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A SIMPLE METHOD FOR ESTIMATING THERMAL RESPONSE OF BUILDING MATERIALS IN TROPICAL CLIMATIC ZONES

E. E. IHEONU

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ABSTRACT

This paper develops a simple method for estimating the thermal response of building materials in the tropical climatic zone using the basic heat equation. The efficacy of the developed model has been tested with data from three West African cities, namely Kano (lat. 12.1°N) Nigeria, Ibadan (lat 7.4° N) Nigeria and Cotonou (lat. 6.4°N) Republic of Benin, by considering a reference building with a flat ceiling option. Results show that the interior air temperature obtained as a direct response to the fluctuations of the outside air temperature indicate daily temperature reductions of varying magnitudes, depending on the building insulation, material thickness used and also on property value of the material adopted. It is concluded from the model's estimates that interior temperatures for thermal comfort can be realized through the appropriate application of passive systems.

KEY WORDS: Thermal Response, Heat equation, Flat ceiling option, Building insulation, Passive systems.

. INTRODUCTION.

he design of buildings to achieve thermal omfort has been a major problem onfronting architects and building scientists the tropics. Problem arises due to the irect response of the inside air temperature o the variations of the harsh external limatic conditions which prevail within the nvironment. Thermal comfort is generally chievable by the application of suitable aterials as insulators to reduce the external mbient temperature to a tolerable level in a uilding system.

hermal insulation perhaps provides the implest means of achieving thermal comfort buildings. In very broad terms, thermal nsulation can be considered as the etardation of heat energy transfer whether y conduction, convection or radiation.

asically, there are four dominant factors, vhich influence the conditions of thermal omfort in a building. These are:

air temperature
) mean radiant temperature

) relative air velocity and
) relative humidity (water vapour pressure in the ambient air)

ir temperature is probably the most ommonly used variable to measure the egree of thermal comfort in buildings. laximum value of indoor temperature may ierefore be used as a good index to valuate the relative thermal performance of uilding envelopes.

The concept of thermal comfort [illegible] subjective. The effective temperatures for comfort are generally taken to be between 21°C and 24°C. These limits can probably be exceeded by about ± 3°C [illegible] serious discomfort being experienced. Values of effective temperatures beyond these limits may indicate conditions [illegible] or cold for thermal comfort, depending [illegible] the climatic zone. Based on the corrected effective temperature monogram scale, Ojosu et al (1990) opined that thermal comfort occurs between the index of 24°C and 29.5°C. Garg and Gupta (1986), however, put the accepted limit for comfort at 27° C.

In the major urban settings, mechanical systems involving expensive equipment utilizing fuel and electrical energy have, in most cases, been used to achieve the required thermal comfort in buildings. Such sophisticated 'active' systems cannot be easily afforded by an average person in developing economy because of their escalating costs and maintenance difficulties.

Several passive solar building architectures have been designed to reduce building temperature swings in the hot arid climatic zones, worldwide. Amongst the commonest of such design strategy is the use of layered walls to reduce the actual interior temperature fluctuations (Duffin and Knowles, 1984) and other design patterns aimed at achieving thermal comfort in building envelopes (Duffin and Knowles, 1981 and Garg, 1991).

E. E. IHEONU, Nigerian Building & Road Research Institute, Building Physics Unit, Ota, Ogun State, Nigeria

This study examines a simple procedure for determining the internal temperature fluctuations in a typical building envelope by solving the heat equation.

Data used for the study were obtained at the Ibadan station of the International Institute of Tropical Agriculture (IITA-Ibadan), Nigeria. Selected building materials have been used to test the efficacy of the developed model.

2. THE BASIC HEAT EQUATION

The heat equation (conservation of energy) may be expressed in the form:

$$\frac{\partial T}{\partial t} = Q - C - M \qquad (1)$$

where $\frac{\partial T}{\partial t}$ is the rate of change of temperature

Q is the rate of effective heat production

C is the cooling rate and

M is the rate of heat flow due to convection – conduction.

Temperature variations in the tropical climatic zones may be assumed to be in a state of quasi – equilibrium during most periods of the day such that $\partial T/\partial t$ is always considerably smaller than the other terms in the heat equation and may be ignored in the solution of the equation.

Thus, if $\partial T/\partial t = 0$ then the heat equation (1) becomes:

$$Q = C + M \qquad (2)$$

The cooling term may also be considered to be due to the contributions from mechanical cooling systems which in this instance, has no relevance to the development of the model and could be neglected. Hence, the quasi-equilibrium condition of the basic heat equation reduces to:

$$Q = M \qquad (3)$$

3. QUANTITATIVE ANALYSIS OF THE QUASI-EQUILIBRIUM HEAT EQUATION

3.1 The rate of effective heat production.

Solar radiation plays a very dominant role in the energy balance of a building. Application of the concept of effective heating of solar radiation to buildings will involve the determination and /or relevance of several parameter such as reflectivity, absorptivity and/or surface emisivity, and transmissivity of the building material. For radiant energy incident on a material surface, reflectivity η will be defined as the fraction of incident radiation reflected, absorptivity α, the fraction absorbed and transmissivity,τ the fraction transmitted. The three variables are related according to the well-known equation (McDaniels , 1984) given by:

$$\eta + \alpha + \tau = 1 \qquad (4)$$

The effective heating coefficient of solar radiation in this model is the transmissivity of the material.

If this be the case, then

$$\tau = 1 - \alpha \qquad (5)$$

where reflectivity of the material is assumed to be zero, since it has no contributory effect on the interior temperature fluctuations of the builded enclosure.

The rate of heat production or heat gain is an effective input to the inside energy balance and accounts for the portion of thermal radiation that is transmitted to modify the interior temperature swings of a building. The heat production rate Q may be given by the expression:

$$Q = (1 - \alpha)\, q_{lw} \qquad (6)$$

where q_{lw} is the long wave radiation heat transfer coefficient.

Following Desmarais et al (1999), q_{lw} can be approximated by the equation:

$$q_{lw} = A_r \delta E_r [(T_r + 273)^4 - E_o (T_o + 273)^4] \qquad (7)$$

where, for a roofing /ceiling material, for instance,

A_r is the cross – sectional area (m^2), δ is the stefan – Boltzman's constant = 5.670×10^{-8} $W/m^2\,k^4$, E_r is the emissivity of the material surface (%)

E_o is apparent emissivity of the atmosphere, which in this case is taken to be the minimum effective emissivity of clear sky

(= 0.7.). T_r is the temperature at which the emissivity of the building material is obtained (°C) and T_o is the ambient temperature (°C).

The absorptivity α of a material is generally different from its emissivity, E. However, to simplify the analysis of heat energy transfer in a built dwelling system, condition of thermal equilibrium is often assumed and used in many applications. That is,

$$\alpha = E \qquad (8)$$

in conformity with Kirchoff's law.

3.2 Heat Energy Flow

The heat energy flow due to convection – conduction is the most important heat loss mechanism in buildings and is given by Croy and Dougherty (1984) as:

$$M = U A_r (T_o - T_{in}) \qquad (9)$$

$$= \frac{k A_r}{x} (To - Tin)$$

or $$M = -kA_r\left(\frac{dT}{dx}\right) \qquad (10)$$

where

U	is the global heat transfer coefficient, which depends on various factors and characteristics such as the geometry of the system and heat transfer resistance of the material used in the building system
k	is the thermal conductivity of the material
x	is the distance in the direction of the heat flow or the thickness of the material.

The minus sign in equation (10) is a consequence of the second law of thermodynamics, which requires that heat must flow in the direction of lower temperature.

Thermal conductivity, k is strictly a material property. Thermal conductance (c) is however, sometimes use to describe a particular size and thickness of a material. In this case,

$$M = C\,(T_o - T_{in}) \qquad (11)$$

where

$$C = \frac{kA_r}{x}$$

It is obvious from (11) that, for a unit area of material, the higher the value of C, the more rapidly will the material conduct heat across its thickness.

Insulation properties of building materials are often commonly discussed in terms of the R-value concept. Sometimes called the unit thermal resistance, the R- Value is the thermal resistance per unit area of material and thus determines how well a material retards heat energy flow.

The R -value is simply the inverse of thermal conductivity of a specific shape of a material and therefore depends on the thickness of the material.

$$R - value = RA_r = \frac{x}{k}$$

where k is measured in W/m. K. and x in metres (m).

Selected values of E, α and k of materials used in this study were obtained from the literature (Bond et al, 1977; Van Straaten, 1969; Ozisik, 1985; and Kothandaraman and Subramanyan, 1992).

4. EXPERIMENTATION AND APPLICATION OF DEVELOPED MODEL

The functional designs of the building such as the interior partitions, etc would be presumed to have negligible effect and as such, will not be taken into consideration in the analysis.

The incident radiation will be assumed to be totally transmitted from the roof to the ceiling space. The material to be used in the analysis is the rockwool insulation blanket (rockwool batts) which finds application in diverse sectors of the economy including the petrochemical industry, manufacturing industry building and construction industry etc., and will be applied to three tropical cities, namely Kano (latitude 12. 1 °N), Ibadan (latitude 7.4°N) and Cotonou (latitude 6.4°N) for purposes of heat retardation in buildings only.

In this study, the Nigerian Building and Road Research Institute (NBRRI) model house in Kano has been taken as the reference building envelope. Following Maduekwe and Opoko (1998b), the total roof area of the building = 245.904 m^2 and the thickness of the main entrance glass flush door = 0.044 m.

The following property values and dimensions of the insulation blanket will be adopted.

- Thermal conductivity, k = 0.040 W/m. K. obtained at 32^{0}C
- Absorptivity, α = 0.9
- Material thickness, X = 0.075m (and 0.1m)

In addition, the dry season month of March, 1994 is also adopted with mean temperatures of 39°C for Kano, 35°C for Ibadan, and 32°C for Cotonou,

5. RESULTS AND DISCUSSION

Figs. 1, 2 and 3 show the variations of the measured data and the estimated interior air temperatures (using rockwool blankets of thickness 0.075 m and 0.10m on a flat ceiling) for a typical building dwelling house at Kano, Ibadan, and Cotonou, respectively. The outside air temperature is represented by curve (a) while the fluctuations of the estimated interior air temperature are indicated by curves (b) and (c) for material thickness 0.075m and 0.10m respectively. It is observed from curves (b) and (c) that the daily ambient temperature variations [curve (a)] have undergone considerable temperature reductions with the application

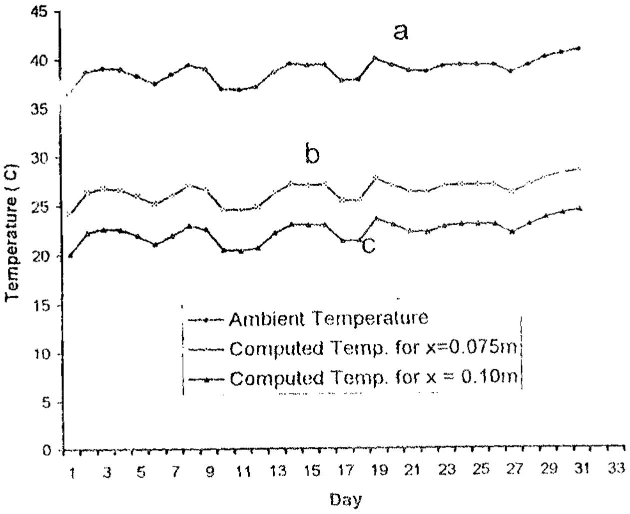

Figure 1: Daily averages of estimated inside air temperatures compared with measured data, (Kano).
a) external ambient temperature
b) inside air temperature for insulation material thickness, 0.075m
c) inside air temperature for insulation material thickness, 0.10m

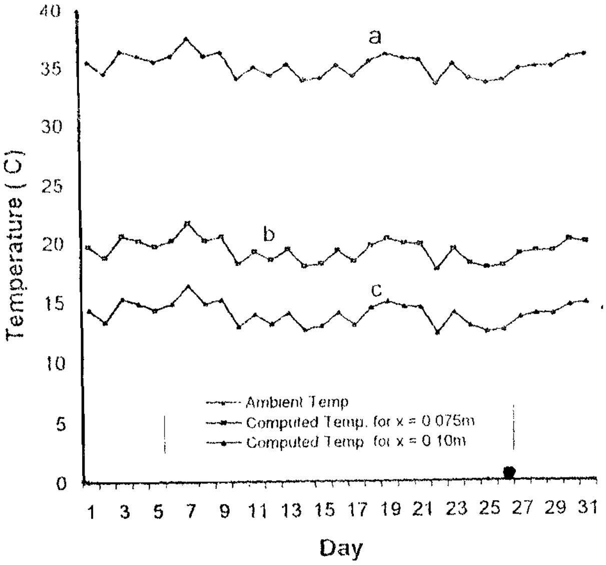

Figure 2: Daily averages of estimated inside air temperature compared with measured data (Ibadan)
a) external ambient temperature
b) inside air temperature for insulation material thickness, 0.075m
c) inside air temperature for insulation material thickness, 0.10m

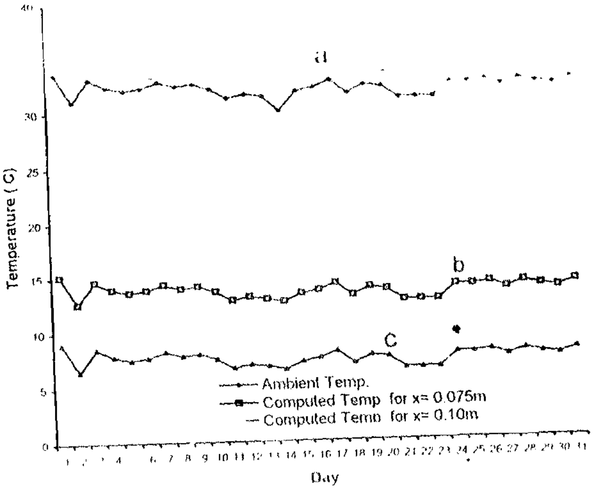

Figure 3: Daily averages of estimated inside air temperature compared with measured data (Cotonou)
a) external ambient temperature
b) inside air temperature for insulation material thickness, 0.075m
c) inside air temperature for insulation material thickness, 0.10m

of the insulating building material in the three cities throughout the month. The magnitude of reduction is found to be dependent on the insulating material thickness used, for a constant value of thermal conductivity of the material. The inside air temperature reduction swings may be summarized as follows:

i) Kano (latitude 12.1°N)

Temperature reductions of between 30-34% and 40 - 45% using rockwool blankets of thickness 0.075m and 0.10 m respectively were achieved. Temperatures for comfort were clearly established, with rockwool blankets 0.10 m thick.

ii) Ibadan (latitude 7.4°N)

Temperature reductions of between 42 - 47% and 56 - 63% using rockwool blankets of thickness 0.075m and 0.10m respectively were also achieved. In this environment, rockwool blankets of thicknes 0.075m will just be sufficient for insulatio purposes whereas the material wit thickness 0.10m, indicates temperatur conditions too cold for thermal comfort.

iii) Cotonou (latitude 6.4°N).

Temperature reductions of between 55 60% and 73 - 80% using rockwo blankets of thickness 0.075m and 0.10 respectively, were achieved at this cit These results show that the adopt thickness of rockwool blankets used in th environment will drive the effecti temperatures well beyond the comfort limi of building dwelling houses. Insulati material thickness far less than 0.075m w the same *k*-value, will certainly perfo better, in terms of thermal comfort within his environment.

A brief application of the above procedure to a glass flush door of the reference building within the Kano climatic environment, with properties values:

k = 0.038 W/m.K at 23^0C
α = 0.90

and dimensions:

X = 0.044m
A = 5.97 m^2

shows that a reduction of temperature of between 4-5%, due to the thermal response of the glass door to the external ambient temperature is barely achievable. This confirms the expected roles to be performed by the different parameters and dimensions of insulation building and other materials in effectively creating some tolerable temperature reductions due to their response to the outside ambient temperature, in order to attain thermal comfort in buildings within the tropical climatic zones.

Some workers have developed design patterns and techniques for controlling temperature in buildings. For example, Duffin and Knowles (1980, 1981) investigated the Adobe wall design in the hot arid climate of the American Southwest in a situation where the mean interior temperature was too high for comfort and showed how to design the wall to cool the house to a comfortable temperature during the hot part of the day. The mathematical techniques used here were developed using composite electrical transmission lines and applied to a building model where heat transformation into the interior is assumed to be through walls only.

In related works, Maduekwe and Opoko (1998 a, b) did not just consider the thermal response of the walls of an NBRRI model house in Kano, but investigated the thermal responses of the different materials used for the building. Their analysis was based on Fourier theory utilizing the sol-air concept in line with the procedure used by Algifri et al (1992). Results from their study showed that the ceiling temperatures were closer to the outside air temperatures on a cold day but exceeded the ambient temperatures during some periods of the day, while the ceiling temperatures were lower than the outside air temperatures during most parts of a hot day. Results from the present work however, show consistency in the daily reduction of the outside air temperatures which invariably imply that hourly temperature reductions will also follow the same trend.

6. CONCLUSIONS.

The simple procedure developed by solving the energy conservation equation is proposed as a criterion to estimate the response and performance of insulation and other building materials to external temperature swings in the tropical climatic zones.

The model enables the assessment of material properties in practically all situations where thermal analysis of any system is desired. The study has shown that the range of temperature reduction due to the application of an insulating building material depends on the conductivity value of the material, the material thickness and on the prevailing climatic conditions within any particular environment. For a 0.075m thick rockwool batt, the percentage temperature reduction varied between 30-34%, 42-47% and 55-60% for Kano, Ibadan and Cotonou, respectively.

The results have also shown the possibility of determining insulating building and other materials that could be applied to a building system to bring about considerable energy consumption savings which would, otherwise, have been utilized for the purpose of cooling.

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