DEVELOPMENT OF A METHOD FOR THE MEASUREMENT OF SPECIFIC HEAT LOSS IN OCCUPIED DETACHED HOUSES

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ABSTRACT

A method has been developed in Sweden to determine the heat loss of electrically heated detached houses; it is intended to form part of a new system of energy performance declarations by house builders. The method is simple, such that the occupant of the house should be able to make the necessary readings. It involves recording the quantity of energy supplied (as indicated by the electricity meter) and the average nighttime temperature difference between indoor and outdoor air for a number of nights.

The paper describes the method and reports some interesting experiences from a number of measurements carried out during the winter of 1993 to 1994. Twenty-one houses were accurately monitored over a period of 30 nights. The paper describes how the measurement errors have been analyzed. The recorded spread of the measurement results is compared to spreads simulated by the Monte Carlo method. Multiple regression analysis is performed to find possible correlations between the measured heat loss and weather data. No such correlation was found.

This new method of determining the loss factor, as described in this paper, requires neither expensive equipment nor extensive specialized knowledge. The measurements are made under normal operating conditions for the ventilation and heating systems.

Accuracy, however, is limited (±7% to 10%), and the method is applicable only to wood-framed detached buildings. Nevertheless, it has considerable value in respect of its capacity to provide information for consumers and to verify that statutory requirements in respect of energy conservation standards are fulfilled.

INTRODUCTION

Ever since the energy crisis at the beginning of the 1970s, energy conservation in the built environment has been important. In Sweden, more than 40% of the country's total energy use (i.e., about 150 TWh) is supplied to residential, commercial, and other buildings, with most of it used for heating. The country's indigenous energy resources are limited, and it has therefore been important to encourage (or require) good energy conservation by means of legislation, standards, loan regulations, etc. High energy prices also provide an incentive for consumers to make good use of their energy supplies.

Consumer information and verification that specified requirements are being met have been mainly in the form of calculations, complemented with tests of materials and components. Unfortunately, in many cases, agreement between actual and calculated values of energy use has been poor, resulting in far too optimistic values. This is because it has been difficult to correctly allow for factors such as quality of workmanship, aging, thermal bridges, distribution losses, occupant habits, and the effects of weather in the calculations. As a result, methods of testing the energy use of entire buildings at system level have been developed in recent years.

This report briefly describes a method of determining the total power demand of occupied detached houses. Its accuracy is limited, but the measurements are easy to make and do not require any expensive equipment. The method received type approval from the Swedish National Board of Housing, Building and Planning in 1992.

THE MEASUREMENT METHOD

Definition of Specific Heat Loss

Specific heat loss, F_T (W/K), is defined as the sum of the transmission and ventilation losses per degree of temperature difference. In principle, it can be determined as the quotient of the input power and the indoor/outdoor temperature difference of a building. Ventilation (air change rate) is understood as the sum of mechanical ventilation and natural ventilation (infiltration). Swedish detached buildings are typically fairly airtight and

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equipped with mechanical exhaust air fans and the natural ventilation normally is negligible.

Applicability and Limitations

The method is intended to determine the specific heat loss of detached buildings having a wooden load-bearing structure, but with any cladding material. The foundation/floor structure can be a suspended floor (i.e., with a crawl space), slab on ground, or a basement. The building must be heated electrically and ventilated by conventional systems, and may be occupied during the measurement period. Ventilation should be mechanical to keep the fluctuations in ventilation heat losses to a reasonable level.

Measurement is carried out at night to limit the heat input effect of insolation and occupants. Long nights, a low diurnal swing of ambient temperature, limited insolation, and a large temperature difference between the indoor and ambient temperatures are all beneficial. In Sweden, a suitable time of year for making these measurements is from November 15 to February 15.

The method cannot be used for

- quantification of the magnitude of loss components;
- buildings with a thermally massive structure (i.e., other than wood);
- buildings with solid fuel, gas, or oil heating;
- buildings with heat pump systems that are used for space heating, unless special precautions are taken in the analysis of the results; and
- buildings with only natural ventilation, unless special measures are taken to allow for the effects of varying ventilation losses.

Measurements should not be made before residual building moisture has dried out and a zone of heated ground has developed below the building. This typically takes about one year.

Recording and Processing of Measured Data

The internal/external temperature difference and the amount of energy used as shown by the electricity meter are recorded for a number of nights. During each of these nights, the mean temperature difference and the mean input power are noted over a measurement period, e.g., from 10 p.m. in the evening to 6 a.m. in the morning.

The temperature difference generally is expressed in degree-hours, DH:

$$DH = \overline{\Delta T} \cdot L = \int_L \Delta T \cdot dt \tag{1}$$

where

DH = number of degree-hours (Kh),
$\overline{\Delta T}$ = mean indoor/outdoor temperature difference (K),
ΔT = indoor/outdoor temperature difference (K),
L = length of the measurement period (h), and
t = time (h).

The amount of electrical energy used during the period, Q_{meter}, is obtained by direct reading of the meter. This value is then corrected to allow for factors such as heat from the occupants and heat stored in the building to a value, Q (Wh), which is assumed to represent the heat losses through the building envelope during the measurement period.

As one part of the building's heat losses is related to the difference in temperature between the indoor and outdoor air and another part is related to the difference in temperature between the indoor air and the ground, it is necessary to calculate an adjusted temperature difference, $\Delta T'$, to be able to express the heat loss by means of a simple expression:

$$q = F_T \cdot \Delta T' \tag{2}$$

where

q = rate of heat loss from the building (W),
F_T = specific heat loss of the building (W/K), and
$\Delta T'$ = weighted temperature difference (K).

Calculation of $\Delta T'$ is indicated in the method by correction of the measured temperature difference between the indoor and outdoor air temperatures by a correction factor, γ:

$$\begin{cases} q = F_T \cdot \Delta T' = UA_g \cdot \Delta T_g + (F_T - UA_g) \cdot \Delta T \\ \Delta T' = \gamma \cdot \Delta T \end{cases} \tag{3}$$

where

UA_g = area times the U-factor for that part of the building envelope that interfaces with the ground (W/K) (see Figure 1), and
ΔT_g = average temperature difference between the indoor air and the ground (K) (see Figure 1).

γ can be calculated from these relationships as

$$\gamma = \frac{UA_g \cdot \Delta T_g}{F_T \cdot \Delta T} + \frac{F_T - UA_g}{F_T} = \frac{UA_g}{F_T} \cdot \left(\frac{\Delta T_g}{\Delta T} - 1\right) + 1. \tag{4}$$

In other words, we need to know both the actual temperature in the ground and the proportion of the building's thermal resistance interfacing with the ground. The ratio is calculated from construction drawings or other available information. Fortunately, heat loss to the ground is normally small, and any uncertainty in these data is of only limited effect. The value of γ usually is in the range of 0.80 to 0.95.

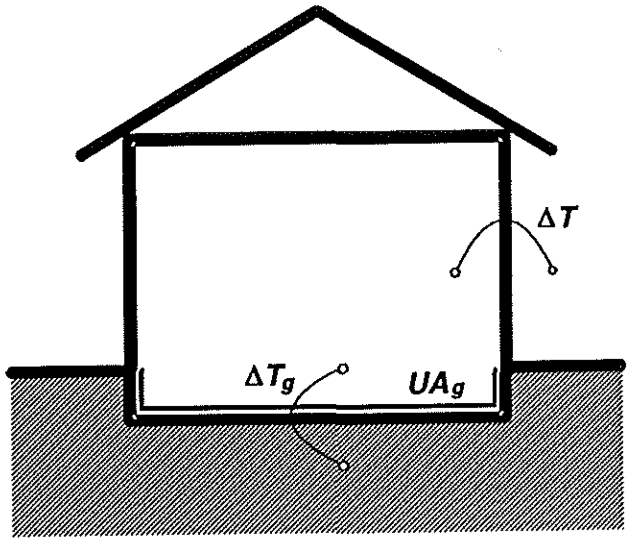

Figure 1 Temperature differences and UA_g for the part interfacing with the ground.

Evaluation

The specific heat loss can be evaluated in two different ways: (a) by determining F_T for a number of nights and then calculating the mean value of F_T, or (b) by simple regression analysis of associated values of energy loss and temperature difference.

Calculation of the Mean Value The number of measured degree-hours for each measurement period is corrected by the γ factor, and the specific heat loss can be calculated as follows:

$$F_T = \frac{Q}{\gamma \cdot DH}. \tag{5}$$

To limit the random errors it is desirable that there should be at least 10 measurement periods from which the mean value of F_T should be calculated. Many things could go wrong during in-situ measurements (e.g., influences from exceptional behavior of the occupants, extreme weather conditions or incorrect readings of the instruments or electricity meter). It is therefore suggested that individual values that vary by more than ±10% from the mean value should be rejected.

Simple Regression Analysis When employing this alternative, we start by assuming that the heat loss to the ground is constant and that other heat losses are proportional to the temperature difference between the indoor and outdoor air:

$$q = A + B \cdot \Delta T \tag{6a}$$

where

q = sum of the heat losses (W),
A = heat losses to the ground (W), and
B = factor that describes the other heat losses (W/K).

Simple regression analysis results in the equation for the straight line as shown in Equation 6a, which is illustrated by the example in Figure 2. With $A \approx 745$ and $B \approx 93$, Equation 6a will be

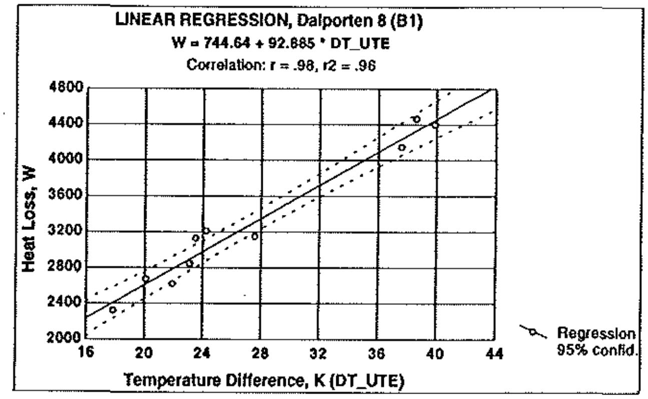

Figure 2 Linear regression; heat loss as a function of indoor/outdoor temperature difference. This diagram is based on measurement set No. 1 in building B1; see also Section 4.

$$q = 745 + 93 \cdot \Delta T. \tag{6b}$$

The specific heat loss can be calculated from the relationships

$$q = A + B \cdot \Delta T = F_T \cdot \Delta T' = F_T \cdot \gamma \cdot \Delta T \tag{7}$$

which gives

$$F_T = \frac{A + B \cdot \Delta T}{\gamma \cdot \Delta T}. \tag{8}$$

The mean value of the temperature difference during the measurement periods should be used for ΔT.

Data for the house in the example in Figure 2, Dalporten 8, are

- calculated specific transmission heat loss for the total building envelope: 92 W/K,
- calculated specific transmission heat loss for the floor construction (over a crawl space): 26.3 W/K, and
- ventilation heat loss (calculated from a measured airflow rate of 52 m^3/h): 17.4 W/K and consequently calculated $F_T = 92 + 17.4 = 109.4$ W/K and calculated $UA_g = 26.3$ W/K.

The average indoor/outdoor temperature difference during the measurements was 26.7 K and the average temperature difference between crawl space and indoor air was 19.2 K. The γ value was calculated as

$$\gamma = \frac{26.3}{109.4} \cdot \left(\frac{19.2}{26.7} - 1\right) + 1 = 0.93 \tag{9}$$

and F_T as

$$F_T = \frac{745 + 93 \cdot 26.7}{0.93 \cdot 26.7} = 130, \tag{10}$$

which was 19% higher than the calculated value.

ERROR ANALYSIS

Systematic and Random Errors

A preliminary estimation of the errors has been made. More experience is needed before final values can be presented.

The systematic errors in determining F_T can be estimated as

- calibration error of the electricity meter, ±2%;
- error in quantification of the number of degree-hours, DH (see Equation 1), ±2%; and
- error in the correction factor, γ (see Equation 3), ±2%.

The systematic errors, in other words, can give rise to a maximum error of ±6%.

The random errors can be estimated as amounting to

- reading the electricity meter, ±500 Wh at the beginning and ±500 Wh at the end of measurement, rectangular distribution;
- heat from the occupants, −20% to +40% of a nominal value taken from tables on the metabolism at different ages, triangular distribution;
- varying indoor temperature, normal distribution with standard deviation ±25% of the applied correction;
- varying outdoor temperature, normal distribution with standard deviation ±25% of the applied correction;
- heat stored in an electric boiler, hot water tank, or domestic hot water tank, ±500 Wh to 1,000 Wh, rectangular distribution; and
- variation in ventilation, normal distribution with standard deviation ±5% to 10% of the estimated value.

The process has been simulated using the Monte Carlo method to obtain an estimate of the spread caused by the random errors. The Monte Carlo simulation is a system that uses random numbers to measure the effects of uncertainty in a spreadsheet model. The result is displayed in a forecast chart that shows the entire range of possible outcomes and the likelihood of achieving each of them. The example is based on actual estimates of the measurement errors in one of the buildings (EE2) described in the next section. The estimated values of the random errors are shown in the Appendix. One thousand simulations indicated a frequency distribution for F_T (W/K), as shown in Figure 3, i.e., approximately a normal distribution with a mean value of 98.8 and a standard deviation of 5.0.

Figure 4 shows actual measured values from a period of 30 nights. A normal distribution fitted to these measured values has a mean value of 100.9 and a standard deviation of 4.9. This extremely good agreement in the standard deviation probably is pure chance, but it does

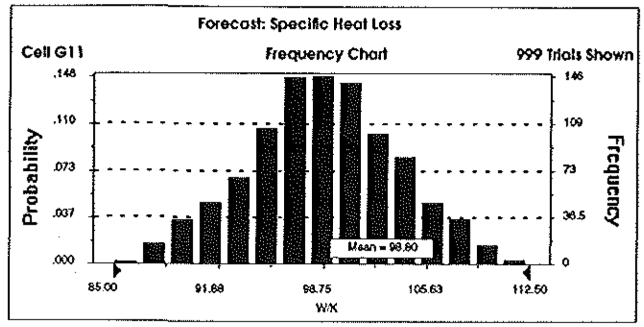

Figure 3 Frequency chart from Monte Carlo simulation.

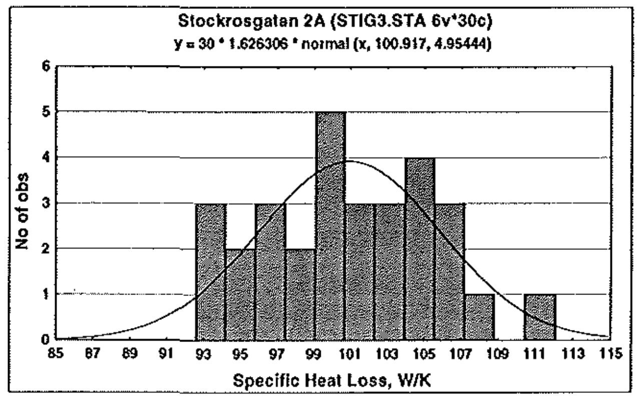

Figure 4 Results from 30 nights' measurements for house EE2: Stockrosgatan 2A, Nässjö.

show that the assumed random errors are of the right order of magnitude.

The standard deviation, s, expressed as a percentage of the mean value, turned out to be about 5%. This agrees with experience from a number of series of measurements (see the next section), which show that typical values are in the range of 4% to 6%. For $s = 5\%$ and 10 measurement periods, the standard error of the mean is given by

$$\frac{5}{\sqrt{10}} \approx 1.6\%, \tag{11}$$

which means that with a 95% confidence level and for 10 measurement periods, the random error is somewhat less than 4%. The maximum total error is then $6 + 4 = 10\%$, although probably only $\sqrt{6^2 + 4^2} \approx 7\%$.

Multiple Regression

One of the questions that has been raised in connection with development of this method is the extent to which wind velocity affects the results. Not only can wind increase infiltration, it also can degrade the thermal insulation performance as a result of forced convection.

Another question concerns the extent to which insolation during the day prior to the measurement period can affect the measured results. The correction for varying indoor temperature applied by the method does not allow for any excess temperature in the structure of the building or its fittings or furniture caused by insolation.

Some of the measured results described in the next section have been analyzed by multiple regression to obtain an impression of the effects of wind and insolation. The power demand has been expressed as a function of three parameters: the indoor/outdoor temperature difference, the square of the wind velocity, and the cloud cover during the afternoon prior to measurement. Data for six houses at two sites in the country have been analyzed. The results showed negligible contributions to the correlation for both wind velocity and cloud cover. In addition, these two parameters resulted in alternately positive and negative regression coefficients.

It can therefore be stated that these analyses showed the negligible effect of both wind and insolation on the measurements.

MEASUREMENTS DURING THE WINTER OF 1994

Measurements were made in a number of detached houses in southern and central Sweden during January and February 1994. They were part of a project financed by the National Swedish Board for Consumer Policies (the project leader was Stig Jahnsson). Most of the readings have been made by the occupants, with the results being processed by heating and ventilating or building inspectors in each town. The project has been described in a preliminary report (Jahnsson 1994). The objective of the project was to investigate

- the reliability of the method of measurement, and particularly of its precision;
- whether calculated and promised energy characteristics accorded with measured characteristics; and
- time, cost, training, and competence requirements for those performing the measurements.

The measurements were made in 21 detached houses and (in most cases) for 30 nights in each house, normally split into three 10-night periods. Table 1 is a summary of the results.

As ventilation in the various houses has differed widely, column 2 shows the calculated specific heat loss, F_T^*, while column 3 shows the difference between the measured and calculated values of F_T^*. F_T^* is the specific heat loss of the envelope (hence excluding ventilation), calculated according to the Swedish building code, which requires the U-factor of the floor construction to be reduced by 25%. Column 4 shows the standard deviation of regression coefficient B (see Equation 6a) expressed as a percentage of B. Columns 5 through 8 show the determination coefficients (R^2) for each measurement period and for all measurement periods together.

TABLE 1 **Results from Measurements in 21 Detached Houses**

House	Calculated F_T^* (W/K)	Difference Between Measured and Calculated F_T^* (% of Calculated)	Standard Deviation for B (% of B)	Coefficient of Determination, R^2 — Measurement Period No. 1	2	3	All
B1	85.4	+17	4.8	0.96	0.96	0.98	0.95
B2	94.6	+23	6.4	0.94	0.90	–	0.92
B3	101.9	+6	5.0	0.89	0.77	0.96	0.94
E1	90.9	+23	7.0	0.81	0.96	0.90	0.89
EE1	58.2	+5	5.3	0.97	0.94	0.90	0.92
EE2	58.2	+14	5.2	0.97	0.92	0.90	0.93
EE3	67.4	+12	3.8	0.94	0.98	0.95	0.96
ER1	89.1	–15	4.9	0.97	0.96	0.93	0.94
F1	115.0	–5	4.6	0.56	0.99	0.98	0.94
F2	77.7	+22	5.6	0.94	0.87	0.88	0.93
H1	111.5	+14	12.0	0.86	0.73	0.89	0.80
H2	97.0	+56	4.7	0.97	0.80	0.96	0.94
H3	–	–	29.7	0.44	0.27	–	0.38
H4	–	–	6.2	0.99	0.91	0.84	0.90
HH1	75.2	+62	3.6	0.99	–	–	–
N1	80.2	–4	6.4	0.89	0.95	0.93	0.90
N2	77.2	+28	5.5	0.87	0.98	0.93	0.93
N3	77.2	+9	8.8	0.95	0.90	0.96	0.82
V1	120.3	+71	8.5	0.73	0.88	0.85	0.84
V2	98.5	+10	5.2	0.93	0.91	0.91	0.93
V3	86.6	+31	4.8	0.96	0.90	0.95	0.94

To further illustrate the precision of the method, the project report reproduces the results from several measurement periods in house EE1.

Date	No. of Nights	Measured F_T^*
Feb. 1990	7	60.3
Feb. 1992	9	61.2
Jan. 1994	10	62.7
Jan. 1994	10	60.3
Feb. 1994	10	61.4

This project has shown that the method has acceptable reliability and an inaccuracy of 7% to 10%. In the majority of cases, explanations such as incorrect readings, lack of supervision, or the use of difficult-to-control heating systems, such as floor heating systems, account for the results shown for certain houses with massive spread and poor precision (primarily houses F1, H3, and V1).

As can be seen from Table 1, the *measured* specific heat losses normally exceed the *calculated* values, in some cases by as much as 50% to 60%. This shows that the methods of calculation need to be significantly improved. The differences are probably also largely due to poor quality of workmanship and/or adjustment of heating and ventilating systems, which indicate a need for improved inspection and supervision in these areas.

Experience from these measurements shows that it is essential that those who are responsible for the measurements and process the results are properly trained. In addition to general technical competence in the building and HVAC sectors, they need to have attended a two- or three-day course covering both theoretical and practical aspects. It might be worth considering whether these measurements should be made only by persons certified for the purpose. The daily readings, on the other hand, are simple and can be made by the occupants.

The time needed to calculate the specific heat loss for a single night, using an ordinary calculator, is about 10 to 15 minutes. A computer program to process the measured data would reduce this time and also increase reliability.

The measurements can be made with equipment costing about $500.

CONCLUSIONS

The recently developed method for determining the specific heat loss of a detached house, as described in this paper, requires neither expensive equipment nor extensive specialized competence. Most of the readings can be made by the occupants, and they are made under normal operating conditions of the heating and ventilation systems.

The accuracy is limited, and the method is suitable only for certain types of buildings (detached houses with a wooden structure and electric heating). On the other hand, this type of building is common in Sweden for private homes. The method can therefore be of considerable value in terms of providing energy-use information for consumers and for mediating in the legal/contractual relationships between builders and house purchasers. It also is important for verifying that government requirements in respect of energy conservation are fulfilled.

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APPENDIX

The following example describes the measurements made between January 11-21, 1994 in Stockrosgatan 2A, Eksjö. Typical energy input per night was 17,810 Wh, with a typical degree-hours value of 180. The measured specific heat loss amounted to 99 W/K, with the calculated ventilation losses amounting to 35% of the total losses.

In a Monte Carlo simulation, the random errors, expressed in Wh/day, have been estimated as follows:

Electricity meter reading	17,400 ± 1000, rectangular distribution
Heat from occupants	Minimum value 421, most probable value 526 and maximum value 736, triangular distribution
Correction for varying indoor temperature	Normally distributed with a mean value of 0 and standard deviation 25% of 840, i.e., 210
Correction for varying outdoor temperature	Normally distributed with a mean value of 0 and standard deviation 25% of 28, i.e., 7
Correction for heat stored in electric boiler	0 ± 700, rectangular distribution
Correction for varying ventilation	Normally distributed with a mean value of 0 and standard deviation of 7.5% of estimated ventilation loss of 6,233, i.e., 468

One thousand simulations gave the following values:

Mean	98.8
Median	98.88
Standard deviation	4.97
Variance	24.70