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A new analytical approach for simplified thermal modelling of buildings: Self-Adjusting RC-network model

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ABSTRACT

A novel method for adjusting the parameters of a lumped parameter model for the transient thermal response of building constructions is presented. Previous analytical adjustment methods can be complex and inaccurate, while optimization algorithms, although more accurate, require prior simulation using a high-order reference model, and so provide no advantages to be integrated into simulation programs. This work presents a methodology for the analytical adjustment of a first-order model based on the hypothesis that the position of the capacitance varies in every time step in response to changes in the excitation value. By comparison with a reference model and using a wide range of constructions (420), the functional form of this dependence was determined in accordance with the value of time step and properties and thickness of the element. Using different typical constructions (41), the method was validated by comparison with the reference model in terms of surface heat fluxes, surface temperatures and indoor air temperature. The results showed an excellent agreement with the reference model for surface temperatures and indoor air temperature, and good agreement for surface heat fluxes. The method can be integrated into simulation programs with a low computational cost, sufficient accuracy, universality and adaptable time step.

1. Introduction

The Finite Element Method and the Finite Difference Method are numerical methods that are extensively used to solve the partial differential equation that governs the conduction heat transfer through the construction elements of buildings, such as external walls, internal partitions, floors and roofs. Some building energy simulation programs, for example ESP-r [1,2], use the Finite Difference Method for calculating the transient thermal response of these elements. However, the computational cost of these methods is too high to be integrated into thermal simulation programs, so they are discarded by most developers. On the other hand, the Response Factor Method [3] or the Transfer Function Method [4] are the most used methods in building thermal simulation programs, such as EnergyPlus [5], TRNSYS [6] and others [7]. These methods are more efficient at calculating surface heat fluxes than the previous ones, because no knowledge is required of the temperature and heat flux distribution within the element. The Transfer Function Method [4] is based on the Response Factor Method [3], and allows the responses of the element to be obtained more efficiently. However, the solution become progressively more unstable as the simulation time step decreases. This is a problem in those cases requiring a short time step, such as those in which there is coupling with the HVAC systems and when the fabric dynamics can not be neglected. This problem can be partly resolved by using transfer function series obtained by means of the approximation of the heat equation by The Finite Difference Method [8,9]. However, using this solution involves a high computational cost, and there can still be difficulties with construction elements with a very high thermal capacity with time steps below 15 min. Another inherent drawback of the methods based on the transfer function is that the time step can not be changed during the simulation. For example, if the transfer function coefficients were obtained for a time step of one hour, the information about the surface temperatures and surface heat fluxes would be given equally every hour, with no possibility of obtaining this information at intermediate times. Some simulation programs, such as EnergyPlus [5], attempt this problem by using the 'Master history with interpolation' method [10].

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Nomenclature

A	Area (m^2)
C	Thermal capacity per unit area (J/m^2 K)
C_p	Specific heat (J/kg K)
e	Thickness (m)
Fo	Fourier number
h	Convection heat transfer coefficient (W/m^2 K)
k	Element constant (1/°C)
$\dot{m}$	Mass flow rate (kg/s)
n	Number of layers of the element
$\dot{Q}$	Heat transfer rate (W)
$\dot{q}$	Heat flux (W/m^2)
R	Thermal resistance (m^2 K/W)
T	Temperature (°C)
t	Simulation time (s)
x	Distance (m)

Greek letters

α	Thermal diffusivity (m^2/s)
Δt	Simulation time step (s)
θ	Temperature increment (°C)
λ	Thermal conductivity (W/m K)
ρ	Density (kg/m^3)
τ	Thermal time (s)

Subscripts and superscripts

°	Universal
*	Referred to capacitance node
1	Referred to surface 1 of the element
2	Referred to surface 2 of the element
a	Air
e	Element
eq	Equivalent
ext	External
hom	Homogeneous
i	Element surface index number
int	Internal
j	Element surface index number
l	layer index number of the element
o	Overall
s	Surface

In this method, the surface temperature and heat flux histories at intermediate instants of time are obtained by interpolation.

Unlike previous methods, lumped parameter methods for modelling the transient thermal response of construction elements of buildings offer simplicity and allow stable simulations in short time steps with a low computational cost, making them advantageous in comparison with detailed or high-order methods for their integration in building energy simulation programs or urban microclimate simulation programs.

Laret [11] and Lorenz and Masy [12] were the first authors to propose a simplified approach to modelling the thermal response of construction elements of buildings based on a first-order lumped parameter model composed of two resistances and one capacitance. Gouda et al. [13] proposed a second-order model in which each construction element is modelled using three resistances and two capacitances. Fraisse et al. [14] went further and developed a fourth-order model by adding to the second-order model (the latter referred to as a '3R2C' model) one capacitance on each surface of the element. The resulting model with three resistances and four capacitances was referred to as a '3R4C' model. Lumped parameter methods can also be applied for modelling the whole zone instead of individual construction elements [15–20]. In this approach, all the thermal capacities of the different construction elements that the zone is composed of (essentially, the higher thermal capacity elements, i.e. external walls, floors, etc.) are concentrated in a single equivalent capacitance, and another additional capacitance is added for the air of the zone (and internal furnishings). Thus, the result is a second-order model. Kämpf and Robinson [19] integrated an improved version of the model by Nielsen [18] in the CitySim [21] solver, a simulating program for urban planning inspired on its predecessor, SUNtool [22,23]. Another example of this approach is the hourly simplified method proposed by ISO 13790:2008 [24] for dynamic simulation of the evolution with time of the internal air and mean radiant temperatures of a building zone. This model, designed for simple and normative approach, is composed of five thermal resistances and one capacitance node representing the mass of the building zone (referred to as '5R1C' model). Although models based on this second approach offer great simplicity and very low computational cost, those based on the first approach provide more detailed and useful information for modelling (i.e. the surface temperatures of the individual elements forming the whole zone, which can be important for calculating the long wavelength radiation exchange), and maintain simplicity and a reduced computational cost. For this reason, this first approach is generally preferred to whole zone lumped parameter models.

However, the accuracy of these simplified models depends largely on the value of their characteristic parameters (resistances and capacitances), so they must be adjusted using a suitable method. Laret [11] proposed a simple analytical method for the division of the overall thermal resistance of the construction element between the two resistances of a first-order model by calculating a factor referred to as the 'accessibility factor'. However, the accuracy of this method is questionable in many situations, as observed by Gouda et al. [13]. Lorenz and Masy [12] and Fraisse et al. [14] proposed other analytical methods to obtain the value of the characteristic parameters of the model. However, these methods required complex mathematical models, so applying the model lost simplicity. In the case of Fraisse et al. [14], the step from a second-order model to a fourth-order one is somewhat arbitrary (the method involved transferring 5% from the two internal capacitances systematically to each of the surfaces of the element) and only one case of validation was presented. Ramallo-González et al. [25] presented an analytical method for generating a second-order lumped parameter model of multi-layered construction elements, which was built to be accurate in the range of the most significant frequencies of the inputs. On the other hand, Gouda et al. [13] used a method of optimization based on a single objective function search algorithm to determine the five free parameters of the second-order model by comparing the response with a high-order reference model. They compared first and second-order models and concluded that the latter were an improvement on the first as regards accuracy, and only required a small additional computational effort. However, their work was limited in several aspects, the main one being the fact that the characteristic parameters were adjusted using a unit step excitation on only one surface of the element. Later, Underwood [26] tried to overcome these limitations and proposed an improved method for adjusting the parameters of the second-order model proposed by Gouda et al. [13] based on a multiple objective function search algorithm that compared the response of the model with that obtained by a rigorous reference model. The end of the study included the value of the characteristic parameters of a wide group of typical construction elements. Crabb et al. [15] proposed a method based on that of Lorenz and Masy [12] for adjusting the resistances of a second-order lumped parameter model of the whole zone. However, the method provided unacceptable results for zones with elements with a very high thermal capacity. Tindale [16] tried to correct this by introducing a