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Inferring the thermal resistance and effective thermal mass of a wall using frequent temperature and heat flux measurements

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ABSTRACT

Evaluating how much heat is lost through external walls is a key requirement for building energy simulators and is necessary for quality assurance and successful decision making in policy making and building design, construction and refurbishment. Heat loss can be estimated using the temperature differences between the inside and outside air and an estimate of the thermal transmittance (U-value) of the wall. Unfortunately the actual U-value may be different from those values obtained using assumptions about the materials, their properties and the structure of the wall after a cursory visual inspection.

In-situ monitoring using thermometers and heat flux plates enables more accurate characterisation of the thermal properties of walls in their context. However, standard practices require that the measurements are carried out in winter over a two-week period to significantly reduce the dynamic effects of the wall's thermal mass from the data.

A novel combination of a lumped thermal mass model, together with Bayesian statistical analysis is presented to derive estimates of the U-value and effective thermal mass. The method needs only a few days of measurements, provides an estimate of the effective thermal mass and could potentially be used in summer.

1. Introduction

Energy use in buildings accounts for approximately a third of global primary energy consumption [1], half of which is used for space heating and cooling and hot water production. Ambitious CO_2 reduction targets have been agreed internationally to mitigate climate change [2,3], such as the UK's commitment to reduce emissions by 80% from 1990 levels by 2050 [4]. Reducing emissions from the built environment will be an essential component of these strategies; forecasts show that the energy demand associated with building use may grow [1], but that aggressive policy actions could potentially reduce the energy needs for space heating and cooling by approximately 47%. Numerous models and software tools have been developed to simulate the performance and energy demand of the built environment [5]. Such simulations are used by policy makers to inform large-scale long-term strategies to cut energy consumption in the built environment [6], or by professionals to assess the energy performance of dwellings [7–9], and evaluate the cost-effectiveness of energy-saving measures during retrofitting or building design. However, some studies have revealed a lower than expected improvement in energy performance of the building envelope following retrofitting energy saving measures [10,11], with significant impact on the cost effectiveness of intervention.

The energy performance of the building envelope may be accurately estimated for well-characterised systems [10,12]. For walls, the required parameters include the thickness and in-situ thermal performance of their constituent layers, whilst inaccuracies in these quantities (e.g., thermal resistance and thermal mass) are a major source of uncertainty in the energy performance simulations [12]. However, accurate identification of appropriate thermal properties and thicknesses can be challenging for existing and new walls [12]. Tabulated values of thermal resistance and mass from the literature or software libraries are generally used, plus estimated thicknesses of the expected wall layers, following visual inspection. Significant inaccuracies can result from simulation outputs utilising published thermal values, as the range of thermal properties for visually similar materials can be large [13], for example the thermal conductivity of concrete ranges from 0.76 to 1.37 $W\,m^{-1}\,K^{-1}$ [14]. Similarly,

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Nomenclature

R, R_1, R_2	Thermal resistance or R-Value, $m^2\,K\,W^{-1}$
U-Value	Thermal transmittance ($=1/R_{Total}$), $W\,m^{-2}\,K^{-1}$
T_{mass}, T_{int}, T_{ext}	Temperature of the thermal mass, of the air near the interior and exterior of the surface of the wall respectively, °C
Q	Heat flow into the internal surface of the wall, $W\,m^{-2}$
C	Effective thermal mass of the wall, $J\,m^{-2}\,K^{-1}$
τ	Time step duration between successive recordings, s
p	Time step index number. Data recording index. -
$P()$	Probability distribution. -
H_i, D, I	Hypothesis (the ith hypothesis), Data and background Information. -
^{stat}, $^{sys\text{-}W}$, $^{sys\text{-}inst}$, $^{sys+stat}$	Indicates that the error is statistical; systematic due to wind and moisture; systematic due to instrumentation; systematic combined with statistical. -
σ_{W+TM}, σ_W, σ_{TM}	Uncertainty in the U-value due to wind, moisture and thermal mass; due to wind and moisture only; due to thermal mass only, $W\,m^{-2}\,K^{-1}$

estimating the internal structure of a wall by visual inspection, or from assumptions of the construction, introduces potentially significant error into energy performance estimates [15]. In addition to error in estimating the thickness of layers and their variability across a wall, uncertainties include inhomogeneities in the structure such as thermal bridges, gaps in the materials and delamination, air movement in cavities, moisture content, and local and seasonal environmental conditions [15–18].

Many errors associated with estimating thermal performance from published values and assumptions of wall structure may be avoided by utilising in-situ measurements to estimate the actual thermal properties of building elements. In-situ estimates of thermal performance may also form part of construction quality assurance procedures [15]. The measurement of heat flux and nearby air or surface temperatures can be used to estimate the effective thermal mass, thermal resistance (R-value), or equivalently, thermal transmittance (U-value) [19] of walls. The combination of the effective thermal mass, as opposed to the total thermal mass, and the thermal resistance is analogous to the complex internal thermal admittance as used in frequency domain analysis of walls [20]. Such techniques account for uncertainty in the thermal properties of elements of the wall, their thickness and state of conservation [15], but not of inhomogeneities in the wall construction.

The estimation of thermodynamic parameters (i.e. R-value and thermal mass) of real building elements from the analysis of in-situ measurements is not commonplace, but in recent years considerable interest has been shown in such in-situ performance characterisation [13,15,16,21]. However, steady-state methods [22] are time consuming, seasonally bounded [23] and aim to eliminate the effect of thermal mass, rather than characterise it; dynamic methods may be used to provide more insight into building performance, and may be applied in a wider range of conditions. Studies have been carried out in outdoor test cells to inform in-situ dynamic techniques through the PASSYS project and the PASLINK Network by investigating the thermal performance of well-known building components under real dynamic conditions [24]. These projects have improved testing procedures and the development of dynamic analysis methods for thermodynamic parameter prediction.

In this paper we propose a novel combination of a simple lumped thermal mass model and Bayesian analysis that provides the opportunity for the wider use of real data to assess the performance of buildings in their environment and the impact of interventions. The use of lumped capacitance models to infer thermodynamic properties of building elements is not new in the field [25,26]. However, the proposed analysis technique provides some advantages. Firstly, a significantly shorter measurement campaign may be possible in many conditions. Secondly, because Bayesian analysis is used throughout, the statistical evidence for different models of heat flow may be compared. The method also provides estimates of statistical uncertainties for the inferred parameters and accounts for relationships between them. Thirdly, it enables simultaneous characterisation of the effective thermal mass and the R-value of the element, which is not possible with conventional steady-state methods. Finally, the presented method utilises a simple model of the wall using only four unknown parameters, without the need for additional assumptions on the component's structure and performance, unlike many more complicated dynamic models [25,26]. These parameters may be fully characterised with the typically recorded time series of internal and external temperatures, plus heat flux on the inside face of the building component.

2. Case study and monitoring campaign

The dataset analysed in this paper was collected during the winter of 2010 by the Building Services Research and Information Association (BSRIA) as part of a study to investigate the U-values of walls in occupied domestic properties [21]. Walls at 93 different sites across England were monitored and were expected to be solid (with no cavity or insulation). Measurements were collected in accordance with ISO 9869:1994 [21,22]. Sensors were ideally placed on north-facing walls to exclude the impact of solar radiation on the external surface and away from internal sources of heat [21]. Moreover, sensors were usually placed with reference to structural features; however, sensor location was compromised in some cases for the convenience of the occupants [21]. The wall was instrumented with a heat flux meter (HFM) and thermistor temperature sensors [22]; the data were averaged over 5 minutes and recorded by Eltek 401 [27] data loggers. The HFM (Hukseflux HFP01 [28]) was placed on the inside surface of the wall. Silicon grease was used to achieve good thermal contact between the HFM and the wall surface, while a thin PVC film was applied to protect the wall surface. The thermistors were placed in the air near the internal and external surfaces of the wall. Internally the temperature sensor was placed as close as possible to the HFM. Surface mounted thermometers are often used to minimise deviations due to air movements and wind [29]. However, fixed estimates of the boundary layer resistances must then be incorporated into U-value calculation. Appropriately placed air temperature thermometers can be used to account for real environmental conditions adjacent to the wall and better reflect the real in-situ U-values.

The data presented in this paper comes from a single wall in a terraced house, which was typical of all the walls surveyed, it was approximately 300 mm thick and of brick construction. Measurements of the heat flux, Q, (Fig. 4) and air temperatures, T_{int} and T_{ext}, (Fig. 5) were made over a 14-day period in February 2010.

3. Theory and calculation

3.1. Conventional methods

3.1.1. Calculating the thermal properties using assumed material properties

Physical measurements of the individual components of the wall were not made during the survey, however a rough identification