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Quick measurements of energy efficiency of buildings

Mesures rapides de l'efficacité énergétique des bâtiments

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ABSTRACT

In this study, we propose a way to develop rapid measurements of the energy efficiency of buildings. We show that measuring transient states during the heating and free cooling of an empty low-consumption house can lead to a rather good estimate of the total heat loss coefficient K and of the apparent heat capacity C of the building. These measurements can be made typically within a couple of days.

RÉSUMÉ

Dans cette étude nous proposons une méthode pour mesurer rapidement l'efficacité énergétique de bâtiments. Nous montrons qu'en mesurant les états transitoires lors du chauffage et du refroidissement d'une maison basse consommation vide, on accède au coefficient de fuite thermique K et à la capacité calorifique apparente du bâtiment. Ces mesures peuvent être obtenues en un ou deux jours.

1. Introduction

Driven by energy and environmental issues, the improvement of the Energy Efficiency (EE) of buildings is a priority for most governments. Indeed, in developed countries, buildings are the largest reservoir of energy savings. All governments are passing laws which increase the thermal efficiency regulation and most countries encourage low- and very low-consumption buildings. An important change in most of the regulations is that, while continuing to give construction rules (Building Code), they increasingly target the global performance of buildings. Typically, the new rules are designed to limit the annual consumption of the building (usually calculated in energy used per unit surface and per year: $kWh/m^2/year$ or its equivalent in kW/m^2 in I.U.[2]).

In most cases, the performance is estimated theoretically by knowing all the technical characteristics of the building: the nature of all the elements of the envelope (walls, glazing, roofs, floors ...), the choice of the ventilation and the heating

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[2] 1 $kWh/m^2/year = 1.14 \times 10^{-4}$ kW/m^2. Depending upon the regulation or the label, values as low as 15 $kWh/m^2/year$ for passive houses in Germany, 38 $kWhpe/m^2/year$ for Minergie in Switzerland (heating, hot water, ventilation) and 50 $kWhpe/m^2/year$ for low-consumption houses BBC label by Effinergie in France (heating, cooling, hot water, ventilation and lighting) are indicated. Here, kWhpe stands for primary energy.

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device. The solar gain can also be estimated in certain cases. Classical methods[3] are used to estimate the energy efficiency of the building taking into account the local climate (averaged over many years) and typical usage of the dwelling. This theoretical estimate assumes that the materials and the systems used for the building are perfectly assembled and that the building is effectively used in a standard way. This calculation is very often done before starting the construction and the building is qualified on the basis of this theoretical estimate. No verification is done on the final building: sometime there is an inspection of the building once finished. Sometime a measurement of the air-tightness of the building is done which is most often the only quantitative measurement. Compared to the relative sophistication of the calculation, direct measurements of the EE before delivering the building and even after are not the norm. This is largely due to the fact that it does not exist a way to measure with acceptable accuracy the EE of buildings in a reasonable amount of time.

Several techniques can, however, be used to check whether the EE of the building, when finished, corresponds effectively to the calculated expected values. The most obvious one consists of measuring the total energy spent during one year. Obviously this takes a full year (at least a winter...) to collect the data. The comparison with the calculation is not always straightforward. Indeed, the obtained numbers depend on the fluctuations of the weather (the specific year) and more importantly on the way the dwelling is used by the occupants. More and more measurements of this type are made, and eventually show discrepancies between the expected energy consumption and the actual consumption. It is sometime very difficult to understand the origin of these discrepancies and in particular what is coming from the use and what is coming from the building itself [1].

Another way to obtain the EE of the building is to measure over some time (several weeks or months) the energy consumption while recording at the same time both the outside temperature and the inside temperature. As we will see, the amount of heat needed by the building to maintain a difference of temperature between inside and outside is proportional to this difference of temperature. The averaging over a period of time (from a few days to a few weeks) leads to a correlation between the total amount of energy used during this period of time for heating and the average difference of temperature during the same period. If this is a more direct way of measuring the energy consumption, again it might depend on the way the building is being used and also on more complex phenomenon such as the heat input due to solar radiation which is usually neglected and can disturb the measurements.

We can think that using model houses [2] and test houses [3] the EE can be estimated by using the amount of energy needed to maintain a constant inside temperature while using a period of time short enough to assume that the outside temperature is constant. However, this method suffers from the fact that the characteristic time of a house (defined in the following as the ratio between the loss coefficient and the heat capacity of the building) is of the order of several days for well insulated houses. This means that the house is never in a pseudo steady state since outside temperatures are varying faster: typically from day to night with a 24 h period.

A very interesting method, proposed by Nielsen and Nielsen [4], uses the Pseudo Random Binary Sequence (PRBS) of heating to obtain the dynamic response of the building. This analysis can lead to both the total heat loss coefficient and the total heat capacity of the building. They also show that a simple RC-circuit model could represent the dynamic response of the building.

Another way which has been explored, is to use the BEM (Building Energy Management) of the building (when equipped) and to try to correlate, on a given period of time, the power needed to maintain a given temperature inside following the variations of the outside temperature [5]. While it is very difficult to generalize to all building (most small residential buildings are not equipped) it is a method which again takes into account the dynamics (time dependency) of the building. It also requires some time of analysis (several weeks/months) and depends on the way the building is used.

All these methods are interesting, but long and difficult to be used as a standard method to estimate the EE of a building.

Surprisingly, one finds that there is no simple method to qualify the building performance envelope on a rather short period of time and independently of the way the building is used. More precisely, if the quality of the heat leakage of the building can be estimated from the calculation, there is no convenient way to measure it!

Even if we assume that the algorithms used in the software to calculate the EE of a building are reasonably accurate, when comparing the conception and the realization of a building one may expect differences for several reasons. For example, some information is missing in the calculation (such as the way cables or pipes are positioned and connected) or some changes in the choice of the materials and systems have been made compared to the initial planning and, even more often, some poor workmanship leads to a degradation of the performance of the building. In all cases, it would obviously be very interesting to have a way to estimate the EE performance of the building envelope within an accessible period of time (typically a few days) with no interference with the way it is occupied and compare it to the calculation and eventually the performance when occupied.

In what follows, we propose a simple technique which might reach these objectives. It is based on using transient states for both heating and free cooling the building. In following the evolution of the internal temperature as a function of time, we demonstrate on a real and rather complex building that such analysis can be performed with a reasonable accuracy (typically within 10%). The basic principles are straightforward: they consist of starting with a building with an inside temperature higher than the outside temperature and then shutting down all heating sources. The decay of the temperature is then followed as a function of time. In a second step the building is heated in a controlled way with a constant power

[3] E.N. ISO, 13790: 2008 — Energy performance of Buildings — Calculation of energy use for space heating and cooling.

spread as homogeneously as possible. The variation of temperature inside is recorded all along this process. We will see that measuring the kinetics of the temperature variation in both cooling and heating for a few hours is enough to estimate the value of the leakage parameter together with the heat capacity of the building.

2. The model

In order to understand the experiment, let us go through a very simple analytical model. We start with the strong simplifying assumption that a house can be represented as a closed box having an average coefficient of leakage coming from the sum of all the interfaces between inside and outside constituting the envelops of the building (walls, roof, floor, windows, ...) [4]. In this model, there are two main contributions to the energy needed to maintain that building at a temperature different from the outside temperature: the first one being the loss of heat through the envelope and the second one is due to the air renewal. Indeed, fresh air coming from outside has to be heated to room temperature. When considering a variation of temperature the heat capacity of the mass inside the insulating envelope has to be taken into account. This heat capacity inside the envelope can be different from the total heat capacity of the building (it depends on the position of the insulating materials: inside or outside...) we will henceforth refer to it as the "apparent" heat capacity C.

The simple dynamic equation describing the behavior of the building is consequently [4]:

$$C\,\mathrm{d}T = (P - K_0 \Delta T)\,\mathrm{d}t \tag{1}$$

where C is the apparent heat capacity of the house, P is the inside power brought by all heating sources inside the house and possibly the solar gain, K_0 is the total heat loss coefficient of the building, ΔT is the difference between the inside and outside temperature.

As explained, K_0 is usually composed of two contributions: the heat loss through the envelope of the building (K_{01}) and the energy power needed for heating the outside air which is penetrating per unit time in the house (fCa).

$$K_0 = K_{01} + fCa \tag{2}$$

f being the flux of air entering in the house (ventilation air flow + possible air leaks) and Ca is the total heat capacity of the air.

We can investigate two simple cases which can easily be reproduced experimentally.

The first case corresponds to a "free cooling" experiment where we start with a given temperature inside the building higher than the outside temperature and all heating sources are suppressed (we assume that this experiment is done with no solar gain or internal source of heat, i.e. preferably at night in a non-occupied building). The inside temperature is recorded as a function of time. Assuming that the external temperature is constant during the experiment and that the temperature inside is homogeneous, one obtains through a simple integration of Eq. (1) (assuming $P = 0$):

$$\Delta T^c = \Delta T_0^c\big(\exp(-t/\tau)\big) \quad \text{with } \tau = C/K_0 \tag{3}$$

τ can be defined as the characteristic time of the building.

The second case corresponds to the "heating" case: constant power P is added to an initial state with a difference of temperature between inside and outside whose variation as a function of time is again recorded.

Integration of Eq. (1) leads to:

$$\Delta T^h = \big(\Delta T_0^h - P/K_0\big)\exp(-t/\tau) + P/K_0 \tag{4}$$

where ΔT_0^c and ΔT_0^h correspond to the initial difference of temperature (at $t = 0$) between inside and outside the house for respectively the cooling and the heating experiment. Assuming the experiment to be short enough, and that no other transient states corresponding to a shorter time will dominate, both equations can be linearized leading respectively to:

$$\Delta T^c = \Delta T_0^c(1 - t/\tau) \tag{5}$$

and

$$\Delta T^h = \Delta T_0^h + \big(P/C - \Delta T_0^h/\tau\big)t \tag{6}$$

One can imagine performing these two experiments one after the other for a period of time which is short enough to enforce the assumption of a constant external temperature. This can be done if the temperatures are measured with a sufficiently good accuracy to detect small variations. Recording the inside temperature as a function of time and measuring the slope of both the "cooling" and the "heating" experiments leads to two coefficients of the linear behavior:

Respectively, for the cooling experiments:

$$\Delta T^c = \Delta T_0^c - \alpha_c t, \quad \text{where} \tag{7}$$

$$\alpha_c = \Delta T_0^c K_0/C \tag{7bis}$$

and for the heating experiments:

$$\Delta T^h = \Delta T_0^h + \alpha_h t, \quad \text{where} \tag{8}$$

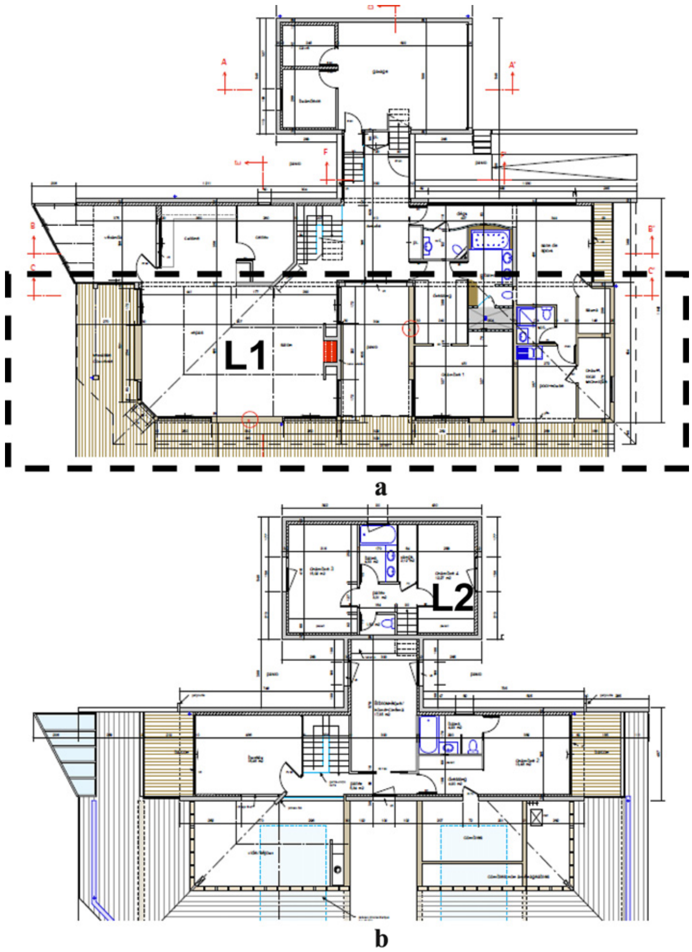

Fig. 1. Plans of the house. This figure represents the plans of the house used for the measurements. It is a two story building (a: first floor, b: second floor) with a concrete part insulated from inside and a wood frame part (within the dotted rectangle). L1 and L2 are the location of the probes measuring the temperature of the air inside the building.

Fig. 1. Plans de la maison. Ce dessin correspond aux plans de la maison utilisée pour les mesures. C'est une maison à deux étages (a : premier étage, b : deuxième étage) avec une partie en parpaings de béton avec une isolation par l'intérieur et une partie en ossature bois (à l'intérieur du rectangle en pointillé). L1 et L2 sont les emplacements des sondes de places à l'intérieur du bâtiment.

$$\alpha_h = P/C - K_0 \Delta T_0^h / C \tag{8bis}$$

Once these two coefficients α are measured, it is easy to obtain the two relevant parameters characterizing the building:

$$K_0 = P / \left(\Delta T_0^h + \Delta T_0^c \alpha_h / \alpha_c \right) \tag{9}$$

and

$$C = P / \left(\alpha_h + \Delta T_0^h \alpha_c / \Delta T_0^c \right) \tag{10}$$

In what follows, we will use this technique to estimate the energy efficiency of a house. As a first step, and then using it as a reference, we have performed, on the very same house, a typical calculation of the "theoretical" EE based on the design and a stationary (quasi-static) measurements during a full winter in order to compare the rapid method to more classical ones.

3. Description of the house and quasi-static experiments

The building used for the experiment is a private house situated in the southwest of France. This house was built in 2009 as a low energy house and is composed of two parts: the first part is made of concrete blocks with inside insulation and the other part is wood frame construction. The concrete block part is a two story building whereas the wood frame part is one story. Fig. 1 shows the plan of the house. The total heated surface is 280 m^2.

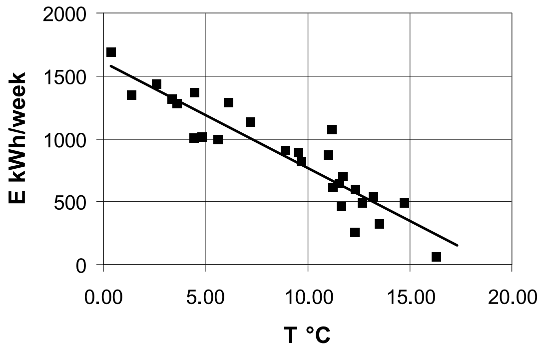

Fig. 2. Energy versus averaged outside temperature. Energy per week needed to maintain a constant temperature (20 °C) inside the building as a function of the outside temperature. Each point represents the amount of energy used and the average temperature over that week. Data was recorded during the winter 2009–2010.

Fig. 2. Mesure de l'énergie en fonction de la différence de température. Energie nécessaire par semaine pour maintenir une température intérieure constante (20 °C) en fonction de la différence de température moyenne entre l'intérieur et l'extérieur. Chaque point correspond à la quantité d'énergie en fonction de la moyenne de la différence de température pendant une période d'une semaine. Ces données ont été obtenues durant l'hiver 2009–2010.

Before construction, an estimation of the performance of the house was made using classical software. After completion, the home was qualitatively checked with an infrared camera to confirm that the building was well insulated and that no unexpected thermal bridges or leakage due to defects were present.

The total heat loss coefficient of the envelope can be estimated in the classical way:

$$K_{01} = \left(\sum_i A_i\right) * U_{\text{bat}} = \sum_i (U_i A_i) + \sum_j (\psi_j l_j) + \sum_k \chi_k \tag{11}$$

where U_i is the overall heat transfer coefficient of each part i of the envelope ($\text{W}\,\text{m}^{-2}\,\text{K}^{-1}$), A_i is the internal area of each part i of the envelope (m^2), ψ_j is the linear thermal bridge coefficient of the junction j ($\text{W}\,\text{m}^{-1}\,\text{K}^{-1}$), l_j is the length of the junction j (m). χ_k is the punctual thermal bridge coefficient of the 3D thermal bridge k ($\text{W}\,\text{K}^{-1}$).

The other contribution coming from the renewal of the air is estimated by calculation taking into account the ventilation system type (simple flux).

$$K_{02} = f\,Ca \tag{12}$$

with f (270 m^3/h) being the ventilation air flow estimated from the total installed ventilation system and Ca the heat capacity of the air ($Ca = 0.34$ Wh/m^3/K).

One obtains: $K_{01} = 405$ W/K and $K_{02} = 92$ W/K, leading to:

$$K_0 = 497\ \text{W/K} \tag{13}$$

The house is equipped with a geothermal heat pump. The cold source is placed in the garden under a pond and the hot source is a hot water circuit embedded in the flooring of the house which covers all the heated part of the building. The hot source is at a constant temperature of 35 °C. The power of the heat pump is 5 kW and the Coefficient of Performance (COP) is 4.28 for a low temperature (at 7 °C). There is a separate energy meter to measure the electrical energy consumed by the heat pump. The evolution of the COP with temperature is known[4] and we can obtain the total real power delivered to the home directly from the electrical power measured. The pond temperature is measured independently, it is considered to be the cold source.

Before presenting the transient states experiments we have performed a full year measurement of the energy efficiency of the house. Every week, we have recorded both the total consumption of the heat pump during that week and the average temperature outside and inside the building. The inside temperature has been measured at different places in the house one in the concrete block part and the other one in the wood frame part. The outside temperature of both the air and the pond are recorded separately. The inside temperature is regulated at 20 °C and the recorded data shows oscillation within plus or minus 1 °C with from time to time a strong increase (not more than 3–4 °C) due to solar gains. The house was used by a family of four during the year for which these measurements were made.

Fig. 2 shows the result recorded during the winter 2009–2010. We plotted the results where we have corrected the heat pump COP for the variation with the pond temperature.[5] We have checked that these results are not so different from

[4] This evolution follows the expected thermodynamic law (COP is proportional to the difference of temperature $\Delta T = T_{\text{hot}} - T_{\text{cold}}$ between the hot source (T_{hot}) and the cold one (T_{cold})). The hot source has a temperature constant and equal to 35 °C, the cold one is the taken to be the temperature of the pond (measured). For temperature around 7 °C: $\text{COP}_T = \text{COP}_{7\,^\circ\text{C}} * (35 - 7)/(35 - T_{\text{pond}})$.

[5] See footnote 4.

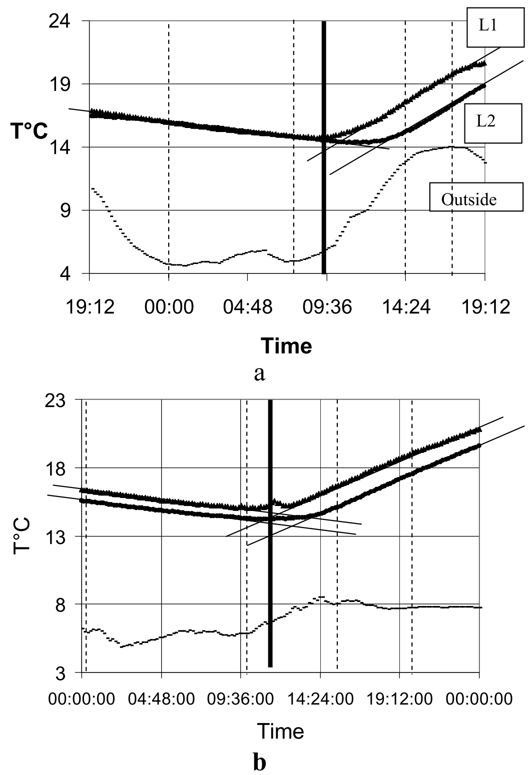

Fig. 3. Transient response of the house. Temperature of the two locations L1 and L2 inside the house recorded after shutting down the heat and restarting it (respectively the two upper curves: L1 triangles and L2 lozenges). The lower curve is the recorded outside temperature. The vertical full line indicates the time at which the heater was started again. The vertical dotted lines indicate the time scale chosen for the linear fit of Fig. 4 with the first set of lines for the cooling rate and the second set for the heating rate. The two experiments are done at different times of the year (February for **a** and April for **b**).

Fig. 3. Réponse transitoire de la maison lors d'un test rapide. Température mesurée par les sondes L1 and L2 situées à l'intérieur de la maison lors du refroidissement et du chauffage (respectivement les deux courbes du haut L1 les triangles et L2 les losanges). La courbe du bas représente la température extérieure mesurée en même temps. La ligne verticale pleine indique le moment ou le chauffage est remis en route. Les lignes verticales pointillées indiquent le domaine choisi pour le fit linéaire représenté en Fig. 4. Le premier ensemble de lignes correspond à l'expérience de refroidissement alors que le second ensemble correspond au chauffage. Les deux expériences ont été faites à des moments différents de l'année (février pour **a** et avril pour **b**).

the non-corrected results. Each point corresponds to the total energy consumption plotted as a function of the average temperature during a week. One can see that there is a linear relation as expected from Eq. (1) if both inside and outside temperatures were kept constant. The linear fit of the corrected curve leads to:

$$E = 84.5\ \text{kWh/week/K}(19.1 - T_{\text{outside}}) = 503\ \text{W/K}(19.1 - T_{\text{outside}}) \tag{14}$$

The correlation coefficient R^2 is 0.85.

We can learn already a lot from this curve. Interestingly the fit gives an extrapolated value for the inside temperature of 19.1 °C being very close to the set-point (and measured) interior temperature of 20 °C. The K_0 value measured at 503 W/K is also very close to the estimated one (497 W/K). The slight difference between the average temperature measured inside the house (20 °C) and the one extrapolated could come from a mixture of solar gain (weak during the winter) and internal source of heat due to the occupancy of the house. Indeed, rewriting Eq. (14) as Eq. (15), we obtain a weekly constant value of 453 W for the extra source of heating:

$$E = 503\ \text{W/K}(20 - T_{\text{outside}}) - 453\ \text{W} \tag{15}$$

This is a reasonable amount for an internal energy brought by a family of 4 with a low occupancy rate. In addition, the fact that averaging over a week leads to a relatively good linear behavior is a rather positive result.

4. Rapid method: Transient measurements

We are coming now to the rapid method using transient measurements. The idea was to perform the experiment during approximately one day or so. Two different experiments were done at different periods of time during the winter, separated by several months. The heater was shut down for twenty-four hours and then re-started at full power (5 kW). Inside and outside temperatures were recorded every 10 min. The inside temperature was measured at two different locations inside the house. In each room, the temperatures were recorded both in the air 150 cm above the floor and on the walls. Both

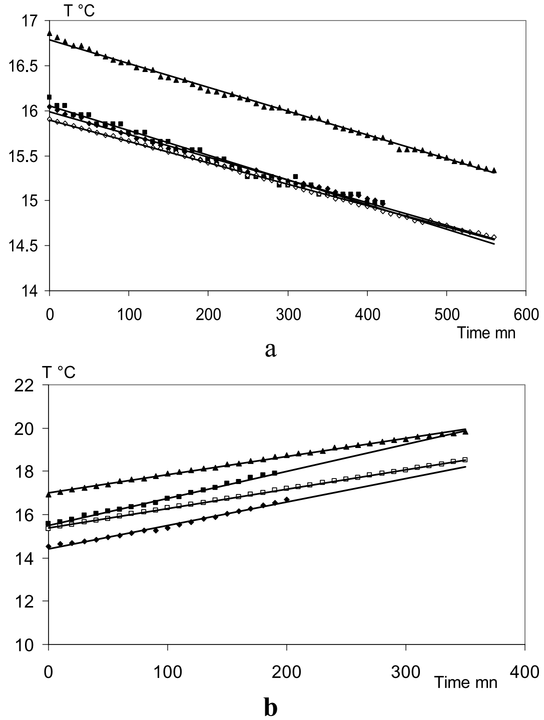

Fig. 4. Linear fits of the cooling and heating rates. This figure represents the linear fits for both experiments **a** and **b** for the probes L1 and L2 during cooling and heating. For the cooling curves (upper part): full square L1a, empty diamond L2a, full triangles L1b, full diamond L2b. For the heating curves (lower part): full square L1a, full diamond L2a, full triangles L1b, empty square L2b. Extracted quantitative data are listed in Table 1.

Fig. 4. Paramétrages linéaires pour le chauffage et le refroidissement. Cette figure représente les résultats des paramétrages linéaires pour les expériences **a** et **b** et pour les sondes L1 et L2 durant le refroidissement et le chauffage. Pour les courbes de refroidissement (figure du haut) : Carrés pleins L1a, Losanges vides L2a, Triangles pleins L1b, Losanges pleins L2b. Pour les courbes de chauffage (figure du bas) : Carrés pleins L1a, Losanges pleins L2a, Triangles pleins L1b, Carrés vides L2b. Les valeurs quantitatives extraites de ces paramétrages sont données dans le tableau 1.

results are identical and therefore we just show the result obtained in the air. The two locations are respectively in the main room (South orientation, wood frame part of the house first floor: labeled L1) and at the opposite end in the bedroom number 4 (North orientation, concrete block part of the house, second floor: labeled L2). The locations are indicated with a cross on Fig. 1.

Figs. 3a and 3b show the results for the two experiments. We can see that in both cases the qualitative behaviors look similar. The inside temperature measurements are very similar for the two different locations L1 and L2. Outside temperatures were quite different in the first case (experiment **a**) starting at 5 °C during the night (when the temperature was going down) and increasing during daytime to reach 14 °C; in the second experiments (**b**) there was less variation from 5 °C during the night to 8 °C during the day.

Linear fits were performed in all cases and reported in Fig. 4a for the cooling part and Fig. 4b for the heating part. Table 1 shows the results of linear fits of all the data recorded.

For the cooling part we get very similar results in the two experiments while the heating part shows a larger slope in experiment **a** than in experiment **b**. As we will see, it can be very easily understood by the temperature difference between the inside and outside which is typically 1 °C in experiment 1 and 8.2 °C in experiment 2. As a reference for the external temperature, we took the average exterior temperature during the period of time for which we fitted the linear behavior.

Using Eqs. (9) and (10) we can extract from these experiments the values of K_0 and C. The heating power P is taken to be COP $\times$ 5 kW (COP being 4.58 at 9 °C which was the temperature of the pond when the experiment **a** was performed and 3.95 at 5 °C when experiment **b** was performed).

Averaging over the two temperature measurements L1 and L2, we found:

$$\textbf{a}: \quad K_0 = 462\ \mathrm{W/K} \quad \text{and} \quad C = 112\ \mathrm{MJ/K}$$

$$\textbf{b}: \quad K_0 = 466\ \mathrm{W/K} \quad \text{and} \quad C = 104\ \mathrm{MJ/K}$$

These results are almost identical (around 464 W/K), and not far from either the calculated value or the value measured previously by the averaging method for a year of data (around 500 W/K). Note that the characteristic time τ is around 4000 min corresponding to almost 3 days. As expected, this time is greater than a day.

As we can see the dynamic measurements lead to values slightly lower than the stationary ones. This can be partly attributed to the fact that these experiments were performed in an empty house with all the shutters closed. This may be

Table 1
Results of the linear fits of the data for the cooling and heating rates of both experiments **a** and **b**. The value **a** was obtained from the slope of Fig. 4 and the values K_0 and C calculated from Eqs. (9) and (10). The outside and inside temperatures were taken as the average of the temperature measured during the same period of time as the data used to fit the linear behavior.

Tableau 1
Résultats des paramétrages linéaires des données des deux expériences **a** et **b** lors du refroidissement et du chauffage. Les valeurs des coefficients **a** sont obtenues à partir des pentes de la Fig. 4 et les valeurs de K_0 et C sont calculés à partir des Éqs. (9) et (10). Les températures extérieures et intérieures des coefficients ΔT sont prises comme les moyennes des températures mesurées pendant la même période que les paramétrages linéaires.

	Exp **a** L1	Exp **a** L2	Exp **b** L1	Exp **b** L2
T^c_{ext} (°C)	5.0	5.0	6.0	6.0
$T^c_{i,m}$ (°C)	16.0	15.3	15.3	15.2
α_c (K/min)	−0.0026	−0.0027	−0.0025	−0.0024
T^h_{ext} (°C)	14.0	14.0	8.0	8.0
$T^h_{i,m}$ (°C)	16.6	17.8	18.5	17.0
α_h (K/min)	0.0107	0.0125	0.0083	0.0090
T_{pond} (°C)	9.0	9.0	5.0	5.0
COP	4.58	4.58	3.95	3.95
P (W)	22 900	22 900	19 750	19 750
K_0 (W/K)	478	445	477	454
C (MJ/K)	121	102	106	104

investigated further but at this stage of our understanding, we might expect that there is less contribution from the air renewal when the house is not occupied. A rough estimation of the value of C taking into account the materials inside the envelope leads to values of the same order of magnitude as the one measured by the present method.

5. Discussions and conclusion

We have demonstrated experimentally, on a specific building, that transient state measurements can be used to estimate within a short time the energy efficiency of a building. These measurements can take one day or two and are compatible with a protocol which can be followed in an empty building without solar gain. Comparison between the a priori calculated heat loss, stationary measurements made during a full winter and these transient measurements leads to surprisingly good agreement of the data. The studied house was a rather complex building with different types of envelopes. Taking this into account, the quality of the obtained results may appear surprisingly good. We believe that this is due to two important points:

1. The house is quite new and well designed and therefore has a rather homogeneous envelope in terms of heat loss coefficient;
2. A very homogeneous source of heating is used (floor heating covering the entirety of the house floor).

We believe that the fact that the heat is brought by the floor and allows enough time for the air and the walls to equilibrate is probably important to get reliable data.

The fact that the outside temperature does not vary too much during the experiment is especially important for the cooling part. Indeed, in this case, for the heating part the behavior is dominated by the heating power (Eq. (8bis)) and the leakage of heat can be seen as a perturbation. If needed, one can easily take into account variations of the outside temperature leading to second order corrections in the equations.

Even though, we believe that transient states measurements of these types open up new ways to measure the energy efficiency of buildings, it will be important to better understand their limits. Experiments on other buildings are in progress to better understand the limit of the method. We might imagine numbers of variation of the method presented here, including the fact that a good estimate of C or an independent measurement can lead to an even simpler method, for example recording the cooling rate of the building once the heating power has been stopped.

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