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Static and dynamic thermal properties of construction components: A comparison in idealized and experimental conditions using lumped parameter models

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Abstract. The U values assumptions for construction components represent a significant source of uncertainty when estimating the energy performance of buildings. This uncertainty affects decision-making processes in multiple ways, from policy making to design of new and refurbished buildings. The correct estimation of both static (e.g. thermal transmittance) and dynamic thermal properties is crucial for quality assurance in building performance assessment. Further, while today many sophisticated simulators are available for building performance modelling, lumped parameter models can help reducing computational time for parametric simulation or optimization and enable inverse estimation of lumped thermal characteristics. A lumped parameter approach for construction components is proposed, for example, by the ISO 52016-1:2017 norm, introducing simplifications that are intrinsically dependent on component's stratigraphy. This approach complements ISO 13786:2017 norm method, which is limited to steady-state periodic temperature and heat flux boundary conditions. In this research we consider these two different approaches, detailed and lumped modelling, comparing them first in idealized conditions and then in experimental conditions to analyse the robustness of methods.

1. Introduction

The U values assumptions for construction components represent a significant source of uncertainty when estimating the energy performance of buildings [1]. This uncertainty affects decision making processes in multiple ways, from policy making to design of new and refurbished buildings [2], including aspect such as indoor environmental quality [3], technical systems sizing [4] but also critical issues such as long-term preservation of historical heritage buildings [5]. Indeed, performance should be monitored during building life cycle, for example by using indicators for heating and cooling systems [6, 7], electricity and interaction with the grid [8] and primary energy consumption [9], comparing also design phase estimates and operation data [10], to learn from feedback and reduce progressively the performance gap [11, 12]. Considering the present necessity of linking calculation methodologies that are applied for performance assessment in different phases of building life cycle, we report in this paper preliminary results from a test facility, following an experimental campaign on different pre-fabricated (structural and anti-seismic) opaque construction components for high-efficiency and low-cost development in the Mediterranean area. More specifically, the research presented is part of a more general activity focused on modelling approaches for simulation and inverse estimation (using reduced order models) that could be easily employed in probabilistic simulation strategies [13, 14], to investigate building technologies performance in terms of heat transfer [15], acoustics [16], as well as dynamic interaction with other innovative energy technologies [17, 18].

2. Methodology

Many sophisticated simulators are available today for building performance modelling, but a performance gap is generally observed empirically [11]. This gap between simulated and measured performance is due to the relevant uncertainties of the assumptions introduced in building performance assessment. Physical-statistical lumped parameter models can help reducing computational time in simulation (forward modelling) and enable also inverse parameter estimation (inverse modelling) [19]. In the recently introduce ISO 52016-1 standard [20] (which supersedes the consolidated ISO 13790) a lumped modelling approach for walls is proposed, with a classification based on walls' stratigraphy. This approach is part of the strategy of ISO 52000 framework [21] that retains and updates other standards, for example ISO 6946 for construction component stationary thermal performance, and ISO 13786 [22] for dynamic construction components thermal performance. The approach proposed at the normative level for building performance simulation (ISO 52016-1) is substantially similar, in principles, to research focused on lumped parameter modelling using resistance-capacitance (RC) analogy [23] and analytical calculations [24, 25]. The conversion of RC models in state-space form and then in time series is described in detail in recent literature [15, 26]. Further, the correct identification of the impact of thermal capacity of building fabric (ideally represented as a lumped capacitance) is a relevant research issue [27]. Finally, the use of reduced order models for building performance simulation is an active research field at present, with multiple possible applications [28].

3. Case study analysis

In this research we analyse two approaches, detailed and lumped parameters modelling, comparing them first in standard conditions and then in experimental conditions, considering the issues highlighted in Section 2. The experimental setup and the related lumped model are depicted in Figure 1.

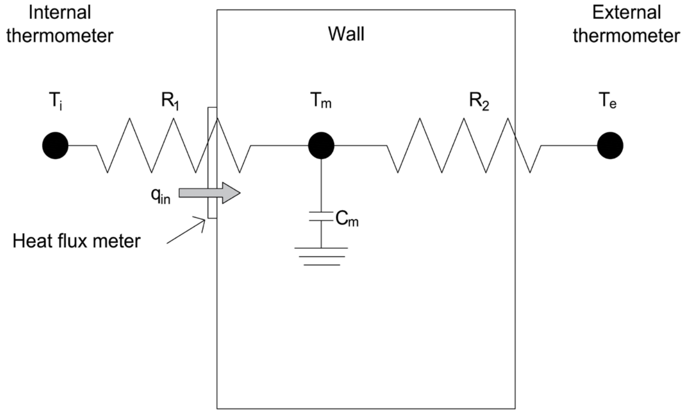

Figure 1. Experimental setup and simplified model considered for the analysis

The research is split into two parts, the first part, described in Section 3.1 involves the use of standardized calculation methodologies both for design (ISO 6946 [29], ISO 13786 [22]) and experimental activity (ISO 9869 [30]). The second part of the research, depicted in Section 3.2, is focused on testing a simplified time series model for the dynamic simulation of wall heat flux. The development of this model has been conducted starting from recent advances in the field [23, 26]. However, as outlined in Section 2, our goal was also to create a modelling formulation compatible with the ongoing normative evolution in building performance assessment (ISO 52016-1 [20]). Therefore, model formulation is defined as follows:

$$U = \frac{\sum_{t=0}^{n} q_{in,n}}{\sum_{t=0}^{n} \Delta T_{n}} = \frac{1}{\frac{1}{U_1} + \frac{1}{U_2}} = \frac{1}{R_1 + R_2} = \frac{1}{R} \tag{1}$$

$$C_m \frac{dT_m}{dt} = q_{in} - q_{out} \tag{2}$$

$$q_{in} = U_1 (T_1 - T_m) \tag{3}$$

$$q_{out} = U_2 (T_m - T_e) \tag{4}$$

$$C_m \frac{dT_m}{dt} = U_1 (T_1 - T_m) + U_2 (T_e - T_m) \tag{5}$$

$$T_{m,i+1} = T_{m,i} \left(1 - \left(\frac{U_1 \Delta t}{C_m} \right) - \left(\frac{U_2 \Delta t}{C_m} \right) \right) + \left(\frac{U_1 \Delta t}{C_m} \right) T_{i,i} + \left(\frac{U_2 \Delta t}{C_m} \right) T_{e,i} \tag{6}$$

where U (W/m^{2}K) is thermal transmittance experimentally determined using ISO 9869, q_{in} (W/m^2) is the heat flux entering in the lumped capacity of wall, q_{out} (W/m^2) is the heat flux exiting from the lumped capacity of wall, n is the number of data points, U_1 and U_2 (W/m^{2}K) are conductances on the internal and external side, R (m^{2}K/W) is the total resistance, R_1 and R_2 (m^{2}K/W) are thermal resistances on the internal and external side, T_i (°C) is internal air temperature, T_e (°C) is external air temperature, $\Delta T = T_i - T_e$, C_m (J/m^{2}K) is the lumped thermal capacity per unit of wall area, t (s) is time, i is a time index in the time series.

The time series model used for calculation (Equation 6) corresponds to the explicit discretization of Equation 5 in ARX (Autoregressive with Exogenous Input) form. Assumptions for the calculation of U_1 has been made considering the thermal mass lumped on the internal side, as prescribed by ISO 52016-1 for the specific stratigraphy of our component (with insulation on external layer). Further, the lumped thermal capacity C_m assumed in simulation (estimated from regression coefficients) is very near to the internal areal heat capacity k_1 calculated using ISO 13786, i.e. assuming sinusoidal periodic steady-state conditions. A detailed explanation on this assumption can be found in [26] and extensions in [31].

3.1. Initial research activity

As anticipated, the construction component tested is part of a test facility and has been design to adaptable in terms of insulation levels, for code compliance in different conditions. The stratigraphy of the component is reported in Table 1, where layers are defined from the internal to the external side.

Table 1. Summary of assumptions on thermo-physical properties of construction component in design phase (before experimental activity)

	Layers	Thickness (d)	Conductivity (λ)	Density (ρ)	Specific heat (c)
		[m]	[W/mK]	[kg/m3]	[J/kgK]
1	Internal coating	0.010	0.640	1500	1000
2	Lightweight brick	0.120	0.600	750	940
3	Reinforced concrete	0.160	1.800	2500	1000
4	EPS - thermal insulation	0.100	0.037	35	1480
5	External coating	0.010	0.640	1500	1000

Aggregated stationary (U) and dynamic ($|Y_{ie}|$, $|\Delta t_f|$, k_1) thermal properties have been calculated using data from Table 1 and ISO 6946 [29] and ISO 13786 [22] methodologies. The results are summarized in Table 2. In the same table, we compare the U value estimated in the design phase with the one determined experimentally following ISO 9869 [30] methodology. The initial estimate lays within the confidence interval of the experimental value.

Table 2. Result of performance calculation in design phase and experimental activity conducted using standard normative approaches

Phase	Technical standards	Thermal transmittance (U)	Periodic thermal transmittance ($\lvert Y_{ie} \rvert$)	Modulus of time lag of periodic thermal transmittance ($\lvert \Delta t_f \rvert$)	Internal areal heat capacity (k_1)
		[W/m²K]	[W/m²K]	[h]	[kJ/m²K]
Design	ISO 6496, ISO 13786	0.31	0.03	10.05	48.58
Experimental	ISO 9896	0.33 ± 0.03	-	-	-

3.2. Testing of simplified time series model for dynamic wall simulation

In this part of the research, the goal is simulating the dynamic behaviour with a simplified time series approach (Equation 6). Experimental (external and internal) air temperatures are presented in Figure 2.

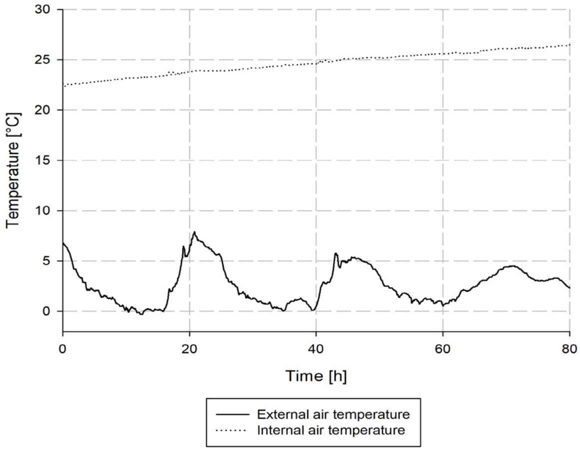

Figure 2. External and internal air temperature for the experiment

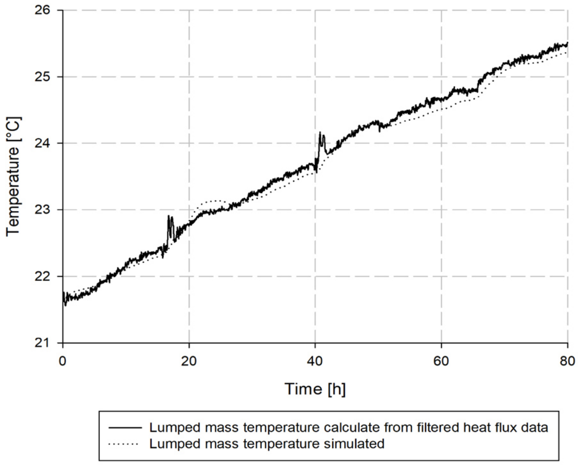

Figure 3. Lumped mass temperature calculated from measurements and simulated data

As it can be noticed in Figure 2, internal air temperature is kept steadily increasing in our experiment, and data are collected for 80 hours (the minimum suggested time span for applying ISO 9869 is 72h, i.e. 3 days of measurements) with a temporal resolution of 1.5 minutes. In Figure 3 we compare the temperature of lumped thermal mass simulated by means of time series model (Equation 6) and calculated from filtered heat flux data (more details on heat flux measurement filtering can be found in

[32]). The goodness of fit of the time series models proposed is high for the construction component considered in this experiment, essentially confirming the validity of the simplification adopted in ISO 52016-1 standard and in recent research work on dynamic thermal behaviour of walls. Further research is will be necessary to improve model fitting by reducing deviations and identifying patterns in time, using both time and frequency domain analysis.

4. Conclusion

This research aims to present a simplified time series based approach compatible both with dynamic performance simulation in design phase and inverse model parameter estimates in operation phase. In this case study we conducted our analysis on a pre-fabricated opaque construction component, which is part of a test facility. The approach proposed can be used potentially for other types of components which present a similar stratigraphy, following the classification given in ISO 52016-1. The methodology presented aims to trace a line of continuity between design phase simulation and operation phase analysis (in situ measurement in this specific case), including extensions to regression-based methods for overall building performance analysis. The continuity in the use of models as well as their comparability and ease of use are important factors to reduce the performance gap and to improve the ability to learn from technology evolution on continuous base. The approach tested is a simple analytical approach using linear algebra and regression and its performance can be improved by further research focused on the reduction of deviations and on the identification of patterns in time, using both time and frequency domain analysis. In any case, the goodness of fit of the time series models proposed is adequate for the level of accuracy normally considered in building performance simulation, essentially confirming the validity of the simplification adopted by ISO 52016-1 standard and by recent research work on dynamic thermal behaviour of walls.

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