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TECHNIQUES FOR ESTIMATING THE ENERGY CONSUMPTION OF HOUSES

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Reprinted from
CIB 83
The 9th. CIB Congress, Stockholm, Sweden
Energy Technology and Construction, Vol. 3a
p. 201 - 212

DBR Paper No. 1202
Division of Building Research

Price $1.25 OTTAWA NRCC 23438

Canada

Title of the paper TECHNIQUES FOR ESTIMATING THE ENERGY CONSUMPTION OF HOUSES

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Key words houses; heating energy; calculation methods

Summary

The evaluation of a house design requires a method for estimating the effect of various design features on the heating energy requirements. Such a method must account for the following: heat loss, primarily by conduction, through the exterior envelope; heat loss due to exchange of indoor air and outdoor air; heat loss to the earth through basement walls and floor; heat gain from occupants and appliances; solar heat gain through windows; and the performance characteristics of the heating system.

Although a number of computer programs have been developed to simulate the thermal behaviour of a house, simpler methods are more appropriate for use as design tools, or for evaluating house designs for building code or labelling applications. Simple methods sacrifice some accuracy, particularly when the effects of heat storage and variations in room temperature become significant, but they are adequate for many practical applications. Recent research at the National Research Council of Canada has resulted in improved methods for calculating below-grade losses and the utilization of solar gains through windows that can be incorporated into such calculation procedures.

Titre du texte TECHNIQUES POUR L'ESTIMATION DE LA CONSOMMATION ENERGETIQUE DES MAISONS

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Mots-clés habitations; énergie de chauffage; méthodes de calcul

Sommaire

Une évaluation de la conception d'une habitation exige une méthode pour calculer les effets des diverses caractéristiques sur l'énergie nécessaire au chauffage. Une méthode de calcul de ce genre doit tenir compte des points suivants : pertes de chaleur, surtout par conduction, à travers l'enveloppe extérieure ; pertes de chaleur entraînées par l'échange d'air intérieur-extérieur ; pertes de chaleur au sol à travers le plancher et les murs du sous-sol ; gains de chaleur provenant des occupants et des appareils ménagers ainsi que du rayonnement solaire à travers les fenêtres ; enfin, caractéristiques de rendement du système de chauffage.

Bien qu'un certain nombre de programmes d'ordinateurs aient été conçus pour simuler le comportement thermique d'une habitation, des méthodes plus simples sont préférables comme outils de conception ou comme moyen d'évaluation de la conception domiciliaire appliqué à un code du bâtiment ou à l'homologation. Les méthodes simples manquent quelque peu de précision, notamment lorsque les effets du stockage de la chaleur et les fluctuations de température d'une pièce revêtent de l'importance, mais elles conviennent néanmoins à un bon nombre d'applications pratiques. De récents travaux du Conseil national de recherches Canada ont permis de mettre au point de meilleures méthodes de calcul des pertes de chaleur sous le niveau du sol et de l'utilisation des gains de chaleur solaire par les fenêtres.

TECHNIQUES FOR ESTIMATING THE ENERGY CONSUMPTION OF HOUSES

D.M. Sander, Canada

INTRODUCTION

There has long been considerable interest in modelling the thermal behaviour of houses and estimating their annual heating energy requirements. This interest has evolved in recent years from academic studies to methods that address specific practical needs for calculating the energy requirements of houses.

This paper discusses some of these needs in the context of current Canadian conditions, as well as a number of available calculation methodologies. Recent Canadian research to improve calculation methods for below-grade heat losses and utilization of solar heat gains is described briefly.

THE NEED FOR AN ENERGY ESTIMATING METHOD

Thermodynamic simulation has long been used, in research institutions, as a means of investigating the heat transfer processes in a house. Although inspired by a desire to gain a better understanding of the problem, these studies have also been valuable for developing recommendations and guidelines for construction practice, insulation standards, and other energy conservation measures. It is only in the last ten years that energy consumption and the consequent cost of heating a house have become a significant concern in Canada. This concern has been expressed in a number of government programs (1). The problem is twofold - to reduce the energy consumption of existing houses, and to improve the construction of new houses.

For existing houses, programs have been introduced to provide financial incentives to homeowners, through grants and interest-free loans, for reinsulation and retrofit. In 1981, as part of a national strategy to reduce the country's dependence on imported oil (2), the Canadian government initiated a program to subsidize the conversion from oil-fired heating systems to those using natural gas, electricity, or renewable energy. There has developed a resulting need for a method of assessing the energy reduction potential of alternative retrofit measures. Moreover, since most homeowners must bear at least part of the cost of an energy retrofit, they demand some means of estimating the expected return on their investment.

To improve new houses, work was initiated to develop an energy conservation standard. A model document (3) specifying requirements such as higher insulation levels and better windows was produced. This document also contains a provision permitting construction of any type of house that can be shown to use no more energy than one built in accordance with the standard. Therefore, the building official must have some means of evaluating a building design in order to ensure that it meets the standard.

A number of "low-energy" houses have been built in Canada recently. Some have very high levels of insulation, airtight construction and small windows, while others feature passive solar designs incorporating large south-facing glass areas and thermal mass. Such innovative houses require design decisions quite different from those for conventional construction. Normally a number of features would be evaluated in terms of their energy conservation potential, cost effectiveness, and possibly resultant problems such as overheating, excessive moisture or unacceptable air quality. There is a need for an analysis tool for the designer to evaluate and compare design alternatives for a specific house. There are new government incentives (4,5) for the construction of "low-energy" houses and since the eligibility criteria are based on a maximum allowable heating energy consumption, there must be a way to determine the eligibility of proposed designs.

There is also a need to protect buyers considering the purchase of a "low-energy" house. The Canadian Standards Association is developing a labelling procedure (6) which would establish an energy consumption rating for each new house. This would permit the buyer to base his decision on the comparison of costs and anticipated benefits.

It is evident therefore that there is a need both for sophisticated computer modelling techniques and simple calculation methods suited for the designer, builder, approval authority, and the homeowner.

CALCULATION OF HOUSE HEATING ENERGY

All methods for calculating the energy required for heating must account for heat losses, heat gains, and the efficiency of the heating system. Heat losses consist of transmission through components of the building envelope (such as walls, ceiling, doors and windows), transmission through basement walls and floor to the ground, and heat loss due to the exchange of indoor and outdoor air, either through infiltration or by controlled ventilation. Heat gains consist of solar radiation through windows as well as heat generated by occupants, lights and appliances.

Energy calculation techniques may be divided into two groups: simulation and modelling, which can only be performed using computers, and simplified methods, which permit manual calculation (although it may often be convenient to use a computer as well).

COMPUTER MODELLING

The most detailed and most flexible analysis technique is dynamic simulation of the thermal performance of the house. Either finite difference or thermal response methods are used to model the non-steady-state heat transfer due to thermal storage in the materials of the house. Heat gains and heat losses are calculated, using weather and solar data, typically for an hourly time interval.

Heat losses through walls and roofs may take into account the rise in exterior surface temperatures due to absorbed solar radiation as well as the decrease in exterior surface temperatures due to longwave radiation to the sky. Infiltration may be modelled as a function not only of the leakage characteristics of the house itself but also of outdoor air temperature, wind speed, wind direction, and the surrounding terrain. The calculation of solar gains may account for the effect of inset windows, shading by roof overhangs, and shading by adjacent parts of the building or by other buildings. The behaviour of the occupant may be simulated by time scheduling the internal loads, such as lights and appliances, and operation of blinds, drapes and insulating shutters.

The thermal storage characteristics of the room are simulated to predict both the heating required and the variations in space temperature. When heat gains exceed losses the excess heat is stored, resulting in a rise in room temperature. When heat losses exceed gains, stored heat is recovered as the room temperature decreases. The heating system is called on to provide the heating necessary to prevent the temperature from falling below the thermostat setting. Heating systems can be simulated in detail including variation of system efficiency with load and outdoor air temperature.

Many simulation programs model individual rooms which may be at different temperatures; in this case, heat transfer occurs between the rooms. This further permits modelling of unheated or partially heated spaces, such as attics, garages, porches and vestibules, attached sunspaces and greenhouses.

Computer modelling is a powerful technique particularly suited to research applications in which the objective is to study a phenomenon in great detail, to compare a theoretical model with experimental data, or to extrapolate experimental data to produce more generalized conclusions. The complex calculations, however, require a great deal of input data such as the dimensions, geometry and material properties of all building components. As a result, such programs are generally difficult as well as expensive to use.

SIMPLIFIED METHODS

Practical applications are generally not concerned with modelling a heat transfer process, but with obtaining answers to questions such as whether a house design satisfies the requirements of a building (energy) code, what energy label to attach to a house, or which design alternative should be chosen. Simple methods may be sufficiently accurate for this purpose; the important considerations are that such methods be easy to use, readily available, and inexpensive to apply. Since access to computers cannot always be assured, there is a need for methods that can be applied manually.

It is necessary to compromise some accuracy and flexibility to achieve the necessary level of simplicity. Simplified methods generally consider the entire house as a single space at a uniform and constant temperature. Attached unheated spaces are approximated as equivalent additional insulation. An indoor space temperature must be assumed; variations in temperature are not calculated. Thus dynamic heat transfer is not modelled; the effects of thermal storage are either ignored or accounted for by correction factors or correlations. These correlations are usually obtained from computer simulation studies. Effects of solar radiation and long-wave radiation on the opaque portions of the building envelope are usually ignored (they are assumed to cancel each other).

It should be noted that the limitations of energy calculations are more often due to uncertainty of the input data than to the calculation method itself. Therefore, the compromises inherent in the simple methods do not necessarily reduce the accuracy of an energy estimate.

A description of several simplified methods follows. This categorization is by no means complete; there are many variations and combinations of these methods.

Temperature Bin Methods

The hourly simulation requires 8760 hourly calculations for one year. The bin method reduces this number to between 10 and 100 by calculating only once for each range of outdoor temperature (typically 1°C to 5°C), multiplying by the number of hours during which the temperature is in this range, and totalling the results of all the ranges. This procedure can account for the variation of heating system efficiency with outdoor temperature. Similarly, infiltration may be considered as a function of outdoor temperature. However, the method does require that all other thermal components such as solar and internal gains also be assumed a function of outdoor temperature. That is, an average value of gains is used in the calculation for each temperature range. Heat storage effects are not considered. The temperature bin method is particularly well suited to the analysis of heat pumps (7).

Degree-Day Methods

The following methods are based on weather data which are averaged or integrated over a relatively long time period, typically one month or the entire heating season. With the aid of a computer this calculation is normally done on a monthly basis, whereas a seasonal calculation may be preferred for a manual procedure since it requires considerably less effort. For many applications under Canadian conditions, it has been found that there is no substantial loss of accuracy in the seasonal approach.

The degree-day methods described below assume an average heating system efficiency over the time period.

Simple degree-day method. The simple degree-day method has been in use for over 40 years. It is based on a historical correlation of house heating energy and degree-days to the base 18.3°C (65°F). The difference between actual room temperature and 18.3°C is assumed to compensate for the useful heat gains from occupants, lights, appliances, and solar radiation.

Changes in both construction and use of houses (more insulation, higher internal heat gains, larger windows, lower thermostat settings, etc.) have made the degree-day correlation less appropriate for modern houses. Consequently, modified methods which include correction factors to improve the correlation (8) have been developed.

The degree-day method has the advantage of being very simple and of using readily available data. "Degree-days" has become the recognized measure of "coldness" and values are published for a large number of locations. The degree-day method, however, is based on the "average" house; the basic limitation is that it does not account for heat gains specific to a particular house.

Variable-base degree-day method. Studies have shown that better correlations may be obtained by using degree-days with a base temperature other than 18°C. An improvement over the simple degree-day method can, therefore, be achieved (9) by determining the base temperature which accounts for the useful heat gains for a specific house. This base temperature is a function of solar gains, internal gains, the heat loss characteristics of the house, the space temperature and, possibly, the thermal storage characteristics of the house.

Degree-days for base temperatures other than 18°C are not generally available; however, correlations have been derived (10) to obtain them from simple degree-days and average monthly temperatures.

Net annual heat loss factor method (11). This variation on the degree-day method apportions the heating requirement for the house among the various building components - walls, windows, ceiling and indoor-outdoor air exchange. Factors for each component (NALF's), derived from computer simulation studies of a "standard house", are given as a function of degree-days. The annual heating requirement is obtained by summing the products of area and NALF for all components.

The NALF's do account for the effect of solar radiation on opaque surfaces and permit evaluation of different wall absorptivities, orientation, and window type. The method is somewhat limited by the conditions assumed for the standard house model (inside temperature, internal gains, thermal storage characteristics, etc.) and by the assumption that solar radiation is a function of degree-days. It is, however, simple and relatively accurate for houses that do not differ much from the standard house.

Energy balance method. This method is based directly on the heat balance equation for a house, as illustrated in Figure 1. Since the sum of heat gains must equal the sum of heat losses,

$$H = L_t + L_a + L_b - \eta_i G_i - \eta_s G_s$$

where,

- H = total heating required,
- L_t = total of heat losses due to transmission through exterior walls, windows, ceilings, etc.,
- L_a = total of heat losses due to indoor-outdoor air exchange (infiltration and ventilation),
- L_b = total below-grade heat loss,
- G_i = total of heat gains from internal sources (lights, appliances, occupants, etc.),
- G_s = total of solar heat gains through windows,
- η_i = utilization factor for internal gains,
- η_s = utilization factor for solar gains.

The utilization factors η_i and η_s account for the fact that not all of the heat gains are useful in reducing the amount of energy required for heating. Values of η_i and η_s can be estimated once the gains and losses are known.

In order to calculate the heating energy from the above equation, it is first necessary to determine each of the loss and gain components. The calculation may be performed on either a monthly or seasonal basis.

Since above-grade losses are normally assumed to be directly proportional to the indoor-outdoor temperature difference, L_t and L_a can be calculated using degree-days with a base temperature equal to the indoor temperature. It is often more convenient, however, to calculate above-grade losses using the difference between indoor and average outdoor temperature which can be readily obtained from weather data. This is a good approximation provided that the outdoor temperature does not exceed the indoor temperature too often during the time period (i.e., the month or the heating season) considered.

Mitalas (12) has developed an improved procedure for calculating below-grade heat loss, L_b. This method, which is based on both experimental measurements and finite-element computer models, accounts for the time variation of heat loss through basement walls and floors during the year. A feature is that many different configurations of insulation (inside, outside, different depths, under the floor, etc.) can be considered.

The basement wall and floor are divided into sections as shown in Figure 2, and the heat loss through each section is computed separately. Heat loss through each section consists of two parts: a steady-state component which does not vary with time, and a time-varying component which is approximated by a sine wave having a period of one year.

The steady-state component is proportional to the difference between inside temperature and mean ground temperature. The time varying component is a function of the amplitude of the variation of ground surface temperature about this mean; this function accounts for time lags due to the effect of thermal storage in the ground.

Reference 12 contains tables of coefficients for many different configurations of basement insulation. Using these tables and published values of ground temperature, the method provides a flexible and relatively simple means of calculating basement heat loss.

The magnitude of the internal gains, G_i, depends on the occupancy of the house. While data on the rate of heat release by various appliances are available, it is always necessary to make arbitrary assumptions regarding occupant behaviour and, therefore, of the internal gains. For most situations in which G_i is less than 25% of the heat losses, all of the internal gains can be assumed to be useful ($\eta_i = 1$).

The seasonal solar gain through the windows can be calculated using tabulated values of solar radiation incident on surfaces of different orientation. In Canada this information is available from the Atmospheric Environment Service as 10-year averages for 130 locations.

The solar utilization factor, η_s, is defined as the fraction of the total solar gain, through all windows of a house, that contributes to a reduction of the heating requirement; that is,

$$\eta_s = \frac{\text{Useful solar gain}}{\text{Total solar gain}}$$

The useful solar gain for any hour includes the solar gain used to offset heat losses during that hour, plus the portion stored in the thermal mass and used to offset losses at a later time. It does not include the excess gain that must be discarded to prevent room temperature from exceeding a preset maximum, nor does it include any gain utilized to offset additional losses caused by a rise in room temperature above the thermostat setting.

It has been found (13) that the solar utilization factor can be expressed as a function of two normalized parameters, namely the "gain-load ratio" (GLR) and the "thermal mass-gain ratio" (MGR). The gain-load ratio is defined as:

$$GLR = \frac{G_s}{L_t + L_a + L_b - \eta_i G_i}$$

The gain-load ratio is the ratio of the solar gain through windows to the net heating load, where the net heating load is the amount of heating energy required in the absence of solar gains to maintain the room temperature at the heating thermostat setting.

The mass-gain ratio reflects the thermal storage characteristics of the building as well as the area, type and orientation of the glazing. It is defined as,

$$MGR = C/g_s$$

where,

C = thermal capacity of the building interior (MJ/K),

g_s = average hourly solar gain for season (MJ/h),

($g_s = G_s$/hours in heating season).

Figure 3 shows the solar utilization factor plotted against the GLR for various values of MGR and a room temperature swing of 5.5°C. Curves for the cases of 0°C and 2.75°C temperature swings are also available (13).

SUMMARY

A number of different calculation methods have been developed in response to the different needs for estimating the heating energy requirements of houses. While computer simulation is the most powerful technique it tends to be best suited for research studies. Simpler methods are more appropriate for use as design tools, or for evaluating house designs for building code or labelling applications.

The simple degree-day method does not account for the features of a specific house such as type and orientation of glass, internal heat gains, or building thermal mass. Both the variable-base degree-day and the energy balance methods can account for many of the features of a particular house. The author feels that the energy balance method has some advantages over the other simplified methods. It is conceptually more direct in its accounting of internal gains, solar gains, and below-grade heat losses. It not only permits investigation of various building features including thermal mass but also allows identification of the individual components of heat loss and heat gain. The method may be applied manually with the aid of a pocket calculator and tables of climatic data. It has also been implemented in the form of a microcomputer program (14).

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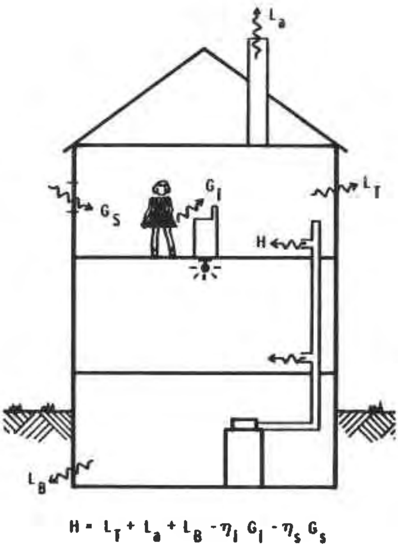

FIGURE 1
HOUSE HEAT BALANCE

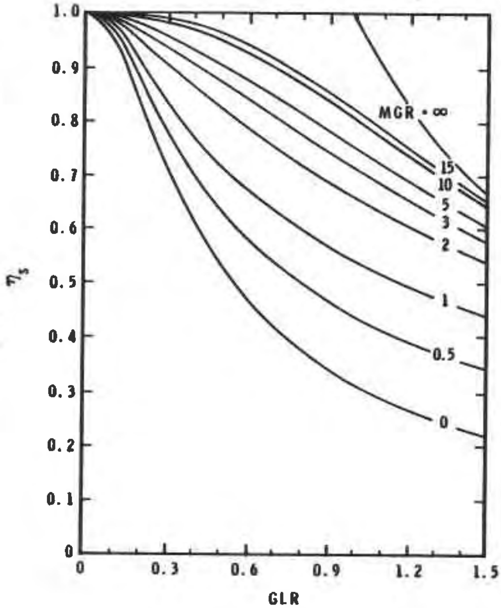

FIGURE 3
SEASONAL SOLAR UTILIZATION FACTOR
(ROOM TEMPERATURE SWING = 5.5°C)

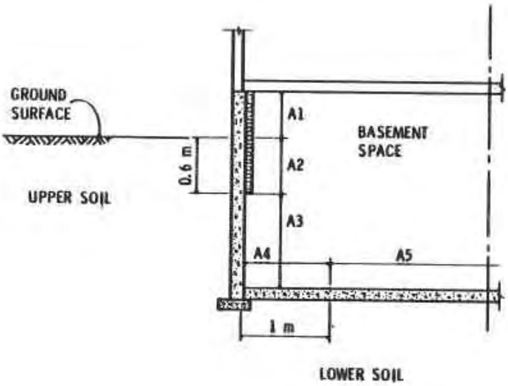

FIGURE 2
BASEMENT MODEL