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Inferring the thermal resistance and effective thermal mass distribution of a wall from in situ measurements to characterise heat transfer at both the interior and exterior surfaces

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ABSTRACT

The estimation of the thermophysical characteristics of building elements based on in situ monitoring enables their performance to be assessed for quality assurance and successful decision making in policy making, building design, construction and refurbishment. Two physically-informed lumped thermal mass models, together with Bayesian statistical analysis of temperature and heat flow measurements, are presented to derive estimates of the thermophysical properties of a wall. The development of a two thermal mass, three thermal resistance model (2TM) enabled the thermal structure of the wall to be investigated and related to the known physical structure of two heavy-weight walls of different construction: a solid brick wall and an aerated clay, plaster, woodfibre insulation and gypsum fibreboard wall. The 2TM model produced good match to the measured heat flux at both interior and exterior surfaces for both walls, unlike a one thermal mass model (1TM); Bayesian model comparison strongly supported the 2TM over the 1TM model to accurately describe the observed data. Characterisation of the thermal structure and performance of building elements prior to decision making in interventions will support the development of tailored solutions to maximise thermal comfort and minimise energy use through insulation, heating and cooling strategies.

1. Introduction

The thermophysical properties of the building envelope have been identified as key parameters in the determination and explanation of the energy performance of buildings and are widely used in models to predict the energy demand of the built stock [1–3]. However, a performance gap has been identified between the expected energy use of buildings and their measured energy use [4–6]. The origins of the performance gap are multi-layered and complex, involving issues such as occupant behaviour, technological performance, construction defects, and changes to the materials and design [5,7].

Deviation between the expected thermophysical performance of building elements from tabulated data and their measured performance has been identified as a significant issue in a number of studies [8–11]. Unlike the use of standard published values, the measurement and analysis of in situ data to infer thermophysical properties enables the environmental conditions the envelope is exposed to and its state of conservation, such as moisture accumulation, to be accounted for [8,12]. In situ measurement also facilitates the quality assessment of building construction and the assessment of the performance of building elements where the material properties and stratigraphy are not certain [13,14]. The impact of inhomogeneities in the structure, such as delamination and cracks [12,15], poor detailing, layout and/or workmanship [8,15], and thermal bridges [12] may also be better understood with in situ measurements.

In addition to contributing to the performance gap, the use of unrepresentative thermophysical characteristics may affect the proposed heating strategy of a building, the cost-effectiveness of energy-saving measures and the implementation of appropriate retrofitting strategies. Consequently, the evaluation of the actual thermophysical properties of the building stock from monitored data is widely considered advantageous compared to the use of tabulated data [16] both to minimise the performance gap and to improve the overall quality of the building process by feeding back the learnings into the system.

In situ measurements have been widely used in industry and academia to estimate the thermophysical properties of building elements [17–20]. However, the cost, time and expertise required

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Nomenclature

T_{int}, T_{ext}	measured internal and external surface temperature (°C)
$T^0_{\mathrm{C}_n}$	initial temperature of the nth lumped thermal mass (°C)
$Q_{\mathrm{m,in}}$, $Q_{\mathrm{m,out}}$	measured heat flux into and out of the internal and external surfaces ($\mathrm{Wm^{-2}}$)
$Q_{\mathrm{e,in}}$, $Q_{\mathrm{e,out}}$	estimated heat flux into and out of the internal and external surfaces ($\mathrm{Wm^{-2}}$)
S	complex Laplace variable representing the derivative operator
Z	time-shift operator
τ	sampling interval (*i.e.* the interval between measurements) (s)
R_n	n-th lumped thermal resistance (starting from the internal side) ($\mathrm{m^2KW^{-1}}$)
C_n	n-th lumped thermal mass (starting from the internal side) ($\mathrm{Jm^{-2}K^{-1}}$)
T_{C_n}	estimated temperature of the nth lumped thermal mass (°C)
θ	vector of the unknown parameters of the model
$\mathrm{P}(\theta\|D, H)$	posterior probability distribution, given the data D and the model H
$\mathrm{P}(D\|\theta, H)$	likelihood
$\mathrm{P}(\theta\|H)$	prior probability distribution
$\mathrm{P}(D\|H)$	evidence
ΔL_j	width of the uniform prior probability of the jth parameter
$\Phi_{\mathrm{e},\varepsilon}$, $\Phi_{\mathrm{m},\varepsilon}$	estimated and observed time series for the data stream ε
$\sigma_{\Phi,\varepsilon}$	standard deviation of a noise term affecting the measurements
$\delta^{\mathrm{r}}_{\Phi,\varepsilon}$, $\delta^{\mathrm{a}}_{\Phi,\varepsilon}$	relative and absolute uncertainty affecting the measurements
$\chi^2_\varepsilon(\theta, H)$	Chi-squared function for the data stream ε
A	inverse of the Hessian of the negative logarithm of the posterior at MAP

Superscripts

$p, p-1$	current and previous time step

Subscripts

1TM	single thermal mass model
2TM	two thermal mass model
MAP	maximum a posteriori estimation

to undertake high-quality in situ measurement and analysis is a barrier to the wider adoption of this method [21]. Several methods have been developed to estimate the thermophysical properties of buildings from monitoring campaigns (*e.g.*, [16,22–25]). The choice of method is generally dictated by the final purpose of the analysis, the available data, and the experience and expertise of the team; none of these methods can be considered the best in absolute terms [22]. The analysis may be undertaken by white-box methods, using models derived from first principles, or by inverse (or data-driven) methods matching our understanding of the system (*i.e.* the model) to the measured data using black- or grey-box models [26]. Black-box methods use statistical techniques to infer the relationships amongst the inputs and outputs and do not require any knowledge of the system; the parameters of the model do not have a direct physical interpretation [27]. Conversely, grey-box models combine the advantages of white- and black-box models by including physical knowledge in the statistical description of the system and its behaviour, using prior information of the relationships of its parameters [28], but can require the adoption of a large number of parameters.

This paper presents the development of a dynamic inverse grey-box method of estimating effective thermal mass, *U*-values and *R*-values, building on that presented in Biddulph et al. [13]. The method uses lumped thermal mass models to describe the heat transfer across the building element and Bayesian-based optimisation techniques to estimate the best set of model parameters, and includes detailed error analysis. This statistical framework provides the most probable value for the parameters, an estimate of their uncertainties, their probability distribution and correlations [13]. The method is non-destructive, in line with standard techniques [29], and requires limited knowledge about the materials and structure of the building element, which is essential for the robust study of different built forms where these parameters are often not well characterised.

The lumped thermal mass models adopted here enable the estimation of parameters with clear physical interpretation (*e.g.*, *R*-value and effective thermal mass), which can be subsequently used to gain useful insights into the thermophysical behaviour of the building and how this may be improved. Additionally, the short measurement campaigns required facilitate estimation of the response of the thermal properties of the building to changing conditions, such as wind and moisture. The use of interior and exterior heat flux measurements enable the inference of the thermal structure of the building element, and its response to heat flow out of and into the building. As such, the models are also scalable – more complex models may readily be implemented if corresponding data is available. Finally, this paper presents the use of Bayesian model comparison to select the model that best represents the recorded data. For this purpose we use the ratio of the evidences of the models tested [30, Chapter 28], which embodies the Occam's razor principle. The improved fit of more complicated models is offset against the increased prior space associated with the greater number of parameters. Unlike the likelihood ratio, this method does not require that the models tested are nested.

2. Case studies and monitoring campaign

Two solid walls of different construction have been studied using in situ monitoring and Bayesian statistical methods for the estimation of their thermophysical properties. The thermal resistance and mass of the two walls were explored by means of lumped thermal parameter models of different complexity, designed to provide a description of the heat transfer through the building element. Specifically, a single thermal mass model, as applied previously in [13] and now with an improved analysis method, and a two thermal mass model were implemented. The walls studied were expected to exhibit significantly different thermal performance: the first (OWall) was of brick construction and formed part of the external wall of an office building [50], whilst the second (TCWall) utilised aerated clay blocks and was located in a thermal chamber [51]. The two case studies and monitoring campaigns are discussed below.

2.1. Brick wall in an office building

The first case study (OWall) was a solid-brick wall located on the first floor above ground of an office building in central London (UK), oriented north-west-facing (327° between the normal to wall and north). The wall was 370 ± 7 mm thick, consisting of 20 ± 5 mm of plaster (expected to be lime) on the inside and 350 ± 5 mm of exposed solid brick masonry on the outside. The masonry depth