Co-heating test – state-of-the-art and application challenges

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SUMMARY:
Several studies show that the actual 'as-built' thermal performance of the building envelope can differ significantly from the theoretical, calculated value. Characterisation of building envelope performances based on in situ dynamic measurements can help to bridge this gap between 'designed' and 'as-built' performances. A common method to evaluate the thermal performance of a building in situ is the co-heating test, which is a quasi-stationary method based on linear regression analysis of dynamic measurement data.

After a short state-of-the-art on the co-heating test methodology, the limitations and opportunities associated with the use of the co-heating test method to characterise the thermal performance of buildings are investigated on the basis of a real full-scale experiment: a co-heating test performed on a terraced house in Herstal, Belgium. Renovation induced drops in the overall heat loss coefficient of the dwellings are characterised by the test method and compared with calculated values.

1. Introduction

In order to reduce the energy use of buildings, several countries have put forward more stringent demands on energy performance of new 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 rather significantly (Bell et al. 2010, Lowe et al. 2007).

The energy performance of a building is essentially determined by the (1) thermal characteristics of the building envelope, (2) installed services and (3) building usage. As the latter is not easily predicted nor controlled, the first two are decisive in achieving the envisaged building energy performance, both for new buildings and renovations. Hence, the thermal performance characterisation of a building envelope represents a crucial first step to bridge the gap between its designed and as-built energy performance. A common method to evaluate the thermal performance of a building envelope in situ is the co-heating test.

To the knowledge of the authors, (Sonderegger and Modera 1979) is first to mention the use of thermostatically controlled electric heating experiments to assess a building's energy performance. 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 it's conception, the co-heating test method has been used to (Sonderegger and Modera 1979):

- assess thermal efficiency of the installed services, e.g. distribution efficiency of duct systems (Sonderegger and Modera 1979);
- estimate thermal characteristics of the building envelope, e.g. overall heat loss coefficient and solar aperture (Bell et al. 2010, Lowe et al. 2007, Bauwens et al. 2012);
- load localisation (Sonderegger and Modera 1979)

The method was further explored during the 1980's and applied sporadically throughout the 1990's. Several transient and steady-state derived test procedures were proposed along the way. Recently, renewed interest in the characterisation of the thermal performance of buildings (Roels 2011) is apparent and has brought about a revival and further development of the co-heating test method (Bauwens 2012).

This paper tries to crystallise the current state-of-the-art on the co-heating test, as it is applied to assess the thermal characteristics of the building envelope. The co-heating test methodology is defined, with a clear focus on its data analysis part: basic heat balances are set up and applied simplifications are discussed. The analysis procedure is applied to measurement data collected during a co-heating test performed on a terraced house in Herstal, Belgium. During the test period multiple renovation steps were performed, allowing to, aside from a benchmark characterisation, characterise the renovation induced improvement of the fabrics' thermal performance.

2. Co-heating test methodology

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. The electrical energy use necessary to retain this elevated temperature, the indoor and outdoor temperatures, wind speed and direction, and solar radiation are monitored throughout the test. Using regression analysis on averaged data, the monitored indoor and outdoor conditions are related to the electrical heating energy needed to sustain a constant indoor air temperature (Eq. 1(1).

$$Q_h + \sum(A_{sw,*}q_{sw,*}) = HLC(T_a - T_i) = HLC\Delta T \qquad (1)$$

where
Q_h energy supplied by heaters and dissipated by ventilators (*W*)
$A_{sw,*}$ solar aperture coefficient of surface * (m^2)
$q_{sw,*}$ global solar radiation, normal to surface orientation * (W/m^2)
HLC overall heat loss coefficient (*W/K*)
$T_a - T_i = \Delta T$ indoor –outdoor temperature differential (*K*)

The coefficients describing the stationary heat balance in Equation 1 represent building thermal performance characteristics of interest: the overall Heat Loss Coefficient (*HLC*), in W/K, and one or more characteristics relating the heating energy to e.g. solar radiation. The overall HLC, on its turn, constitutes a combined transmission and ventilation heat loss. To decouple both, a co-heating test can be combined with a building air leakage test, i.e. blowerdoor or tracer gas test.

Notwithstanding a stationary heat balance is assumed, the measurement data are intrinsically dynamic, due to weather conditions. To diminish thermal dynamics resulting from charging and discharging of the buildings' thermal mass, the experiment period needs to be chosen sensibly and the collected measurement data averaged over a sufficient time span (mostly days, but possibly also several days or weeks). Hence, the co-heating test essentially represents a quasi-stationary test method based on linear regression analysis of building performance data.

3. Co-heating test data analysis

3.1 Revisiting the stationary heat balance: applied simplifications

3.1.1 Correlation between solar radiation projections

As a consequence of practical and statistical issues, Equation 1 is challenging to solve. When considering measurement data averaged over a larger time span, for instance 1 day, the global solar radiation normal to different orientations * naturally exhibit a strong mutual correlation. For example, on a sunny day, we are likely to monitor, on average, high global solar radiation values, regardless of how our pyranometer is orentied. Hence, $q_{sw,*}$ are linear dependent vectors and factors $A_{sw,*}$ in Eq. 1 cannot be estimated separately. The stationary heat balance equation is simplified accordingly:

$$Q_h + \sum(A_{sw,*}q_{sw,*}) = Q_h + A_{sw,*}q_{sw,*} = HLC\Delta T \qquad (2)$$

where $A_{sw,*}$ now represents the solar aperture coefficient corresponding to the sole global solar radiation component selected as input. For instance, in a next section, measurements of global solar radiation on a horizontal surface, $q_{sw,hor}$, is selected.

3.1.2 Disaggregation of transmission and ventilation heat loss

As mentioned earlier, the overall heat loss coefficient *HLC* actually comprises transmission heat losses, $\sum(AU)$, and ventilation heat losses, c_aG_a, as illustrated in Equation 3. On the basis of a separate estimate of the actual air change rate occurring over the course of the measurement period (Bell et al. 2010), both can be decoupled. The actual air change rate can be estimated on the basis of a blowerdoor tests or tracer gas tests. The latter comes with greater accuracy, but also with greater cost.

$$Q_h + A_{sw,*}q_{sw,*} = HLC\ \Delta T = (\sum(AU) + c_aG_a)\ \Delta T \qquad (3)$$

where $\sum(AU)$ transmission heat loss (W/K);
c_aG_a ventilation heat loss (W/K)

The blowerdoor test yields an estimate of the air change rate occurring at a pressure difference inside-outside of 50 Pa (n_{50}-value). Evidently, this pressure difference is not representative for real scenarios. Using a rule of thumb, following Kronvall and Persily (Sherman 1987), the n_{50}-value can be related to the average actual air change rate taking place under real pressure difference scenarios: $n_{actual} = n_{50}/20$. The corresponding average ventilation heat loss, c_aG_a, can then be calculated as:

$$c_aG_a = c_a(1/3600)\rho_a n_{actual}V \approx (1/3)n_{50}/20 \qquad (4)$$

where ρ_a density of air (kg/m³)
V air volume of dwelling (m³)

3.2 Estimating parameters using linear regression analysis

Assuming the heat balance in Equation 3 to hold, the parameters of interest, framed in Eq. 5, are generally determined by applying simple or multiple linear regression techniques on co-heating measurement data:

$$Q_h = \boxed{HLC}\Delta T - \boxed{A_{sw,*}}q_{sw,*} + \boxed{c} \qquad (5)$$

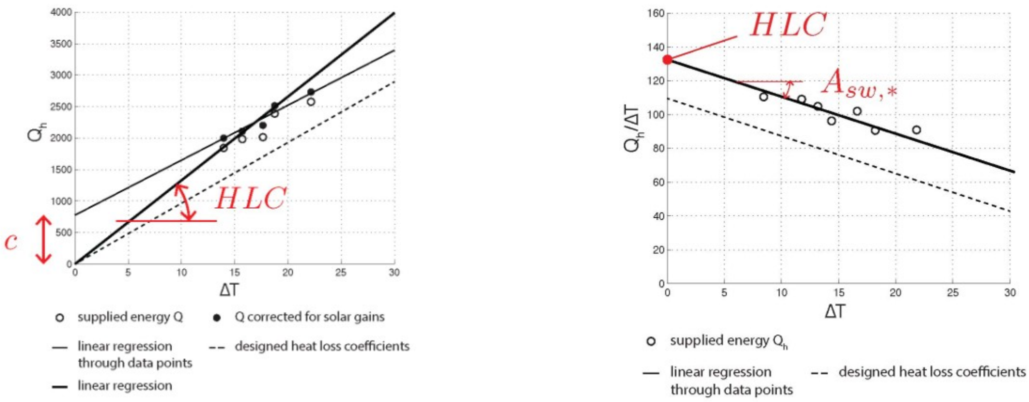
Where c describes the discrepancy between the regression model fit and the actual aggregated measurement data.

Essentially, three options can be discerned:

1. The energy supplied to the interior under the form of electrical energy can, on a daily average basis, be corrected for solar gains and plotted as a function of ΔT. This correction implies that an assumption is made for the solar aperture parameter $A_{sw,*}$. As illustrated in Fig. 1 (a), the slope of the regression line resulting from a simple linear regression on this corrected measurement data set yields an indication of the overall heat loss coefficient (Bell et al., 2010);
2. An alternative to the method described above is to, aside from ΔT, consider $q_{sw,*}$ as an additional independent variable explaining the variability of Q_h. Multiple regression techniques allow to determine both *HLC* and $A_{sw,*}$ in Eq. 5 (Lowe et al., 2007; Everett, 1985).
3. A third method is based on dividing all terms in Eq. 5 by ΔT. An equation is obtained on which a simple linear regression can be performed, assuming $Q_h/\Delta T$ as dependent variable and $q_{sw,*}/\Delta T$ as independent or explanatory variable, as in Eq. 6.

$$Q_h/\Delta T = \boxed{HLC} - \boxed{A_{sw,*}} q_{sw,*}/\Delta T \quad (6)$$

As illustrated in Figure 1 (b), an estimate of *HLC* is then given by the intercept. Note that this mathematical transformation implicitly forces the above described multiple linear regression through zero. In both of the earlier mentioned methods, a non-zero intercept is possible due to discrepancies between the measurement data and the assumed stationary model to which it is fitted. In the third method, these errors are included in the *HLC*-estimate.



(a) Simple linear regression

(b) Simple linear regression transformed equation

FIG 1. Estimation of HLC and $A_{sw,*}$ by applying simple linear regression

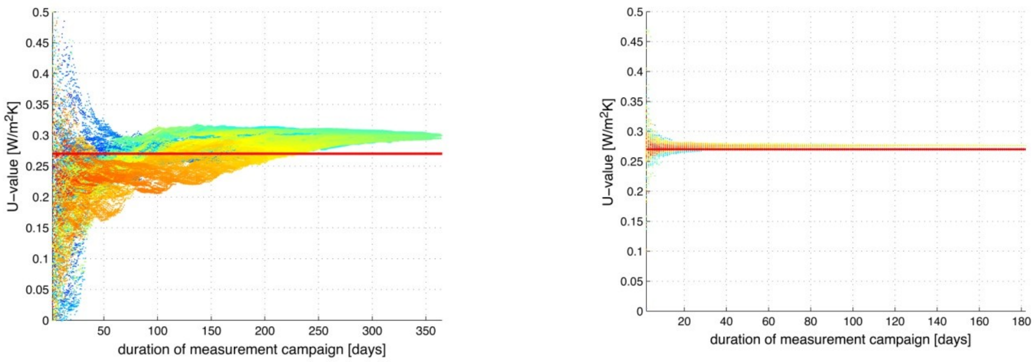
3.3 Thermal lag

From a harmonic analysis, it can be derived that the building fabric typically introduces a phase shift, between the internal heating power Q_h and the external temperature T_a and solar radiation $q_{sw,*}$. Due to this phase shift, ΔT at time t will not be representative for the needed energy supply Q_h at that time. To cope with this, Q_h at time t can be correlated with ΔT and/or $q_{sw,*}$ averaged over time step *t* and *t-1*:

$$Q_{h,t} = \boxed{HLC}\,(0.5\Delta T_t + 0.5\Delta T_{t-1}) - \boxed{A_{sw,*}}\,(0.5q_{sw,*,t} + 0.5q_{sw,*,t-1}) + \boxed{c} \quad (7)$$

3.4 Reliability of co-heating test methodology

Regardless of the effort made to diminish the transient effects introduced by weather conditions and the investigated buildings' thermal mass, stationarity will never fully hold during a co-heating test. Averaging measurement data and taking into account thermal lags, as described in Section 3.3, only partly addresses this issue. Hence, the estimates for HLC, $A_{sw,*}$ and possibly c, resulting from linear regression analysis are necessarily associated with a certain bias (e.g. if solar radiation is not taken into account) and error. In general, the reliability of co-heating test analysis results will depend on the investigated building, the imposed regression model and the period (start date and duration) in which the experiment is performed. To illustrate this, regression analysis can be performed on various subsets of the available co-heating measurement data, with each subset having a different starting date and a different duration. The reliability of the co-heating method can then be visualised by plotting the resulting collection of estimates. This is exemplified in Figure 2 (Bauwens et al. 2012). As the duration of the experiment increases, the regression result converges, hence the influence of the experiment starting date diminishes. For shorter measurement durations, however, the starting date is shown to be crucial. Fig. 2 (b) collects the results of applying multiple linear regression on measurement data, collected around winter. It can be seen that the results are generally reliable, and more so for high average Q_h monitored during the experiment.



(a) Basic multiple linear regression: ΔT as descriptive variables, thermal lag not taken into account, intercept c.

(b) Multiple linear regression when only considering winter months, ΔT and $q_{sw,*}$ as descriptive variables, taking into account thermal lags and forcing intercept through zero ($c = 0$).

FIG 2. U-value estimation through multiple linear regressions applied on data acquired during a simulated co-heating test on an insulated cavity wall component. Different subsets of the measurement data are considered: with different starting dates (vertically aligned points) and various durations (along the x-axis). The data points are coloured according to the average Q_h during the considered measurement data subset: red points indicate a high average Q_h, blue points indicate a low average Q_h.

FIG 3. Investigated terraced house in Herstal, Belgium. (a) Front façade; (b) Garden façade.

FIG 4. Co-heating test equipment: heat sources controlled by thermostats, ventilators, temperature sensors and pulse meters spread throughout the investigated dwelling. Sensor data (including weather station data) is transmitted to a central logger located on site.

4. Co-heating in practice: terraced house in Herstal, Belgium

From the 2nd of February to the beginning of May, an extensive co-heating measurement campaign was performed on a social row house in Herstal, north of Liège, Belgium. During the experiment, two renovation steps were executed:

- Renovation step 1: blowing in of insulation in the façade wall and party wall cavities and insulating the attic floor slab;
- Renovation step 2: insulating the floor above basement from underneath.

As depicted in Figure 4, the co-heating measurement equipment was fully deployed. A weather station was placed in the garden to monitor the outdoor air temperature, solar radiation, wind speed and wind direction. The indoor air temperatures in every room and the heat input necessary to elevate the indoor air temperature to 25°C were monitored throughout the test. Two blowerdoor tests were performed, before and after renovation step 1 (insulating wall cavities and attic floor slab).

4.1 Estimates of renovation induced performance improvement of fabric components

For verification purposes, the *U*-value reductions for the outside walls, cavity walls and ceilings are calculated on the basis of the applied insulation thicknesses and their respective λ-values (Table 1).

TABLE 1. Predicted thermal performance improvement induced by renovation step. d=thickness of applied insulation (cm); λ=heat conductivity (W/(mK)); R=thermal resistance (m^2K/W); hi = indoor surface heat transfer coefficient (W/m^2K), he=outdoor surface heat transfer coefficient (W/m^2K); U=heat transfer coefficient (W/m^2K), A=component surface (m^2).

	d (cm)	λ (W/mK)	h_i (W/m^2K)	h_e (W/m^2K)	ΔU (W/m^2K)	A (m^2)	$\Delta(UA)$ (W/K)
roof insulation	25	0.045	7.70	7.70	-2.00	40.32	-80.77
cavity wall insulation	5	0.034	7.70	23.00	-0.68	51.03	-34.94
party wall cavity insulation	5	0.034	7.70	7.70	-0.74	79.1	-58.40

Table 1 does not take into account certain aspects that could lead to an underestimation or overestimation of the corresponding reduction of the overall Heat Loss Coefficient *HLC*:

- Some areas of the cavity are not filled with insulation. The reason for this lies in the way the building was originally constructed. At the time of construction, it was common practice to close the cavity around the windows to facilitate installing and stabilising window frames. Where the cavity is closed no insulation will be added and thermal bridges are created. In other words, locally the thermal performance will not be improved. Other impurities in the cavity wall, e.g. interconnections of both masonry wall leafs, rubble in the cavity, …, further reduce the potential *HLC* reduction;
- The neighbours moved out shortly after the first renovation step, hence the party wall heat loss is expected to increase, leading to a possible overestimation.

4.2 Estimates of renovation induced HLC reduction

Figure 5 shows the *HLC*'s estimated on the basis of a multiple linear regression – Q_h as a function of ΔT and $q_{sw,hor}$, taking into account thermal lags and forcing the regression surface through the origin – applied on the co-heating measurement data before the renovation step, after renovation step 1 and after renovation step 2, respectively. Similar to Fig. 2, discussed in Section 3.4, different data subsets (different durations, different start dates) were considered in each case, effectively showing how the estimates for *HLC* converge towards the values reported in Table 2. As expected, renovation step 1, which included insulating the cavity walls and the attic floor slab, induces a far more significant reduction of the *HLC (*110.92 W/K) than renovation step 2, during which the floor slab above basement was insulated (reduction of 27.79 W/K). It is seen that renovation step 1 only attains about 63.7% of the projected performance improvement. On the basis of the aspects listed in Section 4.1, however, this falls within the expected range.

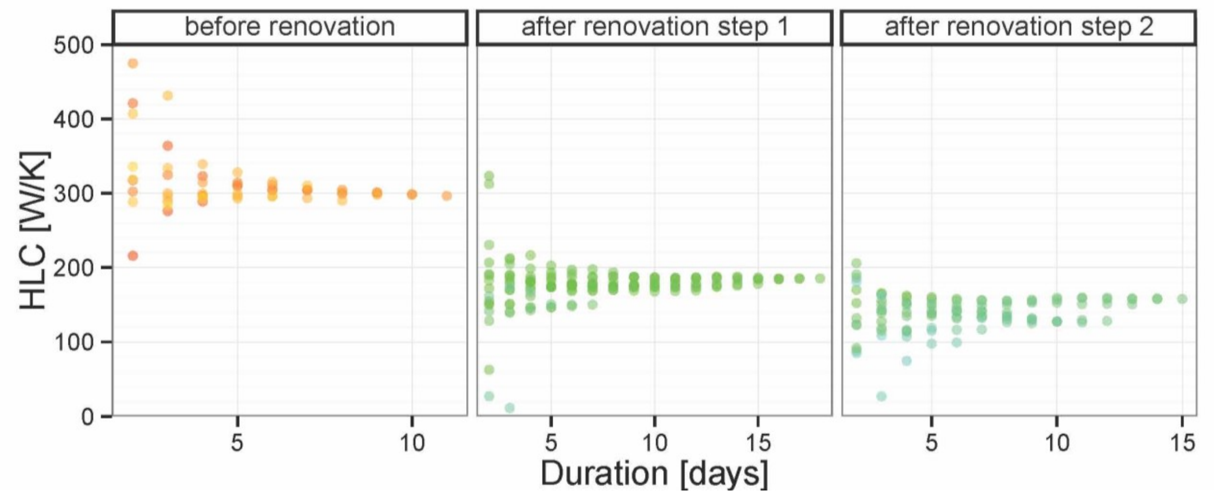


FIG 5. HLC estimates through multiple linear regressions with Q_h as a function of ΔT and $q_{sw,hor}$, taking into account thermal lags and forcing regression surface through the origin, applied on measurement data acquired during co-heating test on a terraced house in Herstal, Belgium. Different subsets of the measurement data are considered: with (1) different starting dates and (2) different durations. The data points are coloured according to the average Q_h over the course of the considered measurement data subset: red points indicate a high average Q_h, blue points indicate a low average Q_h.

TABLE 2. Results of applying simple and multiple linear regression on daily averaged co-heating test data, before and after renovation step 1 and 2: coefficient of determination R^2, estimates for HLC and $A_{sw,*}$, p-value $Pr(>|t|)$. The p-value indicates the probability the variable is not significant.

	R^2	*HLC*	*Std.Error*	*Pr(> |t|)*	$A_{sw,*}$	*Std.Error*	*Pr(> |t|)*	
	-	*(W/K)*	*(W/K)*	-	*(m2)*	*(m2)*	-	*ΔHLC*
Before	0.9983	296.55	13.51	3.98e-09	3.15	3.85	0.433	
After step 1	0.9935	185.63	6.27	2.14e-15	4.76	0.69	3.70e-06	110.92
After step 2	0.9899	157.84	9.62	4.54e-10	2.48	0.68	3.06e-03	27.79

Both ΔT and $q_{sw,*}$ prove to be significant variables in all cases but one. Before renovation step 1, the average solar radiation was rather limited, which explains the fact that the solar radiation as a descriptive variable proves to be less significant in that case (*p*-value > 0.05).

4.3 Decoupling HLC into transmission and ventilation heat loss

Before renovation step 1, the measured n_{50}-value was 3.58 h^{-1}, corresponding to a ventilation heat loss of approximately (1/3) * (n_{50}/20) * V = (1/3) *(3.58/20) * 270.91 = 16.16 W/K. After the first renovation step, the n_{50}-value has risen slightly to 3.92 h^{-1}, corresponding to a ventilation heat loss of 17.70 W/K. During part of the measurement campaign following renovation step 1 (26th of March to 2nd of May), detailed air change rate measurements were performed, using a tracer gas test with constant tracer gas pressure. The average air change rate was found to be 0.48 h^{-1}, which is significantly higher than the air change rate estimated on the basis of the blowerdoor test result and the rule-of-thumb.

5. Conclusions

This paper investigated the applicability of a co-heating test to determine the overall Heat Loss Coefficient (HLC) of a dwelling. The co-heating test was introduced and the corresponding data analysis methodology developed.

A co-heating test was performed on a terraced house in Herstal, Belgium, over an extended period of time (three months). During the measurement period, two renovation steps were performed. The co-heating test proves to be a valuable tool here, not only to assess the *HLC* benchmark value, but also its reduction as a result of renovations. Multiple linear regression analysis was performed, with the heating power as a function of indoor-outdoor air temperature difference and global horizontal solar radiation, taking into account thermal lags introduced on both and forcing the intercept through zero. Confidence in the *HLC*-estimates is backed by the fast and rather steady convergence seen in scatter plots of *HLC*-estimates resulting from applying the regression analysis on measurement data subsets with different (increasing) duration and different start dates.

The blowerdoor test, generally used to decouple the *HLC* into its transmission and ventilation heat loss parts needs to be used with caution. Tracer gas tests showed that the average actual air change rate far outpassed the value estimated by reducing the measured n_{50}-value by a factor 20. The considerable cost associated with a tracer gas test, however, prevents its use on a frequent basis.

6. Acknowledgements

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References

Sonderegger, R. C., Modera, M.P. (1979). Electric Co-heating: A method for Evaluating Seasonal Heating Efficiencies and Heat Loss Rates in Dwellings. In *Second CIB Symposium on Energy Conservation in the Built Environment*. Lawrence Berkeley National Laboratory, March 1979.

Everett, R. (1985). Rapid thermal calibration of houses, ERG, Open University Energy Research Group, Milton Keynes UK.

Roels, S. (2011). Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements. Annex text, November 2011. (http://www.kuleuven.be/bwf/projects/annex58/index.htm)

Bell, M., Wingfield, M. and Miles-Shenton D. (2010). Low carbon Housing. Lessons from Elm Treed Mews. Technical report, Joseph Rowntree Foundation.

Lowe, R.J., Wingfield, J., Bell, M. and Bell J.M. Evidence for significant heat losses through party wall cavities in load-bearing masonry construction. *Building Services Engineering Research and Technology*, 28 2:161-181, 2007.

Bauwens, G., Standaert, P., Delcuve, F., and Roels, S. (2012). Reliability of co-heating measurements. First Building Simulation and Optimization Conference. IBPSA, September 2012.

Max Sherman, Estimation of Infiltration for Leakage and Climate Indicators, in Energy and Buildings, 10, 1987, p.81.