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An improved design method for estimating the annual auxiliary energy requirement for solar heating building

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Abstract

Thermal design of a passive building is closely interrelated to the architectural design of the structure itself, there is a spectrum of methods for estimating long-term thermal performance of these buildings that ranges from practical experience using of charts and tables that are based on combinations of experience and calculations to correlation and useful methods that are the counterparts of the methods for active systems. The design method to be described in more details in the following, have common basic feature. It uses the correlations of result of simulations to determine long-term performance. The correlating variables, the definitions of terms, the ways in which the correlations are used are however very different from one to another. In this paper the unutilizability method design collector–storage wall will illustrate in details.

Keywords: Design; Energy requirement; Solar; Building

1. Introduction

1.1. A collector–storage wall

In passive heating systems, storage of thermal energy is provided in the walls and roofs of the buildings. A case of particular interest is the collector–storage wall, which is arranged so that solar radiation transmitted through glazing is absorbed on one side of the wall. The temperature of the wall increases as energy is absorbed and time-dependent temperature gradients are established in the wall. Energy is lost through the glazing and is transferred from the room side of the wall to the room by radiation i.e., convection. Some of these walls may vented, have openings in the top and bottom through which air can circulate from and to the room by natural convection, providing an additional mechanism

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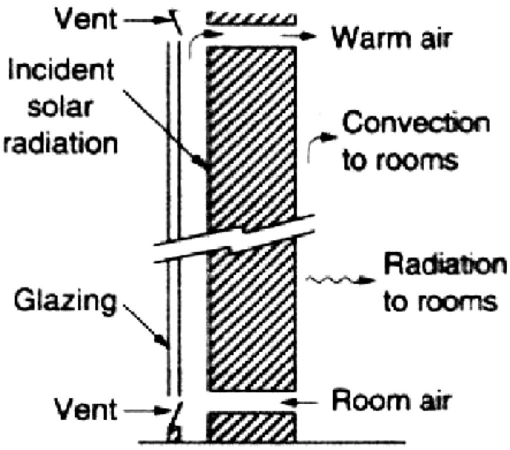

Fig. 1. Section of a storage wall with glazing and energy absorbing surface on one surface.

for transfer of energy of the room. Fig. 1 shows a section of the wall.

The monthly average absorbed radiation $\bar{S}$ can be calculated from:

$$\bar{S} = \overline{H_b}\,\overline{R_b}\,\overline{(\tau\alpha)}_b + \overline{H_d}\,\overline{R_d}\,\overline{(\tau\alpha)}_d\left(\frac{1+\cos\beta}{2}\right) + \overline{H_g}\rho_g\overline{(\tau\alpha)}_g\left(\frac{1-\cos\beta}{2}\right) \quad (1)$$

where $\overline{\tau_\alpha}$ is estimated from:

$$\overline{(\tau\alpha)} = \frac{\bar{S}}{\overline{H_T}} = \frac{\bar{S}}{\overline{H}\,\overline{R}} \quad (2)$$

An isotropic-diffuse assumption is used for the diffuse and ground reflected terms, $(\tau\alpha)_b$ and $(\tau\alpha)_d$ can be evaluated by using the effective incidence angle. As functions of properties of the cover and absorber and, the collector slope angle β, and so do not change with time. Mounted at fixed β the hourly and monthly values are thus following the same pattern and they all can be written with or without a mean value.

The long-term value of $\bar{R}$ can be calculated by integrating G_T and G from sunrise to sunset.

For all days over many years of data $\bar{R}$ can be written as:

$$\bar{R} = \frac{\sum_{\text{day}=1}^{N}\int_{\text{tsr}}^{\text{tss}} G_T \mathrm{d}t}{\sum_{\text{day}=1}^{N}\int_{\text{tsr}}^{\text{tss}} G \mathrm{d}t} \quad (3)$$

To evaluate the numerator, it is convenient to replace G_T by I_T, where I_T is the radiation at any time of the day. So for N days this radiation is defined as:

$$NI_{\mathrm{T}} = N\left\{(\bar{I} - \bar{I}_d)R_b + \bar{I}_d\left(\frac{1+\cos\beta}{2}\right) + \bar{I}_g\rho_g\left(\frac{1-\cos\beta}{2}\right)\right\} \quad (4)$$

where $\bar{I}$ and $\bar{I}_d$ are long-term average of the total and diffuse radiation, obtained by summing the values of I and I_d over N days. Then Eq. (3) becomes:

$$\bar{R} = \frac{\int_{\text{tsr}}^{\text{tss}}\left(\bar{I} - \bar{I}_d\right)R_b + \overline{I_d}\left(\frac{1+\cos\beta}{2}\right) + \overline{I_g}\rho_g\left(\frac{1-\cos\beta}{2}\right)}{\overline{H}} \quad (5)$$

The ratio of total hourly to total daily radiation, r_t, can be evaluated from:

$$r_t = \frac{\Pi}{24}\left(a + b\cos\omega\right)\frac{\cos\omega - \cos\omega_s}{\sin\omega - \frac{\Pi\omega_s}{180}\cos\omega_s} \quad (6)$$

where:

$$a = .409 + .5016 \sin(\omega_s - 60) \quad (7)$$

$$b = .6609 - .4767 \sin(\omega_s - 60) \quad (8)$$

a similar equation can be obtained for the ratio of hourly to daily diffuse radiation, r_i, Eqs. (7) and (8) relate r_d and r_t to ω and sunset angle ω_s. Combining equations (5), and substituting r_d and r_t leads to:

$$\bar{R}=\frac{\cos(\phi-\beta)}{d\cos\phi}\left[\begin{array}{l}\left(a-\frac{\overline{H_d}}{\overline{H}}\right)\left(\sin\omega_s'-\frac{\Pi\omega_s'}{180}\cos\omega_s''\right)\\+\frac{b}{2}\left(\frac{\Pi\omega_s'}{180}\sin\omega_s'\left(\cos\omega_s'-2\cos\omega_s''\right)\right)\end{array}\right]+\frac{\overline{H_d}}{\overline{H}}\left(\frac{1+\cos\beta}{2}\right)+\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (9)$$

where ω_s' is given by

$$\omega_s'=\min\left[\begin{array}{l}\cos^{-1}\left(-\tan\phi\tan\delta\right)\\\cos^{-1}\left(-\tan\left(\phi-\beta\right)\tan\delta\right)\end{array}\right] \quad (10)$$

and

$$\omega_s''=\cos^{-1}\left(-\tan\left(\phi-\beta\right)\tan\delta\right) \quad (11)$$

Also a and b given by equation and d is given by:

$$d=\sin\omega_s-\frac{\Pi\omega_s}{180}\cos\omega_s \quad (12)$$

2. The unutilizability method

2.1. Collector–storage wall

This method establishes the limiting cases of zero and infinite capacitance buildings; where a real building lies between the limits is determined by correlations based on simulations. The calculations are done monthly, with the significant final result being the annual amount of auxiliary energy needed for the passively heated structures.

The monthly energy flows in a collector–storage wall building are shown schematically in Fig. 2. The heating loads are shown in two parts. The load L_{ad} is that which would be experienced if an adiabatic wall which replaced the collector–storage wall. The load L_w is the monthly energy loss from the building through the collector storage-wall that would be experienced if the transmittance of the glazing for solar radiation were zero, and can be estimated by:

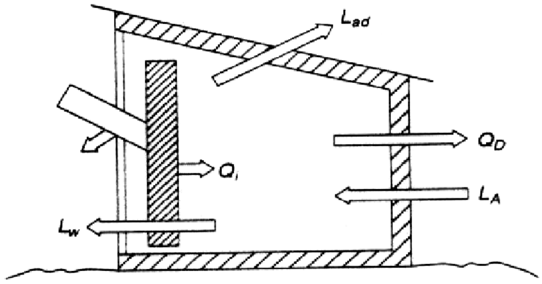

Fig. 2. Monthly energy flows for a collector–storage wall building storage of energy in the wall or structure is not indicated from Monsen (1982).

$$L_{ad}=\left(UA\right)_{ad}\left(DD\right) \quad (13)$$

$$L_w=\left(UA\right)_w\left(DD\right) \quad (14)$$

$$U_w=\frac{1}{\frac{1}{\overline{U_L}}+\frac{1}{U_i}+\frac{\delta}{k}} \quad (15)$$

where U_i is the heat transfer coefficient between the inner wall surface and the air in the room. The wall thickness is δ and its thermal conductivity is k; $\overline{U_L}$ is the average heat loss coefficient from the outer wall surface through the glazing to ambient. $\overline{U_L}$ is conceptually the same as loss coefficients from plates and has typical value for one to three glazing 3.7, 2.5, 1.9 (w/m^2°C). If night insulation is used, $\overline{U_L}$ would be estimated as a time-average of the day and night conduction:

$$\overline{U_L}=(1-i)U_L+i\left(\frac{U_L}{1+R_N U_L}\right) \quad (16)$$

U_L is the loss coefficient without night insulation; R_N is the thermal resistance of the night insulation and i is the fraction of 24-hour day in which the insulation is utilized.

The load L_{ad} and L_W are calculated assuming the indoor temperature to be at the low thermostat set temperature. In general the room temperature is more than this temperature, and the actual losses from the building will be greater than $L_{ad} + L_W$; this increase is represented by Q_D.

The other contribution is energy, which must be removed from the building to keep the indoor temperature from exceeding the high thermostat set temperature.

Let Q_n be the net monthly heat transfer through the collector–storage wall into the heated space. It is a complex function of wall parameters and resistance, capacitors and current source, as shown.

However, by assuming:

(a) There are no vents in the wall to allow circulation between the room and the gap between the wall and glazing.

(b) The wall thermal storage capacity over a month is negligible compared to the total energy flow through the wall. It can be shown that the temperature profile through the wall is linear. For monthly average daily energy computations, the network of Fig. 3 is replace by the simple resistance network

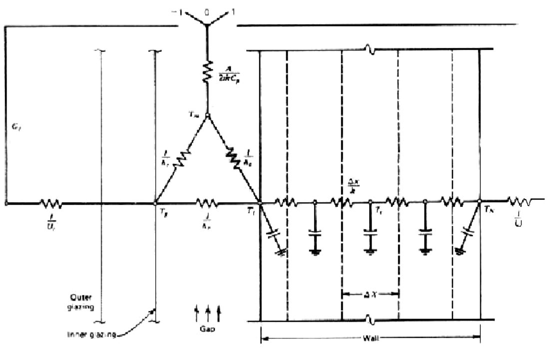

Fig. 3. Thermal circuit diagram for a collector–storage wall with double-glazing.

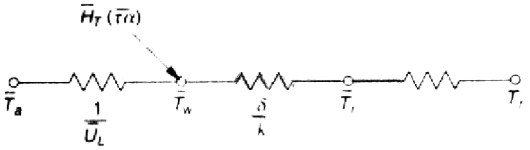

Fig. 4. Monthly average resistance network for collector–storage walls. From Monsen et al. (1982).

shown in Fig. 4. Estimation of Q_n can be based in this network, given in Fig. 4. If $\overline{T_a}$ and $\overline{U_L}$ are assumed to be constant at their monthly average values,

$$\overline{S} = U_K(\overline{T_W} - T_r)\Delta t + \overline{U}_L(\overline{T_W} - \overline{T_a})\Delta t \tag{17}$$

where U_K is the conduction from the wall surface to the room given by

$$\overline{U}_K = \frac{U_i K}{K + U_i \delta} \tag{18}$$

Here $\overline{T_W}$ is the monthly average of outer wall temperature and T_r is the room temperature, which is assumed to be at the low thermostat, set temperature. Additional losses through the wall occurring as a result of the average room temperature being above the T_r will be accounted for in Q_D.

Δt is the number of time unit in a day. The average outer wall temperature can be found by

$$\overline{T_W} = \frac{\overline{S} + (U_K T_r + \overline{U_L}\,\overline{T_a})\Delta t}{(U_K + \overline{U_L})} \tag{19}$$

This can be used to calculate the net monthly heat transfer to the building:

$$Q_n = U_k A_r(\overline{T_W} - T_r)\Delta t N \tag{20}$$

Now we establish the limits of performance of building with collector–storage wall. For a hypothetical building with infinite thermal capacitance, all of the net gain Q_n can be used.

For monthly energy balance on this infinite thermal capacitance is

$$L_{A,i} = (L_{\text{ad}} - Q_i)^+ \tag{21}$$

A hypothetical building having zero thermal capacitance in the collector–storage wall has the maximum auxiliary but not the time of the solar gains to the building. A monthly energy balance on this zero-capacitance building gives:

$$L_{A,Z} = (L_{\text{ad}} - Q_n + Q_D)^+ \tag{22}$$

where Q_D, the energy dumped, is the month's energy entering building through the wall that dose not contribute to reduction of the auxiliary energy requirement. Here Q_D can be determined by integrating $\dot{Q}_D$, the rate at which excess energy must be removed to prevent the indoor temperature from rising above the low thermostat set temperature is calculated by:

$$\dot{Q}_D = \left[U_K A_r (T_W - T_r) - (UA)_{\text{ad}} (T_a - T_b)\right]^+ \tag{23}$$

An energy balance on the absorbing surface of the hypothetical zero thermal capacity collector–storage walls at any time gives:

$$I_T (\tau\alpha) A_r = U_L A_r (T_W - T_a) + U_K A_r (T_W - T_r) \tag{24}$$

This can be solved for T_W:

$$\dot{Q}_D = \left[U_K A_r \left[\frac{I_T(\tau\alpha) - U_L(T_r - T_a)}{U_K + U_L}\right] - (UA)_{\text{ad}}(T_a - T_b)\right]^+ \tag{25}$$

Assuming $(\tau\alpha)$ and T_a to be constant at their monthly mean values $\overline{\tau\alpha}$ and $\overline{T}_a$, Eq. (25) can be integrated over the month to give Q_D for this zero-capacitance building.

$$Q_D = \frac{U_K A_r \overline{(\tau\alpha)}}{U_K + U_L} \sum (I_T - I_{TC})^+ \tag{26}$$

where the critical reduction level I_{TC} makes $\dot{Q}_D$ zero is given by:

$$I_{TC} = \frac{1}{\overline{(\tau\alpha)} A_r} \left[(UA)_{\text{ad}} \left(\frac{U_L}{U_K} + 1\right) \frac{T_b - \overline{T}_a}{T_r - \overline{T}_a} + U_L A_r\right] (T_r - \overline{T}_a) \tag{27}$$

The summation in Eq. (24) is the same as that in the definition of the daily utilizability $\overline{\varphi}$ that is given by following equation

$$\overline{\varphi} = \frac{1}{\overline{H}_{\text{T}} N} \sum_{\text{days}} \sum_{\text{hour}} (I_T - I_{TC})^+ \tag{28}$$

thus:

$$Q_{\text{D}} = \frac{U_K A_r \overline{S} N \overline{\varphi}}{L_{\text{ad}} + L_W} \tag{29}$$

Eqs. (21) and (22) provide estimates of the limits of the performance of collector–storage wall systems. The solar fractions corresponding to the limits are defined as:

$$fi = 1 - \frac{L_{A,i}}{L_{\text{ad}} + L_W} = \frac{L_W + Q_i}{L_{\text{ad}} + L_W} \tag{30}$$

and

$$f_z = 1 - \frac{L_{A,z}}{L_{\text{ad}} + L_W} = f_i - \frac{U_K}{U_K + U_L} \overline{\varphi} X \tag{31}$$

where the solar-load ratio is defined as:

$$X = \frac{\overline{S} N A_r}{L_{\text{ad}} + L_W} \tag{32}$$

In order to establish where between these limits, a real system will operate, correlation methods are used. A parameter is needed that describes the storage capacity of the building, S_b, and that of the wall, S_W building thermal storage capacity for a month (i.e. with N cycle) is:

$$S_b = C_b(\Delta T_b)N \tag{33}$$

where C_b is the effective building storage capacitance and ΔT_b is the allowable temperature swing i.e., the difference between the high and low thermostat set-points values of C_b can be estimated from information in table (A).

The storage capacity of the wall for the month (i.e. with N cycle) is

$$S_W = C_P \delta A_r \rho(\Delta T_W)N \tag{34}$$

where C_p, ρ, δ and A_r are the heat capacity, density, thickness, and area of the wall, and inside ΔT_W is one-half of the difference of the monthly average temperature of the outside and inside surfaces of the wall (the monthly average gradient through the wall being linear) The heat transfer through the wall into the heated space Q_i can be expressed in terms of ΔT_W is:

$$Q_i = \frac{2KA_r}{\delta}(\Delta T_W)\Delta t N \tag{35}$$

Thus:

$$S_W = \frac{\rho C_P \delta^2}{2k\Delta t} \tag{36}$$

A correlation for monthly solar fraction f (here defined as $1 - L_A/(L_{ad} + L_w)$) is a function of f_i and a dimensionless storage-dump ratio, then:

$$Y = \frac{S_b + 0.047 S_W}{Q_D} \tag{37}$$

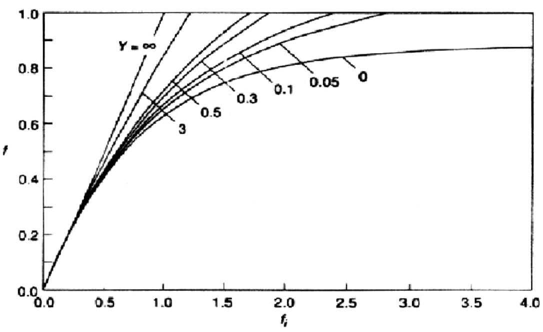

Fig. 5. Correlation for f as a function of f_i and storage dump ratio Y. From Monsen et al. (1982).

The correlation for f is shown in Fig. 5.

The equation of solar fraction is:

$$f = \{Pf_i + 0.83(1-P)[1-\exp(-1.26 f_i)],1\} \tag{38}$$

$$P = [1-\exp(-0.144Y)]^{0.53} \tag{39}$$

(Monsen et al. did not use zero capacitance limits in the correlations. However as shown Eqs. (29), (36) and (37) predict approximately the solar fraction at zero thermal storage.)

To estimate the annual performance of a collector–storage wall system, a set of steps for each month is to be followed:

First, the month's absorbed radiation is calculated by Eq. (2).

Second, the load L_{ad} and L_W are estimated, taking into account internal generation if necessary.

Third, the month's heat gain across the collector–storage wall Q_i is estimated using Eqs. (18) to (20).

Forth, the energy dumped that would be occurring in a zero-capacitance system Q_D is calculated from Eq. (29). This requires that daily unutilizability be known; it is based on the critical radiation level given by Eq. (27).

Fifth, a series of additional parameters are needed to calculate f from Eq. (38). These are f_i from (30) S_b and S_W, (the building and wall effective thermal capacitances from Eqs. (33)

Table 1
Calculated parameters (W/m^2)

Month	$\overline{S}$ (MJ/m^2)	$\overline{\tau\alpha}$	$L_w + L_{ab}$ (GJ)	Q_n (GJ)	$I_{T,C}$ (W/m^2)	$\overline{\Phi}$	Q_D (GJ)	f_i	f	L_A (GJ)
Apr.	6.36	0.58	2.95	1.37	192	0.442	0.442	0.61	0.57	1.3
Aug.	6.42	0.55	0.20	2.17	0	1.000	1.000	11.31	1.00	0
Dec.	6.61	0.70	8.23	0.69	485	0.120	0.120	0.23	0.23	6.4
Feb.	8.47	0.67	7.48	1.10	504	0.120	0.120	0.29	0.29	5.3
Jan.	7.60	0.70	9.13	0.85	535	0.097	0.097	0.24	0.23	7.0
July	5.63	0.52	0.14	2.02	0	1.000	1.000	14.66	1.00	0
June	5.63	0.54	0.25	1.83	0	1.000	1.000	7.44	1.00	0
Mar.	7.32	0.63	6.16	1.20	400	0.172	0.172	0.34	0.33	4.1
May	5.84	0.55	1.18	1.58	41	0.849	0.849	1.48	1.00	0
Nov.	8.44	0.70	5.38	1.59	309	0.315	0.315	0.44	0.43	3.1
Oct.	9.35	0.66	2.32	2.39	115	0.703	0.703	1.17	0.94	0.2
Sep.	7.98	0.61	0.65	2.29	0	1.000	1.000	3.65	1.00	0
Total										27.4

and (36)), Y (the storage-dump ratio, Eq. (37)). The last step is to calculate the auxiliary energy required for the month:

$$Q_A = (L_{\text{ad}} + L_W)(1 - f) \tag{40}$$

The monthly auxiliary energy requirements are the summed to get the annual auxiliary energy needs.

3. Case study

A collector–storage wall system at 40° Latitudes to be designed for degree days to base 18.3°C. The south-facing vertical collector–storage wall is double glazed (Night insulation is not to be used) the monthly average daily radiation on horizontal surface $\overline{H}$ is MJ/m^2, is shown in the table that follows. The ground reflection coefficient is assumed to be 0.3 for all months. The angular dependence of $(\tau\alpha)$ for two-cover glazing is 0.83 $((\overline{\tau\alpha})/(\tau\alpha)_n)$. The glass has KL = 0.0125 per sheet. The building has the following characteristics, the minimum allowable inside temperature T_r is 18.3°C. The allowable temperature swing Δt is 6°C, and internal energy generation is small. $(UA)_h$ is 138 w/°C and the effective heat capacity of the building C_b is 23.5 $MJ/°C$. The overall heat transfer coefficient from the storage wall to interior is 8.3 w/m°C.

The wall has the following characteristics, it is masonry with density of 2105 kg/m^3, and its heat capacity is 0.95 kJ/kg°C. The wall is 0.46 m thick and has an area of this report to be 2.5 w/m^2°C. The U of windows (which do not have night insulation) is 4.17 w/m^2°C.

The solution has been done for all month of the heating season and the result is shown in the Table 1.

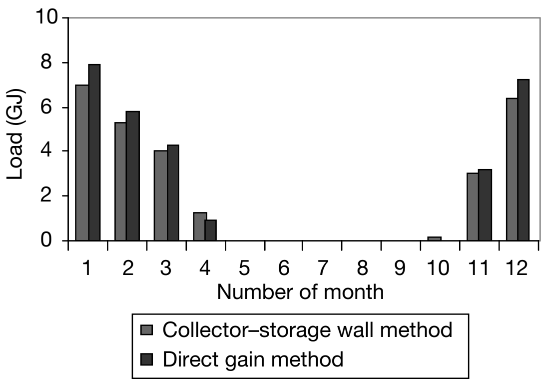

Fig. 6. Total load of building for a year.

The results of collector–storage wall method and direct gain method are shown in Fig. 6 for comparison with this method. As it has shown collector–storage wall method is a useful method for designing a collector.

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