Evaluation of a new numerical method for solving hygrothermal transfer through walls in the context of a historical city centre

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Abstract

To properly evaluate retrofit solutions for historical city centres on an urban scale, it is necessary to consider moisture exchange through walls. However, urban climate models usually neglect moisture transfer through walls. This work proposes a new numerical method for solving coupled mass and heat transfer, especially adapted to urban scale simulation. This method has been numerically validated by comparison with a reference tool DELPHIN, on several study cases. Moreover, its reliability for representing old walls is verified by comparing the results of the simulations with data measured in historic buildings in Cahors (France). The integration of a coupled transfer model solved with this resolution method into an urban climate model allow the simulation of the hygrothermal behaviour of old walls and the evaluation of their energy and microclimatic impact at the urban scale.

Keywords: historical wall; numerical scheme; in-situ measurement; urban climate model; hygrothermal transfer

1. Introduction

Building performance simulation is an efficient method to evaluate different retrofit solutions and helps to choose the most suitable strategy according to energy issues. In order to effectively simulate historic buildings, it is important to take into account the specificities of historical walls and in particular the hydric behaviour of these walls [1]. Moisture exchange through walls is a phenomenon that is often considered at the building scale, but generally neglected at the urban scale. The objective of this work is to develop a suitable numerical method to integrate this phenomenon into an urban climate model.

2. New numerical method for solving heat and moisture transfer through walls

The 1D hygrothermal transfer model and the numerical method used are based on the work of Ruiz et al [2]. It consists of two equations (conservation of mass and energy) to be solved according to two unknown variables: temperature and capillary pressure. The objective of this section is to develop an appropriate method for solving these equations in an urban climate model. However, urban models do not simulate each building individually, a neighbourhood is usually represented by a typical street. Due to the approximations made and the large spatio-temporal scales solved, the same level of accuracy is not expected for a wall-scale model as for a city-scale model. Therefore, the computation time must be reduced, and the numerical scheme adapted for future integration into an urban model. The developed solution method has the following characteristics:

- Lower-Upper (LU) decomposition
- Implicit-Explicit (IMEX) discretisation scheme
- Decoupled numerical approach (The mass equation and the heat equation are solved by two separate systems. Thus, the heat equation has only one unknown: the temperature, and the mass equation solves capillary pressure.)
- Fixed time step of five minutes reduced to ten seconds in critical moments for numerical stability, identified by five tests (which check the absorbed rain rate, oscillations, large variations between time steps).

3. Numerical validation

This resolution method was numerically validated by comparing the results with those of a reference tool (DELPHIN [3]), on fifteen wall configurations and three climate zones (Cahors, Manaus, and Aswan). The evaluation of the new method focuses on the verification of the data used to calculate the exchanges with the indoor environment and the outdoor urban environment, as well as the overall consistency of the simulated data inside the wall. The validation criteria are adapted to the expectations at the urban level. A mesh sensitivity analysis is carried out and shows that walls made of low permeability materials require a finer mesh size than those made of high hygroscopic or capillary materials. In addition, the more layers of material the wall contains, the finer the mesh size should be. Finally, the mesh version that provides satisfactory results for

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all cases has the following characteristics: a first node size of 1mm, a stretch factor of 1.5 and a maximum mesh size of 10cm, without mesh refinement at the interfaces between materials.

4. Comparison with in-situ measurements

This section aims to check the reliability of the developed method to represent the walls of a medieval city centre. A living-lab located in Cahors, a town in south-west of France [4] allows to measure the evolution of temperature and relative humidity (RH) in four walls with different compositions. The example presented in this work is an old brick wall renovated with hemp and lime insulation (Figure 1). These materials have been characterised in the laboratory. Boundary conditions are provided by a weather station located on a roof in the district and by sensors measuring the temperature and RH inside the building.

The results of the simulations carried out using the new method are compared with the measured data, over a period of nine months (from 15 April 2021 to 17 January 2022). The comparison is performed at three points in the wall: at the interface (temperature and RH), in the middle of the insulation (temperature and RH) and at the inner surface (temperature). To evaluate the results obtained, the method developed by [5] is applied to hygrothermal conditions in historical walls. Thus, the two criteria used for validation are the Mean Absolute Error (MAE) and the Pearson coefficient. The threshold value for the Pearson coefficient is 0.5. For the MAE, there are two levels of validation, and the threshold values are 1°C and 5%RH for the first level, 2°C and 10%RH for the second level.

The results obtained for the studied wall are presented in Table 1. All five variables are validated according to the presented criteria. RH is always validated at level 1, surface temperature is also validated at level 1, while interface and insulation temperatures are only validated at level 2. Similar work was carried out on two other walls made of bricks with wooden frame renovated with two different methods, one with polystyrene insulation and the second with hemp and lime insulation. Satisfactory results are also obtained, which allows to conclude that the developed numerical method is adequate for the hygrothermal simulation of historical city centres.

![Figure 1. Façades of the instrumented buildings](image1)

![Figure 2. Configuration of the studied wall](image2)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Tinterface</th>
<th>TInsulation</th>
<th>TSurface</th>
<th>RHInterface</th>
<th>RHInsulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson coefficient</td>
<td>0.991</td>
<td>0.997</td>
<td>0.996</td>
<td>0.783</td>
<td>0.831</td>
</tr>
<tr>
<td>MAE (°C)</td>
<td>1.35</td>
<td>1.11</td>
<td>0.44</td>
<td>2.99%</td>
<td>3.08%</td>
</tr>
</tbody>
</table>

5. Integration of moisture transfer through walls in TEB and perspectives

The developed method has been integrated into the urban climate model TEB (Town Energy Balance). This new version of TEB allows energy and microclimatic simulations on a city scale, including the effects of moisture buffering capacity and evaporative cooling potential of walls. Simulations were carried out on the city of Cahors, and the results obtained show a significant impact of moisture transfer on annual energy consumption. In this way, different retrofit scenarios can be compared regarding indoor and outdoor comfort as well as energy issues. In addition, the combination with a VTT model [6] makes it possible to quantify the risk of mould growth, which is an essential criterion for the retrofit of historic walls. Thus, recommendations can be formulated for the retrofit of historical city centres.

References