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A QUANTITATIVE METHOD FOR THE DESIGN OF BUILDINGS WITH COMFORTABLE MICROCLIMATES BY PASSIVE CONTROL OF SOLAR EFFECTS

by

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ABSTRACT

A simple and inexpensive computer-aided method for designing buildings in which the climate is controlled passively, i.e., without mechanical systems, is described. The computer program determines the maximal and minimal interior temperatures, based on inputs which include building shape, dimensions, thermophysical properties of construction materials, and outdoor transient temperature and insolation. The program includes a comprehensive method for the determination of shaded areas on the building and surrounding ground, and of their influence on internal temperatures, thus allowing the evaluation of self-shading and other shading means as passive methods for interior climate control.

This method has been used to study the courtyard house as a specific example of a self-shading building used in hot arid zones. The effects of building orientation, courtyard dimensions, building height, wall thickness, color, materials, and ground cover, on the interior temperature limits were computed and are presented in the paper. The major influence is that of building height, where higher buildings reduced interior temperatures, confirming the importance of shading as a passive cooling method.

INTRODUCTION

Design with climate and adaptation of building to environment to achieve a comfortable interior climate with minimal use of mechanical equipment are fundamental principles of architecture. In cases where solar radiation contributes significantly to the building's heat input, such design could include the passive control of building insolation by shading, which can serve to achieve interior comfort with minimal expenditure of energy and with maximal reliability. Self-shading of a building (one part of the building's envelope shaded by other parts) can thus be regarded as a passive solar cooling system.

Both design with climate and the design of passive solar systems require a good quantitative basis for their implementation, which consists of an adequate heat transfer analysis of the building and its relevant surroundings. Several computer programs for building heating/cooling load calculation are in existence (e.g. ref. 1,2,3), but they are quite complex and expensive to use or do not include a sufficiently detailed consideration of shading and self-shading effects.

A simplified heat transfer calculation was developed to evaluate the effects of the different building variables, including shade, on the interior temperature, and was rendered into a computer program which can be used by architects for interactive building design with climate. The analysis described below was applied to the example of one particular traditional dwelling, the courtyard house of the hot-arid regions.

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The courtyard house has appeared early in the history of mankind. Possibly the most primitive and homogeneous settlements employing the courtyard house concept are found in the Troglodyte villages of Tunisia. Urban courtyard houses are found in the early cities of Kahun and Tel-El-Amarna in Egypt. An open court was found in Hellenic homes, and in the Roman Atrium house, and in the courtyard houses of Moslem North Africa. In modern times, many attempts have been made to employ courtyards in contemporary houses, led by Mies Van Der Rohe, L. Hilberseimer and Philip Johnson among others. Most of these attempts dealt mainly with aesthetic and social aspects per se. However, in recent years other examples of contemporary courtyard houses which dealt with the problem of climate emerged in the work of Doxiadis in Iraq, and other architects in India and North Africa.

Apart from providing such benefits as privacy and security, the courtyard house, so common to the architecture of the hot-arid regions, seemed to have offered improved environmental comfort to its residents. In attempting to analyze its thermal characteristics which contribute to this asset, the following comment by Socrates (4) confirmed a key clue:

"When one builds a house must he not see to it that it be as pleasant and convenient as possible? and pleasant to be cool in summer, but warm in winter. In those houses, then, that look toward the south, the winter sun shines down into Paestades (*court patio*) while in summer, passing high above our heads and over our roofs, it throws them in shadow."

Although the utilization of walls with high thermal capacity (e.g. adobe) and of bright (reflecting) colors are usually part of microclimate control in hot-arid regions, the courtyard home geometry thus also offers the passive control of incident solar radiation by partial mutual shading of its envelope. Most significantly, the court house exposes a large surface area to the cool sky at night, while shading part of that area from the sun during the day. This allows a large heat loss at night with a relatively smaller heat gain during the day, serving overall as an efficient passive cooling mechanism.

HEAT TRANSFER ANALYSIS

The major objective of the heat transfer analysis described below is to determine the time-dependent temperatures inside a building as a function of its structure, geometry, exterior color and ground cover. To be able to evaluate the influence of shading, the program contains a comprehensive subroutine which computes the transient shaded areas on the buildings facade, roof and surrounding grounds, and uses these results in the heat transfer calculations. At present, the program does not include the heat transfer effects of wind or of reflections between building walls.

The fundamental segment of the heat transfer model is a slab of the building's envelope (wall or roof), tilted at an arbitrary angle (Σ) to the horizontal and oriented at an arbitrary azimuth angle (ψ). The slab is exposed to direct and diffuse radiation from the sun, and to solar radiation reflected from the surrounding ground. It is composed of n parallel layers of arbitrary thickness and composition, as described in Fig. 1.

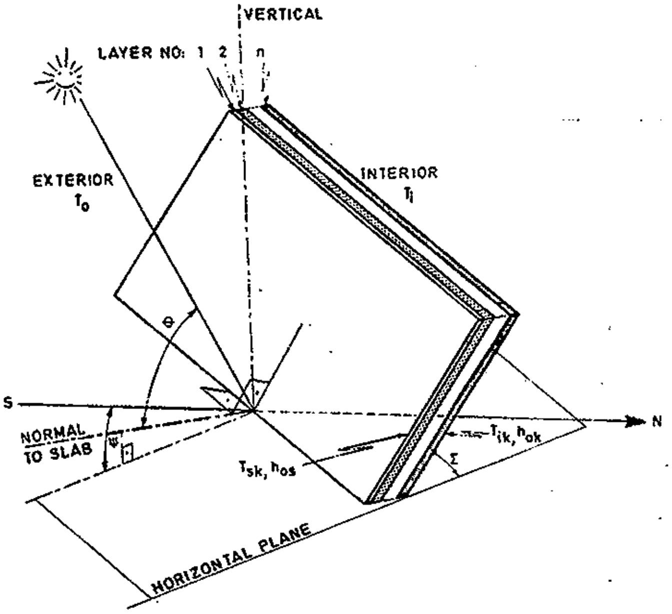


Fig. 1. The building envelope (wall or roof) generalized element for heat transfer calculations

Instead of solving the basic equations of heat transfer through the building, with the radiative and convective boundary conditions, existing intermediate solutions of these equations are utilized in a series of conjugate problems. The simultaneous solution of these conjugate problems yields the interior temperature sought. The solution procedure consists of the following calculations: (1) Solar angle, (2) Shadow, (3) Solar radiative flux, (4) thermal time constant, (5) External surface temperature, (6) Internal surface temperature, (7) Internal air temperature. The different steps are briefly outlined below.

1. Solar angle calculations

These are intended to determine the solar incidence angle (θ in Fig. 1) on the slab, based on the slab's tilt and orientation (Σ,ψ) and on the time-dependent position of the sun. The angle calculations are straightforward, and described in detail in (5).

Based on these angles and on the mutual orientation of the different exterior surfaces of the building, one can proceed and determine the shaded areas and the incident solar radiative flux.

2. Shadow calculation

Basically utilizing the most comprehensive computer method for shadow calculations developed, and described by Groth and Lokmanhekim (2,6), the hourly areas of shade on the different building surfaces and on the surrounding ground are determined.

3. Solar radiative flux calculation

The direct (I_D) and diffuse (I_d) components of insolation are calculated, based on the solar constant, the atmospheric extinction coefficient, sky clearance factor, solar altitude and the shape factor between the sky and the surface, as described in (5). The total insolation is thus $I_t = I_D + I_d$. The radiation reflected from the ground on to a surface is thus

$$I_r = I_{tG} \cdot r \cdot F_A \qquad (1)$$

where I_{tG} is total insolation incident on the ground, r is the ground's reflectance. and F_A the shape factor between the ground and a wall. If the ground is completely shaded, I_{tG} is just the diffuse horizontal component of insolation (I_{dH}), and if the ground is completely in the sun, I_{tG} is the total insolation incident on a horizontal surface (I_{tH}). If part of the ground is in the shade and part in the sun,

$$I_{tG} = \frac{I_{dH} \cdot \text{(area of shadow)} + I_{tH} \cdot \text{(sunny area)}}{\text{(total area)}} \qquad (2)$$

The same method is used to determine insolation on horizontal roof areas.

The value of the insolation on a facade (I_t), is calculated as follows:

a) If the facade is completely in the shade,
$$I_t = I_d + I_r \qquad (3)$$

b) If the facade is completely in the sun,
$$I_t = I_{DN} \cos\theta + (I_d + I_r) \qquad (4)$$

c) If part of the facade is in the shade and part in the sun

$$I_t = \frac{(I_d + I_r) \cdot \text{(shadow)} + [I_{DN} \cos\theta + (I_d + I_r)]\text{(sunny area)}}{\text{(total area)}}$$

Again, the shape factors are appropriately incorporated into the expressions for I_d and I_r.

4. Thermal time constant calculation

To conduct the required transient analysis of heat transfer through the building's envelope, the simplified thermal time constant (Th.T.C.) concept (7,8) is used. It can be defined as the heat stored in the structure per unit of heat transmitted through it, for a unit-step external temperature function:

$$\text{Th.T.C.} = \sum_n \left(\frac{Q}{U}\right)_n \text{hr} \qquad (6)$$

where

n = ordinal number of wall or roof layers

Q = heat stored in the wall per unit of exterior surface

U = heat transferred through an exterior element

$$\sum_n \left(\frac{Q}{U}\right)_n = \left(R_{os} + \frac{1}{2}\frac{L_1}{K_1}\right)L_1 p_1 c_1 + \left(R_{os} + \frac{L_1}{K_1} + \frac{1}{2}\frac{L_2}{K_2}\right)L_2 p_2 c_2 + \dots$$
$$+ \left(R_{os} + \frac{L_1}{K_1} + \dots + \frac{L_{n-1}}{K_{n-1}} + \frac{1}{2}\frac{L_n}{K_n}\right) L_n p_n c_n \qquad (7)$$

where

R_{os} = thermal resistance at the outside surface $= \frac{1}{h_{os}}$, where h_{os} = heat transfer coefficient at the outside surface.

where L_n, p_n, c_n and K_n are the thickness, density, specific heat and thermal conductivity, respectively, of layer n of an exterior building envelope element, starting the count from the outside.

5. External surface temperature calculation

Since the forcing thermal parameters in this problem are the outdoor temperature and insolation, it is necessary to determine the relation between them and the wall (or roof) temperature. The knowledge of these temperatures would then lead to the determination of the interior temperature.

Using the method developed by Hoffman and Givoni (9), expressing the difference between the air temperature and the outer surface as follows:

$$(T_{sk} - T_o)_i = \sum_{j=i_o}^{i} \frac{\Delta(\alpha\, I_s + \text{L.W.R.})_j}{\frac{1}{R_{os}} + \frac{1}{R_s}\, e^{-\frac{i-j}{\text{Th.T.C.}}}} \;{}^{o}\text{F} \qquad (8)$$

where

T_{sk} = external surface temperature of wall or roof, ^{o}F

T_o = outdoor air temperature, ^{o}F

i, i_o = time i and time i_o, (limits of summation)

j = time of summation

α = surface solar radiation absorptivity

I_s = total insolation incident on the surface

L.W.R. = net long wave radiation exchange

$$= \sigma T_{oa}^{4} (a + b \sqrt{P_w} - F\varepsilon) \qquad (9)$$

σ = Stefan-Boltzman constant

T_{oa} = outdoor absolute temperature in deg. R

a, b = constants, see Table 1

P_w = water vapor pressure at ground level, in inches of mercury, (i.e. partial water vapor pressure).

F = correcting operative factor = 1.35

ε = surface emissivity for long wave radiation

R_s = equivalent thermal impedance of the wall

$$\text{or roof} = \frac{\text{Th.T.C.}}{\sum_n Q_{\text{layer } n}} \qquad (10)$$

where

$Q_{\text{layer } n}$ = heat capacity of the layer in the wall (roof) per unit of wall's (roof) external surface = $M_n c_n$ where

M_n = weight of layer n per unit of wall's (roof) external surface

c_n = specific heat of layer n

Inclination of Plane (Σ)	a	b
0^o (horizontal surface)	0.547	0.326
90^o (vertical surface)	0.290	0.163

Table 1. Coefficients a and b for plane inclined at Σ to horizontal (10)

6. Internal surface temperature calculation

Following the method developed by Hoffman and Givoni (11), the internal surface temperature is determined from:

$$\Delta T_{ik} = \sum_{j=i_o}^{i} \left[(\Delta T_{sk})_j \left(1 - e^{-\frac{i-j}{\text{Th.T.C.}}}\right) \right] \qquad (11)$$

where

ΔT_{ik} = incremental contribution at time i to the internal temperature at the heat storing zone or at the most internal layer of the element k, originated by the increment $(\Delta T_{sk})_j$ from $j = i_o$ until $j = i$

$(\Delta T_{sk})_j$ = external surface temperature increments at wall or roof at time j

i, i_o = time i and time i_o, (limits of summation)

j = time of summation

The increment of the internal layer minimal temperature of each heat path is obtained approximately by adding:

$$N_k = (\Delta T_{ik}) \frac{e^{-\frac{12}{\text{Th.T.C.}}}}{1 - e^{-\frac{24}{\text{Th.T.C.}}}} \qquad (12)$$

to the minimum of the corresponding external surface temperature computed according to Eq. 8. Thus,

$$T_{k\,\min} = T_{sk\,\min} + N_k \qquad (13)$$

$$T_{k\,\max} = T_{k\,\min} + \Delta T_{ik} \qquad (14)$$

where

$T_{k\,\min}$ = minimum internal temperature at the place where the Th.T.C. is calculated

$T_{k\,\max}$ = maximum internal temperature at the place where the Th.T.C. is calculated

$T_{sk\,\min}$ = minimum external surface temperature, (Eq. 8)

7. Internal air temperature calculation

Following (11), the minimum and maximum internal temperatures are calculated by the equations:

$$(T_{ia})_{\min} = \frac{\sum_k (T_{k\,\min}) \frac{S_k}{R_k}}{\sum_k \frac{S_k}{R_k}} \qquad (15)$$

$$(T_{ia})_{\max} = \frac{\sum_k (T_{k\,\max}) \frac{S_k}{R_k}}{\sum_k \frac{S_k}{R_k}} \qquad (16)$$

where

$(T_{ia})_{\min}$ = minimum internal air temperature

$(T_{ia})_{\max}$ = maximum internal air temperature

$T_{k\min}$ and $T_{k\,\max}$ are defined in Eq. 13 and 14

S_k = internal area of the external wall or roof "k"

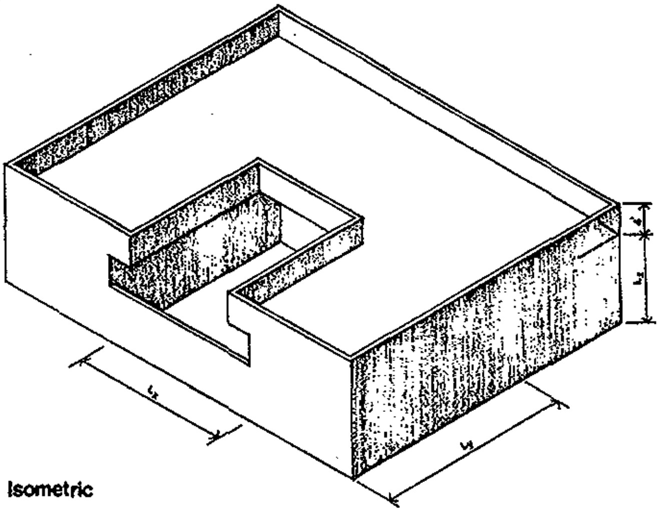
k = ordinal number of wall or roof

R_k = thermal resistance of the inner layer of wall k until the internal air

By determining the minimal and maximal internal air temperature, the objective of the method is accomplished because one can now compare the calculated temperatures with the comfort zone index, thus testing the thermal performance of the building.

PARAMETRIC STUDIES

The computer program was used to study the influence of some of the major courtyard house parameters on one of the interior comfort indices: the maximal and minimal temperature attained in the house. The parameters used included the building's azimuthal orientation, the courtyard dimensions: width L_x, length L_y and height L_z(Fig. 2), the facade's absorptivity α (or color), and the reflectivity r of the ground cover.



Isometric

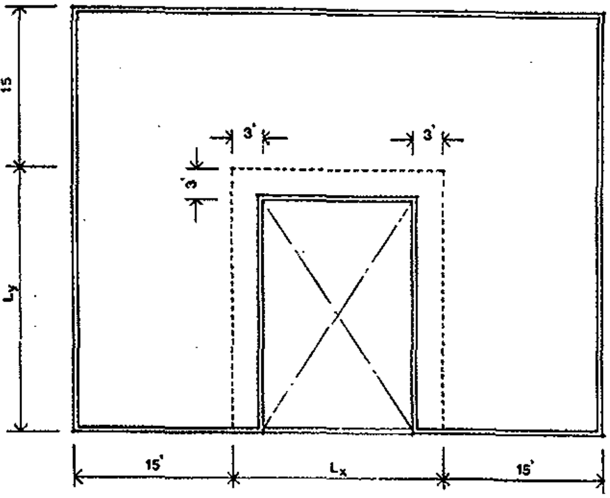
Fig. 2. Isometric view of the court house model

The invariant dimensions of the model used for computation are described in Fig. 3. The model's walls are constructed of common brick with stucco on the outer surfaces and plaster on the inner surfaces. The roof is concrete slab with the following layers on top of it: tile pavings, mortar, sand bed, lightweight concrete, and waterproofing course; and the ceiling is plaster applied directly on the concrete slab.

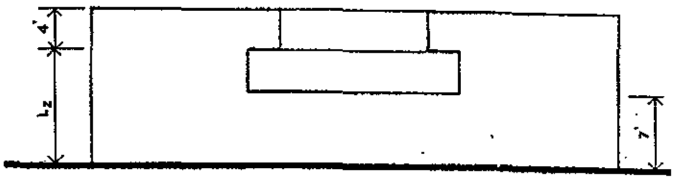
The computations were performed for a 12-hour period (6 a.m. to 6 p.m.) where weather and insolation data used were hourly, for Phoenix, Arizona, on June 21, (5,12).

The results of the parametric study, performed by varying the "test parameter" while keeping the other parameters fixed, are summarized in Table 2.

The major conclusions of the study performed so far, within the specified parameter and climate range, are that orientation, courtyard plan dimensions, (L_x and L_y), color, and ground cover do not play an important role in affecting the indoor temperature limits in the courtyard house. Nevertheless, facade color of lower thermal absorptivity, and ground cover of lower reflectivity tend to reduce the indoor temperature. The main effect is obtained from the building's height, L_z, with a building 42 ft high lowering indoor temperatures by 4.4°F when compared to an 11 ft high building. From the thermal viewpoint, the higher building differs from the lower one only by keeping more of its courtyard wall areas and surrounding ground in shade over the daylight period. Although further studies are needed to draw design conclusions applicable to buildings in general, the importance of the passive control of solar effects, namely of shadow generation, has thus been clearly demonstrated.



Roof Plan



Elevation

Fig. 3. Court house model dimensions

THE COMPUTER PROGRAM AS AN INTERACTIVE DESIGN TOOL

The above-described computer program is relatively easy and inexpensive to use, when compared to available building heat load computer programs. For example, one computer-run for a 12-hour thermal simulation of the model courtyard has cost about $5.00. The inputs consist of the description of the building's geographic location, atmospheric conditions, building envelope, orientation, geometry, construction and color, ground reflectivity, and outdoor air temperature and humidity. The outputs are the maximal and minimal interior air temperatures during the test period, which are used as the only comfort zone index in the existing model.

Test Parameter	Parameters						$(T_{ia})_{min}$ °F	$(T_{ia})_{max}$ °F	Influence
	ψ	L_x, ft	L_y, ft	L_z, ft	α	r			
Orientation	0,90,180,270	20	25	11	0.25	0.20	74.0-74.2	81.9-82.2	negligible
Dimensions	270	30,40,50	25	11	0.25	0.20	74.0-74.1	81.8	negligible
	270	20	35,45,55	11	0.25	0.20	74.0-74.1	82.1-82.3	negligible
	270	20	25	22	0.25	0.20	72.4	79.2	significant
	270	20	25	32	0.25	0.20	71.8	78.2	
	270	20	25	42	0.25	0.20	71.4	77.6	
Facade Absorptivity	270	20	25	11	0.12	0.20	73.9	81.8	small
	270	20	25	11	0.40	0.20	74.1	82.1	
Ground Reflectivity	270	20	25	11	0.25	0.40-0.60	74.1	82.0-82.1	negligible

TABLE 2: RESULTS OF THE PARAMETRIC STUDY

The architect can thus vary the input parameters and evaluate their influence on the comfort zone index, which is the output. Based on this output he can continue varying the parameters till operation within the comfort zone range (say 74° F to 85° F in the hot-arid zones) is arrived at and is compatible with other considerations such as aesthetics and economics. Apart from supplying quantitative design information about the comfort attributes of the building, this interactive procedure enhances creativity and educates its user.

The detailed description of the computer program can be found in (13).

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REFERENCES

1. Kusuda, T. "NBSLD, the Computer Program for Heating and Cooling Loads in Buildings," U.S.D.I., NBS Building Science Series 69, July 1976.
2. U.S. Post Office Dept., "Computer Program for Analysis of Energy Utilization in Postal Facilities," Report on Project No. 67138, 1969
3. Automated Procedures for Engineering Consultants (APEC) Program HCC-III.
4. Socrates, quoted in Arthur B. Gallion and Simon Eisner, *The Urban Pattern* (2nd ed.; D. Van Nostrand Company, Inc., 1963), p. 22.
5. American Society of Heating, Refrigeration and Air Conditioning Engineers, *ASHRAE*, *Handbook of Fundamentals*, 1972.
6. Groth, C. C. and Lokmanhekim, M.: *A New Technique for the Calculation of Shadow Shapes and Areas by Digital Computer*. Research sponsored by the Post Office Dept. of the U.S.A., under POD contract no. RE 49-67.
7. Bruckmayer, F.: The equivalent brick wall, *Gesundheit* *Ingenieur*., 63 (6), 1940.
8. Raychaudhurry, B. C. and Chaudhury, N.K.D.: Thermal performance of dwellings in the tropics, *Indian Construction News*, Dec. 1961.
9. Hoffman, M.E. and Givoni, B.: *Proposal of a Method for Calculating External Surface Temperature*. *Technion, Israel Institute of Technology*, Building Research Station Report. January 1973.
10. Holden, T. S. Calculation of incident radiation temperature upon building surfaces, *ASHRAE Journal*, April 1961, pp. 51-54.
11. Hoffman, M. E. and Givoni, B., *Prediction of Internal Temperature Using the Total Thermal Time Constant as a Building Parameter*. Technion, Israel Institute of Technology, Building Research Station Report, January 1973.
12. U.S. Department of Commerce, Weather Bureau, *Local Climatological Data* (supplement), 1964.
13. Agha, M. F. "The Concern of Microclimate and Comfort Zone as Generator for the Courtyard House Design with Particular Emphasis on the Hot-Arid Zone", *Ph.D. Dissertation* in Architecture, University of Pennsylvania, 1975.