#6588

A SIMPLIFIED METHOD FOR ESTIMATING ENERGY SAVINGS IN INTERMITTENT HEATING

C.Bianchi, G.M. Gislon
Politecnico di Milano
Dipartimento di Energetica
Dipartimento di Programmazione Edilizia

1. Introduction

Energy savings in buildings heating is very important because of the amount of needs compared with total energy requirement.

In 70^s many nations started creating rules and also facilities for thermal insulation of buildings. In the same time, for reaching more savings, also for existing buildings, the intermittent heating studies and experiments received new impulse (1,2,3,4,5,6,7,8,9,10,11,12).

The dynamic thermal performance of buildings is not simple: during the transient periods complex heating exchanges are present between parts of building, inside and outside; only using the computer we can, with a good accuracy, take count of it (13,14,15,16).

The problem solution is very simplified if the building is planned as an omogeneous and isothermal body (17) and by the use of the average season efficiencies of heating system (18,19,20).

2. Expression of energy savings in intermittent heating

The energy savings in intermittent heating are expressed by

$$s = (Q_c - Q_i)/(Q_c = 1 - (Q_i/Q_c) \quad (1)$$

where $Q_c(J)$, $Q_i(J)$ are respectively the building needs in continuous and intermittent heating.

The amount of Q_c is known with a good accuracy from

$$Q_c = Cg \cdot V \cdot D \quad (2)$$

#6588

where Cg (W/m³·°C) is the building total volume heating exchange coefficient, V (m³) is the building volume, D (°C·s) the degree-days. The expression (2) is very often used because of its simplicity in heating calculations, and it is verified in the experimental measurements especially for not too light buildings, see for instance (18).

The degree-days can be expressed as a function of the average external temperature $\bar{T}_{ou}$ (°C) of the heating season and of its lasting period d(s)

$$D = (T_{sp} - \bar{T}_{ou})\, d \tag{3}$$

where T_{sp} is the set-point temperature.

Generally the degree-days are calculated with an inside temperature lower than T_{sp} because of the free energy supplies. In the present work we take no count of it.

The energy needs depend also on the heating system efficiency in heating season, so the fuel savings finally are given by

$$E = (Q_c/\bar{\varepsilon}_c - Q_i/\bar{\varepsilon}_i)/(Q_c/\bar{\varepsilon}_c) = 1-(\bar{\varepsilon}_c/\bar{\varepsilon}_i)(Q_i/Q_c) = 1-(\bar{\varepsilon}_c/\bar{\varepsilon}_i)(1-s) \tag{4}$$

where $\bar{\varepsilon}_c$, $\bar{\varepsilon}_i$ are the medium values of the efficiencies plotted in the heating season, continuous and intermittent heating respectively.

3. Lumped capacity method

The building is planned as an homogeneous and isothermal body, having a surrounding surface in which all thermal resistances heating exchanges are concentrated. The schema is depicted in figure 1.

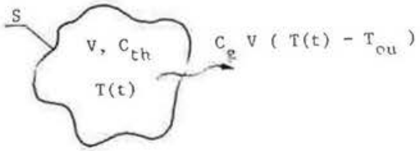

Fig. 1. Building ≡ lumped capacity body; C_{th} (J/°C) is the building thermal capacity; S (m²) is the surrounding surface; T (°C), T_{ou} (°C) are the body and outside air temperatures; t(s) the time.

During the cooling period, the outside temperature is constant, the heat

lost from the body must be equal to the heat released from storage. The integration of the energy balance equation is

$$(T - T_{ou}) / (T_{sp} - T_{ou}) = e^{-(t/\tau)} \tag{5}$$

where T_{sp} is the set-point temperature assumed as starting temperature in the cooling period, τ is the time constant expressed by

$$\tau = C_{th}/Cg\cdot V \tag{6}$$

If W is the internal heat release rate within the building, the heating equation is, in the same way:

$$(T - T_{sh}) / (T_f - T_{sh}) = 1-e^{-(t/\tau)} \tag{7}$$

where T_{sh} is the starting temperature during the heating period, T_f is the final temperature reached in the balance conditions and given by

$$W = \Phi = Cg\ V\ (T_f - T_{ou}) \tag{8}$$

4. Lumped capacity method for intermittent heating

The intermittent heating is defined by three time periods:
t_{sp}, time when T_{sp} is maintained;
t_c , cooling time (heating system off);
t_h , heating time when the building reaches the T_{sp}, starting from the cooling period final temperature.

The intermittent heating cycle must equal to the sum of the three time periods. In a daily cycle that we are considering from now on, time in hours, is

$$t_{sp} + t_c + t_h = 24 \tag{9}$$

Given the values of outdoor and indoor temperature T_{ou}, T_{sp}, we can decide the intermittent heating program by choosing two of the three time periods, for instance t_c and t_h because it is easier than using t_{sp}. From the (5), (7), (8), we have the following equation by which the power needed for maintaining the program is determined

$$W = Cg\ V\ (T_{sp} - T_{ou})\ (e^{t_c/\tau}\cdot e^{t_h/\tau}-1)/(e^{t_c/\tau}(e^{t_h/\tau}-1)) \tag{10}$$

If W_o is the base power, with T_{ou} the design external air temperature,

$$W_o = Cg\ V\ (T_{sp} - T_{ou}) \tag{11}$$

and p is the over power coefficient defined as

$$p = (W - W_o) / W_o \tag{12}$$

the same coefficient can be expressed by the intermittent programm

$$p = (e^{t_c/\tau} - 1) / (e^{t_c/\tau}(e^{t_h/\tau} - 1)) \tag{13}$$

Assuming that the building heating needs are proportional to the supplied powers, the energy savings during an intermittent heating cycle, in the base conditions are

$$s' = (24\ W_o - (t_{sp} \cdot W_o + t_h \cdot W))/24 \cdot W_o = 1 - t_{sp}/24 - (t_h/24) \cdot (W/W_o) =$$

$$= 1 - t_{sp}/24 - (t_h/24)(1+p) \tag{14}$$

We can see that in the energy savings equation there are only two parameters, the heating program t_{sp}, t_c, t_h, and the over power coefficient p. The parameter p, besides, depend on the heating programm and on the building thermal time constant. Thus, supposing that a given heating programm is the same for the entire heating season it comes out

$$s' = s \tag{15}$$

From equations (1) and (2) it comes then

$$Q_i = (1-s)\ Q_c = (1-s)\ Cg\ V\ D \tag{16}$$

expressing the building energy needs in intermittent heating.

5. Average season efficiencies of heating system

We are referring to the most general heating system, of the traditional type. The hypothesis are the followings:

- the heating system is of the centralised type, the boiler is separated from the building;
- the burner regulation is on-off;
- the boiler temperature is constant;
- the automatic regulation is made on the thermal carrier fluid temperature, its efficiency equals one;
- the fuel is gaseous or liquid, without unburat;
- the heating system thermal inertia equals zero.

The heat balance of the whole, building and heating system, is

represented in figure 2.

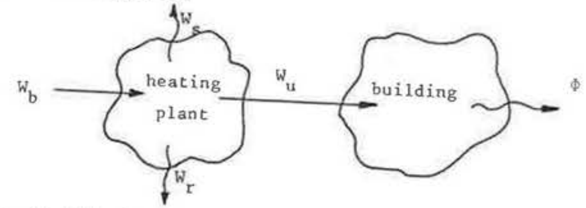

Fig. 2. Building and heating system thermal balance

where W_b, W_s, W_r, W_u, are respectively the fuel heating power, the boiler smoke losses, the boiler radiation and convection losses, the building heating needs.

W_b, W_s and W_r are constant, W_b and W_s are supplied and lost when the burner is on during the time period t_{on}, W_r is lost for the entire heating season period d. W_u is varying with the building heating load, the maximum value comes from the equation (12),

$$W = (1 + p)\ W_o \tag{17}$$

W defines the burner power W_b by means of the heating system nominal efficiency

$$W_b = W/\varepsilon = (1 + p)\ W_o/\varepsilon \tag{18}$$

$$= 1 - W_s/W_b - W_r/W_b = \varepsilon' - \pi \tag{19}$$

where

$$\varepsilon' = 1 - W_s/W_b \quad ; \quad \pi = W_r/W_b \tag{20}$$

The terms ε', π and ε are given generally as a function of the power W_b, related to the heating type, continuous or intermittent, through the over power coefficient p; p equals zero in the continuous heating type.

The average heating season factor is

$$\bar{m} = (T_{sp} - \bar{T}_{ou}) / (T_{sp} - T_{ou}) \tag{21}$$

where T_{sp}, T_{ou}, $\bar{T}_{ou}$ are respectively the set-point temperature, the outside design temperature and the outside average season temperature value, as before said.

We can express the season average value of the efficiency $\bar{\varepsilon}$, by writing the burner balance of the heating season

$$(W_b - W_s)\, t_{on} - W_r \cdot d = Q \qquad (22)$$

$$\bar{\varepsilon} = Q \,/\, W_b \cdot t_{on} \qquad (23)$$

Thus, the season average values of the efficiency in the continuous, $\bar{\varepsilon}_c$, and intermittent, $\bar{\varepsilon}_i$, heating are, taking count of the expressions (2), (11), (16), (18), (19),

$$\bar{\varepsilon}_c = \varepsilon_c \cdot \varepsilon'_c \cdot \bar{m} \,/\, (\varepsilon_c \cdot \bar{m} + \pi_c) \qquad (24)$$

$$\bar{\varepsilon}_i = \varepsilon_i \cdot \varepsilon'_i \cdot \bar{m} \,/\, (\varepsilon_i \cdot \bar{m} + \pi_i) \qquad (25)$$

where the subscripts c and i refer to the continuous and intermittent heating.

6. Results

The expressions (5) and (7) show as building cooling and heating speed increases when the time constant becomes lower. The time constant repreesnts therefore in a synthetic way the building thermal inertia; in fact in its expression the building mass and thermal insulation are included.

The expression (13) shows that for maintaining a given intermittent heating program, an over-power depending on the same program and on the building thermal inertia, but not on the external and the indoor temperature, is needed.

The over-powers increase rapidly when the building time constant increases (fig. 3.a) till τ reaches $\sim$ 50 h and when t_h decreases (fig. 3.b). The over-powers increase about linearly when the t_c increases (fig. 3.c).

The over-powers needed for keeping an intermittent heating program are generally high, except for little inertia buildings, short t_c and/or for t_h longer than 4÷5 h.

The equation (14) shows that the energy savings in the intermittent heating are function only of the intermittent heating program and of the building thermal inertia. It shows also that the energy savings are varying inversely to over-power, so they are rapidly decreasing as the building thermal inertia increass and are increasing as the t_c and t_h increase (fig. 4).

Generally the energy savings are little: for instance, for common intermittent heating programs (t_c = 10 h, t_h = 4 h, t_{sp} = 10 h), the energy savings are lower than 10% when the building time constant is higher than 20÷30 h.

The energy savings are on the contrary high for building having low thermal inertia and for long t_c.

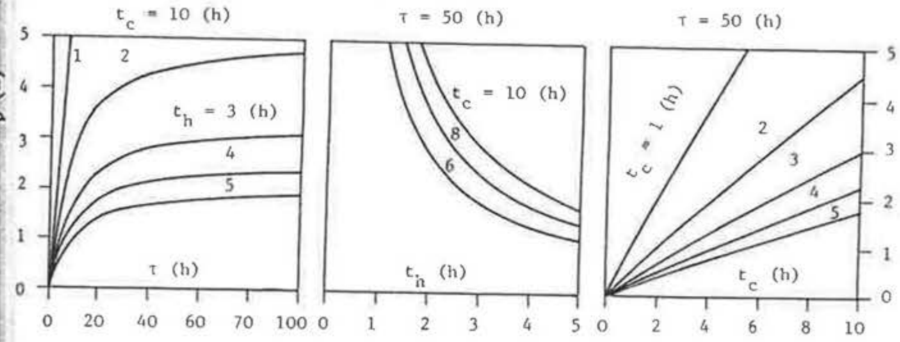

Fig. 3. Over-powers as a function of building time constant (a), t_h (b), t_c (c)

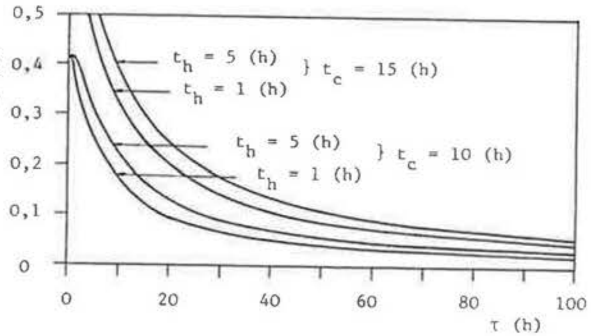

Fig. 4. Intermittent heating energy savings as a function of building time constant and intermittent heating program

Taking count of heating system the energy savings come from the combination of the equations (2), (4), (16), (24), (25)

$$E = 1-(1-s)(\varepsilon_c/\varepsilon_i)(\varepsilon'_c/\varepsilon'_i)(\varepsilon_i \bar{m} + \pi_i(1+p)/(1-s))/(\varepsilon_c \bar{m} + \pi_c) \qquad (26)$$

depending on the climate also, by the average heating season factor, $\bar{m}$, and the system nominal efficiencies and losses, ε, π.

The system losses are nearly constant when the heating power varies, so we can write $\varepsilon_c = \varepsilon_i = \varepsilon$, $\varepsilon'_c = \varepsilon'_i = \varepsilon'$, $\pi_c = \pi_i = \pi$. For good and well maintained heating systems $\pi \ll \bar{m}\,\varepsilon$ (in fact $\pi = 0{,}01 \div 0{,}03$; $\varepsilon = 0{,}85 \div 0{,}95$ $\bar{m} = 0{,}5$ medium value in Italy), so we can write the (26) simply

$$E = s - (\pi \cdot p) \,/\, (\varepsilon \cdot \bar{m}) \qquad (27)$$

The expression (27) takes no count of the losses , denominator, so it is more optimistic than the (26). The same expression shows as the over-power, the efficiency and losses of the system, reduce the energy savings. We see, in particular, that only when $\pi = 0$ the system efficiency, losses and climate do not reduce the intermittent heating energy savings. Little system losses reduce considerably the intermittent energy savings and it is possible the losses cause the continuous heating having more energy savings than intermittent heating. For example we examine the figure 5.

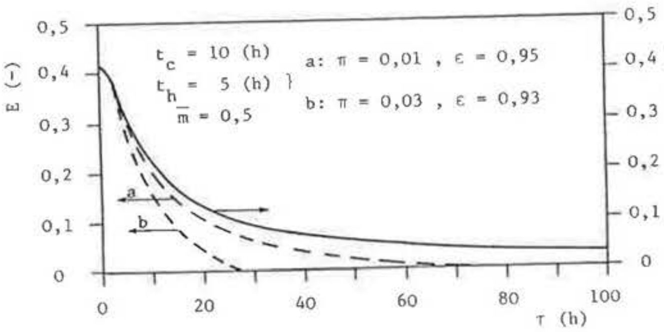

Fig. 5. Energy savings and heating needs as function of building time constant, for different system efficiencies and losses.

7. Conclusions

The lumped capacity model defines the building thermal inertia using the time constant, synthetic and easy determined building parameter. The same parameter we can obtain the intermittent heating energy savings by a simple expression, in which the intermittent heating program is also present.

The lumped capacity method is rigorous if the ratio of the body internal to the external thermal resistances is ≤ 0.1. For the buildings the ratio is not easy defined, however, assuming the surface resistance of the walls as the internal one, the same ratio is near to 0.1. On the other hand the lumped capacity method validity increases as the building thermal insulation increases.

The results obtained are good and in accordance with other authors, researche and studies. The results, besides, show as the energy savings are generally little for houses in presence of an intermittent program and a thermal inertia commonly used.

The energy savings reduce taking into account a traditional heating system and may be they are also negative depending it on the system efficiencies and losses and also on the climate.

We can say, therefore, that the intermittent heating does not afford so many energy savings as expected. Conclusions are unlike for other type of buildings, as school, offices, where the heating intermittance and the thermal inertia can be very different.

8. References

(1) R. Cadiergues et al. "Calcul des puissances et des économies en chauffage discontinu" Annales I.T.B.T.P., Mars 1952; reprinted in Promoclim E, Tome 8E, N. 4, Septembre 1977, pp. 211-248.

(2) D.P. Bloomfield, D.J. Fisk "The optimisation of intermittent heating" - Energy Heating and Thermal Comfort, BRE Building Research Series, Vol. 4 - The Construction Press, 1978, pp. 101-113.

(3) R. Cadiergues "La solution rationnelle pour le calcul des régimes variés" - Promoclim E, Tome 9E, N. 5, Décembre 1978, pp. 295-326.

(4) F. Lorentz, G.Masy "Méthode d'évaluation de l'économie d'énergie apportée par l'intermittence de chauffage dans les bâtiments. Traitement par différences finies d'un modèle à deux constantes de temps" - Laboratoire de Physique du Bâtiment, Université de Liège, Belgique - 1982.

(5) Mao Yu Zheng et al. "Conservazione energetica e riscaldamento intermittente" Condizionamento dell'aria, Riscaldamento, Refrigerazione, 1/83, pp. 39-44.

(6) P. Bondi et al. "Indagine sperimentale sul consumo energetico nel riscaldamento degli edifici" - La Termotecnica, marzo 1984,pp. 57-60.

(7) M. Levy, A. Shitzer "Dynamic Simulation of the Heating Load of Offices Coupled with Measured Occupancy Distribution" - ASHRAE Trans. 1984, Part IA, Vol. 90, pp. 226-244.

(8) D.M. Burch et al. "The Effect of Thermal Mass on Night Temperature Setback Savings" - ASHRAE Trans. 1984, Part 2A, Vol. 90, pp. 184-206.

(9) J.J. Lebrun et al. "Experimental Definition of the Intermittent Space Heating Demand of Different Houses" - ASHRAE Trans. 1984, Part 1B, Vol. 90, pp. 122-136.

(10) A.A. Arafa "The Dynamic Thermal Performance of Buildings" - Heat Transfer in Buildings and Structures. The 23rd National Heat Transfer Conference, Denver, Colorado, August 4-7, 1985, pp. 31-38.

(11) P. Brunello "Intermittenza di funzionamento e fabbisogni energetici nel riscaldamento degli edifici" - Rapporto 6/85 - Università degli Studi di Udine.

(12) J. Ingersoll, J. Huang "Heating Energy Use Management in Residential Buildings by Temperature Control" - Energy and Buildings, 8, 1985, pp. 27-35.

(13) T. Kasuda "Fundamentals of Buildings Heat Transfer" - Journal of Research of the NBS, vol. 82, N. 2, 1977, pp. 97-106.

(14) M.E. Hoffman, M. Feldman "Calculation of the Thermal Response of Buildings by the Total Thermal Time Constant Method" - Building and Environment, vol. 16, N2, 1981, pp. 71-85.

(15) D.P. Bloomfield et al. "Application of an Array Processor to the Solution of Transient Thermal Problems in Buildings" - Building and Environment vol. 17, N. 2, 1982, pp. 95-105.

(16) J. Sicard et al. "Analyse modale des échange thermiques dans le bâtiment" Int. J. Heat and Mass Transfer, Vol. 28, N. 1, 1985, pp. 111-123.

(17) F.P. Icropera, D.P. Dewitt "Fundamentals of Heat and Mass Transfer" John Wiley & Sons, 1985 - pp. 173-180.

(18) M. Godin, G. Piar "Estimation de la consommation calorifique annuelle d'une installation de chauffage. Application à la prévision de COP annuel des pompes à chaleur - Entropie N. 94, 1980, pp. 52-60.

(19) P. Anglesio "Rendimento in funzione del carico di sistemi caldaia-bruciatore per riscaldamento" - La Termotecnica, vol. 36, 1982, pp. 76-90.

(20) D.M. Burch et al. "The Effect of Wall and Mass on Winter Heating Loads and Indoor Comfort - An Experimental study" - ASHRAE Trans. 1984, Part. 1B, Vol. 90, pp. 94-121.