#6581

MINIMISING ENERGY CONSUMPTION IN PASSIVE BUILDINGS BY APPROPRIATE DESIGN

E.H. Mathews
Department of Mechanical Engineering
University of Pretoria, Pretoria 0002
South Africa

P.H. Joubert
National Building Research Institute
Council for Scientific and Industrial Research
P O Box 395, Pretoria 0001, South Africa

1. Introduction

Building designers are often urged to consider their designs from the viewpoint of utilising energy as efficiently as possible. The ultimate in energy efficiency is a completely passive building in which an acceptable indoor environment is achieved by means of natural ventilation, natural lighting and passive thermal performance.

Most methods of predicting the thermal performance of naturally ventilated buildings require measured or assumed values for the expected ventilation rates. At the design stage measured values are often unavailable, which makes it difficult to evaluate alternative design strategies quantitatively (1).

A much simplified method of thermal analysis, including the effect of natural ventilation, was developed at the National Building Research Institute (NBRI) and experimentally verified in a number of buildings (2). Although the method is based on theory, empirical constants represent the typical expected natural ventilation rates in conventional South African buildings. The method is therefore eminently suitable to predict, at the design stage, the indoor air temperature of a naturally ventilated building.

This paper briefly describes the method (3) and shows how appropriate design changes can affect the energy efficiency of the design. Some of the simulated results are compared with measured data. The parameter sensitivities of a naturally ventilated building are similarly investigated to demonstrate the effect of changes to the design on the energy efficiency and cost of the building.

#6581

2. Thermal analysis method

2.1. Temperature variation

The heat flow through a building can be predicted by the simplified electrical analogue model shown in Figure 1. The variation in the indoor air temperature of the building can then be derived from the response of the model to the outdoor air temperature.

It is assumed that the correct orientation of the building, as well as an adequate roof overhang, will limit direct solar penetration to a negligible amount during the summer. Good cross-ventilation is also presupposed.

The assumption is made that the indoor air temperature (T_i) is dependent only on the thermal interaction of the building and the outdoor air temperature (T_o). Due to the simplicity of the model, the effect of exterior surface colour is not taken into account, although its effect is partly allowed for by empirically derived constants and equations.

In the simplified electrical analogue model (Figure 1), the thermal properties of the building are described by the total active thermal capacity (ΣC) of the building, the shell resistance per unit shell area (R_s/ΣA) and the ventilation resistance (R_v). The ventilation resistance is dependent on the ventilation rate, while the shell resistance is dependent on the thermal properties of the building. The total active capacity is that portion of the building's thermal capacity that effectively stores heat. This value therefore takes into account the relative position of mass and insulation in the shell, as well as the contributions of the interior walls and floors of the building. The calculation of the active capacity is based on theory and empirical data (4).

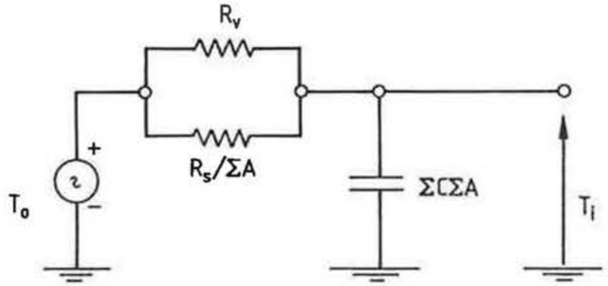

Fig. 1. Simplified electrical analogue thermal analysis model

The electric analogue model can be solved numerically (5). The variation in the indoor air temperature due to any outdoor forcing function, can be described by the following equation:

$$T_i(t) \quad = \sum_{t=t_o}^{t} \Delta T_o(t).(1 - \exp{-((t-t_o)/\tau)}) \qquad (1)$$

where:

$\Delta T_o(t)$ = the increment in the outdoor air temperature [°C]

t = time [h]

t_o = start time of outdoor air temperature [h]

exp = basis of natural logarithms

τ = time constant [h]

The correct value of the time constant (τ) for a building can be derived from the frequency response of the simplified model with the outdoor air temperature as the driving function. The time constant is defined as follows:

$$\tau \quad = 12.\pi^{-1}.\sqrt{1 + (\Sigma C.263^{-1})^2} \qquad (2)$$

where: ΣC = total active thermal capacity of the building per unit exposed shell area [$kJ°C^{-1}m^{-2}$]

The variation in the indoor air temperature is therefore dependent on an empirical constant of 263, the active capacity of the building (ΣC) and the variation of the outdoor air temperature.

The empirical constant represents the relationship between the shell resistance, exposed shell area and the expected ventilation rates. This constant also compensates for the fact that the actual forcing temperature acting on the building is the sol-air temperature and not the outdoor air temperature. The variation in the sol-air temperature is greater than that of the outdoor air temperature and therefore the constant of 263 is greater than would be the case if the sol-air temperature was used as the forcing function.

The numerical solution of Equation (1) was implemented on an Olivetti M24 microcomputer, in Pascal, by means of an optimisation method to reduce the number of computations required to perform the convolution (6).

2.2. Shift in mean indoor air temperature

Although the electrical analogue can be extended to predict the mean indoor air temperature, the following empirically derived equations are employed to calculate the shift (ΔT) in the mean values (2):

$$\Delta T(\text{Summer}) \quad = 2.0 \text{ [°C]} \qquad (3)$$

$$\Delta T(\text{Winter}) = -40.445SR^4 + 89.667SR^3 - 85.307SR^2 + 45.622SR - 2.233 \ [°C] \qquad (4)$$

where: $SR = I_{wt}R_sA_f^{-1}$

and: I_{wt} = the product of the daily solar energy (direct plus diffuse), incident normally on the windows and the percentage transmittance [$kWhday^{-1}$];

R_s = the equivalent thermal shell resistance [$m^2°CW^{-1}$];

A_f = the total floor area [m^2]

The mean values of the indoor air temperature were generally found to be higher than the mean values of the outdoor air temperature. The empirical equations partly compensate for the fact that the higher mean sol-air (and not the lower mean outdoor air) temperature is the mean forcing temperature for heat flow through the building shell. The effect of direct sun penetration in winter is allowed for by the empirical equation (4).

3. Appropriate building design changes

The thermal efficiency of a prototype A house (7) was investigated, to compare the predicted and measured effects of inexpensive changes to the basic design. The building has very little mass in the walls, while the thermal resistance of both the roof and walls is also very low. The walls and roof consist of precast trough elements. Temperature measurements were recorded at the test facility of the NBRI at Pretoria.

Figure 2 shows the indoor temperature variation of the unmodified building. To increase the thermal resistance of the building shell, paper was attached to the inside of the walls and the roof, to bridge the troughs so as to trap a layer of air next to these elements. Figure 3 indicates the resultant improvement. The maximum indoor air temperature was approximately 1.0°C lower, which represents a fair improvement in one aspect of the thermal efficiency of the building. It was thus possible to minimise the energy requirement.

Other features that may influence the energy efficiency of a building can be similarly investigated. These include an increase in the mass of the structure, the insulation of different building elements and the type of floor.

A standard house (4) was used for the parameter sensitivity studies, to demonstrate the predicted energy efficiency of changes to the basic design. The maximum and minimum predicted indoor air temperatures for different shell resistances and north-facing window areas are shown in Figures 4 and 5. All the calculations were done with design weather data for Pretoria.

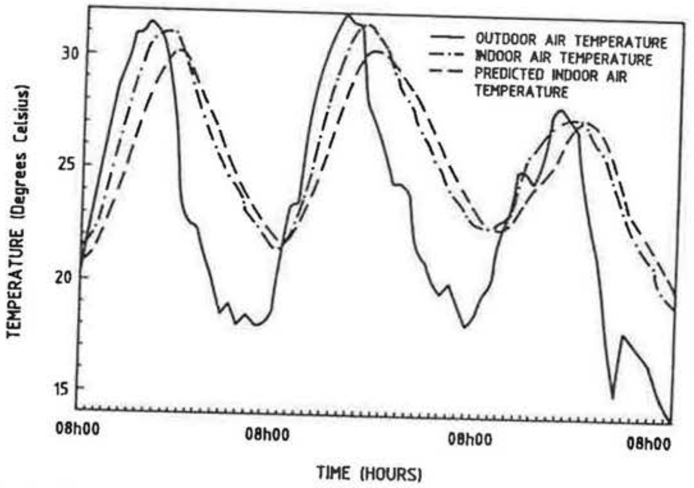

Fig. 2. Predicted and measured inside air temperature of building with windows open

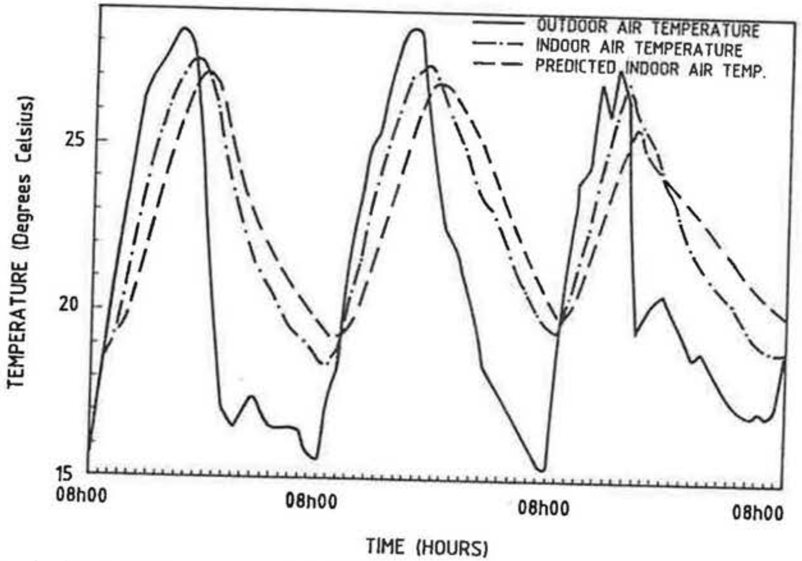

Fig. 3. Predicted and measured inside air temperature of building with increased shell resistance

Figure 4 shows how an increase in the thermal shell resistance from 0.17 to 0.30 $m^2{}^{\circ}C\,W^{-1}$ reduced the summer maximum temperature by 5°C, and raised the winter minimum temperature by 9°C. Some of the means available to the designer to increase the shell resistance are to include more insulation in the walls and roof.

In Figure 5 it is shown that, when a window occupies less than 30 per cent of the area of a wall, even a modest increase in its size may augment winter solar heating. Proportionately larger windows provide little added benefit. The increase in summer maximum temperature will be less than 0.5°C if window size is kept below 30 per cent.

Figures 4 and 5, and other similarly derived parameter sensitivity graphs, will enable the designer to select appropriate changes to his passive building design, in order to produce a cost-effective and energy-efficient design. Only two parameter sensitivity studies are shown but many others can be performed economically by means of the proposed method.

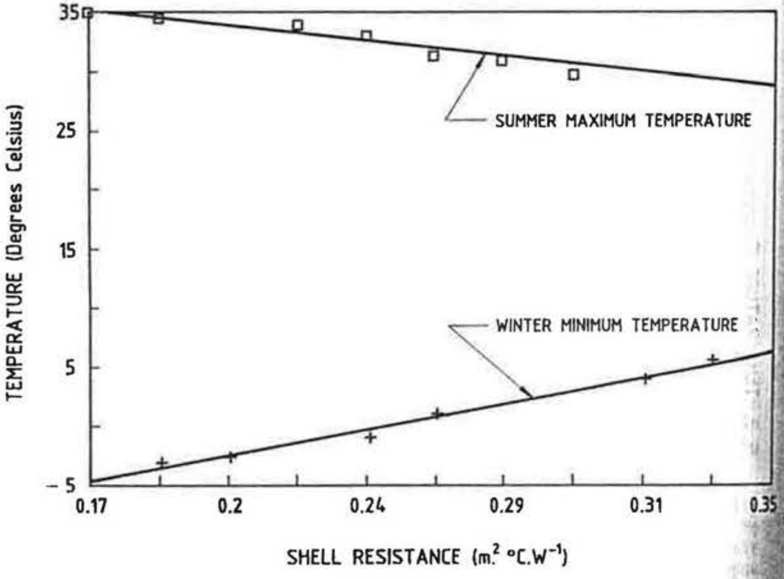

Fig. 4. Predicted maximum and minimum temperatures as a function of the shell resistance of the building

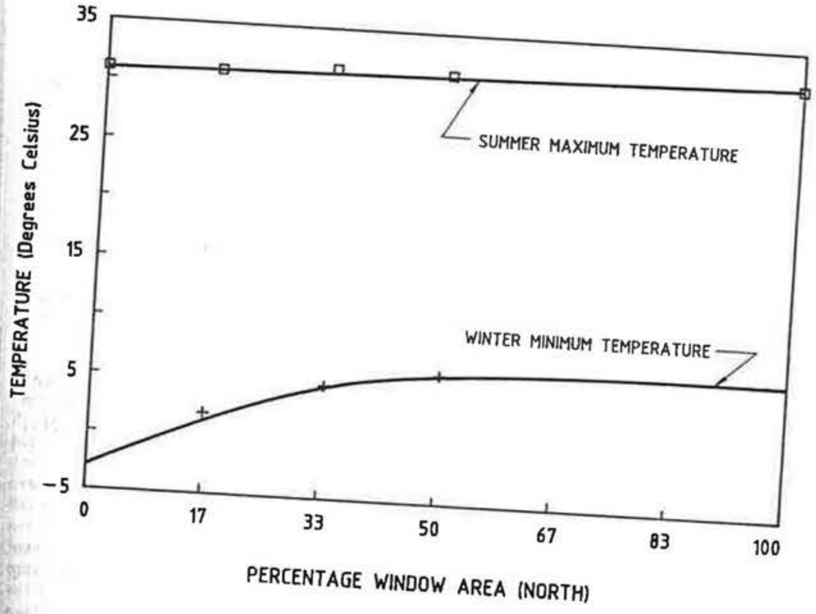

Fig. 5. Predicted maximum and minimum temperatures as a function of the percentage of window area relative to wall area

4. Conclusions

A simplified thermal analysis procedure, as described in this paper, can be used to predict the thermal efficiency of a passive building that is naturally ventilated.

By means of parameter sensitivity studies, the influence of changes to the thermal properties of the building elements can be ascertained. An increase in the active thermal resistance of the exposed shell of the building, will enhance the thermal performance. Other parameters such as the percentage of window area relative to wall area, or the insulation of the roof and the floor, can also be studied in order to design a cost-effective and energy - efficient building.

It is therefore possible, at the conceptual phase, for the designer to select appropriate and inexpensive building elements that will result in a building that consumes a minimum of energy.

5. References

(1) Loudon A.G., Summertime temperatures in buildings without air-conditioning. JIHVE (37) 288, 1983.

(2) Mathews E.H., The prediction of natural ventilation in buildings. D. Eng dissertation, PU for CHE, Potchefstroom, 1985.

(3) Mathews E.H. and Wentzel J.D., Prediction of the thermal performance of low cost housing. 10th CIB Congress, Washington, Proceedings, 1986.

(4) Wentzel J.D. et al., The prediction of the thermal performance of buildings by the CR-method. National Building Research Institute, Pretoria, South Africa. Report BRR 396, 1981.

(5) Joubert P.H. and Mathews E.H., The numerical solution of a novel thermal analysis model. Renewable energy potential in Southern Africa, Conference Proceedings. Energy Research Institute, University of Cape Town, 8-10 September 1986.

(6) Peavy B.A., A note on response factors and conduction transfer functions. ASHRAE Trans., 84, 1, 688-690, 1978.

(7) Arrigone J.L., Low cost roof building technology - Three case studies using locally manufactured building components. Housing Science, 8, 3, 217-229, 1984.