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Transient hygrothermal behaviour of Lime-Hemp Materials

Thèse présentée en vue de l'obtention
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1 Introduction

1.1 Social and environmental context

« Environment and development are not separate challenges; they are inexorably linked. Development cannot subsist upon a deteriorating environmental resource base; the environment cannot be protected when growth leaves out of account the costs of environmental destruction. These problems cannot be treated separately by fragmented institutions and policies. They are linked in a complex system of cause and effect. »¹

Since the middle of the 20th century, the earth can be seen as an organism whose health depends on the health of all its parts. Human activities have an impact on the environment with potentially serious consequences on earth ecosystems, locally as well as globally: air and water quality, natural biodiversity, social equity... We have entered in a new era of development, but a tremendous effort for a truly sustainable development is still needed.

Energy consumption is one of the major factors of influence of these human disturbances and 30-40% of all primary energy used worldwide is in buildings. In developing countries, the share of the residential sector can be over 90%, but the energy consumption in non-residential buildings, such as offices, public buildings and hospitals, is also significant². As presented in Fig.1, the Walloon Region has a high level of energy consumption and carbon dioxide emission³. Walloon people are responsible of one third of national consumption in their housing and transport.

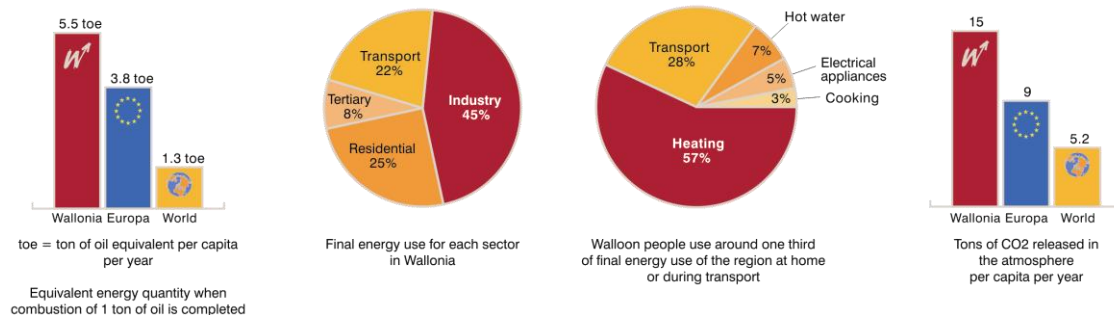


Figure 1 : PMDE, Walloon Region publication, 2003

A few years ago, the European commission edited a new directive 2002-91-EC on Energy Performances of Buildings (EPBD). It will introduce accepted measurements of relative energy performance, regular inspections and re-evaluations, higher standards for upgrading larger buildings (>1000m²), and improved standards for new buildings. This directive needs to be transposed into Member State law, it confines itself to the minimum required in order to achieve those objectives and does not go beyond what is necessary for that purpose.

¹ Our common future, Brundtland Report, 1987

² Building and Climate Change : Status, Challenges and opportunities, UNEP publication, 2007

³ PMDE – Plan pour la maîtrise durable de l’Energie, Walloon Region publication, 2003

Denmark chose to go further when voting Danish Act no. 585⁴, which requires that all buildings “consisting of a construction with a roof and outer walls and in which energy is used to regulate indoor climate” must receive an “energy labelling”. Labelling is a powerful tool to reduce global energy use of building sector. Sometimes called “Energy Performance Certification - EPC”, different label types, presented in Fig.2, were studied in Belgium and Germany⁵.

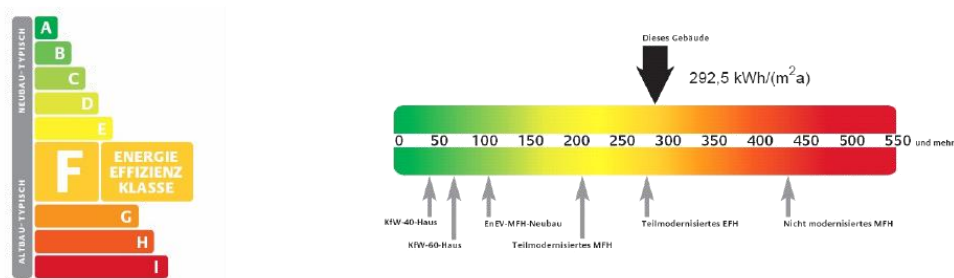


Figure 2 : Energy Performance Certification: stepped label (left) and colour band strip (right)

“Passive House” is another labelling going beyond EPBD, where an air tightness criteria ($n_{50} < 0,6 \text{ h}^{-1}$) is introduced beside strong limitation of energy demand (heating demand $< 15 \text{ kWh.m}^{-2}.\text{year}^{-1}$ and primary energy use $< 120 \text{ kWh.m}^{-2}.\text{year}^{-1}$).

Beside its energy use, the building and construction sector is considered to be a key sector for sustainable development⁶. It generates substantial social and economic benefits to society, and typically provides 5-10% of employment at the national level and normally generates 5-15% of gross domestic product (GDP). It may also have serious negative impacts on environment: greenhouse gas (GHG) emission, use of natural resources, waste generation, transport of building materials, impact on health, etc. Energy efficiency of the building sector thus offers the largest potential to contribute to sustainable development.

The European Commission’s recent package of proposals on climate and energy presents new aims for 2020 (compared to 1990): 20% less energy consumption, 20% of energy coming from Renewable Energy Source (RES), and reducing GHG emission by 20%. Together with European Commission’s Green Paper, these proposals may contribute to define the background for a “new industrial revolution”⁷. This revolution should start with the building sector.

⁴ Act to promote Energy Savings in Buildings, Danish Act no. 585 of 24th June 2005

⁵ Cross country evaluation of energy performance certification, IMPACT (Improving energy performance assessment and certification schemes by tests), 2006

⁶ *Building and Climate Change : Status, Challenges and opportunities*, UNEP publication, 2007

⁷ *Green Paper - A European Strategy for Sustainable, Competitive and Secure Energy*, Commission of the European Communities, 2006

1.1. Scientific context

Building physics is defined by Hugo Hens as an “applied science that studies the hygrothermal, acoustical and light-related properties of building components (roofs, façades, windows, partition walls, etc.), rooms, buildings and building assemblies”⁸. Many aspects of this field of research can still be seen as relatively young. Literature analysis shows a constant evolution in modelling hygrothermal behaviour of buildings since the first energy crisis of 1973, and especially during the last decade. The societal pressure to lower energy consumption and to reduce environmental impact, without degrading comfort or usability, leads to major improvements in the tools used to quantify envelopes and buildings performances, especially in terms of Heat, Air and Moisture transfer (HAM).

Main results of the last decades were gathered in the work of the International Energy Agency (IEA): Annex 14 "Condensation and Energy" (1991)⁹, Annex 24 "Heat, Air and Moisture Transfer in Insulated Envelope Parts" (1996)¹⁰ and Annex 41 "Whole building Heat, Air Moisture Response" (ends on 31/12/08). Much research was also achieved in Fraunhofer-IBP (Germany)¹¹, Technical University of Denmark¹², Lund University (Sweden)¹³, Technical University of Norway, Dresden University of Technology (Germany), Katholieke Universiteit Leuven (Belgium), Institute for research in Construction (Canada), etc.

Nowadays, HAM transfers are no longer limited to case-studies in permanent transfer. Behaviour of building components under natural climate are analysed with dynamic software. Transient response of components, on thermal, moisture or air flow points of view, give realistic results that help designers to optimize the performances of the buildings they design. Nevertheless, the scientific community believes that an accurate global performance analysis is still not possible. A universal linkage between heat, air and moisture storage and transfer which takes into consideration durability is missing. Sound knowledge of occurring phenomena in open-porous materials is thus still based on the triumvirate of simulation / testing / practice.

⁸ *Building Physics – Heat, Air and Moisture*, Hugo Hens, ed. Ernst & Sohn, 2007

⁹ *Condensation and Energy*, International Energy Agency, Annex 14, 1991

¹⁰ *Heat, Air and Moisture Transfer in Insulated Envelope Parts*, IEA, Annex 24, 1996

¹¹ *Simultaneous Heat and Moisture Transport in Building Component: One- and Two-dimensional calculation using simple parameters*, H.M. Künzeli, thesis at Fraunhofer-IBP, Stuttgart, 1995

¹² *Combined Heat Air and Moisture transfer in building constructions*, Carsten Rode Pedersen, PhD thesis at Technical University of Denmark, 1990

¹³ *Retarded sorption in wood – Experimental study, analysis and modelling*, Håkan Håkansson, Lund Institute of Technology, Department of Building Science, 1998

1.2 Lime-Hemp Material (LHM)

Mixing wood or other organic components to lighten any type of concrete is not a brand new idea. Earth and straw were mixed almost all over the world, linen shivs were added for a long time in lime plaster to allow thicker layer and increases thermal performances. In 1994, the European Commission published a report on industrial fibre crop¹⁴ which foresaw a great development of this kind of "Inorganic Matrix Composite". A few years before, hemp particles were first used in France with cement binder. Other experiments were made with hydraulic lime binders or binder including gypsum. Very few decisive results were obtained until lime based binders were used (even when hemp particles were coated with boron salt).

Environmental qualities of LHM start with the specificity of hemp culture. Hemp may be one of the first harvested plants. In Belgium, it is sowed around May and harvested around September. During this relatively short period, one hectare produces approximately 8 to 10 tonnes of dry matter, usually without any herbicides or pesticides and on a wide range of soil. It fits perfectly with organic production, but can also be grown via conventional agriculture. A general synthesis on industrial hemp was published in French in 2006¹⁵.

Hydrated lime (calcium hydroxide - $\text{Ca}(\text{OH})_2$) binder was used since the very early age of architecture all over the world. Limestone (CaCO_3) is cooked around 900°C to first give quicklime which has to be slaked with water to give calcium hydroxide used in building. Carbonation will slowly change it back to limestone. Besides its interesting life cycle, the two main qualities of lime mortar in building are their flexibility, allowing slight distortion without cracking, and their specific open-porosity resulting in good permeability for vapour but not for liquid water. As with hemp, lime binder can be produced in many countries around Earth.

A partial Life Cycle Assessment (LCA) of LHM-wall component was published in France in 2006¹⁶. This LCA was not validated in the critical review of *Ecobilan* but it appears that the main environmental quality of this building technique is probably its carbon dioxide sequestering. LHM's also have low embodied energy, and it is easy to recycle if the component has to be destroyed. Another quality is the possibility to use it either in new or in renovated buildings.

In 2002, an important synthesis of laboratory experiments made on LHM was generated¹⁷. It gathered what was considered as the "state of the art". Specific multiple porosity, beside high hygroscopic and capillary transfers, was pointed out and four mixtures defined in previous researches were described. The name of these mixtures is linked with the use they will fulfil: to build a "wall", to cover a "floor", to insulate a "roof" or to make "plaster" or "render" (see Fig. 3).

¹⁴ *Industrial Fibre Crops*, European Commission report, 1994

¹⁵ *Le chanvre industriel : Production et utilisation*, P. Boulloc et al., ed. France Agricole, 2006

¹⁶ *Etude des caractéristiques environnementales du chanvre par l'analyse de son cycle de vie*, Ministère de l'agriculture et de la pêche, France, 2006

¹⁷ *Bétons de chanvre - Synthèse des propriétés physiques*, A. Evrard, Construire en Chanvre, France, 2002

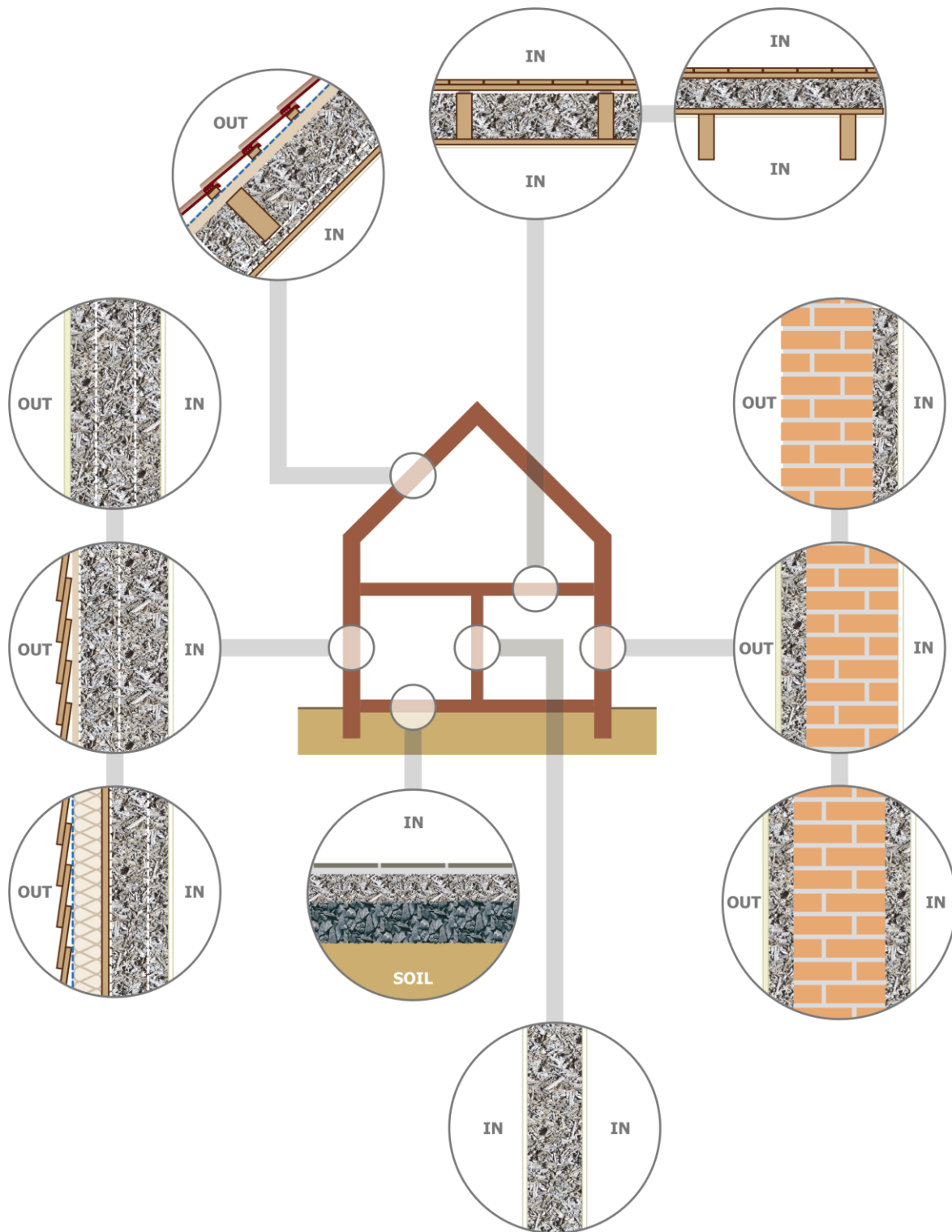


Figure 3 : Numerous uses in buildings depending on the mixture

Literature analysis started in 2002 and was extended during the present work. It appeared that many classical measurements - mechanical behaviour, thermal conductivity and acoustical absorption - were performed on this material. The four mixtures obtained with pre-formulated lime Tradical pf 70[®] and Chanvribat[®] hemp chips were analysed in France^{18,19}, and Switzerland²⁰. In addition, two other research projects, one in France²¹ and the other in England²², were performed on experimental buildings. Acoustic absorption, sound transmission, fire, frost or fungi resistance were not analysed for complete building elements, but some values can be found in literature for LHM-wall mixture. Moisture sorption, vapour or liquid transfer, and moisture related evolution of parameters were barely discussed.

Mechanical properties of LHM are too low to consider it as a structural material²³. Mechanical resistance is 0,5 to 1 MPa (it is ~5 MPa for cellular concrete and can be over ~100 MPa for cement concrete). Young's modulus range from 0,05 up to 0,1 GPa (it is ~30 GPa for cement concrete and ~3 GPa for polystyrene). The samples were dried under laboratory conditions during more than 1 year. Improving these two parameters could reduce thermal performances. LHM-wall has to be associated with a separate structure with sufficient weight-bearing capacity. Many practitioners think that LHM-wall around a timber frame structure improves its stability by reducing buckling length or by contributing to wind or global bracing. No results on structural strengthening of these covered structures could be found in literature.

Thermal conductivity (see §3.2.2.3, §5.4 and §6.5) of LHM ranges from 0,06 to 0,18 W.m⁻¹.K⁻¹ (in laboratory conditions ~50% RH and 20°C) depending on the density. LHM-wall (density of ~400 kg.m⁻³, see §5.1 and §6.3) should have a dry thermal conductivity of 0,9 W.m⁻¹.K⁻¹, rising to 0,11 W.m⁻¹.K⁻¹ at 50% of RH. Dry thermal conductivity of cellular concrete is similar, ~0,12 W.m⁻¹.K⁻¹, and it is ~0,04 W.m⁻¹.K⁻¹ for mineral wool. It appears that thermal conductivity of LHM-wall is not very low, and if only this parameter is taken into account, thermal performance of this material is relatively low. BRE (GB) report gives the following interesting results²⁴: "calculations suggest that the hemp houses (...) should be using significantly more energy than the brick houses and this is not the case" and the monitoring showed that the temperatures were "very similar in both the hemp house and the traditional houses although the hemp houses maintain marginally higher temperatures (one or two degrees)". Thermographic inspection

¹⁸ *Qualification physique des matériaux de construction à base de chanvre*, L.Arnaud and V.Cérézo, Final report, ETPE, France, 2001

¹⁹ *Propriétés mécaniques, thermique et acoustiques d'un matériau à base de particules végétales : approche expérimentale et modélisation théorique*, V. Cerezo, Ph.D. thesis at ENTPE, France, 2005

²⁰ *Utilisation du chanvre pour la préfabrication d'éléments de construction*, P-Y. Butschi, Ph.D. thesis at Université de Moncton, Canada, 2003.

²¹ *Utilisation des matériaux renouvelables en parois de maison individuelles à ossature bois*, Alain Grelat, Final report CEBTP, France, 2005

²² *Final report Final Report on the construction of the Hemp Houses at Haverhill, Suffolk*, Dr. Tim Yates, BRE, 2002

²³ *Propriétés mécaniques, thermique et acoustiques d'un matériau à base de particules végétales : approche expérimentale et modélisation théorique*, V. Cerezo, Ph.D. thesis at ENTPE, France, 2005

²⁴ *Final report Final Report on the construction of the Hemp Houses at Haverhill, Suffolk*, Dr. Tim Yates, BRE, 2002

of the masonry and hemp house²⁵ showed that outside surface temperature of the hemp house was lower than the masonry house by approximately 4°C to 6°C. BRE concludes that external walls of the hemp house retain more heat than those of the traditionally built masonry house. The difference between theoretical calculation and experimental measurements still has no scientific explanation but is largely confirmed by LHM-building users.

Beside material characterisation, it has to be noted that different building techniques are developing in parallel: on site shuttering, spraying, and assembling prefabricated elements. Each of them has its advantages and disadvantages. If shuttering needs almost no equipment, implementation and drying time can be long. Spraying is fast, but needs large building to be profitable. Drying time is supposed to be reduced with this technique but was actually never measured. Prefabricated elements (blocks or panels) are hard to produce but should develop in future as they are dry and fast to build with. In 2004, execution rules were published in France²⁶. These rules are temporarily validated and are already used to cope with the insurability of buildings.

2 Objectives and methodology

The present work is based on a thorough literature review of the domain to gather available hygrothermal parameters of LHM-wall mixture and to analyse dynamical software used to quantify heat and moisture storage and transfer in building components. Chapter 3 details the one-dimensional dynamical model implemented in the software WUFI®4.1 Pro developed in Fraunhofer-Institute for Building Physics (IBP) in Holzkirchen (D).

The influence of how the mixture was mixed, of the consistency (water input) and of positioning (tamped or not) on drying and final performances of LHM were previously mentioned by researchers and practitioners to be important factors. Chapter 4 presents the numerous samples of LHM-wall, LHM-roof and LHM-plaster/render processed to study the evolution of density when those parameters are modified.

Based on the values needed to run WUFI® software, measurements made on LHM-wall are presented in chapters 5 and 6. Chapter 5 gives dry value for five hygrothermal parameters, and chapter 6 quantifies LHM-wall moisture retention and its influence on other hygrothermal parameters. Results are based on a First-BCCB research, directed by A. De Herde in UCL-Architecture et climat. The research was founded by Walloon Region and European Social Fund and industrial partner was Lhoist R&D in Nivelles (B). The measurements were performed in the Fraunhofer-IBP (D) by A. Evrard supported by IBP's team.

²⁵ *Thermographic Inspection of the Masonry and Hemp House – Haverhill, Suffolk*, Dr. Tim Yates, BRE, 2003

²⁶ *Construire en chanvre – Règles professionnelles d'exécution*, Commission Règles professionnelles de la construction en chanvre, 2004

In chapter 7, hygrothermal parameters of LHM-wall are compared to other classical building materials. Combined parameters (diffusivity and effusivity) are defined to give a first view of material dynamical behaviour based on common (and largely available) material parameters. Two typical LHM-components are then defined, as illustrated in Fig.4, and compared to five other classical components through simulations with WUFI® 4.1 Pro. In the simulations, the components are subjected to dynamical climates (theoretical chocks or cycles, or Belgian reference year climate). For each simulation, the results are presented by the means of different “dynamic parameters” allowing the comparison of the performances of all the components.

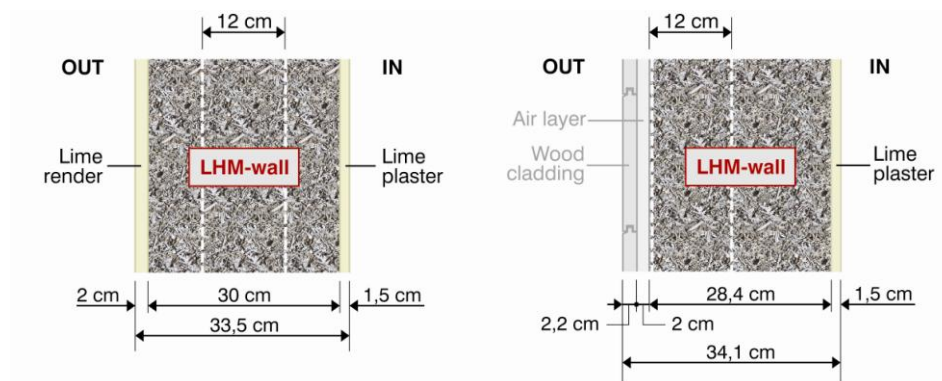


Figure 4 : Two types of LHM-wall components

Numerous possibilities of the software are explored in chapter 7, and its limitation is discussed in chapter 8. Chapter 8 also synthesizes the presumable influence on comfort feeling and energy use when choosing a LHM-wall component.

As announced in §1.2, a LHM-house monitored in Suffolk (GB) by BRE²⁷ and compared to equivalent brick house were theoretically less efficient in terms of energy demand but results showed higher temperature levels (in air), with an equivalent heating demand and lower temperature of outside surface. Together with these promising results, most of the LHM-house occupants attest high comfort feeling and low energy demand. Analysing LHM-wall's properties under dynamic conditions can help in explaining these results.

Focused on LHM, this work should be seen as a contribution to hygrothermal behaviour understanding of a wide range of open-porous materials under dynamic climate conditions.

²⁷ Final report Final Report on the construction of the Hemp Houses at Haverhill, Suffolk, Dr. Tim Yates, BRE, 2002

3 Dynamical modelling

3.1 Global overview of modelling complexity

In the last decades, numerous numerical models for Heat, Moisture and Air storage and transfer in building components (called HAM) were discussed and adapted. Together with hardware development, these models allow computer modelling of complex case with good liability and much faster than before. Experimental devices and measuring process are quite expensive and long to set up, these new tools are thus really welcome for predicting building components behaviour. Measurements and laboratory experiments are still necessary: first to define hygrothermal parameters of each material, and then to check validity of the model in specific conditions.

Classical models are based on fluid dynamics and diffusion law - Fick, Darcy (mass) or Fourier (heat). In these models, transfers are consequences of some “driving forces” resulting of gradients in potentials. To study simultaneous HAM transfers, many combination of driving forces could be use. Three of them are widely accepted: temperature gradient $\nabla\theta$ [K], relative humidity gradient $\nabla\phi$ [%], air pressure gradient ∇P_a [Pa]. Instruments to quantify these fields are widespread and affordable. In addition, they can be expressed by a continuous function through each layer of the component.

In the following relationships, simultaneous transfers are expressed through a linear combination of the 3 driving forces (thermodynamics of irreversible processes). C_x coefficients are called “transfer coefficients”. Liquid water, vapour and ice are grouped under the terms of “moisture”. “Heat” terms correspond to sensible and latent heat, with a combination of conduction, convection and radiation.

Air flow rate [kg.m⁻².s⁻¹]: $\dot{m}_A = C_{A1}\nabla\theta + C_{A2}\nabla\phi + C_{A3}\nabla P_a$ (1)

Moisture flow rate [kg.m⁻².s⁻¹]: $\dot{m}_M = C_{M1}\nabla\theta + C_{M2}\nabla\phi + C_{M3}\nabla P_a$ (2)

Heat flow rate [W.m⁻²]: $\dot{q} = C_{H1}\nabla\theta + C_{H2}\nabla\phi + C_{H3}\nabla P_a$ (3)

The following expressions provide the changes in mass and enthalpy during one time step. B_x coefficients are called “specific capacities”.

Variation in mass of air

$$\begin{aligned} \delta M_A / \delta t &= (\delta M_A / \delta \theta) \cdot (\delta \theta / \delta t) + (\delta M_A / \delta \phi) \cdot (\delta \phi / \delta t) + (\delta M_A / \delta P_a) \cdot (\delta P_a / \delta t) \\ &= B_{A1}(\delta \theta / \delta t) + B_{A2}(\delta \phi / \delta t) + B_{A3}(\delta P_a / \delta t) \end{aligned} \quad (4)$$

Variation in mass of moisture

$$\begin{aligned} \delta M_M / \delta t &= (\delta M_M / \delta \theta) \cdot (\delta \theta / \delta t) + (\delta M_M / \delta \phi) \cdot (\delta \phi / \delta t) + (\delta M_M / \delta P_a) \cdot (\delta P_a / \delta t) \\ &= B_{M1}(\delta \theta / \delta t) + B_{M2}(\delta \phi / \delta t) + B_{M3}(\delta P_a / \delta t) \end{aligned} \quad (5)$$

Variation in enthalpy

$$\begin{aligned}\delta h / \delta t &= (\delta h / \delta \theta) \cdot (\delta \theta / \delta t) + (\delta h / \delta \phi) \cdot (\delta \phi / \delta t) + (\delta h / \delta P_a) \cdot (\delta P_a / \delta t) \\ &= B_{H1}(\delta \theta / \delta t) + B_{H2}(\delta \phi / \delta t) + B_{H3}(\delta P_a / \delta t)\end{aligned}\quad (6)$$

Modelling of simultaneous transfer is based on the conservation of mass and heat axioms. When applied to an open system, and with S_x the eventual source terms, these relationships can be written as followed:

Air balance

$$\begin{aligned}\vec{\nabla} \dot{m}_A \pm S_A &= - \delta M_A / \delta t \\ \Leftrightarrow \vec{\nabla} (C_{A1} \nabla \theta + C_{A2} \nabla \phi + C_{A3} \nabla P_a) \pm S_A &= B_{A1}(\delta \theta / \delta t) + B_{A2}(\delta \phi / \delta t) + B_{A3}(\delta P_a / \delta t)\end{aligned}\quad (7)$$

Moisture balance

$$\begin{aligned}\vec{\nabla} \dot{m}_M \pm S_M &= - \delta M_M / \delta t \\ \Leftrightarrow \vec{\nabla} (C_{M1} \nabla \theta + C_{M2} \nabla \phi + C_{M3} \nabla P_a) \pm S_M &= B_{M1}(\delta \theta / \delta t) + B_{M2}(\delta \phi / \delta t) + B_{M3}(\delta P_a / \delta t)\end{aligned}\quad (8)$$

Heat balance

$$\begin{aligned}\vec{\nabla} \dot{q} \pm S_H &= - \delta h / \delta t \\ \Leftrightarrow \vec{\nabla} (C_{H1} \nabla \theta + C_{H2} \nabla \phi + C_{H3} \nabla P_a) \pm S_H &= B_{H1}(\delta \theta / \delta t) + B_{H2}(\delta \phi / \delta t) + B_{H3}(\delta P_a / \delta t)\end{aligned}\quad (9)$$

When phenomena are in permanent transfer, the right terms equal zero. But in transient transfer, mass and enthalpy can vary from one time step to another, and it is theoretically necessary to know 3x3 transfer coefficients, as well as 3x3 specific capacities for each material. Beside material parameters, exact geometry and composition of the component, boundary and initial conditions source terms, contact conditions between layers... have also to be known. Source terms can be related to latent heat, carbonisation of lime, hydration of hydraulic binder, salt crystallisation or to any heating system.

These relationships are only valid if the material can be considered as isotropic (same properties in all directions), homogenous and without volumetric variations. If the material is not isotropic, each transfer coefficient and each specific capacity is a 3 dimension tensor. That means in this case, that in addition to source terms, boundary, initial and contact conditions, 54 coefficients should be identified for each material (in some cases, a large number of values or measurements per coefficient is needed to trace the dependences of the different driving forces). If sorption/desorption behaviour, with its hysteresis and time dependencies, is also integrated in the model through their effects on hygrothermal parameters, many other measurements have to be achieved. This kind of considerations "leaves researchers with a tremendous task"²⁸.

²⁸ Annex 24: Heat, Air and Moisture Transfer in Insulated Envelope Parts, IEA final report, Task 1, 1996

Seven assumptions help simplifying the model:

1. Studied samples or component will always be considered isotropic, homogenous and without volumetric variations. The “representative volume element (RVE)” is the smallest volume for which the material is assumed to be isotropic and homogenous. As presented in §5.2, RVE of LHM-wall is considered to be around few cubic centimetres.
2. The three phases of water is at thermodynamic equilibrium and there is no chemical reactions between them ;
3. No energy dissipation during flows ;
4. No parameter has time dependency ;
5. No hysteresis is taken into account (univalent relationship between water content and relative humidity, see 6.1) ;
6. Air flow is not taken into account (implementation of the component should avoid it)
 $\Rightarrow C_{A1 \rightarrow 3} = S_A = B_{A1 \rightarrow 3} = C_{M3} = C_{H3} = B_{M3} = B_{H3} = 0$
7. Temperature has no effect on moisture sorption
 $\Rightarrow B_{M1} = 0$.

The simplified model can be written:

Moisture balance

$$\vec{\nabla}(C_{M1}\nabla\theta + C_{M2}\nabla\phi) \pm S_M = B_{M2}(\delta\phi/\delta t) \quad (10)$$

Heat balance

$$\vec{\nabla}(C_{H1}\nabla\theta + C_{H2}\nabla\phi) \pm S_H = B_{H1}(\delta\theta/\delta t) + B_{H2}(\delta\phi/\delta t) \quad (11)$$

Chapter 3.2 will detail the model implemented in WUFI[®] software and show which hygrothermal parameters are needed to simulate components behaviour in dynamical conditions. Relationships (10) and (11) are related to relationships (20) and (28). As detailed in §3.2.3, the inputs for a new material in WUFI[®]'s database are 5 parameters related to dry state of material and 5 moisture related curves.

3.2 Simplified model used in WUFI[®] 4.1 Pro



WUFI[®] software (Wärme und Feuchtetransport Instationär) was developed during H.M. Künzels Ph.D.²⁹ in Fraunhofer-Institut for Building Physics to model heat and moisture transfer and storage in building components. It is available in many languages (see <http://www.wufi-pro.com>). WUFI[®] 4.1 Pro, used in the present work, is a One-dimensional model and WUFI[®]-2D V2.1 is Two-dimensional (and integrates air flow). This chapter shows that numerical hypotheses are equivalent to those presented in previous section.

3.2.1 Moisture transfer and storage

3.2.1.1 Moisture storage

Density of material ρ of materials is expressed in $[\text{kg.m}^{-3}]$, *total porosity* ψ in $[\%_{\text{vol}}]$. Materials with open-porous structure, like Lime-Hemp Materials, are permeable to gas and liquid depending on their specific porous structure. Moisture can be temporary stored during transfer.

In dry state, presented in Fig. 5, water was completely evacuated. Some H_2O molecules can be “trapped” due to chemical reactions within the material **(1)**. *Dry density* is ρ_0 $[\text{kg.m}^{-3}]$. In natural European conditions, relative humidity in building conditions actually never reaches 0%.

Water content is written w , and is expressed in $[\text{kg.m}^{-3}]$ or $[\%_{\text{mass}}]$. In low relative humidity, moisture transfer in the material **(2)** is progressively *adsorbed* on pores surface (BET theory)³⁰, first in large pores then through the whole porous structure **(3)**. This phenomenon is called *hygroscopic adsorption* as referred in Fig. 6.

Fig.7 shows that in higher relative humidity and until free saturation, typically from 80 or 90% to 100% of RH, two other phenomena occur simultaneously with *adsorption*: *surface diffusion* **(4)** and *capillary conduction* **(5)**, as developed in 3.2.1.3. Fig.8 refers to region of *over-saturation* that follows the free saturation. Water content can still rise, theoretically until all pores are filled with unbound water **(6)**. *Maximal water content* w_{max} $[\text{kg.m}^{-3}]$ is calculated through measurements on total porosity, as presented in 6.1.

²⁹ *Simultaneous Heat and Moisture Transport in Building Component: One- and Two-dimensional calculation using simple parameters*, H.M. Künzels, thesis at Fraunhofer-IBP, Stuttgart, 1995

³⁰ *Adsorption of Gases in Multimolecular Layers*, S. Brunauer, P.H. Emmett and E. Teller, Journal of the American Chemical Society, 60(2) pp 309 – 319, 1938

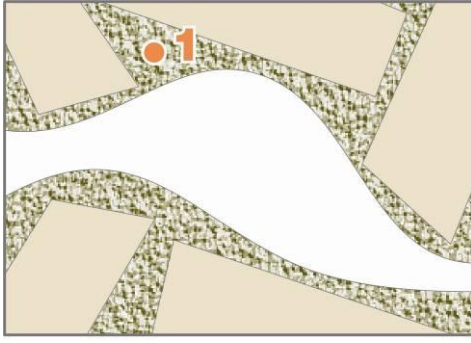


Figure 5 : Dry state

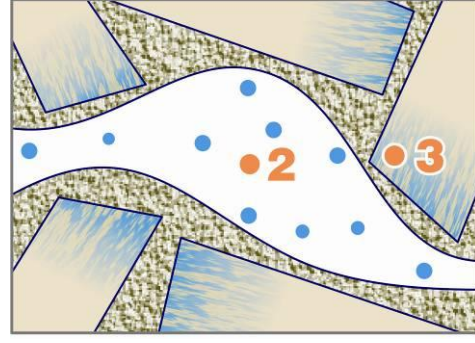


Figure 6 : Hygroscopic adsorption - A

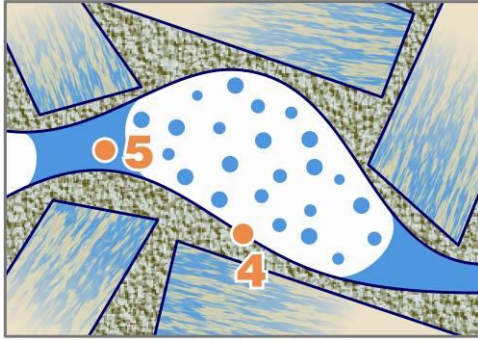


Figure 7 : Capillary condensation - B

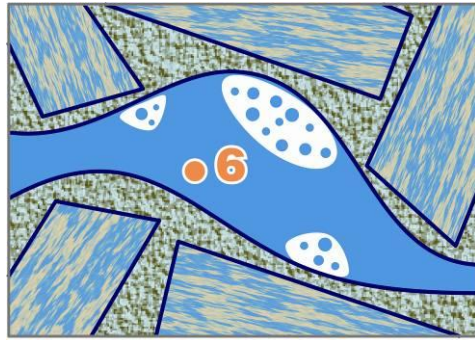


Figure 8 : Over-saturation - C

Water content w is constantly adapting to new hygrothermal conditions and, as observed in §7.5.2, equilibrium is usually long to be reached. Effects of temperature are neglected. *Mass equilibrium* is considered to be reached when mass measurement varies less than 1% between 2 measurements on a 24h basis, as presented in chapter 4. The density is expressed in

$$\rho = \rho_0 + w \quad (12)$$

Fig.9 shows that rising equilibrium (absorption) is slightly different from falling equilibrium (desorption). This hysteresis can be relatively important with specific pores geometry³¹, especially in organic material. *Multiple porosity* of LHM-wall mixture will be described in 5.2.

In WUFI® model, water content is expressed in terms of relative humidity, through the Moisture Retention Curve. MRC corresponds to a sorption isotherm (usually at 23°C), where hysteresis between sorption and desorption is neglected. Results for Lime-Hemp Material are presented in §6.1. Relationship (13) presents the slope of this curve, called the *specific hygric capacity* ξ_ϕ and expressed in [kg.m⁻³].

$$\xi_\phi(w) = \frac{dw}{d\phi} \quad (13)$$

³¹ *Moisture Transport and Storage Coefficients of Porous Mineral Building Materials : Theoretical Principles and New Test Methods*, M. Krus, thesis at Fraunhofer-IBP, Stuttgart, 1996

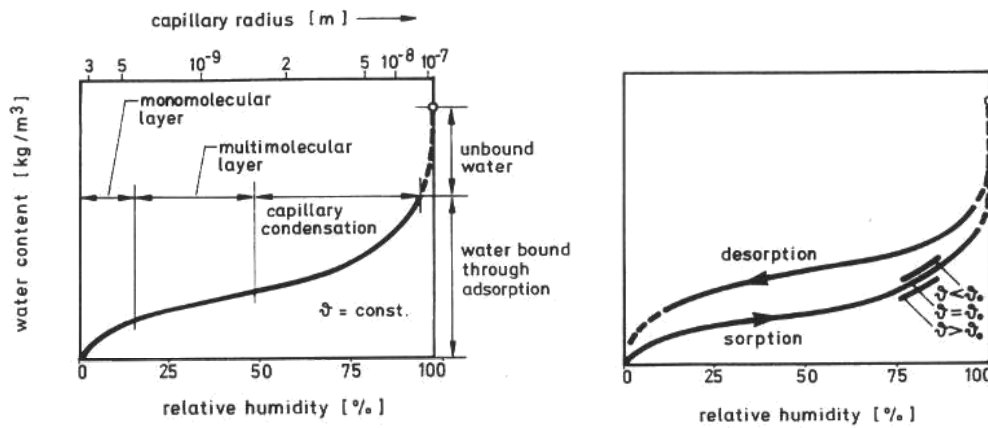


Figure 9 : Sorption and desorption [Krus, 1996]

3.2.1.2 Sources and sink

New WUFI® 4.1 model allows considering moisture sources and sinks in any layers of the component. As illustrated in Fig.10, most of the moisture sources are external. Implementation of the building components should avoid rising damp, inner moisture source or damaging condensations. Section 3.2.4 shows how moisture sources are introduced in boundary layers, or in initial layer conditions, through the climate files.

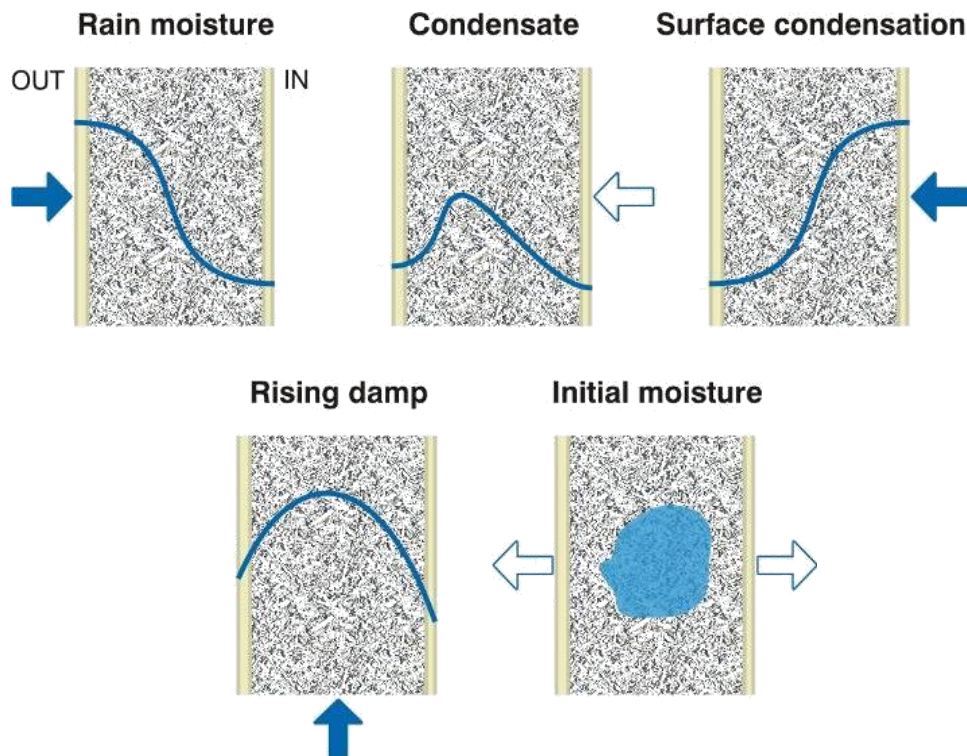


Figure 10 : Theoretical source of moisture and moisture distribution in building components

3.2.1.3

Moisture transfer

Liquid water, vapour and ice are grouped under the terms “moisture”. If there is of course no ice “flow”, vapour flow can be either diffusive or convective. Convective part is linked to air flow and will thus be neglected here. Liquid flow can also be distinguished in two different parts: surface diffusion and capillary conduction. Even if both imply a displacement of matter (convective flows), they are considered as diffusive phenomena (very low discharge in building physics). Fig.11 represents the phenomena taken into account in the model³².

Vapour transfer [$\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$] is expressed by

$$\dot{m}_v = -\delta \cdot \nabla p_v = -\delta \cdot \nabla(\phi \cdot P_{sat}) \quad (14)$$

where δ is the *vapour permeability*, expressed in [$\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$]. As it appears, the true driving force is here the gradient of vapour pressure. The saturation pressure can be expressed with $P_{sat} = a \cdot (b + \theta/100)^n$, where a, b and n take different value depending on temperature³³ (DIN 4108).

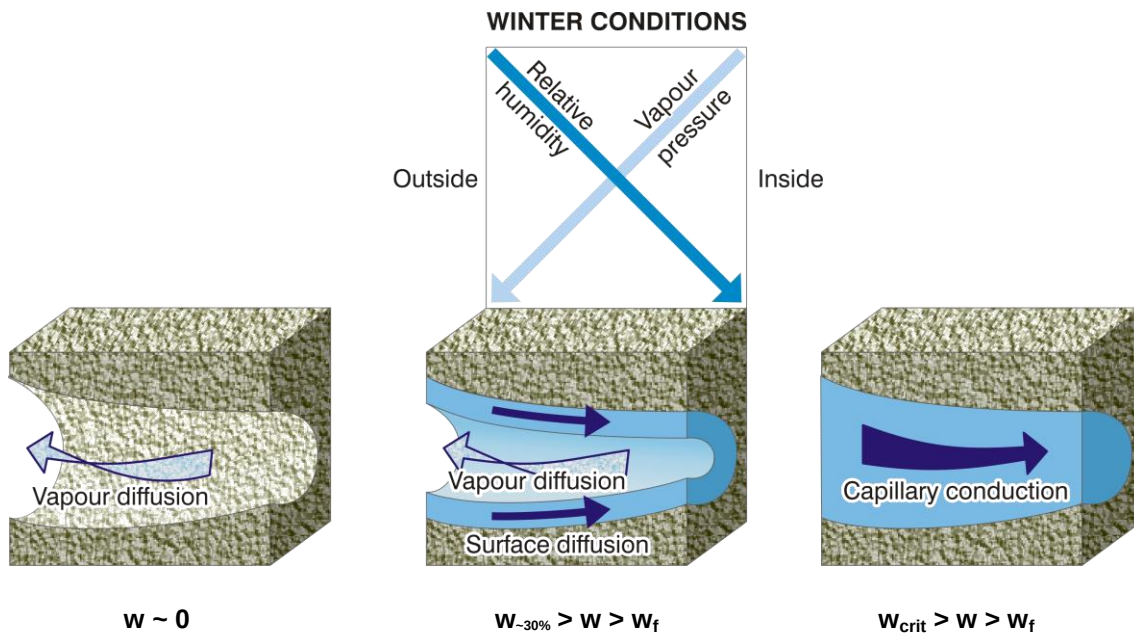


Figure 11 : Moisture transfers

³² *Simultaneous Heat and Moisture Transport in Building Component: One- and Two-dimensional calculation using simple parameters*, H.M. Künzeli, thesis at Fraunhofer-IBP, Stuttgart, 1995

³³ If θ is between -20 et 0°C : $a = 4,689$ [Pa], $b = 1,486$ [-] and $n = 12,30$ [-] ; if $0 \leq \theta \leq 30^\circ\text{C}$: $a = 288,68$ [Pa], $b = 1,098$ [-], $n = 8,02$ [-]

As vapour pressure is the product of relative humidity and saturation pressure, moisture flow could also be expressed as in 3.1 with a part due to temperature gradient, and another due to relative humidity gradient. Vapour permeability is dependent on temperature and air pressure. The *vapour diffusion resistance factor* of a material, written μ [-], is usually presented instead of vapour permeability. As it appears in

$$\mu = \delta_a / \delta, \quad (15)$$

this factor is the ratio between the *vapour permeability of air* δ_a (in the same condition) and the *vapour permeability* of the material δ . It is considered to have no dependency on temperature or air pressure. The next relationship gives vapour permeability of air δ_a [$\text{kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}$] (DIN 52615),

$$\delta_a = 2.10^{-7} . \theta^{0.81} / P_a. \quad (16)$$

As presented in 6.6, the *fictitious vapour permeability* δ^* [-] measured with wet-cup method, is usually higher compared to dry-cup results. It was demonstrated in the Fraunhofer-IBP³⁴ that the difference between moist and dry value is due to a liquid flow superimposed on vapour diffusion. According to [Krus, 1996]³⁵, the difference is due to liquid transport superimposed on vapour diffusion. The author used the experiment illustrated in Fig.12 to validate his statement. It is based on the fact that the driving force for vapour diffusion is a gradient of vapour pressure ∇p_v [Pa], whereas the driving force for liquid transport can be expressed with a gradient in relative humidity $\nabla \Phi$ [%] (see §3.2.1.3). The sample separates two ambiances, with respectively $(p_{v1}, \Phi_1, \theta_1)$ and $(p_{v2}, \Phi_2, \theta_2)$. Fig.13 shows that the two phenomena can be distinguished through an appropriate choice of ambiance. When choosing $\Phi_2 < \Phi_1$ and $p_{v2} < p_{v1}$ ($\theta_1 = \theta_2$), both vapour and liquid transfer are going in the same direction. When choosing $\Phi_2 > \Phi_1$ and $p_{v2} > p_{v1}$ ($\theta_2 < \theta_1$), the transfer have opposite direction.

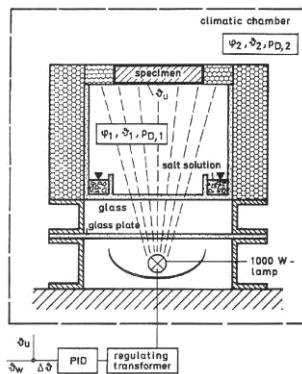


Figure 12 : Experimental device
[Krus, 1996]

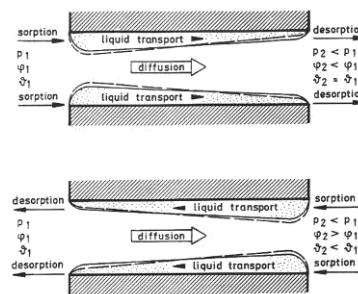


Figure 13 : Liquid transport vs. vapour diffusion
[Krus, 1996]

³⁴ *Moisture Transport and Storage Coefficients of Porous Mineral Building Materials : Theoretical Principles and New Test Methods*, M. Krus, thesis at Fraunhofer-IBP, Stuttgart, 1996

³⁵ *Moisture Transport and Storage Coefficients of Porous Mineral Building Materials : Theoretical Principles and New Test Methods*, M. Krus, thesis at Fraunhofer-IBP, Stuttgart, 1996

Results from dry state measurements, the *dry vapour diffusion resistance factor*, μ_0 [-], can thus be used as a constant for vapour diffusion resistance factor in moist state because liquid transfer is considered through other parameters. As presented in 6.7.1, results from measurements in the moist state, called *fictitious vapour diffusion resistance factor*, μ^* [-], can be used for liquid transfer determination in hygroscopic region.

For liquid transfer, experimental determination (measuring of water content profile) cannot distinguish surface diffusion from capillary conduction. The actual driving force of surface diffusion is the gradient in water content (different thickness in adsorbed water film). For capillary conduction, it is the gradient in capillary pressure.

Based on Thomson's law (link between capillary pressure and relative humidity) and on the definition of Moisture Retention Curve (univalent relationship between water content and relative humidity), both described in 6.1, the two phenomena can be expressed as diffusive phenomena (very low discharge) with one single relationship (17). The influence of temperature is neglected in this formula. D_w is the *liquid transfer coefficient*, it is also called *liquid diffusivity* and is expressed in $[m^2.s^{-1}]$.

$$\dot{m}_w = -D_w(\theta, w) \cdot \nabla w = -D_w(w) \cdot \nabla w \quad (17)$$

D_w also depends on the boundary conditions. Experiments of absorption of water on one side of samples, followed by redistribution measurements, as presented in 6.7.2, confirmed this fact. Two different liquid transfer coefficients will be defined: D_{ws} for absorption ("Wasser Saugen") and D_{ww} for redistribution ("Wasser Weiterleiten"). As soon as the water is removed from the suction surface, the field of capillary pressures changes to a new equilibrium. "Now, moisture can only be redistributed through capillary actions as the small pores are filled at the expense of larger pores"³⁶. Depending on the material, this redistribution can be 3 to 20 times slower than absorption.

To express liquid transfer in terms of relative humidity gradients, D_ϕ is the *liquid conduction coefficient*, expressed in $[kg.m^{-1}.s^{-1}]$. Liquid transfer coefficient D_w and liquid conduction coefficient D_ϕ are link through

$$D_\phi = D_w \cdot \frac{dw}{d\phi} = D_w \cdot \xi_\phi \quad (18)$$

where ξ_ϕ is the *specific hygric capacity*, expressed in $[kg.m^{-3}.\%_{HR}^{-1}]$ or $[\%_{mass}.\%_{HR}^{-1}]$ and defined in 3.2.1.1 as the slope of Moisture Retention Curve.

Moisture flow, expressed in $[kg.m^{-1}.s^{-1}]$, can thus be written with

$$\dot{m}_M = \dot{m}_w + \dot{m}_v = -D_\phi \cdot \nabla \phi - \delta \cdot \nabla (\phi \cdot P_{sat}) \quad (19)$$

³⁶ Simultaneous Heat and Moisture Transport in Building Component: One- and Two-dimensional calculation using simple parameters, H.M. Künzle, thesis at Fraunhofer-IBP, Stuttgart, 1995

3.2.1.4 Moisture balance

At each time step, conservation of mass and energy can be used to write the moisture variation δw expressed by

$$\frac{\delta w}{\delta t} = \xi_\phi \cdot \frac{\delta \phi}{\delta t} = \bar{\nabla}(-D_\phi \cdot \nabla \phi - \delta \cdot \nabla(\phi \cdot P_{sat})). \quad (20)$$

This relationship can be related to relationship (10), where $B_{M2} = \xi_\phi$; $C_{M2} = -D_\phi$; and C_{M1} is linked to δ through relationships (15) and (16).

3.2.2 Heat transfer and storage

3.2.2.1 Heat storage

Dry enthalpy h_0 [J.m^{-3}] of a material corresponds to the quantity of energy contained by 1m^3 of the material. Only temperature dependency is considered in the model, as expressed in

$$h_0 = \rho_0 c_0 \theta \quad (21)$$

where ρ_0 is the *dry density* [kg.m^{-3}] and c_0 the *dry thermal capacity* [$\text{J.kg}^{-1}.\text{K}^{-1}$]. Those parameters are respectively detailed in 5.1, and in 5.3.

Moisture enthalpy h_M [J.m^{-3}] is expressed as

$$h_M = w \cdot c_w \cdot \theta \quad (22)$$

where w is the total water content [kg/m^3] and $c_w = 4187 \text{ J.kg}^{-1}.\text{K}^{-1}$ the thermal capacity of liquid water (at 20°C).

Moist material enthalpy, h_w [J.m^{-3}], can thus be written as

$$h_w = h_0 + h_M. \quad (23)$$

Enthalpy flows resulting from liquid transfer are neglected in the model. According to Künzle, if “the driving rain hits the wall at the outside temperature, (it) is completely absorbed and evenly distributed over rain screen, we obtain a heat transfer rate of less than 0.2 W/m^2 through liquid transport”. “(...) evaporative cooling results in a heat loss for the rain screen of 32 W/m^2 , which in this relatively extreme example, is of the same magnitude as the gain from solar radiation”³⁷.

Total moist enthalpy h_{tot} [J.m^{-3}] is expressed by

$$h_{\text{tot}}(w, \theta) = h_w + S_H = \rho_0 c_0 \theta + w \cdot c_w \cdot \theta + h_{\text{lat}} \quad (24)$$

where latent energy, h_{lat} [$\text{J.kg}^{-1}.\text{K}^{-1}$], is taken into account in terms of heat source.

³⁷ *Simultaneous Heat and Moisture Transport in Building Component: One- and Two-dimensional calculation using simple parameters*, H.M. Künzle, thesis at Fraunhofer-IBP, Stuttgart, 1995

3.2.2.2 Sources and sink

New WUFI® 4.1 model allows considering *heat sources or sinks* S_H [W/m²] in any layers of the component. Phase transition during transfer of moisture generates *latent heat of vaporisation and solidification*. WUFI® model considers *latent energy* h_{lat} [J.kg⁻¹.K⁻¹] expressed in

$$h_{lat} = h_{vap} \cdot \vec{\nabla} \dot{m}_v = h_{vap} \cdot \vec{\nabla} (-\delta \cdot \nabla (\phi \cdot P_{sat})), \quad (25)$$

in the source term. It is calculated with the gradient of vapour transfer, see (14), and the *enthalpy of vaporisation (or evaporation)* $h_{vap} = 2257$ kJ/kg. In addition, another term can be defined to consider latent heat of freezing ($h_{ice} = 333,5$ kJ/kg).

3.2.2.3 Heat Flow

Heat is transferred by conduction, convection and radiation. The convective part is related to air flow and will be neglected here. Transfer by radiation will mainly occur at the surface, and will influence boundary conditions as described in 3.2.5.

Density of conductive heat flow through a material $\dot{q}_{cond}$ [W.m⁻¹] follows Fourier's Law expressed as

$$\dot{q}_{cond} = -\lambda^*(w) \cdot \nabla \theta. \quad (26)$$

Radiation between pores surface and convection in the large pores could occur in open-porous materials but the *fictitious thermal conductivity* λ^* , expressed in [W.m⁻¹.K⁻¹], is considered to be only dependent on water content, through

$$\lambda^*(w) = \lambda = \lambda_0 \cdot \left(1 + \frac{b \cdot w}{\rho_0}\right). \quad (27)$$

The *dry thermal conductivity* λ_0 , expressed in [W.m⁻¹.K⁻¹], is detailed in 5.4, and b [-], the *moisture-induced thermal conductivity supplement*, in 6.5.

3.2.2.4 Heat balance

At each time step, conservation of mass and energy can be used to write the enthalpy variation δh , as expressed by

$$\frac{\delta h}{\delta t} = \frac{dh_w}{d\theta} \cdot \frac{\delta \theta}{\delta t} = \vec{\nabla} (-\lambda^* \cdot \nabla \theta) + h_{vap} (\delta \cdot \nabla (\phi \cdot P_{sat})) \quad (28)$$

This relationship can be related to relationship (11), where $B_{H1} = dh_w/d\theta$ (B_{H2} is not necessary since h_w integrates variation of moisture) ; and $C_{H1} = -\lambda^*$ (C_{H2} is not necessary since λ^* integrates variation of moisture).

3.2.3 Material database

WUFI® software contains a large database, gathering data of building materials from different sources -“North American Database”, “Fraunhofer-IBP”, “Norwegian University of Science and Technology”, “Technical University of Vienna” – and structured in distinguished “catalogs” - “Plasters and Mortars”, “Insulation Materials”, etc. However, if the database is quite complete, the typical data it contains are not always appropriate in specific case. Large variations can be found in different batches of the same material or in equivalent materials of different manufacturers. This may lead to variations in the hygrothermal behaviour of the investigated components. Before drawing conclusion from simulations, uncertainties or variations in the input data should be evaluated, and a sensitivity analysis of the results should be performed when necessary. In specific case, it may be necessary to determine some input data very precisely to get a reliable result, while other input data may have no discernible effect on the results.

Referring to previous sections, the basic material parameters, needed as a minimum to input a new material in the database and achieve simulations, are relative to dry materials:

1. bulk density [kg.m^{-3}] ;
2. total porosity [$\text{m}^3.\text{m}^{-3}$]
which will be used to define the maximal water content ;
3. specific heat capacity [$\text{J.kg}^{-1}.\text{K}^{-1}$] ;
4. thermal conductivity [$\text{W.m}^{-1}.\text{K}^{-1}$] ;
5. water vapour diffusion resistance factor [-].

Some “hygric extensions” are not mathematically required, but are necessary to describe accurately the hygrothermal behaviour of a component:

1. Moisture Retention Curve [kg.m^{-3}]
as a table or approximated by sorption moisture at 80% RH (w_{80}) and free saturation (w_f) ;
2. moisture-dependent vapour diffusion resistance factor [-]
only if no liquid transfer is used (see 3.2.1.3) ;
3. liquid transport coefficient for suction [$\text{m}^2.\text{s}^{-1}$]
as a table or generated from the water absorption coefficient (6.7.1.3) ;
4. liquid transport coefficient for redistribution [m^2/s]
as a table or generated from the water absorption coefficient (6.7.1.3) ;
5. moisture-dependent thermal conductivity [$\text{W.m}^{-1}.\text{K}^{-1}$]
as a table or generated from the moisture-induced thermal conductivity supplement.

Parameters used for LHM-wall and other materials (from Fraunhofer-IBP's database) of the components defined and analysed in chapter 7 are presented in Appendix 1.

3.2.4 Climate file

Building components modelled in WUFI® software separate outdoor and indoor climate. Those climates are described in terms of meteorological parameters which may contain measured weather data, average weather data (such as Test Reference Years in Uccle -Belgium- illustrated in Fig.15) or completely artificial data (e.g. to describe a laboratory experiment).

Different type of climate files can be used in WUFI® software - *.WET, *.TRY, *.DAT, *.IWC, *.WBC or *.KLI. Most of them need the following climate data for each time step:

1. the *rain load vertically incident on the exterior surface* in [Ltr/m²h],
for the determination of this rain load, the inclination and orientation of the surface must be taken into account ;
2. the *solar radiation vertically incident on the exterior surface* in [W/m²],
for the determination of the amount of radiation, the inclination and orientation of the surface must be taken into account ;
3. the *temperature of the exterior air* in [°C] ;
4. the *relative humidity of the exterior air* (0..1) ;
5. the *temperature of the interior air* in [°C] ;
6. the *relative humidity of the interior air* (0..1) ;
7. the *barometric pressure* in [hPa],
since the barometric pressure has only a minor effect on the calculation, specification of a mean value over the calculation period can be sufficient ;
8. the *long-wave atmospheric counter radiation* [W/m²],
if radiation cooling is to be accounted for during the night.

In order to convert the solar radiation data contained in the climate files for receiving surfaces of arbitrary orientation and inclination, WUFI® needs to compute the position of the sun in the sky. For this, data of geographic coordinates and time zone of the climate location has to be input. For each user-defined climate file the user must create an *.AGD file with the relevant "Additional Geographic Data". WUFI® allows then the analysis of the weather data as illustrated in Fig.16 (Sun radiation sum: $\max_{30^\circ, \text{sud}} = 1007 \text{ kWh.m}^{-2}.\text{a}^{-1}$, $\min_{90^\circ, \text{nord}} = 407 \text{ kWh.m}^{-2}.\text{a}^{-1}$).

Standard EN15026 (normal moisture load), illustrated in Fig.17, will be used to define inside temperature and humidity when referring to classical inside environment in residential houses. Other climate file will be defined in chapter 7 to analyse specific phenomena.

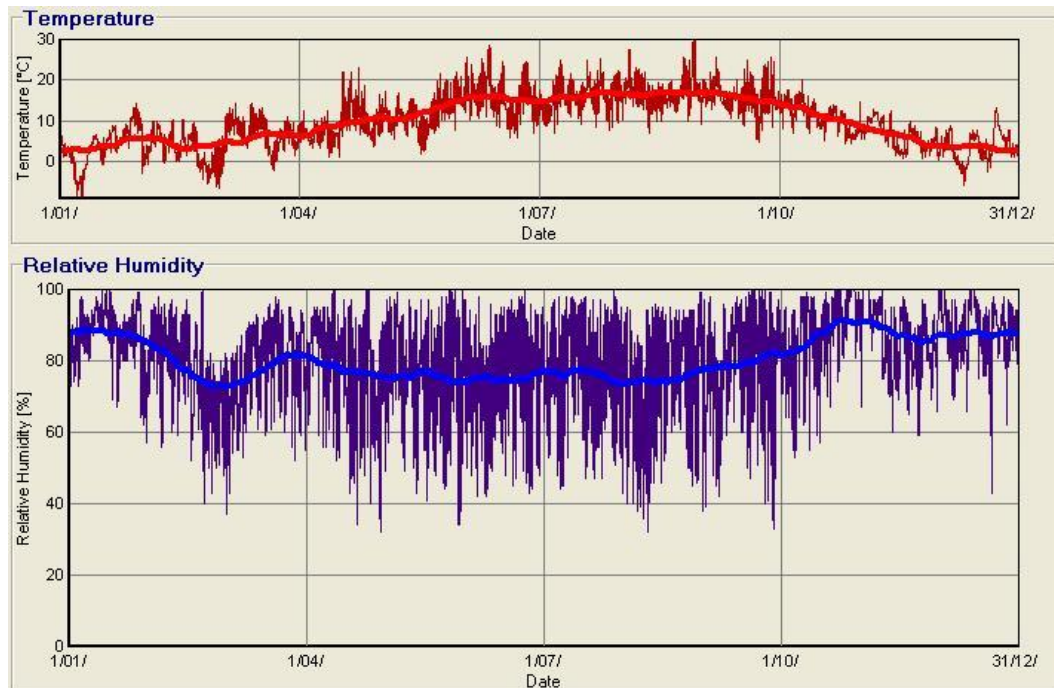


Figure 14 : Reference year in Uccle / Belgium (source IRM)

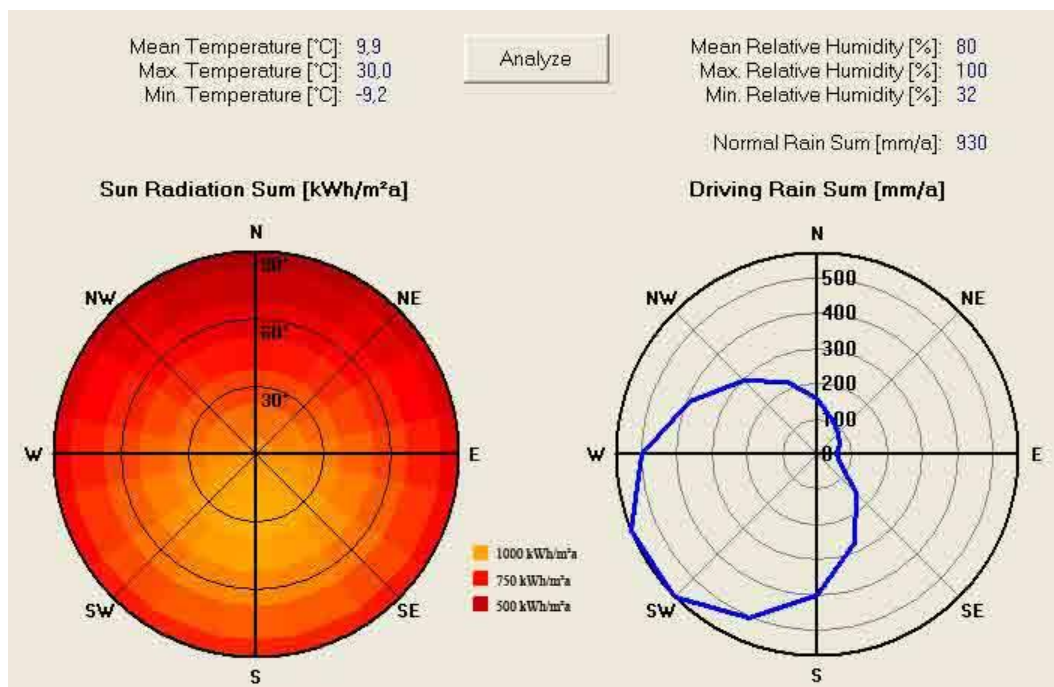


Figure 15 : Climate analysis from WUFI®

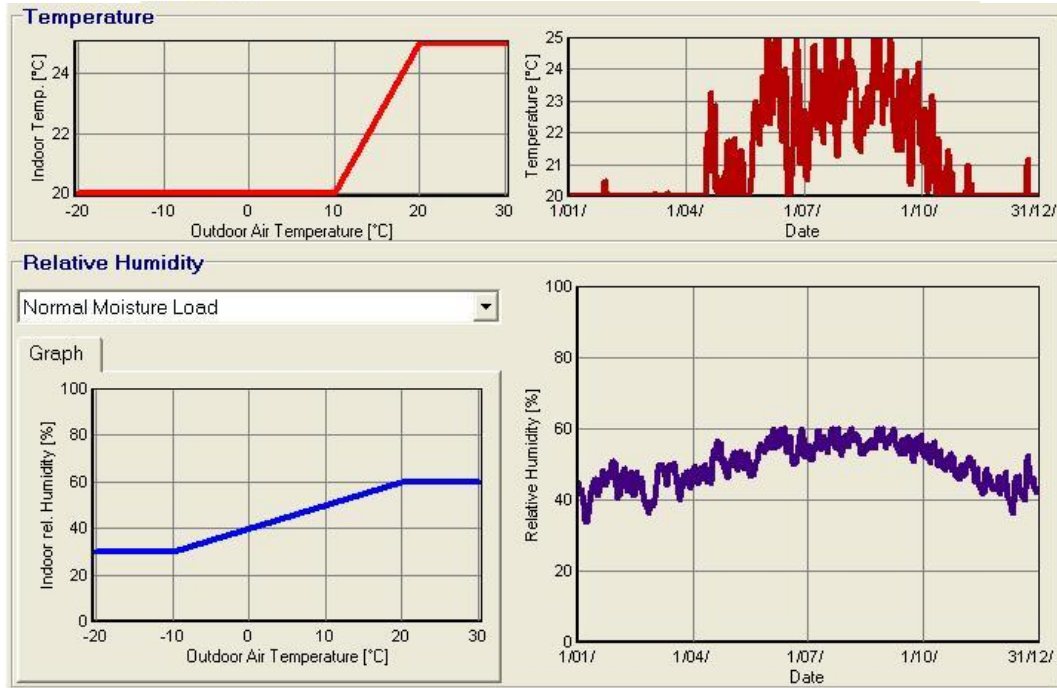


Figure 16 : Reference indoor climate in houses (normal moisture load) – EN15026

3.2.5 Boundary conditions

Heat flow through the surface $\dot{q}_{surf}$ [W.m⁻²] depends on convection and radiation occurring between the surface and ambient conditions proportionally to the difference between ambient and surface temperatures, respectively θ_{amb} [°C] and θ_{surf} [°C]. It is expressed by means of a *heat transfer coefficient* h_{surf} [W.m⁻².K⁻¹], where h_{conv} is the *convective heat transfer coefficient* [W.m⁻².K⁻¹] and h_{rad} , the *radiation-related heat transfer coefficient* [W.m⁻².K⁻¹]:

$$\dot{q}_{surf} = h_{surf}(\theta_{amb} - \theta_{surf}) \quad (29)$$

$$h_{surf} = h_{rad} + h_{conv} \quad (30)$$

The *heat transfer coefficient of an inside surface* h_i [W.m⁻².K⁻¹] has a different value than the *heat transfer coefficient of outside surface* h_e [W.m⁻².K⁻¹]. In Belgium, the standard NBN 62-002 gives the values for both coefficients.

The *heat transfer coefficient of inside surface* h_i depends on the configuration of the wall element and the orientation of the heat flow. For a vertical wall, $h_{i,rad} = 4,5$ W.m⁻².K⁻¹ and $h_{i,conv} = 3,5$ W.m⁻².K⁻¹. The value used for h_i is thus $h_i = 8$ W.m⁻².K⁻¹.

The heat transfer coefficient of an outside surface h_e is considered to be only dependent on *wind speed* v_{wind} [m.s⁻¹]. For a vertical wall, $h_{e,rad} = 3,5 \text{ W.m}^{-2}.\text{K}^{-1}$ and $h_{e,conv} = 4,6 + (3,6 \cdot v_{wind}) \text{ W.m}^{-2}.\text{K}^{-1}$. The standards suggest to use the value of $h_e = 23 \text{ W.m}^{-2}.\text{K}^{-1}$ (corresponding to an average wind speed of $\sim 4 \text{ m.s}^{-1}$).

In WUFI® model, *vapour flow through the surface* $\dot{m}_{v,surf}$ [kg.m⁻².s⁻¹] is expressed similarly to heat transfer by means of *vapour transfer coefficient* β_v [kg.m⁻².s⁻¹.Pa⁻¹], proportionally to the difference between ambient and surface vapour pressure, respectively p_{amb} [Pa] and p_{surf} [Pa],

$$\dot{m}_{v,surf} = \beta_v (p_{amb} - p_{surf}). \quad (31)$$

The vapour transfer coefficient β_v is considered to be equal to $\beta_v = 7.10^9 \cdot h_{conv}$. It has to be noticed that the default value for h_{conv} used in WUFI® model for outside transfer is different than the Belgian standard ($h_{e,conv} = h_e - 6,5$).

The *heat flow from solar radiation* $\dot{q}_{solar}$ [W.m⁻²] can be calculated with

$$\dot{q}_{solar} = a_s \cdot I_N \quad (32)$$

where a_s [-] is the *short-wave absorptivity* and I_N [W.m⁻²] the *solar radiation vertical to the building component surface*.

The water uptake from driving rain is more difficult to model accurately. The *liquid flow on the surface* $\dot{m}_w$ [kg.m⁻².s⁻¹] can be approximate by

$$\dot{m}_w = a_r \cdot R \quad (33)$$

where a_r [-] is the *rain absorptivity* and R [kg.m⁻².s⁻¹] the *rain load vertical to the building component surface*.

In order to determine the rain load R on the whole component, it is necessary to calculate first the *rain load* R_s [kg.m⁻².s⁻¹] for each section of the building component surface. R_s is found with

$$R_s = r_s \cdot v_{wind} \cdot R_N \quad (34)$$

where r_s [s.m⁻¹] is the *site-specific driving rain coefficient*, v_{wind} the *wind speed* [m.s⁻¹] and R_N [kg.m⁻².s⁻¹] the *normal rain*.

It appears that material properties are not taken into account in the formulation of boundary conditions, except for the colour and the roughness of the surface which affect a_r and a_s . Further researches could address the influence of *thermal emissivity of materials* ϵ [-], or surface temperature, on radiation-related heat transfer coefficient, as well as the effects of surface properties on the vapour or liquid transfer coefficients of the material surface.

3.2.6 Calculation model

For calculation, the differential equations presented in relationship (20) and (28) are discretised by means of an implicit finite volume method. Solving process follows iteration of the flow chart illustrated in Fig.17. Size of the mesh, time step and convergence criteria influence the accuracy of the numerical solution. Effect of numerical parameters is usually not significant in comparison with the effects of the physical parameters like materials and climate data. Results should always be critically assessed in order to exclude user errors or severe convergence errors (quantify by WUFI®).

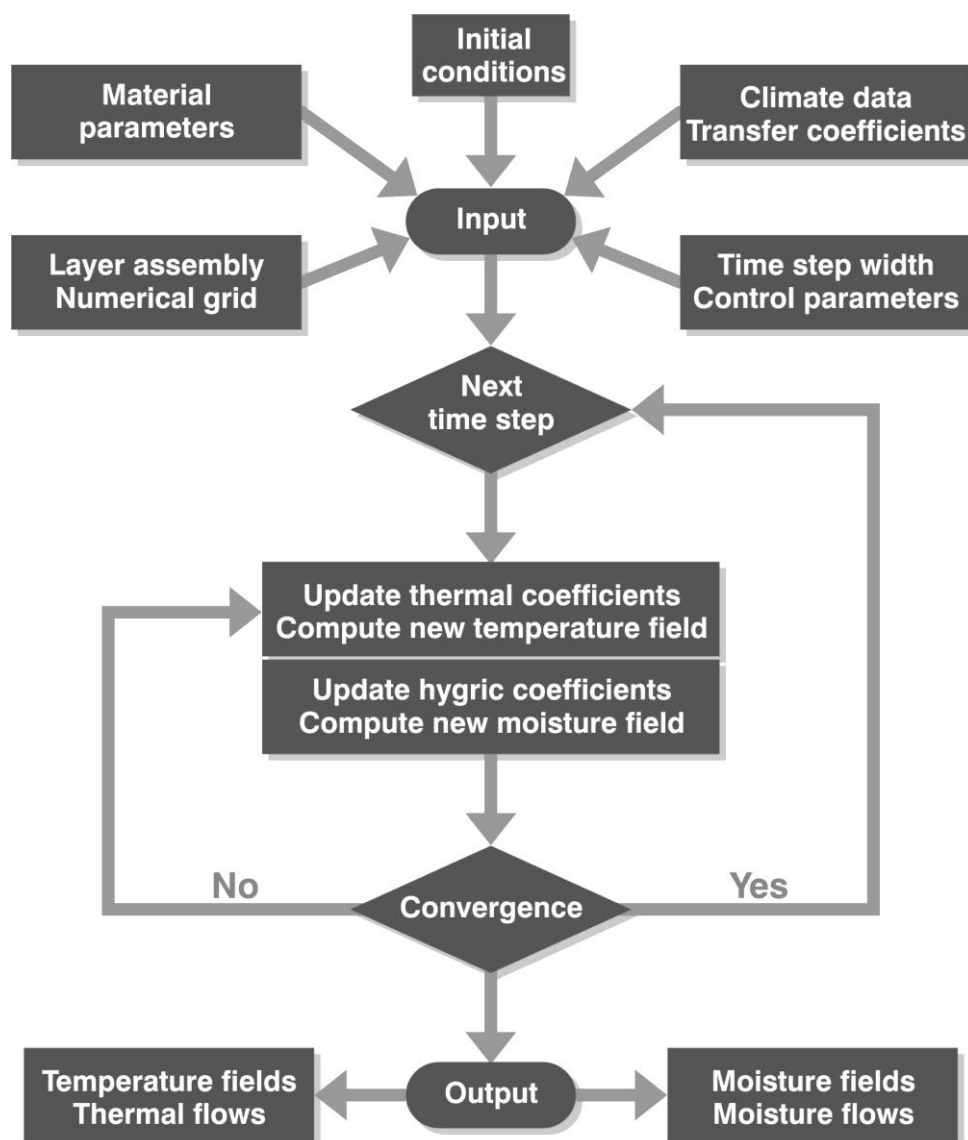


Figure 17 : Flow chart for WUFI® model

4 Samples processing

4.1 Components

4.1.1 Lime binder

The aim of this work is not to give a description of the development of LHM use during the last 20 years. Many problems were encountered on building sites, mainly because of inappropriate binders. The first mixtures were made with cement binder and later some practitioners tried to use hydraulic lime alone or mixed binder containing gypsum with hemp particles. Undesired results resulted from powdering, water retention or moulding.

These problems can be avoided when using specific binder, containing a major part of hydrated lime, or more specifically of slaked calcium lime “CL90S” (following terminology of European standard EN 459-1:2001). Main quality of hydrated lime is the ductility given to final material, allowing slight distortion without cracking, and their specific open-porosity resulting in good permeability to vapour. The water absorbed in hemp particles needs time to be available for binder reaction; this fact agrees with lime chemical reaction (carbonation). Hydrated lime also has strong antifungal and antibacterial effects (high pH), destroying sprout of fungi and bacteria in hemp after mixing. The calcareous barrier also protects for a long period the relatively sensitive hemp particles. The main disadvantage of hydrated lime binder is the time needed for complete carbonation. Adding hydraulic and pozzolanic binders in the hydrated lime basis allows a faster start of the reaction, and a thorough process through the thickness of component. Few other additives can improve the quality of reaction or workability of mixings.

Further research projects can be carried out to optimise the binder used in LHM mixtures, on environmental or performances points of view. In this work, binder Tradical® pf 70 is used for LHM-wall and LHM-roof mixtures, and Tradichanvre® is used for LHM-plaster/render mixture. Both are products of Lhoist (see <http://www.bcb-tradical.fr>). Some samples were also prepared with pure calcium lime (CL90S) produced in Jemelle plant in Belgium: “Alpha 63” and “Éclat”. Table 1 gives details on the properties and on the chemical composition. Batching is presented in [%_{mass}].

Tradical® pf 70*:	75% of hydrated lime CL90S 15% of hydraulic binder 10% of pozzolanic binder ~0,5% of additives Density: 650 ± 20 kg/m ³ Grading: 0,001 to 0,09 mm (D50= 5,99 µm; D90= 27,72 µm)
Tradical® pf 70**:	Density: from 540 ± 15 kg/m ³ to 900 ± 20 kg/m ³ (Depending on settlement level)

Tradichanvre ^{®*} :	65% of Tradical [®] pf 80 35% of sand (CaCO ₃)
Tradichanvre ^{®**} :	Density: 870 ± 5 kg/m ³ (Minimal settlement)
Tradical [®] pf 80*:	85% of hydrated lime CL90S 15% of hydraulic lime ~0,8% of additives Density: 620 ± 20 kg/m ³ Grading: 0,001 to 0,09 mm (D50= 6,17 µm; D90= 25,78 µm)
Alpha 63**:	(from Jemelle plant in Belgium) 100% hydrated lime CL90S Density: from 356 ± 9 kg/m ³ to 593 ± 15 kg/m ³ (Depending on settlement level)
Éclat**:	(from Jemelle plant in Belgium) 100% hydrated lime CL90S Density: from 356 ± 7 kg/m ³ to 594 ± 12 kg/m ³ (Depending on settlement level)

Table 1
Chemical composition of binder

[% _{mass}]	Tradical [®] pf 70 (at 900°C)*	Tradical [®] pf 80 (at 900°C)*	Alpha 63 ***	Éclat ***
CaO	78,36	86,16	-	-
CaCO ₃	-	-	2,3	5,2
Ca(OH) ₂	-	-	96,4	92,8
MgO	1,02	0,78	0,584	0,879
Al ₂ O ₃	3,66	3,28	0,112	0,115
SiO ₂	10,51	8,21	0,141	0,203
Fe ₂ O ₃	1,58	0,36	0,179	0,322
Mn ₂ O ₃	0,08	0,01	-	-
MnO	-	-	0,021	0,036
Na ₂ O	0,25	0,22	0,053	0,073
P ₂ O ₅	0,07	0,08	<0,01	0,012
K ₂ O	0,42	0,22	0,023	0,035
SO ₃	1,6	1,27	0,119	0,195
Cl	0,01	0,01	0,011	0,016

Sign “*” means that the values are coming from technical document of the producer (1999); “***” when values are from First-BCCB measurements in Fraunhofer-IBP (2005). Average mass of the three samples of each binder was: 54 ± 1 grams for Tradical[®] pf 70, 87 ± 1 grams for Tradichanvre[®], 36 ± 1 grams for Alpha 63 and 36 ± 1 for Éclat. First value for density is measured when hemp particles are softly poured out in a cylinder (diameter: 10 cm, volume: 1 liter). The second value refers to the measure made after 50 bumps (to reach stabilized settlement); and “****” when they are from Lhoist R&D X-ray fluorescence (June 2005).

4.1.2 Hemp particles

Hemp growing produces around 8 to 10 tons of dry matter for one hectare: 2 tons of fibres (bark of the straw), 1 ton of seeds (containing ~300 Litres of a hydrated oil for food or cosmetic), around 5 tons of hemp particles (used for horse bedding or in LHM), and some dust³⁸.

Hemp particles measure few centimetres, as illustrated on Fig.18, and contain 50 to 60% of cellulose, 15 to 20% of hemicelluloses, 20 to 30% of lignin and 4 to 5 % of ashes³⁹. They can thus be considered as a type of wood. In addition, their cellular pattern is close from birch (lat. *betula*) or willow (lat. *salix*), as it appears on Fig.19.



Figure 18 : Hemp particles

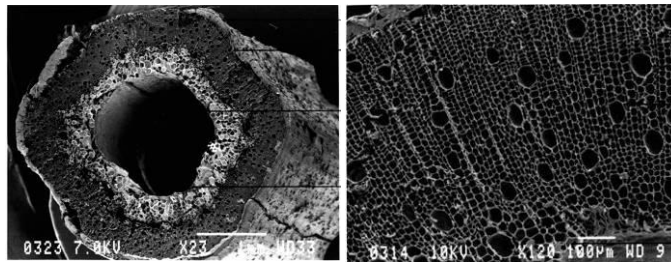


Figure 19 : SEM view of hemp particles [CERMAV-CNRS, 1993]

Chanvribat®:

(from La Chanvrière de l'Aube-LCDA in France)

Particles size from 0,5 cm to 2 cm

Almost no fibre or dust

Density: from $97 \pm 2 \text{ kg/m}^3$ to $162 \pm 2 \text{ kg/m}^3$
(Depending on settlement level)
Around 120 kg/m^3 when “placed”

Barvaux's Hemp:

(from André Barvaux's farm in Belgium)

Particles size from 0,5 cm to 8 cm

Contains many short fibres and dust

Density: from $52 \pm 1 \text{ kg/m}^3$ to $103 \pm 3 \text{ kg/m}^3$
(Depending on settlement level)
Around 100 kg/m^3 when “placed”

Chanvribat® hemp particles were chosen because they have a relatively constant size distribution, and low fibre/dust content. Some samples were also made with hemp particles grown and processed in Belgium (in the farm of André Barvaux). First density is measured on three samples (97 ± 1 grams for Chanvribat® and 52 ± 1 grams for Barvaux's Hemp) when hemp particles are softly poured out in a cylinder (diameter: 10 cm, volume: 1 litre). The particles form some “arches”, leaving empty zone under them (low density). A second value is measured after 50 bumps to reach stabilization. The third value obtained when “positioning” the particles manually, layers by layers in the cylinder, giving

³⁸ *Essai de comportement du chanvre en différentes station de Wallonie*, Sorghal, Report, Belgique, 2001

³⁹ *Nouvelles applications du chanvre en valorisation non-alimentaire*, Centre de Recherche sur les Macromolécules Végétales CERMAV-CNRS, Report, France, 1993

them a relative order (corresponding approximately to how LHM mixtures are implemented in the mould). The values are coming from First-BCCB measurements in Fraunhofer-IBP (2005). The very light bulk density of Barvaux's hemp is due to the presence of large size particles (~8cm) and fibres which generate arches in the cylinder. Arching is reduced with "settlement" and "positioning".

Ground, weather or harvesting process can influence product composition and a precise method for characterisation is still missing: size of particles, fibre or dust content (and characterisation), retting level... These aspects have an unknown influence on LHM parameters and should be analysed in further research. Other type of particles (cork, wood, expanded clay, vermiculite, perlite...) should also be analysed.

4.1.3 Batching of components

Three types of Lime-Hemp Material mixture was studied in this work: LHM-roof (Fig.20), LHM-wall (Fig.21) and LHM-plaster/render (Fig.22).

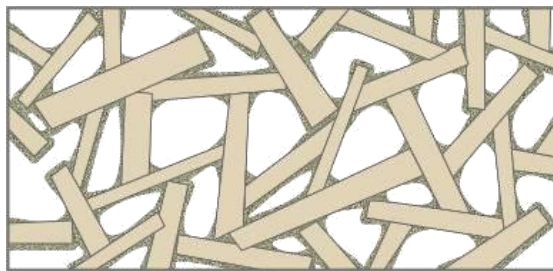


Figure 20 : Schematic view of LHM-roof

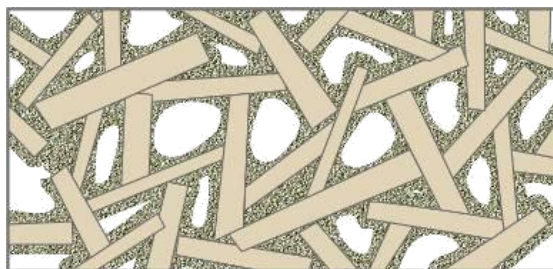


Figure 21 : Schematic view of LHM-wall

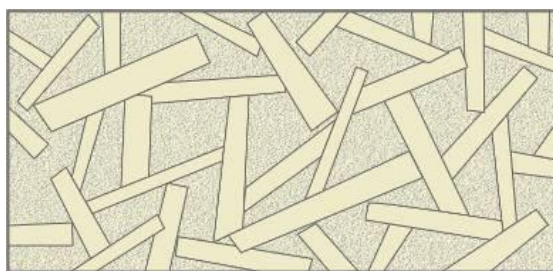


Figure 22 : Schematic view of LHM-plaster/render

Batching of components was adapted, based on producer's prescriptions, and expressed in terms of mass and volume. In Fig.23, Fig.24 and Fig.25, mass batching of the samples processed in Fraunhofer-IBP (2005) during the research First-BCCB is expressed in [%mass] and volumetric batching in terms of [%vol]. In addition, mass batching is also expressed in [kg] when 20kg of Chanvribat® is used (1 bag) and volumetric batching is given in [litre], corresponding to what is needed to obtain 1m³ of final material (based on bulk volume of reference samples defined in 4.3.1 and density of components presented in previous sections).

LHM-roof mix	Mass batching		Volumetric batching	
	[%mass]	[kg] if 20kg of Chanvribat	[%vol]	[litre] to obtain 1m³
Chanvribat	25%	20	73%	870
Tradical pf 70	25%	20	10%	120
Water	50%	40	18%	210
Total	100%	80	100%	1200

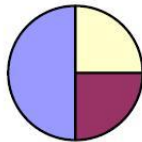


Figure 23 : Batching for LHM-roof

LHM-wall mix	Mass batching		Volumetric batching	
	[%mass]	[kg] if 20kg of Chanvribat	[%vol]	[litre] to obtain 1m³
Chanvribat	17%	20	55%	1010
Tradical pf 70	33%	40	23%	410
Water	50%	60	22%	400
Total	100%	120	100%	1820



Figure 24 : Batching for LHM-wall

LHM-pl/r mix	Mass batching		Volumetric batching	
	[%mass]	[kg] if 20kg of Chanvribat	[%vol]	[litre] to obtain 1m³
Chanvribat	9%	20	43%	910
Tradichanvre	55%	120	36%	750
Water	36%	80	21%	440
Total	100%	220	100%	2100



Figure 25 : Batching for LHM-plaster/render

Three reference set of samples, LHM-roof, LHM-wall and LHM-plaster/render are illustrated on Fig.26, Fig.27 and Fig.28. The mould for LHM-roof were 9,5cmx 20cmx 6cm (~1,14 litre). For LHM-wall and LHM-plaster/render they were cylinder-shaped with a diameter of 19cm; their height were 3,5cm for LHM-wall (~1 litre) and 3cm for LHM-plaster/render (~0,85 litre).



Figure 26 : LHM-roof



Figure 27 : LHM-wall



Figure 28 : LHM-plaster/render

All the samples were wrapped in aluminium foil except for the top surface to allow drying. Three identical prototypes of each set of sample were produced. Reference samples were processed with “normal” mixing, consistency and positioning, as further detailed in §4.2. For the other samples, only one parameter was changed.

For LHM-roof or LHM-wall samples using Belgian hydrated lime (Alpha 63 or Éclat) instead of Tradical® pf 70, the same mass of binder was used. Substituting Tradical® pf 70 with an equivalent volume of binder would have been a better choice. If the relatively small samples prepared with these binders had a good overall behaviour, the use of pure calcium lime (CL90S) to fill thick building elements could lead to a longer delay before being operational.

Some samples were made directly after mixing the components together. For others, the mixture was stored one day in a closed bucket, then mixed before implementation in the mould (type “T” for “Tag”). The mixture could be mixed the day after. To avoid initiating carbonation to start in porous structure of hemp particles partially filled with water (hydrated lime reacts with dissolved CO₂), other samples were produced by mixing only water and hydrated lime, respectively one days (type “Tb”) and one week (type “Wb”) before adding the hemp particles, mixing and implementing the mixture in the mould (lime paste was stored in a closed bucket). These differences, reproducing hydrated lime practitioners’ habits, did not have a significant effect on samples behaviour. Few samples are illustrated in Fig.29, Fig.30 and Fig.31.



Figure 29 : LHM-roof
(Alpha 63 "Tb")



Figure 30 : LHM-wall
(Éclat)



Figure 31 : LHM-wall
(Éclat "Wb")

For samples using Barvaux's hemp (Fig.32 and Fig.33), an equivalent bulk volume of hemp was used. Compared to what was observed when measuring bulk density of these hemp particles, arching is strongly reduced when they are wrapped in lime paste and when the mixture is "placed" in the mould. This fact was not taken into account and the quantity of Barvaux's hemp introduced in the samples could have been higher to give results equivalent to those obtained with Chanvribat[®]. It has to be noticed that mixing and positioning were more difficult with Barvaux's hemp because of long fibres and the wide range of particles size.



Figure 32 : LHM-roof
(Barvaux's hemp)



Figure 33 : LHM-wall
(Barvaux's hemp)

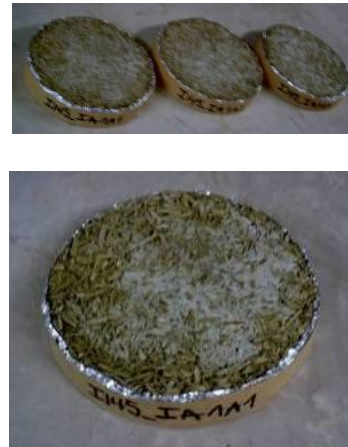


Figure 34 : LHM-wall
(High water input)

4.2 Implementation

4.2.1 Consistency / Water input

Optimal water input can be defined as the minimum amount of water that allows good workability of the mixture. If there is less water, the binder could have to less water to react completely (except when spraying). Water input of reference samples was not optimised, but a set of samples, illustrated in Fig.34, was produced to analyse the effect of high water input. The water input of these samples was 33% higher than the reference samples. The time needed for drying process of these samples was increased and final density was smaller, as detailed in §4.3.1.

4.2.2 Mixing

Many practitioners consider that Lime-Hemp Material should not be mixed too long or in a too violent way, because it could damage the hemp particles. A set of samples was processed, using Tradical® pf 70 and Chanvribat®, to analyse the influence of violent mixing. The reference mixture was softly hand mixed for 3 to 4 minutes (Fig.35). The mixture has to be homogeneous; this operation takes typically 3 to 4 min. “Violent” mixing (5min) was possible with a fast and powerful mixer (vertical axe), illustrated on Fig.36. Hemp particles were damaged, but arching in the hemp particles leads to strong resistance and the mixer was also damage after the third sample. Nevertheless, the samples produced under “violent” mixing did not show major differences compared to the other: drying process appeared to be shorter as reference samples, as presented in §4.3.1, and “positioning” the mixture in the mould was easier because the hemp particles were smaller.



Figure 35 : Hand mix



Figure 36 : “Violent” mixing



Figure 37 : Mould and board

4.2.3 Positioning

Implementation of reference samples in the mould (Fig.37) was made as close as possible as what is suggested on building sites⁴⁰: the mixture was manually filled (lightly pressed against edges, the rest was left loose). Two sets of samples, illustrated in Fig.38 and Fig.39, were processed to analyse the effect of “positioning”. The first set, called “loose”, was obtained by dropping the mixture in the mould and striking-off the surplus without pressing the mixture. For the other set, called “tamped”, mixture was pressed and “tamped” in the mould avoiding “arching” or empty zone (see §4.1.2). Next section shows the major influence of this factor on drying and final bulk density.



Figure 38 : LHM-wall
(not pressed)



Figure 39 : LHM-wall
(tamped)



Figure 40 : Saturated conditions

⁴⁰ *Construire en chanvre – Règles professionnelles d'exécution*, Commission Règles professionnelles de la construction en chanvre, 2004

4.3 Drying and carbonation

4.3.1 Drying

Once filled, the moulds were placed in saturated conditions (100% RH, $\sim 20^{\circ}\text{C}$) during 3 to 5 days, in boxes illustrated on Fig.40. This is a classical procedure for mortar and concrete samples. Loss of mass of the samples was negligible during this period of time. After that period, all the samples were stored in a climate room regulated at 65% (23°C) and their mass m^* [kg] was measured twice a day, during more than 1 month.

Bulk volume V^* [m^3] was measured for all samples at the end of measurement period. Shrinkage of LHM-wall, V_{mould}/V^* , was 2,4% of volume for the reference samples. It was negligible for “tamped” samples ; 3,8% for samples “loose” ; 5,3% for samples with “violent mixing” ; and 6,9% for samples with “high water input”. The values are very high compared to what is usually observed on building site and further researches should define the factors of influence for shrinkage of large size components.

If the shrinkage (ΔV) is neglected, the evolution of *density*, ρ [kg.m^{-3}], during drying/carbonation process can be calculated with $\rho(t) = m(t) / V^*$, where m [kg] is the mass of the samples and t , the *time* [h]. Evolution of density for all the samples is illustrated in Fig.41 to Fig.44. It has to be noticed that the geometrical conditions of the experiment (1 side is drying), the size of the samples (much thinner than building components) and the boundary conditions (climate chamber at 65%/23°C vs. wind, sun...) are not representative of real building conditions. The time expected for drying a wall component on building site (30cm wide) is discussed in 7.5.1 and is longer than for the small samples analysed here.

Drying and carbonation processes occur at the same time. Drying results in a loss of mass through top surface. Carbonation is the chemical reaction that changes the hydrated lime into lime stone, as presented in 0. Carbonation is a slow reaction that increases density, as molar mass of lime stone is 35% higher than hydrated lime. Drying process is much faster in the beginning. Mass increase of carbonation equilibrates mass release from drying when mass reaches a minimum value. This value is referred as the *minimum mass*, m_{min} [kg] and *minimum density* [kg.m^{-3}] is defined as $\rho_{\text{min}} = m_{\text{min}} / V^*$. The period before the minimum mass was obtained is referred as “drying”, and the period that follows (until end of measurements), as “carbonation”. Carbonation actually starts before this moment and drying may not be yet completed during the second period. Next section will discuss how to assess carbonation progress in LHM-wall reference samples.

Reference LHM-wall samples took 29 days to reach their minimum density $400 \pm 4 \text{ kg.m}^{-3}$. Compaction appears to have a great influence on water release and density: the stronger the mixture was pressed, the heavier it gets ($309 \pm 3 \text{ kg.m}^{-3}$ for “loose” and $470 \pm 7 \text{ kg.m}^{-3}$ for “tamped”) and the slower it dries (19 days for samples “loose” and 33 days for samples “tamped”). “Violent” mixing has no significant effects ($400 \pm 15 \text{ kg.m}^{-3}$ in 25 days) but increases the standard deviation of measurements. High initial water content decrease minimum density of approximately 10 % ($362 \pm 22 \text{ kg.m}^{-3}$) and slightly increases drying time (31 days).

LHM-wall samples reached respectively $422 \pm 9 \text{ kg.m}^{-3}$ in 31 days for “éclat”, $385 \pm 1 \text{ kg.m}^{-3}$ in 35 days for “éclat T”, $406 \pm 4 \text{ kg.m}^{-3}$ in 40 days for “éclat Tb”, $407 \pm 12 \text{ kg.m}^{-3}$ in 29 days for “éclat Wb”, $406 \pm 7 \text{ kg.m}^{-3}$ in 30 days for “alpha63 Tb”, $395 \pm 3 \text{ kg.m}^{-3}$ in 29 days for “alpha63 Wb”. LHM-wall samples made with Barvaux’s hemp took 18 days to reach $503 \pm 15 \text{ kg.m}^{-3}$. Density is higher because the same bulk volume of hemp was introduced instead of Chanvribat® (see 4.1.3) but “arching” is strongly reduced when lime and water is added. Equivalent mass of Barvaux’s hemp should give similar density.

Reference LHM-roof samples took 32 days to reach their minimum density $217 \pm 22 \text{ kg.m}^{-3}$. LHM-roof samples made with Barvaux’s hemp took 24 days to reach $277 \pm 17 \text{ kg.m}^{-3}$ (same remark on density). LHM-roof samples made with different binder respectively reached a minimum density of $243 \pm 5 \text{ kg.m}^{-3}$ in 41 days for “éclat Tb”, and $245 \pm 4 \text{ kg.m}^{-3}$ in 44 days for “alpha63 Tb”.

Minimum density of reference LHM-plaster/render samples is higher than for the other mixtures: $785 \pm 20 \text{ kg.m}^{-3}$. It took 28 days to reach this value. For the samples with “high water input”, the minimum density was $515 \pm 10 \text{ kg.m}^{-3}$ and was reached in 40 days. It can be noticed that initial density is almost the same (the mould were full). The deviation is mainly due to a strong difference in porosity of final material.

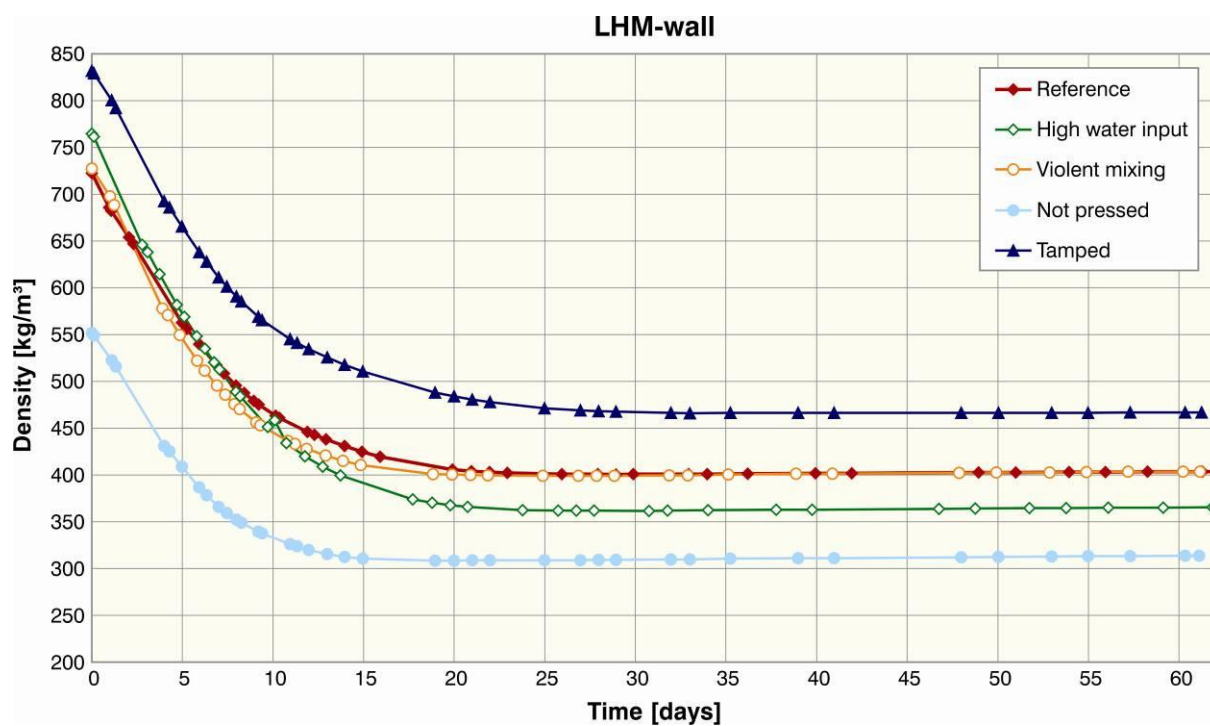


Figure 41 : Evolution of density of LHM-wall samples using Tradical® pf 70 and Chanvribat®

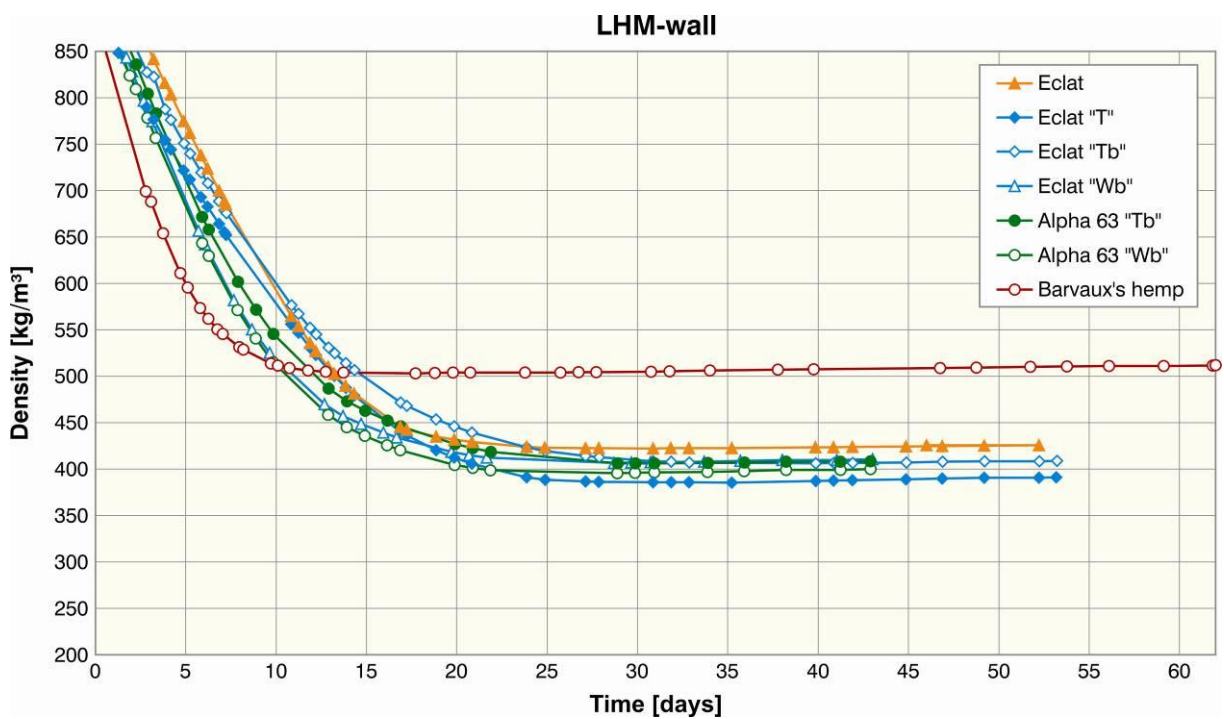


Figure 42 : Evolution of density of LHM-wall samples using other components

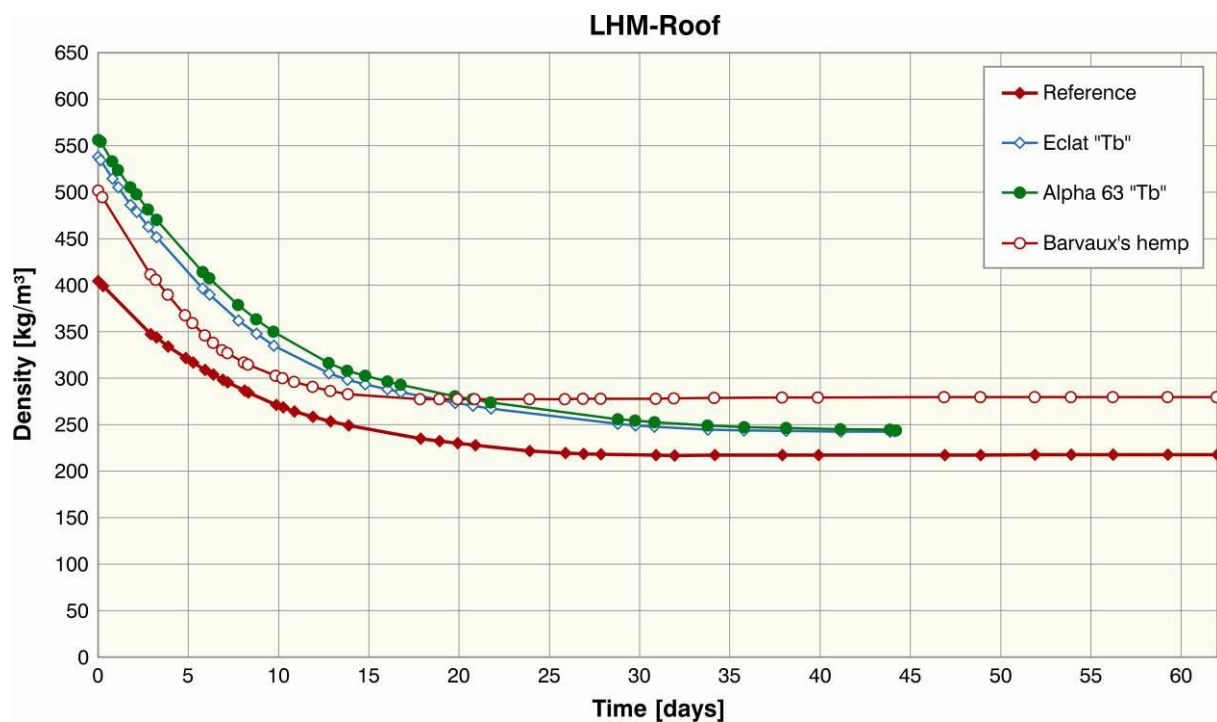


Figure 43 : Evolution of density of LHM-roof samples

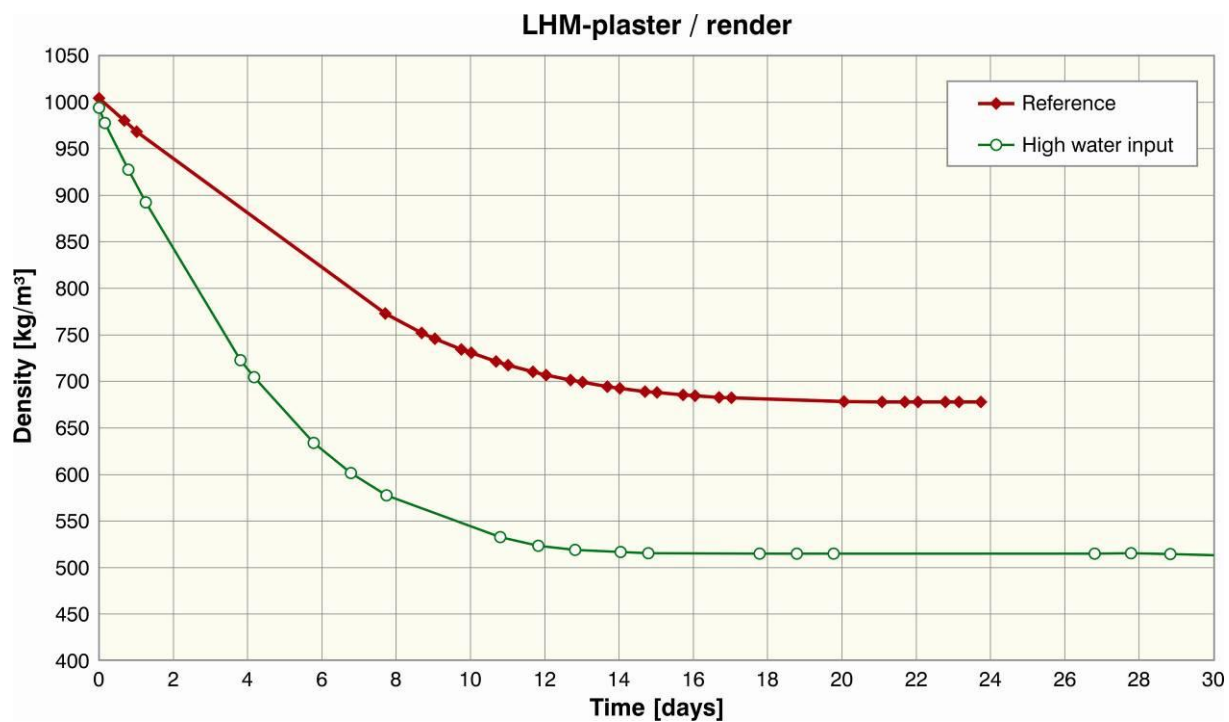


Figure 44 : Evolution of density of LHM-plaster/render samples

4.3.2 Carbonation

Carbonation is the chemical reaction that changes the hydrated lime, Ca(OH)_2 , into lime stone, CaCO_3 :



This slow reaction increases density because *molar mass*, M [g/mol], of lime stone is 35% higher than hydrated lime ($M_{\text{Ca(OH)}_2} = 74$ g/mol ; $M_{\text{CaCO}_3} = 100$ g/mol).

From the moment the minimum mass is reached and until the end of the measurements, a slight increase of mass was measured for all the samples. Both the *water content of the samples* w [kg.m^{-3}] and the *mass increment due to carbonation* m_{carb} [kg] are linked through

$$\Delta m^* = \Delta(w + \rho_{\text{carb}}). \quad (36)$$

Dry mass of the samples and water content during carbonation process were not measured. It is thus not possible to distinguish mass variation due to drying from what is due to carbonation.

The *theoretical dry density, when carbonation is completed*, is $\rho_{\text{th},s}$ [kg.m^{-3}]. It is expressed as

$$\rho_{\text{th},s} = (\rho_{\text{init}} - w_{\text{init}}) + \rho_{\text{carb,th}} = 421 \text{ kg.m}^{-3} \quad (37)$$

where complete carbonation of the binder (244 kg.m^{-3} of Tradical® pf 70) should produce in reference LHM-wall a *theoretical increase of mass due to carbonation* of $\rho_{\text{carb,th}} = 58 \text{ kg.m}^{-3}$ (moisture “trapped” in hydraulic reactions is neglected); and where ρ_{init} [kg.m^{-3}] is the *initial mass of components used to produced 1m^3 of material*. For reference sample of LHM-wall $\rho_{\text{init}} = 365 \text{ kg.m}^{-3}$. *Initial water content in the components* w_{init} [kg.m^{-3}] was measured (components came from closed bags) and it is expressed in terms of mass in 1m^3 of material. It is $w_{\text{init}} = w_{\text{init,hemp}} + w_{\text{init,lime}} = 2,1 \pm 0.1 \text{ kg.m}^{-3}$.

The *theoretical equilibrium density at 65% of RH (23%) and when carbonation is completed* is $\rho_{\text{th},65\%}$ [kg.m^{-3}] is expressed as

$$\rho_{\text{th},65\%} = (\rho_{\text{init}} - w_{\text{init}}) + \rho_{\text{carb,th}} + w_{65\%} = 452 \text{ kg.m}^{-3} \quad (38)$$

where *equilibrium moisture content of LHM-wall* in 65% of RH is considered to be $w_{\text{eq},65\%} = 31 \text{ kg.m}^{-3}$, as detailed in 6.1 (different samples).

Three assumptions are made on LHM-wall reference samples :

- 1/ equilibrium of moisture content is reached after 29 days (minimum mass), $w_{29d} = w_{eq,65\%}$ (see 6.1) ;
- 2/ moisture content stays constant for 33 more days (62 days of measurements) ;
- 3/ the samples will reach $\rho_{th,65\%}$.

Based on these assumptions, it is possible to calculate the *increase of mass due to carbonation*: after 29 days ρ_{carb} , $\rho_{carb,29d} = 6 \text{ kg.m}^{-3}$; and after 62 days, $\rho_{carb,62d} = 10 \text{ kg.m}^{-3}$. 10% of carbonation would be achieved after 29 days ($\rho_{carb,29d} / \rho_{carb,th} = 0,1$), and 17% after 62 days ($\rho_{carb,62d} / \rho_{carb,th} = 0,17$). The relationship

$$\Delta\rho_{carb,d} = (\rho_{carb,end} - \rho_{carb,init}) / \Delta t_{carb} \quad (39)$$

defines the *daily increase of mass due to carbonation* $\Delta\rho_{carb,d} [\text{kg.m}^{-3}.\text{days}^{-1}]$, where $\Delta t_{carb} [\text{days}]$ is the *carbonation period*. In this case, $\Delta t_{carb} = 33$ days, and $\Delta\rho_{carb,d} = 0,12 \text{ kg.m}^{-3}.\text{days}^{-1}$. At this speed, the carbonation should be finished in 396 days (> 1 year). These assumptions were not validated rigorously. They have strong influence on results.

5 Hygrothermal parameters in dry state

Measurements presented in this chapter were achieved on samples cut out from blocks of LHM-wall mixture prepared three years earlier and shown on Fig.45. Those blocks were produced on building site. If batching of Chanvribat[®] and Tradical[®] pf 70 corresponds to producer's prescriptions (see 4.1.3), water input, mixing and implementation did not receive the precision enabled in Fraunhofer-IBP's laboratory. During three years, the samples were stored in typical inside conditions (~20°C/50% of RH). Both drying and carbonation are considered to be achieved after this period.

5.1 Density

Surprisingly, *dry density* ρ_0 [kg.m⁻³] of LHM-wall was never specifically discussed in other researches. On producer's documents, density of LHM-wall and LHM-roof are announced to be: $\rho_{\text{roof}} = 200$ to 220 kg.m⁻³ ; and $\rho_{\text{wall}} = 300$ to 350 kg.m⁻³ (climatic conditions are not given). These value are low compared to the measurements performed at ENTPE⁴¹ on samples stored 6 months in a room with 60% of RH and ~20°C: $\rho_{\text{roof}} = 256$ kg.m⁻³ ; $\rho_{\text{wall}} = 398$ kg.m⁻³. Carbonation may not be fully completed, see §0.



Figure 45 :
Using LHM-wall blocks



Figure 46 :
Drying oven



Figure 47 :
Electronic scale



Figure 48 :
Size measuring

⁴¹ *Propriétés mécaniques, thermique et acoustiques d'un matériau à base de particules végétales : approche expérimentale et modélisation théorique*, V. Cerezo, Ph.D. thesis at ENTPE, France, 2005

In order to reach dry state, samples were introduced in an oven at 40°C with dry air supply, as illustrated in Fig.46. As introduced in 3.2.1.1, mass equilibrium is considered to be reached when mass measurement varies less than 1% between 2 measurements on a 24h basis. Mass of the samples was measured with an electronic scale, shown in Fig.47, and their size, with a set of instruments presented in Fig.48.

Dry density was measured on 10 dry samples of LHM-wall ($38,5 \pm 2 \text{ cm}^3$, $13,5 \pm 0,5 \text{ g}_{\text{dry}}$): $\rho_{s,\text{small}} = 480 \pm 20 \text{ kg.m}^{-3}$. Those samples were smaller than RVE, see §3.1. Dry density block-samples was then measured on 5 larger samples ($318 \pm 4 \text{ cm}^3 > \text{RVE}$, and $140 \pm 4 \text{ g}_{\text{dry}}$). Considering carbonation and water content, density of these samples roughly correspond to density of “reference” samples detailed in 0 (the difference may come from a difference in implementation process of block-samples). Reference value for LHM-wall is given by

$$\rho_0 = \rho - w = 440 \pm 20 \text{ kg.m}^{-3}. \quad (40)$$

5.2 Porosity

Chapter 1.2 and 3.2.1.1 already introduced the specific porosity of LHM-wall. Macroscopic porosity includes pores from 1mm to a few centimetres large, as presented in Fig.49. The pores are interconnected: large pores open on smaller ones (pores in hemp particles $\sim 10\mu\text{m}$), through the porosity of the lime binder ($\sim 1\mu\text{m}$).

“Representative volume element” (RVE) of LHM-wall is not easy to define. Theoretically, RVE is not larger than few cubic centimetres (size of particles). Visual analysis of Fig.50 shows that only samples larger than 100 cm^3 (cubes with side $> 4,7 \text{ cm}$) enable to take into account the specific pores and particles distribution (arching) of the material.

In a few experiments, the samples were smaller than RVE. This is the case for the six samples of LHM-wall ($\sim 1,5 \text{ cm}^3$, $2,4 \pm 4 \text{ g}_{\text{dry}}$) introduced in helium pycnometer (Fig.51) to measure *average density of solid part of LHM* $\rho_s [\text{kg.m}^{-3}]$ (considering hemp particles and lime matrix). Size of the samples was thus not a problem here, since proportion of hemp particles and matrix is considered to be constant. Results was $\rho_s = 1660 \pm 30 \text{ kg.m}^{-3}$. *Dry total porosity* $\psi_0 [\%_{\text{vol}}]$ is calculated using ρ_s as well as reference dry density through

$$\psi_0 = 100 \times (1 - \rho_0 / \rho_s). \quad (41)$$

Reference dry total porosity of LHM-wall approximately corresponds to value of *open porosity* $\psi_a [\%]$ measured in ENTPE⁴² on equivalent LHM-wall mixture through air pressure measurement in a piston ($\psi_a = 77\%$). It is given by

$$\psi_0 = 73 \pm 1 \%_{\text{vol}} \quad (42)$$

⁴² *Propriétés mécaniques, thermique et acoustiques d'un matériau à base de particules végétales : approche expérimentale et modélisation théorique*, V. Cerezo, Ph.D. thesis at ENTPE, France, 2005



Figure 49 : Macroscopic porosity

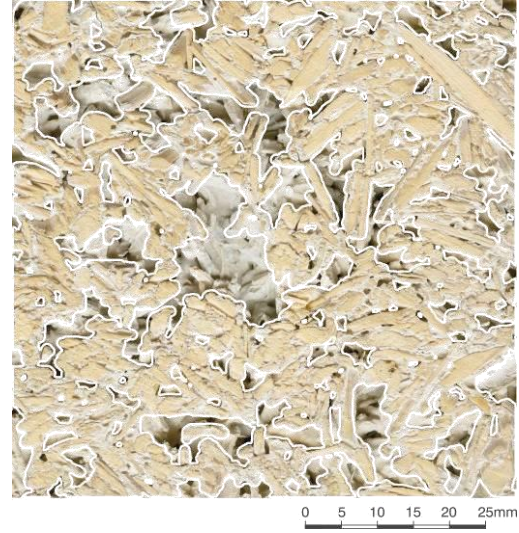


Figure 50 : Porosity analysis



Figure 51 :
Helium pycnometer



Figure 52 :
Measuring of thermal capacity



Figure 53 :
Aluminium samples

5.3 Thermal capacity

Dry thermal capacity c_0 [$\text{J.kg}^{-1}.\text{K}^{-1}$] was measured on 5 samples ($318 \pm 4 \text{ cm}^3$, and $140 \pm 4 \text{ g}_{\text{dry}}$) with equipments illustrated in Fig.52. Samples were first dried and heated to $\theta_{\text{init}} = 100^\circ\text{C}$. They were then introduced into an adiabatic can filled with water at $\theta_{\text{init,w}} = 22^\circ\text{C}$ (room temperature). Water temperature is measured until new equilibrium (θ_{end} [$^\circ\text{C}$]). Thermal capacity of the samples was determined through

$$c_0 = c_w \cdot m_w \cdot (\theta_{\text{end}} - \theta_{\text{init,w}}) / m_0 \cdot (\theta_{\text{end}} - \theta_{\text{init}}), \quad (43)$$

from the *thermal capacity of water* at 20°C $c_w = 4176 \text{ J.kg}^{-1}.\text{K}^{-1}$, the *mass of water* m_w [kg] and the *dry mass of samples* $m_s = 140 \pm 4 \text{ g}$. The method was validated with measurement on aluminium samples ($c_{\text{alu}} = 920 \text{ J.kg}^{-1}.\text{K}^{-1}$) illustrated on Fig.53. Reference *dry thermal capacity* of LHM-wall, given by

$$c_0 = 1560 \pm 30 \text{ J.kg}^{-1}.\text{K}^{-1}, \quad (44)$$

is the mean value of the 5 samples. It is slightly higher than the value ($1400 \text{ J.kg}^{-1}.\text{K}^{-1}$) measured by CSTB (France) in 1999 on another mixture called «Isochanvre construction – chaux naturelles» and used in other research until now.

5.4 Thermal conductivity

Thermal conductivity of numerous samples was measured at ENTPE⁴³ in dry and moist state. For equivalent density, the results are in good agreement with results presented hereafter.

Dry thermal conductivity λ_0 [$\text{W.m}^{-1}.\text{K}^{-1}$] of 3 LHM-wall samples ($1180 \pm 30 \text{ cm}^3$, $530 \pm 25 \text{ g}_{\text{dry}}$) was measured following DIN 52 616. Each sample was dried, then subjected to a temperature difference of $\Delta\theta=10^\circ\text{C}$ between a hot and a cold plate at three different temperature steps. The mean temperature was respectively of $18 \pm 0,2^\circ\text{C}$, $26 \pm 0,2^\circ\text{C}$ and $34 \pm 0,3^\circ\text{C}$. Each step takes around 2 hours. Water uptake of the samples after the three steps was less than 0,4% of mass. Equipment is illustrated in Fig.54 and Fig.55 (the insulated bow is closed during measurments).

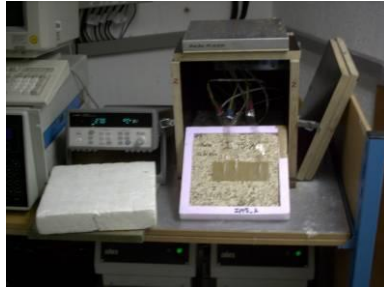


Figure 54 : Sealing with paraffin



Figure 55 : Dy-cup experiment

The dry thermal conductivity is calculated by

$$\lambda_0 = \frac{\dot{q}.d}{\Delta\theta}, \quad (45)$$

with the ratio of *heat flow* $\dot{q}$ [W.m^{-2}] and *temperature difference between the two plates* $\Delta\theta$ [$^\circ\text{C}$], where d is the *thickness of the samples* $d= 30 \pm 0.7 \text{ mm}$. Heat flow through sample 1 is illustrated in Fig.56 during the three temperature step.

As illustrated in Fig.57, reference value for of LHC-wall mixture is the mean value of extrapolation of results at 10°C for the 3 samples:

$$\lambda_0 = 0,115 \pm 0,006 [\text{W.m}^{-1}.\text{K}^{-1}]. \quad (46)$$

It is compared to dry thermal conductivity of other materials in 7.1.

⁴³ *Propriétés mécaniques, thermique et acoustiques d'un matériau à base de particules végétales : approche expérimentale et modélisation théorique*, V. Cerezo, Ph.D. thesis at ENTPE, France, 2005

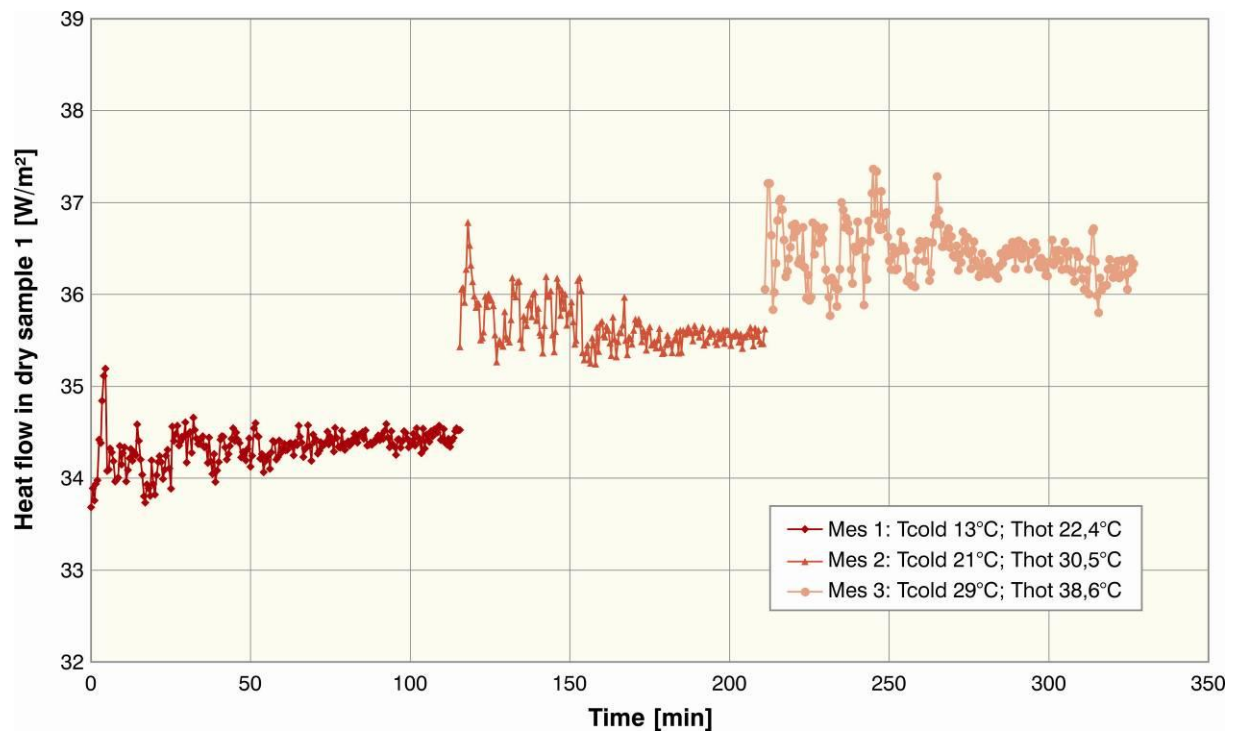


Figure 56 : Heat flow through LHM-wall samples

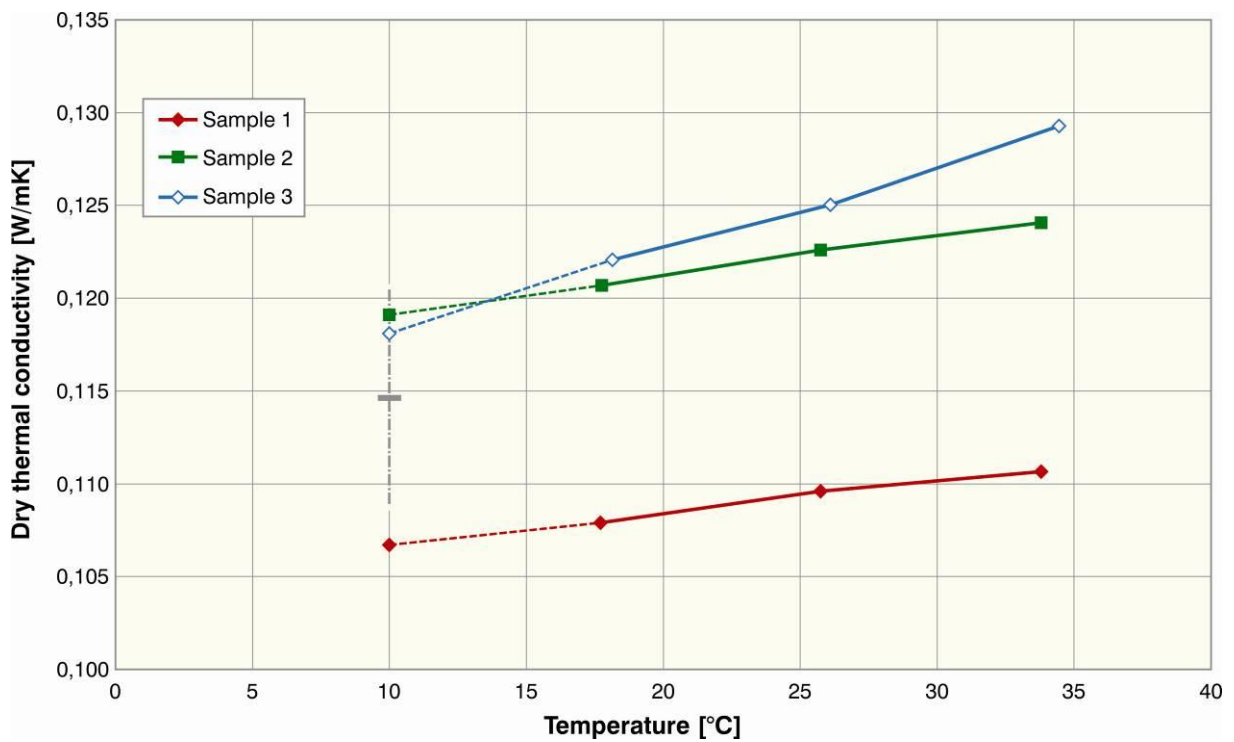


Figure 57 : Dry thermal conductivity of LHM-wall

5.5 Vapour permeability

Water vapour permeability of LHM-wall was measured following DIN 52 615 (EN ISO 12572). Fig.58 shows the operating diagram of the experiment. The 4 block-samples ($846 \pm 12 \text{ cm}^3$, $407 \pm 7 \text{ g}$) were sealed on glass cups with paraffin (L~18cm, l~13cm, H~18cm). The paraffin avoids any vapour transfer on the sides of the samples; the moisture flow can only go through top surface. “Dry-cup method” is used to determine *dry vapour diffusion resistance factor* μ_0 [-]. Glass cups were filled with silica gel, leaving a 2 cm air layer under the sample surface (RH of 3% when the silica gel are dried before the experiment). The 4 samples were then introduced in a climate chamber at 50% of RH (23°C) as illustrated in Fig.59.

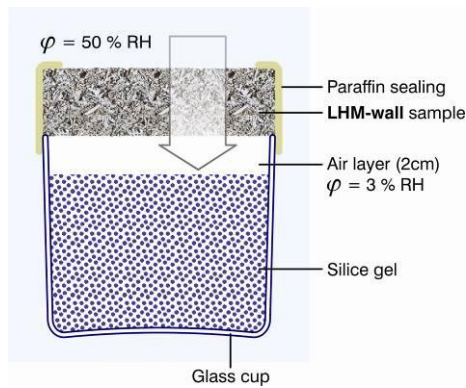


Figure 58 : Operating diagram for dry-cup



Figure 59 : Dry-cup experiment

To find the dry vapour diffusion resistance factor, μ_0 , of the material, it is necessary to define the *vapour diffusion thickness* S_d [m], which is the thickness of the equivalent air layer in terms of vapour permeability. S_d -value is calculated with

$$S_d = \mu \cdot d \quad (47)$$

The driving force bringing the moisture in the cups is the gradient of vapour pressure. The flow is positive when going from out to in, and $\Delta p_v = p_{v,in} - p_{v,out} = -1320 \text{ Pa}$. *Time interval* during which permanent transfer was reached was $\Delta t = t_{12d} - t_{4d} = 192 \text{ h}$. *Mean mass uptake of the samples during this interval* was $\Delta m = 0,022 \text{ kg}$, and the *surface of transfer* was $S_{\text{sample}} = 213 \pm 4 \text{ cm}^2$. The *vapour permeability of air* in this conditions was $\delta_a = 7,53 \cdot 10^{-7} [\text{kg} \cdot \text{m}^{-1} \cdot \text{h}^{-1} \cdot \text{Pa}^{-1}]$. The next relationship

$$\dot{m}_v = \frac{\Delta m}{S_{\text{sample}} \cdot \Delta t} = - \frac{\delta_a}{S_{d_{\text{tot}}}} \cdot \Delta p_v \Rightarrow S_{d_{\text{tot}}} = \frac{\delta_a \cdot S_{\text{sample}} \cdot \Delta t \cdot (-\Delta p_v)}{\Delta m} \quad (48)$$

combines expressions (14), (15) and (45) to calculate the *vapour diffusion thickness*, $S_{d_{\text{tot}}}$ [m], of both the sample and the 2cm air layer between sealed sample and silica gel in the cup.

The vapour diffusion thickness of these both layers, $S_{d_{\text{tot}}}$ [m], is equivalent to the sum of the vapour diffusion thickness of each layer, $S_{d_{\text{sample}}}$ [m] and $S_{d_{2\text{cm}}}$ [m]. The *mean thickness of the samples* is $d = 3,57 \pm 0,06 \text{ cm}$, and *vapour diffusion resistance factor of air* $\mu_a = \delta_a / \delta_a = 1$ [-].

The relationships

$$Sd_{tot} = Sd_{sample} + Sd_{2cm} = \mu_{tot} \cdot d_{tot} = \mu_0 \cdot d + \mu_a \cdot d_{2cm} \quad (49)$$

$$\mu_0 = (Sd_{tot} - d_{2cm}) / d_{samples} \quad (50)$$

allows calculating the dry vapour diffusion resistance factor μ_0 [-] of the samples.

Mass increase of the samples vapour transfers from climate chamber to silica gel in the cup is expressed in Fig.60 in terms of *mass uptake* [kg.m⁻²]. The reference *dry vapour diffusion resistance factor* of LHM-wall, μ_0 [-], given by

$$\mu_0 = 4,85 \pm 0,24 \quad (51)$$

is the mean value of the 4 samples. Using relationship (15), their *dry vapour permeability* δ_0 [kg.m⁻¹.s⁻¹.Pa⁻¹] can be expressed as

$$\delta_0 = \delta_a / \mu_0 = (1,56 \pm 0,08) \cdot 10^{-7} \text{ kg.m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1} \quad (52)$$

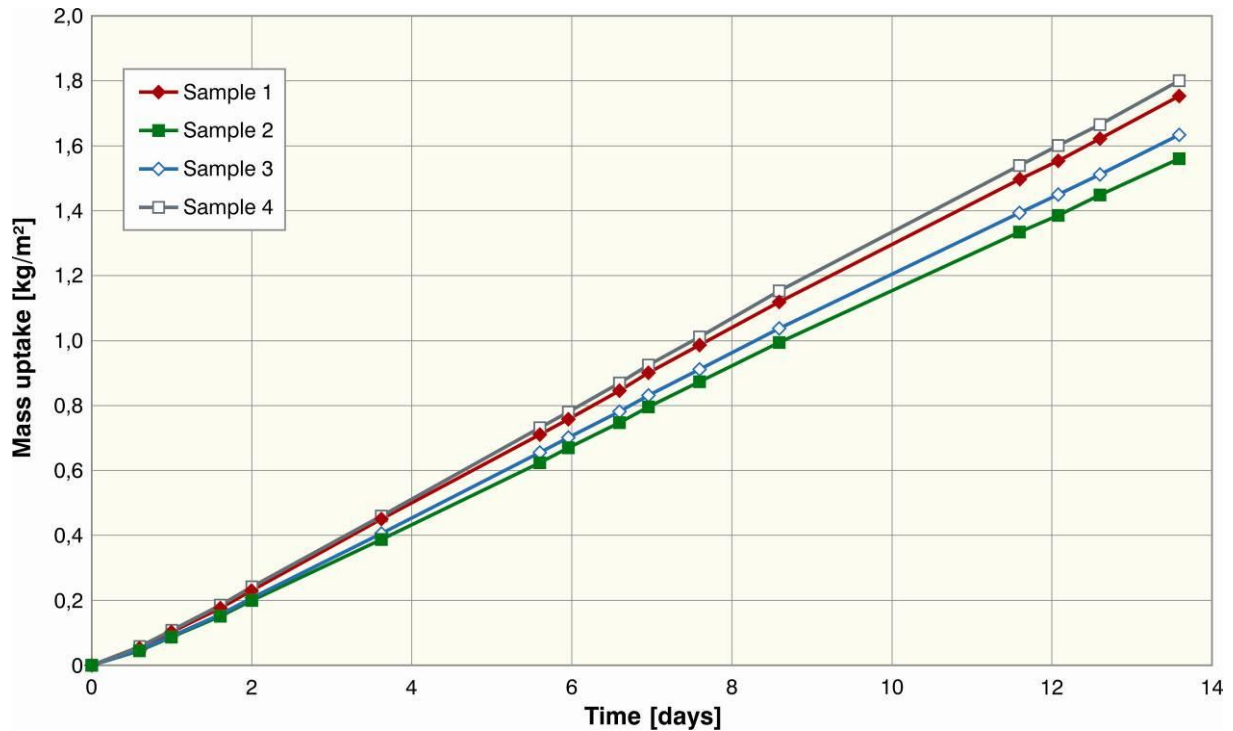


Figure 60 : Mass uptake during dry-cup experiment

6 Moisture retention and influence on parameters

6.1 Moisture Retention Curve

Like other materials with open-porous structure, Lime-Hemp Materials, are permeable to gas and liquid depending on their specific porous structure. Moisture can be temporary stored during transfer and three moisture storage regions were detailed by Künz⁴⁴. WUFI[®] model only allow to input a single sorption curve (no difference between sorption and desorption process).

As presented in 3.2.1.1, hygroscopic (ad)sorption is rising from dry-state to high relative humidity. Region A stops when capillary condensations (condensation in the small pores) and surface diffusion (adsorbed film of water is thick enough to allow water movement) in porous structure of material start to be significant compare to hygroscopic sorption. For LHM-wall these two phenomena are considered to start around 93% RH. Region B thus extends from 93% until free saturation (100% of RH). Over free saturation, water content can still rise but its value is not unique for a given RH level and strongly depends on pressure and time. Fig.61 to Fig.63 give schematic view of porous structure in these 3 regions.

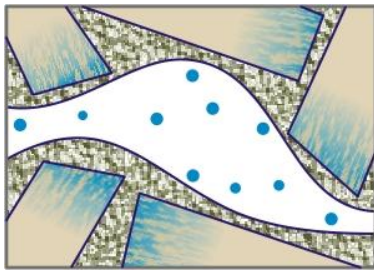


Figure 61 : Region A

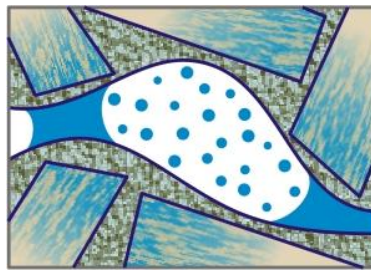


Figure 62 : Region B

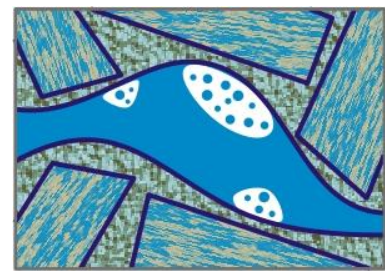


Figure 63 : Region C

Hygroscopic sorption was measured on a relatively low amount of crushed material. According to Fraunhofer-IBP knowledge, block-samples and crushed samples have the same sorption curve but equilibrium is attained faster with crushed samples. However, samples described in §6.5 were relatively big block-samples ($1180 \pm 30 \text{ cm}^3$, $530 \pm 25 \text{ g}_{\text{dry}}$) and never reached the equilibrium moisture content of crushed samples. Further sorption experiments are needed to explain these deviations.

Crushed samples ($20 \pm 1,3 \text{ g}_{\text{dry}}$) are presented in Fig.64. Like in the previous chapter, mass equilibrium is considered to be reached when mass measurement varies by less than 1% between 2 measurements on a 24h basis. Desired relative humidity was obtained (for sorption measurements and for other experiments) either in climate chamber (50%, 65% and 80% of RH) or in glass desiccators (32%, 93% and 96% of RH) containing salt solution (respectively MgCl_2 , $(\text{NH}_4)_2\text{HPO}_4$, KH_2PO_4). An example of glass desiccator is illustrated in Fig.65.

⁴⁴ *Simultaneous Heat and Moisture Transport in Building Component: One- and Two-dimensional calculation using simple parameters*, H.M. Künz⁴⁴, thesis at Fraunhofer-IBP, Stuttgart, 1995

Table 2 presents the results of hygroscopic sorption experiment as well as calculation of specific hygric capacity ξ_ϕ (defined in 3.2.1.1) for each relative humidity. Water content and hygric capacity are expressed in [%_{mass}] (mass in moist state is divided by dry mass), and in [kg.m⁻³] by multiplying results by the reference dry density ($\rho_0 = 440 \text{ kg.m}^{-3}$).



Figure 64 :
Samples for hygroscopic
sorption measurements



Figure 65 :
Glass desiccator



Figure 66 :
Free saturation

TABLE 2
Results for hygroscopic sorption

Relative humidity [% _{HR}]	w [% _{mass}]	ξ_ϕ [% _{mass}]	w [kg.m ⁻³]	ξ_ϕ [kg.m ⁻³]
0	0	-	0	-
32	3,2 ± 0,2	9,9	14 ± 1	43,8
50	4,7 ± 0,2	7,6	20 ± 1	33,3
65	6,4 ± 0,2	12,1	28 ± 1	53,3
80	7,6 ± 0,2	7,6	33 ± 1	33,3
93	9,2 ± 0,3	15,7	42 ± 2	69,2
96	14,2 ± 0,5	151,5	62 ± 3	666,7

All the measurements were made at 23°C. Effects of temperature on sorption behaviour were thus neglected. It has to be noticed that equilibrium was sometimes long to get, even with the small crushed samples: from a few days in low RH to more than 15 days in high RH. Hysteresis between sorption and desorption in region A was observed during complementary measurements, but this phenomenon is not considered in WUFI[®] model. This hysteresis seems to be dependent on initial and final RH, as well as on the geometry of samples. Additional experiments are still necessary to understand and quantify this phenomenon. Results obtained in France^{45,46} on the same mixture are slightly higher.

⁴⁵ *Caractérisation hydrique et thermique de matériaux de Génie Civil à faibles impacts environnementaux*, F. Collet, Ph.D. thesis at INSA de Rennes, France, 2004

⁴⁶ *Propriétés mécaniques, thermique et acoustiques d'un matériau à base de particules végétales : approche expérimentale et modélisation théorique*, V. Cerezo, Ph.D. thesis at ENTPE, France, 2005

Complementary measurements were necessary to establish the complete Moisture Retention Curve (MRC) of LHM-wall mixture, as defined in 3.2.2.1. First, the water content at free saturation, called *free saturation* and written w_f , was determined by placing dry samples under water until mass equilibrium was obtained. 3 samples ($875 \pm 30 \text{ cm}^3$, $407 \pm 7 \text{ g}_{\text{dry}}$), illustrated in Fig.66, were used. Its value can be expressed in [%_{mass}] and in [kg.m^{-3}], as

$$w_f = 124 \pm 3,5 \text{ \%}_{\text{mass}} = 546 \pm 16 \text{ kg.m}^{-3} . \quad (53)$$

Maximal water content w_{max} was then calculated based on total porosity measurement. If the porous structure is considered to be completely filled with water (the *density of water* at 23°C is $\rho_w \sim 1000 \text{ kg.m}^{-3}$), its value is given by

$$w_{\text{max}} = \psi_0 \cdot \rho_w = 730 \pm 10 \text{ kg.m}^{-3} = 166 \pm 3 \text{ \%}_{\text{mass}} . \quad (54)$$

Water content in higher humidity (between 93% and 100%) has to be measured with specific equipments. Fig.67 presents pressure plate apparatus of Fraunhofer-IBP. This equipment is detailed in [Krus, 1996]⁴⁷. Fig.68 gives a schematic description of the equipment. After complete drying, 10 samples ($28,3 \pm 0,8 \text{ cm}^3$, $13,6 \pm 0,5 \text{ g}_{\text{dry}}$) were placed under water until mass equilibrium was obtained (free saturation) before being introduced in the apparatus, as presented in Fig.69 to Fig.71. Starting from a very low overpressure (0,001 bar), inside pressure was successively increased to higher overpressure: 0,05 bar ; 0,15 bar ; 0,5 bar ; 1,5 bar ; 5 bar and 15 bar. Each pressure step ends when no more water is leaking out through ceramic plate. Mass of the samples is then measured before being subjected to the next pressure step.



Figure 67 :
Pressure plate apparatus

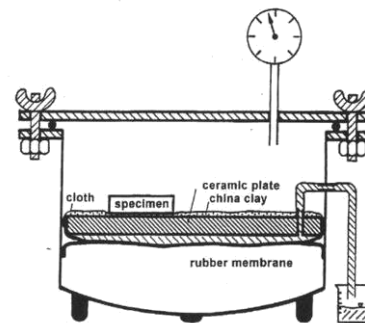


Figure 68 :
Schematic description



Figure 69 :
Drying in oven



Figure 70 :
Reaching free saturation



Figure 71 :
Samples disposals

⁴⁷ *Moisture Transport and Storage Coefficients of Porous Mineral Building Materials : Theoretical Principles and New Test Methods*, M. Krus, thesis at Fraunhofer-IBP, Stuttgart, 1996

Capillary phenomenon can be modelled with a simple single capillary assumption. In partially filled capillary, a concave or convex bending of the surface (meniscus) develops depending on surface tension of the liquid and the interfacial tension between liquid and wall of the capillary column. The curved surface of the liquid creates a pressure directed toward the centre of the curve. For a cylindrical capillary, *capillary pressure* p_k [Pa] can be expressed by

$$p_k = \frac{2 \cdot \sigma \cdot \cos \varphi}{r} \quad (55)$$

where σ [$\text{N} \cdot \text{m}^{-1}$] is the *surface tension of water*; r [m], the *radius of curvature* (equals capillary radius if curved surface is hemispherical); φ [grad], the *wetting angle*.

Capillary condensations are linked to variation of saturation vapour pressure in porous structure of the material. The assumption of spherical menisci in a singular cylindrical capillary, allows expressing Thompson's law (Lord Kelvin):

$$\phi = \exp \left[- \frac{2 \cdot \sigma \cdot \cos \varphi}{r \cdot \rho_w \cdot R_v \cdot T} \right] \quad (56)$$

It shows the relationship between *relative humidity*, Φ [-], and *capillary radius*, r [m], up to which the cylinder pores are filled with capillary condensation. In this equation ρ_w is the *density of water* ($\rho_w \sim 1000 \text{ kg} \cdot \text{m}^{-3}$ at 23°C); R_v the *gas constant for vapour* ($R_v = 461,52 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$); and T [K] the *absolute temperature* ($T = 273,15 + \theta$, if θ is the *temperature*, expressed in $^\circ\text{C}$).

Overpressure in pressure plate apparatus can thus be related to corresponding relative humidity through relationships (55) and (56), and pressure steps respectively correspond to relative humidity of 99,999% (for 0,001 bar), 99,996% (for 0,05 bar), 99,989% (for 0,15 bar), 99,963% (for 0,5 bar), 99,890% (for 1,5 bar), 99,635% (for 5 bar), 98,908 (for 15 bar). Table 3 presents results of pressure plate measurements where water content and hygric capacity are expressed in [%_{mass}] and in [$\text{kg} \cdot \text{m}^{-3}$].

TABLE 3
Results of pressure plate measurement

Relative humidity [% _{HR}]	w [% _{mass}]	ξ_ϕ [% _{mass}]	w [$\text{kg} \cdot \text{m}^{-3}$]	ξ_ϕ [$\text{kg} \cdot \text{m}^{-3}$]
98,908	$26,2 \pm 2,4$	414	115 ± 10	1823
99,635	$32,8 \pm 2,5$	969	146 ± 11	4264
99,890	$62,6 \pm 2,5$	11497	275 ± 11	50588
99,963	$88,9 \pm 2,7$	36115	391 ± 12	158904
99,989	$103,5 \pm 2,1$	55944	455 ± 9	246154
99,996	$108,3 \pm 2,0$	71429	477 ± 9	314286
99,999	$124,1 \pm 3,5$	392045	546 ± 16	1725000

The values presented here before enable to draw Moisture Retention Curve (MRC) of LHM-wall as illustrated in Fig.72. It appears that capillary region (region B) starts for LHM-wall around 93% of RH.

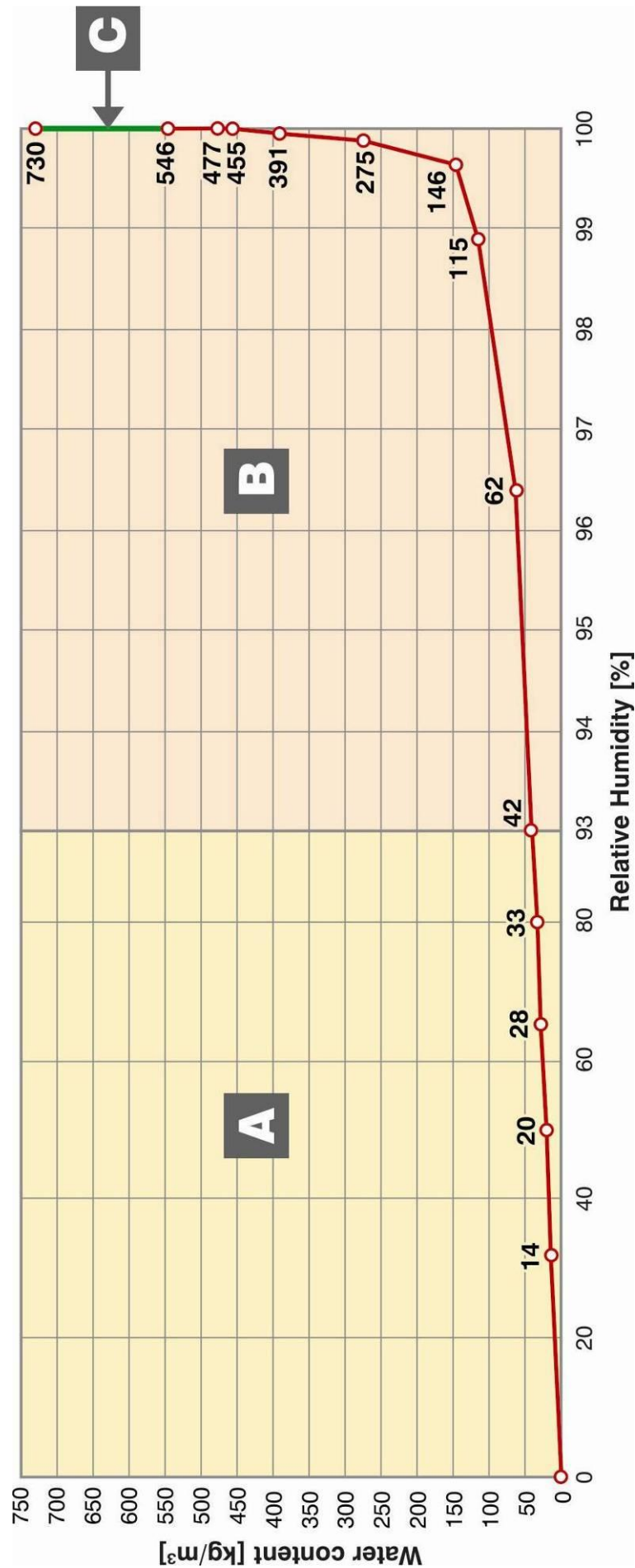


Figure 72 : Complete Moisture Retention Curve of LHM-wall

6.2 Swelling and shrinkage

When material's water content varies, cell's structure and volume may also vary. To assess swelling of LHM-wall in rising humidity, 3 block-samples ($240 \pm 12 \text{ cm}^3$, $105 \pm 5 \text{ g}$) were first dried completely and were then placed successively in 32%, 50%, 65%, 80% and 93% RH, as illustrated in Fig.73. At each step, length variations were carefully measured referring to a standard metal sample (at 23°C). Results are presented in Fig.74. Swelling and shrinkage of LHM-wall were in the same range as wood (radial). They were neglected in this work.



Figure 73 : Measuring swelling of LHM-wall

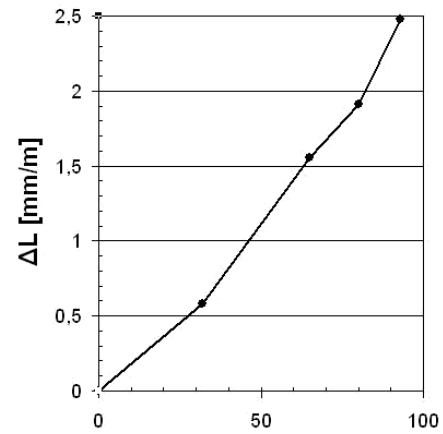


Figure 74 : Swelling of LHM-wall

6.3 Density and porosity

As suggested in previous figures, variation of water content influences the main hygrothermal parameters as density, total porosity and thermal capacity. If relationship (12) allows calculating the density in moist state, moist total porosity ψ [%_{vol}] when humidity is rising is given in the next relation, as illustrated in Fig.75,

$$\psi = 100 \cdot [\psi_0 - (w / \rho_w)] \quad (57)$$

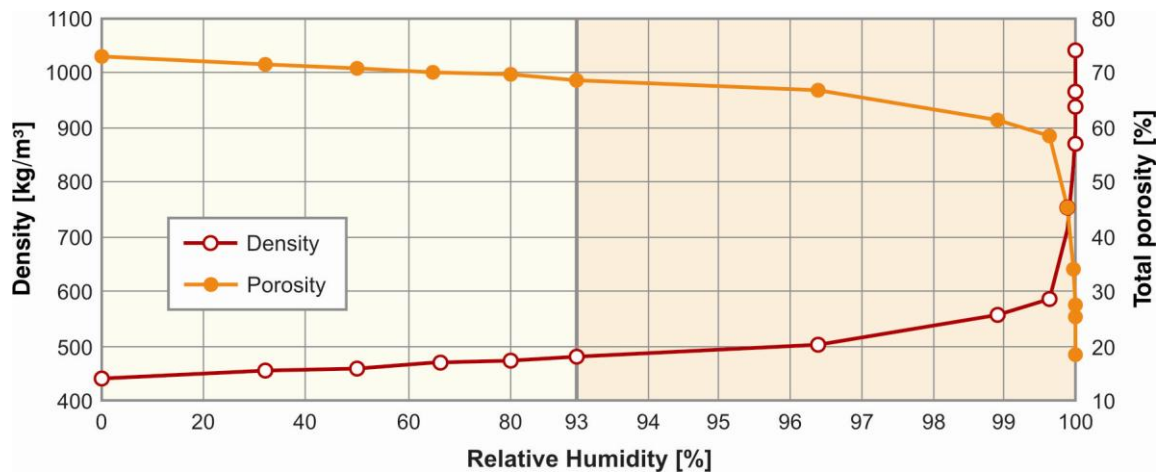


Figure 75 : Evolution of density and porosity of LHM-wall in moist state

Fig.76 shows a set of schematic mass and volumetric distribution of LHM-wall's mixture at different relative humidity.

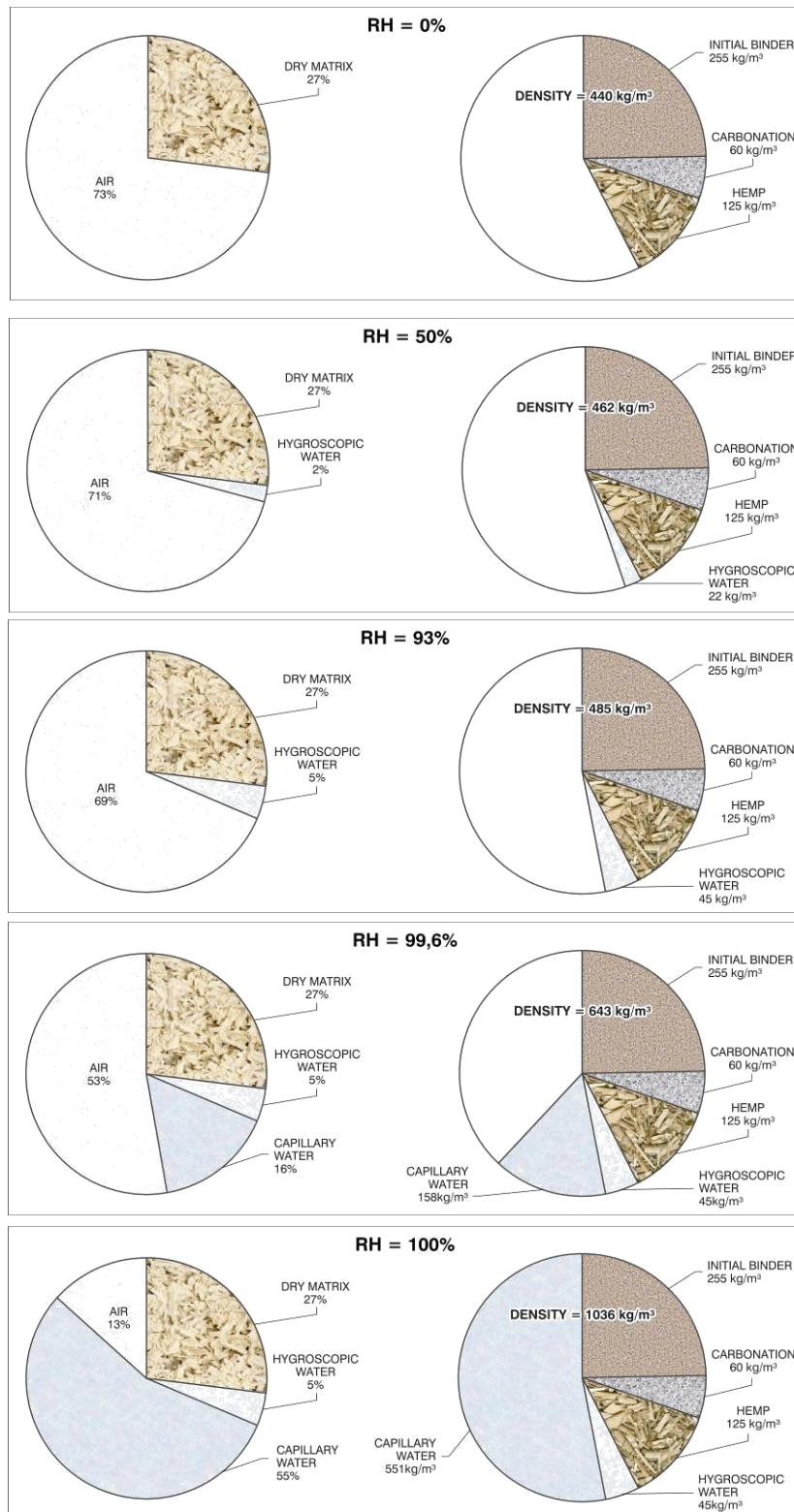


Figure 76 : mass and volumetric distribution of LHM-wall's mixture at different relative humidity

6.4 Thermal capacity

Fig.77 illustrates the relationship

$$c(w) = (\rho_0 \cdot c_0 + w \cdot c_w) / \rho \quad (58)$$

used to determine thermal capacity c [$\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$] at any relative humidity. It considers the direct increase from thermal capacity of water stored in porous structure, with $c_w = 4187$ [$\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$].

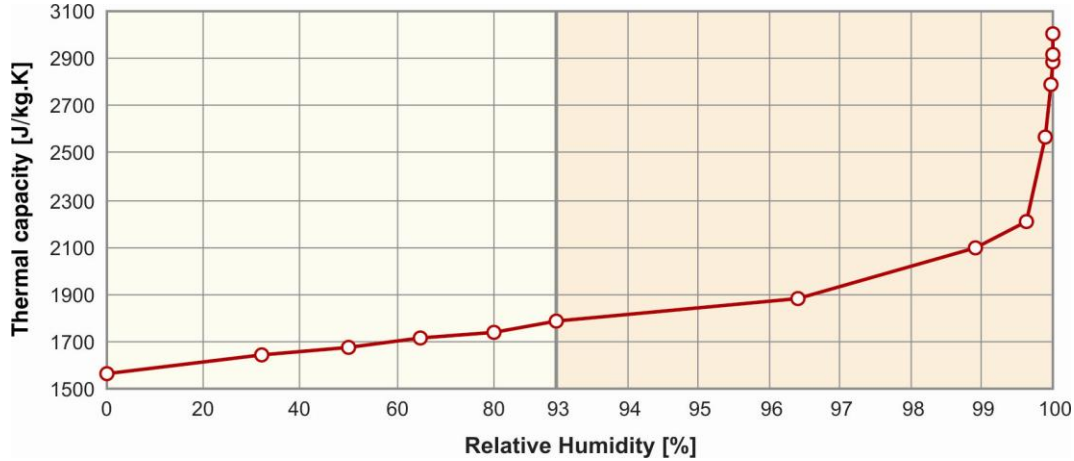


Figure 77 : Evolution of thermal capacity of LHM-wall in moist state

6.5 Thermal conductivity

Thermal conductivity in moist state was measured with the samples described in §5.4 ($1180 \pm 30 \text{ cm}^3$, $530 \pm 25 \text{ g}_{\text{dry}}$) following the same procedure. This experiment was not planned to be done initially (value are available in literature, and was one of the last experiments performed in the Fraunhofer-IBP. Some results were apparently not accurate and no time was left to start the procedure again.

Three relatively large samples (n°1 to 3) were subjected to respectively 80%, 65% and 50% RH. First their water content never reached the reference equilibrium moisture content (even after more than 6 months). Equilibrium moisture content of the three samples was almost constant from Nov05 to May06: $w_{\text{sample1}} = 18,9 \pm 0,6 \text{ kg} \cdot \text{m}^{-3}$; $w_{\text{sample2}} = 14,4 \pm 0,4 \text{ kg} \cdot \text{m}^{-3}$; $w_{\text{sample3}} = 15,4 \pm 0,4 \text{ kg} \cdot \text{m}^{-3}$ (with less than 0,2%_{mass} variation during the experiment). Referring to values used to define the MRC in §6.1, the expected water content was respectively: $w_{\text{sample1},80\%} = 33 \text{ kg} \cdot \text{m}^{-3}$, $w_{\text{sample2},65\%} = 28 \text{ kg} \cdot \text{m}^{-3}$, $w_{\text{sample3},50\%} = 20 \text{ kg} \cdot \text{m}^{-3}$. Further sorption experiments should explain these deviations. Only results for sample 1 and 2 are presented in Fig.78 and Fig.79 results for sample 3 were not valid). Relationships

$$\lambda_{\text{sample 1}} = 0,122 \pm 0,002 [\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}] \quad (59)$$

$$\lambda_{\text{sample 2}} = 0,132 \pm 0,002 [\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}] \quad (60)$$

give moist thermal conductivity at 10°C for sample 1 and 2 (results for sample 2 obtained in May06 were not used to calculated mean value at 10°C).

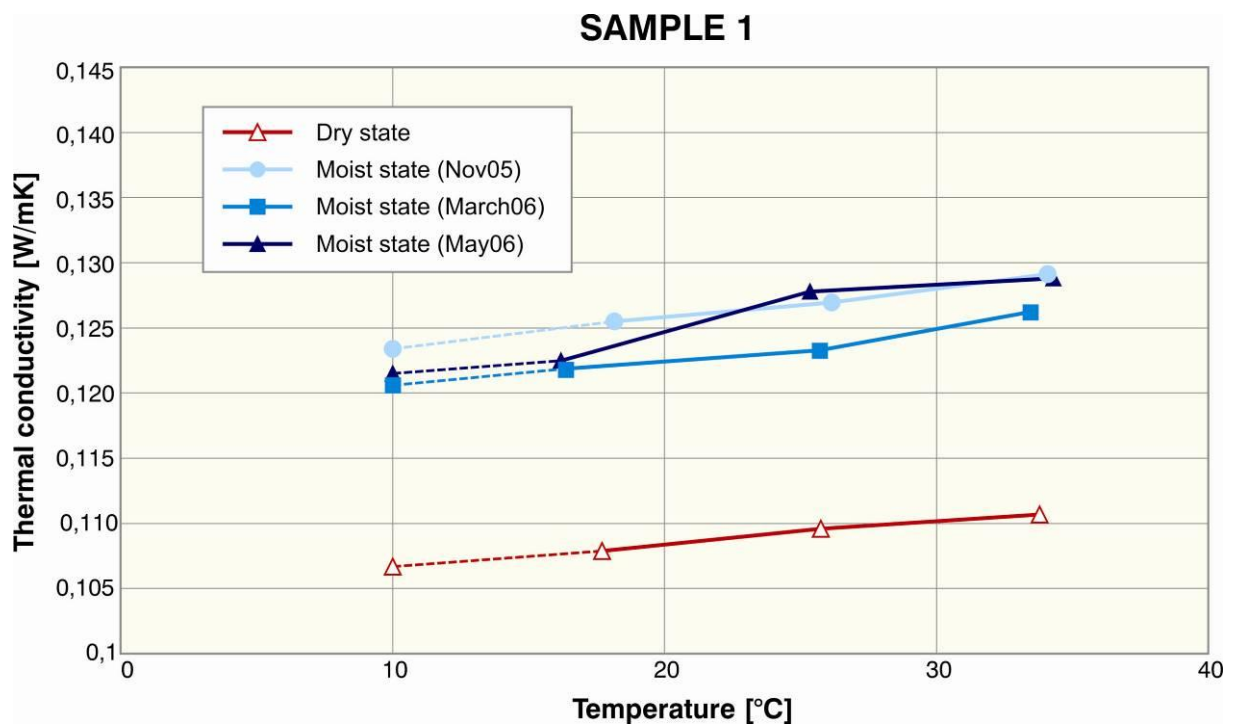


Figure 78 : Thermal conductivity results for LHM-wall in moist state (sample 1)

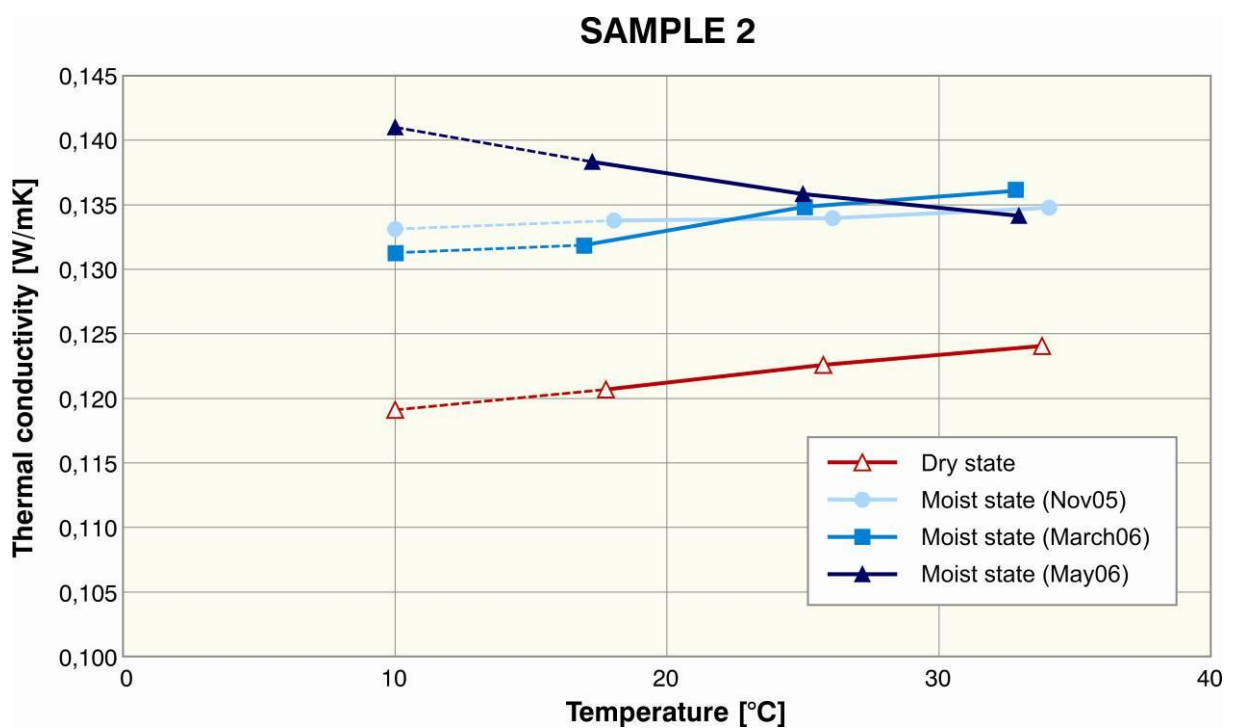


Figure 79 : Thermal conductivity results for LHM-wall in moist state (sample 2)

The *thermal conductivity supplement*, b [%/%_{mass}], quantifies the increase of thermal conductivity (in [%] referring to dry value) when the water content rises of 1% referring to dry mass. Its value can be found using

$$b = \frac{\rho_0 \cdot (\lambda - \lambda_0)}{\lambda_0 \cdot w}, \quad (61)$$

considering that dry thermal conductivity of sample 1 was 0,107 W.m⁻¹.K⁻¹, and it was 0,119 W.m⁻¹.K⁻¹ for sample 2. The use of this coefficient implies that the thermal conductivity rises linearly with water content, as it is usually considered for other materials. Experiment results presented in [Kehrer, 2003]⁴⁸ and in [Cerezo, 2005]⁴⁹ show that this may not be the case for LHM-wall. In the present work, it was observed that $b_{\text{sample1}} \cong b_{\text{sample2}}$ and the mean value is chosen to be reference thermal conductivity supplement for LHM-wall, as given in relationship

$$b = \frac{b_{\text{sample1}} - b_{\text{sample2}}}{2} = 3,34 \pm 0,24 \text{ \%/%}_{\text{mass}}. \quad (62)$$

Fig.80 illustrates the following relationship

$$\lambda(w) = \left(1 + \frac{b \cdot w}{\rho_0} \right) \cdot \lambda_0 \quad (63)$$

from which evolution of thermal conductivity in moist state under these hypotheses can be calculated, based on dry thermal conductivity given in §5.4. Comparison values of other materials are given in §7.1.

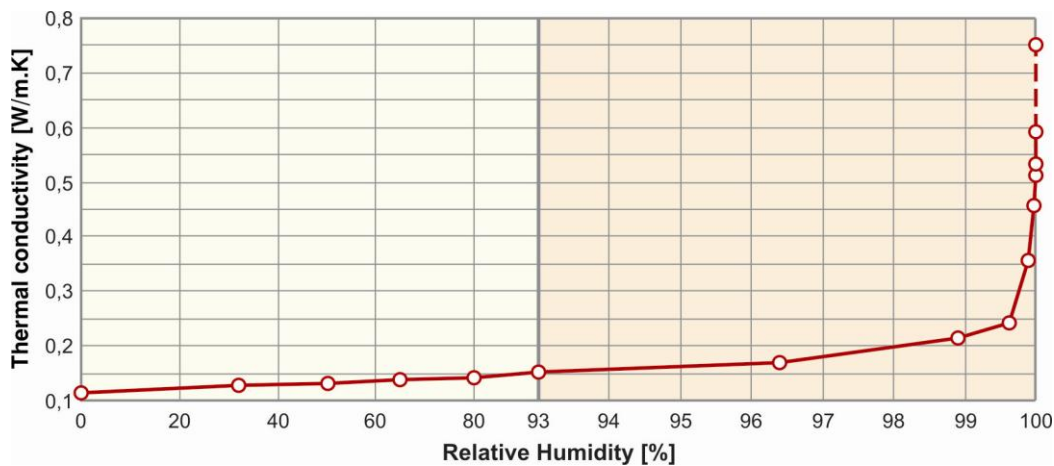


Figure 80 : Evolution of thermal conductivity of LHM-wall in moist state

⁴⁸ *Ecological insulation materials – Does sorption moisture affect their insulation performance?*, M. Kehrer et al., Journal of thermal envelope and building science, vol 26 n°3, January 2003

⁴⁹ *Propriétés mécaniques, thermique et acoustiques d'un matériau à base de particules végétales : approche expérimentale et modélisation théorique*, V. Cerezo, Ph.D. thesis at ENTPE, France, 2005

6.6 Vapour permeability

As presented in §5.5, the standard DIN 52 615 (EN ISO 12572) is used measured water vapour permeability of LHM-wall. “Wet-cup method” allows assessing *vapour diffusion resistance factor* μ [-] of the material at different relative humidity. For this experiment, 4 block-samples ($875 \pm 30 \text{ cm}^3$, $407 \pm 7 \text{ g}$) were sealed on glass cups (L~18cm, l~13cm, H~18cm) as described for dry-cup method (paraffin avoids transfer through lateral sides). In this case, represented in Fig.81, the glass cups were filled with salt solution, leaving a 2 cm air layer under sample surface (to be able to move the sample and its glass avoiding the salt to touch the sample). The salt solution was $(\text{NH}_4)\text{H}_2\text{PO}_4$ which gives a RH of 93% in the 2 cm air layer. Block-samples sealed on glass cups were placed in a climate chamber at 50% of RH (23°C), as illustrated in Fig.82. The mean relative humidity between 93% and 50% is thus 71,5% of RH.

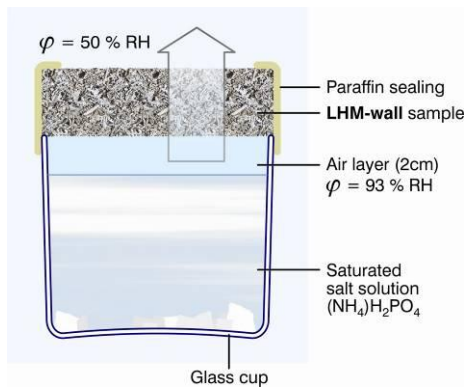


Figure 81 : Operating diagram for wet-cup



Figure 82 : Wet-cup experiment

As presented in §3.2.1.3, the dry vapour diffusion resistance factor will thus be used for vapour diffusion resistance factor at any RH in this work. The following relationship can be written

$$\mu = \mu_0 = 4,85 \pm 0,24 \text{ [-]}. \quad (64)$$

The fictitious vapour diffusion resistance factor, $\mu^*_{71,5\%}$ [-], measured at 71,5% of RH and used in next section, is given by

$$\mu^*_{71,5\%} = 4,76 \pm 0,47 \text{ [-]}. \quad (65)$$

6.7 Liquid transfer

As presented in §3.2.1.3, liquid transfer is strongly dependent on water content and boundary conditions. Two cases are classically distinguished: absorption (liquid source against the material) and redistribution (no water source is in contact with the material, the moisture in the material moves toward equilibrium). In this chapter, *liquid transfer coefficients for absorption*, D_{ws} (“Wasser Saugen”), and *for redistribution*, D_{ww} (“Wasser Weiterleiten”), are first assessed based on literature and simple measurements. As liquid transfer coefficients are the last input to run the software WUFI® with LHM-wall, the second step is to adapt liquid transfer coefficients to fit simulations results with absorption, redistribution and drying measurements.

6.7.1 Künzels exponential relationship

6.7.1.1 Absorption

In low RH, the bounding of water molecules on pores surface are strong and liquid transfer can be neglected. Liquid transfer starts shortly before capillary region (mainly due to surface diffusion). In this work, liquid transfer in LHM-wall is considered to start at 71,5% of RH where water content is presumably around 30 kg.m⁻³.

According to [Künzel, 1995]⁵⁰, wet-cup results can be used to calculate *liquid transfer coefficient in hygroscopic region* $D_{w,wet-cup}$ [m².s⁻¹] with

$$D_{w,wet-cup} = \left(\frac{1}{\mu^*} - \frac{1}{\mu_0} \right) \cdot \frac{\delta_a \cdot P_{sat}}{\xi_\phi} \quad (66)$$

Liquid transfer coefficient at 71,5% gives $D_{w,wet-cup,71,5\%} = 6,87 \cdot 10^{-11}$ m².s⁻¹ [m².s⁻¹] knowing $\mu_0 = 4,85 \pm 0,24$ [-] from 5.5, $\mu_{71,5\%}^* = 4,76 \pm 0,47$ [-] from §6.6 and hygric capacity, $\xi_\phi = 33,3$ kg.m⁻³ from §6.1. Air permeability is $\delta_a = 2,09 \cdot 10^{-10}$ kg.m⁻¹.s⁻¹.Pa⁻¹ and saturation pressure, $P_{sat} = 2808,44$ Pa (at 23°C). It is 2 times smaller than for most of the material (value are usually given at 80% of RH).

In his thesis, H.M. Künzels develops another method to assess *liquid transfer for absorption* D_{ws} [m².s⁻¹]. The following exponential function is used to define its value

$$D_{ws}(w) = 3,8 \cdot \left(\frac{A}{w_f} \right)^2 \cdot 1000^{\frac{w}{w_f} - 1}, \quad (68)$$

⁵⁰ Simultaneous Heat and Moisture Transport in Building Component: One- and Two-dimensional calculation using simple parameters, H.M. Künzels, thesis at Fraunhofer-IBP, Stuttgart, 1995

where A [$\text{kg.m}^{-2}.\text{s}^{-1/2}$] is the *liquid absorption coefficient*. It was measured during 24h following (DIN 52 617), placing 4 block-samples of LHM-wall ($960 \pm 24 \text{ cm}^3$, $487 \pm 11 \text{ g}$) in 5mm of water (lateral side protected with paraffin). Fig.83 illustrates the experiments. Mass measurements of the 4 samples were performed respectively after: 1min, 5min, 10min, 30min, 1h, 2h, 3h, 4h, 5h, 6h, 21h, 22h30, 23h, 24h... The liquid transfer coefficient A is the slope of the mass uptake curve, when expressed with the square root of time ($\sqrt{h}$, or $\sqrt{s}$). Mass uptake appears linear for the first 24h on Fig.84. The shape of the rest of the curve is related to the size of the sample and was not used for material characterisation (moulding appeared on the samples after 20 days). Water absorption coefficient of LHM-wall is given by

$$A = 4,42 \pm 0,27 \text{ kg.m}^2.\text{h}^{-1/2} = (7,36 \pm 0,45).10^{-2} \text{ kg.m}^2.\text{s}^{-1/2} . \quad (69)$$



Figure 83 : Water absorption coefficient measurement

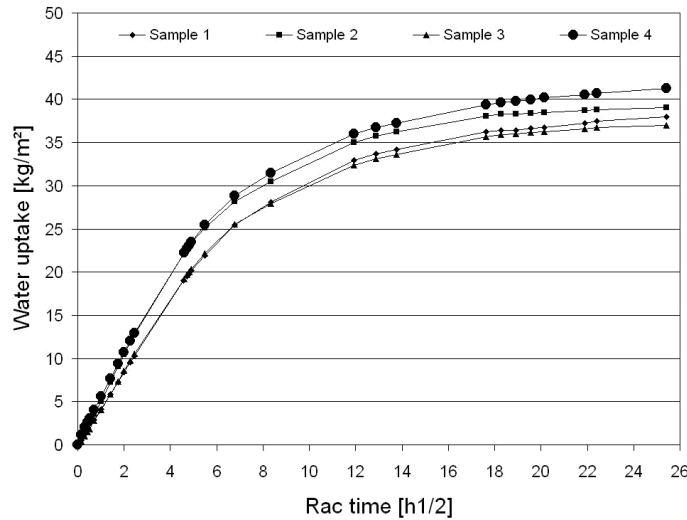


Figure 84 : Water uptake of LHM-wall

Liquid transfer coefficient for absorption of LHM-wall is assessed at 71,5% RH, $D_{ws,71,5\%}$ [$\text{m}^2.\text{s}^{-1}$], and at free saturation, D_{wsf} [$\text{m}^2.\text{s}^{-1}$] by

$$D_{ws,71,5\%} = D_{ws}(w = 30 \text{ kg.m}^{-3}) = 1.10^{-10} \text{ m}^2.\text{s}^{-1} \quad (70)$$

$$D_{wsf} = D_{ws}(w = 546 \text{ kg.m}^{-3}) = 7.10^{-8} \text{ m}^2.\text{s}^{-1} \quad (71)$$

It is interesting to remark that $D_{ws,71,5\%}$ is similar to $D_{w,wet-cup,71,5\%}$.

6.7.1.2

Redistribution

In hygroscopic region, the “distinction between absorption and redistribution does not appear to be physically meaningful”, because the “liquid transport takes place in the sorbate film” (surface diffusion)⁵¹. Liquid transfer during redistribution thus starts at the same point than during absorption: $D_{w,71,5\%}$, given in relationship (70). As presented in 3.2.1.3, redistribution can be 3 to 20 times slower than absorption around free saturation. For mineral materials, a ratio of ten is considered to be a good approximation⁵². The next relationship gives approximate liquid transfer coefficient for redistribution at free saturation, D_{wwf} [$m^2.s^{-1}$]:

$$D_{wwf} = D_{wsf} / 10 = 7.10^{-9} m^2.s^{-1} \quad (72)$$

6.7.1.3

Curve generated by WUFI®

Using Künzels exponential relationship and results from measurements of liquid absorption coefficient, WUFI® software can generate liquid transfer coefficients for absorption and for redistribution considering linear evolution of liquid transfer coefficient until free saturation. They are expressed in terms of *normalised water content* $w_{norm} = w / w_{max}$ [-] as other materials in WUFI®'s database.. In oversaturated region, the liquid transfer coefficient stays constant. Fig.85 illustrates these curves.

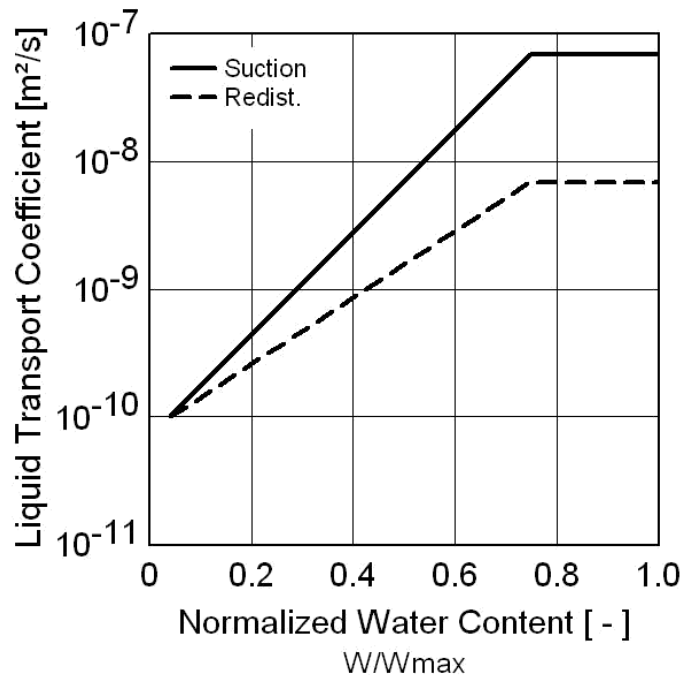


Figure 85 : Liquid transfer coefficients of LHM-wall generated by WUFI®

⁵¹ Simple methods to approximate the liquid transport coefficients describing the absorption and drying process, M. Krus, A. Holm, Proceedings of the 5th Symposium “Building Physics in the Nordic Countries”, pp.241-248, Göteborg, Sweden, 1999

⁵² Simultaneous Heat and Moisture Transport in Building Component: One- and Two-dimensional calculation using simple parameters, H.M. Künzels, thesis at Fraunhofer-IBP, Stuttgart, 1995

6.7.2 Graphical determination

6.7.2.1 Absorption

Liquid transfer coefficients are the last input required to run the software WUFI® with LHM-wall. The first set of simulations uses the parameters gathered previously for LHM-wall (with liquid transfer coefficient generated by WUFI®) and reproduced absorption measurements presented hereunder. Both right (outside) and left (inside) climates are set to a temperature of 23°C and 50% of RH. Outside climate file was defined with very large amount of rain (10 000 mm/h) and rain absorption coefficient on this side was set to one to model the side of the sample placed in the water. Heat transfer coefficient on both surfaces was set to $h_i = h_e = 8 \text{ W.m}^{-2}.\text{K}^{-1}$. Initial conditions of the material are constant, at 23°C and 50%, through the component (1 layer of LHM-wall, thickness: $d = 24,4 \text{ m}$).

Evolution of water content profiles through the component during absorption was measured with Nuclear Magnetic Resonance apparatus of Fraunhofer-IBP on 4 block-samples ($441 \pm 3 \text{ cm}^3$, $254 \pm 3 \text{ g}$). The samples (thickness: $d = 24,4 \pm 0,5 \text{ cm}$) were placed in 1cm of water after protecting their lateral sides with epoxy resin, as illustrated in Fig.86 to Fig.88.



Figure 86 :
Sample used in
NMR apparatus



Figure 87 :
Absorption



Figure 88 :
NMR apparatus

Each sample was scanned after 5min, 30min, 1h, 2h, 3h, 4h, 5h, 16h, 24h and 48h. Fig.89 compares results from measurements of one sample output from first simulation. As it appears, liquid transfer generated with WUFI® is too low. Retarded sorption of LHM-wall also appears (w_f is reached only after ~2 days), but this time dependency of water content is neglected in WUFI's model.

A set of five simulations was run to assess the liquid transfer corresponding to measurements. Each liquid transfer curve, respectively called $D_{ws}T1$, $D_{ws}T2$, $D_{ws}T3$, $D_{ws}T4$ and $D_{ws}T5$, is illustrated in Fig.90.

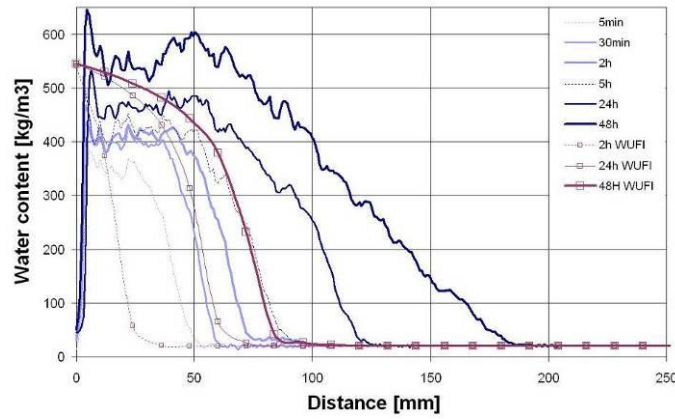


Figure 89 : Water content profiles from absorption measurements and from simulation with D_{ws} generated with WUFI®

First test, using $D_{ws}T1$, increase the speed of absorption by bringing liquid transfer coefficient used in the simulation from free saturation to maximum water content to the value of $D_{wsf} = 2.10^{-6} \text{ m.s}^{-2}$. The first simulation shows that this curve gives good results for absorption process during not more than 2 hours. On the other hand, simulated liquid transfer is much too fast when absorption process is longer as illustrated in Fig.91.

The second test, using $D_{ws}T2$, fixed $D_{wsf} = 2.10^{-7} \text{ m.s}^{-2}$ from free saturation to maximum water content. Fig.92 shows that moisture distribution from the simulation fits the measurement for 24h hours of absorption. Third test, using $D_{ws}T3$, showed that liquid transfer coefficient relative to low water content should be increased to flatten the profile after 1 or 2 days. Liquid transfer coefficient corresponding to $w = 62 \text{ kg.m}^{-3}$ is set to $2.10^{-7} \text{ m.s}^{-2}$.

The next two tests, using $D_{ws}T4$ and $D_{ws}T5$, show that the slope of absorption profile after 2 days accurately fits the measurements when D_{ws} is defined with a sudden increase over $w = 455 \text{ kg.m}^{-3}$ (Fig. 93). These results show that liquid transfer coefficient for absorption can be time dependant. Results from Test, $D_{ws}T5 (w)$, will be used as the *reference liquid transfer*, $D_{ws} [\text{m.s}^{-2}]$, for general simulations. For specific case, simulations may be run with an adapted liquid transfer coefficient for absorption.

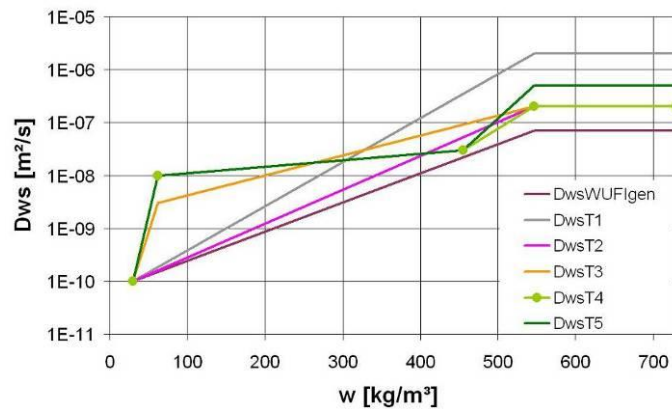


Figure 90 : Adaptation of D_{ws}

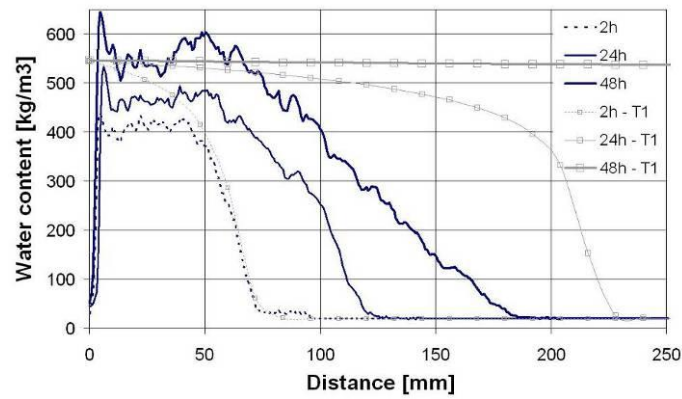


Figure 91 : Profile for absorption with DwsT1

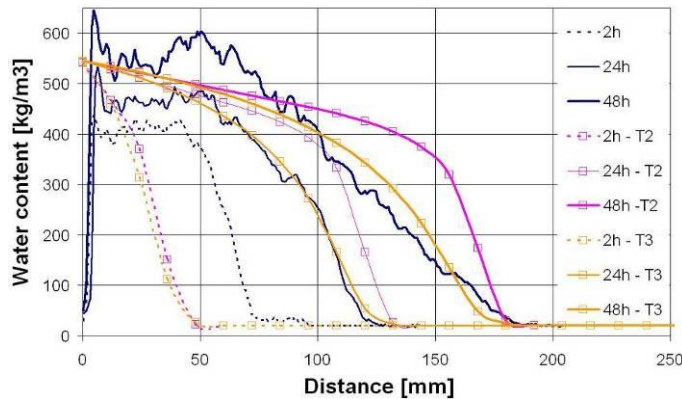


Figure 92 : Profile for absorption with $D_{ws}T2$ and $D_{ws}T3$

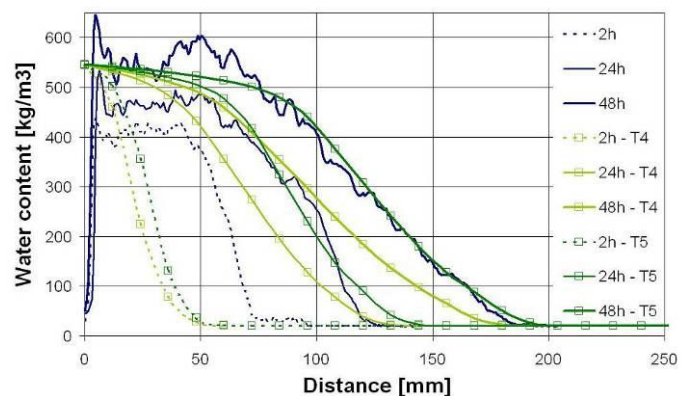


Figure 93 : Profile for absorption with $D_{ws}T4$ and $D_{ws}T5$

6.7.2.2 Redistribution

When no water source is in contact with the material, water content is redistributed through the porous structure of the material. If vapour can be released, the material dries out. According to [Krus, 1999]⁵³, the determination of *liquid transfer coefficient for redistribution*, D_{ww} , can be based on the comparison of *drying* results in climate rooms to simulations reproducing the experimental setup. Drying of reference samples presented in 4.3.1 will be used for comparison (thickness of the samples is $d = 3,4\text{cm}$, 23°C and 65% of RH on both sides, aluminium foil on all sides except front surface, carbonation is neglected).

⁵³ Simple methods to approximate the liquid transport coefficients describing the absorption and drying process, M. Krus, A. Holm, Proceedings of the 5th Symposium "Building Physics in the Nordic Countries", pp.241-248, Göteborg, Sweden, 1999

The second set of simulations uses the parameters gathered previously for LHM-wall (starting with liquid transfer coefficient generated by WUFI®). The simulations reproduce experimental setup: 23°C and 65% of RH on both sides, metal foil (Sd= 10000m) on the right side, 1 layer of LHM-wall: d= 3,4cm. Initial water content is constant through the component at 345 kg.m⁻³ to match the last part of the curve ($w_{eq,65\%} = 28 \text{ kg.m}^{-3}$).

The first part of the drying curve (linear) is considered to be only dependent on the surface transfer coefficient. In WUFI®, the *vapour transfer coefficient* β_v , defined in 3.2.5, is linked to the heat transfer coefficient. The heat transfer coefficient used in the simulations shall thus be adapted to match results from measurements, starting from value $h_e = 8 \text{ W.m}^{-2}.\text{K}^{-1}$ (only left side should be adapted, the metal foil avoiding any moisture transfer to the right).

Drying process from both simulations and measurements are compared in Fig.94. It appears that liquid transfer from redistribution coefficient generated by WUFI® is too slow. The two first adaptations on liquid transfer for redistribution, respectively using $D_{ww}T1$ and $D_{ww}T2$ illustrated in Fig.95, give approximately the same results (heat transfer coefficient was not modified).

As defining a single curve for D_{ww} that enable to reproduce the results of experimental setup for *drying* conditions is not possible, a third set of simulation was defined. Redistribution experiment starts after 48h of absorption measured with NMR apparatus, when the samples ($441 \pm 3 \text{ cm}^3$, $254 \pm 3 \text{ g}$) were wrapped in aluminium foil between the measurements. Before placing aluminium, both ends of the samples were covered by special non permeable film (lateral sides protected with epoxy resin). Water content is trapped and the overall distribution moves toward a new equilibrium. Each sample was scanned after: 4 hours, 27 hours, 50 hours, 3 days, 7 days, 10 days, 2 weeks, and 3 weeks (5 to 10 min each measurement). As expected, the process is much slower than for absorption.

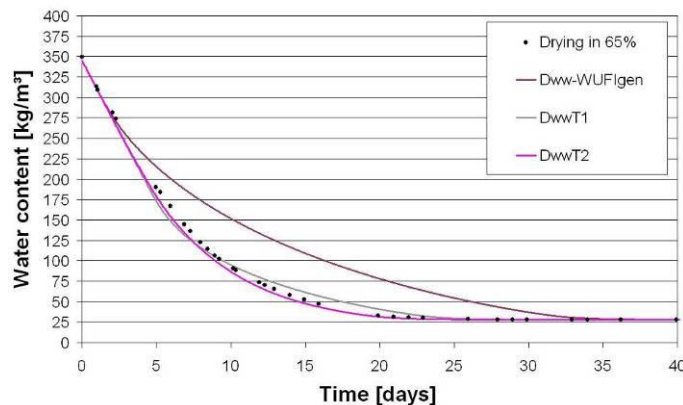


Figure 94 : Drying from simulations and measurement

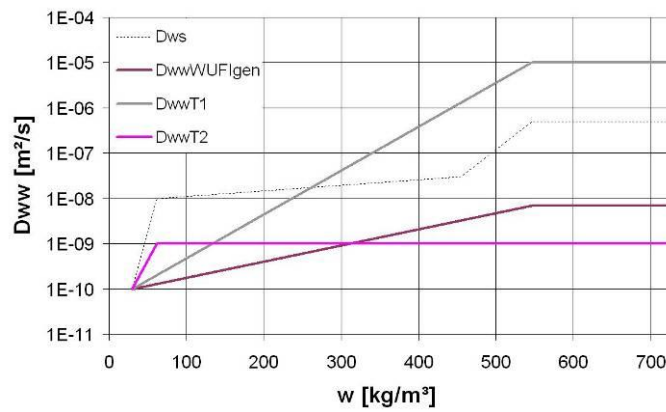


Figure 95 : First adaptation of D_{ww}

Results from simulations reproduce the experimental setup: both sides at 23°C and 50% of RH, covered with metal foil ($S_d = 10000\text{m}$), 1 layer of LHM-wall: $d = 24,4\text{ m}$, initial water content corresponding to absorption profile after 48 hours.

Similarly to drying analysis, Fig.96 illustrates that the liquid transfer coefficient for redistribution generated by WUFI® do not give an accurate view of material's behaviour. Fig.97 shows that aforementioned simulation using $D_{ww}T2(w)$ gives better results. Two complementary simulations are defined with coefficient given in Fig.98 to study water profiles evolution when liquid transfer is adapted. Fig.99 shows that simulation using $D_{ww}T3$ and $D_{ww}T4$ give good results for redistribution.

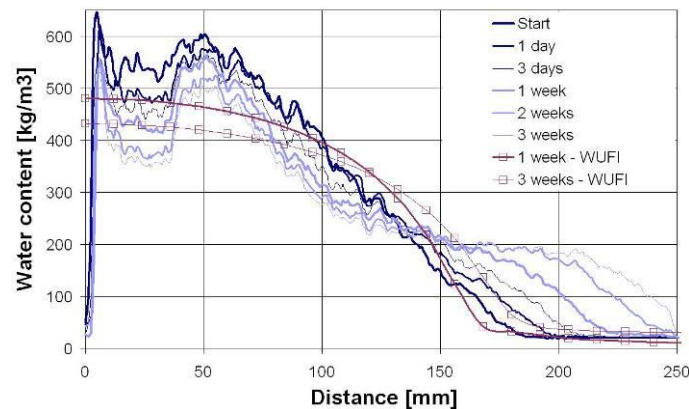


Figure 96 : Water content profiles from redistribution measurements and from simulation with D_{ww} generated with WUFI®

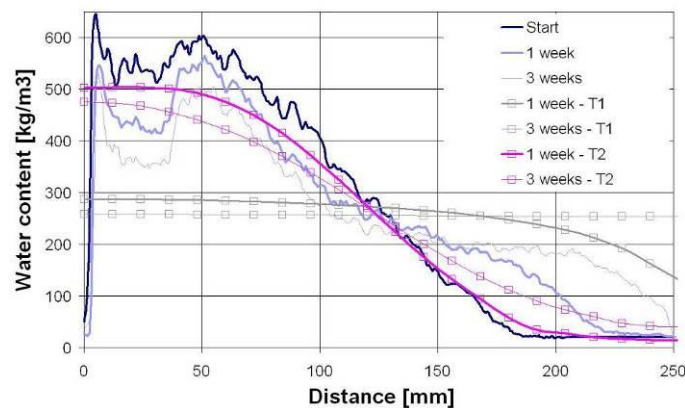


Figure 97 : Profile for redistribution with $D_{ww}T1$ and $D_{ww}T2$

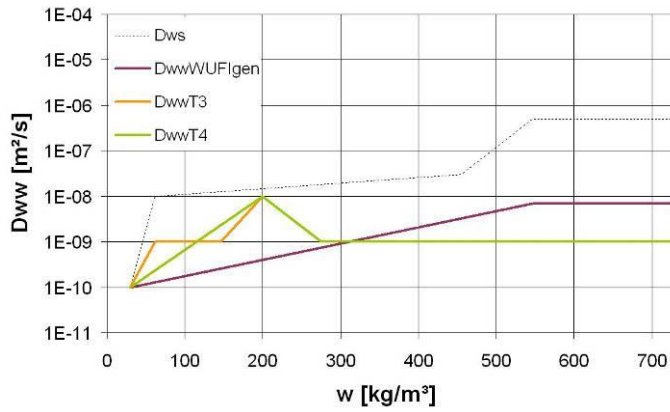


Figure 98 : Second adaptation of D_{ww}

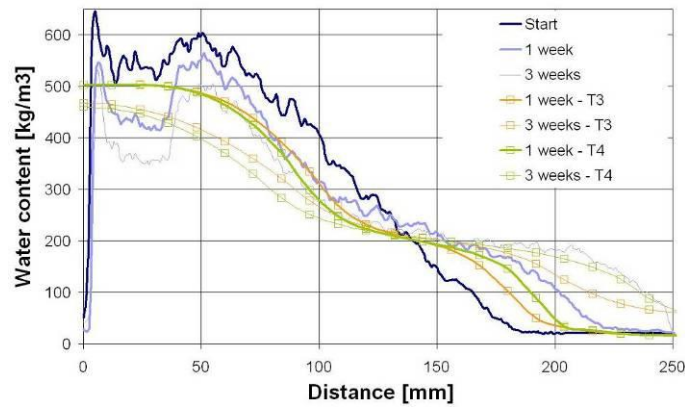


Figure 99 : Profile for redistribution with $D_{ww}T3$ and $D_{ww}T4$

Adaptations made on D_{ww} (comparing different experimental setups) do not fit both drying and redistribution measurements at the same time. On Fig.100, the name of the curve is followed by "b" when the heat transfer coefficient was adapted on the right side to the value of $h_e = 5,5 \text{ W.m}^{-2}.\text{K}^{-1}$. Drying process simulated with $D_{ww}T2$, appears to be the most appropriate for drying, where $D_{ww}T4$ is the most appropriate for redistribution.

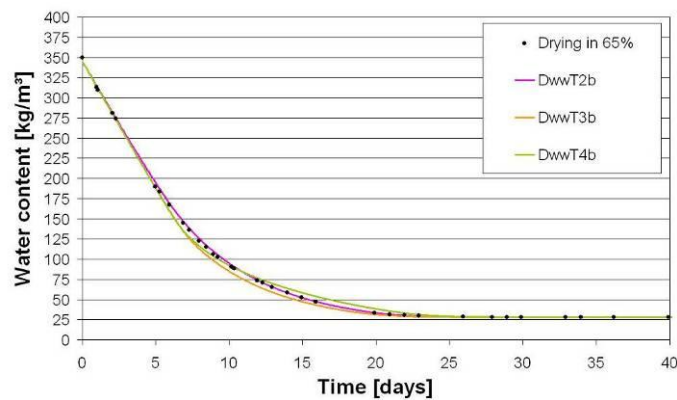


Figure 100 : Drying measurements are compared to simulations results

After a few other simulations, the liquid transfer curve for redistribution, $D_{ww}T5(w)$, approaching both drying and redistribution measurements is defined, as illustrated in Fig.101. Redistribution profile and mass release from drying are respectively given in Fig.102 and Fig.103. $D_{ww}T5(w)$ will be used as the *reference liquid transfer for redistribution*, $D_{ww} [m.s^{-2}]$, for general simulations. For specific case, simulations may be run with an adapted liquid transfer coefficient (ex for absorption during short period).

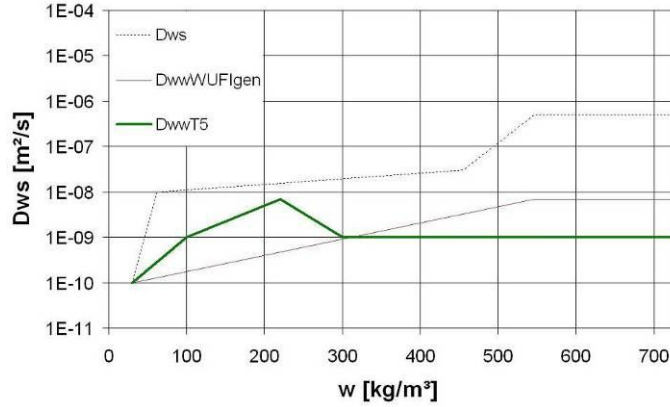


Figure 101 : Third adaptation of D_{ww}

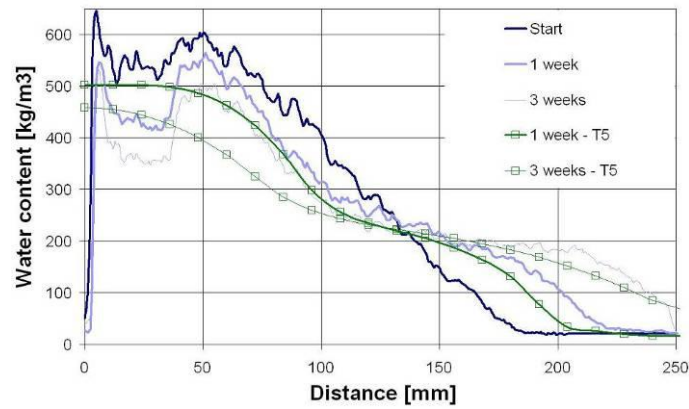


Figure 102 : Profile for redistribution with $D_{ww}T3$ and $D_{ww}T4$

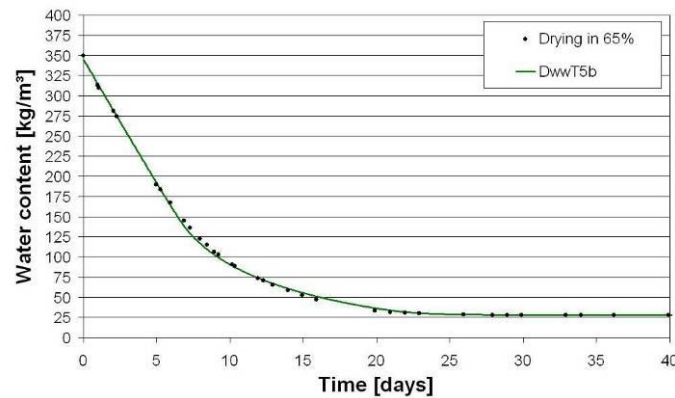


Figure 103 : Drying measurements are compared to simulations results

6.7.2.3

Reference curve used in WUFI®

Reference values for D_{ws} and D_{ww} are presented in Fig.104. They are based on the results from [Krus, 1999]⁵⁴ and expressed in terms of *normalised water content* $w_{norm} = w / w_{max}$ [-] as other materials in WUFI®'s database. Graphical method to assess those liquid transfer coefficients could be completed by further measurements and liquid transfer coefficient used can be adapted depending on experimental condition to model (time dependencies of parameters).

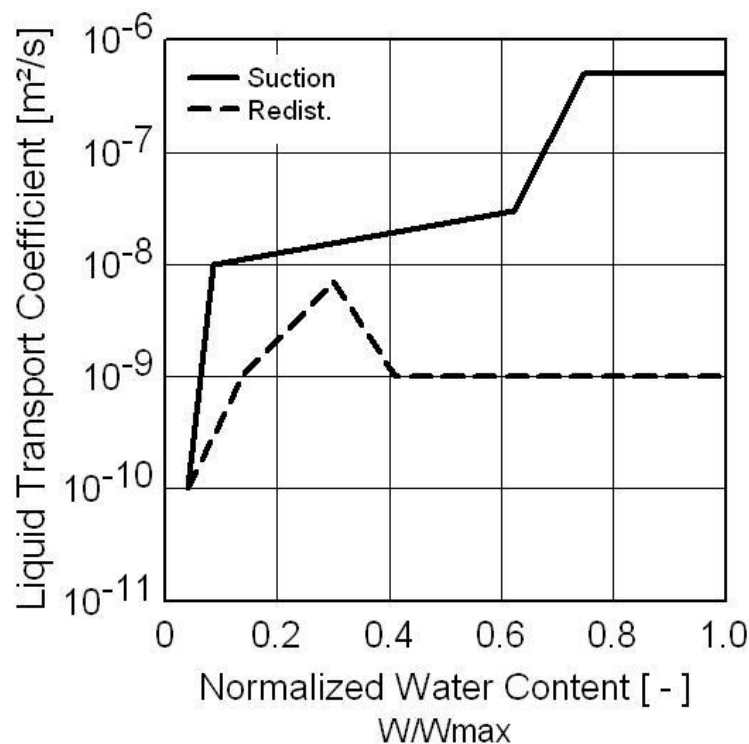


Figure 104 : Reference curve used in WUFI®

⁵⁴ Simple methods to approximate the liquid transport coefficients describing the absorption and drying process, M. Krus, A. Holm, Proceedings of the 5th Symposium "Building Physics in the Nordic Countries", pp.241-248, Göteborg, Sweden, 1999

7 Transient behaviour under dynamic conditions

This chapter analyses behaviour of multilayer components in dynamic conditions. The first step is to compare hygrothermal parameters of material itself to those of other building material, in order to point out its specificities. The first section gives some comparison values for main hygrothermal parameters defined in previous sections. Based on those parameters, the second section defines 4 combined parameters to compare materials in terms of transient response. The rest of this chapter defines and compares the behaviour of multilayer components under various dynamic thermal and hygric stresses.

7.1 Material's data in WUFI®'s database

Beside LHM-wall, a set of 6 materials are presented to enable comparison with LHM-wall: Wood, Autoclaved Aerated Concrete (AAC), Clay brick, Mineral wool (MW), Cement concrete (CEM) and still water. Their hygrothermal parameters come from WUFI®'s material database, respectively from “spruce, radial”, “Aerated Concrete (density: 500 kg/m³)”, “Solid Brick, historical”, “Mineral Wool (heat cond.: 0,04 W/mK)” and “Concrete, w/c=0.5”. They are presented in Fig.105 (MW has no MRC given in the database, the model use a default function depending on porosity) and Fig.106 (together with water's main parameters).

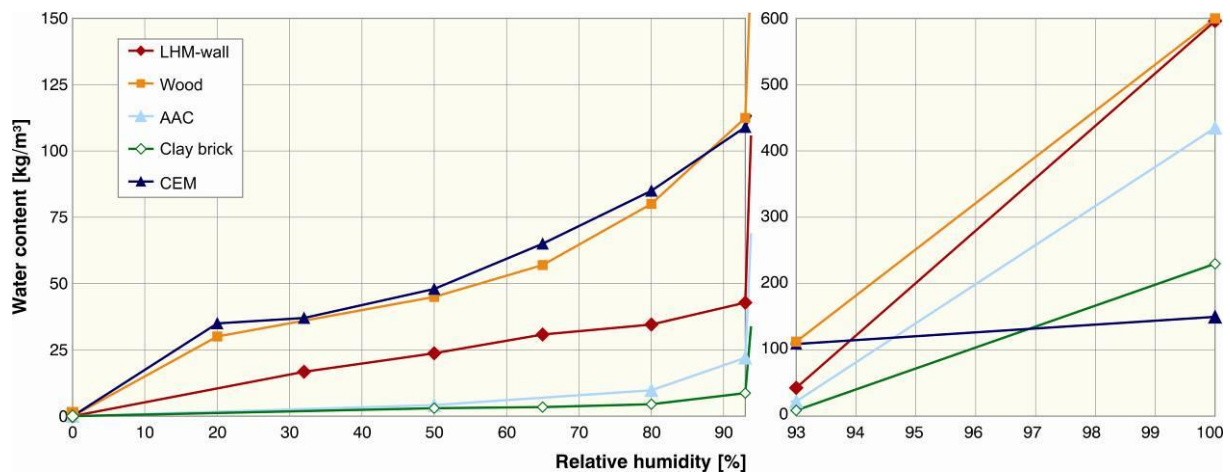


Figure 105 : Moisture retention curve of 5 materials

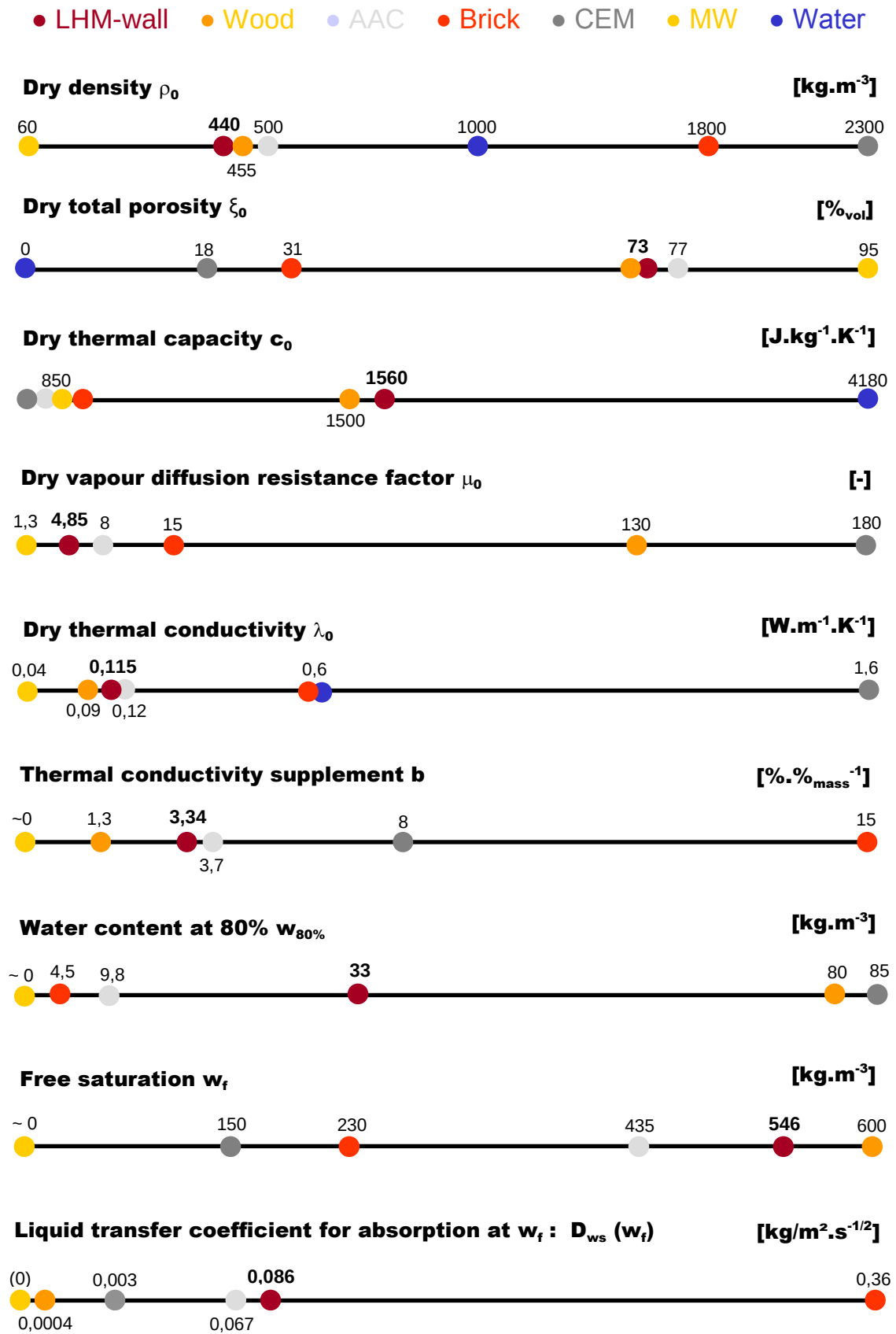


Figure 106 : Main hygrothermal parameters of 7 materials

7.2 Diffusivity and Effusivity

7.2.1 Thermal transfer and storage

Hygrothermal parameters given in chapter 5 and 6 are measured in permanent transfer. When hygrothermal conditions change at the surface of components, hygrothermal distribution through the component are adapted until permanent transfer corresponding to boundary conditions is reached. Four parameters can be defined to compare material's behaviour to the other during transient transfer. *Thermal diffusivity*, written α [$\text{m}^2.\text{s}^{-1}$], and *thermal Effusivity*, written Eff [$\text{J}.\text{m}^{-2}.\text{K}^{-1}.\text{s}^{-1/2}$], are calculated only based on material's hygrothermal parameters presented in previous chapters.

Thermal diffusivity represents the rate at which the temperature of the material can vary. It is calculated as the ratio of thermal conductivity over the product of density and thermal capacity, as expressed by

$$\alpha = \lambda / \rho.c . \quad (73)$$

The lower it is, the slower will change the temperature of the material. The dry thermal diffusivity of LHM-wall is thus

$$\alpha_0 = \lambda_0 / \rho_0.c_0 = 1,68 .10^{-7} \text{ m}^2.\text{s}^{-1} . \quad (74)$$

Fig.107 illustrates evolution of thermal diffusivity with relative humidity, for LHM-wall and other materials. Thermal diffusivity of LHM-wall is very low compared to other materials. Its value stays almost constant when approaching free saturation.

Thermal Effusivity represents the quantity of energy given to (or out from) a material when it was subjected to heating (or cooling) during a given time laps. It is calculated with the square root of the product of density, thermal capacity and thermal conductivity, as expressed by

$$\text{Eff} = (\rho.c.\lambda)^{1/2} \quad (75)$$

The bigger it is, the more the amount of energy exchanged when material's temperature changes is large. Thermal Effusivity is also responsible of warm (Eff small) or cold (Eff big) feeling when touching the material. The dry thermal Effusivity of LHM-wall is thus

$$\text{Eff}_0 = (\rho_0.c_0.\lambda_0)^{1/2} = 297 \text{ J}.\text{m}^{-2}.\text{K}^{-1}.\text{s}^{-1/2} . \quad (76)$$

Fig.108 illustrates its evolution with relative humidity, for LHM-wall and other materials. Thermal Effusivity of LHM-wall is relatively low compared to most of masonry materials, but it is higher than classical insulation materials ($\sim 45 \text{ J}.\text{m}^{-2}.\text{K}^{-1}.\text{s}^{-1/2}$). Its value is much higher (i.e. comparable to dry brick $\sim 1000 \text{ J}.\text{m}^{-2}.\text{K}^{-1}.\text{s}^{-1/2}$) when approaching free saturation.

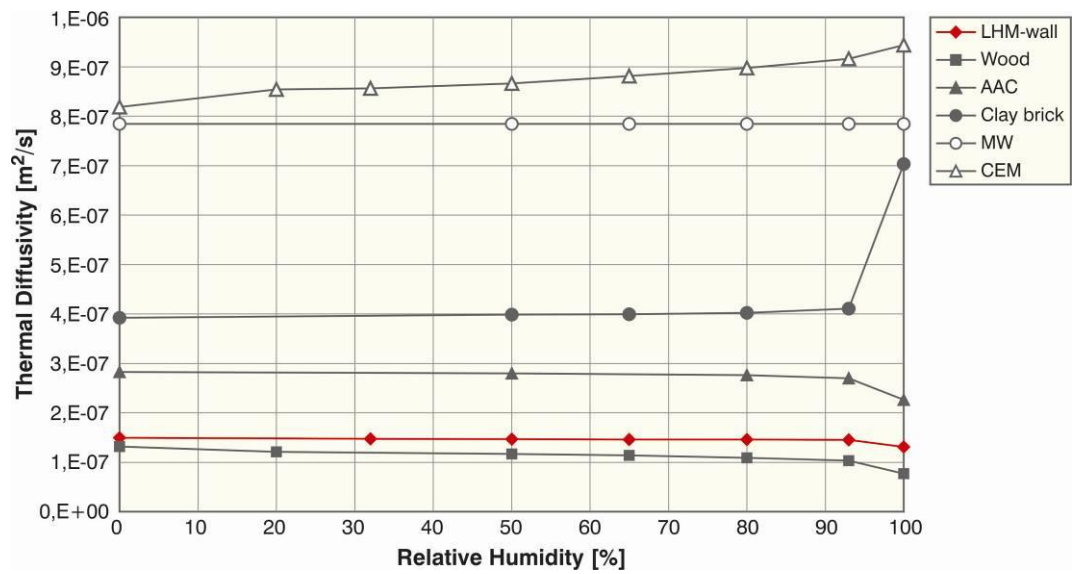


Figure 107 : Thermal diffusivity of LHM-wall and other materials

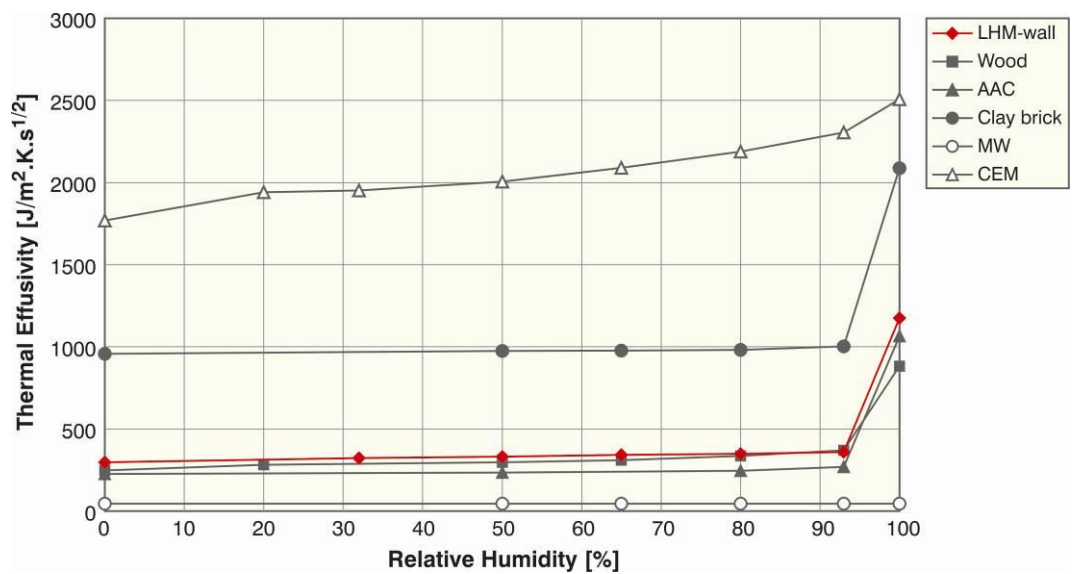


Figure 108 : Thermal Effusivity of LHM-wall and other materials

7.2.2 Moisture transfer and storage

Based on an analogy on heat transfer, recent research project Nordtest⁵⁵ gives an expression of *moisture diffusivity* and *Effusivity*. Compared to their thermal equivalent presented in previous section, following relationships

$$\alpha_m = \delta \cdot P_{\text{sat}} / \xi_\phi \quad (77)$$

$$\text{Eff}_m = (\delta \cdot \xi_\phi / P_{\text{sat}})^{1/2} \quad (78)$$

show that moisture diffusivity, written α_m [$\text{m}^2 \cdot \text{s}^{-1}$], and moisture Effusivity, written Eff_m [$\text{kg} \cdot \text{m}^{-2} \cdot \text{Pa}^{-1} \cdot \text{s}^{-1/2}$], are not only depending on materials hygrothermal parameters. They also depend on saturation pressure P_{sat} . In these relationships, δ [$\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$] is the vapour permeability, defined in 3.2.1.3, and ξ_ϕ [$\text{kg} \cdot \text{m}^{-3}$] the hygric capacity defined in 3.2.1.1.

In Nordtest project, “moisture” diffusivity and Effusivity are referring to transient “vapour” transfer. Heat transfer analogy could also be used to define “liquid” diffusivity and Effusivity, referring to transient liquid transfer. As presented in previous chapter, liquid transfer depends on boundary conditions, and liquid diffusivity and Effusivity should be distinguished for absorption and redistribution. These theoretical developments are considered to be beyond the aims and scope of this work.

According to these remarks, moisture diffusivity represents in this case the rate at which the water content of the material can vary due to vapour flow, and moisture Effusivity represents the quantity of moisture uptake (or release) when the material is subjected to a vapour flow during a given time laps. Following relationships give reference values for LHM-wall in the dry state when $P_{\text{sat}} = 2338$ Pa (20°C):

$$\alpha_{m,0} = 8,30 \cdot 10^{-6} \text{ m}^2 \cdot \text{s}^{-1} \quad (79)$$

$$\text{Eff}_{m,0} = 5,39 \cdot 10^{-5} \text{ kg} \cdot \text{m}^{-2} \cdot \text{Pa}^{-1} \cdot \text{s}^{-1/2} \quad (80)$$

Fig.109 and Fig.110 give evolution of both parameters with relative humidity, for LHM-wall and other materials. It appears that in hygroscopic region, moisture diffusivity of LHM-wall is about hundred time higher compared to Wood or CEM (fast moisture transfer), and around 2 times lower than for AAC or Clay brick. Moisture Effusivity of LHM-wall is 3 to 5 time higher than for other materials (important quantity of moisture transferred).

⁵⁵ *Moisture buffering of building materials*, C. Rode et al., final report, Department of Civil Engineering, Technical University of Denmark, 2005

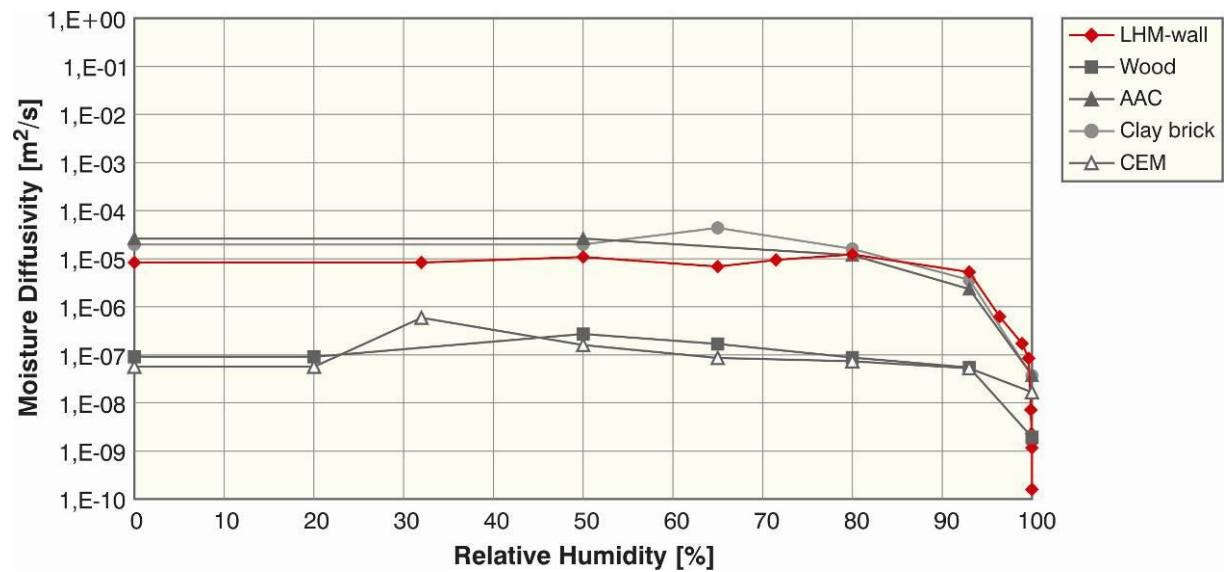


Figure 109 : Moisture diffusivity of LHM-wall and other materials

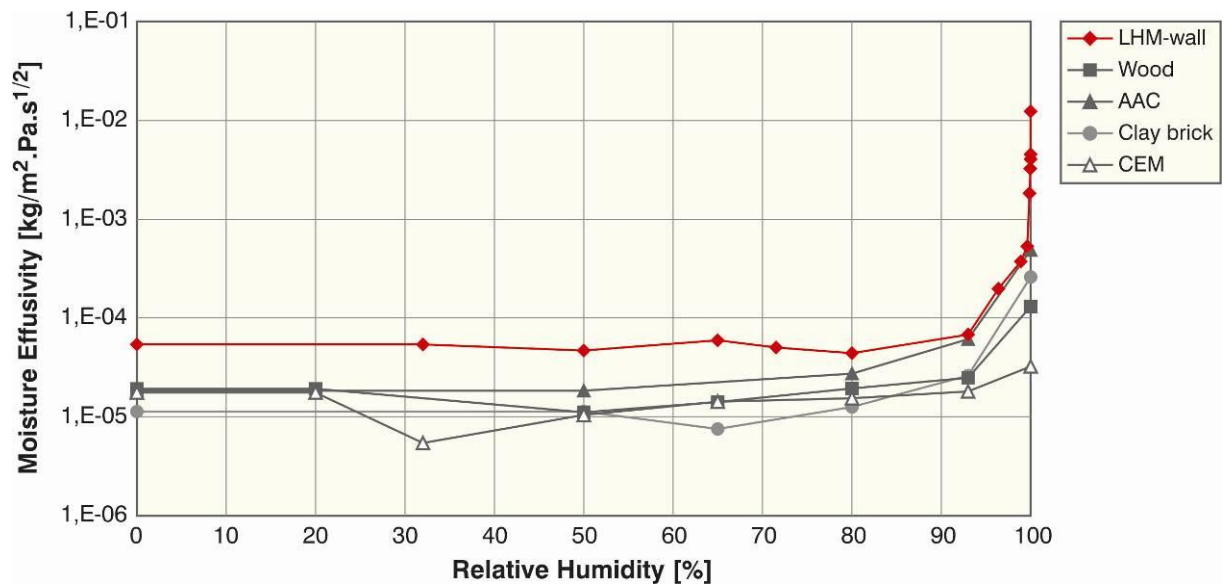


Figure 110 : Moisture Effusivity of LHM-wall and other materials

7.3 Definition of the components and U-value

Component (A) is a 30cm layer of LHM-wall (timber frame is not considered here), covered on both sides with lime based plaster and render. As illustrated on Fig.111, outside render is 2cm and inside plaster is 1,5cm. No measurements were made on plaster/render's hygrothermal parameters, their hygrothermal parameters were both considered to correspond to "Lime Plaster (stucco)" in WUFI®'s material database. The heat transfer coefficients of outside and inside surface correspond to Belgian standard: $h_i = 8 \text{ W.m}^{-2}.\text{K}^{-1}$, $h_e = 23 \text{ W.m}^{-2}.\text{K}^{-1}$. Short-wave absorptivity is 0,4 and rain water absorption factor is 0,7.

In building physics, thermal performance of building components is classically based on thermal transfer in permanent transfer. When permanent transfer is installed, heat flow through a building component can be expressed by the product of its *thermal transfer coefficient*, written $U \text{ [W.m}^{-2}.\text{K}^{-1}]$ and the temperature difference between both sides of the component, as presented in

$$\dot{q}_{\text{component}} = U \cdot (\theta_{\text{hot}} - \theta_{\text{cold}}). \quad (81)$$

The thermal transfer coefficient, sometimes called "U-value", is defined by $U = 1/R_{\text{tot}}$ (82)

where $R_{\text{tot}} \text{ [m}^2.\text{K}^{-1}.\text{W}^{-1}]$ is the *total thermal resistance* of the component. R_{tot} is the sum of the thermal resistance of each layer (thickness: $d_{\text{layer}} \text{ [m]}$, thermal conductivity: $\lambda_{\text{layer}} \text{ [W.m}^{-1}.\text{K}^{-1}]$) and of the thermal resistance of both surfaces:

$$R_{\text{tot}} = \frac{1}{h_e} + \sum \frac{d_{\text{layer}}}{\lambda_{\text{layer}}} + \frac{1}{h_i} \quad (83)$$

Based on these relationships, thermal transfer coefficient of reference LHM-wall component, $U_{\text{ref}} \text{ [W.m}^{-2}.\text{K}^{-1}]$ can be calculated. The first question is to know which thermal conductivity has to be used for each layer in relationship (83). As a matter of fact using dry thermal conductivity is unrealistic. Thermal conductivity of the material, depending on its water content, is constantly adapting to the climate conditions the component is subjected to.

To define which thermal conductivities should be used in the U-value calculation, a preliminary simulation was run to determine average moisture content of each layer when component is subjected to average conditions of Belgium. Referring to 3.2.4, outside climate corresponds to Belgian (Uccle) Test Reference Years and inside climate corresponds to classical environment in residential buildings. The simulation was run for a 3 years period with initial conditions of 20°C and 80% RH through the components. Components are oriented to the south. The thermal conductivities used in U-value calculation and presented in Table 6, correspond, for each layer, to the average moisture content of the last year (34,5 kg.m^{-3} for LHM-wall layer, equivalent to ~80% RH in the MRC). λ for LHM-wall is thus $0,145 \text{ W.m}^{-1}.\text{K}^{-1}$. The *total thickness of LHM-wall reference component* is $d_{\text{tot}} = 33,5\text{cm}$ and the thermal transfer coefficient is

$$U_{\text{ref}} = 0,439 \text{ W.m}^{-2}.\text{K}^{-1}. \quad (84)$$

Experiments achieved in the UK indicates better U-value (i.e. $0,26 \text{ W.m}^{-1}.\text{K}^{-2}$) for equivalent component. LHM mixture measured in these experiments may be slightly different (lower density, lower $\lambda \sim 0,084 \text{ W.m}^{-1}.\text{K}^{-1}$).

As introduced in 1.2, beside this first LHM-wall component, another LHM-wall component is analysed in this chapter. This second component, component (B), is illustrated in Fig.112. It is defined with a 2,2cm wood cladding on outside surface separated from LHM-wall layer with a 2cm ventilated air layer. Inside surface is covered with 1,5cm of lime based plaster. In order to define which thermal conductivities should be used in the U-value calculation, the same preliminary simulation was executed. As thermal resistance of all the layers after a ventilated air layer should not be considered in the U-value, the simulation was run without wood cladding and air layer ($h_i = h_e = 8 \text{ W.m}^{-2}.\text{K}^{-1}$ and no sun or sun absorption allowed). Average moisture content of the last year and thickness of the layer was defined after few iterations to obtain the same thermal transfer coefficient as component (A). Average moisture content of the last year is $30,1 \text{ kg.m}^{-3}$ for LHM-wall layer ($d_{\text{layer}} = 28,4 \text{ cm}$). The *total thickness of the component* is $d_{\text{tot}} = 34,1 \text{ cm}$.

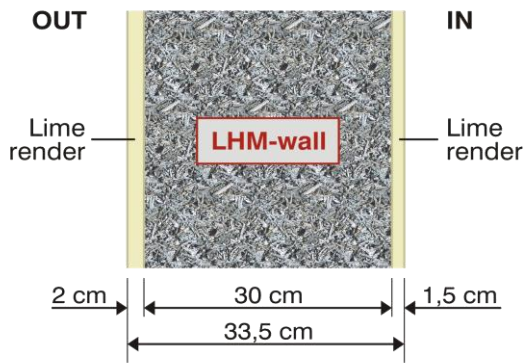


Figure 111 : Component (A)

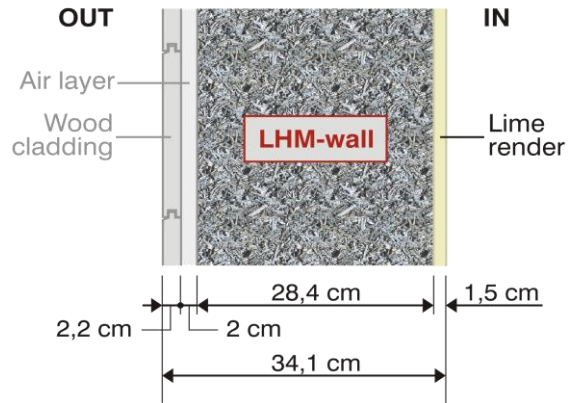


Figure 112 : Component (B)

LHM-wall components are compared to four types of “equivalent” components. Those components all have the same thermal transfer coefficient (U-value). Two types correspond to classical wall components of new buildings: cellular concrete (C) and double wall (D). The two others correspond to thermal improvements of existing wall: outside insulation (E) and inside insulation (F). Except for component (C), insulation layer is defined with a extruded polystyrene foam insulation layer (XPS) with approximately constant thermal conductivity ($\lambda_{\text{XPS}} = 0,03 \text{ W.m}^{-1}.\text{K}^{-1}$). The same preliminary simulation is executed on these components, with few iterations, where the thickness of only one layer is adapted (red text on the figure) to obtain the same thermal transfer coefficient as component (A). Fig.113 to Fig.116 illustrate those components and give the thickness of each layer input in the simulations. Table 4 presents thermal conductivity values used for U-value calculations of each components. Thickness of the components is: (C) $d_{\text{tot}} = 28 \text{ cm}$; (D) $d_{\text{tot}} = 34,08 \text{ cm}$; (E) $d_{\text{tot}} = 36,9 \text{ cm}$; (F) $d_{\text{tot}} = 36,21 \text{ cm}$. For equivalent thermal transfer coefficient, total thickness of the components thus appears to be higher than LHM-wall component for all the selected components except for component (C).

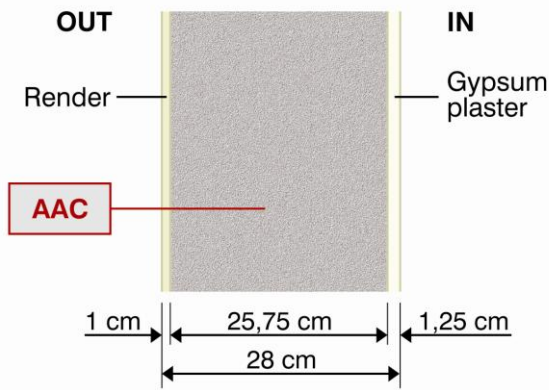


Figure 113 : Component (C)

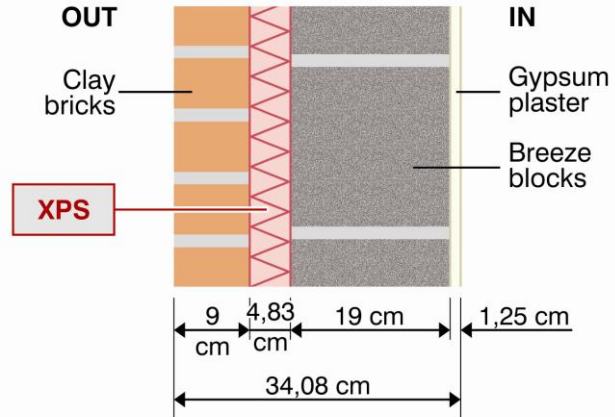


Figure 114 : Component (D)

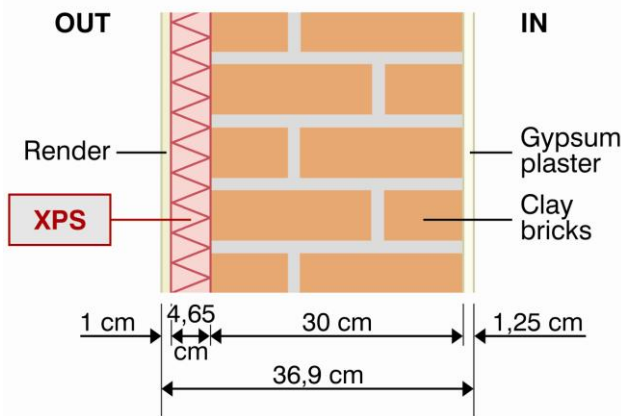


Figure 115 : Component (E)

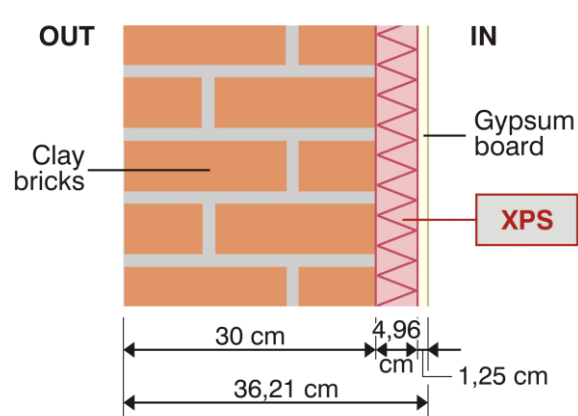


Figure 116 : Component (F)

In this chapter, LHM-wall components are also compared to a low thermal transfer coefficient wall: component (G). In this case, the component is defined with an equivalent size as component (B): $d_{tot} = 34,1\text{cm}$. As illustrated in Fig.117, it is defined as a timber frame wall filled with mineral wool and covered on outside surface by wood cladding (+2cm of ventilated air layer) and on inside surface by a gypsum board. Those layers are completed by a with a vapour barrier ($\mu = 1,5 \cdot 10^6$) inside (under gypsum board) and a weather resistive barrier ($\mu = 500$) outside. Its thermal transfer coefficient is only $U = 0,135 \text{ W.m}^{-2}.\text{K}^{-1}$ (the two external layers are not taken into account and the same preliminary simulation is performed in order to define the lambda value of the layers).

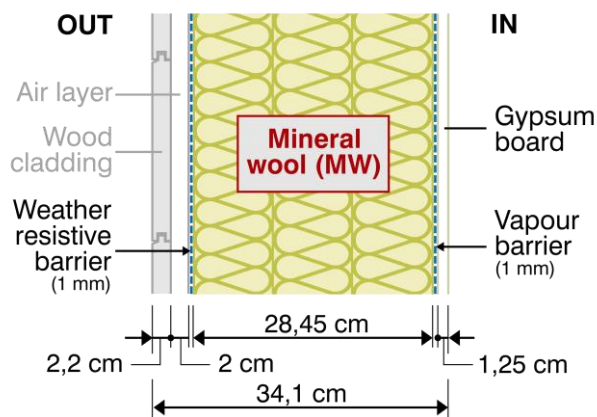


Figure 117 : Component (G)

All the components are illustrated on the back cover of this document !

Table 4

Values used for U-value determination of the components

Components / Layers	Thickness [m]	Average WC w [kg/m³]	Lambda suppl. [%lambda init]	Lamda moist [W/mK]	Thermal res. [m².K/W]	U-value [W/m².K]
A	0,335					
Outside surface	/			/	0,043	
Lime render	0,020	66,48	0,33	0,933	0,021	
LHM-wall	0,300	34,49	0,26	0,145	2,067	
Lime plaster	0,015	20,57	0,10	0,772	0,019	
Inside surface	/			/	0,125	
Total thermal res.					2,277	0,439
B	0,341					
Wood cladding	0,022	/		0,000	0,000	
Air layer	0,020	/		0,000	0,000	
Outside surface	/			/	0,125	
LHM-wall	0,284	30,12	0,23	0,141	2,010	
Lime plaster	0,015	20,38	0,10	0,771	0,019	
Inside surface	/			/	0,125	
Total thermal res.					2,279	0,439
C	0,280					
Outside surface	/			/	0,043	
Render	0,010	48,31	0,20	0,963	0,010	
AAC	0,258	7,06	0,05	0,126	2,039	
Plaster	0,013	3,86	0,04	0,207	0,060	
Inside surface	/			/	0,125	
Total Thermal res.					2,279	0,439
D	0,341					
Outside surface	/			/	0,043	
Brique	0,090	12,69	0,11	0,663	0,136	
XPS	0,048	1,98	(WUFI approx)	0,030	1,610	
Parpaing béton	0,190	6,11	0,05	0,629	0,302	
Plaster	0,013	3,89	0,04	0,207	0,060	
Inside surface	/			/	0,125	
Total thermal res.					2,277	0,439
E	0,369					
Outside surface	/			/	0,043	
Render	0,010	48,38	0,20	0,963	0,010	
XPS	0,047	0,97	(WUFI approx)	0,030	1,550	
Brique	0,300	3,08	0,03	0,615	0,487	
Plaster	0,013	3,88	0,04	0,207	0,060	
Inside surface	/			/	0,125	
Total thermal res.					2,277	0,439
F	0,362					
Outside surface	/			/	0,043	
Brique	0,300	32,16	0,27	0,761	0,394	
XPS	0,050	3,70	(WUFI approx)	0,030	1,653	
Gypsum paInels	0,013	3,90	0,04	0,207	0,060	
Inside surface	/			/	0,125	
Total thermal res.					2,276	0,439
G	0,341					
Wood cladding	0,022	/		0,000	0,000	
Air layer	0,020	/		0,000	0,000	
Outside surface	/			/	0,125	
Weather res. barrier	0,001	0,00				
Laine minérale	0,285	0,77	(WUFI approx)	0,040	7,113	
Vapour barrier	0,001	0,00	(WUFI approx)	2,300	0,000	
Gypsum paInels	0,013	3,77	0,04	0,207	0,060	
Inside surface	/			/	0,125	
Total thermal res.					7,423	0,135

7.4 Thermal shock and cycles

7.4.1 Thermal shock

Abstract

Outdoor temperature in Belgium can vary relatively fast. Variation of 10°C, or sometimes of 20°C, between night and day can happen all along the year. This section shows how the components behave after a sudden cooling of outdoor environment. Two parameters giving relative transient behaviour of the components are defined. The first one quantifies the time needed before permanent transfer can be assumed and the other represents how much energy will be transferred after 24h (as this kind of fast variation does not persist longer than 1 day).

In this section, the wall components, defined in section 7.3 (and illustrated on the back cover of the present document), are subjected to a theoretical thermal shock through WUFI® simulations. Initial temperature is set to 20°C in both in and out environments as well as through the components. To simplify the presentation, moisture transfer is not taken into account in the calculation. Relative humidity outside and inside are set to 50% during the whole simulation period (1year), and moisture content of each layer is fixed to the value used in the U-value calculation. From first time step and until the end of simulation, outside temperature is decreased to 0°C (sudden cooling). Temperature evolution at different time step (30min, 1h, 2h, 3h, 6h, 12h, 24h, 48h and 72h) is analysed. Fig.118 shows results obtained for component (A). A linear distribution of temperature through the component is reached almost 3 days after thermal shock.

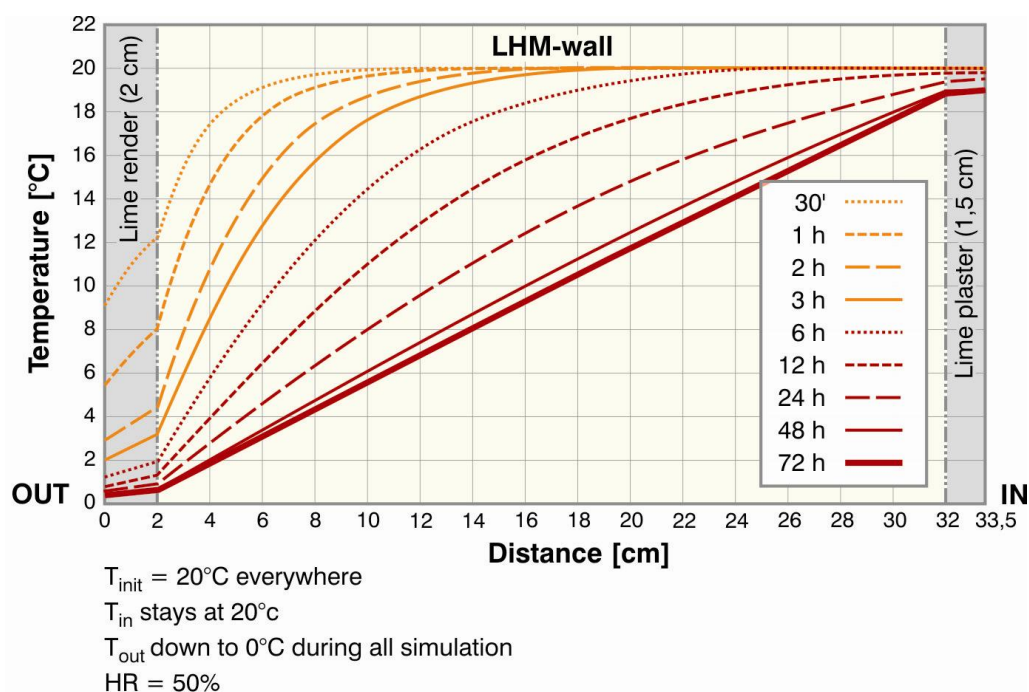


Figure 118 : Evolution of temperature through LHM-wall component (A) after a sudden cooling of outside environment

Temperature evolution in component (B) and (G) is compared in Fig.119 and it appears that the temperature profile in LHM-wall component (B) adapts much slower than in component (G).

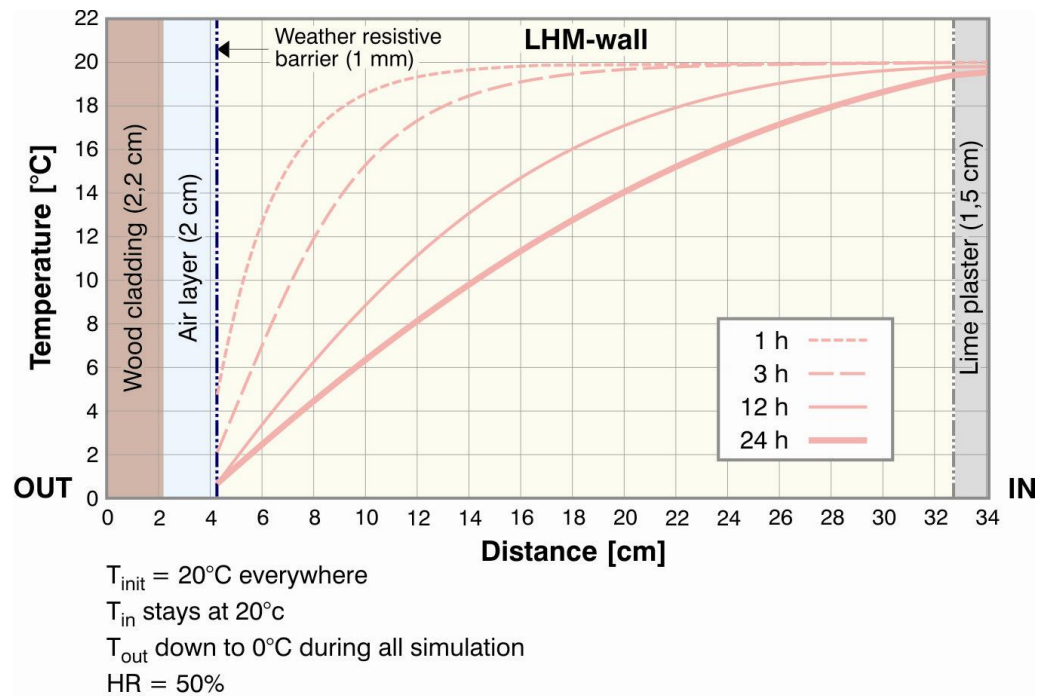


Figure 119 : Evolution of temperature through component (B) after a sudden cooling of outside environment

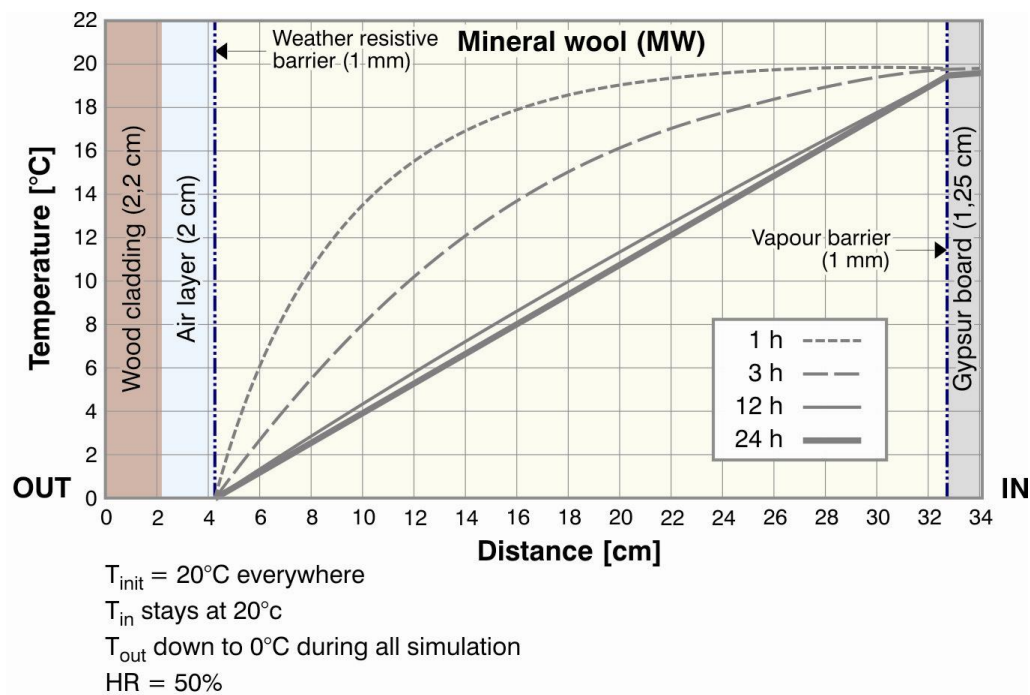


Figure 120 : Evolution of temperature through component (G) after a sudden cooling of outside environment

Fig.121 presents heat flow through the inside surface for each component, the negative value means flow is going from inside to outside. It corresponds to the heating loss through 1m^2 of the component when inside temperature stays at its level (20°C). Heat flow in permanent transfer is the same for component (A) to (F): $8,78\text{ W.m}^{-2}$ because they were defined with the same U-value. The U-value is equal to $2,7\text{ W.m}^{-2}$ for component (G).

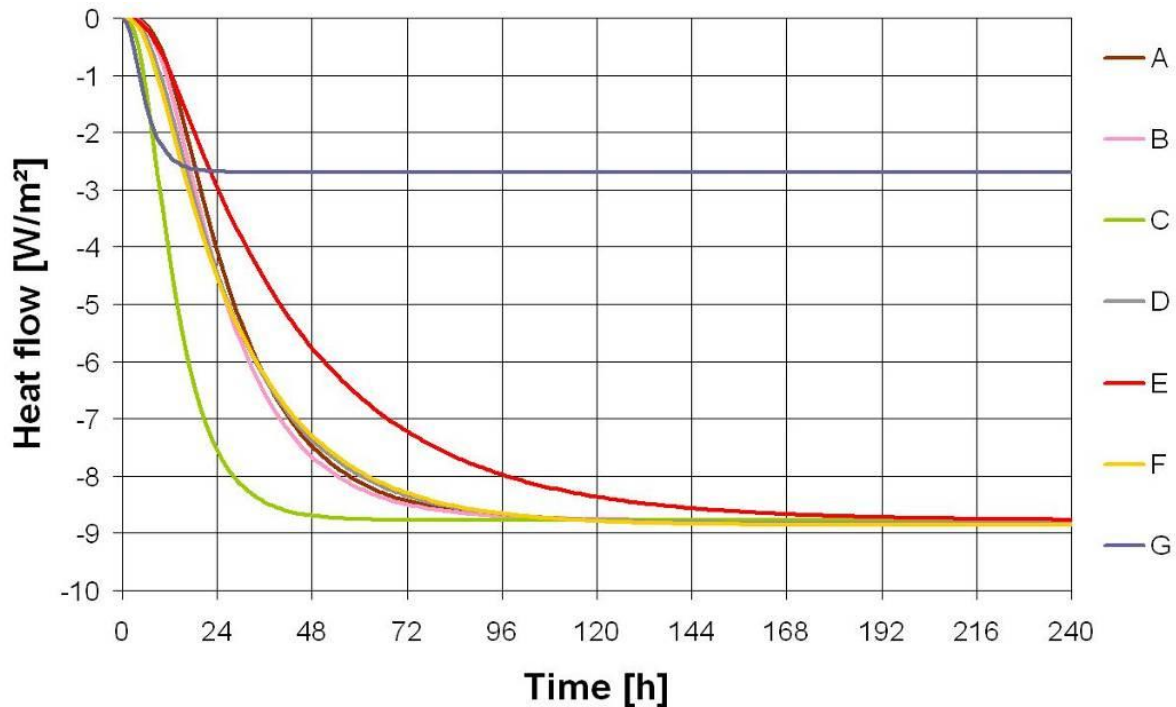


Figure 121 : Evolution of heat flow through inside surface of the components during 10 days after a sudden cooling of outside environment

Permanent transfer is considered to be obtained when the heat flow reaches 95% of its “final value” (i.e. the value after 1 year is called “final value” in this case). Fig.122 illustrates the results obtained for the different components. Permanent transfer is thus approximately reached after the same time period, between 64 and 77 hours, for component (A), (B), (D) and (F). The longest delay, 118 hours, was obtained for component (E) (thermal mass was “protected” by the insulation layer). Delay for component (C) was relatively short, 33 hours, but the shortest was for component (G), 15 hours.

Evolution of cumulative quantity of energy transferred through inside surface (from in to out) during the 24 first hours is illustrated in Fig.123. Results obtained for component (G) is surprisingly higher than all the other components except component (C). If thermal difference between outside and inside persists longer, component (G) is more adapted because of its low thermal transfer coefficient. This simulation is defined to analyse components behaviour under a thermal shock, values at 12 and 24h are the most relevant in this case.

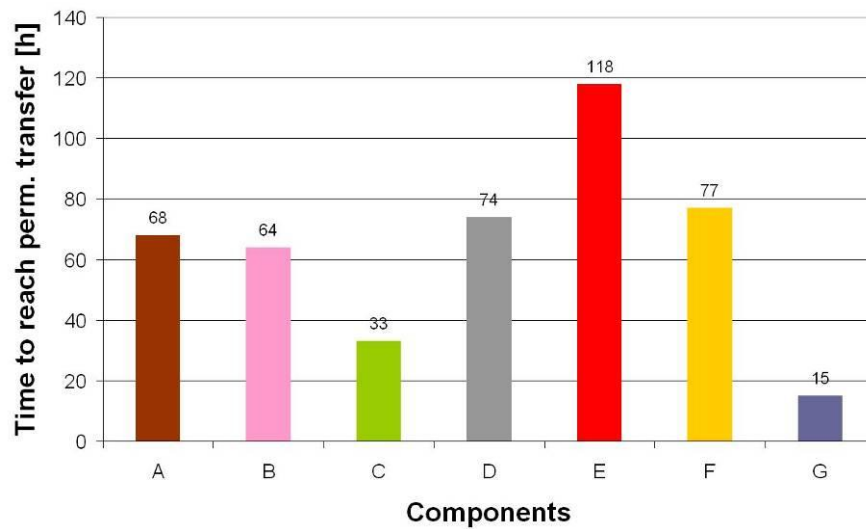


Figure 122 : Time to reach permanent transfer for all components after a sudden cooling of outside environment

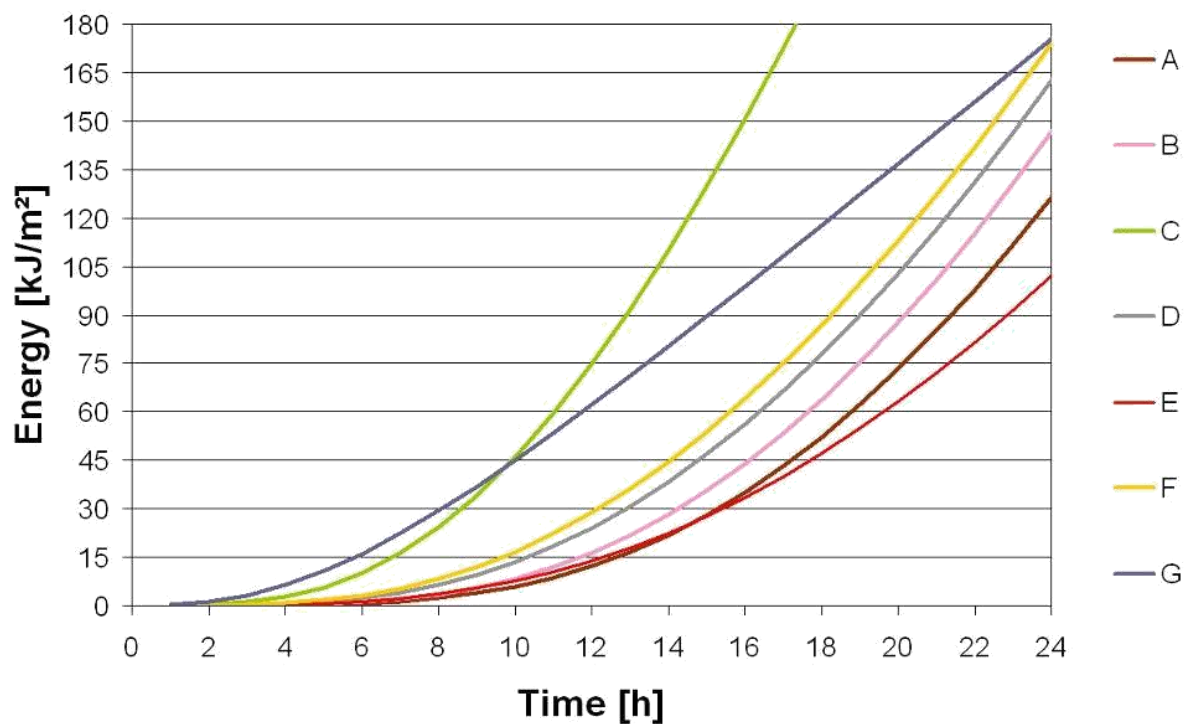


Figure 123 : Cumulative quantity of energy transferring through inside surface of components during 24 hours after a sudden cooling of outside environment

Cumulative quantity of energy transferred after 24 first hours is divided by the cumulative quantity of energy transferred if permanent transfer is assumed. As illustrated in Fig.124, the results are expressed in [%] and written Q_{24h} .

It is interesting to remark that similar simulations give equivalent results in terms of delay and energy loss: complementary thermal shock simulations made with a temperature gradient of 10°C (from 20°C to 10°C) showed that the time to get to permanent transfer and Q_{24h} were not influenced by temperature gradient. Sudden heating gives rigorously opposite results as equivalent sudden cooling. Other simulations showed that a sudden sun radiation has the same effect as sudden heating, except for component (B) and (G) for which the sun do not reach the layer under wood cladding. Moisture influence is analysed in §7.5.

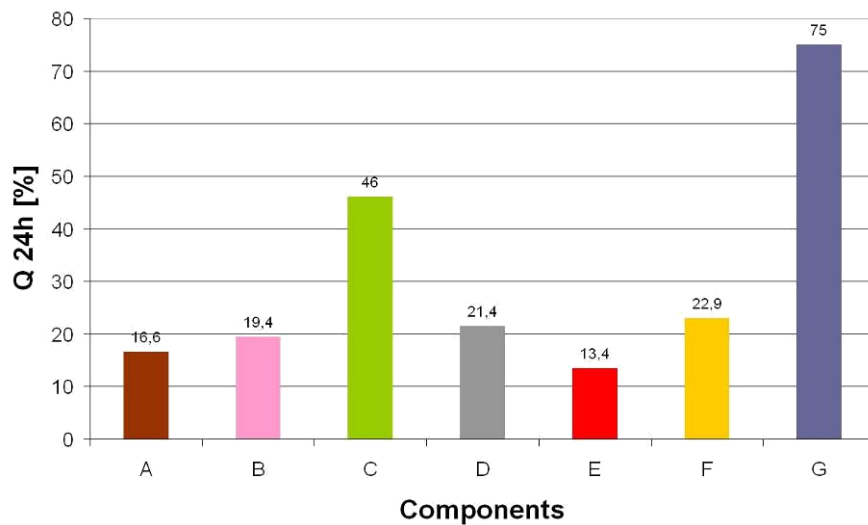


Figure 124 : Ratio between cumulative quantity of energy transferred through inside surface of components and cumulative quantity of energy transferred if permanent transfer is assumed 24 hours after sudden cooling of outside environment

It shows that only less than 20% of the calculated transfer of energy through component (A) was achieved after 24h, and even less after 12h. LHM-wall components appear to have strong transient effects on heat flow under heat shock: 1/ inside environment will benefit of sun radiation of the evening during cold nights; 2/ keeps inside environment fresh from the night during scorching days; 3/ reduce the influence of strong direct sun radiations.

If the thermal transfer coefficient (U-value) describes thermal flow through the component in permanent transfer, it gives no information on its transient behaviour. Even if component (G) has a very low U-value, it is not as efficient as the other studied components to protect inside environment from short thermal variation in outside environment (i.e. cold nights vs. intense sun radiation and heat in summer).

7.4.2 Thermal cycles

Abstract

Outdoor temperature is constantly changing. In Belgium, strong variation between night and day can be observed. Average daily temperature also varies all along the seasons. This section shows how the components behave under thermal cycles. Daily variations of inside and outside environment are defined on a 24h basis, as well as a seasonal variation on a 365d basis. Three parameters are defined after WUFI® simulations to give reference value about their dynamic behaviour. Results show that if LHM-wall components have strong transient effects on heat flow under short-term heat cycles, influence of transient effects under long-term heat cycles is negligible.

7.4.2.1 Outside thermal cycle - 1 day period

First, outside temperature variations (left) is defined with a daily thermal cycle (time step: 1 hour) that follows a sine curve with a 24 hours period and amplitude of 10°C around a mean temperature of 10°C (starting at 10°C, and minima occurring during the 6th hour of each cycle). Evolution of temperature at different depth and of thermal flow through the inside surface (right) are used to describe components behaviour, respectively illustrated in Fig.125 and Fig.126. Inside temperature is fixed to 10°C to focus on the effects of transient transfer (average flow is null). Moisture content of each layer in each component is fixed at the level obtained in preliminary simulation defined for the calculation of U-value in §7.3.

In Fig.125, the curves “P.transf1” and “P.transf2” correspond respectively to $U=0,439 \text{ W.m}^{-2}.\text{K}^{-1}$ and $U=0,135 \text{ W.m}^{-2}.\text{K}^{-1}$. These theoretical curves illustrate heat flow when no transient transfer occurs (linear distribution of temperature in each layer of components, minima occurring during the 6th hour of each cycle).

As it appears, distribution of temperature is actually never linear in such daily cycles. Thermal inertia of the components under thermal cycles is here referred in terms of *phase shift* and *thermal damping*.

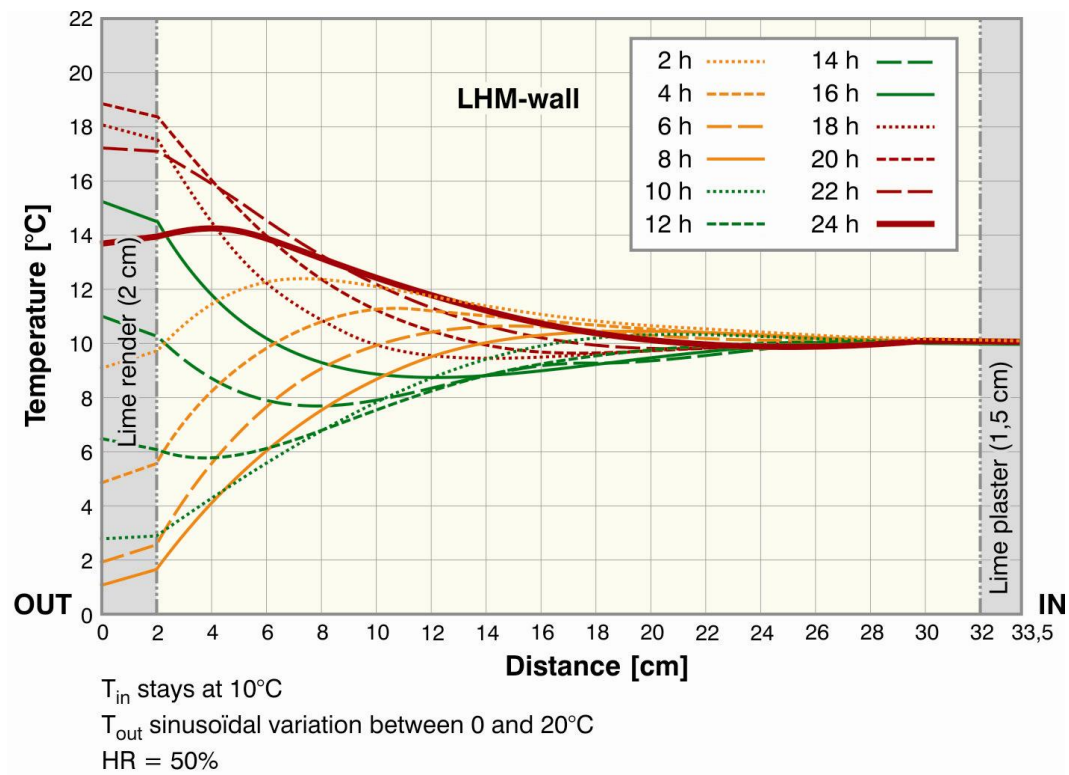


Figure 125 : Evolution of the temperature through LHM-wall component (A) under daily thermal cycles in outside environment

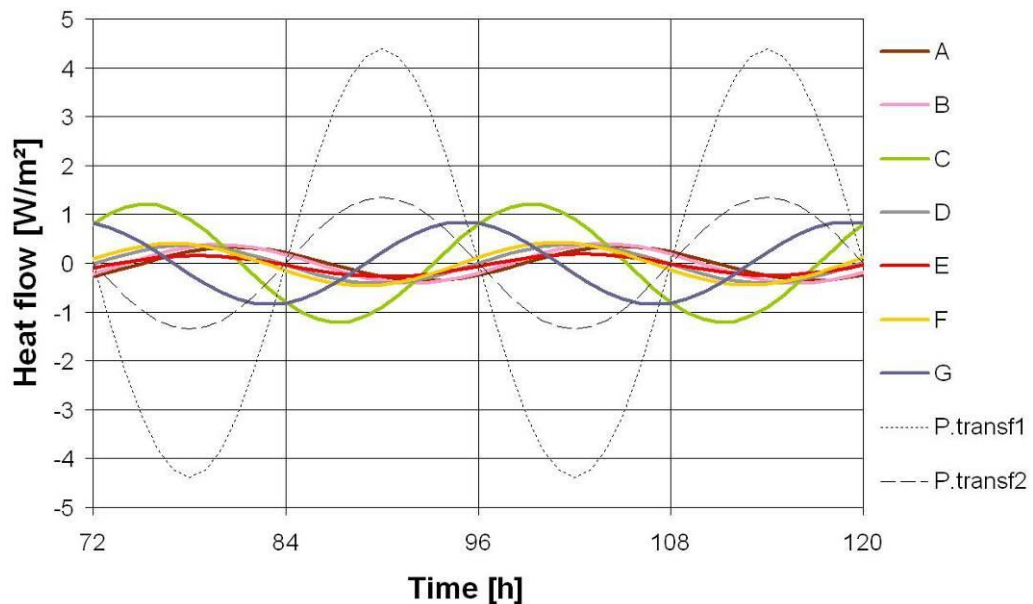


Figure 126 : Evolution of the heat flow through inside surface of the components during 36h under daily thermal cycles in outside environment

The *phase shift* [h] for daily thermal cycle expresses the delay to reach extremes values on inside (right) surface considering variations in outside (left) environment. Results presented in Fig.127 compare the theoretical heat flow in permanent transfer (“P.transf1” and “P.transf2”) to the heat flow through inside surface obtained with WUFI® simulations during the third cycle (the 3rd day). The component with the lowest phase shift is component (G). For LHM-wall components the phase shift is respectively 15 hours and 14 hours for (A) and (B). The maximum temperature is thus only reached on inside surface when temperature is already back to its minimum value in outside environment (inside surface is the warmest in the early morning if the highest outside temperature occurs at 14pm).

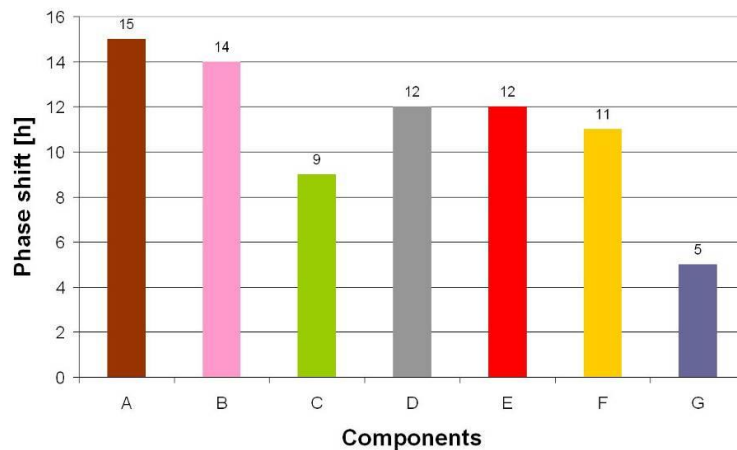


Figure 127 : Thermal phase shift of the components under daily thermal cycles in outside environment

Thermal damping [%] of daily thermal cycle is the proportion of theoretical flow variation on inside surface that did not occur due to transient effects. Magnitudes of the flow variation are in both cases calculated based on the difference between maximum and minimum flow in the 3rd day. All the components are referred to “P.transf1”, except component (G) referring to “P.transf2”. As it appears on Fig.128, component (E) has the highest thermal damping and component (G) the lowest. It is 92% for LHM-wall component (A), and 91% for component (B). The total energy transferred is null for all the components because the average temperature inside and outside is 10°C in this case (hygric effects are neglected).

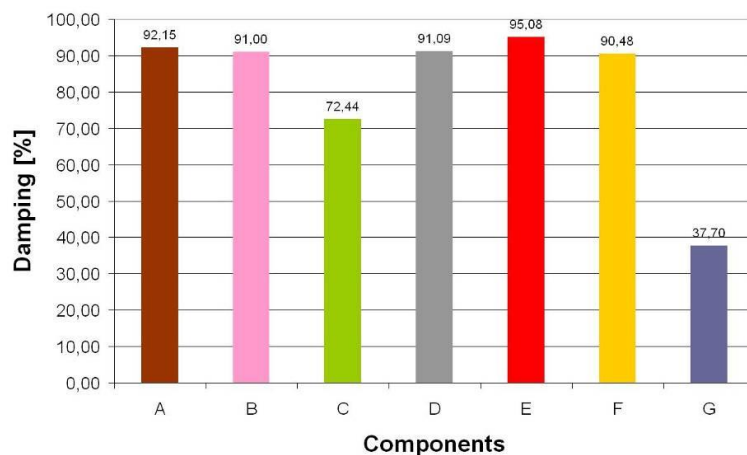


Figure 128 : Thermal damping of the components under daily thermal cycles in outside environment

7.4.2.2

Outside thermal cycle - 1 year period

A second set of simulations is defined with a yearly variation of outside temperature to analyse the influence of transient behaviour if outside temperature evolution is defined with a single value every 24h (average temperature for each day of the year). In the simulations, outside temperature (left) follows a sine curve with a 365 days period (time step: 24 hours); temperature variations have the same magnitude as the previous simulations (from 0 to 20°C); starting on September 3rd at 10°C and with a mean outside temperature of 10° (day of maximum: 3 June). Inside environment is maintained at 50% of RH and 20°C.

Thermal flow on the inside surface of all the components appears to be identical. They correspond to the results obtained using U-value, temperature of inside and outside environment and relationship (81), illustrated in Fig.129. Curve “P.transf1” represents flow for component with $U=0,439 \text{ W.m}^{-2}.\text{K}^{-1}$ and “P.transf2” represents component (G) with $U= 0,135 \text{ W.m}^{-2}.\text{K}^{-1}$.

Mean value is $-4,39 \text{ W.m}^{-2}$ for “P.transf1” and $-1,35 \text{ W.m}^{-2}$ for “P.transf2”, corresponding to a permanent flow though the component when outside temperature is set to 10°C and inside 20°C. There is thus no *phase shift* or *thermal damping* with this particular thermal cycle (long term).

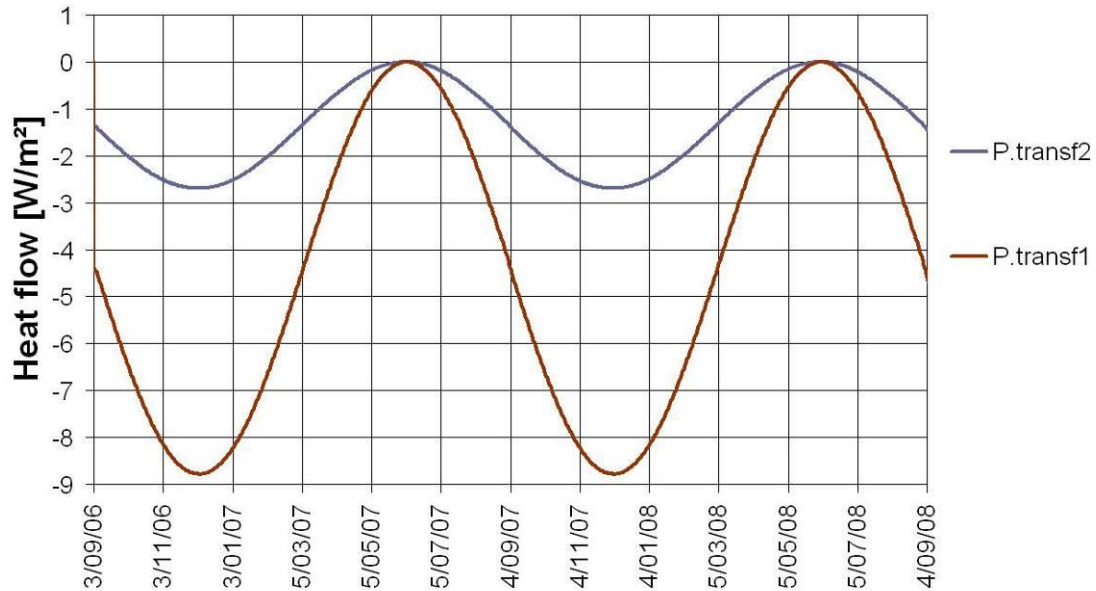


Figure 129 : Evolution of the heat flow through inside surface of the components during 2 years under yearly thermal cycles in outside environment

7.4.2.3

Inside thermal cycle

A third set of simulations is based on thermal analogy to Nordtest protocol, presented in 7.5.3. Environmental conditions are referring to typical winter day: inside environment is heated during the day (to 20°C) but heating system is stopped during the night (and air cools do to 18°C). Temperature of inside air never follows so sharp variation: values presented here should thus be seen as extreme values that the components may not reach in practice.

During simulation, the components are subjected to thermal cycle in the inside environment (right) where temperature remains equal to 20°C during 16 hours (day) and is then lowered to 18°C for the next 8 hours (night). Outside temperature and initial temperature of the components are fixed to 19,33°C (average value for inside temperature). Relative humidity is fixed to 50% in both environments and through the component. Again, moisture transfer is not taken into account in the calculation.

After three days, heat flow through inside surface follows regular cycles. Integration of the heat flow gives, for each time step, the cumulate quantity of energy transferred through this surface for each component, as illustrate in Fig.130 (average is not null because of initial value, and negative value means the heat was taken from inside environment). As expected, component (A) and (B) have the same behaviour (same composition of inside layers) and are grouped on the graph. Component ((D) and (E) were also grouped because results for both components were very close.

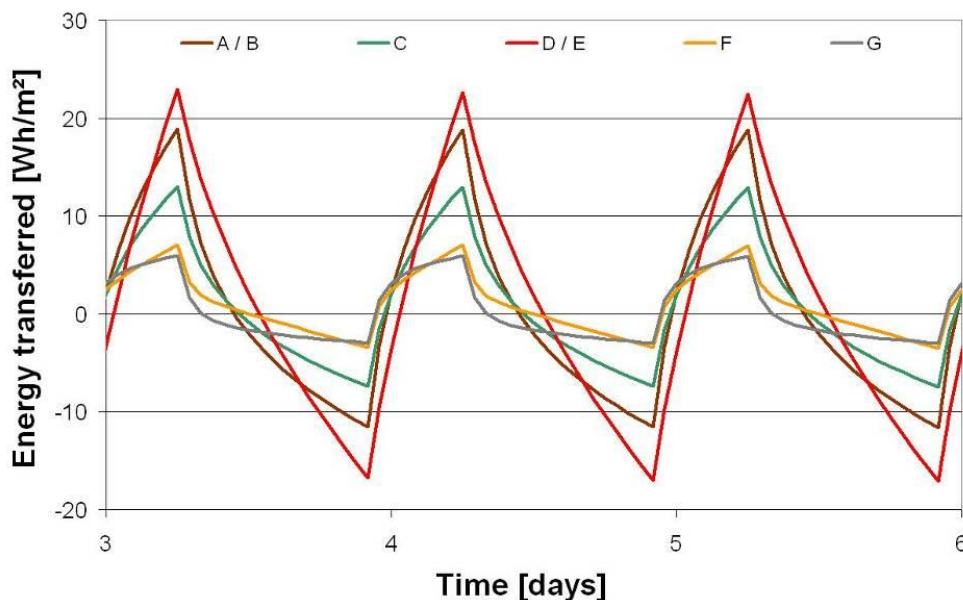


Figure 130 : Evolution of the cumulative quantity of energy transferred through inside surface of the components during 3 days under thermal buffering of inside environment

Thermal Buffering Value of components (analogy of Moisture Buffer Value), $TBV_{18-20, \text{simul}}$ [$\text{Wh}\cdot\text{m}^{-2}$], is here defined to be the theoretical energy released by the component during the night in these conditions. The higher it is, the more energy the component is able to exchange with inside environment during the cycles. Its values are presented for each component in Fig.131. TBV is high for components with heavy mineral material close to inside surface, i.e. (C) and (D), and it is low for components with light material behind inside finishing material, i.e. (F) and (G). LHM-wall components have an intermediate response between those two types (TBV relatively high). It has to be noticed that in practice, if the heating is stopped, the temperature of inside environment during the day (i.e. 20°C) do not switch directly to night value (i.e. 18°C). Complementary software (i.e. TRNSYS[®], WUFI[®]plus) could be used to define the reverse influence of components behaviour on inside environment.

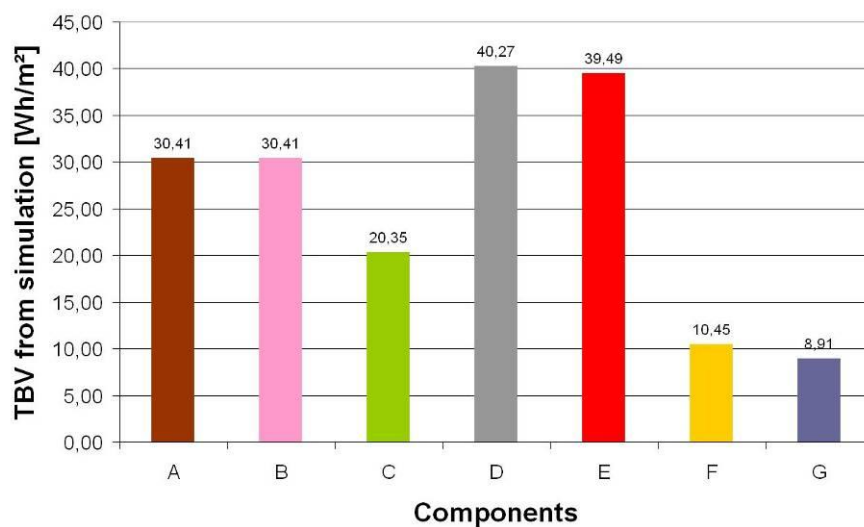


Figure 131 : Thermal buffer value of the reference components under thermal buffering of inside environment

Fig.132 shows the evolution of the inside surface temperature for each component. It appears that, in the present situation, where room temperature is changing instantaneously from one temperature level to another, the difference in surface temperature during “hot” and “cold” period is low. It is interesting to remark the link between surface temperature variations and thermal buffer of the component: components with high $TBV_{18-20, \text{simul}}$ have low variation of surface temperature. As presented in Fig.132, the difference in surface temperature is, in this case: $1,3^{\circ}\text{C}$ for component (D) and (E); $1,6^{\circ}\text{C}$ for (A) and (B); $1,7^{\circ}\text{C}$ for (C); and $1,8^{\circ}\text{C}$ for (F) and (G). In this model, neither the surface transfer coefficients nor inside environment is influenced by components behaviour. Evolution of surface temperature has a great influence on comfort feeling. Complementary measurements in experimental building should confirm high comfort feeling through measurement of thermal buffering of components and evolution of the temperature on inside surface of components.

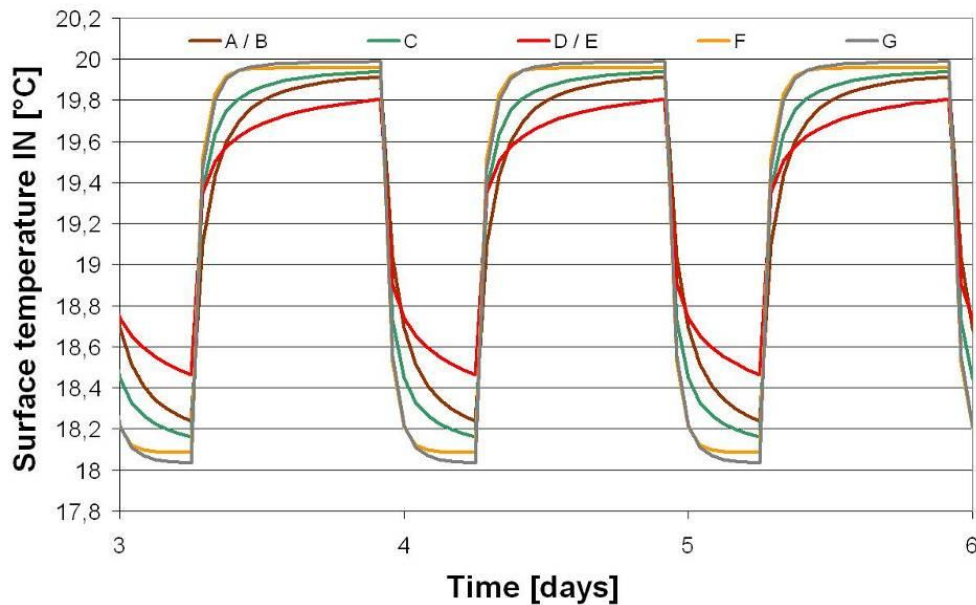


Figure 132 : Evolution of surface temperature of components
During 3 days under thermal buffering of inside environment

7.5 Hygric shock and cycles

Abstract

When lime binder and hemp particles are mixed on a building side, most of the water input of the mixture has to dry out of the component. This section shows that LHM-wall component (A) takes around 3 months to reach hygroscopic region. If render and plaster are adapted, their influence on the drying of LHM-wall is not significant. LHM-buildings should not be used during drying period or heating and ventilation demand will be increased during the period. It is interesting to remark that in the same condition, an equivalent component, where LHM-wall is replaced by cement concrete, takes much longer to release its water.

The first set of simulations corresponds to a pragmatic case of drying after implementation in an open-air environment. Results for component (A) will be compared to a wall component in cement concrete implemented and dried on an open building site (both components have south exposition). Outside and inside climate are considered to be the reference year in Uccle, as presented in 3.2.4 (outside climate file includes sun, rain and wind) and Belgian standard surface coefficients are used. Implementation is supposed to be made on the first of May and the simulation period is 3 years. Initial temperature in LHM-wall is 20°C. Initial moisture content (400 kg.m^{-3}) is chosen on the basis NMR results presented in 6.1. They are lower than free saturation $w_f = 546 \text{ kg.m}^{-3}$, because the mixing process followed by implementation never takes more than 2 hours.

Fig.133 shows initial water content profile for 4 drying configurations: without plaster/render, and when both lime based plaster and render are respectively applied after 1, 2 and 3 months.

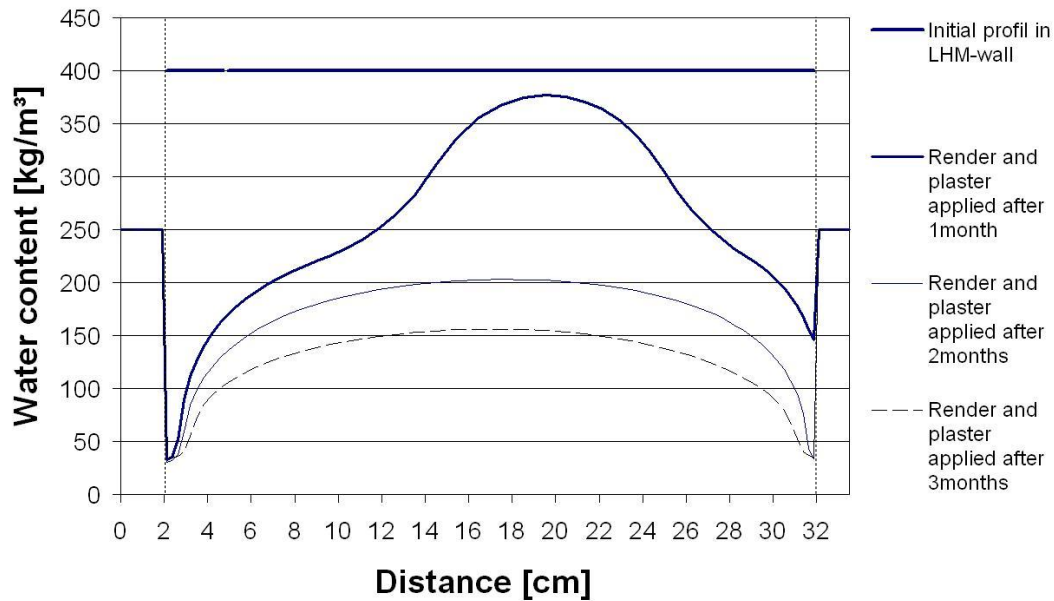


Figure 133 : Initial water content profile in LHM-wall component (A) under 4 drying configurations

Fig.134 shows the evolution of water content in LHM-wall layer in each case. Globally, water content is rising in winter and decreasing in summer. It appears that applying these specific render/plaster layers do not have a significant effect on moisture release during drying period (all the curve except “without plaster/render” are overlaid at this scale). The figure also shows that moisture uptake of the component during reference year is lower with plaster and render (mostly because the render reduces the absorbed amount of rain). In this simulation, most of capillary water is considered to be evacuated when average water content of 150kg.m^{-3} in LHM-wall layer is reached. It takes respectively **73 days** without plaster and render, **78 days** if the plaster and render are applied after 1 month and **76 days** if applied after 2 months.

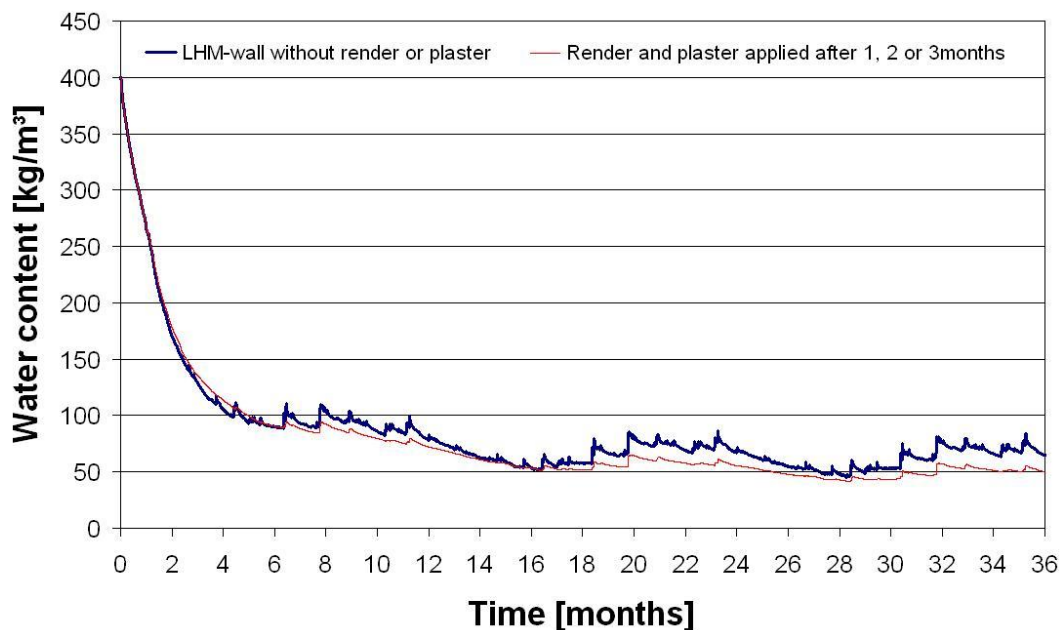


Figure 134 : Evolution of water content when component (A) is drying during 3 years under reference climate

It is important to remark that the quantity of energy transferring through the component is influenced by high water content (higher of thermal conductivity) and by latent heat effects of evaporation during drying. This phenomenon was not quantified in the present work, but it is assumed that LHM-building should not be used during drying (when the walls are drying, LHM-building has higher heating and ventilation demand).

It also appears that, when running simulation with LHM-wall components and with component (C) subjected to reference climate, some combination of layer lead to moisture accumulation problem and damaging condensation (low permeability render on outside surface, high rain absorption and low evaporation).

LHM-wall component need around 75 days to dry. This time period relatively long, especially if compared to dry assemblies. A complementary simulation, presented in Fig.135, analysed water content evolution of a 20cm cement concrete component, also implemented on the 1 May and subjected to the same climate conditions. It shows the component is still releasing initial water after 7 years.

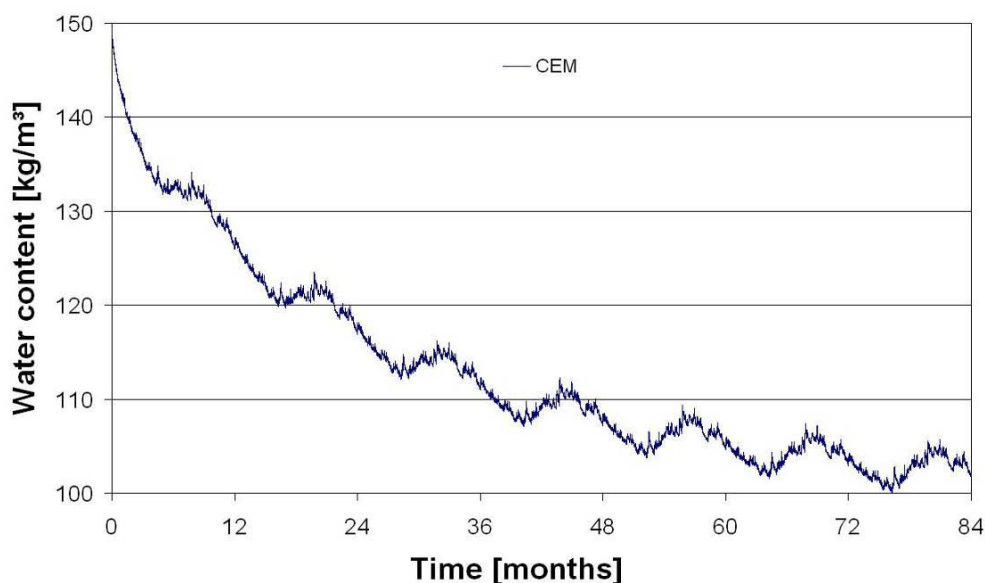


Figure 135 : Evolution of water content in a cement concrete component with the same thickness as component (A) drying during 7 years under reference climate

These observations are beyond the scope of this work, and precise criteria should be defined to allow comparing different material in terms of dynamic behaviour (evolution of water content, of relative humidity or of saturation level in each layer). Designers should balance the disadvantage of drying period with the opportunities, in terms of architecture, offered by a monolithic envelope (cast walls).

7.5.2 Hygric shock

Abstract

When outdoor relative humidity varies, water content through the component adapts and a diffusive flow of vapour starts depending on the relative vapour pressure on both sides. Moisture equilibriums, and thus permanent moisture flow, are much longer to be reached than thermal equilibrium. Components are subjected to a theoretical hygric shock where inside RH is lowered to 50% and outside RH stays at 80% (simulation is run in hygroscopic region). If no other variation of climate occurs (no variation, no rain, no sun...), permanent transfer can only be assumed after one year for component (A). The vapour flow in permanent transfer is very low in this case because of the small difference of vapour pressure between in and out (link between RH and temperature). The flow goes from in to out and §0 will show that it is the case during most of reference year if no rain is taken into account.

The theoretical hygric shock defined in the simulation starts with initial relative humidity outside and inside, as well as through the whole component of 80% RH. At the first time step and for the rest of the simulation, inside humidity is changed to 50% RH. Heat transport is not taken into account in the simulation. Outside temperature is fixed to 10°C and inside temperature to 20°C, with a linear distribution through the component (permanent flow). Because of temperature difference, partial pressure of vapour is higher inside (1169 Pa) than outside (983 Pa) and permanent flow is going from in to out (negative value).

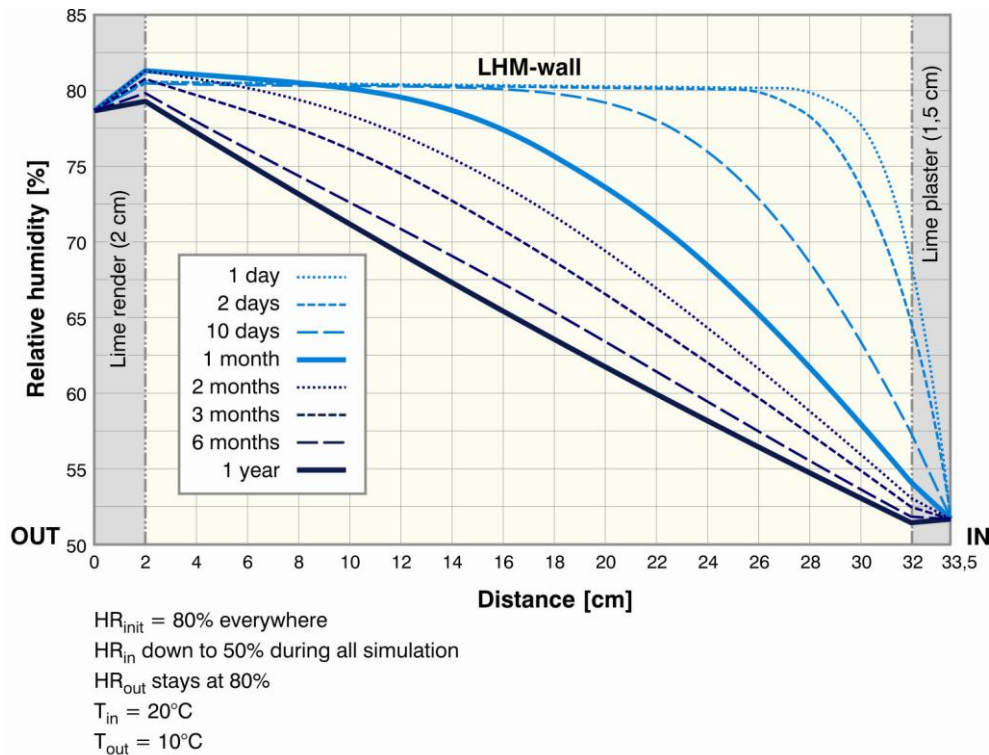


Figure 136 : Evolution of RH profile through LHM-wall component (A) after sudden decrease of inside RH

Fig.136 shows relative humidity distribution through LHM-wall component after 1 day, 2 days, 10 days, 1 month, 2 months, 3 months, 6 months and 1 year. The initial water content has significant effects (transient behaviour) during few months.

Fig.137 shows daily moisture flow (diffusion of vapour) through inside surface (negative value when flow is going from in to out) for all studied components. As for thermal shock, permanent transfer is considered to be obtained when the moisture flow reaches 95% of its final value (after 2 years). Components can be compared in terms of relative time needed to install permanent transfer, as presented in Fig.138.

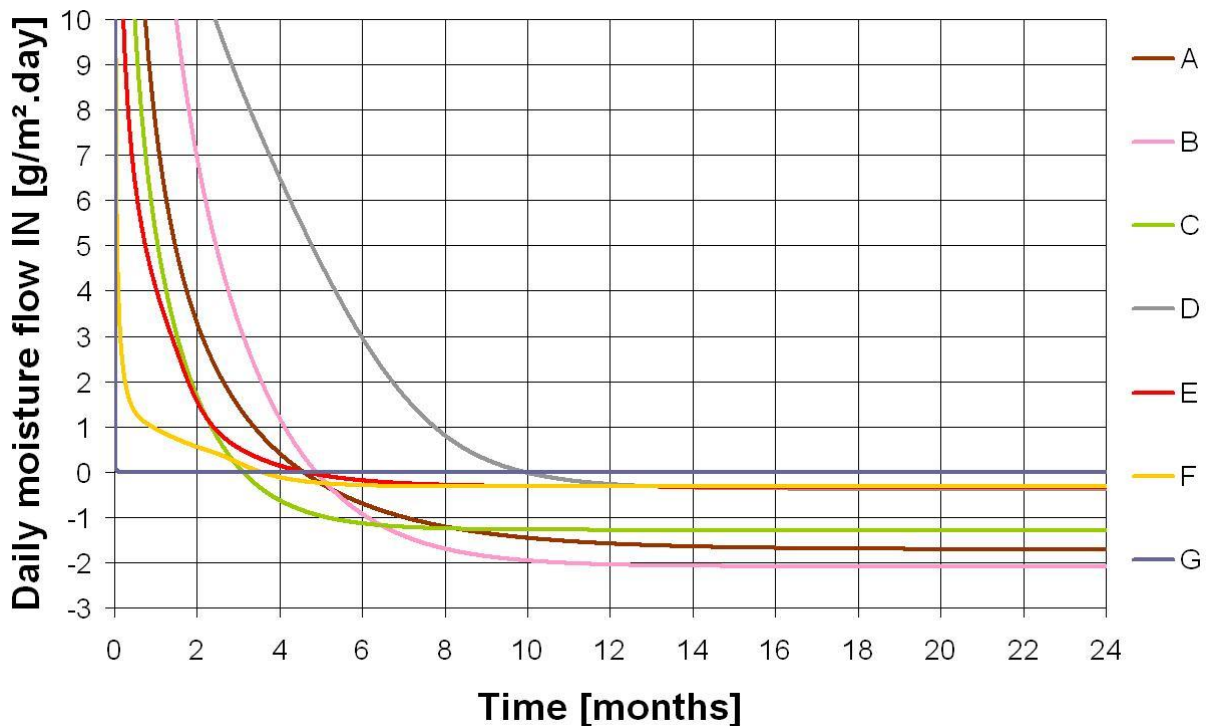


Figure 137 : Evolution of the daily moisture flow through inside surface of all components 2 years after sudden decrease of inside RH

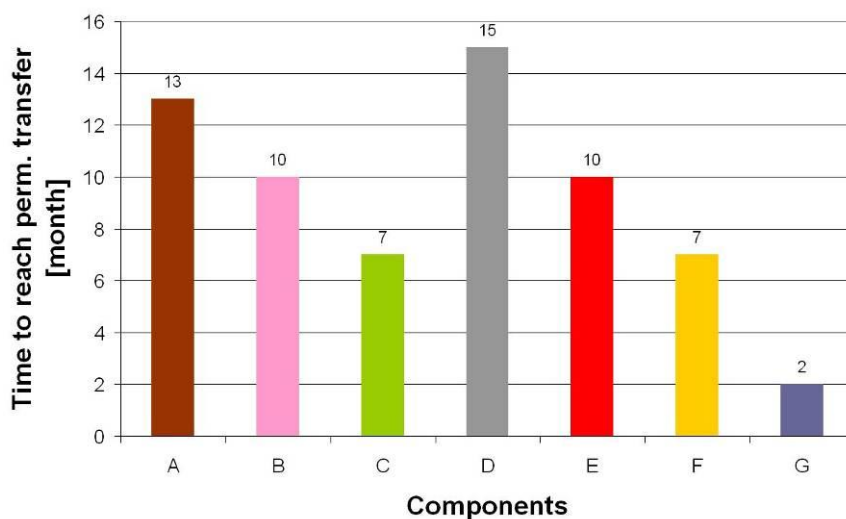


Figure 138 : Time to reach permanent hygric transfer after sudden decrease of inside RH

Fig.139 gives the permanent flow (after 2 years) through each component. Components (A), (B), and (C) are more open to vapour flow than the other components. Results from the figure are directly related to the *total vapour diffusion thickness* Sd_{tot} [m] defined in 5.5. Sd_{tot} of the component can be calculated based on materials vapour diffusion resistance factor given in Appendix 1, and is respectively : 170m for (A); 148m for (B); 241m for (C); 818m for (D); 950m for (E); 956m for (F); and 150km for (G). Transferred quantity of humidity is relatively low because of the small vapour pressure difference between inside and outside in this case (185 Pa).

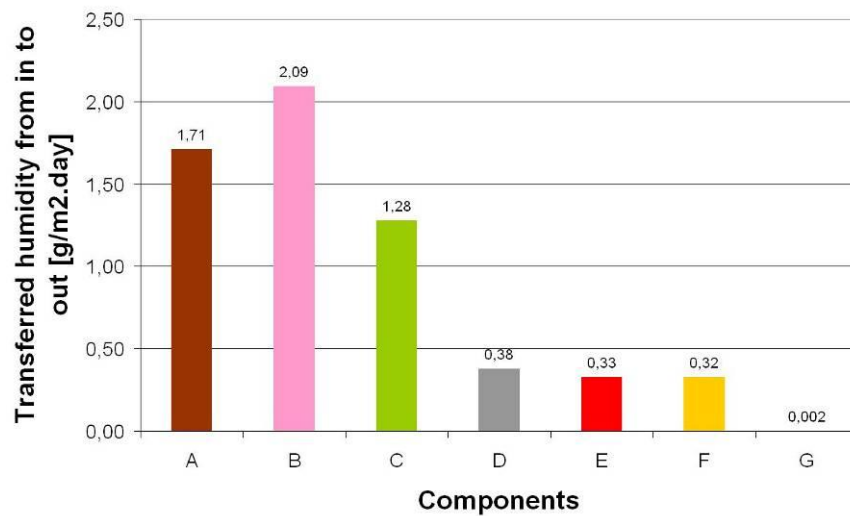


Figure 139 : Daily amount of humidity transferring from in to out in permanent transfer when $T_{in}=20^{\circ}\text{C}$; $HR_{in}=50\%$; $T_{out}=10^{\circ}\text{C}$; $RH_{out}=80\%$ (no sun/rain/wind)

7.5.3 Hygric cycles

Abstract

Next section shows the component behaviour under reference climate, but before, dynamic response under inside variation of humidity is analysed. First, a comparison of experimental measurement results and simulation results reproducing experimental setup shows that large deviation can be found. Results from simulations appear to be overestimated but they can be used to compare components one to the others. The second part of the section shows that moisture buffering of LHM-wall component is very high relatively to others. MBV is considered to be the best dynamical parameter to illustrate LHM-wall specificity.

7.5.3.1

Moisture buffer of LHM-wall

A first set of simulations are inspired by the Nordtest protocol⁵⁶, referred in 7.2.2. Nordtest method gives a single value, called Moisture Buffer Value (MBV), for each tested material. MBV “indicates the amount of water that is transported in or out of a material per open space area, during a certain period of time, when it is subjected to variations in relative humidity of the surrounding air”. The unit of MBV is $[\text{g.m}^{-2}.\%_{\text{RH}}^{-1}]$. It give an idea of material's behaviour when used as a finishing in inside environment in winter (heating is often responsible of dry air during the day).

Before measuring MBV of LHM-wall, a preliminary simulation helps defining appropriate humidity cycles and thickness of the samples. Results were not influenced either by the thickness of the samples (if bigger than 1,75 cm) or by the humidity level (50-80%, 50-65%, and 33-75% were checked). Moisture flow through outside (left) surface is avoided with metal foil ($S_d = 10000\text{m}$). If final simulated buffer values were equal no matter of the thickness, the time needed to reach a constant values was 4 days for samples of 1,75 cm, 28 days for 5 cm and 90 days for 10 cm.

Samples with a thickness of 1,75 cm were chosen (Surface: 235 cm^2). They are subjected to humidity cycles with 16 hours in 50% of RH followed by 8hours in 80% (climate rooms of Fraunhofer-IBP). An automatic data acquisition gives hourly mass variations of samples. It has to be noticed that these cycles do not correspond to final Nordtest protocol defined after achieving the measurements. Temperature of the climate rooms are fixed to 23°C and moisture flow through all surfaces is avoided with aluminium foil (except top surface).

Fig.140 illustrates the results from the measurements together with results from corresponding simulation. As it appears, the simulations do not fit properly with the measurements. According to the following relationships

$$\text{MBV}_{\text{LHM-wall,meas}} = 1,42 \text{ g.m}^{-2}.\%_{\text{RH}}^{-1} \quad (85)$$

$$\text{MBV}_{\text{LHM-wall,simul}} = 2,63 \text{ g.m}^{-2}.\%_{\text{RH}}^{-1} \quad (86)$$

the *measured* MBV, $\text{MBV}_{\text{LHM-wall,meas}} [\text{kg.m}^{-2}.\%_{\text{RH}}^{-1}]$, is smaller than the *simulated* MBV, $\text{MBV}_{\text{LHM-wall,simul}} [\text{kg.m}^{-2}.\%_{\text{RH}}^{-1}]$. In addition, water content of the samples did not yet reach periodic cycles after 14 days, as expected.

Retarded sorption⁵⁷, linked to the large range connected pores in LHM-wall, may be responsible for these important deviations. Further research could bring additional information on this kind of specific sorption behaviour of LHM-wall.

⁵⁶ *Moisture buffering of building materials*, C. Rode et al., final report, Department of Civil Engineering, Technical University of Denmark, 2005

⁵⁷ *Retarded sorption in wood – Experimental study, analysis and modelling*, H. Håkansson, Lund Institute of Technology, Department of Building Science, Sweden, 1998

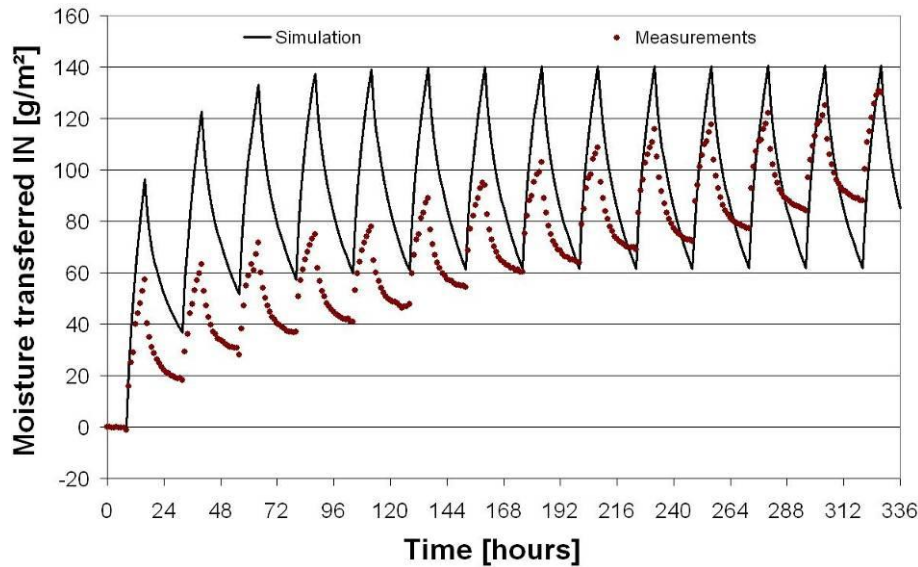


Figure 140 : Moisture buffer value of LHM-wall resulting from simulation and measurement under moisture buffering of environment

Nevertheless, if simulated MBV may be over estimated, measured MBV of LHM-wall appears to be very high compared to results for other materials presented Nordtest and illustrated in Fig.141. MBV of finishing material has a great influence on MBV of components, and precise MBV of lime plaster applied on LHM-wall is still missing.

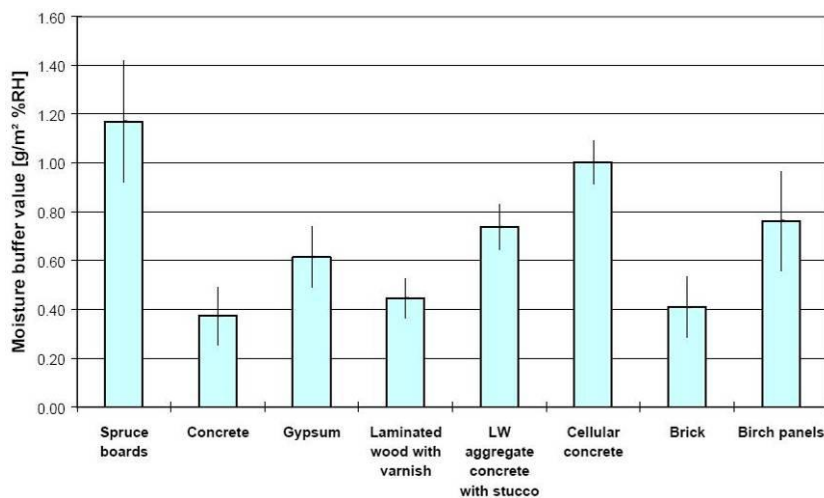


Figure 141 : Moisture buffer value of different material measured during Nordtest project⁵⁸

⁵⁸ *Moisture buffering of building materials*, C. Rode et al., final report, Department of Civil Engineering, Technical University of Denmark, 2005

7.5.3.2

Moisture buffer of multi-layers components

Following simulations propose to use WUFI® software to define MBV_{simul} of the 7 reference wall components. Those components are subjected to inside humidity cycles with 16 hours in 33% of RH followed by 8 hours in 75% (as suggested in Nordtest). RH difference is thus 42%. The Nordtest protocol is not defined to characterize wall components and the simulation did not fit the protocol rigorously. Outside and inside temperature is set to 20°C during the whole simulation. Initial temperature and RH of the components is fixed to 20°C and 47% through the whole component (corresponding to average value of inside environment). Outside relative humidity is constant: 47%. No sun, rain or wind, are introduced in climate file.

After three days, moisture flow through inside surface follows regular cycles. Integration of moisture flow gives, for each time step, the cumulate quantity of moisture transferred through this surface for each component, as illustrate in Fig.142 (average is not null because of initial value, and negative value means the moisture was taken from inside environment). As expected, component (A) and (B) have the same behaviour (same composition of inside layers) and are grouped on the graph. Component called (Abis) correspond to component (A), but without inside plaster. In this case, component (C) and (D) were grouped because results for both components were very close.

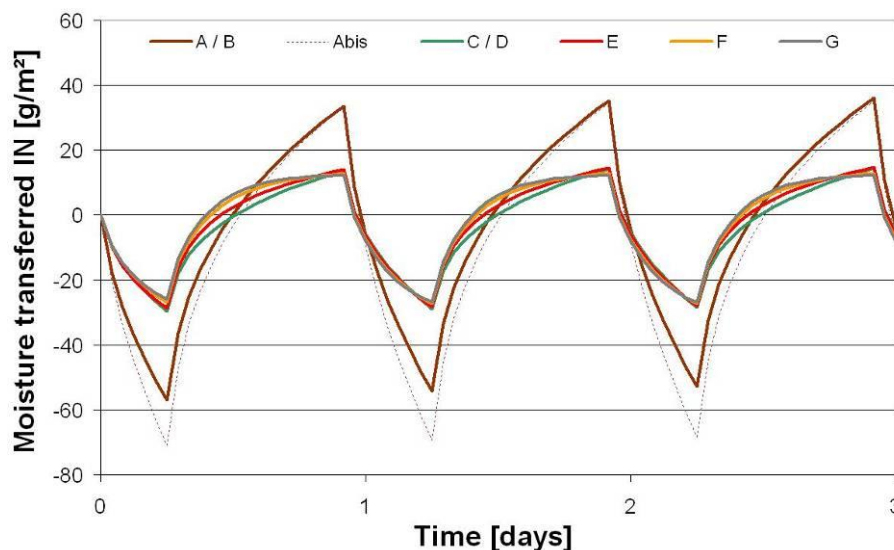


Figure 142 : Cumulative amount moisture transferred through inside surface of the components under moisture buffering of inside environment

From these results, it is possible to assess MBV_{simul} of all components (which is the moisture taken from inside environment during the 8h of high RH). Fig.143 shows it is $2,15 \text{ g.m}^{-2}.\%HR^{-1}$ for the two LHM-wall components and between $1,04$ and $0,93 \text{ g.m}^{-2}.\%HR^{-1}$ for all the other components. It has to be noticed that the average moisture transferred is null because initial RH of component and outside RH is 47% (corresponding to the average value of inside environment).

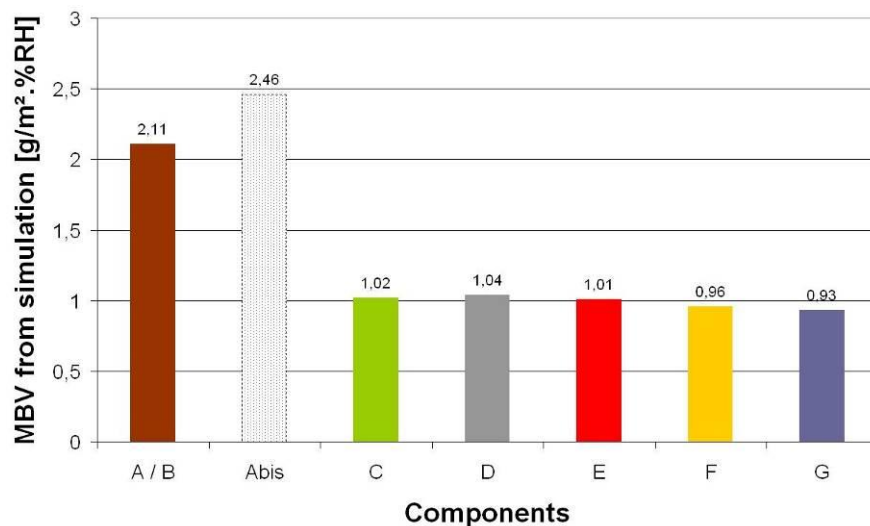


Figure 143 : Simulated moisture buffer value of the components under moisture buffering of environment

As observed in §0 results from the simulations appear to be higher than expected (Gypsum is presented in Nordtest to have a MBV of $\sim 0,6 \text{ g.m}^{-2}.\% \text{HR}^{-1}$). The main interest of these results is to give a relative value to compare the components one to the others. Another remark concerns the fact that if 2 occupants, producing around 50 g.h^{-1} of vapour each, sleeping 8h in a bedroom with 75 m^2 of LHM-wall will release $\sim 800 \text{ g}$ of vapour in inside environment. Using the same RH level as for the simulation illustrated in Fig.143, the bedroom's wall should be able to absorb more than 6kg of moisture if build in LHM-wall with lime plaster, and more than 3kg if build like component (C), (D), (E), (F) or (G). As presented when thermal buffer was defined, see 7.4.2.3, the values presented here should thus be seen as extreme values that the components may not reach in practice.

Last remark concerns the latent heat effect related to these variations in moisture content. Fig.144 gives the latent energy released (absorption of moisture) in inside environment during humid period (8h of night) for all the components. It appears that high moisture buffering of LHM-wall components (A) and (B) induces in this case a release of 43 Wh.m^{-2} during night period, which corresponds to average heat loss through these components during winter (these are extreme values that may not be reached in practice).

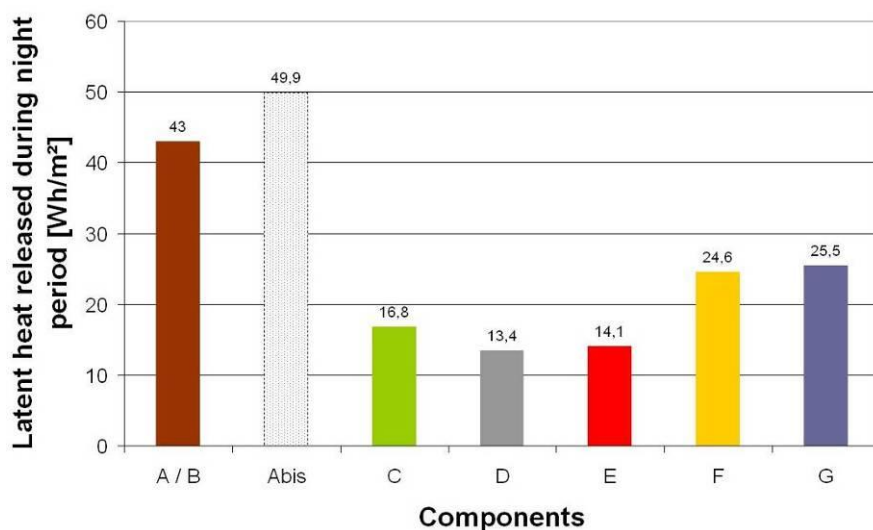


Figure 144 : Latent heat released through inside surface of the components during 8h of humid period

7.6 Simultaneous transfer under reference year

7.6.1 Moisture transfer and storage

Abstract

The theoretical simulations of the previous sections give a set of dynamical parameters to assess how do the multi-layer components behave under simple shock or cycles in inside or outside environments. Those parameters allow comparing the components behaviour one to the other, but when components are subjected to reference climate, combined effects of simultaneous heat and mass transfer and storage, and of other dynamic elements like sun, wind and rain, increase the complexity of the results. The simulations showed that assessing moisture transfer and storage only based on permanent transfer, or without taking the rain into account can lead to major deviations in the results.

7.6.1.1 Component (A)

As it appears on Fig.134 when analysing drying process of component (A), moisture storage is changing all along the year: rising in winter and decreasing in summer. This section will use WUFI® simulations to analyse evolution of moisture content when the components (south exposition) are subjected to reference year in Uccle outside and classical inside environment in houses (EN15026), both defined in 3.2.4. The components initial water content and temperature distribution comes from the preliminary simulations used in 7.3 to calculate U-value of each component. Simulation period is 3 years and results of third year are used.

Fig.145 shows yearly evolution of total moisture content (output from WUFI), expressed in $[\text{kg.m}^{-2}]$, in LHM-wall component (A). The average value on the whole year is **12 kg.m^{-2}** , with a minimum of **9,5 kg.m^{-2}** on the 6th of September and a maximum of **17,6 kg.m^{-2}** on the 23rd of December. Total water content buffering between minimum and maximum is **8,1 kg.m^{-2}** . Water content is thus lower during summer period (average of **10,2 kg.m^{-2}**) than during winter (average of **13,8 kg.m^{-2}**). Average water content buffering between summer and winter is **3,6 kg.m^{-2}** . There is no long term accumulation since water content repeats every year exactly the same evolution with the chosen combination of layer (some renders where not appropriate). Latent heat effects of water content buffering are discussed in chapter 8.

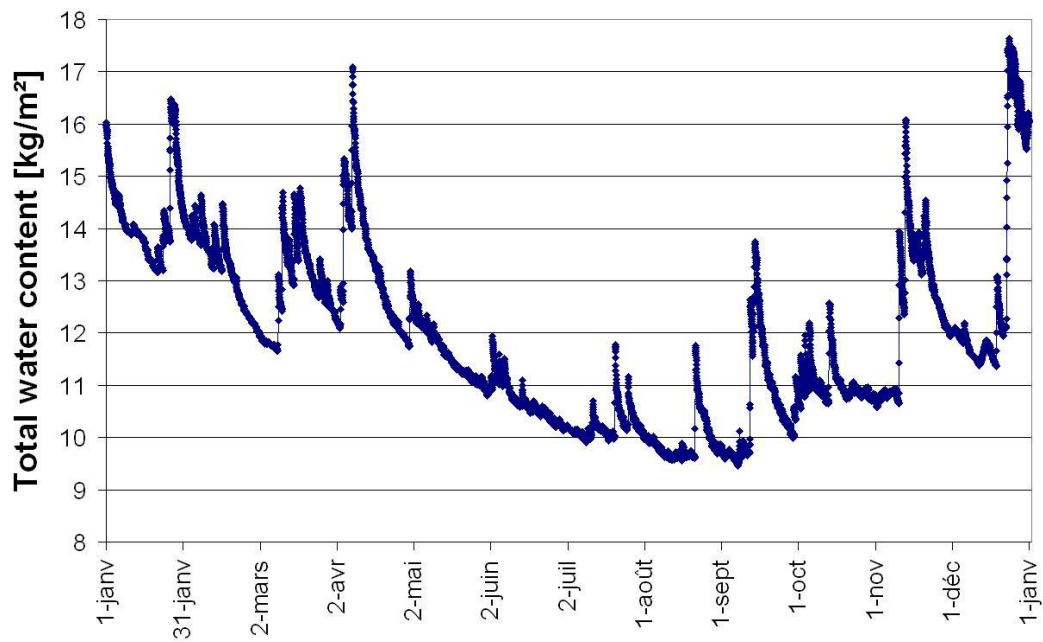


Figure 145 : Yearly evolution of water content in LHM-wall component (A) under reference climate

A complementary simulation showed that the major part of water content increase is linked to rain load on outside surface. Fig.146 shows the cumulative amount of moisture transferred through both surfaces in this case and when water absorption factor is set to zero (no rain is absorbed by the component). This cumulative curve results from the integration of simulated moisture flow. The amount of moisture transferred after one year from out to in (positive value of the flow) is 694 g.m^{-2} in reference case, and -757 g.m^{-2} (the negative value means moisture is extracted from the inside environment) when no rain is absorbed by the component.

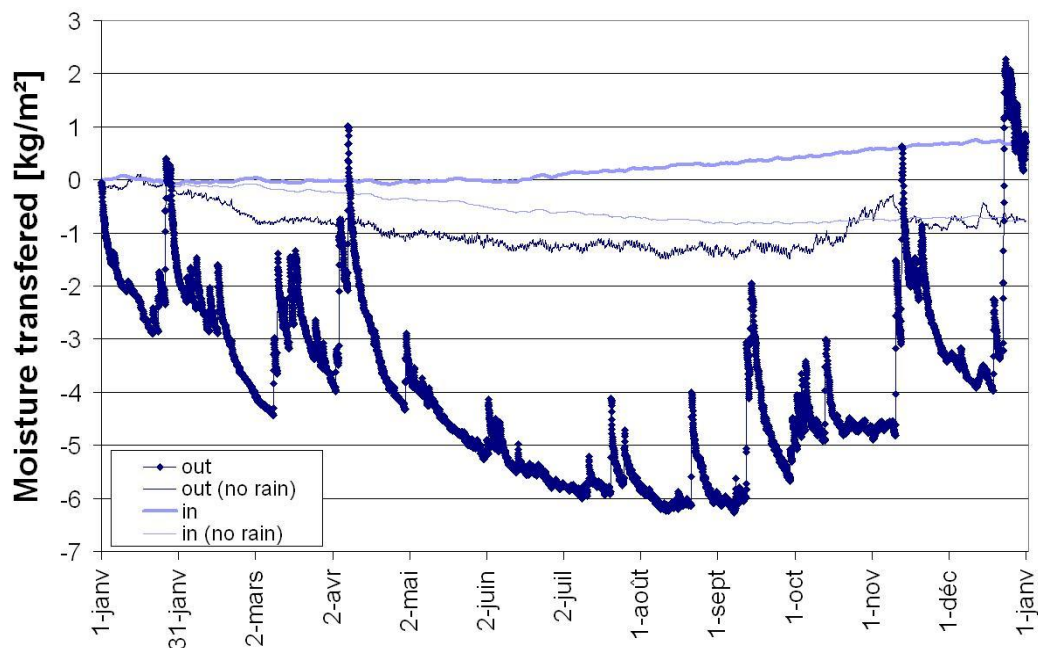


Figure 146 : Cumulative amount of moisture transferred through outside and inside surface of LHM-wall component (A) under reference climate, with and without rain absorption

Results of simulations defined with no rain absorption can be related to results given in 7.5.2: moisture is globally extracted from inside environment. It has to be noticed that for a room with 75m² of LHM-wall component (A) will transfer ~57kg.year⁻¹ of moisture without rain, corresponding to an average of ~6,5 g.h⁻¹. Beside, the same room will transfer ~52kg of moisture from out to in when rain is taken into account, corresponding to an average of ~6 g.h⁻¹. These values should be compared to the 50 g.h⁻¹ of vapour produced by 1 occupant.

Rain appears to have a great influence on the quantity of moisture transferred and stored in the component. Rain absorption was assessed by BRE (GB)⁵⁹ through visual analysis, but a precise rain absorption coefficient of LHM-wall components is still missing. Rigorous data for rain load and wind direction, as well as precise value for rain absorption coefficient thus have significant influence on results under reference year.

7.6.1.2 Comparison of all components

All the components were subjected to the same simulation and evolution of cumulative amount of moisture transferred under reference climate through inside surface of each component is illustrated in Fig.147. Total quantity of moisture transferred during the reference year is expressed on Fig.148.

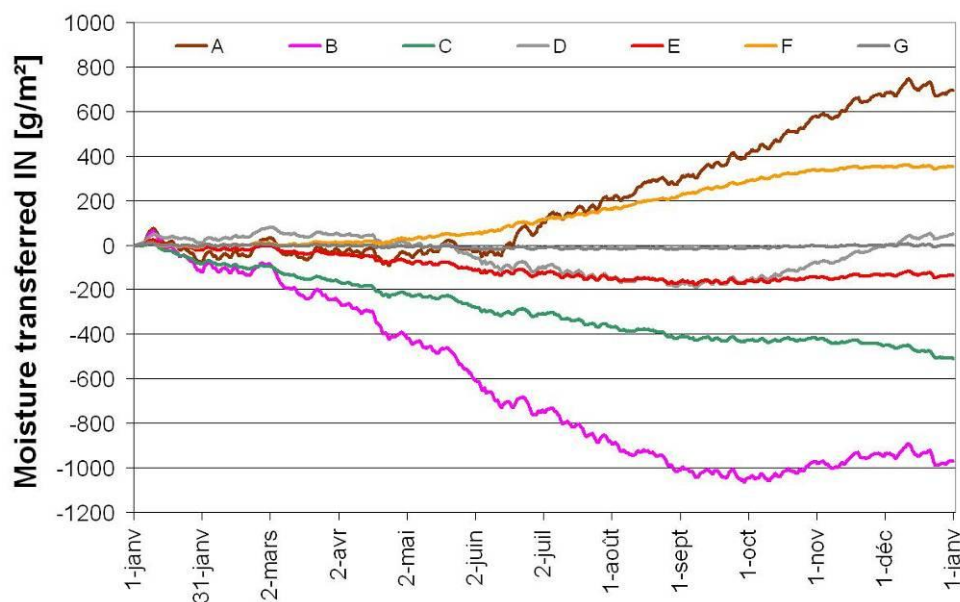


Figure 147 : Evolution of cumulative amount of moisture transferred through inside surface of the components under reference climate

⁵⁹ Final report Final Report on the construction of the Hemp Houses at Haverhill, Suffolk, Dr. Tim Yates, BRE, 2002

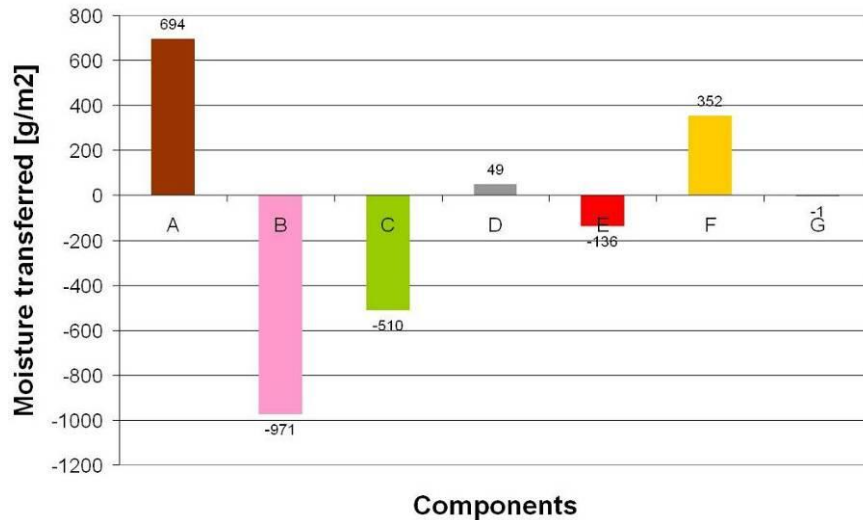


Figure 148 : Total amount moisture transferred through inside surface of the components after 1 year under reference climate

It appears that most of the moisture is released in the inside environment during summer and spring (i.e. from 21/6 to 21/12) for component (A). During these 6 months, the average amount of vapour released in inside environment of a room 75m² of LHM-wall component (A) is ~12 g.h⁻¹. (more than 4 times smaller than vapour produced by 1 occupant producing around 50 g.h⁻¹ of vapour).

Results from previous section help understanding the deviation between the results for component (A) and those for component (B). As a matter of fact, a wood cladding protects component (B) from rain influence (moisture is globally extracted from inside environment), component (A) having a significantly different response because of rain influence (moisture is globally transferred from outside to inside).

Results for the other components are between these two limits. They depend on the choice of material for each layer of the components: i.e. flow through inside surface of component (G) is negligible because of the vapour barrier.

7.6.2 Energy transfer and storage

Abstract

As presented in 7.4.2.1 for theoretical cyclic variations, it appears that daily variations are strongly dampened and that there is a phase shift between evolution of outside climate extreme and its effects on inside environment. For yearly variation (time step of 24h), transient effects are negligible. In reference climate, daily variation of outside temperature (between day and night) combines to a yearly evolution (between seasons) and to irregular cooling or warming of outside environment for few days. Under reference year climate, all these factors lead to an overall complexity of simultaneous influence on heat and mass storage and transfer through the components. Heat flow through inside surface of components and cumulative quantity of energy transferred through this surface after a defined time period are analyzed for component (A), focussing on the influence of driving rain or sun radiation. Those parameters are compared to results obtained when permanent transfer is assumed and when other components are analysed. The influence of sun radiation is important when components are facing the south. If wood cladding protects from driving rain, it also stops the benefit of sun radiation. It also appears that the cumulative quantity of energy transferred through equivalent components - in terms of thermal transfer coefficient – is similar (less than 10% of deviation). This important result has to be balanced with results from previous sections concerning short term behaviour and its influence on comfort feeling.

7.6.2.1 Component (A)

This section compares heat flow results from WUFI® simulations for component (A) to theoretical results if a permanent transfer is assumed (negative value when flow is going from in to out). The flow in permanent transfer is calculated with relationship (81), based on outside and inside temperature evolution and on U-value of components (fixed value).

Results for summer and winter are illustrated in Fig.149 and Fig.150. Fig.151 and Fig.152 focuses on one week of each of these periods. Transient effects described in previous sections (phase-shift, damping...) clearly appears in the figures. Results do not correspond exactly to those expected from theoretical case (shock and cycles) because of the overall complexity of combined phenomenon: day/night variations; seasonal variation; warming or cooling for few days; sun radiation; and driving rain.

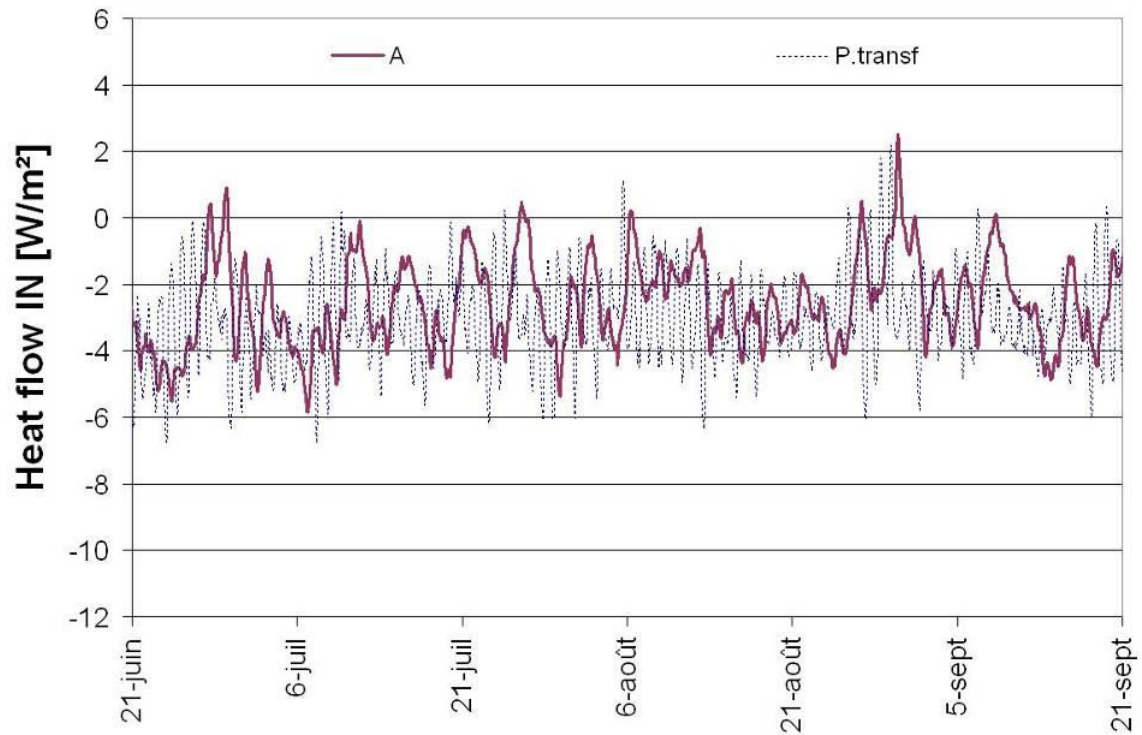


Figure 149 : Heat flow through inside surface of component (A) and if permanent transfer is assumed during summer of reference year

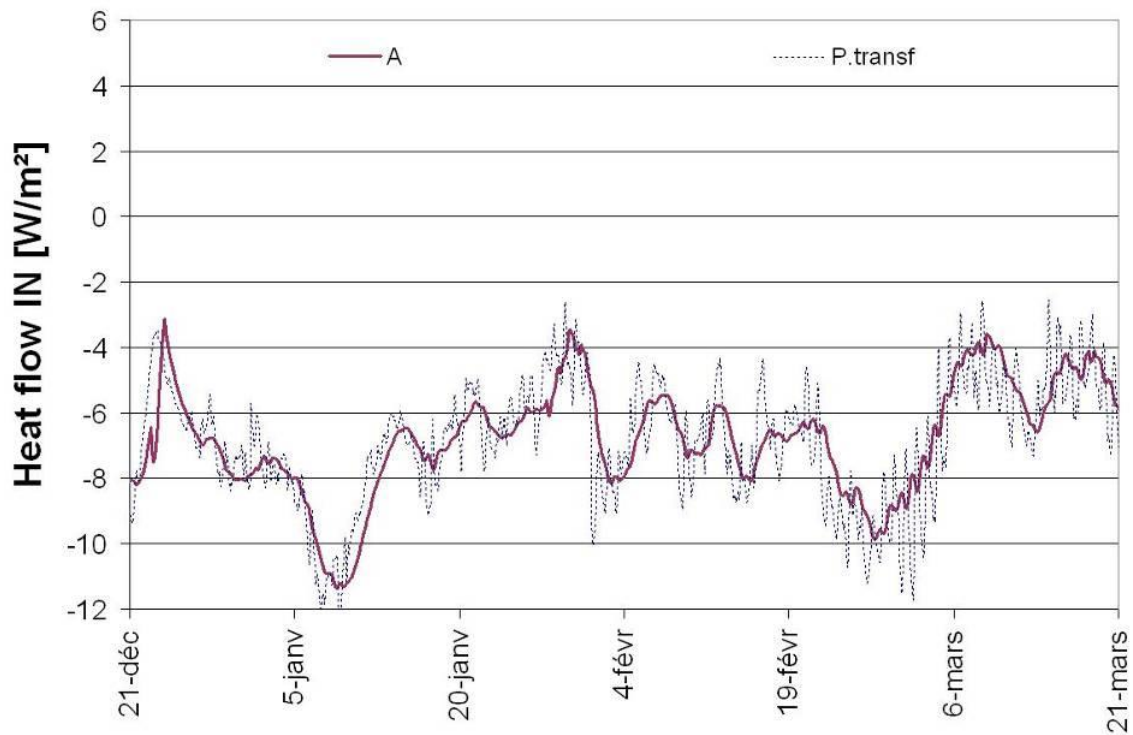


Figure 150 : Heat flow through inside surface of component (A) and if permanent transfer is assumed during winter of reference year

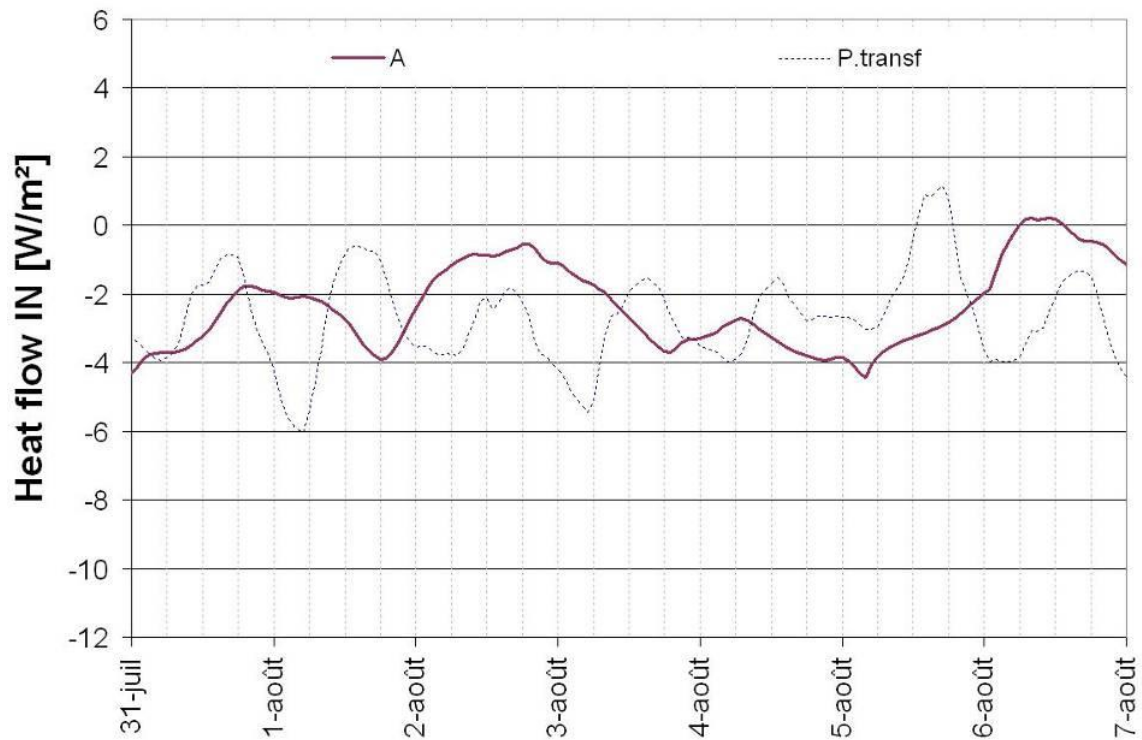


Figure 151 : Heat flow through inside surface of component (A) and if permanent transfer is assumed during one summer week of reference year

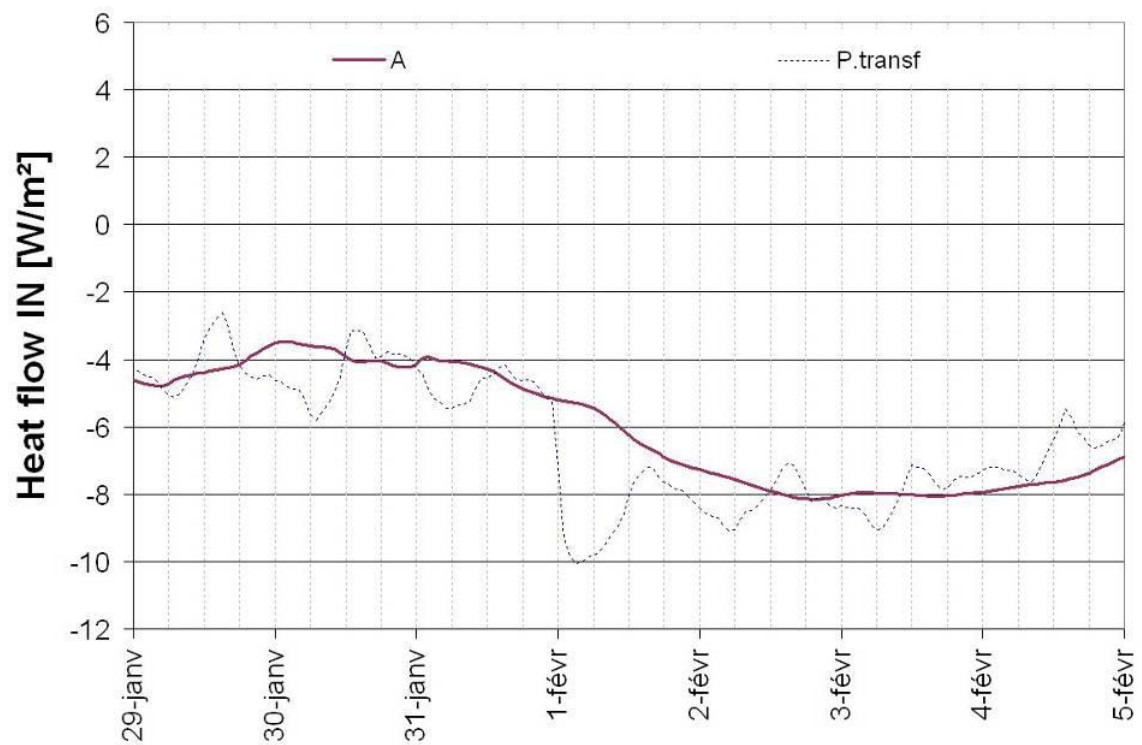


Figure 152 : Heat flow through inside surface of component (A) and if permanent transfer is assumed during one winter week of reference year

Benefits due to combined influence of quoted factors can be quantified through the *cumulative quantity of energy transferred through inside surface* [Wh/m²]. It is calculated for each time step by integrating the heat flow on the desired period. Beside reference case, a simulation is run excluding latent heat calculation (evaporation and fusion). Another simulation sets the sun absorptivity of the component to 0 [-] (no sun radiation is absorbed by the component). The last case combines those two criteria (no latent heat and no sun absorption).

The four cases are illustrated in Fig.153 and Fig.154 for summer and winter period. In the graphs, the cumulative quantity of energy transferred through inside surface is expressed in terms of difference with theoretical case where a permanent transfer is assumed and is called *energy difference* [Wh.m⁻²].

Most of the year the heat flow is going from in to out and the energy difference represents the amount of energy spent to keep inside environment at temperature level fixed in the simulations. It is negative when the results from the simulations are smaller than the calculation made assuming permanent transfer.

It appears that heat loss of the reference case is lower than theoretical calculation: about 1000 Wh.m⁻² less for summer but only 150 Wh.m⁻² less for winter.

The second simulated case shows that without latent heat effects, heat loss is even smaller: almost 1500 kWh.m⁻² less for summer and 670 Wh.m⁻² less for winter. The difference with reference case is due to the additional energy (latent heat of evaporation) needed to evaporate rain water absorbed by the component: ~500 kWh.m⁻² for summer and ~520 Wh.m⁻² for winter.

The third simulated case, where no sun absorption is taken in account, shows that sun radiation has a great influence on heat loss: if heat loss is compared to the reference case, there is more than 1500 Wh.m⁻² additional loss for summer and around 1000 Wh.m⁻² for winter in this case.

In the last simulated case, where both sun radiation and latent heat effects are excluded, the so-called *energy difference* is negligible after 1 year (< 0,1 Wh.m⁻²). As illustrated on Fig.154, energy difference for winter is ~300 Wh.m⁻² in this case (40 Wh.m⁻² for summer and -380 Wh.m⁻² for fall). Transient effect appears to have no significant effects on energy loss on the long term when sun and rain influence are not taken into account.

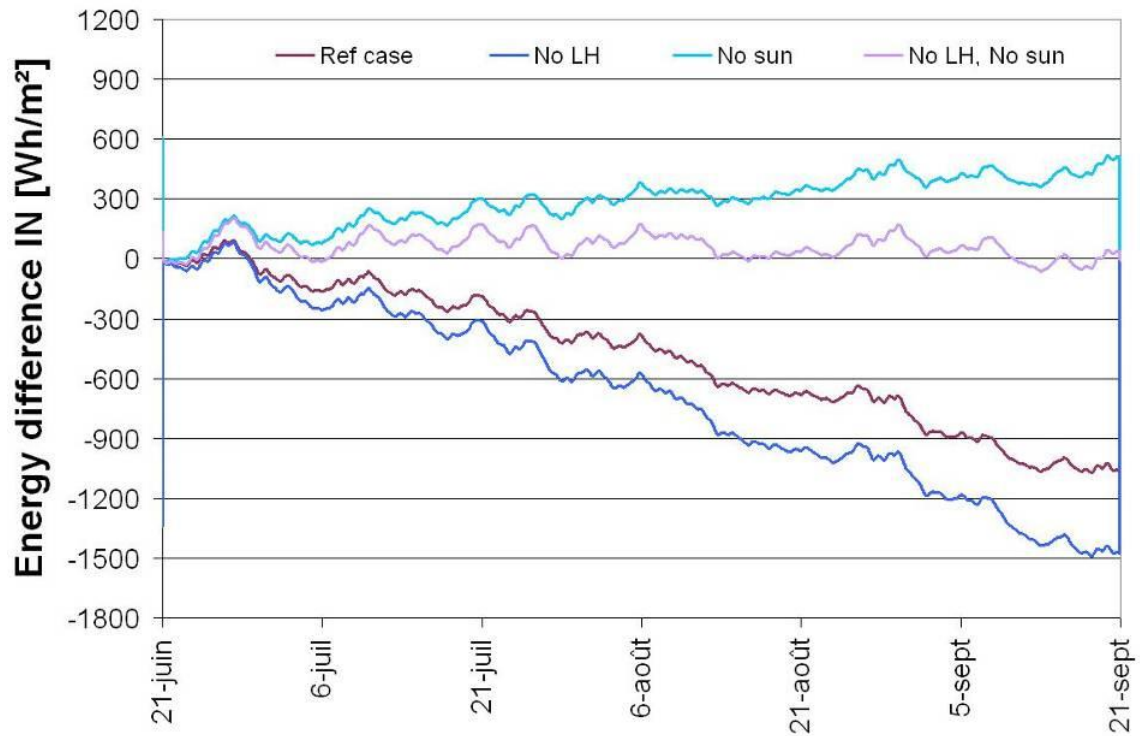


Figure 153 : Difference of energy transferred through inside surface of component (A) and if permanent transfer is assumed during summer of reference year

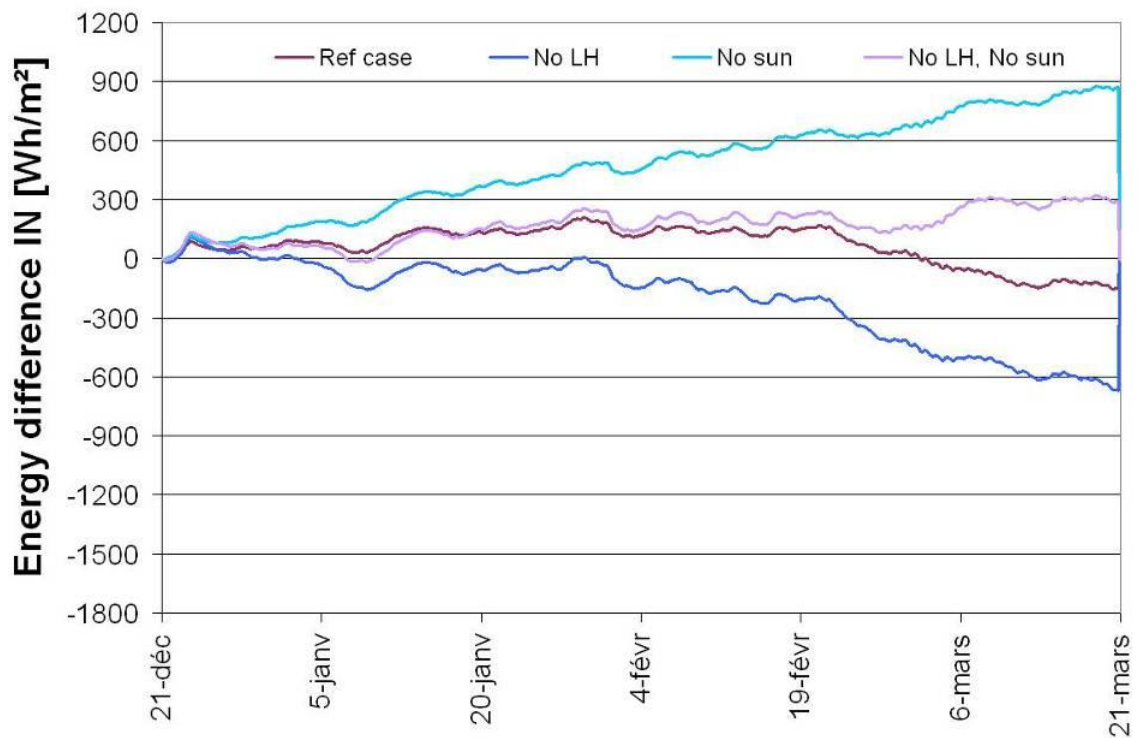


Figure 154 : Difference of energy transferred through inside surface of component (A) and if permanent transfer is assumed during winter of reference year

Fig.155 gives a global overview of the cumulative quantity of energy transferred through inside surface of the component during the whole year for the 4 cases.

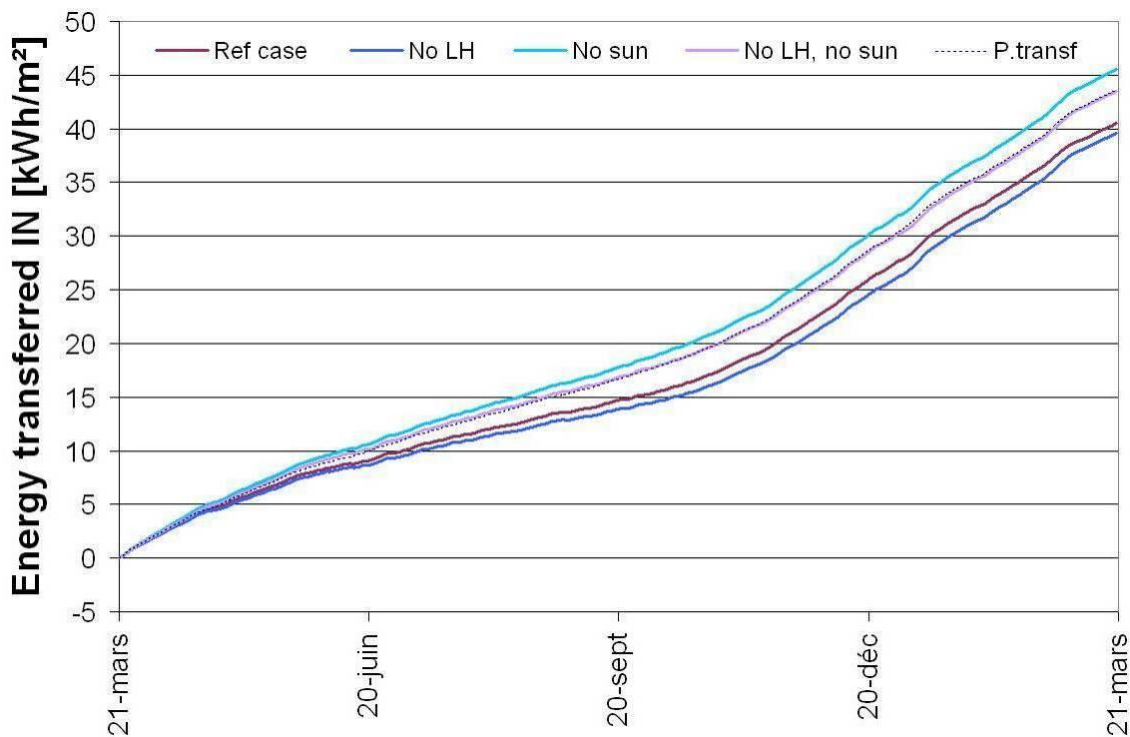


Figure 155 : Evolution of the cumulative quantity of energy transferred through inside surface of component (A) and if permanent transfer is assumed under reference climate

WUFI® simulation allows considering marginal benefits but the quantity of energy transferred through equivalent components - in terms of thermal transfer coefficient – is similar: less than 10% of deviation between components response and theoretical permanent transfer.

Under Belgian reference climate, *transient benefits* are not significant 1/ because the gains under fast cooling of outside environment (during night) are lost when fast outside environment is warming up (during the day); 2/ benefit from sun radiation is combined to supplementary energy demand due to latent heat of evaporation after rain; 3/ transient effects from inside variation of temperature of RH have strong influence on short term energy demand and comfort feeling but almost no influence on global heat demand on a yearly period.

Marginal benefits could be optimised though complementary simulations with dynamical modelling, analysing components behaviour in other climate and focusing on effective heat flow during reference day of each season, and influence of specific climate period (strong rain followed by cold days, canicular days and influence of humidity...). Global hygrothermal performances and high comfort feeling of LHM-building are discussed in chapter 8, but it is already interesting to remark that results from this section cannot explain surprising results from BRE presented in §1.2.

7.6.2.2

Comparison of all components

This section presents dynamic thermal behaviour of all components under reference climate. As in the previous section, it compares heat flow results from WUFI® simulations to theoretical results if a permanent transfer is assumed. Results for all the components during a specific week in summer and in winter are respectively illustrated in Fig.156 and Fig.157 (negative value when flow is going from in to out, “P.transf1” if $U = 0,439 \text{ W.m}^{-2}.\text{K}^{-1}$ and “P.transf2” if $U = 0,135 \text{ W.m}^{-2}.\text{K}^{-1}$).

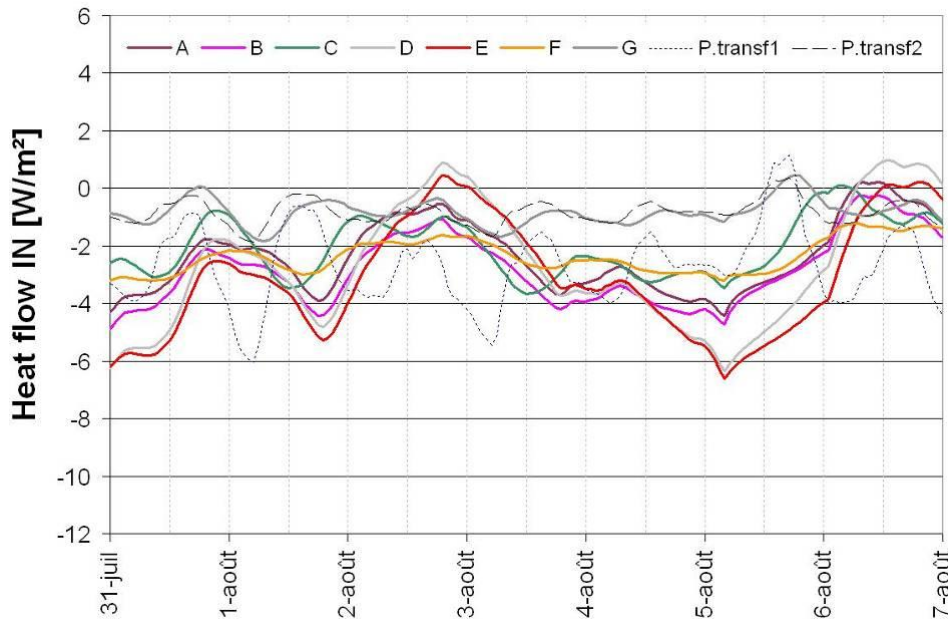


Figure 156 : Heat flow through inside surface of the components and if permanent transfer is assumed during one summer week of reference year

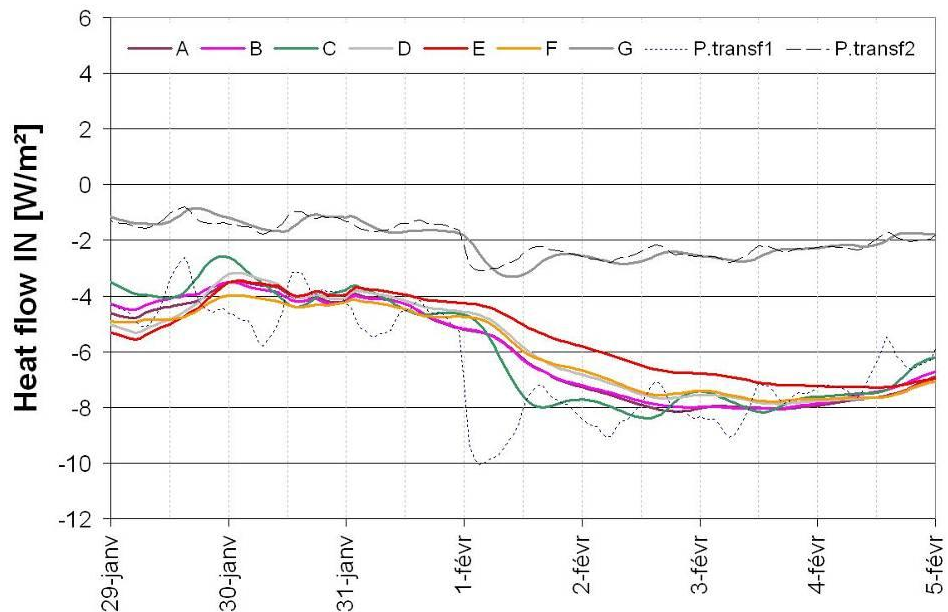


Figure 157 : Heat flow through inside surface of the components and if permanent transfer is assumed during one winter week of reference year

As noted in previous section, damping of daily variations and phase shift between extreme values presented in 7.4.2.1 appear clearly. However, combined influence of numerous factors (day/night variation, seasonal variation, warming or cooling for few days, sun radiation and driving rain) lead to a great complexity in components behaviour that could be further analysed.

In this work, benefits due to combined influence of these factors are quantified through the *cumulative quantity of energy transferred through inside surface* [Wh/m²]. It is calculated for each time step by integrating the heat flow on the desired period. Evolution of this cumulative value during reference year is illustrated in Fig.158.

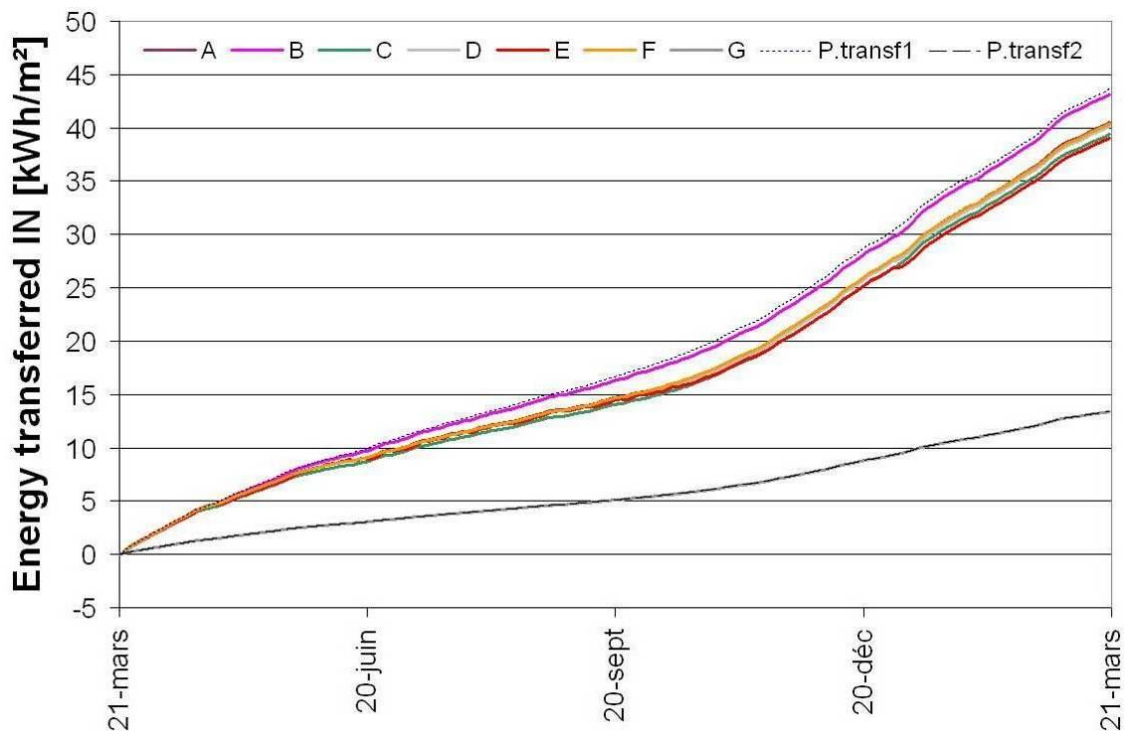


Figure 158 : Evolution of the cumulative quantity of energy transferred through inside surface of the components and if permanent transfer is assumed under reference climate

Fig.159.gives the cumulative quantity of energy transferred after 1year under reference climate for all the components. As it appears, U-value of the component has a great influence on total energy transferred.

Fig.160 shows the *energy difference* between theoretical and simulated results on a yearly period (negative when predicted results from the simulations are lower than theoretical calculation). After 1 year, it is around 10% of theoretical quantity of energy transferred through component C and E; 7or 8% for component A, D, and F; and almost negligible for component B and G (the wood cladding protects the components from sun and rain).

Under Belgian reference climate, *transient benefits* are not significant and cannot explain surprising results from BRE presented in §1.2 as detailed in previous section. Marginal benefits could be optimised though complementary simulations with dynamical modelling.

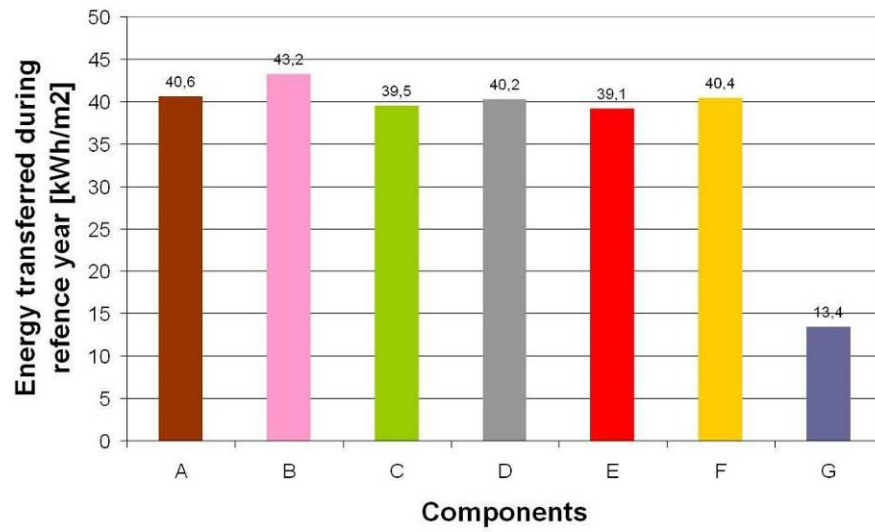


Figure 159 : Total energy transferred through inside surface of the components during reference year

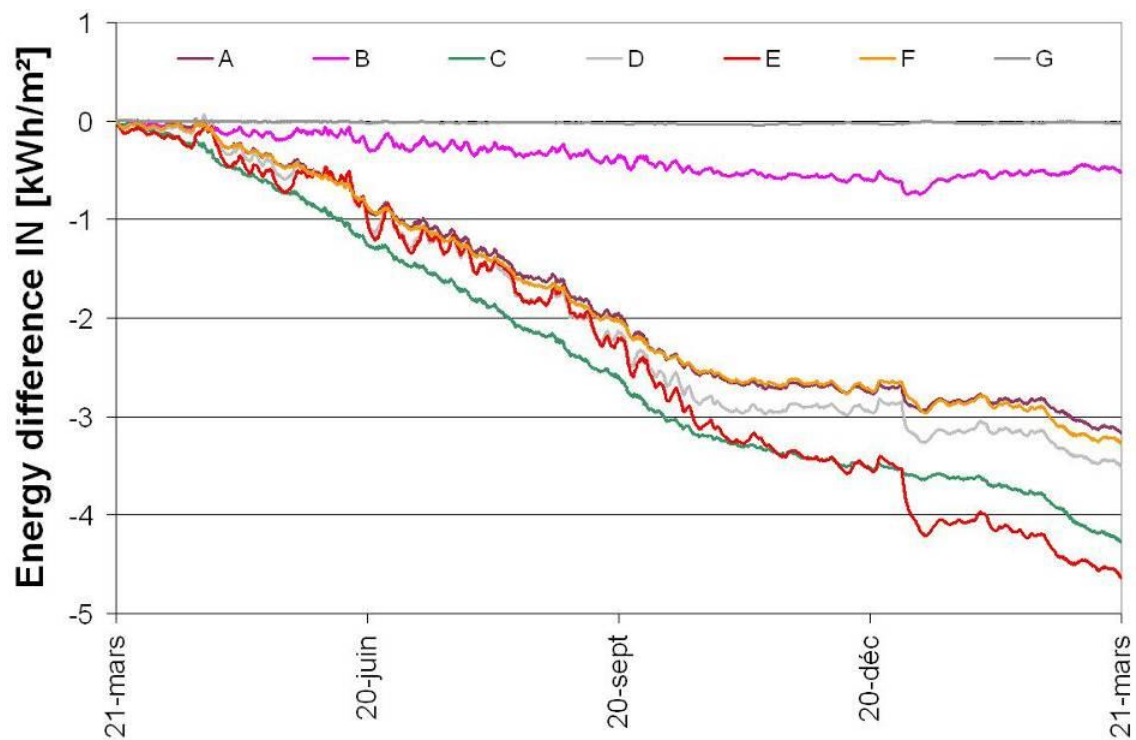


Figure 160 : Difference of energy transferred through inside surface of the components and if permanent transfer is assumed during winter of reference year

8 Discussion

8.1 Characterisation

8.1.1 Lime-Hemp Materials data

The main objective of the present work is to present a complete set of hygrothermal parameters for a Lime-Hemp wall mixture (LHM-wall) to introduce this innovative material in the database of the dynamic software WUFI[®]. Section 3.1 gives an overview of dynamic modelling complexity and presents the assumptions used to simplify the model. Based on the same assumptions, the WUFI[®] model needs at least 5 parameters related to dry state and allows the introduction of 5 moisture related curves for each material. Some hygrothermal parameters of LHM-wall (same mixture and full information on experimental conditions) were already available in the literature when the present work started. Measured values were found to be in good agreement with available results (density, thermal conductivity, vapour permeability). When no equivalent values was available, measurements were validated with complementary experiments (moisture retention, thermal capacity, liquid transfer, moisture buffering).

Density of LHM-wall can vary, depending on consistency, mixing and positioning, as described in chapter 4. Final density (after carbonation) varies between 350 to more than 500 kg.m⁻³, mostly depending on the type of positioning (tamped or not). Theoretical calculations show that carbonation can be considered complete after 1 year, and the drying period of the samples was ~1month (there is a strong influence of size and geometry of the samples for the 2 parameters).

Moisture retention curve (MRC) of LHM-wall has a great influence on its hygrothermal behaviour: evolution of thermal conductivity and of moisture transport coefficients. Some limitations of considering a univalent relationship between water content and relative humidity were pointed out when some differences between sorption and desorption, called hysteresis of sorption, were observed. According to [Rode, 2004]⁶⁰, this phenomenon may not have a significant influence on hygrothermal behaviour.

Evolution of thermal conductivity is considered to have a linear evolution with water content. Influence of moisture should be further analysed in future research, using the self-consistent model presented in [Cerezo, 2005]⁶¹ and complementary measurement (in hygroscopic and capillary region). The experiment used to measure this parameter could be adapted, considering moisture influence and results from [Kehrer, 2003]⁶² (influence of micro-condensation and evaporation effects in the samples).

⁶⁰ Modeling of Moisture Transport in Wood with Hysteresis and Temperature-Dependent sorption Characteristics, C. Rode et al., proceedings Building IX Clearwater Beach (Florida), Norway, 2004

⁶¹ *Propriétés mécaniques, thermique et acoustiques d'un matériau à base de particules végétales : approche expérimentale et modélisation théorique*, V. Cerezo, Ph.D. thesis at ENTPE, France, 2005

⁶² *Ecological insulation materials – Does sorption moisture affect their insulation performance?*, M. Kehrer et al., Journal of thermal envelope and building science, vol 26 n°3, January 2003

A constant vapour diffusion resistance factor - μ - is used for LHM-wall (dry-cup measurements). Liquid transfer, that combines to vapour flow in contact with liquid or in high RH, is taken into account through liquid transfer coefficients for absorption - D_{ws} - and for redistribution - D_{ww} . Important deviations between simulation and measurement were observed when approximating these coefficients based on the liquid absorption coefficient. Better results were obtained were using measurement from NMR.

Liquid transfer presented in §6.7.2, gives satisfactory results when modelling materials behaviour on a time period of a few days (medium term). In the short-term (few hours) or the long term (few months), liquid transfer coefficients should be adapted to fit experimental results. A good example of deviation is the results obtained for moisture buffering experiment – MBV- of LHM-wall and presented in §0. Retarded sorption effect, developed by [Håkansson, 1998]⁶³, could be responsible of these deviations. Complementary measurements should focus on this specific domain, especially if dynamic of sorption and desorption is further analysed.

8.1.2 Parameters for related materials

Two multi-layer components integrating LHM-wall were defined and compared to 4 wall components with equivalent thermal transfer coefficient - U-value, or equivalent thickness - d_{tot} (for the “low-energy” wall). Hygrothermal parameters used for all materials, except LHM-wall, come from WUFI®’s material database presented in Appendix 1.

Hygrothermal behaviour of lime plaster and render used to cover LHM-wall (outside or inside) can have a large influence on components performances when subjected to natural climate conditions (rain, sun, wind...). Simulations showed that some combinations of layers lead to moisture accumulation problem and damaging condensation. Fig.161 and Fig.162 show an example of water content evolution of LHM-wall layer in component (A) under reference year climate in Uccle (B) when two different renders are used on an outside surface, respectively an hydrated lime render (“*Lime plaster (stucco)*”) or a hydraulic lime render (“*Lime cement plaster (stucco)*”). Another interesting result on drying process modelled through simulations is presented in §7.5.1: applying on LHM-wall component the chosen lime render and plaster did not have significant effects in the simulated results. Hygrothermal equilibrium between LHM-wall and the timber frame was never analysed thoroughly, and could give a better view on their complementarities (hygrothermal, mechanical, fire and frost resistance ...). These observations show that a precise characterization of finishing layers and related materials is necessary and should be further analysed with additional research.

⁶³ *Retarded sorption in wood – Experimental study, analysis and modelling*, H. Håkansson, Lund Institute of Technology, Department of Building Science, Sweden, 1998

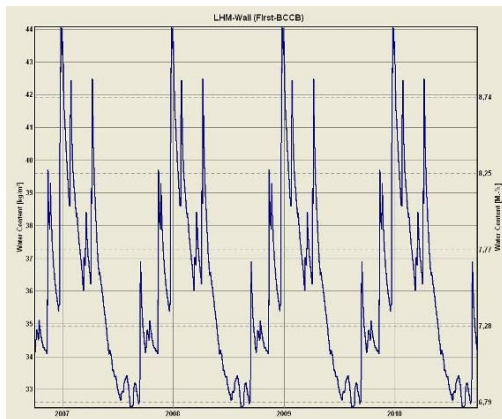


Figure 161 : Evolution of water content in component (A) with hydrated lime render under reference climate in Uccle

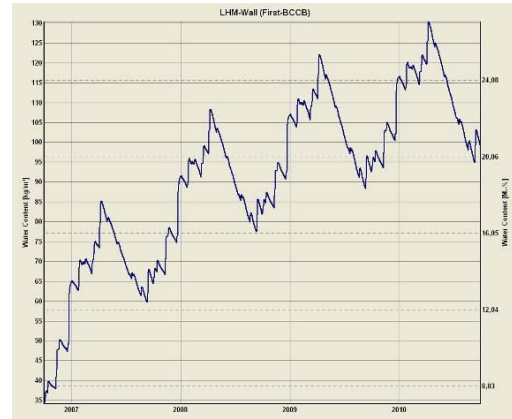


Figure 162 : Evolution of water content in component (A) with hydraulic lime render under reference climate in Uccle

8.1.3 Surface transfer coefficients

A last remark on characterization should be made on surface transfer coefficients to highlight the influence they have on hygrothermal assessments. As a matter of fact, distinction between the convective heat transfer coefficient (depending on the texture of the surface and the wind) and radiation-related heat transfer coefficient (depending on emissivity and temperature of the surface) is still assessed through a rather imprecise general expression. Precise values for moisture transfer surface coefficients (vapour transfer, rain absorption...) are also necessary and should be examined in future research.

8.2 Energy loss and moisture transfer

8.2.1 Permanent flow

Cumulative quantity of energy transferring through an inside surface (generally from in to out) is used to analyse and quantify heating demand to keep the inside environment at the level chosen in the simulations (cooling demand is not considered). 6 wall components were defined with equivalent thermal transfer coefficients: $U = 0,439 \text{ W.m}^{-2}.\text{K}^{-1}$, and 1 with $U = 0,135 \text{ W.m}^{-2}.\text{K}^{-1}$ (low-energy wall). To define an average water content of each layer during the reference year, a preliminary 3 year simulation was executed on each component, as presented in §7.3. The average water content of each layer during the third year is used in the U-value calculation.

Assessment of “heating demand” based theoretical flow if a permanent transfer is assumed (i.e. using only U-value and thermal evolution of inside and outside climate) gives a good approximation of the total energy transferred during the reference year. Cumulative quantity of energy crossing the inside surface of the components is between 40 and 45 kWh.m⁻² for all of them, except the low-energy wall (15 kWh.m⁻²). Influence of transient effects, sun, wind or rain is not significant on this value (less than 10%, as detailed in §7.6.2).

Dynamic simulations thus confirmed that, in the Belgian climate, the best way to reduce the yearly amount of energy transferred through the component from inside to outside is to minimise U-value of the components. To lower U-value of LHM-wall components, either their thickness could be increased or a complementary insulation layer could be applied. In Fig.162, component (A) is adapted, increasing the thickness of LHM-wall layer to 55cm. Fig.164 shows how component (B) can be adapted, adding 10cm of light insulation (with a low μ -value, and $\lambda \sim 0,04 \text{ W.m}^{-1}.\text{K}^{-1}$). Both examples lead to $U=0,24 \text{ W.m}^{-2}.\text{K}^{-1}$, but they each have a specific effect on transient behaviour and moisture regulation, as discussed hereafter for the 7 studied components.

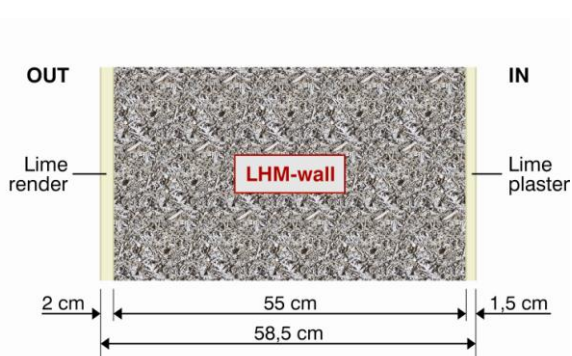


Figure 163 : Adaptation to decrease U-value of component (A) to $U=0,24 \text{ W.m}^{-2}.\text{K}^{-1}$ with 55cm of LHM-wall

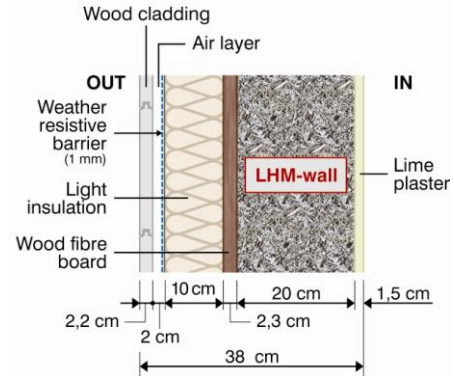


Figure 164 : Adaptation to decrease U-value of component (B) to $U=0,24 \text{ W.m}^{-2}.\text{K}^{-1}$ with 20cm of LHM-wall and 10cm of light insulation

To reduce U-value to $U=0,135 \text{ W.m}^{-2}.\text{K}^{-1}$, as for component G, either thickness of LHM-wall layer in component (A) is increased to 82cm, or the adaptation of component (B) presented in Fig.163 designed with around 20cm of light insulation (with $\lambda \sim 0,04 \text{ W.m}^{-1}.\text{K}^{-1}$) instead of 10cm. This light insulation should be a light breathable hygroscopic material, like loose fill cellulose material or fibre insulation (wood, hemp, flax, sheep's wool...). These related materials should be further analysed following the methodology developed in the present work.

LHM-wall components (A) and (B) are more permeable to vapour than the classical component ($S_{d_{tot}}$ is smaller, see §7.5.2), especially compared to component (G) defined with a vapour barrier (high vapour diffusion resistance factor: $\mu = 1,5.10^6$ [-]). Simulations showed that assessing the yearly vapour flow through the component when a permanent transfer is assumed (i.e. without taking the rain into account) can lead to unrealistic results. Component (A) under reference year climate (with rain) transfers around $700 \text{ g.m}^{-2}.\text{year}^{-1}$ from the outside to the inside environment. Component (B), protected from the rain by a wood cladding, extracts an average of $1000 \text{ g.m}^{-2}.\text{year}^{-1}$ from inside the environment after the reference year. Results for the other components are between these two limits. Moisture flow through inside surface of component (G) is negligible (vapour barrier). As occupants and their activity produce vapour, the fact that component (B) extracts moisture from inside environment is considered to be an advantage, but it has to be balanced with the fact that 1/ most of the moisture transfer occurs during summer and fall period, when ventilation can be used to regulate moisture flow; and 2/ quantity of moisture transferred is much smaller than was could be produced by occupants (50 g.h^{-1}), see 7.6.1.2.

8.2.2 Transient behaviour

8.2.2.1 Variation of outside climate

Transient thermal effects of components are referred in terms of “thermal inertia”. Thermal inertia can influence heat flow through components and thus the heating (or cooling) demand of the building.

Based on the knowledge of three classical parameters - density, thermal capacity and thermal conductivity - two combined parameters, *thermal diffusivity* and *thermal effusivity*, are defined to compare materials in terms of dynamic thermal behaviour. LHM-wall appears to have a low thermal diffusivity (slow to heat up or to cool down) with a relatively high effusivity compared to classical insulation materials (relatively high quantity of energy stored and released).

These parameters are good indicators of thermal inertia of monolayer components, but they do not fit reality with multi-layer components. Component (F) has almost the same layers than component (E), but in a different order; they do not have the same dynamic response under variations of temperature outside or inside. Thermal diffusivity and thermal effusivity are useful to compare component (A) to (C), comparing the behaviour of LHM-wall to the behaviour of cellular concrete because they have an equivalent distribution of layers. In addition, component (B) can be compared to component (G), comparing diffusivity and effusivity of LHM-wall and mineral wool, for the same reason.

The *time to reach permanent transfer* and the *cumulative quantity of energy transferred after 24h* were defined after a sudden cooling of the outside environment to compare components thermal inertia. Sudden heating and solar radiation gave similar results (opposite values). Components (A), (B), (D) and (F) gave equivalent results. Component (E) had more thermal inertia: longer delay, important effects on transient heat transfer during the first hours (layers close to inside surface had higher diffusivity and much higher effusivity than LHM-wall). Component (C) has slightly less thermal inertia (higher diffusivity and lower effusivity than LHM-wall). If component (G) has a very low thermal transfer coefficient, the fact LHM-wall layer from component (B) was replaced by a layer of mineral wood (relatively high diffusivity and very low effusivity) leads to very low thermal inertia. Simulations detailed in §7.4.1 thus give elements to quantify thermal inertia of components and demonstrate that components with equivalent thermal transfer coefficient can have different transient thermal behaviour under heat shocks.

Section 7.4.2 shows that the thermal inertia of components can also be discussed in terms of *thermal phase-shift* and *thermal damping* of theoretical thermal cycles of outside environment. For cycles with a period of 24h, thermal damping is over 90% for all the components except component (C), ~70%, and component (G), ~40%.

LHM-walls have the highest thermal phase shift: 1/ the effect of low temperature at night on the inside surface of LHM-wall components is delayed of 14 -15h, after this time lapse, solar radiation can compensate cold surface effect; 2/ the inside surface is the warmest in the early morning (~6am) if the highest outside temperature occurs in the early afternoon (~3pm) the day before; 3/ the risk of overheating is reduced since heat flow through the inside surface of the component during a hot summer day only arrives when the outside (lower) temperature can compensate for this heat transfer through night ventilation.

For thermal cycles with a period of 365 days, there is no thermal damping and no phase-shift. Influence of thermal inertia, or *transient benefit*, on long term heating demand assessment (1year) is negligible.

When using the dynamic software WUFI®, it appears that moisture transfer and storage phenomena are complex. The “risk of condensation” in permanent transfer (using Glaser model) should not be reduced to a binary assessment (Yes/No). Transient moisture transfer modelling allows a more accurate view regarding various phenomena: vapour and liquid transfer, and water content evolution with redistribution and evaporation of surplus. Conclusions are harder to draw, but specificity of hygroscopic and capillary materials should not be neglected. Is there residual condensation? How much water condenses? How does water content vary in the long-term? As a matter of fact, neither water content nor relative humidity in the material brings information on how close the material is from free saturation. Comparing the results for different materials needs to describe new parameters to analyse the influence of simultaneous liquid, vapour and heat transfer. Evolution of the saturation level of material concerns durability (mould risks), as well as heat loss or comfort feeling. The present work defines two parameters related to transient moisture phenomena in analogy with transient thermal effects: *hygric diffusivity* and *hygric effusivity*. In the hygroscopic region those two parameters were both very high for LHM-wall compared to other materials: high hygric diffusivity - fast variation of moisture content; high effusivity - important quantity of moisture transferred.

“Hygric inertia” extends transient moisture effects for much longer than transient thermal effects. Simulations presented in §7.5 show that simple hygric shocks are delayed for few months for component (A). Transient moisture evolution during drying of component (A) will take several months to stabilise. Drying period is around 3 months ($w < 150 \text{ kg.m}^{-3}$), but the equilibrium water content of the reference year (between 45 and 85 kg.m^{-3}) will not be reached before more than 6 months. This time period is relatively long when people are waiting for their house, but it is relatively short compared to drying process of a fresh cement concrete wall.

The combination dynamic parameters like sun, wind and rain can lead to 10% of energy savings (south exposition). Section 7.6 showed that rain provokes variations in water content of component (A) (and thus variation of the thermal conductivity of its materials, see §7.3) and needs latent heat of evaporation when the absorbed rain has to evaporate (around $-1000 \text{ Wh.m}^{-2}.\text{year}^{-1}$, see §0). Latent heat of evaporation is largely balanced by solar radiation ($\sim 5000 \text{ Wh.m}^{-2}.\text{year}^{-1}$). Component (B) is protected from the rain by the wood cladding but receives no solar radiation. Component (B) has the same U-value than component (A), but additional energy loss is almost $3000 \text{ Wh.m}^{-2}.\text{year}^{-1}$ (when analysing component under dynamic climate, with sun and rain).

Those marginal benefits (compared to energy demand) could be optimised though appropriate design validated by complementary simulations with dynamical modelling. Components behaviour should be analysed in other climates: if LHM-wall appeared to have good global thermal performances under Belgian climate, its specificities can lead to very interesting results under hot and fast changing climate. Beside this analyse under other reference climate, a special focus on effective thermal performances could be made during one single reference day of each season, and on the influence of critical climate period (strong rain followed by cold days, very hot days and influence of humidity...).

8.2.2.2 Variation of inside climate

The previous section discusses the transient response of the component when outside climate varies. Based on the results of [Rode, 2005]⁶⁴, the moisture buffer value – MBV – of LHM-wall is measured. Large deviations in the results were observed when simulations reproducing the experimental setup were defined. They are justified by a strong retarded sorption effect; linked to the large range connected pores in LHM-wall. The software gives an overestimated value, but allows a comparison of the studied multi-layer components. The MBV of LHM-wall components is larger than the other components (large hygric effusivity of inside layers). Those components are more efficient at regulating the amount of moisture in the inside environment (between 1 and $2 \text{ g.m}^{-2}.\%RH^{-1}$ extracted and released after 1 cycles of 24h).

Based on the analogy of MBV, the present work defines a thermal buffer value – TBV. It is the quantity of energy that the components release during the “cold period” of the cycle presented in 7.4.2.3. The thermal buffer value of LHM-wall components is high: $\sim 30 \text{ Wh.m}^{-2}.\text{K}^{-1}$. It is higher than components (C), (F) and (G) (lower thermal effusivity of inside layers), but lower than component (D) and (E) (higher thermal effusivity of inside layers).

⁶⁴ *Moisture buffering of building materials*, C. Rode et al., final report, Department of Civil Engineering, Technical University of Denmark, 2005

This work also point out a secondary effect moisture buffering on thermal behaviour of components. When moisture is adsorbed (i.e. during winter nights), the latent heat of condensation slightly heats up the component surface. When moisture is released (i.e. during hot summer day), latent heat of evaporation slightly refreshes the component surface. These effects are not significant on the energy loss of components but they slightly improve comfort feeling of occupants. Higher MBV leads to higher benefits in terms of latent heat. Complementary measurements (on samples, wall-elements or even experimental buildings) are necessary to validate the results of MBV and TBV simulations.

8.3 Comfort feeling

Previous section showed that, using WUFI® model as described in this work, the specific hygrothermal inertia of LHM-wall components turned out to have an important influence on short term storage and transfer but not on long term assessment of heating demand. Components defined with the same thermal transfer coefficient had a very similar yearly demand of energy.

It appeared that the model used in this work did not explain the surprising results from BRE⁶⁵ presented in §1.2. BRE report announce: “calculations suggest that the hemp houses (...) should be using significantly more energy than the brick houses and this is not the case”. In the present work, LHM-wall component was defined with the same thermal transfer coefficient and should thus be using significantly “less” energy than the brick houses, but “this is not the case”.

After thermographic inspection of the masonry and hemp house in Suffolk⁶⁶, surface temperature of outside walls appeared to be 4 to 6°C lower in LHM-houses (lower difference with outside temperature implies lower loss of energy). In WUFI®'s model, if the same thermal transfer coefficient and the same surface transfer coefficients are used, WUFI®'s model gives approximately the same surface temperature. Result from BRE may be discussed in terms of specific surface emissivity and in terms of effusivity.

A link between surface temperature and thermal effusivity can be made when touching the component: LHM-wall has high surface contact temperature because of relatively low effusivity, $\text{Eff}_{\text{LHM}} = \sim 350 \text{ J.m}^{-2}.\text{K}^{-1}.\text{s}^{-1/2}$ (compared to a “cold touch” material, such as metal, $\text{Eff} = 11700 \text{ J.m}^{-2}.\text{K}^{-1}.\text{s}^{-1/2}$ or glass, $\text{Eff} = 1369 \text{ J.m}^{-2}.\text{K}^{-1}.\text{s}^{-1/2}$). As thermal comfort depends on both air and surface temperature, a monitoring of surface transfer of LHM-wall components should bring important values to analyse effective comfort feeling near those components.

⁶⁵ *Final report Final Report on the construction of the Hemp Houses at Haverhill, Suffolk*, Dr. Tim Yates, BRE, 2002

⁶⁶ *Thermographic Inspection of the Masonry and Hemp House – Haverhill, Suffolk*, Dr. Tim Yates, BRE, 2003

BRE's monitoring in Suffolk also showed that the temperatures were "very similar in both the hemp house and the traditional houses although the hemp houses maintain marginally higher temperatures (one or two degrees)". The present work compares 7 components in terms of moisture and heat transfer using WUFI[®] dynamic software, where inside and outside reference climate are fixed when the simulation starts. It was thus also not possible to reproduce this result with simulations.

The reverse influence of components' hygrothermal buffering on inside hygrothermal levels (resulting in overheating, or humidity regulation) can thus not be calculated with this model. Other software (i.e. TRNSYS) allows calculating inside climate evolution but the parameters of the material defined in the components are constant. Iterations between the two types of software are needed to assess air temperature and humidity variation of the inside environment together with dynamic heat and mass flows through the component. New software, WUFI[®]Plus 1.2, is apparently able to deal with this objective.

Nevertheless, previous section shows that results can be used to quantify thermal and hygric inertia of studied components. High thermal and hygric inertia of LHM-wall components, can explain high comfort feeling reported by people living in LHM-buildings. Those components delay and dampen the effects of outside variation of the climate, regulate inside environmental variation of temperature and humidity, and generate latent heat effects (slight heating when water content of the component is rising – i.e. during winter – slight cooling during evaporation – i.e. during summer), offering an important and increased comfort feeling, even if they just offer marginal benefits on heating demand.

The present research contributes to understand the role of thermal and hygric inertia on effective comfort feeling. It clearly appears that components with similar thermal performances offer different comfort feeling. Indirect energy savings could be accounted for if components were compared on the basis of a similar comfort feeling.

Comfort feeling is also linked to air, light and acoustical quality. Global comfort (considering the time to reach it) and global energy saving is a large and complex domain and many researchers are still developing tools to help designers to integrate research results in their design. Interesting hygrothermal behaviour of LHM-wall in relation to indoor comfort was confirmed. A deeper analysis of global comfort criteria will certainly help to quantify other qualities of this type of material.

9 Conclusion

Lime-Hemp Material is a new building material for heat and moisture regulation applicable to any type of buildings (new or old) in Europe and in the world. The market is growing fast in France and England (Belgium may follow) but the knowledge on their transient hygrothermal behaviour was still lacking of reference values.

First, a complete set of hygrothermal parameters for LHM-wall was gathered (through measurement in Fraunhofer-IBP) describing the related experimental procedure. The main hygrothermal parameters are first measured in the dry state. Moisture dependencies are then quantified in detail. Based on classical hygrothermal parameters, diffusivity and effusivity are defined on both thermal and hygric point of view and results for different materials are compared. If thermal parameters of LHM-wall are similar to wood material (slow to heat up or to cool down, relatively high quantity of energy stored and released), material's hygroscopic behaviour is surprisingly high and lies between clay brick or cellular concrete (for their fast change in moisture content) and wood (high quantity of moisture transferred).

A powerful software tool, WUFI® 4.1 Pro, was analysed in detailed and used to run various simulations. Seven wall components were defined and compared in terms of heat and moisture transfer through inside surface. Short term variations leads to significant difference between results of the dynamic simulations and equivalent calculations if a permanent transfer is assumed.

Reference indicators were defined and analysed to quantify thermal and hygric inertia of LHM-wall components. High inertia of LHM-wall components allows them to dampen the effects of daily variation of outside climate, and to delay the effects of peak values or sudden variations. They also regulate inside level of temperature and humidity (TBV and MBV).

Simulations under reference year climate showed that when taking transient effects, sun, rain and wind, the total energy theoretically transferred after 1 year can be 10% lower than theoretical assessment if a permanent transfer is assumed. This important result confirmed that, in Belgian climate or in colder countries, the best way to reduce the yearly amount of energy transferred through the component from inside to outside is to minimise thermal transfer coefficient (U-value) of the components.

Hot climate, fast changing climate, or climates having important difference of temperature between day and night, should be further analysed because they appeared to be the most appropriate for LHM-Technology.

In cold countries, building designer can adapt the thickness of their walls or combine LHM with other light insulation materials. Adaptations to the reference components, decreasing their U-value to $U=0,24$ and then to $0,135 \text{ W.m}^{-2}.\text{K}^{-1}$, were discussed. The need to increase energy efficiency of buildings should be balanced with the need of a constant comfort feeling, in summer and in winter.

Other materials were pointed out as loose fill cellulose material or fibre insulation (wood, hemp, flax, sheep's wool...) and should be further analysed based on the methodology developed in the present work. These materials combine low thermal conductivity to relatively high thermal and hygric inertia.

The present work can be used to help the designers to optimize effective performances and comfort feeling in their buildings. LHM-wall was chosen as an example because of its global sustainability and because it appeared to have competitive hygrothermal performance in terms of insulation and very good behaviour in terms of inertia. Studied components were similar in terms of total energy transferred after 1 year (less than 10% deviation). Furthermore, their behaviour is relatively different during transient transfer. Moisture and heat regulation of LHM-wall allows increased comfort feeling. When occupant reaches faster his comfort feeling, or enjoy comfort feeling during a longer period, his global energy demand should be related to indirect energy savings he could make. LHM-wall thus leads to better performances when the components are compared in terms of comfort feeling.

LHM-Technology is developing on European's market. During the three last years, many researches, associations and colloquium focused their interests on this material in France, England, Belgium, Germany, Canada... Quality of Lime-Hemp Material is expressed in terms of global sustainability: global comfort; good thermal performances; thermal load; moisture regulation; and also air quality; high noise reduction; low production cost and low environmental impact; CO_2 storage; easy to recycle; low waste...

Analysing LHM-wall's properties in dynamic conditions allowed a better understanding of LHM specificities which lead to high comfort feeling and low energy demand reported by monitoring and occupants of LHM-buildings. Further research is suggested on specific dynamic behaviour of LHM and other hygroscopic open-porous material. Research on prefabricated wall using LHM or on spraying of LHM-wall and LHM-plaster/render can help to optimize their implementation. Presented results should contribute to these further developments and support designers on their way toward a sustainable Architecture.

10 Literature

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11 Nomenclature

Symbols:	[K]	θ	Temperature
	[%]	ϕ	Relative humidity
	[Pa]	P_A	Air pressure
	[Pa]	p_{sat}	Saturation pressure
	[Pa]	p_v	Partial vapour pressure
	$[\text{kg.m}^{-2}.\text{s}^{-1}]$	$\dot{m}_A$	Air flow rate
	$[\text{kg.m}^{-2}.\text{s}^{-1}]$	$\dot{m}_M$	Moisture flow rate
	$[\text{W.m}^{-2}]$	$\dot{q}$	Heat flow rate
	$[\text{m}^3], [\text{cm}^3]$	RVE	Representative volume element
	[kg]	m	Mass
	$[\text{m}^3]$	V^*	Bulk volume
	[m]	d	Thickness
	$[\text{kg.m}^{-3}]$	ρ	Density of material
	[% _{vol}]	ψ	Total porosity
	$[\text{kg.m}^{-3}], [\%_{\text{mass}}]$	w	Water content
	$[\text{kg.m}^{-3}], [\%_{\text{mass}}]$	w_f	Water content at free saturation
	$[\text{kg.m}^{-3}], [\%_{\text{mass}}]$	w_{max}	Maximal water content
	$[\text{kg.m}^{-3}.\%_{\text{HR}}^{-1}], [\%_{\text{mass}}.\%_{\text{HR}}^{-1}]$	ξ_ϕ	Specific hygric capacity
	$[\text{kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}]$	δ	Vapour permeability
	$[\text{kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}]$	δ_a	Vapour permeability of air
	[-]	μ_0	Dry vapour diffusion resistance factor
	[-]	μ^*	Fictitious vapour diffusion resistance factor
	$[\text{m}^2.\text{s}^{-1}]$	D_w	Liquid transfer coefficient, liquid diffusivity
	$[\text{m}^2.\text{s}^{-1}]$	D_{ws}	Liquid transfer coefficient for absorption
	$[\text{m}^2.\text{s}^{-1}]$	D_{ww}	Liquid transfer coefficient for redistribution
	$[\text{kg.m}^{-1}.\text{s}^{-1}]$	D_ϕ	Liquid conduction coefficient
	$[\text{J.m}^{-3}]$	h	Enthalpy
	$[\text{J.kg}^{-1}.\text{K}^{-1}]$	c_0	Thermal capacity
	$[\text{W.m}^{-1}.\text{K}^{-1}]$	λ^*, λ	Fictitious thermal conductivity
	$[\text{W.m}^{-2}.\text{K}^{-1}]$	h_e	Heat transfer coefficient of outside surface
	$[\text{W.m}^{-2}.\text{K}^{-1}]$	h_i	Heat transfer coefficient of inside surface
	$[\text{m.s}^{-1}]$	v_{wind}	Wind speed
	$[\text{kg.m}^{-2}.\text{s}^{-1}.\text{Pa}^{-1}]$	β_v	Vapour transfer coefficient
	$[\text{W.m}^{-2}]$	$\dot{q}_{\text{solar}}$	Heat flow from solar radiation
	[-]	a_s	Short-wave absorptivity
	$[\text{W.m}^{-2}]$	I_N	Solar radiation vertical to the surface of component
	$[\text{kg.m}^{-2}.\text{s}^{-1}]$	$\dot{m}_w$	Liquid flow on the surface
	[-]	a_r	Rain absorptivity
	$[\text{kg.m}^{-2}.\text{s}^{-1}]$	R_N	Normal rain
	$[\text{kg.m}^{-2}.\text{s}^{-1}]$	R	Rain load vertical to the surface of component
	[-]	ε	Thermal emissivity of materials

$[\text{W.m}^{-2}.\text{K}^{-1}]$	U	Thermal transfer coefficient, U-value
$[\text{m}^2.\text{K}^1.\text{W}^{-1}]$	R_{tot}	Total thermal resistance of the component
[m]	Sd	Vapour diffusion thickness
$[\text{W.m}^{-2}]$		Heat flow through inside surface of component
$[\text{Wh.m}^{-2}.\text{day}^{-1}]$		Cumulative quantity of energy transferred per day
$[\text{g.m}^{-2}.\text{day}^{-1}]$		Cumulative quantity of moisture transferred per day
[h], [month]		Time to reach permanent transfer
[%]	$Q_{24\text{h}}$	Ratio between cumulative quantity of energy transferred through inside surface of components and cumulative quantity of energy transferred if permanent transfer is assumed 24 hours after sudden cooling of outside environment
[h]		Thermal phase-shift
[%]		Thermal damping
$[\text{Wh.m}^{-2}]$	TBV	Thermal buffer value
$[\text{g.m}^{-2}.\%\text{HR}^{-1}]$	MBV	Moisture buffer value
$[\text{Wh.m}^{-2}]$		Latent heat released during the night

Subscript:

0	Relative to dry state
init	Relative to initial state
A	Relative to air transfer and storage
M	Relative to moisture transfer and storage
v	Relative to vapour
w	Relative to liquid water
H	Relative to heat transfer and storage
f, sat	Relative to free saturation
conv	Relative to thermal transfer by convection
cond	Relative to thermal transfer by conduction
rad	Relative to thermal transfer by radiation
lat	Relative to thermal transfer by latent heat
surf	Relative to thermal transfer through the surface
amb	Relative to out side or inside environment

12 Abbreviation

General:

EPBD

European directive on energy performance of building

EPC

Energy performance certification

RES

Renewable energy sources

GHG

Greenhouse gas

GNP

Gross national product

LCA

Life cycle assessment

IEA

International Energy Agency

PMDE

Plan pour la maîtrise durable de l'énergie (Région wallonne)

Research centre:

UCL

Université catholique de Louvain (Louvain-la-Neuve / Bruxelles)

FIRST-BCCB

« Utilisation et comportement des Bétons de Chaux et de Chanvre dans les constructions à ossatures de bois en Région wallonne » research in Architecture et climat by A. Evrard, with partnership with Lhoist R&D and co-financing from Waloon Region and European Social Found

Fraunhofer-IBP

Fraunhofer-Institut for building physics in Holzkirchen

ENTPE

Ecole Nationale des travaux publiques de l'état

BRE

Building Research Establishment

Materials:

LHM

Lime-Hemp Materials

LHM-wall

Lime-Hemp Materials / "wall" mixture

LHM-roof

Lime-Hemp Materials / "roof" mixture

LHM-plaster/render

Lime-Hemp Materials / “plaster” or “render” mixture

AAC

Autoclaved Aerated Concrete

XPS

Extruded Polystyrene – Foam insulation

MW

Mineral wool insulation

CEM

Cement concrete

CL, DL, NHL, HL

Calcium limes, Dolomitic limes, Natural hydraulic limes, Hydraulic limes

CL-Q

Calcium quicklimes

CL-S

Calcium hydrated limes

Characterisation/modelling:**HR**

Relative humidity of air

HAM

Referring to Heat Air and Moisture transfer and storage models

WUFI

Wärme und Feuchtetransport Instationär

Dynamic software to simulate heat and mass transfer in building components

MRC

Moisture retention curve

RVE

Representative volume element

SEM

Scanning electron microscope

NMR

Nuclear magnetic resonance

13 Appendix

Appendix 1: *Material's data from WUFI®'s database*

Appendix 2: *Bioclimatic envelopes made of lime and hemp concrete*, Proceedings from conference CISBAT 2005, pp.25-30, A. Evrard, A. De Herde, Lausanne, Switzerland, 2005

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