Hygrothermal modelling of a sustainable retrofit taking into account the urban microclimate. Case study of the medieval city center of Cahors (France)

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Design to Thrive

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Abstract: With the global need to improve building energy efficiency, numerous old dwellings representing a large part of the building stock need to be retrofitted. In the centre of the city of Cahors, France, old dwellings are considered as historical heritage and have to be internally retrofit to preserve the architecture value of the exterior façade. Such retrofits can lead to damage due to, for example, interstitial condensation. That's why, before the retrofit, a careful hygrothermal study must be run to predict the moisture behaviour of construction assemblies. However, most models assume a stand-alone building without taking into account surrounding buildings, whereas in reality buildings will be influenced by their neighbouring environment. In our case study, historical buildings are located in a very dense urban environment, as typical medieval pattern where urban morphology cannot be neglected. In this study, the urban environment modification of the exterior boundary conditions (mainly solar radiation and convective heat transfer coefficient) and consequent hygrothermal performance of the wall was investigated. The model is implemented by coupling the hygrothermal model Delphin to the whole-building simulation model EnergyPlus and Geographic Information Systems (GIS) tool ArcGIS. The goal is to predict exterior boundary conditions in the real geometry of the dense urban area as well as hygrothermal transfer in building envelopes. An open insulation system based on bio-sourced materials is studied. The simulation results indicate a quantitative correlation between urban morphology features and the hygrothermal performance of the fabric and the impact of the insulation system on the fabric decay.

Keywords: internal wall insulation, hygrothermal performance, urban microclimate

Introduction

Context

The centre of Cahors (south west of France) is characterized by its historical heritage and it's subject to specific regulations, implying adapted methods of intervention for thermal refurbishment as internal retrofit. But adding interior insulation significantly affects the thermal and hygric behavior of the masonry (Maurenbrecher, 1998). Insulation may cause the temperature within the masonry wall to drop, increasing the potential risk of damage due to interstitial condensation. Another pitfall of adding vapour-tight interior insulation is that it can inhibit internal drying, whereas an uninsulated wall can dry to the interior as well as the exterior. This reduces the drying rate and leads to higher levels of moisture accumulation. External drying may also be influenced by wind and solar shading by neighbouring buildings, particularly in the dense medieval city centre of Cahors (see Figure 1). In this study, indoor insulation systems in Cahors are assessed using in-situ monitoring of building, hygrothermal characterization of construction materials in the lab, and building physics modelling. An open vapor-system, with bio-based materials as insulation is studied. The high hygrogroscopicity of bio-based materials make them highly sensitive to moisture and because of the risk of mould growth they are often discarded from refurbishment projects. The moisture accumulation in a wall is often determined by boundary conditions (BC) and site-specific climate can significantly influence decay of the construction materials. In this paper, the building physics modelling of insulated walls with open (bio-based materials) is described, with the objective of preserving cultural heritage without risking moisture damage to the valuable historical buildings.

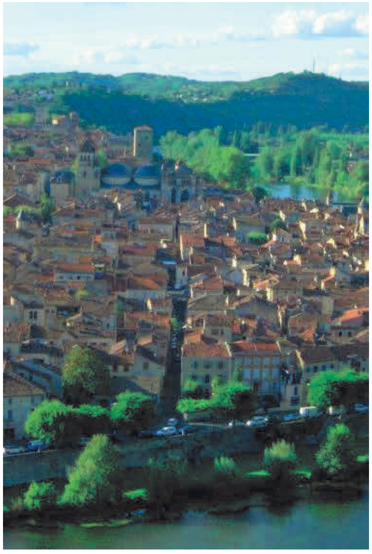

Figure 1: View of the city center of Cahors

Urban morphology and microclimate

The boundary conditions imposed on a mathematical model are often as critical to its accuracy as the proper modelling of the moisture physics. But in practice, detailed building energy simulation (BES) still typically rely on stand-alone building configurations, not accounting for the influence of neighbouring buildings, except perhaps for shading. The urban microclimate can strongly affect the boundary conditions (Dorer, 2013), particularly in a medieval city centre such as Cahors, where buildings may be very close together.
Urban morphological parameters are dominating factors for the formation of urban climate conditions (Matzarakis & Mayer, 1988) . The urban microclimate is determined by

(i) local air velocity, temperature and humidity;
(ii) solar irradiation and specular and diffuse reflections;
(iii) surface temperatures of building and ground, and the respective long-wave radiation exchange, also with the sky.

The urban microclimate modifies the exterior boundary conditions (mainly solar radiation, convective heat transfer coefficient and wind pressure on the building modifying the Wind Driven Rain (WDR) exposure) and so the hygrothermal performance of the wall. In urban configurations, wind velocity and pressure on buildings may not be easily evaluated, and studies have sought to examine factors such as urban canyon wind velocity and direction (Oke).

Case study

Method and focus on boundary conditions

In this study, the insulation systems are modelled using hygrothermal simulations for individual buildings and their estimated internal and external boundary conditions. To do this, a model is implemented by employing the hygrothermal model Delphin with EnergyPlus and ArcGIS (see Figure 2).
Individual building geometry, and the geometry and location of neighbouring buildings, is exported from a GIS database with building footprint and height data using ArcGIS. The same data was then used to model the building envelopes in the modelling tool EnergyPlus allowing the whole-building modelling of each building and its neighbours with its geometry. Here, EnergyPlus is used to obtain specific internal and external boundary conditions, such as the surface temperature of the external fabric elements , we consider that all outdoor thermal influences are lumped into equivalent outdoor air surface temperature (Hagentoft, 2001), which combines air temperature, as well as solar and longwave radiation which will vary depending on shading buildings. To alter wind building exposure, two roughness terrains are tested here (Country and City). Following the EnergyPlus simulations, air surface temperature is implemented in Delphin hygrothermal simulations as exterior boundary conditions; Delphin is used here rather than the Heat and Moisture Transport (HAMT) tool in EnergyPlus due to the ability to model wind-driven rain, and greater discretisation of the fabric elements. The climate conditions at the interior side of the wall are applied according to modelling standard EN13788 (ISO13788, 2012) for relative humidity and air temperature.

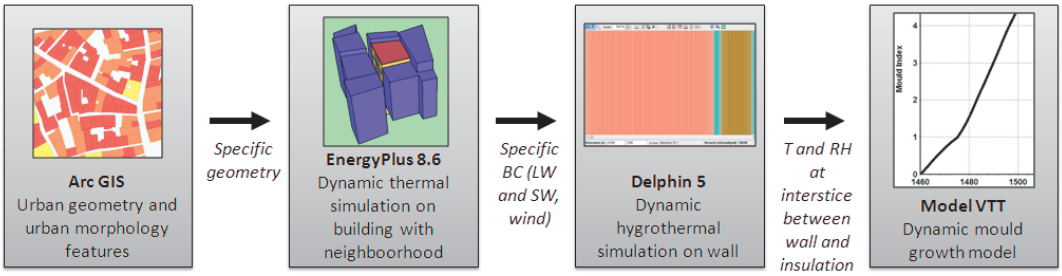

Figure 2: Simulation methodology

Building and wall description : construction assembly and materials

In this initial work, a building is studied first as a stand-alone building and secondly in its urban configuration and each floor of the building is studied. The analysis is performed for a single leaf massive masonry wall outfitted with an interior insulation system. Results of only one building are presented, a west-oriented building with a single external wall.

The original wall is made of massive clay brick. Buildings in the historical Cahors centre are dated from 12th to 19th century (ref Cahors). Due to numerous refurbishments of walls over the centuries, walls present heterogeneous historical brick materials making the dating and a global thermal characterization of the masonry difficult. Two historical bricks were hygrothermally characterized in the lab. According Vereecken (Vereecken, 2015), two hygric brick characteristics that are of main importance in this moisture transport are the capillary absorption coefficient Acap (kg/(m2s)) and the capillary moisture content wcap (kg/m2) and proposed the moisture penetration factor : Acap/(wcap x dbrick), where a high factor stands for a larger risk for the moisture to reach the warm side of the masonry. The analysis is performed with the brick presenting the highest moisture penetration factor (prop table 1).

To assess the hygrothermal performance of the wall after refurbishment, the wall is modelled with a 10cm bio-based insulation made of hemp shives and lime. The brick mortar composition of the masonry wall is simplified to a single isotropic brick layer. Hence, the analysis can be completed based on one-dimensional simulations.

Hygrothermal properties of the mix of hemp and lime insulation system were tested in the lab.

Table 1 : Hygrothermal properties of building materials

Materials	Historical Brick (40cm)	Hemp and lime insulation (10cm)
Apparent density [kg/m3]	1616	430
Total porosity [-]	0.45	0.79
Thermal conductivity [W/(m.K)]	0.45	0.07
Capillary absorption coefficient (Acap) [$kg/(m^2s^{1/2})$]	0.28	0.16
Capillary moisture content (wcap) [kg/m^2]	26.48	47.11
Water vapour diffusion factor	9	6.5

Heat and moisture analysis, hygrothermal risks and performances, methodology of assessment

Bio-based insulators are often discarded because of risk of mould development, which appears in specific temperature and relative humidity. The VTT model is an empirical and dynamic mould growth prediction model developed by Hukka and Viitanen (Hukka & Viitanen, 1999), (Viitanen, 2011). The mould growth development is expressed by the mould index (M), where M=1 is defined as the maximum tolerable value since from this point on the germination process starts.

In our study the relative humidity and temperature at interstitial point were calculated on an hourly basis for a period of five years. The failure criteria are applied on last year simulation.

Results and Analysis

Thermal radiation modifications due to urban morphology

Thermal radiation may have a significant impact on the water condensation risk in a wall (Kehrer & Schmidt, 2008). Urban morphology modifies both long-wave and short-wave radiations (see Figure 3), with highly sheltered façades receiving less solar radiation, more ground and buildings emission and less sky emission, avoiding the night overcooling.

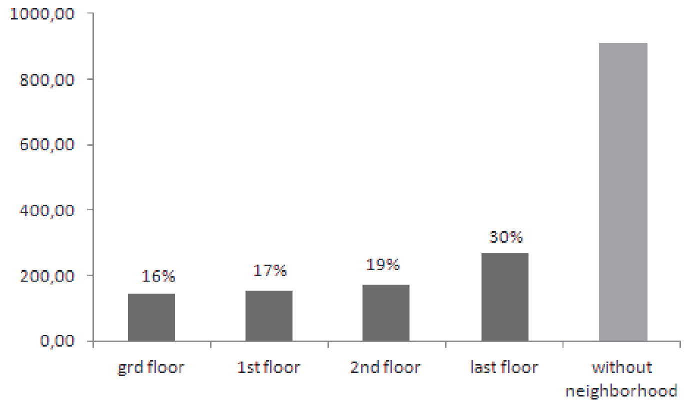

Figure 3 : Access to solar radiation in kWh/m² per year and percentage of solar radiation available at this solar orientation for each façade with neighbourhood, EnergyPlus calculations.

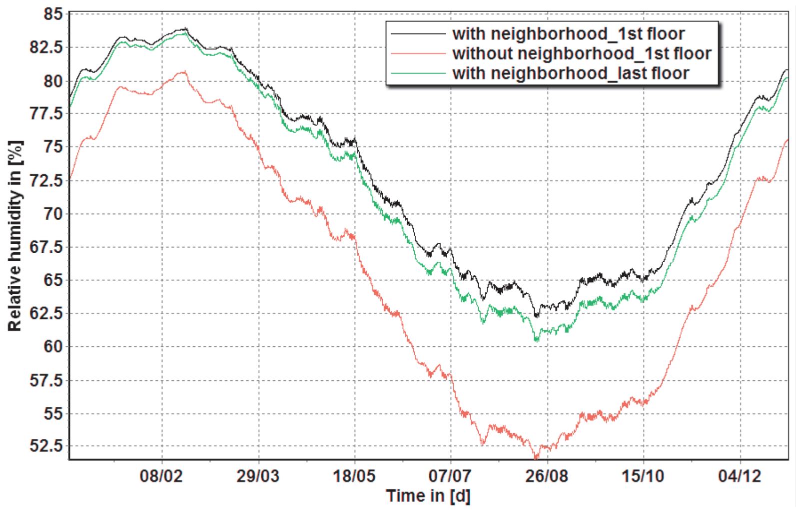

Figure 4 : Evolution of relative humidity between solid wall and bio-based insulation, fifth year of simulation, indoor boundary conditions according to EN13788

To illustrate the impact of external boundary conditions, the same inside boundary conditions (EN13788) are applied in each case (see Figure 4). The first floor of the sheltered building presents higher relative humidity than stand-alone building (yearly average difference of RH= 7,44%), and more than 95 days above 80% while only 10,5 days with stand alone building. VTT model gives an initiation of mould growth (M>1) for wall with neighbourhood while no development of mould for stand-alone buildings. In this case, each floor of the building receiving very low solar radiation, the difference between floors is not so relevant.

Impact of urban morphology on interior boundary conditions

Comparing the in-situ indoor climate values obtained during the monitoring campaign in Cahors to the temperature and RH of EN13788, the standard seems not adapted to describe the indoor conditions in the historical district. Indeed, as in several vernacular cities, the dense form of the built create a very specific indoor climate (Coccolo, 2016), which needs to be taken into account in the hygrothermal simulation. Each floor is now modelled with the same simple occupation scenario in EnergyPlus.

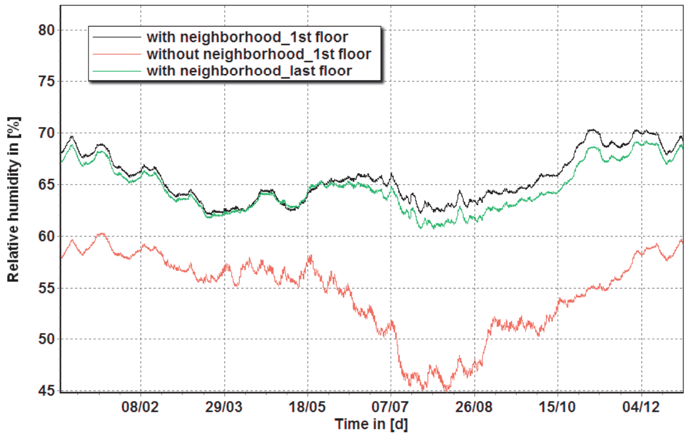

Figure 5 : Evolution of relative humidity between solid wall and bio-based insulation, fifth year of simulation, adapted indoor boundary conditions.

Using EnergyPlus modelled indoor conditions for temperature and RH (see Figure 4), we observe the same trend as with EN13788 indoor conditions with sheltered buildings presenting higher relative humidity at the interface between solid wall and insulation. But, no greater risk of mould development with adapted interior and exterior boundary conditions for bio-based insulation was observed.

Wind modification due to urban morphology

Urbanization has a notable effect upon the speed and direction of near surface wind, and many local factors influence the wind in urban environments (Santamouris, 2001). Wind impacts several parameters of hygrothermal transfer such as WDR (Blocken, 2009), external convective coefficient (ref) and surface moisture coefficient (ref), changing both the external surface temperature and drying capacity of the wall. In Cahors city, the complex topography of the Lot river and surrounding hills leads to irregular wind patterns. While EnergyPlus does not allow for wind shading based on specific geometries on neighbouring buildings, it does allow for the wind pressures to be adjusted by factors representing the surrounding terrain (Rural, Urban and City (ASHRAE, 2005)). In order to observe influence of wind in HAMT transfer, we chose to work with three wind velocities: Country and City Terrain (different surface roughness (Oke, 1987)) from the EnergyPlus model and a three-time wind acceleration. The TARP algorithm in EnergyPlus enables the convective coefficient to be calculated dynamically from the wind velocity.

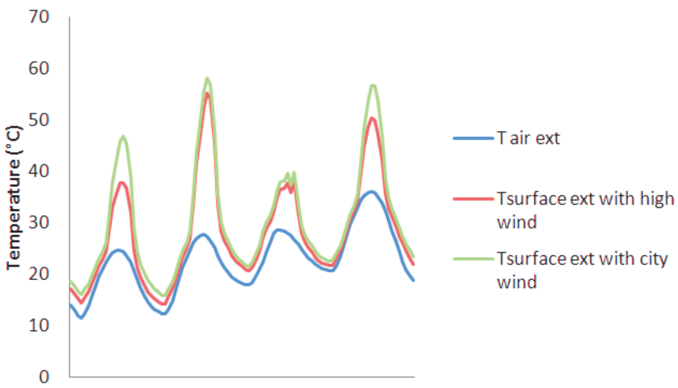

Figure 6 : Four days of simulation in July with EnergyPlus - Surface temperatures with different wind speed on top floor of stand-alone building

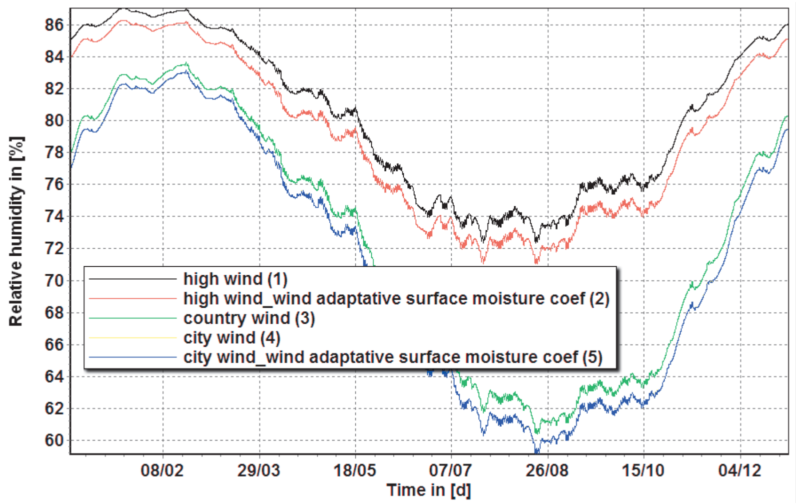

Figure 7 : Evolution of relative humidity between solid wall and insulation of the last floor façade with different exterior wind speed, fifth year of simulation, interior BC EN13788

Figure 6 shows how thermal convective coefficient modifies external surface temperature, where with higher wind speed, the surface temperature tends to outside air temperature.
Wind mainly impacts WDR, provoking a raise of relative humidity with the acceleration of wind speed (comparison of curve (1), (3) and (5)). The effect is not counter-balanced by drying effect thanks to wind. Indeed, Delphin 5 offers two vapour diffusion model, respectively with a constant or a wind adaptative surface moisture coefficient. The variable air velocity provokes an acceleration of drying with high wind velocity (curve (1) and (2)), while the effect turns to be negligible for low wind velocity (superposition of the two curves (4) and (5)). First floor wall results demonstrates a risk of mould growth (M>1) with Country wind velocity, while this risk disappears with City wind velocity.

Conclusion

This paper presented a study conducted for the estimation of the long-term moisture response of the façades taking into account the urban morphology. The study highlights that a building in a highly dense area shouldn't be treated as a stand-alone building, especially in term of thermal radiation and indoor boundary conditions. In the region of Cahors, the global low wind velocity makes the wind a less critical parameter. But in region with high wind velocity, this parameter should be taken carefully into account. Simulating walls with unadapted BC, can lead to discard insulation materials as bio-sourced insulations, while these materials present interesting features for a low carbon refurbishment of historical buildings. Further work will model numerous individual buildings and their façades in the city center to have a larger view of the critical parameters and influence of urban form.

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