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SIMPLIFIED CALCULATION OF HEATING ENERGY CONSUMPTION FOR NATURALLY VENTILATED BUILDINGS

P Basnett
Electricity Council Research Centre, Capenhurst, Chester, United Kingdom

A computer program is presented which calculates the heating energy requirements of single zone, intermittently heated buildings with reasonable accuracy. Calculation of preheating energy is based on the 'average internal temperature' concept of CIBSE Energy Code 2. Solar gains and long-wave radiation losses are treated approximately on the basis of regression equations for radiation as a function of daily average external temperature for different periods of the day. Results are produced both as tables and graphically as 'Heating Analysis Charts' showing a cumulative frequency curve of total energy requirement and the way in which it is satisfied. Separate tables and charts are produced for the occupied and preheat periods. The results of comparisons between prediction and measurement for eleven buildings are presented to demonstrate the quality of the predictions.

SCOPE OF THE PROGRAM

The computer program described in this paper was developed on a PR1ME 650 mini-computer, and has been adapted to run on IBM-PC micro-computers. It is intended for use by sales engineers in the Electricity Supply Industry in Great Britain as an aid in evaluating the energy and financial consequences of their recommendations as to how a building should be heated.

The target in writing this program was to provide a tool which would be simple and quick to use, as accurate as possible within the constraints of requiring only simple and easily acquired data, and which would provide both graphical and numerical results.

The program concerns itself solely with buildings which may be considered as a single zone. The data required for the building structure is the area, transmittance (U-value) and admittance of each element of the opaque envelope of the building, the area and glazing type or shade factor for each transparent element in the envelope, and the area and admittance of each element of internal structure, together with the ventilated volume and (occupied and unoccupied) infiltration rates.

Design internal and external temperatures allow the design heat loss to be calculated from this data.

Additional information needed to calculate the buildings annual gross heat loss is as follows: the weather station (of which 40 are available covering the whole of Great Britain) and severity (Mild, Normal and Severe years are available for each station), a definition of the heating season, including any possible breaks, the period of occupancy (hours per day and days per year) and the way in which the preheating is controlled.

The occupied and unoccupied rates of internal gain allow useful gains to be subtracted from the gross heat loss to give the useful heat requirement of the building, and system information enables this to be converted to the amount of energy required to be supplied to the heating systems and finally to an annual energy cost.

To complete the picture, non-weather dependent heating loads, such as the supply of domestic hot water, can be included in the calculations.

A sensitivity analysis shows how the space heating requirement would be expected to vary with some of the most important factors which are unlikely to be known with great accuracy.

At all stages the program will supply the user with help (on request). The data upon which the 'help' tables are based is derived from the wide experience of the British Electricity Supply Industry in this field.

GROSS HEAT LOSS

The starting point for this calculation is the statement in the CIBSEE Energy Code Part 2 that the average indoor to outdoor temperature difference over a given day and for a given building can be calculated from the difference between the design internal temperature and the average external temperature for that day, the response factor of the building, and the hours of operation of the heating system using the equation:

$$d = \frac{H\ R}{HR + (24-H)} D$$

where
R is the building response factor, defined as the ratio of the total building admittance to the total building thermal transmittance,

$$R = \frac{\Sigma AY + nV/3}{\Sigma AU + nV/3}$$

where the sum in the numerator runs over all the exposed surfaces in the building, and that in the denominator over the external surfaces.

If now we assume that the building is occupied for P hours out of the H hours that the heating is running, and that it is maintained at the design internal temperature throughout these P hours it is easy to see that the average temperature difference during the unoccupied period must be:

$$\delta = \frac{HR - P(24-H)/(24-P)}{HR + (24-H)} \bar{D}$$

with R calculated on the basis of the air change rate during the unoccupied period.

We can then calculate the gross heat loss during the occupied period by multiplying together the hours of occupancy P, the temperature difference during the occupied period D and the building thermal transmittance $\sum A\ U + nV/3$, calculated using the air change rate appropriate for the occupied period.

Similarly we can calculate the gross heat loss for the unoccupied period. Here we multiply the unoccupied hours (24-P), the average temperature difference during the unoccupied period d and the thermal transmittance $\sum A\ U + nV/3$, calculated using the air change rate appropriate for the unoccupied period.

So far we have assumed that all days are similar. No account has been taken of weekends. A crude adjustment is made for totally unoccupied days by assuming that the preheat energy required on a 'Monday' (the day following one or more unoccupied days) is calculated on the same basis as above, but with 24 (the number of hours in a day) replaced by 24(W+1), where W is the number of unoccupied days in a week. This is the number of hours between the end of the last heating cycle in the week, and the end of the Monday heating cycle. We then take an average preheating requirement based on one Monday and 6-W normal days. This procedure will overestimate the temperature drop over a weekend, and hence underestimate both the total heat loss during the weekend and the preheating requirement to restore that energy loss on a Monday morning.

If the capacity of the heating plant available during the preheat period is insufficient to supply all the calculated energy requirement before the preheat period ends the shortfall will be added to the energy requirement during the occupied period.

Several options are provided for the control and optimisation of the preheating. They affect the calculations as follows:

If the preheating is required to be completed by 7 a m, (the end of the availability of night-rate electricity), and occupancy starts later than this, the hours of operation of the heating system are taken as running from the start of preheating to the end of occupancy, ignoring the gap when no heat is supplied. This will have the effect of heating the building above the required temperature at 7 a m, and allowing it to cool to the correct temperature at the start of occupancy.

If the preheating is fully optimised, this is done by adjusting the start time so as to just supply the required amount of energy by the end of the preheat period (the beginning of occupancy or 7 a m as the case may be), provided that this does not entail starting the preheat before midnight.

If the start of the preheat is controlled by weather compensation, this is done by fixing the start time on a design day, and adjusting the preheat period to be proportional to the difference between the internal design temperature and the actual daily average external temperature. This is analogous to the operation of many so-called 'optimum start' controllers.

If the start-up time is fixed, as it might be for an off-peak electrical preheating system, the rate of supply of energy is assumed to be adjusted so as to just supply the required amount of energy during the preheat period, provided that this is within the capacity of the system to supply heat.

Since the latter two options control the preheat time by reference to factors which do not completely reflect the amount of energy required during the preheat period, or indeed, not at all, they may result in the preheating time being either too long or too short, or one in cold weather and the other in mild weather. If the preheating time turns out too short, this means that the building will not be up to temperature at the start of occupancy, and the shortfall in energy supply must be made up during the occupied period. On the other hand, if the preheating time turns out to be too long, the energy required during the preheat period will be greater than it need be, since the heating is operating for longer than necessary and hence the overnight building average temperature will be increased.

DATA SMOOTHING

Heating analysis curves are cumulative frequency curves of daily average external temperature for a given location and heating season. They tend to be rather ragged and it is desireable to smooth them when this is possible. Since the smoothing process is rather tedious the appropriate coefficients are pre-calculated and stored for each of the complete weather years available to the program. This means that it is not possible to produce smoothed curves if the user specifies a heating season other than a whole year.

The smoothed data is represented by a series of ten coefficients of normalised cubic B-splines over a fixed set of knots. The result is an approximation to the cumulative frequency by a function of temperature that has a continuous second derivative everywhere within the range from the minimum to the maximum temperatures occurring in the particular year in question, and has discontinuities in the third derivative only at the (six) internal knots.

The procedure used in the fitting was first to normalise the temperature range so that the minimum daily average temperature was transformed to zero, and the maximum to one. Coefficients for the B-spline representation with internal knots at 0.15, 0.25, 0.35, 0.65, 0.75 and 0.85 were then calculated using the NAG subroutine E02BAF. The results were such that the greatest difference between smoothed and unsmoothed cumulative frequencies for a given temperature, over a range of 120 weather years, was less than 0.015, or approximately 5 days in a year.

Within the program itself, the NAG subroutine E02BBF is used to reconstruct the smoothed curve from the ten coefficients.

ESTIMATION OF GAINS

This area falls into two sections, firstly the estimation of the available solar gains, and then the estimation of the proportion of the overall uncontrolled gains (solar, metabolic and lighting and small power) that is useful.

Solar Gains

P G T Owens (2) produced a method in 1980 of predicting daily average solar gains from the daily average temperature by means of linear interpolation from values at 5oC and 15oC derived from the January and July averages at Bracknell and location dependent corrections. This method was modified when it was discovered that the base figures did not agree with the results of a linear regression carried out on data measured at Kew, and to take account of long-wave radiative losses at night.

Despite the fact that the detailed results of this method are in conflict with experience, since it predicts the lowest solar gains in very cold weather, while it is a matter of observation that the coldest days are usually rather sunny, it can be shown [Basnett (1)] that the seasonal solar gains can be predicted quite accurately (within ±5%) by this method.

The original method is not directly applicable to intermittent heating since it provides no means of dividing the solar gain between the occupied and unoccupied periods. It has therefore been developed by taking separate regressions for the deep night period (2100-0300) and for each two-hour time band during the day (0300-0500, 0500-0700, 0700 0900,. . 1900-2100). Where an end of the occupied period falls inside one of these bands the gain is proportioned relative to the time inside and outside the ocuupied period. The same location correction factors as in the original method are still used. In accordance with the admittance method, if the building is 'heavy' (response factor greater than 5) the gains are assumed to occur one hour later than is really the case.

This allows us to calculate the incidental solar gain during the occupied and unoccupied periods separately. However, a large part of this radiative gain is absorbed into the fabric of the building and reradiated at a later time. This is taken into account firstly by taking a constant base level equal to the average radiative gain (solar plus half of the metabolic and other gains) and then reducing the swing about this base level by applying the 'alternating solar gain factor', according to Table A8.5 of the CIBSE Guide. This is approximated by the formula:

$$G = 0.65 - 0.03 R$$

which assumes that the 'heavy' building referred to in the guide has a response factor of 7, and the 'light' one one of 3, also that there are no internal blinds.

Estimation of Usefulness

Not all of the uncontrolled gains are useful in reducing the heating energy requirements of a building, even though their average level may be less than the gross heat requirement of the building. There are several interacting reasons for this. Firstly, within any one day, the times at which the uncontrolled gains occur are unlikely to coincide exactly with the times at which heating is needed. This means that, if uncontrolled gains occur when heating is not required the temperature in the building will rise above the design value, causing an increase in the heat loss. In extreme cases ventilation rates will have to be increased, possibly by opening windows, causing still more energy to be rejected from the building. Also, since the estimate of solar gain is averaged, not only over the whole of the occupied or unoccupied period, but also over all days with similar external average temperatures, some days will be sunny, with much more than the average solar gain, some of which may be excessive, while others will be dull, with much less than the average gains. Similar considerations apply to the other sources of uncontrolled gains. Two methods of assessing the amount of useful gain are provided. The first aims at preserving consistency with an earlier program for continuously heated buildings, and with the RIBA calculator (3), while providing plausible estimates of the proportion of the uncontrolled gains that is useful.

In the RIBA Heat Balance Method and in the earlier program the assumption was made that if the solar gain were less than half of the net heat requirement of the building, after allowing for the other internal gains, all of it would be useful, while if the solar gain were more than twice the net heat requirement no heat would need to be provided by the heating system. For intermediate amounts of solar gain the useful proportion was interpolated linearly. This assumption works well in practice, and produces results that are compatible with monitored heating energy consumptions in continuously heated buildings.

This cannot be transferred directly to the intermittent calculations since part of the peakiness has already been taken into account. In order to produce similar results with occupied periods of 8 to 10 hours roughly in the middle of the day, while still preserving the simplicity of the calculations the factors of two in the preceding paragraph have been changed to three. Thus, during the occupied and unoccupied periods separately, if the radiative gain is less than one-third of the net heat requirement, it is all assumed to be useful, while if the radiative gain is more than three times the net heat requirement no heat needs to be supplied by the heating system.

In assembling the heating analysis charts the amounts of useful gain are shown as if the gains which appear higher on the charts were not present. However, in the printed results no distinction between the sources of uncontrolled gains is made, and the useful proportion refers to the total of the uncontrolled gains.

The second method of assessing the useful gain is taken directly form the CIBSE Energy Code Part 2, and depends on the number of thermostats controlling the heating. If there are none, the useful solar gain is that which would fall on the building if all its surfaces faced North, and none of the internal gains are useful. If there is one thermostat per floor or group of floors, the useful solar gains are again those for a north face, while up to an average of 10 watt/sq metre of internal gain is useful. If there are separate thermostats for rooms or groups of rooms, all of the solar gain, and up to an average of 10 watt/sq metre of internal gain are taken as useful.

TYPICAL RESULTS

Since the results from this program amount to approximately 12 A4 pages, together with two heating analysis charts, space does not allow them to be presented in this paper. To give an indication of the type of results produced the final summary sheet, and one of the heating analysis charts, are presented at the end of the paper. The heating analysis charts are normally in four colours, but the shading has been selected so that they can still be interpreted if reproduced in monochrome, as in this paper.

ELECTRICAL FEATURES

Since the program is designed to be a tool for the Electricity Supply Industry it obviously contains features of particular interest to that industry, but fossil fuel fired systems are also included. The particular electrical features are:
Differential costs for the off-peak (midnight - 7 am) and day rate periods,
The specific operating characteristics of air-to-water heat pumps are built into the program.
The characteristics of storage systems are extensively covered in 'help' tables for the sizing and efficiency of heating systems.
Fossil fuel fired and direct-acting electrical systems are catered for by providing three separate efficiency factors. The first is for the efficiency of heat generation, which is set to 1.00 for electrical systems, the second is the efficiency of the distribution system, which may be set to 1.0 for heaters located in the spaces being heated, or if the distribution losses are shown individually as non-weather dependent loads, and the third is the control efficiency, which reflects the degree to which the control system provides heat only in the amounts, and at the times, that are required.

ACCURACY OF RESULTS

Table 1 shows a comparison of the results with energy consumptions measured in eleven commercial buildings. When the building has a comparatively large heating energy requirement the results are within 15% of the monitored data, which compares well with more sophisticated programs. For buildings with lower energy requirements the accuracy is better expressed as the absolute figure of ±20 kWh/sq metre, since it is the result of subtracting two numbers of comparable magnitude, the gross heat loss of the building, and the useful gains Both the losses and gains are subject to error, so that the error in their difference is not proportional to the size of that difference. This variation of ±20 kWh/sq metre corresponds to a variation in cost of heating the building of less than £1 per square metre at current costs, and this should be quite acceptable. It will also be observed that the differences between the calculated and measured energy consumptions are compatible with the reliabilities of the calculated consumptions derived from the sensitivity analysis.

SYMBOLS USED

A = surface area of a building element (m^2)

d = 24-hour average internal to external temperature difference (K)

D = difference between the design internal temperature and the average external temperature (K)

H = period the heating system operates (hours)

n = infiltration rate in air changes per hour

P = period of occupancy (hours)

R = building response factor

U = thermal transmittance of a building element (Watt/m^2 K)

V = ventilated volume of the building (m^3)

W = number of 'weekend' days in a week (days)

Y = admittance of a building element (Watt/m^2 K)

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RIBA 1980 Energy CROM E2, RIBA Publications, London, 1980

TABLE 1 - Comparison of measured and calculated energy consumptions for eleven buildings.

Building	Area m2	Response Factor	Energy Consumption [W/m2] Meas.	Calc.	Diff.	Difference %	Reliability %
A	550	2.39	85.0	70.5	-14.5	-17	51
B	5729	5.53	130.4	142.8	12.4	10	17
C	9853	4.69	122.8	110.4	-12.4	-10	23
D	641	4.12	212.2	199.7	-12.5	-6	14
E	285	4.47	146.3	161.8	15.4	11	23
F	371	4.25	100.8	104.8	4.0	4	31
G	1415	3.62	67.1	73.5	6.4	10	24
H	19176	4.28	120.5	136.5	16.1	13	25
J	1584	4.28	77.6	85.9	8.2	11	16
K	5846	5.11	125.4	108.6	-16.8	-13	22

The 'reliability' is obtained from the program's sensitivity analysis.

CIB-EXAMPLE PAGE 7

ANNUAL HEATING ENERGY AND COST SUMMARY

Building CIB-EXAMPLE Weather BRISTOL NORMAL

Occupied by 600 people for 9.0 hours on 5 days/week

Lighting etc 90.0 kW (occupied period) 10.0 kW (unoccupied)

Useful gains assessed by ECRC formula

Building Characteristics:		Design characteristics
Area	5897. sq.metres	19.0 C inside
G	1.24 Watt/cu.m K	1.20 air ch/hr (occupied)
Response	7.58	0.50 air ch/hr (unoccupied)

The heating is switched on

1 OCT to 24 DEC
3 JAN to 31 MAY

USEFUL HEATING ENERGY REQUIREMENTS

Preheat (0000 to 0700)	192446. kWh
Preheat (0700 to 0800)	0. kWh
Occupied (0800 to 1700)	23182. kWh
TOTAL	215629. kWh

Which could vary by plus or minus 32 %

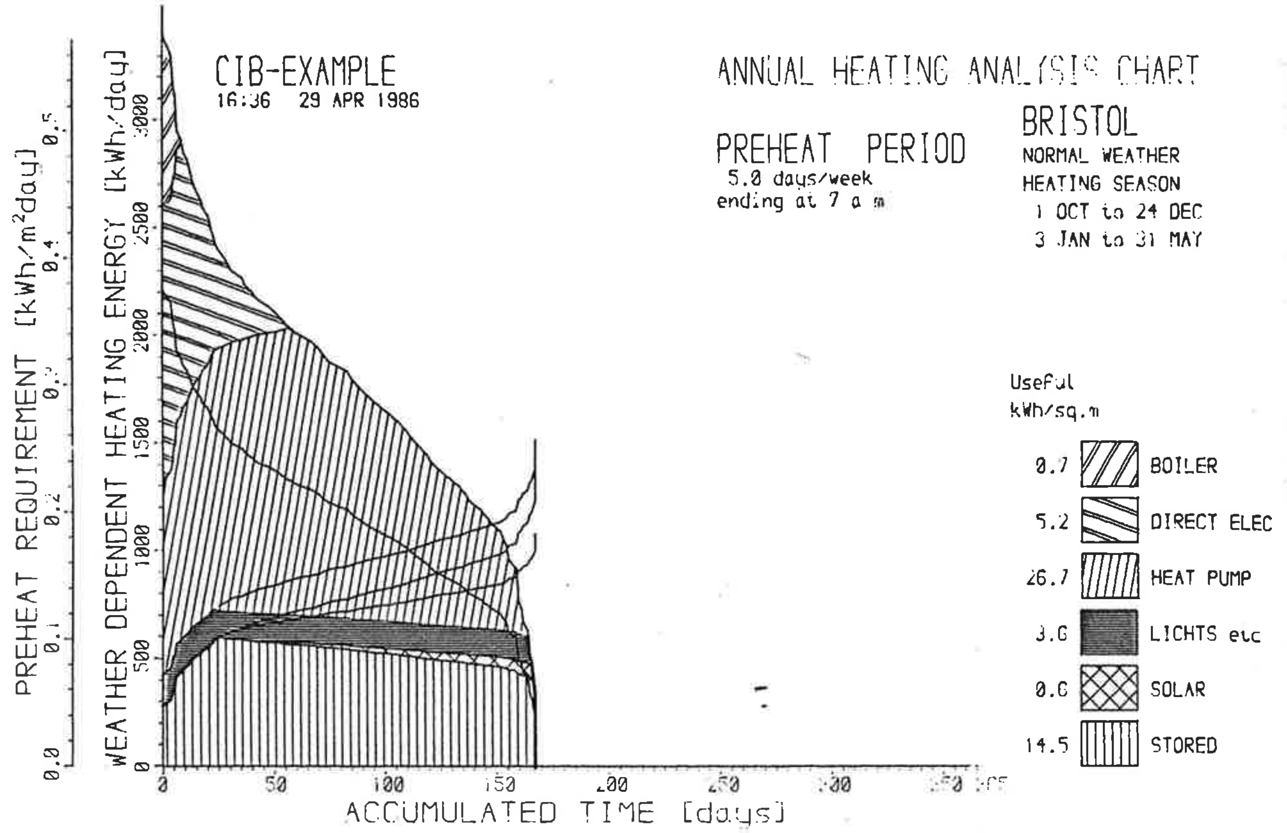
ANNUAL HEATING FUEL CONSUMPTION AND COST

Fuel	System number	Name	Consumption		Cost (Pounds)
Electricity	1	HEAT PUMP	75073. kWh	@ 2.000 p	1501.47
Electricity	1	HEAT PUMP	22462. kWh	@ 6.000 p	1347.69
Electricity	2	DIRECT ELEC	32378. kWh	@ 2.000 p	647.55
Gas	3	BOILER	204. therms	@ 39.00 p	79.53

The building requires a total equivalent of 135875. kWh of fuel

supplied at a total cost of £ 3576.

Figure 1 Summary sheet for sample building



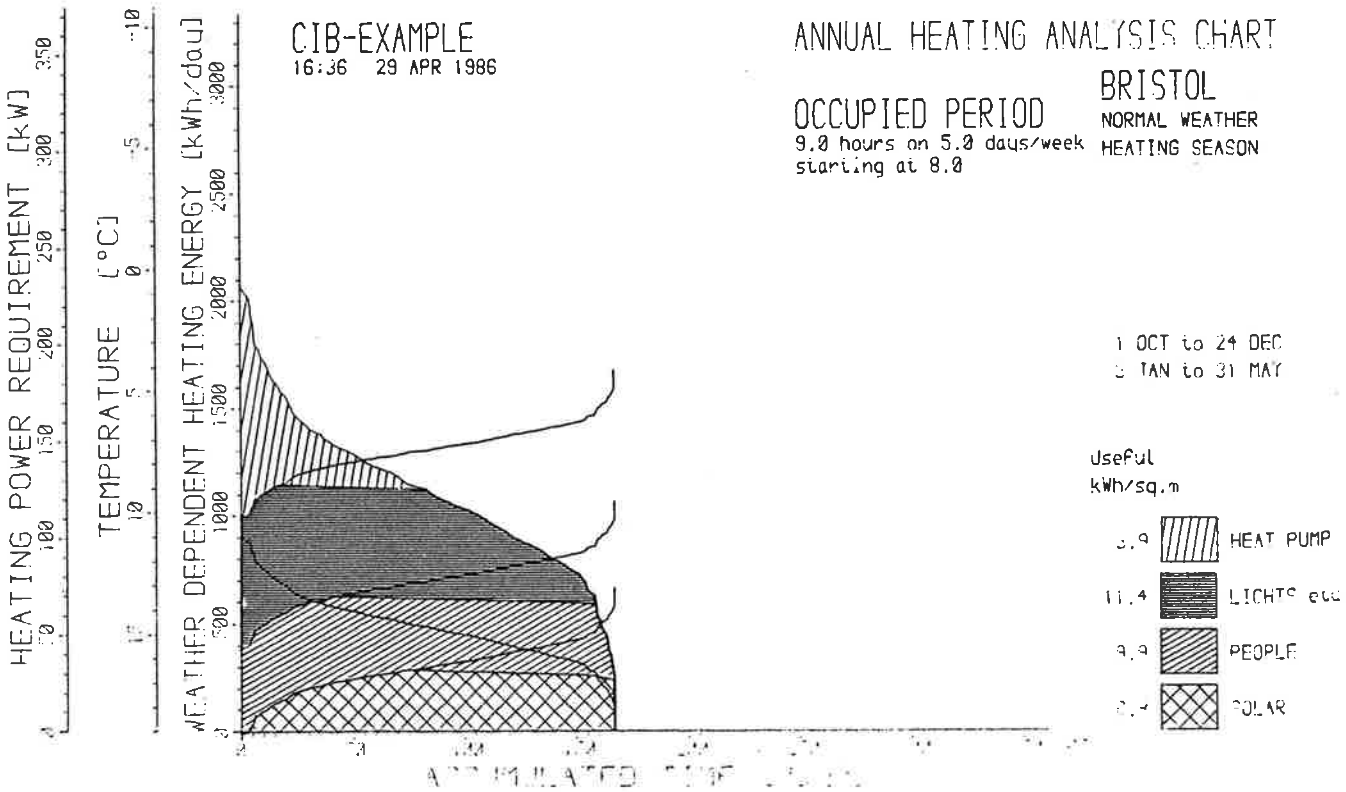


Figure [illegible]. Heating analysis charts for example building