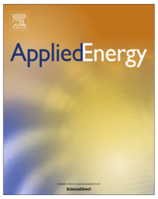
Applied Energy 190 (2017) 266–277

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



An innovative method for the design of high energy performance building envelopes

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HIGHLIGHTS

- It presents innovative method to compute parameter dependant model of heat conduction.
- For building envelope optimisation relatively to material diffusivity and thickness.
- Accurate solution computed at once 100 times faster than standard numerical approach.
- Two-layer wall analysis for 76 insulation thickness and 100 material properties.
- Low-storage cost providing real-time applications of building energy management.

ARTICLE INFO

Article history:
Received 5 August 2016
Received in revised form 14 December 2016
Accepted 26 December 2016
Available online 6 January 2017

Keywords:
Parametric simulation
Optimum insulation thickness
Building envelope optimisation
Proper Generalized Decomposition

ABSTRACT

In this paper, an innovative method to minimise energy losses through building envelopes is presented, using the Proper Generalised Decomposition (PGD), written in terms of space x, time t, thermal diffusivity α and envelope thickness L. The physical phenomenon is solved at once, contrarily to classical numerical methods that cannot create a parameter dependent model. First, the PGD solution is validated with an analytical solution to prove its accuracy. Then a complex case study of a multi-layer wall submitted to transient boundary conditions is investigated. The parametric solution is computed as a function of the space and time coordinates, as well as the thermal insulation thickness and the load material thermal diffusivity. Physical behaviour and conduction loads are analysed for 76 values of thermal insulation thickness and 100 types of load material properties. Furthermore, the reduced computational cost of the PGD is highlighted. The method computes the solution 100 times faster than standard numerical approaches. In addition, the PGD solution has a low storage cost, providing interesting development of parametric solutions for real-time applications of energy management in buildings.

1. Introduction

The current energy and environmental issues lead to focus on the building sector as it represents almost 33% of the world global energy consumption and about 20% of the CO_2 emissions [1]. On the other hand, the building stock increases slowly. For instance, in France, the average growth is around 1% [2]. Thus, the issues related to energy efficiency in existing buildings are primordial. Different tools have been developed since the past decades for the precise assessment of building energy efficiency. The Annex 41 [3] of the International Energy Agency reported on most detailed wall models and their successful applications for engineering, expertise or research purposes.

However, challenging problems appear from practical applications of whole building energy performance assessment. Consider for instance the investigation of the building energy efficiency as a function of different parameters such as insulation properties, size and orientation of windows, performance of HVAC equipment or geometric configurations and location of the building, among others. In the context of environmental issues and thermal regulations, the building energy efficiency might be optimised as a function of those parameters.

Several studies of parametric simulations are presented in the literature. In [4], the influence of wall thermal inertia on the energy consumption was investigated by using the EnergyPlus program for 24 construction types. In [5], a probabilistic approach combined with EnergyPlus simulations is used to analyse the influence of building parameters as thermal insulation on the energy consumption and thermal comfort, running about 200 simulations for the

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http://dx.doi.org/10.1016/j.apenergy.2016.12.119

Nomenclature

Latin letters

c	specific heat (J/kg/K)
h	convective heat transfer coefficient (W/m^2/K)
L	length (m)
T	temperature (K)
E	conduction loads (W h/m^2)
k	thermal conductivity (W/m/K)
q	heat flux (W/m^2)
t	time (h)

Greek letters

α	thermal diffusivity (m^2/s)
ρ	density (kg/m^3)
β	solar absorptivity (–)

investigation. In [6–12], numerical methods are used to determine the optimum insulation thickness of different wall configurations.

Those parametric simulations are based on models using numerical methods due to almost no restriction in terms of boundary conditions, geometry, material properties, among other considerations. Nevertheless, for parametric studies, they require a large numbers of simulations. Indeed, the numerical model is not dependent on parameters of interest. Thus, a computation of the numerical model is required for each value of the parameters within their domain of variation, demanding a high calculation cost, even after the dramatic evolution of computer hardware since the 70's. As reported in [13,14], numerical models are replaced by analytical approaches to determine wall optimum insulation thickness, in order to reduce the computational cost. Other works report the use of lumped models, based on a degree-day approach such as the one presented in [15]. Simplified models based on regression techniques from dynamic models are adopted in [16,17]. All those approaches using analytical solution are limited to simplified boundary conditions and are not applied to hourly boundary conditions based on weather data.

Parametric simulations to optimise building energy efficiency face important issues to reduce their computational cost. Therefore, innovative and efficient numerical methods are worth of investigation and model order reduction techniques appear as advantageous alternatives. This paper proposes to explore the use of the model reduction technique knozn as Proper Generalised Decomposition (PGD) to drastically reduce the computational cost of parametric simulations. As illustrated in other domains [18–20], the PGD method provides efficient, accurate and parameter dependent reduced order models. For instance, in [18,21,22], the heat transfer equation is solved only once as a function of any value of the thermal conductivity parameter. In [23], the Navier-Stokes formulation is solved considering different Reynolds numbers. In [24], epidemiology modelling is considered as a function of the initial conditions. In [25], some parametric analysis are reported treating the heat and moisture transfer phenomena and considering the hygrothermal properties as extra-coordinates. In [26], two different case studies were presented. The first one considers the dry-basis thermal conductivity as a coordinate of the problem. The second case study aims at optimising the insulation of a wall as a function of the vapour permeability of the material. The temperature and vapour pressure are calculated as a function of those coordinates for each case. Parametric multizone problems have been addressed with the PGD method in [27], in terms of mould growth risk and thermal comfort, for different climates and different ventilation rates. Nevertheless, no geometric configuration was integrated in those parametric models.

In this study, the method is applied for the solution of parametric heat transfer problem as a function of wall diffusivity and insulation thickness. A parametric solution, depending on usual space and time coordinates as well as diffusivity and thickness parameters, is computed. After stating the physical problem, the PGD method is presented and its accuracy validated by means of comparison to an analytical solution. Then, the thermal behaviour of a multi-layer wall is analysed as a function of both load material diffusivity and thermal insulation thickness. The computational cost, the accuracy and the numerical efficiency of the PGD solution are analysed and discussed.

2. Physical problem and mathematical formulation

The physical problem involves the transient heat conduction through a wall of thickness L for a time interval $\Omega_t =]0, \tau]$ [28,29]:

$$\frac{\partial T}{\partial t} - \frac{1}{L^2}\nabla \cdot (\alpha \nabla T) = 0 \quad x \in [0,1], t \in \Omega_t \tag{1}$$

The initial temperature is supposed uniform and equal to T_0:

$$T = T_0 \quad x \in [0,1], t = 0 \tag{2}$$

Robin boundary conditions are considered at the bounding surfaces of the wall, with subscript ∞ denoting the reference temperature of the ambient air:

$$-\frac{k}{L}\nabla T \cdot \mathbf{n}_1 = h_o(T - T_{\infty,o}) + \beta q_o \quad x = 0,\ t > 0 \tag{3a}$$

$$\frac{k}{L}\nabla T \cdot \mathbf{n}_2 = h_i(T - T_{\infty,i}) + q_i \quad x = 1,\ t > 0 \tag{3b}$$

where $\alpha = \frac{k}{c}$ is the thermal diffusivity of the material, k, the thermal conductivity, c, the volumetric heat capacity (corresponding to the product between the specific heat and the volumetric mass), h, the convective heat transfer coefficient, β, the solar absorptivity of the outdoor wall surface and q, the incident heat flux. All the thermophysical properties are supposed constant. The boundary $x = 0$ represents the external surface, submitted to outdoor boundary conditions, while at boundary $x = 1$ the wall internal surface.

The objective is to reduce the wall conduction load E computed by integrating the heat flux at the inner surface ($x = 1$) over the time [30]:

$$E_{d,m,y} = \int_t h_i(T_{\infty,1}(t) - T(x = 1, t))\mathrm{d}t \tag{4}$$

Subscripts d, m and y of the conduction load E denote for a time integration period of a day, a month or a year, respectively.

A parametric simulation can be formulated by optimising the conduction load E as a function of parameters as the thermal insulation thickness L and the wall diffusivity α. The issue herein is therefore to compute E, or more precisely $T(x = 1, t)$, obtained by the solution of problem (1), for all values of parameters α and L in given intervals within the Ω_α and Ω_L domains, at a reduced numerical cost.