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2D whole-building hygrothermal simulation analysis based on a PGD reduced order model

Julien Berger[a,*], Walter Mazuroski[a], Nathan Mendes[a], Sihem Guernouti[b], Monika Woloszyn[c]

[a] Thermal Systems Laboratory, Department of Mechanical Engineering, Pontifical Catholic University of Paraná, Brazil
[b] Cerema, Dter Ouest, Nantes, France
[c] LOCIE, UMR CNRS 5271, Université de Savoie Mont Blanc, Chambéry, France

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ABSTRACT

Innovative and efficient ways to carry out numerical simulations are worth of investigation to reduce the computational complexity of building models and make it possible to solve complex problems. This paper presents a reduced order model, based on Proper Generalised Decomposition (PGD), to assess 2-dimensional heat and moisture transfer in walls. This model is associated with the multizone model `Domus` using an indirect coupling method. Both models are co-simulated to perform whole-building hygrothermal simulation, considering 2D transfer in walls. The whole-building model is first validated with data from the IEA Annex 41. Then, a case study is considered taking into account a 2-zones building with an intermediary shared wall modelled in 2 dimensions to illustrate the importance of the technique to analyse the hygrothermal behaviour of the wall. It has been highlighted that the whole model enables to perform more precisely analyses such as mould growth on the internal surface. In addition, important theoretical numerical savings (90%) are observed when compared to the large original model. However, the effective numerical savings are not so important (40%) due to the limitations of the co-simulation method.

1. Introduction

Excessive level of moisture in buildings may damage the construction quality and durability [1]. High level of indoor relative humidity and temperature can lead to mould growth on inside surfaces and moisture also affects the indoor air quality and thermal comfort of the occupants. Assessment of relative humidity is also important for management and performance of HVAC systems. The development of these disorders depends on material properties as well as on hygrothermal conditions in constructions [2]. The latter is governed by heat, air and moisture balances with the outdoor climate and with the indoor conditions, including impact of factors such as ventilation, internal sources, heating system etc. Recently, the Annex 41 of the International Energy Agency reported on most of detailed models and their successful applications for accurate assessment of hygrothermal transfer in buildings [3]. Most of existing tools can be grouped into two categories:

1. the *wall model*, performing simulation of heat and mass transfer in multi-layer walls. Several one- (1D) [4–6], two- or three- (2 or 3D) dimensional [7–12] models can be found in the literature for commercial or research uses.
2. whole-building hygrothermal simulation tools, including one dimensional (1D) transfer through the envelope and able to calculate the indoor conditions and energy consumption are presented in [13–21].

First category tools requires high computer run times. Indeed, several reasons can lead to increase the complexity of models. First, 2- or 3-D transfer impose high numbers of elements of the space domain. Secondly, due to the high moisture content dependence of material properties, short time step is required for long-time simulation periods of one or many years. Thirdly, problems become more complex when they are considered as parametric, as for instance, assess the hygrothermal performance of a building for different types of insulation materials. For these reasons, the use of 2- or 3-D wall model for whole-building hygrothermal simulation (tools of the second category) is a complex task due to their significant numerical complexity [22–25]. Some models can be referenced in literature, detailed in [25–28]. They associate Computational Fluid

* Corresponding author.
E-mail address: julien.berger@pucpr.edu.br (J. Berger).

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Nomenclature

Latin letters

A	surface [m^2]
C	heat capacity [J/kg/K]
g	moisture flow [kg/s]
K_l	liquid permeability [s]
L_v	latent heat evaporation [J/kg]
P	vapour pressure [Pa]
R_v	gas constant for water [J/kg/K]
φ	relative humidity [–]
t	time [s]
T	temperature [K]
V	volume [m^3]
w	moisture content [kg/m^3]

Greek letters

α	convective heat transfer coefficient [W/m^2/K]
λ	thermal conductivity [W/m/K]
β	convective mass transfer coefficient [s/m]
ξ	moisture capacity [kg/m^3/Pa]
ρ	density [kg/m^3]
τ	coupling time step [s]
δ_v	vapour permeability [kg/Pa/s/m]

Subscript

a	air
l	liquid
m	material
s	surface
v	vapour

Dynamic (CFD) models for the inside air volume building with 2- or 3-D models for transfer in porous walls. However, these models may only be used to assess the hygrothermal behaviour of a single room surrounded by walls (as a museum room). Their use for a whole-building remain theoretical. To our knowledge, no models associating 2- or 3-D models for heat and moisture transfer in porous walls materials for whole-building simulation are referenced in literature.

Thus, innovative and efficient ways of numerical simulation solving the hygrothermal transfer are worth of investigation to reduce the computational complexity of HAM models and enable to speed up whole-building hygrothermal simulations to solve complex problems.

This paper focuses on the issue of reducing the complexity of the wall model. The aim is to be able to integrate two or three dimensional wall model into a tool for whole-building simulation and analyse precisely the hygrothermal behaviour. To assess this aim, model reduction techniques are explored. In [29], a whole-building hygrothermal reduced order model was proposed. The whole model was compared with the commercial model `Wufi`. The results highlight its accuracy to compute the fields and important computational savings (order of 98%). However this approach only considers 1-dimensional heat and moisture transfer through the wall. In this work, a Proper Generalized Decomposition reduced order model, proposed in [30], is used to simulate the coupled transfer through the porous walls. It is associated with the validated multizone model `Domus` with an indirect coupling method. Both models are co-simulated to perform whole-building hygrothermal simulation, considering 2D transfer in walls.

The paper proposes to specify first the governing equations of each model. Then, knowing that each model has already been validated, the coupling method is validated on the exercise CE1 IEA Annex 41 benchmark [3]. Then, a case study is considered. It takes into account a 2-zone building with an intermediary shared wall modelled in 2 dimensions. Influence of internal surface convection and apparition of moisture disorders (mould growth, thermal performance) are investigated. The features of the numerical solution are also discussed.

2. Whole-building reduced order model

In this section, the hypotheses and the equations of both models are detailed. The first concerns the heat and mass transfer in walls. The second deals with the moist air multizone model. In the third sub-section, the coupling method is also described to highlight the construction of the global model.

2.1. Wall model

2.1.1. Equations

It is assumed that pores are filled with a fluid phase, composed of liquid water, and a gaseous phase, considered as a mixture of dry air and water vapour. The mass balance of water depends on moisture flows of the vapour phase. The heat balance takes into account conductive and convective flows. Equation of heat and mass transfer can be expressed as:

Problem 1. Find $T(x, y, t) : \Omega = \Omega_x \times \Omega_y \times \Omega_t \longrightarrow IR$ and $P(x, y, t) : \Omega = \Omega_x \times \Omega_y \times \Omega_t \longrightarrow IR$

$$\int\int\int_V \left(c_{11}\frac{\partial T}{\partial t} + c_{12}\frac{\partial P}{\partial t} - \mathrm{div}\left(d_{11}\mathrm{grad}T + d_{12}\mathrm{grad}P\right)\right) dV = 0 \tag{1a}$$

$$\int\int\int_V \left(c_{21}\frac{\partial T}{\partial t} + c_{22}\frac{\partial P}{\partial t} - \mathrm{div}\left(d_{21}\mathrm{grad}T + d_{22}\mathrm{grad}P\right)\right) dV = 0 \tag{1b}$$

$$+\,\text{boundary conditions} \tag{1c}$$

$$+\,\text{initial conditions} \tag{1d}$$

with $\{c_{i,j}\}_{i=1,2,j=1,2}$ and $\{d_{i,j}\}_{i=1,2,j=1,2}$ corresponding to storage and respectively diffusion properties of the materials, expressed as:

$$\begin{aligned} c_{11}(T,P) &= \rho_m\left(c_m + c_v w\right) & c_{12}(T,P) &= c_v T\xi \\ c_{21}(T,P) &= 0 & c_{22}(T,P) &= \xi \\ d_{11}(T,P) &= \lambda & d_{12}(T,P) &= \delta_v L_v \\ d_{21}(T,P) &= 0 & d_{22}(T,P) &= \delta_v + K_l\frac{\rho_l R_v T}{P} \end{aligned}$$

All symbols concerning transfer equations are clarified in the nomenclature section. More details of the wall model are given in [30]. Finally, the problem of interest considered is a system composed of two non-linear coupled partial differential equations with temperature T and vapour pressure P as driving potentials.

2.1.2. Reduced order model

Problem 1 is solved by using *Proper Generalised Decomposition* (PGD) model reduction technique. The PGD method originates in the radial space-time separated representation proposed by Ladeveze in 1985 [31]. In 2006, the separated representations were extended to the multidimensional case by Chinesta and co-workers [32]. See Chinesta et al. [33,34] for additional details on the method as well as [35] for an introduction. This strategy has been successfully applied and validated for various industrial applications. For instance, the PGD resolution was applied