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A SIMPLE METHOD FOR COMPUTING THE DYNAMIC RESPONSE OF PASSIVE SOLAR BUILDINGS TO DESIGN WEATHER CONDITIONS

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ABSTRACT

In contrast to the lengthy computations required to simulate hour-by-hour building performance using response-factor or thermal network models, design-day performance can be analyzed simply by using a method developed based on Fourier transforms. This paper describes how Fourier response functions are derived from the building's thermal properties and shows how approximations can be made which allow the results to be expressed as algebraic formulas which can be computed rapidly using a hand-calculator.

A program written for a hand-calculator which can perform this analysis requires as inputs building design parameters such as "UA" products (conductances), specific heats of materials, and weather parameters. Since similar materials (e.g. frame walls and ceilings) can be lumped together, data for only a few different construction types are needed. Weather parameters are: daily solar gains for sunny and cloudy design days, length of cloudy design weather cycle, average ambient temperature of the design day and typical diurnal temperature fluctuation. Output from the program is hourly room temperatures for each of the design days.

1. INTRODUCTION

Passive solar buildings frequently operate in the floating temperature mode, in which heat gains and losses result in changes in room temperature rather than heating or cooling loads. To the extent that a building can be designed such that its temperature always floats in the comfort range, no heating or cooling will be necessary. Floating temperature on a design day is therefore one of the most important measures of passive solar building performance. Adjustments in the building design which raise the temperature on a cloudy design-day while keeping the temperature sufficiently cool on a sunny design-day can be considered as improvements in design. But for the designer to be able to choose optimum values of building parameters requires a method for predicting performance.

This paper presents a method for calculating design-day performance of a single-zone passive solar building. The method takes simple building parameters such as U-values and heat capacities as input along with a few parameters characterizing weather. The results are room temperatures as a function of time for winter or summer design days. Computations by this method are much simpler than those for computerized building models, and can be performed on a pocket calculator [1].

2. RESPONSE FUNCTION MODELS

Design calculations for buildings have usually been performed using either very simple methods, such as design heat loss calculations [2], or using complex computerized models [3] which treat both the building and the weather in great detail. But design heat loss methods start to break down for well-insulated structures, and are especially weak in simulating passive solar buildings, which involve precise analysis of heat storage, while the present computer models are more complex and expensive than necessary to model design-day performance of simple buildings such as houses.

In this paper an intermediate-level method is presented in which the behavior of the building is described by Fourier response functions. This method employs more approximations than the computerized models, and is more limited in scope in that it describes design-day performance rather than integrated annual performance. However, it uses a structure which parallels those of the computerized models, incorporating the effects of thermal storage and thermal insulation. With suitable simplifying assumptions about the building and weather, the model can be run in one-half hour or less on a programmable hand calculator.

The basis of the method is to derive response functions for the room temperature of the building in terms of the driving forces of solar heat gain, ambient temperature, and heater or air-conditioner output. These response functions, which are typically just frequency-dependent design heat loss coefficients, give the response of room temperature to stimulation at a given frequency. Multiplying the building response functions by weather input at a given frequency gives the room temperature at that frequency. When the weather can be described using only a few frequencies, that is, on a design-day, the room temperature results can be added for only those few frequencies, giving an easily computed answer.

3. MODELLING METHODOLOGY

Heat transfers from the room air to the surroundings can be divided into two classes, quick and delayed, as is done in the computerized building models. Quick heat transfers are always proportional to the temperature difference between inside and outside. Examples of quick heat loss mechanisms include window heat losses and infiltration. Delayed heat transfers are those which involve heat storage, such as heat flow through massive walls, floors, or ceilings. These are described by materials response functions.

3.1. Materials Response Functions: R_1 and R_2

Delayed heat transfers are modelled using Fourier response functions. For each building element j, we compute the response of surface temperature on the inside or room-side surface (T_{sj}) to the driving forces of solar heat gain on that surface ($\bar{\alpha}_j S$) and ambient temperature (T_A). The results can be expressed [4] as

$$T_{sj}(\omega) = R_1(\omega)\left(h_j T_R(\omega) + \alpha_j S(\omega)\right) + R_2(\omega)\, T_A(\omega) \qquad (1)$$

where

h_j is the film heat transfer coefficient coupling the j^{th} surface to the room (including the effects of convection and radiation) (Btu/hr-ft^2-°F or W/m^2-°C),

T_R is the room temperature (°F or °C),

$\bar{\alpha}_j S$ is the average flux of solar energy absorbed on the j^{th} surface ($Btu/hr\text{-}ft^2$ or W/m^2),

T_A is the ambient air temperature (°F or °C).

The materials response functions R_1 and R_2 describe how surface temperature reacts to sunlight and ambient temperature. R_1 is the temperature response to a unit heat flux on the same side of the building element. It has dimensions of thermal resistance. R_2 describes the temperature response to temperature input on the opposite side of the building. It is dimensionless. Both R_1 and R_2 are complex-valued functions, but start out real-valued for zero frequency.

The materials response functions R_1 and R_2 for a realistic multi-layer element (e.g., wall, roof) can be computed exactly by solving diffusion equations for each layer of the element. But considerable simplification is possible by considering the thermal mass of only the innermost layer. This approximation can be used because the results for R_1 are much more dependent on the thermal mass of the inside layer than on the layers closer to the outside surface, while precise evaluation of R_2 is unnecessary for nonzero frequency [5].

Table I gives the formulas for R_1 and R_2 using this two-layer model. The inside layer in the two-layer approximation has the conductivity, specific heat, and density of the room-side first layer or layers, while the outside layer has the U-value of all the rest of the element, including the outside film coefficient.

TABLE 1. Materials response functions for two-layer model.

$$R_1(\omega) = \frac{\cosh kd + \dfrac{U_r}{Kk}\sinh kd}{(h+U_r)\cosh kd + \left(Kk + \dfrac{hU_r}{Kk}\right)\sinh kd}$$

$$R_2(\omega) = \frac{U_r}{(h+U_r)\cosh kd + \left(Kk + \dfrac{hU_r}{Kk}\right)\sinh kd}$$

where

K is the thermal conductivity of the inside layer (Btu/hr-ft-°F or W/m-°C),

d is the thickness of the inside layer (ft or m),

$k = \sqrt{i\omega\rho c/K}$,

ρc is the heat capacity per unit volume of the inside layer ($Btu/°F\text{-}ft^3$ or $W\text{-}hr/°C\text{-}m^3$),

h is the inside surface film heat transfer coefficient (radiative/convective) ($Btu/hr\text{-}ft^2\text{-}°F$ or $W/m^2\text{-}°C$),

U_r is the U-value of the outside layer ($Btu/hr\text{-}ft^2\text{-}°F$ or $W/m^2\text{-}°C$).

The two-layer model is almost exact for a wall with a thick, massive component inside, such as 8-inch solid concrete with 1-inch polyurethane or polystyrene insulation and stucco outside. It is also within about 5% for a wood-frame stud section, (½" gypsum board with 3½" wood studs and siding outside) if we model the thermally massive part by using the weighted average conductivity and heat capacity of wood and gypsum board* for the massive layer.

The two-layer model breaks down if there is a massive component outside a lighter but not massless inside layer, such as 1-inch wood tiles over a concrete floor. In this case, a multi-layer model must be used to calculate R_1 and R_2.

The materials response functions both start out constant as frequency increases from 0, then decline with increasing frequency. Both begin to fall off at the same frequency, but the rate of decline is greater for R_2. Thermally massive materials show a much greater decline with frequency than light-weight materials. Response functions for a massless wall are constant at all frequencies.

Building elements whose inside layer has some resistance but little or no thermal mass, such as carpeted floors, show little variation in R_1 and R_2 with frequency. Such materials can be modelled as quick heat transfers for calculational simplicity.

The materials response functions R_1 and R_2 can be related to the response factors X, Y and Z, or the Z-transforms B, C and D, if they are all expressed in comparable form (that is, as response factors or Z-transforms or Fourier transforms). The relationships are:

$$R_1 = \frac{1}{h+Z} = \frac{D}{hD+C} \quad ,$$

$$R_2 = \frac{Y}{h+Z} = \frac{B}{hD+C} \quad .$$

3.2 Building Response Functions: A, B, and C

The behavior of room air temperature is derived from a room heat balance. The room air is in thermal contact with the inside surface of each component, and with the outside air. In addition, it receives direct heat gain from the heater and from solar heat absorption on thermally light materials such as upholstery. Quick heat transfers (Q) to the outside air are given by

$$Q = \sum_i U_i A_i (T_R - T_A) + (\rho c)_{air} \times V \times ach \times (T_R - T_A) \qquad (2)$$

where

- U_i is the heat transfer coefficient on the i^{th} quick-heat-transfer construction section (Btu/hr-ft^2-°F or W/°C-m^2),
- A_i is the area of the i^{th} section (ft^2 or m^2),
- T_R is the room air temperature (°F or °C),
- T_A is the ambient air temperature (°F or °C),

*The average of 1/conductivity should be used to retain the correct U-value, rather than the average of conductivities.

$(\rho c)_{air}$ is the heat capacity of air per unit volume (Btu/°F-ft^3 or W-hr/°C-m^3),

V is the volume of the building,

ach is the air exfiltration rate in air changes per hour.

For simplicity, these terms are combined into a single quick heat loss coefficient $\hat{U}_q$, which is defined by (2) and

$$Q = \hat{U}_q(T_R - T_A) \tag{3}$$

Solar heat gains can be apportioned among the surfaces within the building which absorb sunshine. The total solar heat gain from all windows is S; then the fraction absorbed on the surface of the j^{th} material can be expressed as $\alpha_j S$, where α_j is a fraction ranging from zero to one. If the absorbing surface is thermally light; that is, if response functions are not computed for that surface, then its solar heat gain is treated as being absorbed directly into the room air. The term α_R represents the fraction of solar gain absorbed in the room air.

Numerical evaluation of the α's is a difficult problem which is not generally treated in building models. We modelled the radiation balance in a prototype passive solar room using a proprietary illumination engineering program assuming clear winter day solar patterns [1]. For a dark floor and light walls and ceiling, we found the following values for α_j: for the envelope walls, 0.10; for the partition walls, 0.20; for the ceiling, 0.10; for the floor, 0.45; and for the room, 0.15.

The temperature T_R can be expressed in terms of the driving functions of solar heat gain S, ambient temperature T_A, and as heater output H

$$T_R(\omega) = \frac{B(\omega)}{A(\omega)} S(\omega) + \frac{C(\omega)}{A(\omega)} T_A(\omega) + \frac{1}{A(\omega)} H(\omega) \tag{4}$$

with

$$A(\omega) = \sum_j h_j A_j (1 - h_j R_{1j}) + \hat{U}_q ,$$

$$B(\omega) = \sum_j \alpha_j h_j R_{1j} + \alpha_R ,$$

$$C(\omega) = \sum_j h_j A_j R_{2j} + \hat{U}_q .$$

It should be noted that A_j is the area of the j^{th} surface and the sum is over all surfaces j.

While Eq. (4) was derived [4] using a number of approximations, the form of this equation still holds for a more exact solution: R_1 and R_2 can be calculated as exact, multi-layer response functions and the inside surfaces can be inter-connected by radiation as well as coupled to the air by convection, and Eq. (4) is still correct, with some alteration in the form of A, B, and C.

The building response functions $A(\omega)$ and $C(\omega)$ act as design heat loss coefficients. For zero frequency A and C are both real-valued and equal to the conventional design heat loss (per degree) of the building. As frequency increases from zero, the magnitude of A increases while that of C decreases. For a good passive solar design, A may be several times larger at a frequency of one cycle per day than it is at zero frequency.

The building response function $B(\omega)$ is a dimensionless number. Evaluated at zero frequency, B can be interpreted as the collector efficiency of the solar windows. For a direct gain building B(0) is almost unity, but for a Trombe wall, B(0) can be less than 0.50. $B(\omega)$ decreases with frequency, describing the building's ability to damp out variations in solar heat gain. For a direct gain building, B may be down to half its steady-state value for the frequency of one cycle per day; in addition, it may have a small phase delay.

All of the dependence on location of solar absorption (whether the thermal mass is in direct sunshine) is contained in the $B(\omega)$ response function. This dependence is expressed in (4) through the α's. $B(\omega)$ is the weighted average of the $R_1(\omega)$ response functions for all inside surfaces, with the weights supplied by the α's. Additional terms in A, B, and C produced by a Trombe wall can also be modelled at the expense of some extra numerical manipulation [6].

3.3. Computation of Floating Room Temperature from Building Response Functions

Equation (4) gives the response of room temperature at a given frequency to driving forces at that frequency. To get room temperature as a function of time, the results must be summed over all frequencies.

Weather patterns have been Fourier analyzed and are found to be heavily peaked at only a few frequencies [7]. Most of the time-dependence of the weather occurs at a frequency of one cycle per day, or in low integral multiples of one cycle per day. Longer term cycles have frequencies of one cycle per year and in the neighborhood of one cycle every one to two weeks. Thus Eq. (4) can be evaluated simply for a design day by considering only a few frequencies.

Formulas for computing the Fourier coefficients of the driving forces for a design day are described below. Two types of design days can be modelled — one in which the weather is assumed constant from day to day, and a more sophisticated case in which the weather varies sinusoidally over a multi-day period. For the constant-weather design day, solar gain can be modelled as half-sine wave [8]

$$S(t) = \begin{cases} S_1 \sin \omega_1 t & \text{[day]} \\ 0 & \text{[night]} \end{cases}$$

which can be Fourier-analyzed into the series

$$S(t) = S_1 \sum_{n=0}^{3} d_n \, e^{in\omega_0 t}$$

where

$$\omega_0 = 2\pi \text{ radians/24 hours.}$$

The formula for d_n is given in Table 2. The series is truncated at n=3 for computational speed. Ambient temperature is given by (the real part of)

$$T_A(t) = \overline{T_A} + \Delta T_A \, e^{i\omega_0 t} \quad .$$

where $\overline{T_A}$ is the average ambient temperature and ΔT_A is the amplitude of its diurnal variations. Heater output can also be Fourier-analyzed for any given form; however, for convenience a constant heater output is usually assumed.

Table 2. Fourier expansion coefficients for solar gain function.

$$S(t) = S_1 \sum_{n=0}^{n_{max}} d_n e^{in\omega_0 t} = \begin{cases} S_1 \sin\omega_1 t & \text{[day]} \\ 0 & \text{[night]} \end{cases}$$

where

$$\omega_0 = 2\pi \text{ radians/24 hours},$$

$$d_0 = \frac{\omega_0}{\pi\omega_1},$$

$$d_n = \begin{cases} \dfrac{\omega_0\omega_1}{\pi} \dfrac{1 + e^{-in\pi\omega_0/\omega_1}}{\omega_1^2 - (n\omega_0)^2} & n\omega_0 \neq \omega_1 , \\ \dfrac{\omega_0}{2i\omega_1} & n\omega_0 = \omega_1 . \end{cases}$$

Departures from these simple driving functions will not produce significant error, because the departure can be expressed as a Fourier series with entirely high frequency terms whose amplitudes are small. The influence of these omitted terms on room temperature is not large because the building response function $A(\omega)$ increases rapidly with frequency.

To analyze the response to multi-day weather cycles, weather variations can be represented by a single extra frequency ω_w. The solar gain amplitude S_1 is taken as a sinusoidally modulated function of time:

$$S_1 = \bar{S} + \Delta S_w \cos \omega_w(t - t_s) ,$$

where $\bar{S}$ is the average noontime solar heat gain over the weather cycle, ΔS_w is the amplitude of weather cycle variation in noontime solar heat gain, ω_w is the frequency of the weather term and t_s is the time at noon on the day of maximum sunlight. Thus the solar gain can be described by:

$$S(t) = \begin{cases} \left(\bar{S} + \Delta S_w \cos \omega_w(t - t_s)\right) \sin\omega_1 t & \text{[day]} \\ 0 & \text{[night]} \end{cases} \quad (5)$$

At present there is no empirical way of deriving $\bar{S}$ and ΔS_w for a given climate; the best judgment of the user must be employed. We plan to analyze weather data to derive best-fit values of $\bar{S}$ and ΔS_w for design days in different climates. S_1 can be approximated by using ASHRAE solar heat gain calculations for the windows [9]. Daily solar heat gain for a clear design-day can be computed and compared with the daily solar heat gain from the half-sine-wave: $2S_1/\omega_1$. Setting them equal, the result is:

$$S_1 = \frac{\omega_1}{2} \times \text{(daily total solar heat gain)}$$

For a cloudy day, solar heat gain is reduced by about a factor of 3, so that a first approximation for $\bar{S}$ and ΔS_w would be

$$\bar{S} = 2/3 \times \frac{\omega_1}{2} \times \text{(daily total solar heat gain, sunny day)}$$

$$\Delta S_w = 1/2\ \bar{S}$$

Long-term variations in temperature are modelled analogously, by replacing $\overline{T_A}$ with

$$\overline{T_A} + \Delta T_{A_w}\, e^{i\omega_w(t-t_a)}$$

where t_a is the time of maximum temperature in the weather cycle.

Room temperature response for the constant-weather design day can be evaluated by using Eq. (4) along with the Fourier coefficients of the design-day weather. The result can be expressed as

$$T_R(t) = S_1 \sum_{n=0}^{3} d_n \frac{B(n\omega_o)}{A(n\omega_o)} e^{in\omega_o t} + \overline{T_A} + \Delta T_A \frac{C(\omega_o)}{A(\omega_o)} e^{i\omega_o t} + \frac{1}{A(0)} H \tag{6}$$

The real part of (6) is the room temperature.

For variable weather, an additional approximation is needed. The Fourier expansion of the variable solar heat gain function, Eq. (5), involves terms at a number of extra frequencies besides $n\omega_o$ and ω_w. These computations can be avoided by an approximation [6] which accounts for the effect of varying solar gain. The result is:

$$\begin{aligned} T_R = {} & \left(\bar{S} + \Delta S_w \cos \omega_w(t-t_s)\right) \sum_{n=1}^{3} d_n \frac{B(n\omega_o)}{A(n\omega_o)} e^{in\omega_o t} \\ & + \bar{S}\, d_o \frac{B(0)}{A(0)} + \Delta S_w\, d_o \frac{B(\omega_w)}{A(\omega_w)} e^{i\omega_w(t-t_s)} + \overline{T_A} \\ & + \Delta T_{A_w} \frac{C(\omega_w)}{A(\omega_w)} e^{i\omega_w(t-t_w)} + \Delta T_A \frac{C(\omega_o)}{A(\omega_o)} e^{i\omega_o t} + \frac{1}{A(0)} H \end{aligned} \tag{7}$$

In the first term of (7), $t-t_s$ is evaluated at noon on the design day.

3.4. Computation of the Building Response

Reference 1 presents hand-calculator routines which compute $T_R(t)$ for simple direct-gain buildings using card-reading Hewlett-Packard HP-67 and Texas Instruments TI-59 calculators [1]. As input to these programs, the building elements are divided into quick or delayed construction sections. For quick sections, UA is calculated, and the results used (along with infiltration) to compute $\hat{U}_q$. Solar energy absorbed on the inside surface of these quick sections is added to compute α_R.

Delayed constructions are divided into two layers: the inner layer characterized by heat capacity per unit volume, thickness, and conductivity, and the outer layer characterized only by thermal resistance. The division between layers is made when the materials change properties abruptly from relatively massive to relatively light. If the division is not obvious, the program cannot be used and outside calculations must be made to derive R_1 and R_2.

Since response functions must be computed for the surface of each delayed material, the smaller the number of materials, the greater the speed of calculation. To reduce the number of materials, it is a good approximation to combine materials of similar properties into a single material with averaged properties. For example, the stud portions of wood-frame envelope walls, ceilings, and partition walls can be combined to good approximation ($\lesssim$3% error) by using averaged properties. The conductivity, heat capacity, and thickness of the composite material can be taken as the area-weighted average of the properties of the three component construction sections. The exterior resistance is chosen such that the design heat loss of the composite is the same as that of the sum of the components. Similar combination is possible for the insulated portion of the walls. For example, for a combination of envelope walls, ceiling, and partition walls, the design heat loss (per unit temperature difference) is given by

$$Q = U_e A_e + U_c A_c$$

where U_e is the U-value of the envelope walls (Btu/°F-ft^2-hr or W/°C-m^2),

U_c is the U-value of the ceiling,

A_e is the area of the envelope walls (ft^2 or m^2),

A_c is the area of the ceiling.

But for a two-layer wall with outside resistance R,

$$U = \left(\frac{d}{K} + R\right)^{-1}$$

where

d is the thickness of the massive layer (ft or m),

K is its conductivity (Btu/°F-ft-hr or W/°C-m),

so

$$Q = \left(\frac{d_e}{K_e} + R_e\right)^{-1} A_e + \left(\frac{d_c}{K_c} + R_c\right)^{-1} A_c \quad . \tag{9}$$

This must be equal to the design heat loss of the combined wall, or

$$Q = \left(\frac{d_{comb}}{K_{comb}} + R_{comb}\right)^{-1} A_{comb} \tag{10}$$

where $A_{comb} = A_e + A_c + A_p$,

A_p is the area of the partition walls,

d_{comb} and K_{comb} are weighted averaged thickness and conductivity of all three constructions.

The resistance of the combined material is found by equating the right-hand sides of (9) and (10). In this way, a wood-frame, concrete-floor passive house can be handled with three sets of response functions; for floor, stud sections, and insulated cavity sections, with less than 5% error (or less than 1°F). This simplification is important because the TI-59 program presently allows a maximum of three massive construction sections.

At the present time, extensions to the programs to include the effect of Trombe walls are being developed. Trombe walls produce one or two extra terms in the building response functions A, B, and C. The program can be run on an HP-67 in four minutes per construction section, plus ten minutes for the program overhead.

4. EXPERIMENTAL VALIDATION

This method has been used to model the performance of two test buildings [10] at Los Alamos Scientific Laboratory — one direct gain building and one Trombe wall building. The models of the Los Alamos buildings were quite simple; the simulation of the direct gain building used materials response functions for only one material, while the Trombe wall building model used three construction sections.

The simulation was performed for two days, which resembled the design-days described previously; one day had followed several other days of identical clear sunny weather, and the other day followed two weeks whose weather could be accurately described by the weather-frequency of $\omega_W = 2\pi/2$-weeks.

The comparison between model and experiment is shown in Figures 1 - 4. Details of the simulation are given in Ref. [4]. As seen, the model agrees with experiment to within ±10% at all hours of all days. (Percentage error refers to the error in T_R as a fraction of $T_R - T_A$.) Better than 10% agreement is not meaningful because uncertainties in the values of building parameters can cause ~10% errors.

5. CONCLUSIONS

This paper has described a relatively simple analytic method for predicting design-day response of room temperature in a building to the driving forces of solar heat gain, ambient temperature, and heater output. The model relies on building response functions which can be derived from Eq. (4) and Table 1. The building response functions have as much generality as the response factor and weighting factor methods in complex computerized building models. However, several approximations have been used to simplify their evaluation: the use of combined radiation/convection film coefficients, a two-layer wall model, and constant U-values for materials (e.g., no wind-dependence).

In addition, this method shares a number of other approximations with the more complex models: one-dimensional heat transfer through homogeneous, isotropic materials, well mixed room air, temperature-independent conductivities, linearity of heat transfer equations, well known material properties and construction practices, etc.

The building response function method has been shown to give predictions which follow measurements to within ±10% for simple, small, one-zone buildings. Computations can be performed using this method on a HP-67 or TI-59 hand calculator.

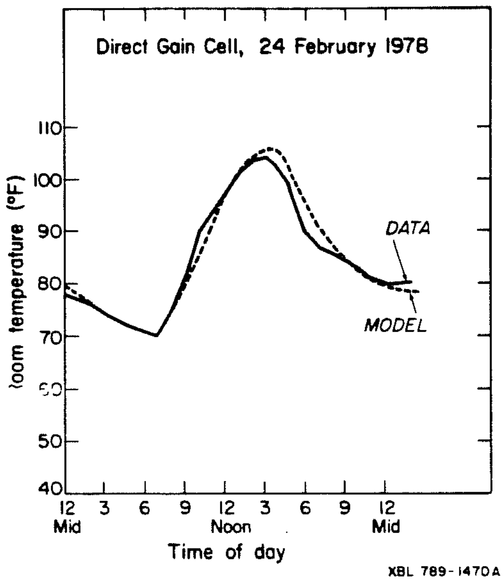

Fig. 1.

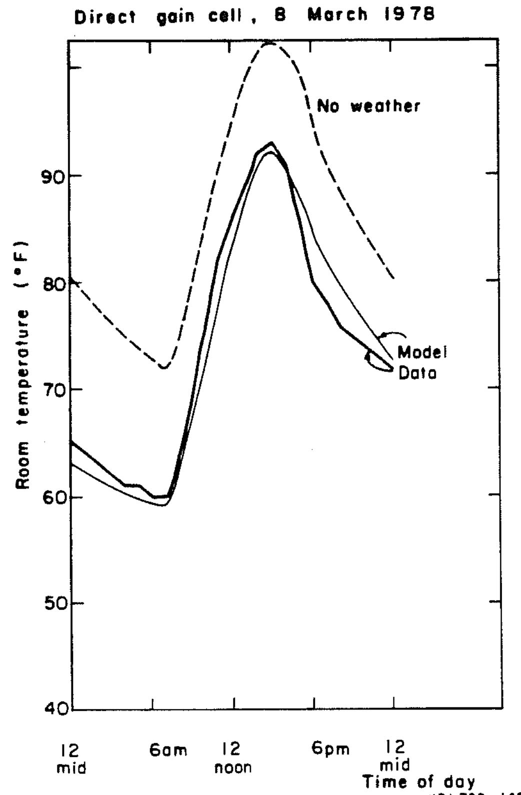

Fig. 2.

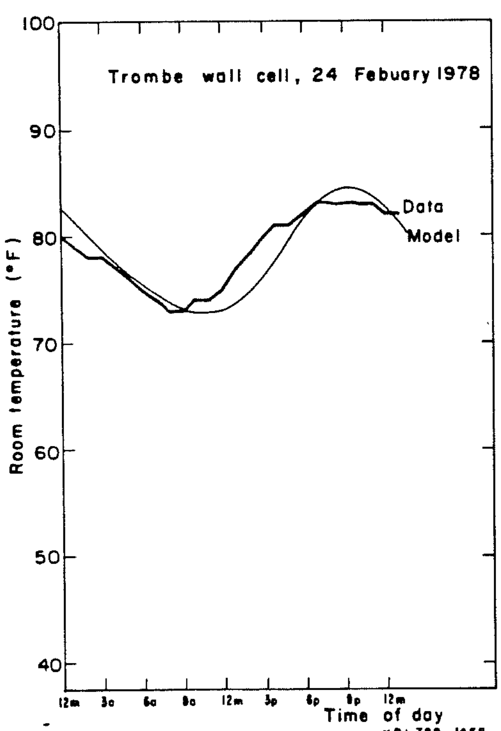

Fig. 3.

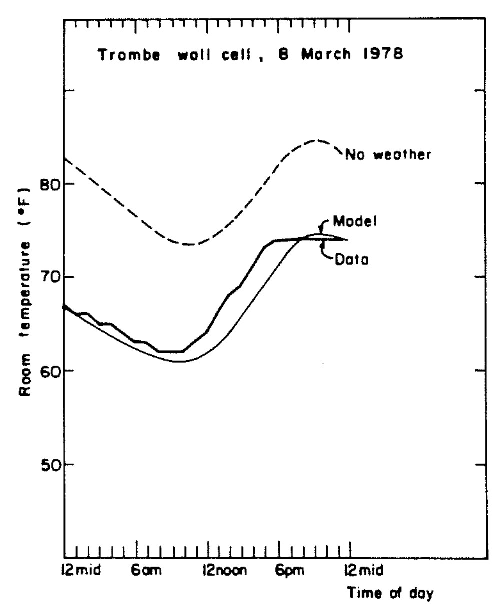

Fig. 4.

Predicted room temperature and observed data as a function of time of day for 24 February 1978 (Figs. 1 and 3), and 8 March 1978 (Figs. 2 and 4). Figures 1 and 2 describe a direct-gain test cell, which can be modelled using present hand calculator programs. Figures 3 and 4 model a Trombe wall cell. The curves for March 8 labelled "no weather" give model predictions assuming that all previous days had the same weather as the test day. The curve labelled "model" accounts for the previous two weeks weather.

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These response function models are part of a study of analytic (as opposed to numeric) approaches to building modelling directed by Sam Berman of the Lawrence Berkeley Laboratory with Robert Richardson of New York University. Alternative approaches to response function techniques, such as lumped parameter approximations, can also be used in calculating design-day performance of simple buildings.

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FOOTNOTES AND REFERENCES

[1] D.B.Goldstein, M.Lokmanhekim, R.D.Clear, "Design calculations for passive solar buildings using a programmable hand calculator," Lawrence Berkeley Laboratory Report LBL-9371 (1979); presented at the Izmir International Symposium-II on Solar Energy Fundamentals and Applications, Izmir, Turkey, 6-8 August 1979.

[2] ASHRAE "Handbook of Fundamentals," Chapter 22 (1977).

[3] These models are usually based on response factor methods described in Ref. [2], Chapter 25.

[4] D.B.Goldstein, Some Analytic Models of Passive Solar Building Performance (Garland Press, New York, 1979), and Lawrence Berkeley Laboratory Report LBL-7811 (1978).

[5] The effect of R_2 on building performance is given by Eq. (4) of this paper; the sum of $h_iA_iR_{2i}$ is added to $\hat{U}_q$. But for insulated walls, $hAR_2 << \hat{U}_q$, so small errors in evaluating R_2 can be ignored.

[6] Ref. [4], Appendix 2.4.

[7] Z.O.Cumali, "Spectral analysis of coincident weather data for application in building heat, cooling load and energy consumption calculations," ASHRAE Transactions 76, Part 2, pp.240-256 (1970).

[8] A.H.C.Van Paassen and A.G.de Jong, "The synthetical reference outdoor climate," Energy and Buildings, Vol. 2, No. 2, p.151 (April 1979).

[9] Ref. [2], Chapter 26, Tables 17-25.

[10] J.D.Balcomb, J.C.Hedstrom, R.D.McFarland, "Passive solar heating of buildings," Los Alamos Scientific Laboratory Report LA-UR-77-1162 (1977).