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Permeable and Hygroscopic Building Envelopes: Hygrothermal Simulations of “Det Naturlige Hus”

DIANE BASTIEN & MARTIN WINTHER-GAASVIG

Abstract Unlike most conventional building materials currently used nowadays, natural building materials tend to be hygroscopic and permeable to water vapour. These two characteristics have the potential to improve the longevity and indoor air quality of buildings. For instance, the use of hygroscopic materials such as clay plasters can significantly reduce indoor humidity fluctuations, which yields many other indirect health benefits. However, with many countries that commonly use vapour retarders, there is lack of knowledge and general design guidelines on how to design safe permeable and hygroscopic building assemblies. This paper presents hygrothermal simulations of “det Naturlige Hus”, a single-family house in Denmark mainly made of wood and clay. Simulation results indicate high levels of moisture on the exterior building layers, especially in the coldest months, mainly caused by driving rain and water vapour diffusion. The mold index calculated at the exterior surface of the exterior wood fibreboard according to ASHRAE 160 grew over the two years simulated period to reach a maximum of 2,7 and would likely reach higher values with a longer simulation period. When removing the exposure to driving rain, the maximum mold index reached a value of 0,2. With a recommended threshold of 3, it seems that the wall design investigated here could perform satisfactorily provided that great care is taken to minimize the wall exposure to driving rain.

Keywords: • Water vapour • hygroscopicity • water management techniques • diffusion • permeability •

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1 Introduction

Water is estimated to be responsible for 75% of building failures [1]. Water management in buildings is therefore one of the biggest driver of building longevity. It is also closely related to the indoor air quality and the health of building occupants. Keeping the indoor relative humidity level between 40% and 60% can reduce asthmatic reactions, mites, fungi and the survival rate of infectious bacteria and viruses [2].

As such, water management strategies should be an important part of building design and should rely on more than one strategy to insure satisfactorily performance over time.

Different moisture management strategies can be effective, depending on the building usage and climate. The use of impervious or inorganic materials is often touted as a safe practice, but these could actually pose additional risks. For instance, manufacturers of petroleum-based insulation products claim that they are safer than natural products because of the absence of organic material available for mold growth. However, natural materials tend to be more hygroscopic (able to retain and release moisture), which reduces the risk for mold growth by having a more uniform moisture distribution [3]. As for impermeable walls, they are much more prone to transient episodes of condensation caused by cooking and washing than pervious surfaces [4].

1.1 Moisture transfer mechanisms

The four predominant moisture transfer mechanisms in buildings are: 1) liquid flow; 2) capillary suction; 3) air movement 4) vapour diffusion [5].

Liquid flow

Liquid flow as rain and groundwater is the most important source of water that buildings are exposed to. Appropriate strategies to control liquid flow include overhangs, gutters, site grading and drainage pipes at the footings.

Capillary suction

Capillary transport occurs through the absorption/desorption of water as liquid in porous materials. It becomes important when materials have a relative humidity above 95%, when water vapour starts to condensate in the smaller pores. The best way to control undesirable capillary transport in building envelopes is by proving a capillary break, such as installing a rain screen cladding and waterproofing below grade elements.

Air movement

Unintended air movement through the building fabric as infiltration or exfiltration can carry a high amount of moisture, which can potentially condensate if a surface colder than the air dew point is met. Energy efficiency concerns are driving the quest for air

tightness in buildings, which also contributes to reduce condensation risks and premature deterioration. Therefore, having airtight buildings is highly desirable from both the energy performance and building durability point of views. Fresh air should be provided year round through dedicated systems, either naturally or mechanically.

Vapour diffusion

In winter, the atmospheric water vapour pressure is lower than the indoor vapour pressure. This vapour pressure gradient can generate a vapour flow from the interior to the exterior of a wall. Water vapour carried out by diffusion through the building envelope typically involves smaller amount of water compared to the three other transport mechanisms. Therefore, water vapour diffusion is less likely to cause severe damage to buildings. It is thus surprising to have building codes in many countries (e.g. Canada, United-States...) that require a water vapour barrier while not having strict requirements to protect buildings from water damage that can occur by the three other transfer mechanisms.

The International Residential Code classified vapour retarders in three classes [6]:

- A class 1 vapour retarder, also called vapour barrier, has a permeability of less than 0.1 perm ($s_d=35$ m - equivalent air layer thickness), such as a polyethylene sheet.
- A class 2 vapour retarder has a permeability higher than 0.1 perm but less than 1 perm ($s_d=3,5$ m), such as a plywood and bitumen coated kraft paper.
- A class 3 vapour retarder has a permeability higher than 1 perm but less than 10 perm ($s_d=0,35$ m), such as latex paint.

Different classes are established in Europe by the CSTC [7], where a vapour barrier (class E4) is defined for materials with $s_d>200$ m and materials are considered weak vapour retarders (class E1) with $2\text{ m}<s_d<5$ m.

Installing a vapour barrier on the interior in cold climates is indeed effective at stopping water vapour flow induced by vapour pressure gradient. However, it also impedes the drying potential of a building enclosure. Vapour barriers or retarders may cause significant damage when the building materials installed during the construction process have elevated moisture levels and during minor accidental moisture intrusion [8].

Rose (2003) notes that the numerical threshold values in the prescriptive requirements for vapour retarders by the Federal Housing Authority is lacking scientific support, although they remain the basis for US practice nowadays. He also describes the marketing strategy for convincing the public to adopt vapour retarders, for instance with a 1951 pamphlet titled “War Against Water” describing “the menace of moisture”. The so-called diffusion paradigm that emerged at this period is based on four elements: 1) vapour pressure gradient as the principal moisture load; 2) diffusion as the principal transport mechanism; 3) the steady-state profile as the main analysis tool; 4) recommendations of

vapour barriers and attic ventilation. However, as mentioned by McDermott, condensation is maybe not the most appropriate term for describing the phase change from vapour to adsorbed/absorbed moisture in materials.

In the diffusion paradigm, the hygroscopicity of building materials is completely ignored. But it plays a major role on the durability of the building envelope.

1.2 Benefits of permeable, hygroscopic building assemblies

Although uncommon in developed countries, hygroscopic and permeable walls may provide many benefits.

Building walls that have the capability to buffer moisture can provide more stable indoor humidity levels year round. In cases where dehumidification is required, such walls allow selecting a dehumidifier with a lower capacity and thus contribute to save energy. A building envelope made of permeable and hygroscopic materials provides a safety net and is more likely to forgive construction errors and future failures in other systems or parts of the fabric, which unavoidably arise throughout the entire lifetime of a building. Natural materials such as timber, clay, straw and natural fibres are both permeable and hygroscopic, therefore they are the best from not only an environmental point of view, but also from a performance point of view [4].

As pointed out by Rode [10], if a hygroscopic material is covered by a non-hygroscopic material and is not directly exposed to the indoor air, its contribution in buffering indoor moisture levels becomes nearly null.

Simonson et al. (2004a) found that a permeable, hygroscopic building envelope primarily made of wood can affect the concentration of CO₂, SF₆ and water vapour. Such a building envelope can reduce significantly the CO₂ concentration in low ventilation conditions, and still moderately when mechanical ventilation is provided. This building envelope reduced significantly the moisture fluctuations in a room in both well-ventilated and poorly ventilated conditions.

Simulations of hygroscopic building materials also showed that they are effective in reducing peak humidity levels and to increase the minimum humidity level in winter. [11]. This study concluded that additional research was needed to determine appropriate hygroscopic and permeable materials for different climates and buildings.

1.3 Selected field and laboratory study

A Canadian study on straw bale houses found that there is no doubt that strawbale houses can successfully function in a cold climate without having an interior vapour barrier. Three case study houses out of the nine that were monitored had borderline or unacceptable moisture readings. Designs which produced these moisture readings had two or more of the following conditions: 1) Insufficient overhangs 2) No capillary break

3) Extreme interior wetting 4) Below grade bales 5) Inadequate backsplash protection 6) Northern exposures. All of these conditions can be addressed by design, except for northern walls, which were found to have sustained humidity levels that resulted only from high atmospheric humidity levels [12].

Laboratory experiments performed by Geving et al. investigated, among other configurations, the conditions of a 50 mm wood fiber board acting as exterior wind barrier with wood fiber batt insulation and an interior gypsum board. The measurements have been recorded in Norway in 2014 over more than six months during the winter period. Even with this configuration without a vapour retarder and a hygroscopic material as inner layer, the relative humidity in the exterior wood fibre board exhibited a satisfactory performance and never exceeded 90%.

1.4 Scope of this study

With a few studies performed in the last 30 years questioning the need for vapour retarders, there is still a lack of design guidelines for the construction of permeable building assemblies. Is it possible to build a durable building envelope without any vapour retarders? If so, then how? Experience from existing buildings shows that the answer to the first question is yes. The second answer can be partly answered by reviewing the different permeable assemblies that were proven successful over time, but because of the lack of general design guidelines, introducing any changes in the building envelope or locating a building in a different climate would require detailed simulations to ensure safe water management.

This contribution presents hygrothermal simulation results of a permeable building, “det Naturlige Hus” (dNH). This house, currently under construction in Denmark, is mainly made of wood and clay. It was designed by the owner with the intent to provide the highest indoor environment quality as possible to his family. The relative humidity and temperature levels of the different layers of the building envelop are examined in order to assess the risk of elevated moisture level and potential mold growth.

This house will be closely monitored. The objectives of the monitoring will be to gather field data for assessing the performance and safety of the building envelope under real conditions and contribute to acquiring knowledge on the dynamic of permeable and hygroscopic building envelopes. The case study presented in this paper is a first step towards the objective to develop guidelines for designing permeable building envelopes that are safe and resilient under various conditions.

2 Hygrothermal Simulation

2.1 Det Naturlige Hus

“Det Naturlige Hus” is a one-storey 187 m² single family wood frame house located in Holbæk, near Copenhagen, in Denmark. The walls of dNH are made of lime plaster, wood

fibreboard, cellulose, clay board and clay plaster, whose hygrothermal properties are provided in Table 1. The ceiling is made of 500 mm of cellulose over a clay board and clay plaster. The wooden floor structure that sits over the concrete footings is slightly above ground level, over a ventilated crawl space. It is made of 300 mm of cellulose sandwiched between a wood fibreboard and oak flooring. The nominal U-values of the exterior walls, ceiling and floor are 0,09 W/(m²K), 0,07 W/(m²K) and 0,11 W/(m²K) respectively. The windows have a double glazed insulated glass unit (IGU) and an additional single pane on the inside, with a glass g-value of 0,55 and an overall U-value of 0,77 W/(m²K). These windows have the possibility to provide preheated fresh air by allowing air through openings in the window sill to flow between the single pane and the IGU and enter the room through an opening at the window head jamb.

Table 1. Wall Layers Material Properties

Material/Layer (from outside to inside)	ρ [kg/m ³]	c [J/kgK]	λ [W/mK]	Thick. [m]	s_d [m]
Lime Plaster	1600	850	0,7	0,005	0,35
Ext wood fibreboard	140	2100	0,04	0,06	0,18
Cellulose	43	2500	0,037	0,34	0,68
Clay board	615	2000	0,128	0,016	0,12
Basecoat clay plaster	1844	850	0,1	0,003	0,04
Topcoat clay plaster	1844	850	0,1	0,002	0,03

For the exterior wall assembly, the layer with the highest equivalent air layer thickness is the cellulose with $s_d=0,68$ m.

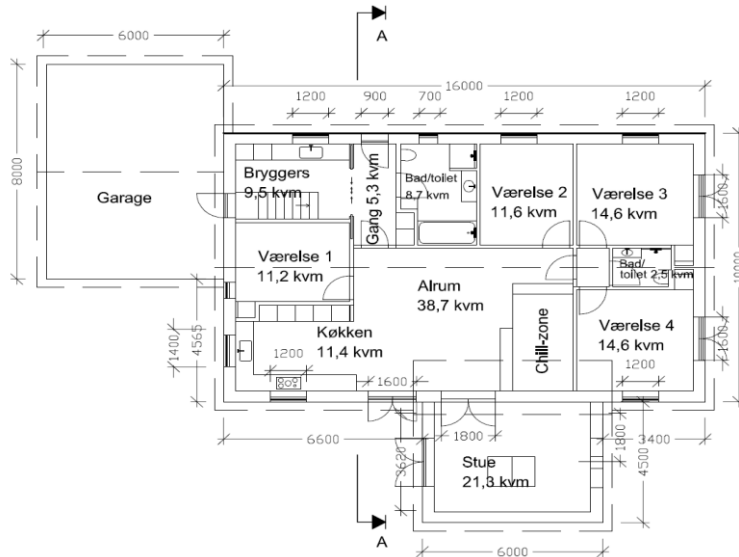


Figure 1. Floor plan of dNH

2.2 Simulation parameters and model limitations

Thermal and hygroscopic conditions inside the building assemblies are simulated with WUFI® Plus, a software that allows the calculation of transient heat and moisture flows. This tool has been validated through many studies [8]. Simulations are performed with the weather data from the WUFI database for the city of Lund, Sweden, which is 120 km East from Holbæk at the same latitude. Simulations are executed during two years, in order to see the initial drying immediately after construction and to allow enough time to get a stable annual dynamic. There are two adults and two children occupying the building constantly except during weekdays (8:00-16:00). The air tightness of dNH being unknown at the time being, the infiltration rate was set constant at 0,1 ACH. The special ventilation windows are considered unvented in the simulation model, but mechanical ventilation at 0,5 ACH with a heat recovery of 60% is included to approximate the ventilation effect that can be obtained with the ventilated windows. Additional natural ventilation at 0,5 ACH is provided from May 15th until September 15th to represent the window opening behaviour of occupants.

At this stage, only one-dimensional simulations are performed. Thus, thermal and hygric transfers through the structural lumber elements are neglected.

The model is divided as six zones. The house and the living room (stue) have a constant heating setpoint of 20°C and no mechanical cooling. The attics and crawl spaces of the house and the living room are continuously ventilated at 3 ACH. There is interzone ventilation between the house and the living room at 30 m³/h. The indoor moisture

generation profiles were defined from the occupancy schedule for the family. In the main zone, the moisture generation is equal to 4610 g/day during the week and 8384 g/day during the weekend. The indoor relative humidity level is between 30% and 45% in winter and 35% and 55% in summer. In the living room, the moisture load is set at 432 g/day and the relative humidity level is similar to the main zone.

The two skylights, the attached garage and the mechanical room in the basement leading to the garage have not been included in the model.

3 Simulation Results and Discussion

The highest water levels are found in the southwest wall assembly because of a higher exposure to driving rain due to the predominant winds (305 L/m² annually for this orientation); thus, only results for this orientation are presented here. The mean relative humidity within the different material layers is presented in Figure 1.

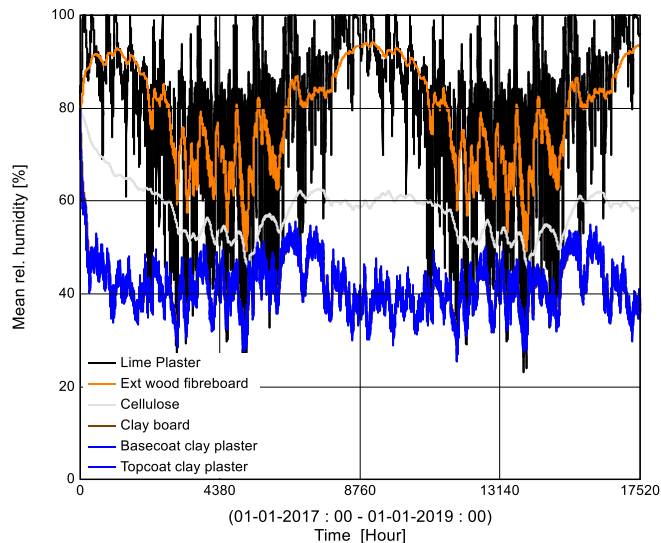


Figure 2. Mean layer relative humidity, SW

The most critical component is the exterior wood fibreboard, especially from December to February 20th (around 8000-10000 hours) when the relative humidity is above 90%. During the second simulated year, the maximum relative humidity is 94% and is reached in early January.

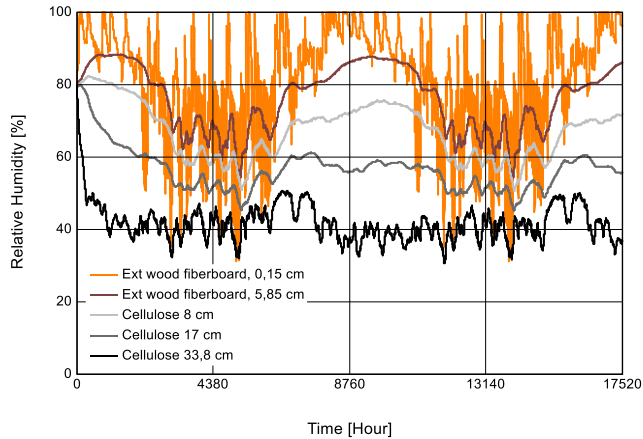


Figure 3. Relative humidity at different depths, SW

The relative humidity at different depths in the SW wall assembly is presented above. At 0.15 cm from the exterior surface of the wood fibreboard, saturation and rapid drying occur frequently because of driving rain and evaporation from solar radiation. The relative humidity level is more stable at 5.85 cm (brown curve), which stays over 80% during 160 days in the cold season.

At 1/4th deep from the exterior side of the cellulose layer, the relative humidity level is always below 74% (8 cm) while it remains below 60% in the middle of the cellulose layer (17 cm).

Observation of Figures 2 indicates a potential risk of mold development, with the exterior wood fibreboard having a mean relative humidity over 80% during approximately 180 days. However, when the humidity of the wood board is high, temperatures are relatively low, as shown in the Figure 4 below. While the mean moisture content is often above 20%, the mean temperature is generally between 5 and 10 when this occurs.

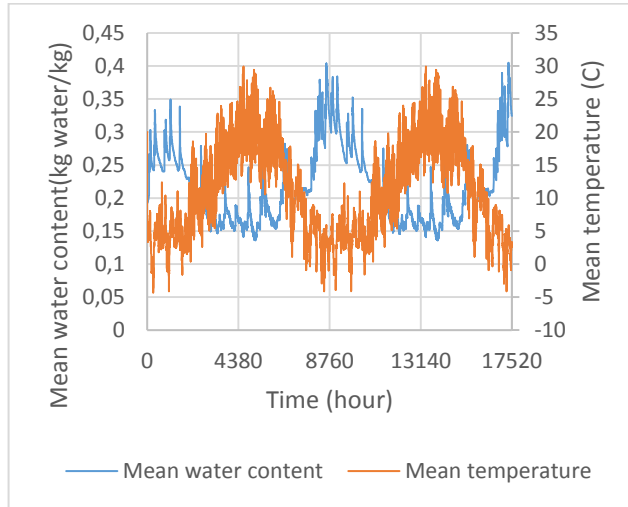


Figure 4. Mean water content and temperature of the wood board, SW

3.1 Mold index

The mold index has been calculated following the procedure described in ASHRAE Standard 160 [13] and addenda for the exterior wood fibreboard. This material was classified as a sensitive material for which a mold index decline coefficient of 0.1 was selected. Computation of the mold index over the two simulated years for the mean temperature and relative humidity of the board yield a maximum mold index of 0.7, which is well below 3, the threshold indicated in the Standard 160. However, the mold index at 0.15 cm from the exterior surface reaches a maximum value of 2.7 and is likely to increase further over a longer simulation period.

When removing exposure to driving rain, the maximum mold index at 0.15 cm from the exterior surface of the wood fibreboard is only 0.2. This indicates that this wall assembly could safely handle moisture flows if adequate protection from rain exposure is provided.

3.2 Discussion

From the results presented above, it becomes apparent that driving rain may compromise the performance of the wall assembly. Measures for minimizing driving rain such as overhangs are required for the durability of the wall assembly investigated here.

In future simulations, the model will be modified and consider the structural wood members, which should not exceed a moisture level of 16%-19%. Effects of varying the permeability of the inner layers on the moisture content of the outer layers will be investigated.

4 Conclusion

Natural buildings materials have lower embodied energy and life cycle impacts than petroleum-based products. They are also highly hygroscopic and can therefore absorb high amounts of moisture, which can contribute to increase the longevity of buildings assemblies.

This paper presented hygrothermal simulation results of “det Naturlige Hus”, a single-family wood frame house in Denmark. This house was specifically designed to be permeable to vapour diffusion and to buffer indoor moisture levels. The exterior walls are made of an exterior wood fibreboard, cellulose, clay board and clay plaster.

Results indicate that the southwest wall has the highest moisture content because of driving rain. When exposed to driving rain, the mold index near the exterior surface of the wood fibreboard reached a maximum of 2.7 over a two year simulation period. However, when removing the moisture contribution from driving rain, the maximum mold index reached 0.2, indicating that the wall assembly may provide satisfactorily performance if adequate protection from rain exposure is provided.

This work is a first step towards the development of design guidelines for durable, permeable and hygroscopic wall assemblies for facilitating the use of natural building materials and reducing the environmental impacts of buildings.

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