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Thermal performance of buildings - In situ testing of building test structures - Part 2: Steady-state data analysis for aggregate heat loss test

Thermische Leistung von Gebäuden - In-situ-Tests von Gebäudeteststrukturen - Teil 2: Steady-State-Datenanalyse für Gesamtwärmeverlusttest

Performance thermique des bâtiments - Mesurage in-situ de bâtiment d'essai - Partie 2 : Analyse des données en régime permanent pour le test de perte de chaleur globale

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European foreword

This document (prEN 17888-2:2022) has been prepared by Technical Committee CEN/TC 89 “Thermal performance of buildings and building components”, the secretariat of which is held by SIS.

This document is currently submitted to the CEN Enquiry.

Introduction

prEN 17888-1 describes a test methodology that enables the actual *in situ* building structure aggregate heat loss (building heat transfer coefficient) to be quantified. This test method is termed the aggregate heat loss test method. This document (Part 2) principally covers numerical methods based on steady-state linear regression techniques. The results obtained using these methods are only valid under the assumption that, in first approximation, the data can be described by these mathematical and physical laws. Statistical tests to check the validity of these assumptions are therefore given. It also results in the determination of an aggregate building heat transfer coefficient for the tested building, along with the uncertainty associated with this coefficient. Both the aggregate building heat transfer coefficient and its uncertainty can be calculated as an output of this document. The reporting format relating to the test data and the resulting analysis is also described.

This document is highly linked with prEN 17888-1 *Thermal performance of buildings — In situ testing of building test structures — Data collection for aggregate heat loss test* to which it applies exclusively. It is also complimentary to prEN 17887-1 *Thermal performance of buildings — In situ testing of completed buildings — Part 1: Data collection for aggregate heat loss test* which deals with newly built and existing buildings.

In first instance, real building co-heating tests and associated data analysis help on determining the global performance of the building that usually take advantage of free solar gains through well oriented glazing surfaces. In this case these solar gains are welcome and contribute in reducing the energy demand for heating of the building. Aggregate heat loss coefficient extracted from data analysis on such real building is then minimized by associated solar gains and may help to better understand the real energy demand of the studied building structure regarding weather conditions.

In second instance it is from interest (as example) to concentrate on aggregate thermal performance of opaque building structures, for more precisely undertake the analysis of the thermal response of the building structure linked to these same climatic patterns. For that purpose, direct solar gains through glazing surfaces are excluded of the study by testing preferatelly opaque structures. In most of the cases, in winter periods, solar gain through opaque insulated surfaces remain poor so that the energy demand for heating become mostly dependent on temperature difference between internal and external environments. Nevertheless, this also offers the opportunity to undertake *in situ* testing with the aim to evaluate efficiency of passive solar systems that would contribute to minimize the energy demand of the tested building structure.

This document describes the input data required to undertake the analysis, various statistical methods that can be used to analyse the data, the uncertainty associated with the measurements, and the reporting format.

Detailed requirements concerning the test procedure and the data recording are specified in prEN 17888-1.

1 Scope

This document specifies the steady-state data analysis methods to evaluate the data from 'the aggregate heat loss test method'. These analysis methods enable the actual *in situ* aggregate heat loss (building heat transfer coefficient) to be estimated.

NOTE The aggregate heat loss method is specified in prEN 17888-1:2022, *Thermal performance of buildings — In situ testing of building test structures — Part 1: Data collection for aggregate heat loss test.*

2 Normative references

There are no normative references in this document.

3 Terms, definitions and symbols

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at https://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1 Terms and definitions

3.1.1
aggregate heat transfer coefficient (H_{agg})
sum of the transmission (H_{tr}) and infiltration component of the ventilation heat transfer coefficient (H_{V}) based upon measurement according to this test standard

3.1.2
external (internal) temperature
temperature of the external (internal) air measured by external (internal) air temperature sensor

3.1.3
heat transfer coefficient (*H*)
heat flow rate divided by temperature difference between two environments; specifically used for heat transfer coefficient by transmission or ventilation

3.1.4
internal room temperature
air temperature measured at the geometric centre of the room

3.1.5
internal whole building temperature
mean air temperature of all of the measured internal room temperatures

3.1.6
solar heat gain
heat provided by solar radiation entering, directly or indirectly after absorption in building elements, into the building through windows, opaque walls and roofs, or passive solar devices such as sunspaces, transparent insulation and solar walls

3.1.7
temperature difference ΔT
difference between the internal whole building temperature and external air temperature

3.1.8
test set point internal temperature
internal whole building air temperature required to achieve the minimum ΔT for the duration of the test

3.1.9
transmission heat transfer coefficient (H_{tr})
heat flow rate due to thermal transmission through the fabric of a building, divided by the difference between the environment temperatures on either side of the construction

Note 1 to entry: to entry: By convention, if the heat is transferred between a conditioned space and the external environment, the sign is positive if the heat flow is from the space to outside (heat loss).

3.1.10
ventilation heat transfer coefficient (H_V)
heat flow rate due to air entering a conditioned space by infiltration or ventilation, divided by the temperature difference between the internal air and the supply air temperature

Note 1 to entry: The supply temperature for infiltration is equal to the external temperature.

Note 2 to entry: In this analysis, the intended ventilation component of the ventilation heat transfer coefficient (H_V) is typically omitted and only the infiltration component is included in the heat transfer coefficient (H), as intended ventilation routes are sealed during the test described within prEN 17888-1.

3.2 Symbols

Symbol	Description	Unit
Inputs for the regression analyses		
P_h	Electrical heating power	W
q_{sw}	Global solar flow (measured or calculated solar irradiance related to the south vertical wall or façade that is expected to receive the highest proportion of solar gains)	W/m²
T_i	Internal air temperature	K
T_e	External air temperature	K
ΔT	Temperature difference between the internal whole building and external air	K
Parameters		
H	Heat transfer coefficient (global, including losses by transmission and ventilation or air infiltration)	W/K
H_{agg}	Aggregate heat transfer coefficient	W/K
H_{tr}	Transmission heat transfer coefficient	W/K
H_V	Ventilation heat transfer coefficient	W/K

Symbol	Description	Unit
H_i	Internal gain coefficient	W/K
H_e	External gain coefficient	W/K
B_0	Bias term	W/K
A_{sw}	Equivalent solar aperture	m^2
θ	Vector of the parameters of the model	-
X	Explicative matrix of the model	-
Y	Vector of the explicated values of the model	-
Intermediary quantities		
B'_0	Intercept for the inverted linear regression	W/m^2
B'_1	Slope for the inverted linear regression	m^2
β^*_1	Dimensionless slope	-
A, H, d, λ_1,λ_2	Internal parameter	-
SF	Scale factor	-
λ	Lagrange weight coefficient	-
Common statistical notation		
r^2	Pearson correlation coefficient	-
r	Coefficient of determination	-
ε	Residuals of the model	W or W/K
SSR	Sum squared residuals	W^2 or W^2/K^2
$t^{n-1}_{1-\frac{\alpha}{2}}$	Student coefficient for a bilateral Student law with (n-2) freedom degrees	-
$F_{(\alpha;v_1;v_2)}$	Fisher coefficient for v_1 = 1 and α = 5 %, with v2 = (n-2) freedom degrees	-
n	Number of points used for the regression	-
$n_{sensors}$	Number of sensors deployed	-
$n_{party\ wall}$	Number of party walls	
Var(θ)	Variance-covariance matrix for the vector of parameters of the model	-
ACF	Autocorrelation function	-
Other index and notation		
B	Bolted: table, vector or matrix	-
B^T	Transposed B matrix	-

Symbol	Description	Unit
B^{-1}	Inverted B matrix	-
x*	Dimensionless	-
$\hat{X}$	Best estimate of the random variable X	-
$\overline{X}$	Average of the random variable X	-
Var(X)	Standard variance of the random variable X	-
Cov(X,Y)	Covariance between random variables X and Y	-
$s(\chi)$	Experimental standard deviation of the random variable X	-
u(χ)	Standard uncertainty of the X quantity	-
U(χ)	Enlarged uncertainty of the X quantity (with a 95 % bilateral confident interval)	-
k	Coverage factor used for expanded uncertainty (k = 2 for 95 % confidence interval)	-

4 General principle

The building aggregate heat loss analysis shall be calculated by the energy balance Formula (1), assuming that the heating power input (P_h) is balanced by thermal losses and solar radiation transfer:

$$P_h = H_{agg} \cdot \left(T_i - T_e\right) - A_{sw} \cdot q_{sw} \quad (1)$$

where

P_h	is the electrical energy supplied by heaters and dissipated by fans [W];
H_{agg}	is the aggregate heat transfer coefficient, which combines the transmission heat transfer coefficient and the infiltration component of the ventilation heat transfer coefficient [W/K];
T_i - T_e = ΔT	is the temperature difference between inside and outside air [K];
A_{sw}	is the solar aperture [m^2];
q_{sw}	is the measured or calculated solar irradiance [W/m^2].

The aggregate heat transfer coefficient H_{agg} and the solar aperture A_{sw} express the relationship between the electrical heating power P_h, q_{sw} and ΔT variables in the regression analysis.

The solar aperture is a parameter that describes the solar gains incident the building as a whole, including diffuse gains, direct gains through glazing of all orientations and those from solar radiation incident upon opaque elements. It can be read as a global solar aperture, which includes the influence of non-perpendicular incidence of solar radiation, geometry and orientation of the building structure (including possible shading), solar absorption at opaque surfaces, solar energy transmittance factor and glazing surface of the building envelope. A_{sw} can be estimated experimentally from the whole building aggregate heat loss test data.

The aggregate heat transfer coefficient H_{agg} can be identified as a mix between heat losses by transmission and, because ventilation openings are sealed during the test, the infiltration component of the ventilation through the envelope of the tested building, H_V.

$$H_{agg} = H_{tr} + H_v H = H_{tr} + H_v \quad (2)$$

The aggregate heat transfer coefficient may be deduced from quasi-steady-state measurements using the energy balance Formula (1). Assuming this energy balance model holds, several identification techniques, all based on linear regression methods, may be used to estimate the parameters of interest. Specifically, simple or multiple linear regression techniques can be applied on whole building aggregated heat loss test measurement data (time averaged data points for P_h, q_{SW} and ΔT).

5 Uncertainty

The accuracy, reproducibility and interpretation of heat transfer coefficient estimates are limited by several factors related to both experimental and statistical uncertainties. The margin of uncertainty in the building aggregated heat loss test results is associated with a number of limitations and sources of error listed in Annex A Attention shall be given to these limitations and sources of error listed in Annex A within both data collection and data analysis. Remaining uncertainty within estimates of the heat transfer coefficient shall then be estimated and stated alongside any results.

Two methods of estimating uncertainty are presented in this document:

a) experimental uncertainty shall be estimated based upon the GUM method (JCGM 100:2008) and may incorporate both Type A (statistical analysis of observations) and Type B (non-statistical analysis, e.g. prior knowledge, previous experiments etc.), providing a stated uncertainty for an estimate of the heat transfer coefficient. An example of this analysis is given in Annex B;

b) statistical uncertainty shall be estimated based on the residuals between best estimates and measured data points. Statistical uncertainty is defined in Annex B and shall be used to determine the most appropriate regression method. Statistical uncertainty may be combined with experimental uncertainty to provide an increased error estimate (8.5).

The heat transfer coefficient, H [W/K], the solar aperture A_{SW} [m^2], and associated uncertainties, shall be indicated in the report according to 8.7.

6 Input data

6.1 Raw data

The raw data set requires a minimum of 15 days of continuous recordings without gaps. Measurements in the raw data set shall be non-biased and meet these requirements:

— sensors shall be calibrated in order to correct constant error (non-biased sensors);

— measurements are representative of the physical parameter. For instance, internal temperature measurements shall be averaged from several non-biased temperature sensors in order to represent the spatial dispersion due to air stratification.

NOTE Requirements to reach these conditions are described in prEN 17888-1.

6.2 Irregularities and gaps in the data

An analysis of the raw data are key to reduce difficulties in the subsequent modelling and provide meaningful results. This analysis shall aim at pointing out unusual phenomena, so-called irregularities, as well as outliers, measurement errors and missing data. These issues are often introduced either in the experiment set-up, by the measuring apparatus, or the data handling. A list of often-encountered phenomena found in the raw data set that can introduce problems, such as nonlinearity and outliers in the modelling and estimation step, is given in Annex A.

It is firstly required to plot the raw data set (for all input variables) as a function of the time step as recorded in prEN 17888-1, in order to check for outliers, measurement errors, missing data and any potential irregularities.

NOTE Scatter plots of pairs of measurements like energy consumption vs temperature difference can also be insightful to show patterns and correlations between variables.

All these irregularities shall be removed from the raw data set. In the end, the quality of the remaining data set obtained (cleaned data set) shall be tested so that:

— in total, all irregularities shall not represent more than 10 % of the global amount of data;

— irregularities for each data input (i.e. T_i, T_e, q_{sw} and P_h) shall not represent more than 15 % each (i.e. no more than 15 % irregularities for T_i data set, even if there are no other irregularities for T_e, q_{sw} and P_h);

— time without data (or with irregularities) shall not exceed 50 min (based upon a 24-h aggregation period) or 4 % for the P_h measurement, as this will be measured as accumulated flow using an energy meter;

— time without data (or with irregularities) shall not exceed 3 h for T_i, T_e, and q_{sw} measurements. If any of the above irregularities are exceeded, then the test is deemed to be invalid.

Any irregularity removed shall be recorded in the report, along with a brief justification of the reasons for their removal (see 8.4).

6.3 Cleaning data

Often, the data recorded from the beginning of the test will need to be removed, as the dwelling will be in the process of being heated-up and the thermal mass charged. Once the thermal mass of the building has charged, the electrical energy input into the building should stabilize and only be influenced by external environmental conditions.

Any experimental overheating periods due to uncontrolled heat input from solar gains shall be excluded to maintain a constant mean internal temperature during the building heat loss test.

Irregularities on T_i, T_e, and q_{sw} shall be corrected by linear interpolations and recorded in the report, along with a brief justification of the reasons for correction and description of the interpolation method (see 8.4).

6.4 Filtering (averaging)

The effects of dynamic behaviour shall be minimized by low pass filtering the time series;, by resampling the time series - i.e. aggregating the measured data points into longer time intervals (e.g. 24 h). The appropriate resampling interval depends on how fast the building fabric responds to external environmental conditions: for insulated buildings, one-day (24-h) averages are usually appropriate, whereas for high performance (well-insulated or heavyweight) buildings a higher resampling interval may be needed.

The following procedure shall be undertaken to select an appropriate resampling interval:

a) start with a short resampling interval (i.e. 24-h averages), check averaged data (see 6.5) and apply statistical analysis (see Clause 7);

b) analyse residuals for autocorrelation and check that the cross-correlation to the inputs, especially to solar radiation, is not significant (see model validation step in Clause 7);

c) if residuals are not autocorrelated and there is no significant cross-correlation, stop the resampling and provide the results (see Clause 8);

d) if residuals are autocorrelated or there is significant cross-correlation, increase the resampling time by 24 h until white noise residuals are obtained (see 7.6);

e) the same averaging interval shall be used for all the signals.

It is important that an integer of 24 h is used to minimize bias from dynamic effects. Additionally, although a daily average using the time period 00:00 to 23:59 is common, a time period of 06:00 to 05:59 may be considered and is often more appropriate, as it allows more time for solar gains to remerge from the thermal mass of a tested building within the same aggregation period. Dawn-to-dawn or a similar interval may also be considered.

A simple check of raw 24-h total power input against average 24-h temperature difference across the valid test period can be useful as a check on the regression process itself, particularly when there is not a wide spread in data points.

If resampling is applied, the resampling interval shall be recorded in the report (see Clause 8).

6.5 Checking averaged data

Linear regression shall be applied only for “regular” groups of points after averaging over integer 24-h periods (i.e. not applied to data sets at shorter time intervals – e.g. 1-h data), meaning that outliers can be removed. Checking outliers is simpler by using Siviour analysis (even if not used to determine the parameters of interest in Clause 7). It is then required to plot, for each averaged data, Y as a function of X where:

$$X = \begin{bmatrix} \frac{q_{\mathrm{sw},1}}{\Delta T_1} \\ \cdots \\ \frac{q_{\mathrm{sw},n}}{\Delta T_n} \end{bmatrix} \quad \text{and} \quad Y = \begin{bmatrix} \frac{P_{\mathrm{h},1}}{\Delta T_1} \\ \cdots \\ \frac{P_{\mathrm{h},n}}{\Delta T_n} \end{bmatrix}$$

All outliers identified shall lead to the removal of the corresponding averaged data from the data set used for statistical analysis. The outlier removed shall be recorded in the report, along with a brief justification of the reasons for their removal (see Clause 8).

7 Data analysis

7.1 General

The parameters of interest shall be determined by applying simple or multiple linear regression techniques according to Table 1, based on the energy balance Formula (1).

Table 1 — Regression techniques

Linear regression technics	Description
Simple linear regression using the Siviour method (see 7.2)	This simple method of linear regression is driven by normalized measurement uncertainties on variables Y and X (see 7.2). There are three cases (see Annex C) where residuals are used to apply the least square method between experimental points and estimations: — the vertical distance; — the horizontal distance; — the orthogonal distance.
Multilinear regression (see 7.3)	Multiple regression is a more complex broader class of regression that encompasses linear and nonlinear regressions with multiple explanatory variables. Two options are proposed (see 7.3.1, Annex C): — biased energy balance model; — unbiased energy balance model. Although a unbiased energy balance model (e.g. zero intercept) may represent a simplification of real world processes, it is typically adopted over biased (non-zero intercept) models.

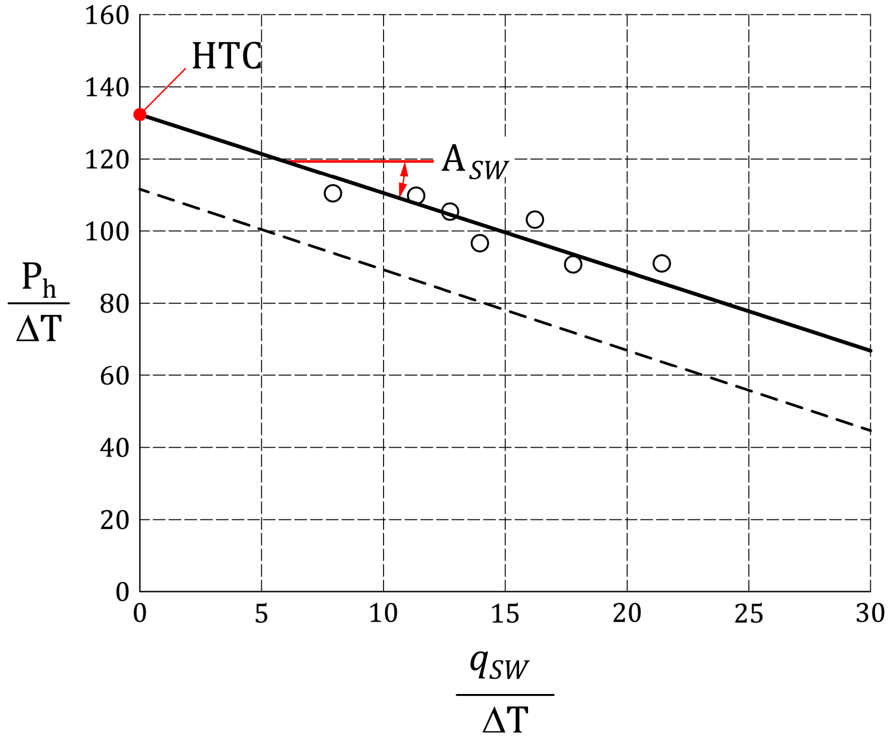
NOTE Methods to calculate and correct for solar gains based upon measured solar radiation and assumed building characteristics (e.g. glazed areas, g-values) are omitted from this document due to the significant uncertainty introduced by assumptions regarding building and glazing properties, alongside increased significance for accurate and complete solar radiation measurements.

Annex C provides information on the data analysis techniques required.

7.2 Simple linear regression using the Siviour method

The Siviour analysis of building heat loss test data shall be used to account for the effect of solar gains in the estimation of the aggregate heat transfer coefficient. The method consists of undertaking a linear regression of the electrical heating power, P_h, divided by the daily mean air temperature difference between the indoor and the external ambient ΔT (dependent variable), against the daily mean global solar irradiance q_{sw}, divided by the daily mean air temperature difference between the indoor and the external ambient ΔT (independent variable). From this analysis, the y-intercept of the regression line represents the aggregate heat transfer coefficient of the building, H [W/K], whilst its gradient is the equivalent solar aperture, A_{sw} [m^2], see Figure 1:

$$\frac{P_h}{\Delta T} = H_{agg} - A_{sw} \cdot \frac{q_{sw}}{\Delta T} \quad (3)$$



Key

○ data points

▬ linear regression through data points

▪ ▪ designed heat loss coefficients

Figure 1 — Example of linear regression analysis

7.3 Multiple linear regression (MLR) techniques

7.3.1 General

MLR can be carried out between the average electrical heating power P_h [W] and two independent variables, namely the temperature difference ΔT [K] and the solar irradiance q_{sw} [W/m^2]. This allows the aggregate heat loss coefficient H_{agg} [W] and the equivalent solar aperture A_{sw} [m^2] to be estimated through regression.

The energy balance model (Formula (1)) is based on the hypothesis that the daily energy balance is not biased. This means that when daily internal and external air temperatures are the same ($T_i = T_e$) and when there is no solar radiation ($q_{sw} = 0$), the daily heat power is assumed to be exactly zero.

It is important to note that Formula (1) represents a simplified energy balance model and not all real world effects are captured (see Annex A). Such effects may be represented by the introduction of a statistical bias or intercept term (B_0). In most cases, a bias term is unlikely to yield improved results and a un-biased, zero intercept model shall be used.

Biased, non-zero intercept model:

$$P_H = B_0 + H_{agg} \cdot \Delta T - A_{sw} \cdot q_{sw} \tag{4}$$

Un-biased ($B_0 = 0$), zero intercept model:

$$P_H = H_{agg} \cdot \Delta T - A_{sw} \cdot q_{sw} \tag{5}$$