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Prediction of the heat gain of external walls: An innovative approach for full-featured excitations based on the simplified method of Mackey-and-Wright

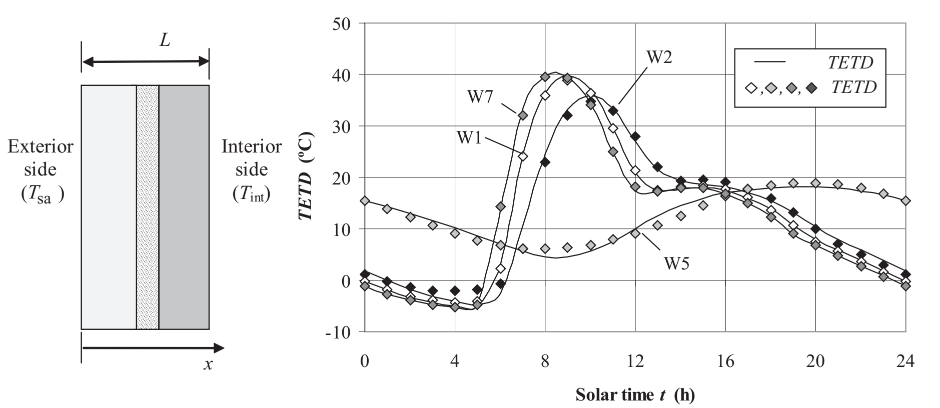
C.R. Ruivo [a,b,*], D.C. Vaz [c,d]

[a] Departamento de Engenharia Mecânica, Instituto Superior de Engenharia, Universidade do Algarve, Campus da Penha, 8005-139 Faro, Portugal
[b] ADAI-LAETA, Departamento de Engenharia Mecânica, Universidade de Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal
[c] UNIDEMI, Campus da Faculdade de Ciências e Tecnologia, 2829-516 Caparica, Portugal
[d] Departamento de Engenharia Mecânica e Industrial, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal

HIGHLIGHTS

- The transient thermal behaviour of external multilayer walls of buildings is studied.
- Reference results for four representative walls, obtained with a numerical model, are provided.
- Shortcomings of approaches based on the Mackey-and-Wright method are identified.
- Handling full-feature excitations with Fourier series decomposition improves accuracy.
- A simpler, yet accurate, promising novel approach to predict heat gain is proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Nowadays, simulation tools are available for calculating the thermal loads of multiple rooms of buildings, for given inputs. However, due to inaccuracies or uncertainties in some of the input data (e.g., thermal properties, air infiltrations flow rates, building occupancy), the evaluated thermal load may represent no more than just an estimate of the actual thermal load of the spaces. Accordingly, in certain practical situations, simplified methods may offer a more reasonable trade-off between effort and results accuracy than advanced software. Hence, despite the advances in computing power over the last decades, simplified methods for the evaluation of thermal loads are still of great interest nowadays, for both the practicing engineer and the graduating student, since these can be readily implemented or developed in common computational-tools, like a spreadsheet.

The method of Mackey and Wright (M&W) is a simplified method that upon values of the decrement factor and time lag of a wall (or roof) estimates the instantaneous rate of heat transfer through its indoor surface. It assumes cyclic behaviour and shows good accuracy when the excitation and response have matching shapes, but it involves non negligible error otherwise, for example, in the case of walls of high thermal inertia.

* Corresponding author at: Departamento de Engenharia Mecânica, Instituto Superior de Engenharia, Universidade do Algarve, Campus da Penha, 8005-139 Faro, Portugal. Tel.: +351 289 800100; fax: +351 289 888405.
E-mail address: cruivo@ualg.pt (C.R. Ruivo).

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The aim of this study is to develop a simplified procedure that considerably improves the accuracy of the M&W method, particularly for excitations that noticeably depart from the sinusoidal shape, while not introducing a need for an excessive volume of data or complexity in the production of results.

In the first simplified procedure discussed in the paper, a full-featured excitation is decomposed into a Fourier series and then the wall's thermal behaviour is reconstructed from the application of the M&W method to each of the N sinusoidal components. Even though this established approach can lead to the most accurate results, given a sufficiently high N, it requires the knowledge of the decrement factor and time lag associated to each component of the Fourier series, which can represent a considerable amount of data.

The chief result of the research though is a novel procedure based on a parameter, γ, that weigh-averages the approximate solution obtained by considering a single term Fourier decomposition of the excitation and the solution by considering the actual excitation. The procedure is more accurate than the original M&W method and will be of interest to researchers with the means of generating values of γ for the walls which the end users of their research are interested in. It provides promising results for walls ranging from massive to negligible mass. It has been noticed that while using the same values of γ that had been optimized for the wall facing east, acceptable results are also obtained when altered external excitations are imposed, namely due to intermittency of the direct solar radiation or due to a distinct value of the external heat transfer coefficient.

1. Introduction

In the scope of thermal comfort and energy efficiency in buildings, the designer or architect has to address a number of complex tasks such as: thermal behaviour assessment, sizing of the air conditioning system, evaluation of energy consumption by the air conditioning system, thermal comfort analysis and assessment of occurrence of condensation phenomena on the envelope. To simulate the dynamic thermal behaviour of buildings, dedicated software has been developed [1,2]. The simulation tools vary in complexity and in computational costs depending on the set of simplifying assumptions adopted in the analysis of phenomena occurring in buildings. For example, for a highly accurate evaluation of the thermal loads of an actual multi-room building, the behaviour of each room should be accurately described. While this is possible, to a certain extent, it involves sophisticated and computationally intensive software tools. However, even then, an exact result of the thermal load may be unattainable due to inaccuracies or uncertainty in some of the input data, for example in what regards variation of the thermal properties, flow rates of air infiltrations, and details of the actual occupancy and operation of the building. The uncertainties associated with the input parameters used in the calculation of thermal loads have been dealt with in several works, for example, using macro-parameters [3] and peak cooling load calculations [4].

From what has been said, it can be stated that the process of estimating thermal loads should always encompass a suitable engineering judgment of the results to take account of the uncertainties in the model inputs and the simplifying assumptions. Even if a sophisticated procedure is adopted, the evaluated thermal load will always be just an estimate of the actual thermal load. Accordingly, there are situations in which it is not worth to invest time in learning how to use advanced software and a more reasonable trade-off between effort and results accuracy can be obtained by using simplified approaches. For this reason, and despite the advance of computing power over the last decades, simplified methods for the evaluation of thermal loads are still of great interest nowadays, for both the practicing engineer and the graduating student. For example, Jaffal et al. [5] developed a fast model providing results with a good agreement with those predicted by TRNSYS [1].

One of the components of the thermal load is due to the heat transfer through the external walls and roofs of the room to be conditioned. While simplified models are often one-dimensional, they must, nevertheless, be transient in order to describe the dynamic behaviour of the building envelope as a result of the variation in time of the combined radiation and convection heat fluxes at the interior and/or the exterior faces of the envelope. The attenuation and delay of a heat wave depends on the material and thickness of the several layers composing the wall (or roof) it traverses. The time interval necessary for the heat wave to propagate from the exterior to the interior surfaces of the wall is defined as time lag. The attenuating parameter is named decrement factor, which depends on the ratio between the external and internal heat wave amplitudes.

There are a number of methods to estimate the thermal load due to heat transfer across a wall: numerical, transfer function, response factor, and harmonic methods. Numerical methods are based on a discretization along the wall thickness and along time, for example using finite-difference approximations of derivatives, to convert differential equations into sets of algebraic equations, to be solved after specification of boundary and initial conditions (e.g. [6–10]). The transfer function method is a quite user-friendly approach based on room transfer-functions and conduction transfer-functions, which are commonly derived from response factors and using pre-calculated conduction transfer-function coefficients that are available for a representative set of roofs and walls [11,12]. Nevertheless, the implementation of the transfer function method is not to the reach of all of those interested in an occasional and quick evaluation of the transient thermal load, and this is even more so in the case of numerical methods. The transfer function method requires the user to perform iterative calculations.

The response factor method [13] makes use of the superposition principle to calculate the response of a system (say, a room) from the knowledge of its unit response functions and the excitation function. Unit response functions are the response of the system to unit time-series excitations and need to be determined only once. The unit response functions thus integrate the pertinent thermal characteristics of the system whereas the excitation function depends on the characteristics of the external environment. This separation is one of the advantages of this method [13].

Harmonic methods adopt periodic boundary conditions that approximate the external excitation by a Fourier series with a reduced number of components (also called a trigonometric polynomial). Since the proposal of these methods by Mackey and Wright [11,12], several works have contributed to their enhancement [14]. In this context, Yumrutas et al. [15] have proposed an