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Co-heating test: A state-of-the-art

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ABSTRACT

Several studies have shown that the actual energy performance of buildings can differ significantly from its designed value. An important part of this performance is constituted by the building fabric's thermal performance. A common method to evaluate the latter for an actual building is the co-heating test. The co-heating test comprises a quasi-stationary heating experiment followed by linear regression analysis of aggregated building performance data. This paper reviews related research work and cristallises the current state-of-the-art. The physical phenomena working behind the scenes of the generally assumed simplified heat balance are discussed. Statistical constraints generally prevent these from being uncovered fully during the analysis. Multiple linear regression is proposed as the most sensible method to analyse co-heating measurement data. A novel way to visualise such analysis, deduce building performance data graphically and compare different co-heating test results is presented.

1. Introduction

In order to reduce the energy use of buildings, several countries have put forward more stringent demands on the energy performance of new buildings and renovated buildings. Without exception, these supervised buildings are characterised or awarded a label in the design phase: a theoretical energy use calculated on the basis of building plans and specifications determines the performance category. An important distinction needs to be made, however, between this theoretical energy performance and the actual as-built performance. Several studies have shown that these can differ significantly (Bell et al. [1], Lowe et al. [2]).

On a building scale, *energy signature* methods have been developed to keep score of the actual energy performance, for instance, PRISM (Fels [3], Kissock et al. [4]), and to simulate building energy consumption based on short-term experiments, as for instance, proposed in the STEM/PSTAR test methodology (Subbarao et al. [5], Palmer et al. [6]). The actual building energy performance, however, depends on many factors. Essentially, it is determined by the (1) thermal characteristics of the building envelope, (2) installed services and (3) building usage. As the latter is not easily controlled, the first two are decisive in achieving the envisaged building energy performance. Hence, thermal performance characterisation of building envelopes on the basis of real performance data represents a crucial first step towards bridging the gap between *designed* and *as-built* energy performance of buildings.

The thermal performance of building fabric components can be evaluated directly on site, but also from tailored and well-equipped test cells or from full-grown test facilities where on site conditions are easily replicated. For instance, the European PASSYS project and subsequent PASLINK Network set out to extract thermal performance characteristics of building components from test cell heating experiments (Baker and van Dijk [7]). A clear overview on tailored test facilities can be found in Janssens et al. [8].

In this paper, we focus on whole building fabric performance assessment. Hence, we look at the aggregated performance of its components. A common method to evaluate this is the co-heating test. This test essentially represents a *quasi-stationary test method* based on *linear regression analysis of aggregated building performance data*, acquired during appropriate heating experiments. During a co-heating test, the investigated dwelling is homogeneously heated to an elevated steady-state interior temperature, e.g. 25 °C, using electric heaters and ventilator fans scattered throughout the building. The electrical energy use, the indoor and outdoor air temperatures and relative humidities, wind speed and direction, and finally solar radiation are monitored throughout the test. The influence of transient effects induced by charging and discharging of the building's thermal mass can be reduced by sensibly choosing the experiment period and averaging the collected measurement data over a sufficient time span. Using *regression analysis*, the monitored indoor and outdoor conditions are related to the electrical heating energy needed to sustain a constant indoor air temperature. The coefficients describing this relationship

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represent building thermal performance characteristics of interest: the total *heat loss coefficient* (*HLC*), in *W/K* and one or more characteristics relating the heating energy to, e.g. solar radiation. The total *HLC* constitutes a combined transmission and ventilation heat loss. To decouple both, a co-heating test is generally combined with a blowerdoor or tracer gas test.

The development of the co-heating test methodology began in late 1970s, with Sonderegger and Modera [9] and Sonderegger [10], where it was originally applied to determine the efficiency of duct heating and cooling systems, in-situ and under realistic boundary conditions. In order to do so, real full-scale dwellings were alternately heated using the building's own services and electric heaters with known efficiency. Hence the name *co-heating*. Ever since its conception, however, the co-heating test method has also been used to estimate thermal characteristics of the building envelope, e.g. overall heat loss coefficient and solar aperture (Deconinck and Leunis [11], Bell et al. [1], Lowe et al. [2], Bauwens et al. [12]), and to localise heating loads (Sonderegger and Modera [9]).

In this paper, we cristallise the current state-of-the-art of the co-heating test, as it is applied to assess the thermal characteristics of building envelopes. Focus lies more on the data analysis methodology, rather than on experimental setup and data acquisition. Evidently, we drew considerable inspiration from literature discussed in the paper's first main section, where a brief history of the co-heating test is unfolded. For reasons of clarity, we rewrote the formulas developed in the presented research to conform to the nomenclature adopted in this paper and specified in Tables 1 and 2. The co-heating test methodology is defined in Section 3. After briefly sketching the actual experiment and its setup, we dig deeper into the building's heat balance. We uncover physical phenomena that work behind the scenes as the co-heating test unfolds. Phenomena that are often neglected in related research work. In a final step, simplifications typically applied in the analysis are discussed.

2. A brief history

To our knowledge, the first building performance assessments using thermostatically controlled portable electric heaters spread throughout an investigated building are presented in Sonderegger and Modera [9] and Sonderegger [10]. Here, real full-scale dwellings are alternately heated using the building's own services and electric heaters: in the initial and final stages of the experiment, the building's heating demand is covered solely by the latter; in an intermediate stage, the former serves to cover part of this demand. Hence the name *co-heating*. As such, the co-heating test was shown to offer a full range of possible assessment results. First, the decrease in electricity used by the electric heaters during service operation allows for an assessment of the latter's efficiency under realistic conditions. It could similarly be used to determine efficiencies of cooling systems. Secondly, as evident from Eq. (1), by dividing averages of the electric heating energy Q_h delivered to the building, by averages of the indoor–outdoor air temperature difference ΔT, the method results in a characterisation of the building envelope performance, under the form of an *overall heat loss coefficient (HLC)*, a parameter of particular interest in this paper.

$$Q_h = HLC\Delta T \tag{1}$$

Lastly, by monitoring the dispersed electric heaters individually and allowing for individual thermostatic control, heat loss contributions from building zones can be separated. An application which Sonderegger and Modera [9] refer to as *load localisation*.

The *HLC* in Eq. (1) was identified to comprise two heat loss mechanisms: (1) transmission heat loss $\sum AU$ and (2) ventilation heat loss c_aG_a, both in *W/K*. To disaggregate the *HLC* into its parts, co-heating experiments are generally accompanied by blowerdoor or tracer gas tests to assess the actual air change rate occurring during the experiment. The air change rate is then often assumed constant over the test period.

$$Q_h = (\sum AU + c_aG_a)\Delta T \tag{2}$$

Table 1
Nomenclature.

Measured variables	Symbol	Unit
Heat flows towards states *k*	$\mathbf{Q}_k$	W
Heat flow towards indoor air	Q_i	W
Electric heating energy	Q_h	W
Direct and indirect solar gains through transparant fabric parts	Q_{sw}	W
Equivalent transmission heat loss through building fabric	$Q_{tr,eq}$	W
Total ventilation heat loss through building fabric	Q_v	W
Latent heat due to hygroscopic loading and unloading of building parts	Q_{latent}	W
Temperature states *k*	$\mathbf{T}_k$	K
Indoor air temperature	T_i	K
Outdoor air temperature	T_a	K
Indoor–outdoor air temperature difference	ΔT	K
Sky temperature	T_{sky}	K
Equivalent outdoor temperature corresponding to * and *j*	$T_{a,eq}^{*,j}$	K
Global solar radiation on *	$q_{sw,*}$	W/m^2
Ground floor heat loss	F	W
Parameters	Symbol	Unit
Overall heat loss coefficient	HLC	W/K
Transmission heat loss	$\sum AU$	W/K
Overall solar aperture coefficient	$A_{sw,*}$	m^2
Ventilation heat loss	c_aG_a	W/K
Heat capacity of air	c_a	J/(kgK)
Natural airflow through building fabric	G_a	kg/s
Density of air	ρ_a	kg/m
Air change rate at 50 *Pa*	n_{50}	h
Actual air change rate	n_{actual}	h
Air volume of dwelling	V	m^3
Latent heat of evaporation of water	h_w	J/(kgK)
Dry-out rate	G_{vP}	kg/s
Latent heat demand	c_{vP}	W
Heat capacities states *k*	$\mathbf{C}_k$	J/(kgK)
Heat capacity indoor air	C_i	J/(kgK)
System and measurement noise	$\mathbf{c}_k$	W
Constant heat loss term	c	W
Absorption factor fabric surface	$\alpha_{sw,j,*}$	–
Long-wave radiative heat exchange at fabric surface; assumed constant	$c_{lw,j,*}$	K
Heat transfer coefficient: *U*-value	U	W/(m^{2}K)
Surface area	A	m
Emissivity of fabric surface material	$e_{lw,j}$	–
Black body constant	C_b	W/(m^{2}K^4)
Angle radiation factor	$F_{sky,*}$	–
Temperature radiation factor	$F_{T,sky}$	–
Convective and radiative surface heat transfer coefficient, resp.	h_{ce},h_{re}	W/(m^{2}K)

Table 2
Nomenclature.

Abbrevations	Symbol	Unit
Surface orientation normal to solar radiation projections:		
when not specified	*	–
Horizontal	*H*	–
East	*E*	–
South	*S*	–
West	*W*	–
North	*N*	–
Building fabric part	*j*	–
Opaque fabric parts	*o*	–
Transparant fabric parts	*w*	–
Weighting factors	*a*, *b*	–