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Estimation of thermal impulse response of a multi-layer building wall through in-situ experimental measurements in a dynamic regime with applications

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HIGHLIGHTS

- Thermal impulse response of a building wall is estimated using a novel computational approach.
- No prior knowledge of thermal properties or dimensions of a multi-layer building wall are needed.
- Only in-situ experimental measurements of surface temperatures and heat fluxes are required.
- Dynamic thermal characteristics of a multi-layered wall are obtained.
- Possible applications related to the energy performance of buildings are demonstrated.

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ABSTRACT

The dynamic thermal characteristics of the components of a building have a primary influence on the energy performance of the building's envelope under real environmental conditions. In this study, a novel approach for estimation of the thermal impulse response (TIR) functions and determination of the dynamic thermal characteristics of a multilayer façade wall with unknown thermal properties, structure, and dimensions is proposed. Unlike existing approaches, such as those presented by Luo et al. (2010) and Fernandes et al. (2015), which are based on the use of known physical parameters and dimensions of the considered structure for determination of the transfer function, the proposed framework is based solely on data from in-situ experimental measurements of surface temperatures and thermal fluxes through the inner and outer wall surfaces in a dynamic regime.

Consequently, the estimated TIR functions and dynamic thermal characteristics reflect the actual physical conditions of the considered building wall. The building wall is modelled as a two-input, two-output linear time-invariant (LTI) dynamic system where the surface temperatures and fluxes from both sides are used as system inputs and outputs, respectively. The input and output quantities are related by the convolution integrals and TIR functions. The TIR functions are obtained using the measured data and the least square estimator. As the corresponding system of linear equations is ill-posed, the Tikhonov regularization technique with a single parameter is implemented to overcome the numerical difficulties. The optimal regularization parameter is obtained using the L-curve approach. The estimated TIR functions are validated by comparison with the analytical solutions. The dynamic thermal characteristics of the considered building wall with unknown parameters are determined using the Fourier transform (FT) of the estimated TIR functions. The practical applications of the estimated TIR functions related to the energy performance of buildings (EPB) and energy efficiency, along with additional validation, are demonstrated by the evaluation of the dynamic thermal characteristics, cumulative heat losses, heat accumulation, conductive part of thermal transmittance (U-value), and surface heat fluxes, using only the estimated TIR functions and a control set of the experimental data.

1. Introduction

According to the International Energy Agency, over one-third of the world energy consumption is in the building sector [1,2]. Possible improvement and optimization of the building envelopes in relation to energy savings and energy consumption have become an active area of

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research in the recent period. The influence of 'green' building envelopes and the shadow effects of plants on energy savings have been considered in a study conducted by G. Pérez et al. [2]. A novel benchmarking analysis for energy performance by means of a linear mixed effect model has been developed by A. Capozzoli et al. [3]. The key findings, actions, and policy measures needed to improve the energy performance of the building envelope have been evaluated in a study conducted by the International Energy Agency. It has been shown that the optimization and improvement of the thermal performance of the building envelope are the key factors for reducing the energy demand [4].

Thus, existing buildings have a huge potential impact on future energy savings [5], and the reduction of energy consumption and improvement of the EPB are very important objectives from the energy efficiency point of view [6].

Among these aspects, the energy consumption in the building sector, together with the expected increase in the world's population, have a huge influence on environmental and sustainability issues, the economy, and the energy system [2]. In an analysis conducted by Zhang [7], it has been shown that policies related to mandatory efficiency improvement targets and electricity prices are significant drivers for improving the energy efficiency. Nevertheless, the economic strategy in the lighting technology and renewable energy sector related to environmental and sustainability issues have been considered in [8], and the possible economic impact on the energy sector through operations in the mineral industry could be analysed using the mathematical model from the study presented in [9].

In the engineering practice, an impulse response (IR) or Green function is a convenient representation of linear time-invariant (LTI) systems in the time domain, which compactly describes the relation between inputs and outputs of the system [10]. In a similar way, the transfer function (TF) completely describes the LTI dynamic system in the frequency domain [11]. A similar approach based on the conduction transfer function (CTF) [12,13] and the thermal response factors [14] has been used in heat conduction and energy calculations through a planar multi-layer wall in a dynamic regime, where the surface temperatures and heat fluxes from both sides of the wall are adapted as input and output quantities.

The CTF coefficients depend only on the physical properties and dimensions of the wall composite. Their usage enables the characterization of the dynamic thermal behaviour of the building walls [12,13]. Some of the developed methods are currently employed in building simulation software [15,16]. A variety of analytical and numerical approaches for solving either direct or inverse heat conduction problems based on the TIR or Green's functions have been reported. Fernandes et al. [10] proposed an analytical method for solving inverse heat conduction problems by employing the TF, where the surface heat flux is treated as the input of the system and the surface temperature as the output. Similarly, I. Simões et al. [11] computed the thermal delays for different multilayer systems by using Green's functions.

Among the other approaches, the Laplace transform has been widely used for thermal problems, such as analysis of composite structures with self-heating sensing films in temperature sensors [17,18], and for inverse problems related to indirect temperature measurements [19]. In order to solve the heat conduction problems, the formalism of thermal quadrupoles has been adopted [20].

The International Standard ISO 13786 [21] describes the thermal exchange in a steady periodic regime between the inside and outside wall surfaces using the TF in the frequency domain. This method is based on the work of Carslaw and Jaeger [22], who showed that the relationship between temperatures and heat fluxes on both sides of a building construction is linear in the case of sinusoidal temperature variations. This relationship is represented through the heat transfer matrix. The elements of this matrix are calculated based on the thermal and physical properties of the building composition layers. In the general case, the TF in the frequency domain for the N-layer planar structures cannot be converted to TIR functions in closed-form in the time domain, and this is one of the main disadvantages of the analysis in the frequency domain [22].

The thermal properties of a building envelope have a primary influence on the energy losses and the EPB. Owing to the influence of different physical and weather conditions, such as fluctuations in temperature, moisture content, solar radiation, and different atmospheric influences, the thermal parameters of the building wall composites are exposed to seasonal variations and natural deterioration [23,24]. Nevertheless, these parameters could be unknown in the case when the project documentation is missing or is unreliable (e.g., in historical and older buildings). This imposes limitations in the application of methods similar to the CTF and the procedure based on the ISO 13786 because both approaches require a prior knowledge on the thermal parameters, structure, and dimensions of the wall. Thus, the estimation of the EPB of building structures with unknown thermal parameters, structure, and dimensions, or considering the variation of theses parameters during the operational phase, is of practical interest for evaluation of the energy efficiency of buildings, including that in their maintenance phase [25].

The first objective of this study is the development of a novel numerical approach for the estimation of the TIR functions of a building wall using only in-situ measurements of surface temperatures and fluxes in a dynamic regime from both sides of a building wall, without a priori knowledge of the thermal properties and dimensions of the wall constituents. The entire estimation procedure is performed in the time domain, and the TIR functions are obtained using the least square estimator and the de-convolution technique.

In the general case of an LTI system, the input and output quantities are related by the convolution integral, where the IR characterize the system in the dynamic regime [10]. The de-convolution techniques belong to the class of the inverse problems [26,27], where the main aim of the whole procedure is to determine an unknown IR function or/and unknown input data. Problems where both the IR function and input quantities are unknown belong to the blind de-convolution [28], whereas techniques such as Wiener filtering or de-convolution based on the last square estimator, where only the IR function or input data are unknown, belong to the class of non-blind de-convolution [28,29]. The de-convolution procedure has been widely used in many practical applications, such as image processing related to astronomy surveys [30], acoustically detected bubble-collapse shock waves [31], and X-ray photoelectron spectroscopy [32].

In the de-convolution problems, a linear model leads to an integral equation of the first kind, where the measured input and output data are related by the convolution integral. In many cases, the de-convolution problems are inherently ill-posed in the sense that small changes in the measured data can cause arbitrarily large changes in the solution [28,29]. To overcome these numerical problems and to filter out the influence of the noise, some kind of regularisation procedure is needed. One of the widely used and good established regularisation methods is the Tikhonov regularisation, with one or more unknown regularisation parameters [33,34]. It has been utilized in a variety of practical applications related to electrical resistance tomography [35], image reconstruction for electrical capacitance tomography [36], or atmospheric inverse problems [37].

In the literature on regularisation, there are many different criteria for choosing the optimal regularisation parameters, such as the discrepancy principle [38], L-curve method [39,40], and generalized cross validation [41]. The Tikhonov regularisation with a single parameter has been adopted in this study [33,34]. The regularisation procedure aims to get an optimal regularisation parameter using the L-curve method owing to its robustness and numerical simplicity [40].

To the best knowledge of the authors, this is the first attempt to use in-situ measurements for identification of the TIR functions using deconvolution techniques of a multi-layer building wall with unknown thermal properties and structure. The estimated TIR functions are