Mesures locales couplées de l'humidité et des transferts thermiques dans les matériaux de construction biosourcés.

Coupled local measurements of humidity and heat transfers in bio-based construction materials.

Van-Truong NGUYEN[1*], Rahima SIDI BOULENOUAR[1], Philippe COUSSOT[1].

[1] Navier, CNRS, Univ Gustave Eiffel, ENPC, Institut Polytechnique de Paris, Marne-la-Vallée, France
[*](Corresponding author: van-truong.nguyen@univ-eiffel.fr)

Résumé - Cette étude examine le transport unidimensionnel de la chaleur et de l'humidité dans un matériau modèle à base de cellulose dans des conditions limites contrôlées. Un échantillon de référence en cellulose compressée permet d'obtenir une porosité et des propriétés thermiques anisotropes reproductibles, avec des thermocouples intégrés confirmant le comportement conducteur unidimensionnel grâce à une excellente concordance avec les solutions analytiques. La migration de l'humidité est caractérisée indépendamment à l'aide de l'IRM-SPI, fournissant des profils non destructifs cohérents avec les prévisions basées sur la diffusion. Des expériences combinées capturent le refroidissement par évaporation et la redistribution interne de l'humidité, offrant des ensembles de données robustes pour valider les modèles hygrothermiques.

Abstract - This study examines one-dimensional heat and moisture transport in a model cellulose-based material under controlled boundary conditions. A compressed cellulose reference sample enables reproducible porosity and anisotropic thermal properties, with embedded thermocouples confirming 1D conductive behavior through excellent agreement with analytical solutions. Moisture migration is characterized independently using MRI-SPI, providing non-destructive profiles consistent with diffusion-based predictions. Combined experiments capture evaporation-driven cooling and internal moisture redistribution, offering robust datasets for validating hygrothermal models.

1. Introduction

The buildings and construction sector accounts for about 37% of global greenhouse-gas emissions, largely due to carbon-intensive materials such as cement and steel. Biobased materials offer a more sustainable alternative and include natural fiber assemblies and plant-based composites commonly used for insulation and wall systems. Their hygroscopic nature strongly influences mechanical performance, durability, and indoor environmental quality, as moisture interacts with cellulose through hydrogen bonding and slow bound-water diffusion. These coupled heat- and moisture-transfer mechanisms, together with sorption-related latent effects, govern their complex hygrothermal behavior.

https://doi.org/10.25855/SFT2026-129

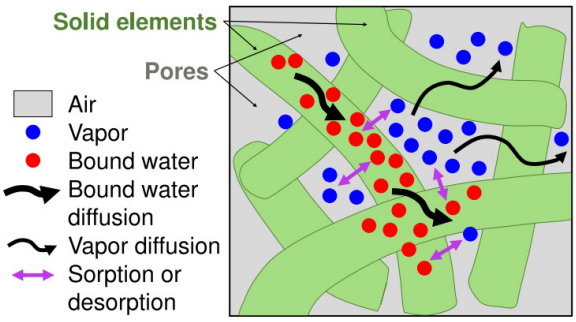

Fig. 1. *The transport of the bound water and water vapor inside the fiber stack [2].*

The hygrothermal response of biobased construction and textile materials is strongly influenced by environmental conditions such as temperature, relative humidity, airflow, and liquid-water exposure. Their moisture-related behavior arises from the ability of cellulose-based constituents to absorb water vapor through hydrogen bonding. At the nanoscale, bound water consists of molecules tightly adsorbed onto fibers and diffusing slowly within the solid matrix; this confined water is extremely difficult to track experimentally, as it resides within the solid structure rather than in the pore space (Fig. 1). These mechanisms, together with the latent heat effects associated with sorption and desorption, govern the complex hygrothermal behavior of such materials and must be understood to predict energy performance [5]. To rigorously evaluate and improve hygrothermal models, it is essential to impose simple, well-controlled heat and moisture fluxes and monitor the material response under one-dimensional (1D) transfer conditions. In this configuration, transport occurs predominantly along a single direction, enabling reliable tracking of temperature and moisture evolution and closely reflecting real building walls with large aspect ratios and nearly uniform boundary conditions. Achieving such conditions requires using samples with small thickness relative to their lateral dimensions and applying uniform boundary conditions on the upper and lower surfaces [8], which minimizes lateral heat losses, particularly important for low-conductivity insulating materials.

This work is organized into three parts. The first section presents the preparation of the cellulose reference sample and the setup ensuring one-dimensional heat and moisture fluxes. The second section characterizes heat transfer and moisture migration separately to validate analytical and diffusion-based predictions. The final section combines both measurements to analyze coupled hygrothermal behavior during simultaneous drying and cooling, providing a dataset suitable for evaluating hygrothermal models in bio-based materials.

2. Material and methodology.

We use a reference material composed of highly pure cellulose fibers (99.5%, Arbocel BC200, Kremer Pigmente). These strip-like fibers exhibit an average thickness of approximately 1 µm, a width of about 20 µm, and an average length of 300 µm. The fiber stack is first conditioned in a desiccator filled with water to establish a relative humidity of 100%. Under these conditions, the cellulose absorbs water vapor from the environment, primarily in the form of bound water. After sufficient time for saturation, the fibers are removed and compressed in a PMMA mold to obtain the desired sample geometry, typically a cylinder 7 cm in diameter and 2 cm in thickness (this size was optimized in [7]). During this step, performed under ambient conditions, the porosity (void to total volume ratio) is determined from the sample volume at the moment of compression. Van der Waals interactions between fibers ensure cohesion, allowing the compressed material to behave as a self-supporting solid.

An impermeable Teflon layer, less than 1 mm thick, is applied to the bottom and surrounding surfaces of the sample to prevent moisture exchange while having negligible influence on heat transfer. The sample is then returned to the desiccator, which is placed inside an oven to impose a uniform thermal field. This procedure ensures that the sample reaches a well-defined initial state combining both moisture and temperature. To minimize heat losses from the sample edges during the experiment, a polyurethane (PU) foam mold is used as thermal insulation (Fig. 2a). This insulating component is also pre-conditioned in the oven to match the initial temperature of the cellulose sample. At the start of the experiment, the sample is rapidly transferred into the PU mold, and a dry air flux (through a tube system staying around 3cm above) is applied to its upper free surface. Under these conditions, convection, drying, and cooling occur simultaneously.

Temperature within the sample is monitored using thermocouples inserted into pre-drilled holes formed during compression (Fig. 2b), while the mass is recorded continuously using a balance. Together, these measurements provide simultaneous insight into both heat and moisture transfer processes throughout the experiment.

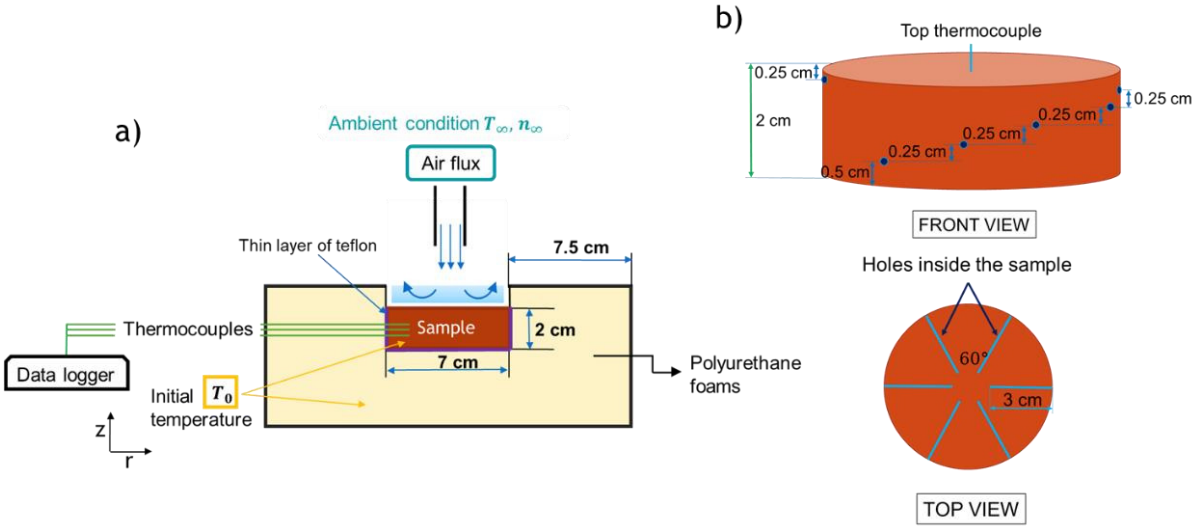

Fig. 2. *a) The experimental setup of heat and mass transfer; b) the arrangement of the thermocouples.*

3. The measurement of the temperature.

Temperature variations inside the sample were monitored in real time using thermocouples, as described in [7]. An illustrative example is provided, like the setup in Fig. 2a, but without the thin Teflon layer, and the sample is totally dry based on the preparation step, which shows the evolution of temperature during the cooling process. It is important to note that the setup corresponds to a simple cooling experiment performed on a dry sample, where the influence of moisture was deliberately excluded. This configuration isolates the thermal response of the material and enables a clearer understanding of the fundamental heat transfer dynamics in the absence of water [7].

The temporal temperature distribution reveals the progression of the cooling front. Under the effect of the cool, dry air flux applied to the exposed surface, the upper layer of the sample consistently begins to cool first. As heat is lost at the surface, a thermal gradient develops between the outer and inner regions. Over time, heat diffuses from the warmer core toward the cooler surface, following the natural direction of the temperature gradient. This behavior highlights the predominance of conductive heat transfer during the cooling phase, particularly

in the absence of evaporation or moisture transport. Based on the origin of the heat transfer equation, the diffusion of heat inside the sample can be expressed:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \tag{1}$$

And when in the boundary layer, when we impose the air flux, in between the interface, based on the thermal conductivity of the sample k_s and the thermal conductivity of air, k_a, the condition can be written:

$$-k_s \frac{\partial T}{\partial z} = -\frac{k_a}{\delta_t}\left(T_\infty - T\right) \tag{2}$$

In which δ is the thermal boundary layer thickness, and it depends on the air flow properties. And the internal heat transfer of the sample can be described by the association of the boundary layer and the thermal conductivity of the sample [7], written:

$$\frac{T - T_0}{T_\infty - T_0} = 1 - \sum_{n=1}^{\infty} \frac{2L\cos(\frac{\beta_n z}{l})\exp(-\frac{\beta_n^2 \alpha t}{l^2})}{(\beta_n^2 + L^2 + L)\cos\beta_n} \tag{3}$$

In which T is the temperature at time t, T_0 is the initial temperature, T_∞ is the temperature at the end of the process, l is the sample height, z is the position of the thermocouple, L is a parameter depending on material properties and experimental conditions $L = lh / k_z$ and $\{\beta_n\}_{n=1,2,...}$ are the positive roots of $\beta_n \tan\beta_n = L$. h is the convective heat transfer coefficient. And one important parameter is the thermal diffusivity $\alpha = k_z / \langle \rho C_p \rangle$, which corresponds directly to the thermal conductivity of the sample k, here we use k_z because the thermal conductivity in the vertical direction (from the top to the bottom of the sample) differs from that in the radial directions. Specifically, we observed that $k_z \neq k_x$ or k_y, with the radial conductivity (k_x or k_y) being approximately twice the value of k_z [6]. This anisotropy is highly relevant for hygrothermal behavior, as it originates from the preferential orientation of the fiber network induced by the compression process used during sample preparation. In this case, with a higher thermal conductivity in the radial direction, somewhat amplified by the presence of the thermocouples, the heat flux is slightly disturbed. However, because heat losses through the edges were minimized, the system ultimately behaves very close to a one-dimensional transfer [7].

In the case of measuring the temperature alone, we achieve a good agreement between the experiment and the solution (Fig. 3), which strengthens our hypothesis about our technique to get the transfer like a real hygrothermal wall.

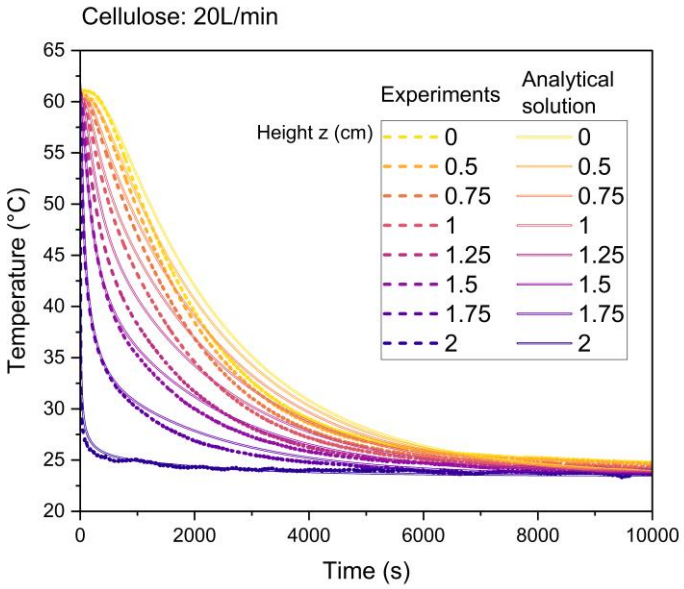

Fig. 3. *Comparison between the experiment and the analytical solution for the temperature distribution of the cooling of the cellulose sample with an initial temperature of 60°C and the air flux rate of 20L/min.*

4. Measuring the moisture.

Another important point of hygrothermal performance is the behavior of the moisture content. To isolate and characterize moisture migration within the material, we employed the experimental setup shown in Fig. 2a, but without the PU Foam part (mainly it is in the ambient condition, there is no effect of temperature), combined with using Magnetic Resonance Imaging (MRI), a non-destructive technique that enables visualization of the internal distribution of water molecules.

Initially, the sample was prepared to be fully saturated with bound water. The cellulose fibers were first conditioned in a desiccator at 100% relative humidity (RH), and the saturated material was then shaped using the compression machine. After the compression step, we verified that the sample remained close to saturation in bound water by weighing it. Moreover, we then placed it in a desiccator at 100% relative humidity to ensure that the initial state of the test corresponded to full moisture saturation. A dry air flux was subsequently applied to the top surface of the sample (Fig. 2), while its mass was continuously recorded using a balance. This procedure corresponds to a drying test conducted at ambient temperature, under the assumption that temperature effects on the measurement are negligible. So the mass that was recorded by the balance can be converted into the saturation of the sample. At the same time, with the MRI, specifically, we employed the Single Point Imaging (SPI) sequence, which is well-suited for observing low-mobility water in porous or dense materials like cellulose [4]. The experimental setup remained the same, as illustrated in Fig. 4, with the addition that the entire assembly was suspended inside the MRI scanner.

A diffusion equation can explain the diffusion of the moisture inside the sample:

$$\frac{\partial s}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial s}{\partial z} \right) \tag{4}$$

With s is the moisture content of the sample. Note that moisture content and relative humidity n have a connection due to the sorption-desorption curve [8]. In the real situation, there are two terms of the water phase transfer inside the sample: the vapor, which is transported inside the pore, and the bound water transport within the solid matrix of the fiber (mainly described in Fig. 1). Following that, the diffusion coefficient D can be expressed by [8]:

$$D = \frac{1}{1-\varepsilon}\left[D_b + \frac{1}{a}\frac{\rho_0 D_v}{\rho_s} \right] \tag{5}$$

Which ε is the porosity of the sample, D_b and D_v are the diffusion coefficients of the bound water and vapor; these parameters depend on the porosity of the sample [8], $a = \partial f / \partial n$ is the slope of the sorption curve, ρ_0 and ρ_s is the density of the water vapor and dry cellulose. Based on the diffusion inside the sample, and combined with the flux at the surface of contact between the sample and the air:

$$J = \frac{\rho_0 D_0}{\delta} n_s \tag{6}$$

In which δ is the boundary layer thickness, and it depends on the airflow properties.

We got a good agreement between the prediction by the theory of diffusion, the condition on the boundary layer, and the experiment under the measurement of the MRI (Fig. 4). The results show the effect of porosity on the diffusion coefficient and the effect of different transport types for the migration of water. In Fig.4, the lower saturation near the bottom edge is a technical artefact, not a real loss of water. In that region, the MRI records a weaker signal, likely due to setup effects such as the hanging system or other geometric interferences, so the apparent decrease reflects measurement limitations rather than an actual reduction in moisture content.

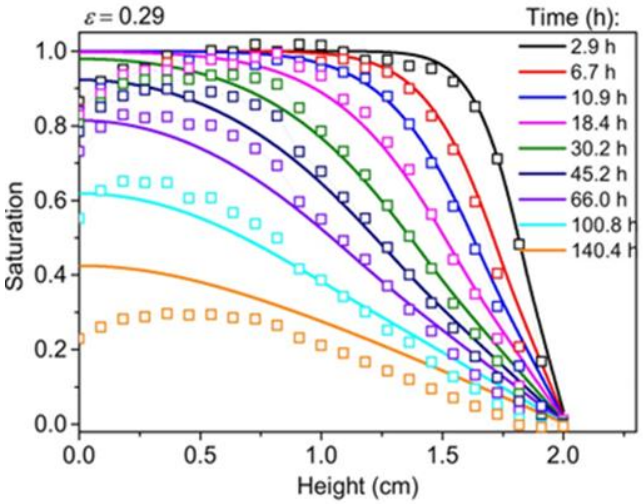

Fig. 4. *Boundwater distribution over time in compressed cellulose sample based on the MRI signal [8].*

5. Coupling of heat and moisture measurement.

By combining 2 different approaches above, we can be clear that we can bring a way to capture the heat and moisture of the sample at the same time (exactly the case in Fig. 2). This combined process introduces an additional layer of complexity, as both heat and mass transfer must be considered. In such cases, moisture evaporation from the surface contributes to the

overall cooling effect, modifying the temperature profile over time. Figure 4a presents this coupled phenomenon, showing the temperature evolution in a moist sample undergoing simultaneous drying and cooling.

Inside the sample, heat is transported primarily by conduction, while moisture transport arises from the diffusion of bound water through the solid fiber matrix and the movement of water vapor through the pore network. A theoretical analysis can therefore describe how these mechanisms interact and become coupled during hygrothermal transfer [2]:

$$(1-\varepsilon)\rho_s a \frac{\partial n}{\partial t} = \nabla \cdot \left(\rho_s D_b a \nabla n\right) + \nabla \cdot \left(D_v \nabla \rho_v\right) \tag{7}$$

$$(\rho C_p)\frac{\partial T}{\partial t} = \nabla \cdot \left(k \nabla T\right) + L_{bv} \nabla \cdot \left(D_v \nabla \rho_v\right) \tag{8}$$

The term L_{bv} is the latent heat, which plays an important role in heat and mass coupling transfer. In such cases, moisture evaporation from the surface, but also the desorption process inside the sample, contribute to an overall cooling effect, potentially decreasing the temperature profile by several degrees. Our current preliminary tests in that field already show this effect, but the full coupled experiments and comparison with simulations using the above complete model are in progress in our group. By comparing the moisture profiles obtained through MRI [8] with results from laboratory-based thermal measurements [7], we will be able to better understand the interaction between heat and mass transfer processes and validate the consistency between temperature evolution and internal moisture migration.

6. Conclusions and perspectives.

This study established an experimental frame for validating a one-dimensional heat and mass transfer - coupled hygrothermal - model for bio-based materials. While the model captures the main physical trends, the full study of couplings is still ongoing. In particular, we still have to take into account possible parameter changes during the test, such as the evolution of porosity and thermal conductivity. Future work will focus on improving the experimental setup, integrating these evolving properties into the coupled formulation, and validating the approach across a broader range of materials and conditions. These developments will ultimately lead to a more reliable framework for analyzing hygrothermal behavior and optimizing insulating materials in practice.

References

[1] *Francesco Asdrubali, Francesco D'Alessandro, and Samuele Schiavoni. 2015. A review of unconventional sustainable building insulation materials. Sustainable Materials and Technologies 4: 1–17.*

[2] *Nicolas Daunais, Yuliang Zou, and Philippe Coussot. 2026. A physical approach to the modeling of hygrothermal transfers in bio-based construction and textile materials. International Journal of Heat and Mass Transfer 256: 127973.*

[3] *U. N. Environment. 2023. Building Materials And The Climate: Constructing A New Future | UNEP - UN Environment Programme. Retrieved December 16, 2025 from https://www.unep.org/resources/report/building-materials-and-climate-constructing-new-future.*

[4] *Jörg Kärger and Wilfried Heink. 1983. The propagator representation of molecular transport in microporous crystallites. Journal of Magnetic Resonance (1969) 51, 1: 1–7.*

[5] *Hartwig M. Künzel. 1995. Simultaneous heat and moisture transport in building components: one- and two-dimensional calculation using simple parameters. IRB Verlag, Stuttgart*.

[6] *K. Mourda, Y. Zou, V.T. Nguyen, and P. Coussot. 2025. Enhancing the accuracy of thermal conductivity measurements with insulating construction materials: Addressing edge effects and methodological improvements. Journal of Building Engineering 109: 112996*.

[7] *V.T. Nguyen, Y. Zou, K. Mourda, R. Sidi-Boulenouar, and P. Coussot. 2026. Realization of one-dimensional heat transfer for the study of hygrothermal behavior of insulating material samples. International Journal of Thermal Sciences 222: 110490*.

[8] *Yuliang Zou, Benjamin Maillet, Laurent Brochard, and Philippe Coussot. 2023. Unveiling moisture transport mechanisms in cellulosic materials: Vapor vs. bound water. PNAS Nexus 3, 1: pgad450*.