag{15}$$

Chapter 3 Methodology

1. Assumption

1.1 Experimental conditional Set-up

To investigate the moisture impact on porous media walls, the experiment conditions of temperature and relative humidity must be defined for both ambient and indoor conditions. This project aims to use the value of meteorological data of Warsaw for ambient environment, which varies across the year. Thermal comfort conditions represent indoor climate conditions and will be the fixed value.

Outdoor condition

- Temperature: ranges from -7°C to 37°C
- Relative Humidity: ranges from 20% to 100%

Indoor condition

- Temperature: 22°C
- Relative Humidity: 60%

1.2 Wall and material

The project aims to observe the vapour migration inside the wall. So, different types of walls with different physical properties must be defined. In addition, a one-dimension analysis of mass and heat transport is applied so that the width of the wall is assumed to be 0.1 meters.

Table 1 Physical properties of selected building materials [2]

Materials	Bulk Density [kg/m^3]	Diffusivity [m^2/s]	Thermal Conductivity [W/mK]	Thermal Conductivity Supplement [%/M%]
Hemp concrete	416	2.3e-11	0.125	4
Traditional concrete	2300	2.43e-12	1.4	8
Polyurethane foam (PUR)	80	1.00e-11	0.03	0.4

2. Mathematical Models

Based on the physical principles of heat and moisture transport, a system of differential equations can be developed to calculate the moisture behavior of building components under fluctuating natural climatic conditions. Various relevant thermophysical principles of the material are used to simulate and visualize the model to study this phenomenon

2.1 Temperature profile

Consider a solid plane wall as medium with area A [m^2], thickness L [m], and density ρ [kg/m^3]. This wall is subjected to different temperatures on both sides. Fourier's law of heat conduction is used for heat transfer through the same wall.

$$q_x = -k\frac{dT}{dx} \tag{16}$$

Assuming a steady-state condition and no internal heat generation for one-dimension heat conduction with a constant heat conductivity problem

$$0 = -k\frac{dT}{dx} \tag{17}$$

Then, the temperature distribution, *T(x),* can be expressed as

$$T(x) = C_1 x + C_2 \tag{18}$$

where C_1 and C_2 are constants to be determined by the boundary conditions, and the conditions are given.

$$T(0) = T_{in}\ at\ x = 0$$

$$T(L) = T_{out}\ at\ x = L$$

And substitute them to the general form

At x = 0; $T(0) = C_1 \times 0 + C_2 = T_{in}$

$C_2 = T_{in}$

At x = L; $T(L) = C_1 \times L + C_2 = T_{out}$

$C_1 = \dfrac{T_{out} - T_{in}}{L}$

Therefore,

$$T(x) = T_{wall} = \frac{T_{out}-T_{in}}{L}x + T_{in} \tag{19}$$

2.2 Mass and energy transport equation

Mass transport can be expressed from equation (5), neglecting the convection term and assuming a steady state for simplification. The simplified expression, which is used in the model, is described as

$$0 = \nabla(\rho D \nabla Y) \tag{20}$$

For energy transportation. It is also assumed to be a steady state, and only heat conduction is applied. The reduced form of energy equation from equation (11) expresses.

$$0 = \nabla(k_{mat} \nabla \mathrm{T}) \tag{21}$$

2.3 Boundary conditions

Predicting the interfacial transfer between air and material (boundary condition) is crucial to accurately reflect realistic scenarios regarding the migration at the material boundary. Mass and heat transfer have similar properties according to their driving force and modes of transformation (diffusion and convection). This analogy determines the distribution of species across the boundary. Three common types of boundary conditions are

1. Dirichlet Boundary Condition – a given value of species density (concentration, mass, or molar fraction) on the boundary

2. Neumann Boundary Condition – a specified species flux on the boundary

3. Cauchy Boundary Condition – a specified species flux on the boundary dependent on unknown surface density or concentration

The model uses the Dirichlet Boundary Condition because the temperature is known based on assumption, and the mass fraction at the boundary can be calculated

$$T(0) = T_{in} \ and \ T(L) = T_{out}$$

$$Y(0) = Y_{in} \ and \ Y(L) = Y_{out}$$

2.4 Moisture content inside the wall and its effects on heat conductivity

Moisture content is determined by the GAB equation, which is the function of relative humidity, and it can be calculated by

$$w_{GAB,m} = \frac{w_m \ C \ K \ \frac{p_i}{p_{sat}}}{(1 - K\frac{p_i}{p_{sat}} \ )(1 + K(C-1)\frac{p_i}{p_{sat}} \ )} \tag{22}$$

Where $w_{GAB,m}$ is mass moisture content [$kg_{moisture}/kg_{medium}$]

As the dependency of moisture content and material density on thermal conductivity is considered, the modal from H. Kuenzel [2] regarding equation (14) is applied.

$$k_{wall} = k_0(1 + b\frac{w_{GAB,v}}{\rho_s}) \tag{23}$$

Where $w_{GAB,v}$ is volumetric moisture content [$kg_{moisture}/m^3_{medium}$]

Chapter 4 Result

1. Material variation

The impact of different material properties on the heat and mass transfer in the system is explored. Several thermal and physical parameters, such as thermal conductivity k, bulk density ρ_{bulk}, water vapour diffusivity D, and thermal conductivity supplement b, are essential for accurately describing the behavior of each material under the same environmental conditions. (Inside and outside temperature is 22°C and 25°C, respectively. Inside and outside relative humidity is 0.6 and 0.5, respectively. The value of physical properties is shown in **Table 1**. Variating these properties helps to understand their effect on the vapour mole fraction distribution, relative humidity across the wall, and overall heat transfer efficiency. Moreover, the parameters for sorption curve fitting in GAB equations depend on the material, as shown in **Table 2**. The analysis considers a range of porous media for building materials, such as hemp concrete, traditional concrete, and polyurethane foam (PUR), to investigate insight into overall heat transfer as a final result.

Table 2 Fitting parameters for sorption curve of selected building material [6]

Materials	w_m	C	K
Hemp concrete	0.028	10	0.62
Traditional concrete	0.01	8.5	0.9
Polyurethane foam (PUR)	0.028	7.9	0.92

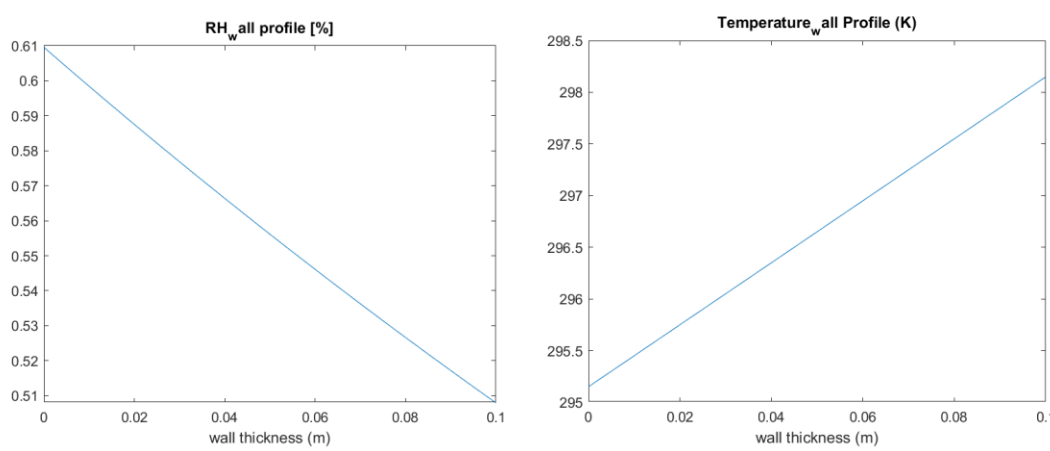

Figure 1. Relative humidity and temperature profiles of the wall of this condition

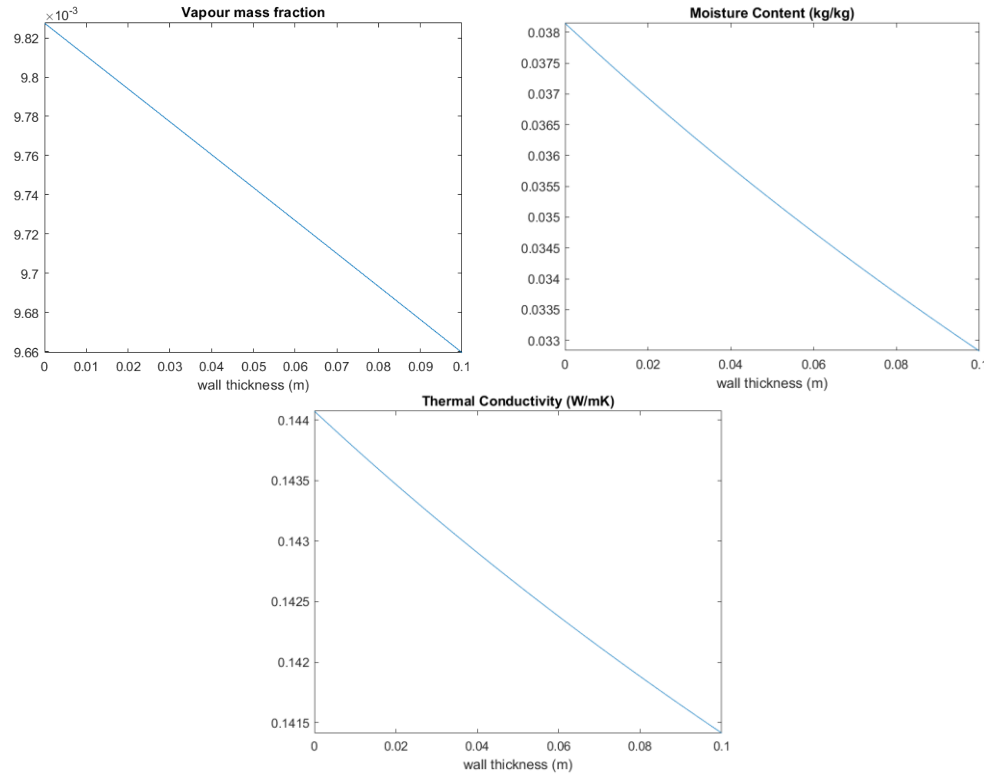

Figure 2. Vapour mass fraction, moisture content, and thermal conductivity of hemp concrete

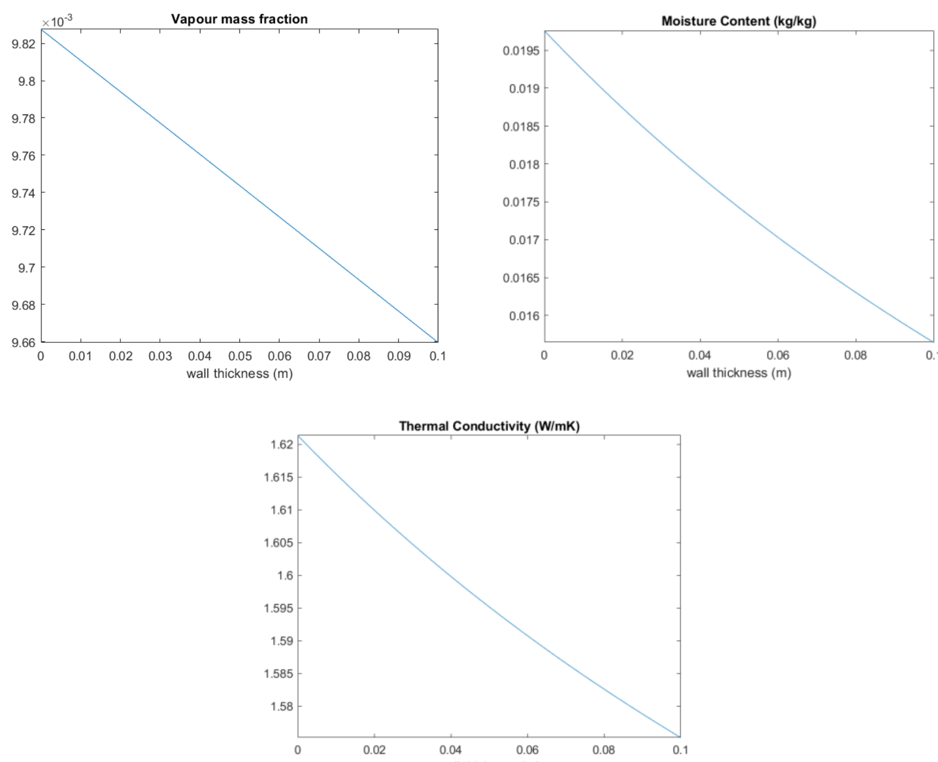

Figure 3. Vapour mass fraction, moisture content, and thermal conductivity of traditional concrete

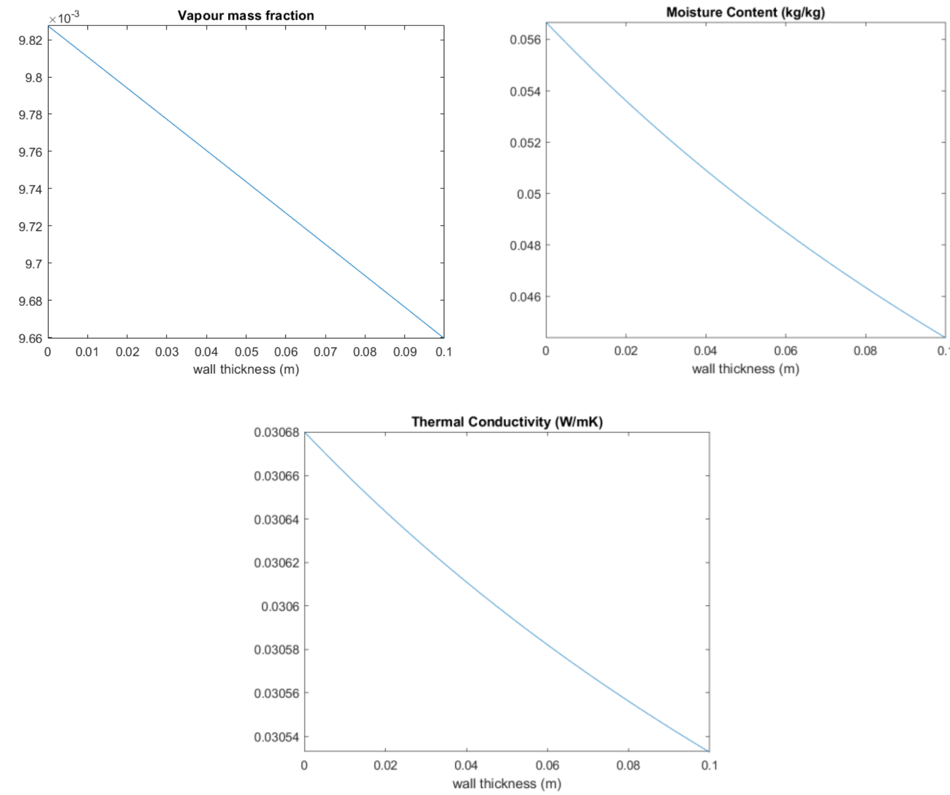

Figure 4. Vapour mass fraction, moisture content, and thermal conductivity of PUR

Table 3 Effect of moisture content on thermal conductivity and average heat transfer of each material

Materials	**Effect of moisture content [%]**	**Q_{avg} [kW]**
Hemp concrete	1.76	4.279
Traditional concrete	19.51	47.85
Polyurethane foam (PUR)	0.0596	0.9179

The vapour mass fraction of every material decreases from inside to outside according to the given boundary condition, indicating the direction of vapour migration. Moisture content, and thermal conductivity also follow the same trend. **Hemp concrete**, a moderately good insulator with an average heat transfer of approximately 4.279 kW and a moisture content effect of 1.76%, has a high moisture content of around 0.036 kg/kg, attributed to its physical properties and the capability of vapour diffusion through the material due to its porosity. **Traditional concrete**, a good conductor with an average heat transfer of 47.85 kW, has significantly poor moisture absorption at less than 0.02 kg/kg due to relatively low diffusivity, conversely showing a high effect of moisture content at 19.51%, indicating a strong dependency on moisture for its thermal. **Polyurethane foam (PUR)**, an excellent insulator with an average heat transfer of 0.9179 kW, has a very low moisture content effect of 0.0596%, minimizing the impact of moisture on heat transfer due to its low thermal conductivity. Overall, the results show the strong dependency of the thermophysical properties of different materials on mass and energy transport.

2. Temperature and Relative Humidity variation

Variation in climate conditions also impacts heat and mass transfer within the system. Temperature and humidity are critical environmental factors affecting materials' thermal performance and moisture dynamics. The model accounts for different ambient conditions, which affect the saturation pressure, vapour pressure, and, consequently, the vapour mole fraction distribution within the material. These factors influence the relative humidity across the wall and affect the heat transfer rate and moisture adsorption behavior. Properties of hemp concrete are used, and the indoor condition is fixed in this investigation

Table 4 Temperature and Relative Humidity in each case

Conditions	**T_{in} (°C)**	**φ_{in}**	**T_{out} (°C)**	**φ_{out}**
Condition I	22	0.6	25	0.5
Condition II			10	0.5
Condition III			25	1
Condition IV			10	0.8

A graphical demonstration of vapour mass fraction, moisture content, and thermal conductivity of Condition I is presented in the section "Material variation" for hemp concrete in **Figure 2**.

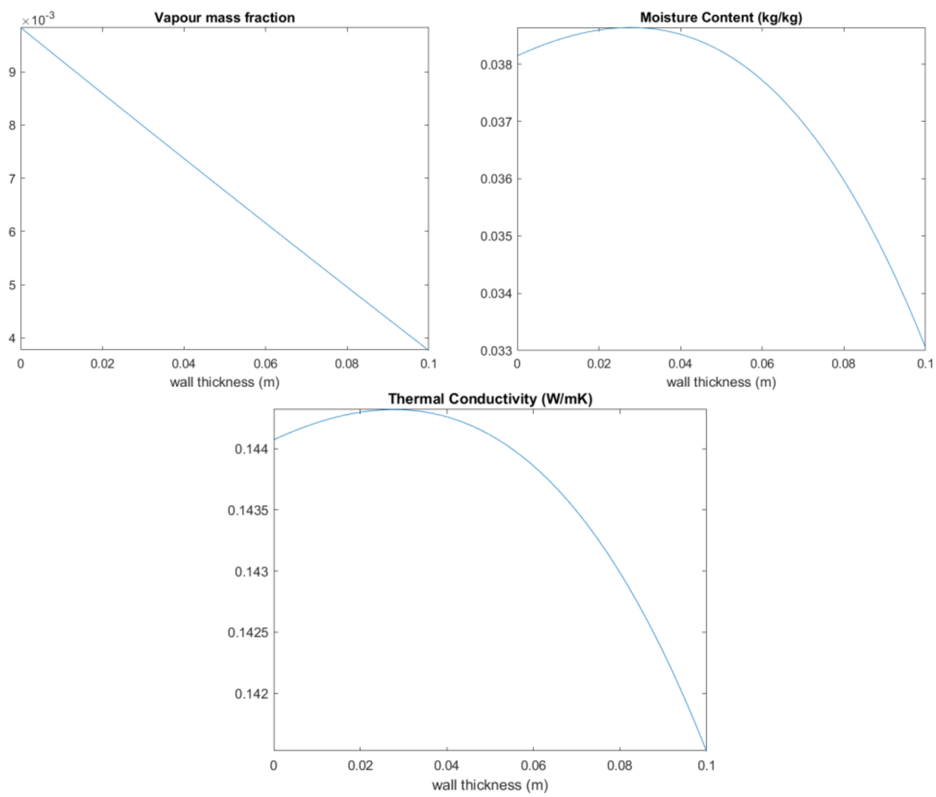

Figure 5. Vapour mass fraction, moisture content, and thermal conductivity of Condition II

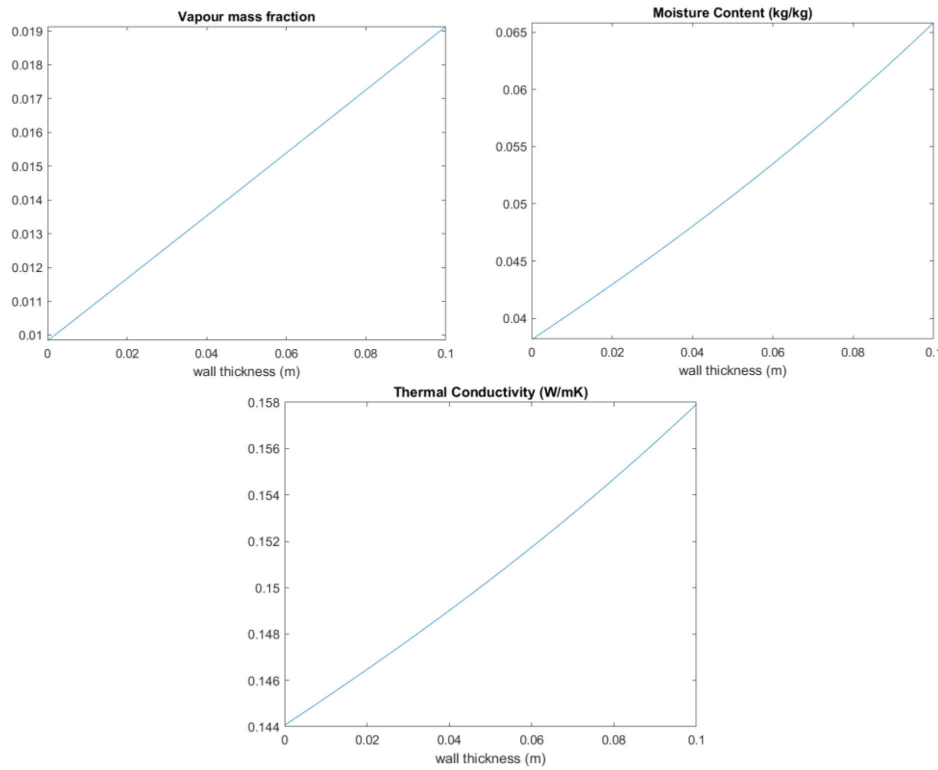

Figure 6. Vapour mass fraction, moisture content, and thermal conductivity of Condition III

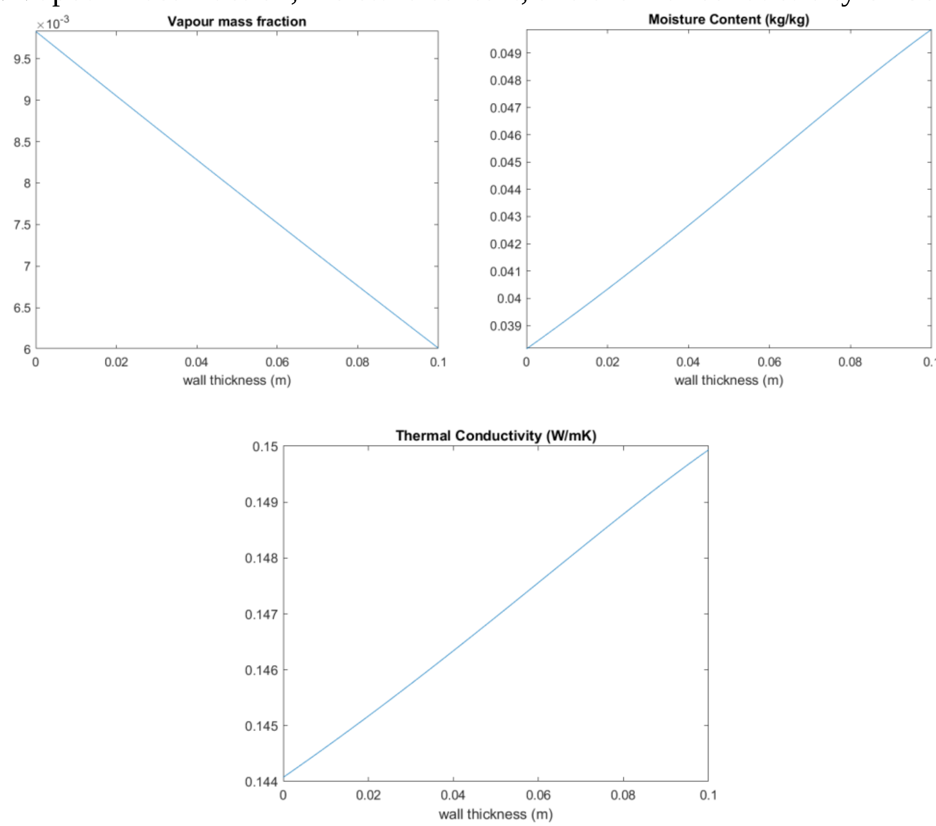

Figure 7. Vapour mass fraction, moisture content, and thermal conductivity of Condition IV

Table 5 Effect of moisture content on thermal conductivity and average heat transfer of each condition

Conditions	**Effect of moisture content (%)**	**Q_{avg} (kW)**
Condition I	1.76	4.279
Condition II	1.91	17.29
Condition III	2.54	4.511
Condition IV	2.19	17.69

Condition I is a base case in which the vapour mass fraction gradient is from the inner, where the temperature is lower but higher relative humidity, to the outer. The same behavior occurs for moisture content, indicating the vapour migration profile. Also, thermal conductivity directly relates to the moisture content in the wall, with a minimal effect of 1.76%, resulting in an average heat transfer rate of 4.279 kW. In **Condition II**, the climate intensifies the average heat transfer due to a more significant temperature difference, reaching 17.29 kW. The vapour mass fraction remains the same as Condition I, but the moisture content is non-linear, peaking at a particular depth in the wall due to the highest ratio between partial and saturated vapour, as the saturated vapour is an exponential function of temperature. **Condition III** focuses on maximizing relative humidity (RH=1) while maintaining the outside temperature at 25°C, showing an inverse result to the first case for every parameter, with a slightly higher heat transfer rate of 4.511 kW due to humidity differences and maximum impact of moisture at 2.54%. **Condition IV** examines an inverse scenario to the first one with higher RH and lower temperature outside. A contradiction between the vapour gradient and RH is observed, with vapour likely transported from low to high RH due to the higher impact of temperature dependency on vapour mass fraction compared to RH. The rising moisture content from the inside results from an exponential decrease in saturated vapour pressure. This condition maximizes the average heat transfer to 17.69%. These results show that the material's moisture absorption slightly alters the thermal conductivity at less than 3%. However, temperature differences have a more significant impact on heat transfer, consistent with Fourier's law of conduction.

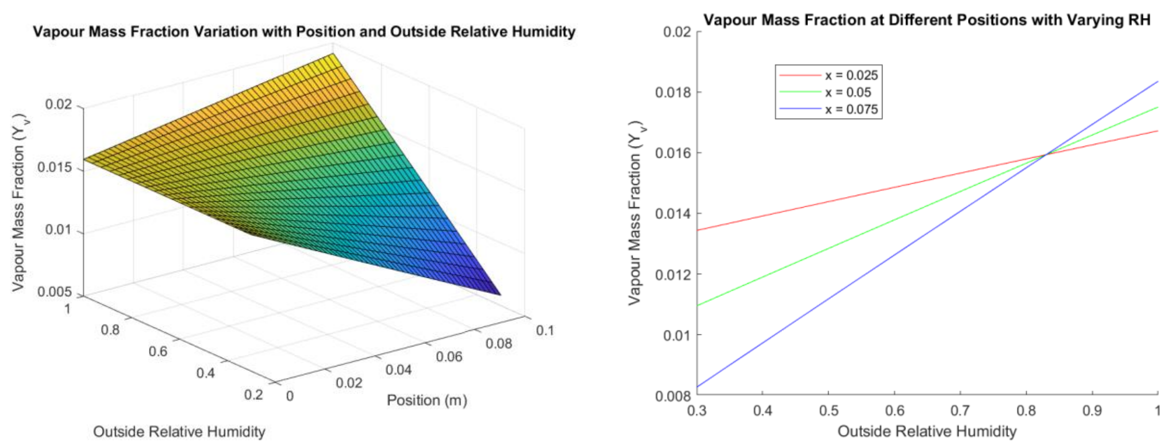

Figure 8. Vapour mass fraction profile with different positions and outside relative humidity (Left) Projection of vapour mass fraction at the specific position of the wall (Right)

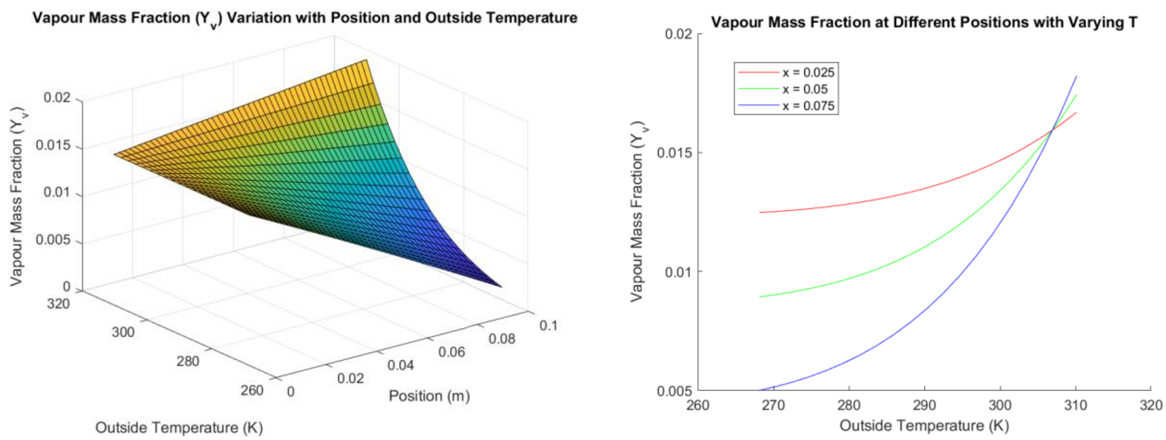

Figure 9. Vapour mass fraction profile with different positions and outside temperature (Left) Projection of vapour mass fraction at the specific position of the wall (Right)

The analysis of the vapour mass fraction variation across different positions and external conditions, as well as relative humidity and temperature, are shown in Figure 8 and Figure 9. Variations of outside relative humidity with the fixed value of temperature and inside conditions show that the linear increase suggests that the material has a consistent moisture absorption capacity throughout its thickness. The line chart shows the projection at different points of the wall positions (x = 0.025 m, 0.05 m, 0.075 m), demonstrating the vapour migrated from outside to inside, where outer RH is from around 0.8 to 1. The intersection of the graph at approximately RH equals 0.8, which represents the point where there is no transport because of identical mass fraction, and the direction is switched after lowering the outside's RH. Monitoring changes in outside temperature show the same trend as relative humidity change, but non-linear patterns are noticed because of the exponential function of the saturated pressure temperature. Vapour transport from outside where its temperature is high and inverse at the point where the temperature is lower than about 37℃. Lastly, the most significant changes occur near the outer surface, reflecting the direct impact of external temperatures and relative humidity.

Chapter 5 Conclusion and Discussion

The analysis of hemp concrete, traditional concrete, and polyurethane foam (PUR) highlights the significant impact of material properties, including thermal conductivity, bulk density, water vapour diffusivity, and thermal conductivity supplement, on heat and mass transfer within building systems. Hemp concrete demonstrates moderate insulating capabilities due to its high moisture absorption and vapour diffusion capacity, supported by its porosity and GAB fitting parameters. In contrast, traditional concrete excels in thermal conductivity, facilitating efficient heat transfer and the highest impact of moisture to thermal conductivity despite its low moisture absorption capacity due to limited diffusivity. Polyurethane foam (PUR) is an exceptional insulator with minimal moisture impact on heat transfer due to its low thermal conductivity and diffusivity. The study underscores the importance of selecting materials based on specific environmental conditions and performance objectives, as different materials exhibit varying capabilities in effectively managing heat and moisture transfer.

Investigating different climate conditions on hemp concrete reveals the complex dependency between temperature, humidity, and heat transfer dynamics. Condition I, serving as a baseline with lower temperature and higher humidity inside than outside, demonstrates minimal impact of moisture content on thermal conductivity and a moderate heat transfer rate of 4.279 kW. With an increased temperature difference, Condition II significantly drives the heat transfer rate to 17.29 kW, with a decrease in overall vapour mass fraction compared to Condition I. Condition III maximizes outside relative humidity and maintains an outside temperature, slightly dropping the heat transfer rate to 4.511 kW due to humidity differences, inverting the Condition I profile. In Condition IV, where the outside relative humidity is higher, but the temperature is lower, vapour transport tends to move from lower to higher relative humidity regions, indicating the dominant influence of temperature on vapour mass fraction over humidity. Despite these variations, the thermal conductivity is marginally affected by changes in moisture content at less than 3% because of low moisture content in the set-up conditions. The study concludes that external climate conditions, especially temperature, and relative humidity, play a crucial role in building components' thermal and moisture transport properties, affecting their overall thermal efficiency and vapour migration behavior.

Lastly, this study utilizes Dirichlet-type boundary conditions where temperature and vapour mass fraction are fixed on both sides, making it impossible to investigate actual temperature and moisture profiles. Moreover, the diffusivity of material is independent because of the calculation of this mathematical model, and only other physical properties and GAB fitting parameters affect the analysis. While Neumann and Cauchy boundary conditions are introduced, the complexity of the model and the limitations of computing power problems appear. Therefore, it is suggested that another kind of boundary condition with the model’s optimization or other analytical tools besides Matlab should be implemented in future studies to obtain a more realistic solution.

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