LA-UR -83-2246

Conf. 830839--1

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--83-2246

DE83 015214

TITLE: PREDICTION OF INTERNAL TEMPERATURE SWINGS IN DIRECT-GAIN PASSIVE-SOLAR BUILDINGS

AUTHOR(S): J. Douglas Balcomb

SUBMITTED TO: Solar World Congress
Perth, Australia
August 14-19, 1983



Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

MASTER

# PREDICTION OF INTERNAL TEMPERATURE SWINGS IN DIRECT GAIN PASSIVE SOLAR BUILDINGS*

J. Douglas Balcomb

Los Alamos National Laboratory
Los Alamos, New Mexico 87545 USA

## ABSTRACT

The diurnal heat capacity method is presented for estimating inside-temperature swings attributable to direct winter solar gain. The procedures are simplified to be suitable for hand analysis, aided by tables of diurnal heat capacity for various materials. The method has been spot checked against computer simulation and has been used successfully by a group of 20 builders in New Mexico to analyze whether temperature swings would be excessive in their designs.

## KEYWORDS

Passive solar, direct gain, temperature swings, diurnal heat capacity, harmonic analysis, design guidelines, design tools.

## INTRODUCTION

A common problem in the design of direct gain passive solar heated buildings is the propensity of some buildings to exhibit large inside-temperature swings. This occurs when there is insufficient heat storage for the area of direct gain glazing used. Besides reducing solar-heating contribution, there are two solutions to this problem: increase the size of direct gain heat storage mass or replace some direct gain with an indirect system, such as an unvented Trombe wall, to supply solar heat out of phase with the direct gain effects.

The problem facing the designer is to predict temperature swings so as to know when corrective design measures are necessary. The analysis should be simple enough for easy use and yet comprehensive enough to account for the primary effects. This paper presents such a simplified method: reference to diurnal heat capacity tables (or graphs) and a procedure for their use. The method does not account for inside-temperature swings caused by the swing in outside temperature because this is normally small and out of phase with the direct gain swing. Temperature swings resulting from variations in internal-heat generation can be predicted by a minor extension of the method.

*This work performed under the auspices of the US Department of Energy, Office of Solar Heat Technologies.

The alternative to a simplified method, such as described here, is computer simulation. This is a powerful approach more often used by building scientists than designers and frequently requiring more time, effort, expertise, and computing equipment than is available or warranted.

## ROLE OF MASS IN DIRECT GAIN

Maintaining good thermal comfort in a direct gain passive solar building requires sufficient internal mass to store daytime solar gains until release at night or during cloudy weather. This mass must be located within the building where it has adequate access to solar gains and must have a sufficient exposed surface area. A rough rule of thumb has evolved calling for at least six times as much mass surface area as surface area of direct gain glazing. It was originally thought that mass must be in the direct sun to be effective for heat storage; we now know that most surfaces that enclose a direct gain space are also quite effective and that light-colored walls can lead to smaller room-temperature swings than dark colors.

For heat to be stored in a massive building element, it must penetrate into the depth of the material. This means that an effective heat-storage element should have the following characteristics:

- It should have a high thermal capacity. That is, the product of density, $\rho$, and specific heat, c, should be large.
- It should have a high thermal conductivity, k. The deep portions of the wall cannot participate in the charging and discharging cycle if they are isolated from the room by a layer of low thermal conductivity material.

From the above considerations, we can understand that if the product $\rho ck$ is high, the heat-storing ability of the wall will be high. This result will be borne out in the equations to follow.

In the initial analysis, a 24-hour sine wave, will be considered; this is the diurnal portion of the building response. At a later stage a modification will be made to account for higher harmonics. The final result is an estimate of the temperature swing resulting from direct gain during a sequence of clear midwinter days.

## ANALYTIC SOLUTIONS

The one-dimensional heat diffusion equation can be solved in closed form for a single frequency (Davies, 1973). Consider a slab of material of thickness (X) with sinusoidal temperatures (T) and heat fluxes (q) at faces 1 and 2. The result is

$$q_1 = q_2 \cosh \gamma X + T_2 k \sinh \gamma X \quad , \tag{1}$$

$$T_1 = T_2 \cosh \gamma X + (q_2/k\gamma) \sinh \gamma X \quad , \tag{2}$$

where $\gamma = (1 + i)\sqrt{\pi\rho c/Pk}$ , $i = \sqrt{-1}$, P = period of the oscillation (1 day).

We are interested in the heat transferred through face 1 during one-half cycle compared with the peak-to-peak temperature swing at face 1. This is the diurnal heat capacity, referred to here as dhc. This is closely related to the thermal admittance, $y_1$, used by Davies (1973):

$$y_1 = \hat{q}_1/\hat{T}_1; \quad dhc = (P/2\pi)y_1 \quad ,$$

where $\hat{q}_1$ and $\hat{T}_1$ refer to the peak departure of $q_1$ and $T_1$ from their average values.

If the wall is infinite in thickness, $dhc_\infty = \sqrt{P\rho ck/2\pi}$ .

If the wall is finite and $q_2 = 0$, $dhc = dhc_\infty Zg$ , where $Z = \tanh \gamma X$ and $g = e^{i\pi/4}$ .

The magnitude and phase of Zg can be expressed in terms of real variables as follows:

$$\mathrm{mag}\ (Zg) = \sqrt{(\cosh 2\tau - \cos 2\tau/(\cosh 2\tau + \cos 2\tau)}\ , \text{ and}$$

$$\mathrm{phase}\ (Zg) = \arctan\ (\sin 2\tau/\sinh 2\tau) + \pi/4\ , \quad \text{where } \tau = X\sqrt{\pi\rho c/Pk}\ .$$

The magnitude of dhc is shown in Fig. 1 for several common building materials. The phase varies from 90° (for thin materials) to 45° (for thick materials).

If the wall comprises several layers of different materials, the dhc of the composite wall can be determined from $y_1$ using Eqs. (1) and (2) as follows:

$$y_1/a = \frac{y_2/a + Zg}{1 + Zy_2/ag} \qquad \text{where} \qquad a = \sqrt{2\pi k\rho c/P}$$

This equation is used repetitively, working from the outside layer inward, layer by layer, by setting $y_2$ for each subsequent layer equal to $y_1$ for the previous layer at the interface. The procedure and derivations are outlined in more detail by Davies (1973) and Balcomb (1983).

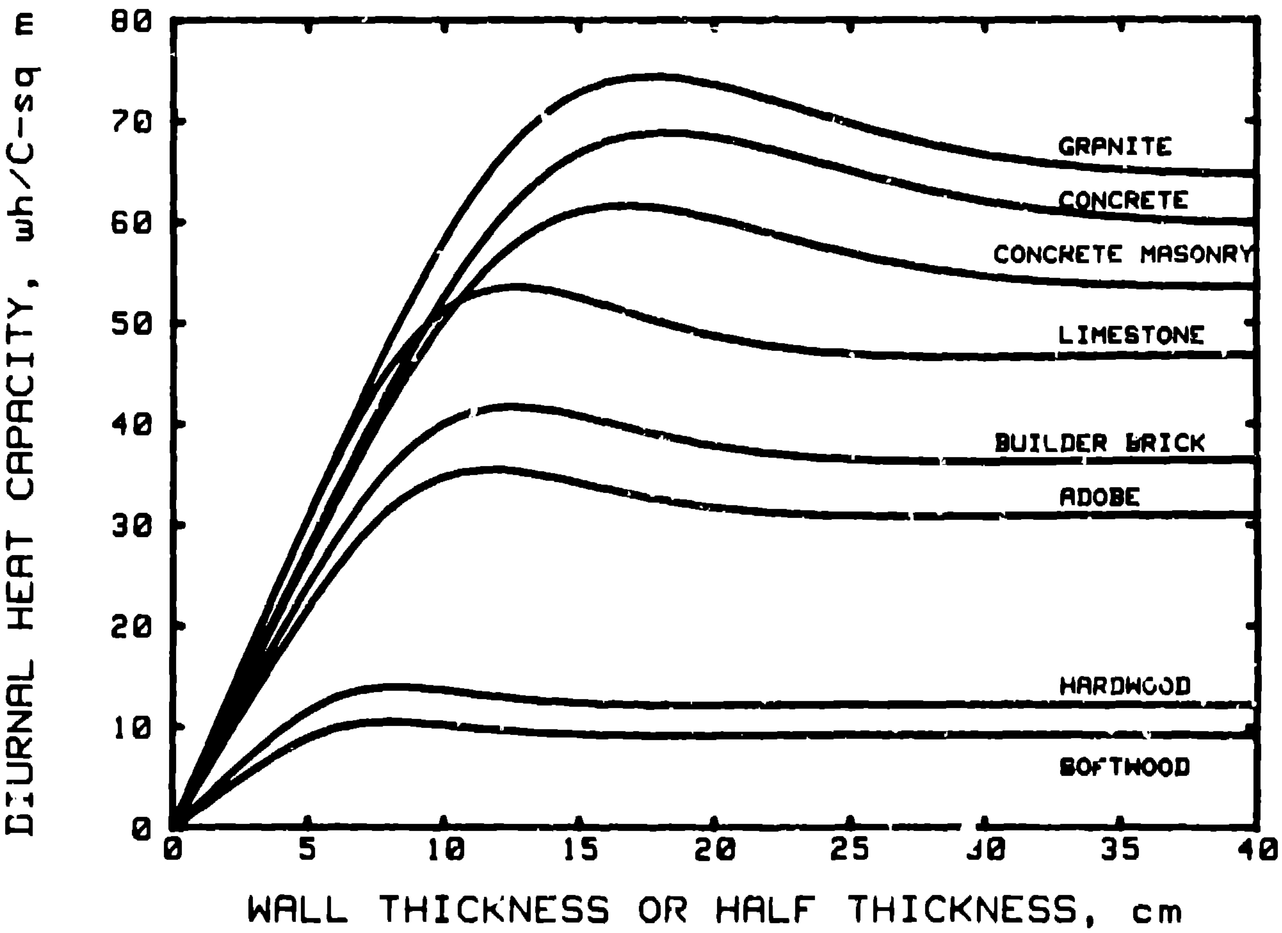


Fig. 1. Diurnal heat capacities of various materials as a function of thickness. For interior partition walls, use 1/2 the total wall thickness to determine the diurnal heat capacity for each of the two surfaces. These curves apply to radiation-coupled mass.

## RELATIONSHIP BETWEEN dhc AND ROOM-TEMPERATURE SWING

Thus far, diurnal heat storage has been related to surface-temperature swing. To use this result, we must somehow establish a relationship between room-temperature swing and surface-temperature swing. The total heat stored will be a sum of heat stored in the various surfaces that enclose the room in question. At this point the procedure becomes approximate because a precise solution is overly complex.

We distinguish two primary categories of situation: those in which the incoming energy is radiatively coupled to the surface (either by shortwave solar radiation or by longwave infrared radiation from other surfaces), and those convectively coupled to the room air. In the first case the air temperature follows the wall-surface temperatures; in the second case the wall temperature follows the air temperature. Furthermore, thermal comfort is related to a composite of air temperature and mean radiant temperature. We simplify by equating room temperature and wall-surface temperature in radiatively coupled situations and by accounting for an air-film impedance in the case of convectively coupled situations. An enhancement factor is used to account for the fact that mass surfaces in the direct sun may be temporarily warmer than the room temperature. To compute dhc for the convectively coupled case, the air-film impedance, $1/U$, is added vectorially to the wall impedance, $1/y_1$, to obtain a modified total impedance that is then used to calculate dhc ($U$ is the air-film conductance).

## PROCEDURE

### Diurnal Heat Capacity of a Whole Room

The diurnal heat capacity of a whole room or a whole building can be determined by aggregating the individual diurnal heat capacities of all surfaces acting in parallel. This will be called DHC. It is the vector sum of all the DHC values for all the various surfaces that enclose the room.

$$DHC = \sum_i A_i \cdot dhc_i \quad , \qquad (3)$$

where $A_i$ is the area of the $i^{th}$ surface, $m^2$, and
$dhc_i$ is the dhc of the $i^{th}$ surface, $Wh/{}^\circ C\ m^2$ ,

so that DHC has units of $Wh/{}^\circ C$.

It is first necessary to classify each inside surface of the building or room according to the coupling between the surface and the solar gain. It is useful to distinguish the following two major categories.

Radiation-coupled mass. Solar energy is transferred to the storage mass by either solar or thermal radiation. The mass must be either within the space that the sunshine enters or form an enclosing surface of the space. It is not necessary for the mass to be in the direct sun, but there must be a direct line of sight between the mass surface and absorbing or reflecting surfaces that are in direct sun.

Convection-coupled mass. Solar energy is transferred to the storage mass by natural convection of warm air. Doorway or other convection openings must be provided with a total open area of at least 4% of the storage-mass surface, or 2% of the storage-mass surface if the openings are spaced more than 2 vertical meters apart.

Categorizing surfaces. We identify four types of surfaces as follows:

Type 1. Surfaces in the direct sun (radiation coupled),
Type 2. Other enclosing surfaces of a direct gain room (radiation coupled),
Type 3. Surfaces that are convectively coupled only, and
Type 4. Surfaces with zero coupling (zero dhc).

Exceptions are the following: (1) all ceilings, because of the excellent heat exchange with room air, are classified Type 2 even if they are in remote rooms, provided there is a suitable convective connection, and (2) floors not in the direct sun, because of the poor convective coupling and the lack of line-of-sight radiative coupling, are downgraded one type number.

The next step is to estimate the area of each Type 1, Type 2, and Type 3 surface. For Type 1 surfaces, estimate the fraction of the solar day that the surface is sunlit, f, and the absorptance of the surface, $\alpha$. Rough estimates are adequate. Next, determine the dhc of each surface using the following:

Type 1: dhc = (radiation-coupled dhc) $\cdot$ $(1 + \alpha f)$
Type 2: dhc = radiation-coupled dhc
Type 3: dhc = convection-coupled dhc
Type 4: dhc = 0

By radiation-coupled dhc, we mean dhc calculated in terms of surface-temperature swing. By convection-coupled dhc, we mean dhc calculated in terms of room-temperature swing using a convective coupling; a value of $U = 0.26$ W/°C m$^2$ is normally used. Next, calculate the DHC of the furniture and room air. This can be estimated as 11 Wh/°C for each m$^2$ of floor area for typical furnishings.

Tables of both radiation-coupled and convection-coupled dhc have been compiled by Balcomb (1983) for common building materials.

## Estimation of Room-Temperature Swing

The amount of heat stored in the building during clear winter days can be estimated knowing the direct gain glazing area, the solar penetration per square meter of glazing area, and the heat-loss characteristics of the building. A heat balance is calculated over the 12-hour period from 0600 to 1800, accounting for solar gains plus internal heat minus heat losses. The heat losses are calculated based on the total heat-loss coefficient of the building (TLC) and the difference between average inside temperature and average outside temperature.

The energy balance described above can be put in equation form as follows:

$$\mathrm{DHC} \cdot \Delta T\ (\mathrm{swing}) = Q_s \cdot A - (T_r - T_a)\mathrm{TLC}/2 + Q_i/2 \quad ,$$

where $\Delta T$(swing) = peak-to-peak room-temperature swing,
$T_r$ = daily average room temperature,
$T_a$ = daily average ambient temperature,
$Q_s$ = clear-day solar gains per unit area of direct gain glazing,
$Q_i$ = daily internal heat (assumed uniform), and
$A$ = direct gain glazing area.

One could account for the detailed structure of the inside and outside hourly temperature profiles in determining $T_r$ and $T_a$; however, this is not done here primarily because we wish to keep the analysis fairly simple and little accuracy would be gained by the complication. In addition, both inside and outside temperatures will be higher than average during the daytime so that there is a tendency for these effects to cancel. Whether they would cancel exactly, of course, depends on the exact magnitude of the two swings. If the building uses no auxiliary heat (the normal case in a passive building on a clear winter day), a daily heat balance gives

$$Q_s \cdot A = (T_r - T_a)\ TLC - Q_i \quad ,$$

$$\Delta T\ (\text{swing}) = 0.50\ Q_s \cdot A/DHC \quad .$$

A factor can be used to account for higher harmonics. From study of typical profiles we find:

$$\Delta T\ (\text{swing, actual}) = 1.22 \cdot \Delta T\ (\text{swing, 24-h harmonic}) \quad .$$

$$\text{Thus, } \Delta T\ (\text{swing}) = 0.61\ Q_s \cdot A/DHC \quad . \tag{4}$$

Design Guideline for Direct Gain

A design guideline can be determined, aimed at limiting temperature swings in direct gain situations, that leads to a minimum required diurnal heat capacity per unit area of direct gain glazing. From Eq. (4) we obtain:

$$DHC/A \geq 0.61 \cdot Q_s/\Delta T\ (\text{swing, maximum}) \quad .$$

Temperature swings greater than about 5°C are usually deemed to be excessive.

For example, if $Q_s = 4360\ Wh/m^2$ and $\Delta T(\text{swing, max}) = 5°C$, we require 530 Wh/°C of room diurnal heat capacity per $m^2$ of direct gain glazing. If the room surfaces are made of 15-cm-thick concrete (dhc = 70 $Wh/m^2$ °C), the required area of heat-storage surface is 7.6 times the direct gain window area. Guidelines for other situations can be developed similarly.

## FURTHER SIMPLIFICATION

The vector addition of Eq. (3) is awkward, greatly increasing analysis time and confusion. If this is regarded as a scalar sum, a slight overestimate of DHC will result, generally no more than 10%, and can readily be offset by ignoring the enhancement factor, $1 + \alpha f$. If these adjustments are done, only two categories of surfaces are distinguished, radiation-coupled and convection-coupled. The analysis becomes a very simple process of adding (dhc) · (A) products using dhc values from tables or graphs and then using Eq. (4). The calculation is hardly more involved than a building heat-loss calculation; in fact, it is quite analagous. The user need never be aware of the complexity behind the calculation of the dhc tables.

A few spot checks have been made by Balcomb (1983) to assess the accuracy of the procedures outlined. Comparisons made between the $\Delta T$(swing) calculated using involved thermal-network computer simulations and the simplified procedures proposed here show correspondence within 5 to 8%.

## REFERENCES

Davies, M. G. (1973), The Thermal Admittance of Layered Walls, Building Science, 8, 207-220, Pergamon Press.

Balcomb, J. D. (1983), Heat Storage and Distribution Inside Passive Solar Buildings, Los Alamos National Laboratory Report LA-9694-MS.