ELSEVIER

Energy and Buildings 28 (1998) 25–32

AIVC 11444

ENERGY AND BUILDINGS

Effectiveness of mass and night ventilation in lowering the indoor daytime temperatures.
Part I: 1993 experimental periods

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Received 7 July 1995; accepted 1 April 1997

Abstract

Buildings with different mass levels were monitored in the summer of 1993 in Pala, South California, under different ventilation and shading conditions. The effect of mass in lowering the daytime (maximum) indoor temperatures, in closed and in night ventilated buildings, was thus evaluated. Night ventilation had only a very small effect on the indoor maxima of the low-mass building. However, it was very effective in lowering the indoor maximum temperatures for the high mass building below the outdoor maxima, especially during the 'heat wave' periods. On an extremely hot day, with outdoor maximum of 38°C (100°F), the indoor maximum temperature of the high-mass building was only 24.5°C (76°F), namely within the comfort zone for the humidity level of California. Comment: In 1994 the monitoring has been continued, first with the original dark color of the envelope and then with the buildings painted white, as well as under natural, all-day ventilation with open windows. The results of the 1994 experiments will be reported in Part II. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Thermal mass; Night ventilation; Passive cooling; Comfort; Hot climate architecture

1. The experimental setup

Three buildings with the same heat loss coefficient but with different mass levels: a 'low-mass' (conventional stud-wall construction), a 'medium-mass' building, and a 'high-mass' (insulated concrete walls), were monitored during the summer of 1993. The monitoring site was near Pala, about 50 miles north east of San Diego. All three have identical two-room floor plans and each building is about 23 m^2 (250 ft^2). The roofs' color was red and the walls' color medium beige. The total window's area (single glazed) is about 4.6 m^2 (50 ft^2), divided equally among the four walls.

The calculated diurnal building loss coefficient of the buildings, BLC, is 2315 W h/day·C (4390 Btu/day·F) or (UA = 96.5 W/C, 183 Btu/h·F). In this paper, only the high-mass and the low-mass buildings will be discussed.

The low mass building is of conventional Californian stud-wall construction with interior 1/2 in. gypsum drywall. All external walls are fiberglass batt insulated to a nominal resistance of R-11. The ceiling is insulated with fiberglass batt in the attic to an R-19 level.

The high mass building has solid concrete walls, 10 cm thick, insulated externally with rigid foam and plastered, so as to have the same level of insulation as the low mass building. The partition wall between the two rooms is also of solid concrete, so that the total volume of the concrete was about 5.75 m^3, or about 0.25 m^3 per each m^2 of the floor area. The interior surface area of the concrete, interacting convectively with the interior space, is about 65 m^2.

The mass characteristics of the buildings can be generalized by the Diurnal Cooling Capacity ([1]), see Section 2.

The measurements were conducted under the following conditions:

1. Windows unshaded, closed day and night;
2. Windows shaded, closed day and night;
3. Windows shaded, closed during the day and ventilated at night (7 p.m. to 7 a.m.) by a fan, with three speeds of the fans.
4. Windows open day and night, fan assisted ventilation at night.

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PII S0378-7788(97)00056-X

Measurements were taken at 10-s intervals, averaged for values at 6 min. Later the data was averages for hourly values.

1.1. Data Acquisition

The monitoring sensors include meteorological conditions and indoor temperatures.

Meteorological conditions (at a station on the roof of one building):

- Ambient air temperature (DBT),
- Relative humidity,
- Wind speed and direction,
- Horizontal global solar radiation.

Indoor temperatures (in each building):

- Air temperature (4 points at height of 1 m),
- Black Globe temperature (2 points at 1-m height)),
- Interior walls' surface temperatures (6 points at walls centers),
- Ceiling temperatures (2 points at rooms' centers).

Additional measurements in the High-mass building: interior wall surfaces (2 points at walls centers).

The indoor temperature data are the average of the four sensors measuring the indoor air temperature. The surface temperatures were taken with thermocouples glued to the surfaces and covered with a paper tape. All the measured data was transferred by a modem to the computer at the UCLA Energy Lab.

1.2. Criteria for evaluating the experimental data

As the main interest in this study was the effectiveness of mass and of night ventilation in improving the daytime temperatures and comfort conditions, the main criterion chosen for evaluating the performance of the buildings was the indoor maximum air temperature and its reduction below the outdoor's maximum.

2. Effect of mass with windows closed day and night

2.1. Unshaded windows

Fig. 1 shows indoor air temperature patterns of the two test buildings, with *closed* and *unshaded* windows, during the period of July 21 through 26, 1993, together with the outdoor temperature patterns and daily averages. Note that the indoor *maxima* follow the pattern of the outdoor temperature *average* more than the pattern of the outdoors' maxima. While during the first four days the outdoor maxima decline, the indoor maxima rise, as do the outdoor averages.

The maximum temperatures of all buildings were above the outdoors' maxima. The temperature elevation of the low mass building was about 6.5°C (12°F) above the outdoors' maxima while that of the high mass building was about 4.5°C (8°F). Thus, the thermal mass has lowered the maximum temperature in the closed buildings with unshaded windows by about 2°C (4°F).

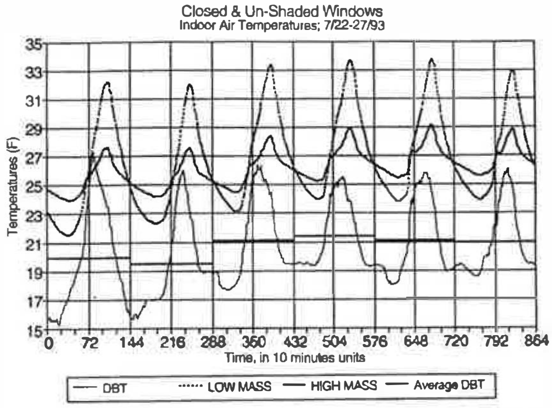

Fig. 1. Outdoor and indoor air temperature patterns of the test buildings, with *closed* and *unshaded* windows, during the period of July 22 through 27, 1993.

Fig. 2 shows the daily averages of the outdoor and the indoor air temperatures for July 21–26. Note the consistency of the temperature increase of the indoor average temperatures of the buildings with the different mass levels and their almost parallel pattern to the changes in outdoor average temperature. The average temperature increase of the low-mass building above the outdoors' average is about 6°C (11°F), and that of the high-mass building is about 5.5°C (10°F).

With a total BLC of 2315 W h/day · C (4390 Btu/day · F) and an average temperature elevation, dT, of about 5.8°C (10.5°F), it is possible to estimate the total effective daily solar gain, SG, of the buildings (through both, windows and opaque envelope) as follows:

$$dT = SG/BLC, \text{ or } SG = dT \times BLC$$

hence:

$$SG = 5.8 \times 2315 = 13{,}427 \text{ W h/day (45.8 K Btu/day)}$$

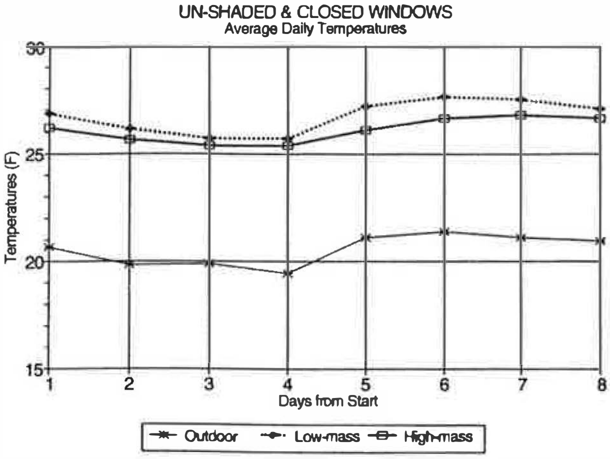

Fig. 2. Daily averages of the outdoor and the indoor air temperatures for July 21–26. Windows closed and unshaded.

The average daily total horizontal solar radiation during that period was 7.8 W h/m^2 day.

2.2. Shaded and closed windows

In the second phase the windows were provided with fixed external shades. Fig. 3 shows the daily indoor temperature patterns of the shaded buildings, together with the outdoor temperature pattern and daily averages, for a period when the buildings were *shaded but not ventilated at night*.

This monitoring period was characterized by mild undulations of the outdoor average temperature and more marked undulations of the outdoors' maxima. Note that again the pattern of the indoor maxima follows closely the pattern of the outdoors' averages. However, the daily rate of change of the indoor maximum in the case of the high-mass building is smaller than the rate of change of the outdoor averages.

With windows shaded but still closed day and night (without night ventilation) the maximum temperature of the low-mass building was about 2°C (4°F) above the outdoors' maxima, while that of the high-mass building was about 2°C (4°F) below the outdoors' maxima, but still about 5.5°C (10°F) above the outdoors' average temperature. Thus, the thermal mass has lowered the indoor maxima, with shaded windows, by about 8°F as compared with the conventional building. It means that mass is more effective in reducing the rise of the indoor temperature caused by heat gain through the external walls (or envelope in general) than that caused by penetrating solar radiation. Still, assuming outdoor maximum of 35°C (95°F), common on hot days in many regions, the indoor temperatures in a high mass building without night ventilation will be too high from the comfort aspect and there will be a need for some type of cooling.

Fig. 4 shows the indoor average temperatures of the test buildings, together with the outdoors' averages. The temperature patterns are almost parallel with an average elevation of about 4.7°C (8.5°F) of the indoor averages above the outdoors'. Thus, the shading of the windows has reduced the indoor average temperature by about 1°C (2°F).

Repeating the procedure for estimating the solar gain, (SG), applied above yields:

$$SG = dT \times BLC$$

hence:

$$SG = 4.72 \times 2315 = 10{,}927 \text{ W h/day (37.3 K Btu/day)}$$

The average daily total horizontal solar radiation during that period was 8.76 W h/m^2 day. Thus, the reduction of the solar gain by the shading, from 13,427 to 10,927 W h/day, was accomplished with an increase of about 1 KWh/(m^2 day) of the impinging radiation.

2.3. Relationship between outdoor weather parameters and the indoor maximum, with closed windows

Fig. 5 shows the daily indoor and outdoor maximum temperatures when the windows were closed day and night, first without shading and then shaded. The daily average outdoor temperature is also shown in this figure.

It can be seen that the patterns of the indoor maxima follow closely the outdoor average but not that the outdoor maxi-

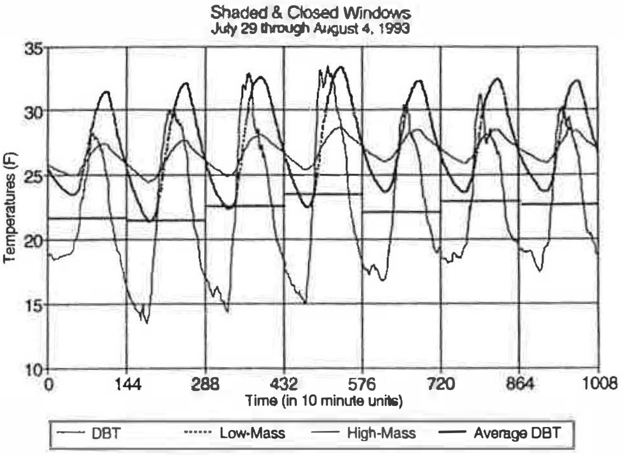

Fig. 3. Daily outdoor and indoor temperature patterns of the test buildings. The windows were *closed and shaded*. July 29 through August 4, 1993.

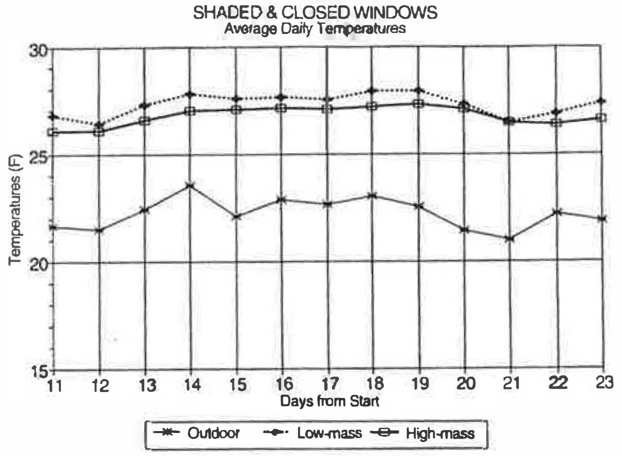

Fig. 4. Indoor average temperatures of the test buildings together with the outdoors' average.

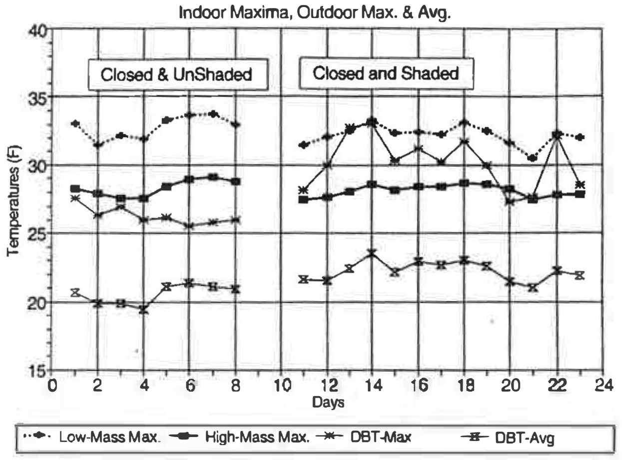

Fig. 5. Daily indoor and outdoor maximum temperatures when the windows were closed day and night, for two series: first without shading and then with shaded windows.

mum. It means that for buildings which are closed during the daytime there is poor correlation between the indoor and the outdoor maximum temperatures. On the other hand, the patterns of the indoor maxima of the two buildings follow closely the pattern of the outdoor average.

The rates of change of the indoor maximum depends on the amount of mass in the buildings. In the case of the low-mass building it is close to the rate of change of the outdoor average. In the case of the high-mass building it is about one half of the change in the outdoor average.

Quantification of the relationship between the indoor maxima and the outdoors' average will be done in the discussion of the development of the predictive formula.

3. Buildings ventilated at night, with shaded windows

From August 12, 1993 through October the buildings were ventilated each night from 7 p.m. till 7 a.m. (local time). Fans (with three speeds) activated by timers, were installed in the south window of each building (the outlets). The western windows (inlets) in each building were opened and closed manually by a person living at the site. The speeds set-ups were changed periodically. At the low and at the high speeds the buildings were ventilated during two discrete periods, and with the mid speed at about the middle of the experimental period.

Measurements of the air flow rate with each fan speed has been performed. The average air speed in front of the fan (on the inside) was measured at 25 points, twice at each point. Thus, each outlet speed is the average of 50 measurements at each speed. The air flow rate and the air change per hour (ACH) was calculated, taking into account the area of the fan's opening. The calculated ACH with the fan's low speed was 30, with the mid speed 37 and with the high speed 45 air changes per hour.

In any situation when buildings are ventilated at night the indoor temperature during the night hours drop down drastically, regardless of the building's mass, thus lowering also the indoor daily average temperature. However, the effect of the night ventilation on the indoor *daytime* conditions may or may not be significant.

When the main interest is in lowering the peak demand for air conditioning there is little interest in the night indoor conditions, except under conditions when the indoor temperatures at night are uncomfortably hot. Generally, night ventilation is of interest mainly when it affects significantly the daytime temperatures. Therefore, the analysis of the data obtained with the night ventilation will emphasize the indoor maximum temperatures.

Figs. 6 and 7 show samples of indoor air diurnal pattern with the buildings ventilated at night, with the fans at low speed and at high speed, respectively.

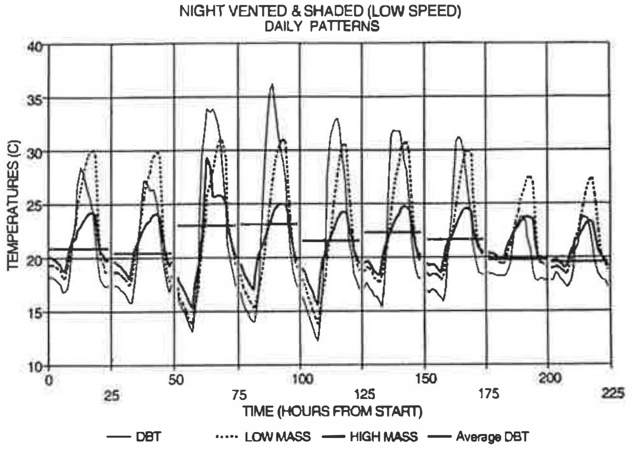

Fig. 6. Indoor air diurnal patterns. Buildings ventilated at night. Fans at low speed.

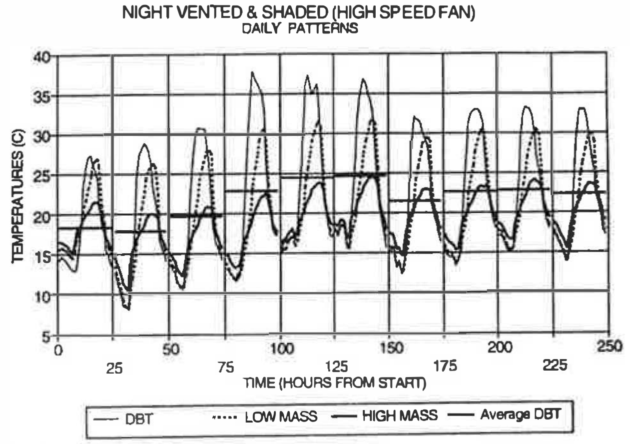

Fig. 7. Indoor air diurnal patterns. Buildings ventilated at night. Fans at high speed.

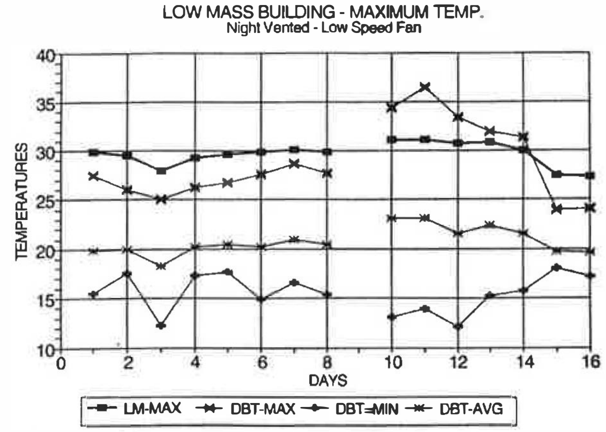

Fig. 8. Indoor maximum temperatures of the low-mass building, and the outdoor maxima, minima and average. Building ventilated at night (by fan at low speed) and closed during the day.

Figs. 8 and 9 show the indoor maximum temperatures of the low-mass and the high-mass buildings, respectively, together with the outdoor maxima, minima and average, during the period when the buildings where ventilated at night with the fans at low speed.

Figs. 10 and 11 show similar patterns during a period when the buildings were ventilated at night with the fans at high speed. The outdoor climate was very unstable during this

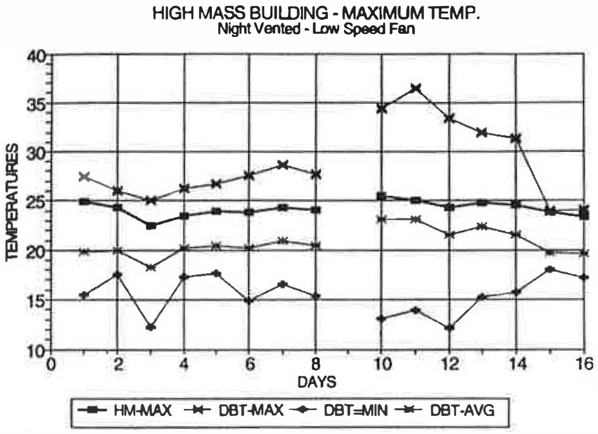

Fig. 9. Indoor maximum temperatures of the high-mass building, and the outdoor maxima, minima and average. Building ventilated at night (by low speed fan) and closed during the day.

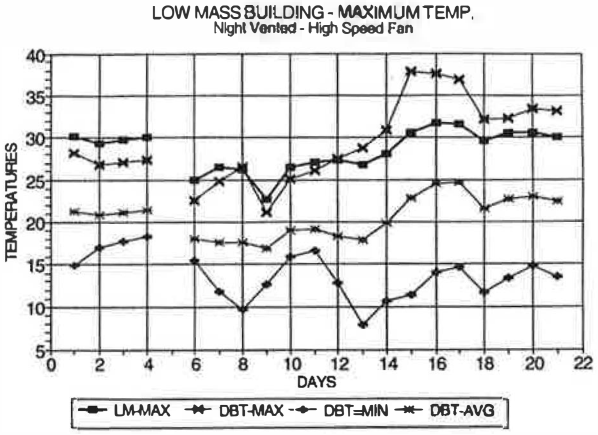

Fig. 10. Indoor maximum temperatures of the low-mass building, and the outdoor maxima, minima and average. Building ventilated at night (by fan at high speed) and closed during the day.

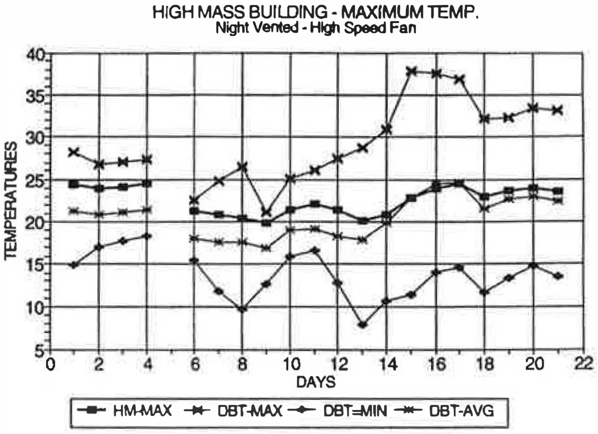

Fig. 11. Indoor maximum temperatures of the high-mass building, and the outdoor maxima, minima and average. Building ventilated at night (by high speed fan) and closed during the day.

period, with very sharp rises and falls in the maxima, with lowest maximum of about 22°C (72°F) and the highest maximum, just five days later, about 38°C (100°F). Also the outdoor minima have changed sharply.

In Fig. 6, it can be seen that the indoor maximum temperature in the low-mass building was rather close to the outdoor maximum, except during days with sharp rise of the outdoor maximum. During the cooler days the indoor maximum was even above the outdoors', in spite of the night ventilation.

In the case of the high-mass building, as shown in Figs. 9 and 11, the night ventilation has lowered the indoor maximum temperature consistently below the outdoor maximum.

A common feature to be noticed in Figs. 6 and 7 is the similarity of the patterns of the *indoor maxima* and that of the *outdoor averages*, similarly to the observation noted when the buildings were not ventilated at night. However, the rates of change in the maximum temperatures were smaller than the corresponding changes in the pattern of the outdoor average.

The daily rates of change in the indoor maxima of the low-mass building were close to the changes in the outdoor average temperature. The daily rates of change in the indoor maxima of the high-mass building were smaller, about one half, in comparison with the changes in the outdoor average temperature.

This observation provided the basis for the development of the predictive formula for the expected indoor maximum temperatures, which is described below.

4. Experimental formula for predicting the expected indoor maximum temperatures

Analysis of the relationship between the indoor maxima and various parameters of the outdoor climate has demonstrated that the best correlation exist between the outdoor *average* and the indoor *maximum*. The following experimental formula has been developed to express the indoor maximum as a function of the outdoor average, the shading of the windows and the ventilation conditions: no ventilation or night ventilation.

At the present state of development, the formula is limited to buildings insulated to the same level of the test buildings, with mass levels as low as the conventional stud-wall construction and as high as the high-mass building in the present study, with medium-dark envelope colors. The effect of the envelope color was evaluated in the second phase of the study and will be reported in a subsequent paper. The ventilation rate is classified at present by the fans' speed: low, medium and high. Subsequently the ventilation will be expressed in terms of air change per hour.

4.1. Observations on which the formula is based

The predictive formula of the expected indoor maximum temperature is based on the following observations in the experimental research: (a) The climatic parameter best correlated with the indoor maximum is the outdoor average; (b) Under steady climate conditions, when the outdoor average is about constant, the elevation of the indoor maximum above the outdoor average depends on the shading conditions of the windows and the color of the opaque envelope, as well as on the thermal mass of the building; (c) Under dynamic climate, when the outdoor average rises of falls, the indoor maximum of the high-mass building changes at a rate about one half of the change in the outdoors' average. The rate of change of the low-mass building maximum is close to that of the outdoor average.

The above observations are expressed mathematically in the general form of the predictive formula:

$$T_{max} = GT_{avg} + DelT + k(T_{avg} - GT_{avg})$$

where: T_{max} = Indoor maximum temperature in a particular day; GT_{avg} = 'Grand average' of the outdoor temperature, the average of the whole period of a given experimental series; $DelT$ = Average elevation of the indoor maximum above the outdoors' average. Its value depends on the mass, shading and ventilation conditions, as shown in Table 1; T_{avg} = Outdoor temperature average in a particular day; k = Ratio of the rates of daily changes of the indoor maximum to the rate of change of the outdoor average, depending on the mass level.

The two variables, *k* and Del*T*, represent the thermal characteristics of the building: thermal resistance, mass, shading, external color, and the nocturnal ventilation rate. They were derived from the experimental data.

Del*T*, the average elevation of the indoor maximum above the outdoor average should become smaller with higher resistance and mass, with lighter colors of the building's envelope, and with higher rates of nocturnal ventilation.

The $(T_{avg} - GT_{avg})$ parameter describes the day to day changes (rise or fall) in the outdoor average temperature. The k variable depends mainly on the effective thermal mass, taking into account also the effect of the surface area of the mass on its effectiveness in storing night coolness.

Comment: Analysis of the data has demonstrated that including the effects of daily solar radiation and/or the outdoor temperature swing (maximum minus minimum), can improve the agreement between the calculated and the measured data. However, the objective of the author in the present stage is to present the simplest formula, utilizing the minimum amount of climatic information. In this form the model can be used even in places were the only climatic data available is the average outdoor temperature.

The data from the Pala monitoring series provided numerical values for these variables for the type of the monitored buildings. These values are shown in Table 1 and were used in calculating the predicted indoor maximum temperatures that are shown in Fig. 12.

4.2. *Agreement between calculated and measured indoor maximum temperatures*

Fig. 12 shows the measured and calculated indoor maximum temperatures of the two test buildings, in all the experimental series when the windows were closed *during the daytime hours, and when the buildings were ventilated at night.*

Table 1
Experimentally derived values of the *k* and Del*T* variables

The *k* variable		
Low-mass buildings	$k = 0.8$	
High-mass buildings	$k = 0.5$	
The Del*T* variable Conditions	Low-mass	High-mass
Windows unshaded, no night ventilation	11	7.5
Windows shaded, no night ventilation	9	5
Windows shaded, night ventilation low speed	8	2.5
Windows shaded, night ventilation high speed	8	2
High-mass room, shaded, white color		
Closed		2.5
Night vented		0.5

Comment: The values for the white rooms were derived in the second phase of the study (in 1994), to be reported in Part II. The experimental data presented below were obtained in a study in Israel ([1]).

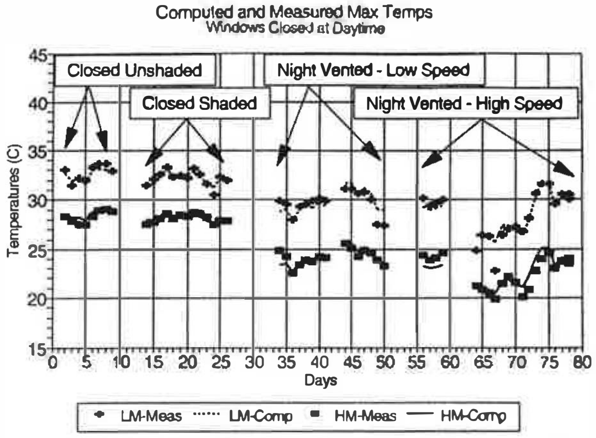

Fig. 12. Measured and calculated indoor maximum temperatures of the two test buildings, and the maxima, minima and averages of the outdoor air temperature.

It can be seen that in spite of the very wide and sharp fluctuations in the outdoor climatic conditions and in the treatments of the buildings (unshaded and shaded, closed and night vented) there is rather good agreement between the measured and the computed maximum temperatures. This demonstrates that the very simple formula can predict the indoor maximum not only under stable climate but also express the response of buildings to sharp changes in the climatic conditions.

4.3. *Effect of mass when with windows open day and night*

It is often assumed that when buildings are cross ventilated continuously day and night, the indoor daytime temperature will follow closely the outdoor pattern, when winds are usually stronger, regardless of the building's mass. One of the series of the study did check this assumption and enabled evaluation of the effectiveness of the mass to utilize the night coolness by lowering the indoor daytime temperatures.

The windows in this series were open and shaded all the time. At night, when the winds in the Pala location usually are unnoticeable, the ventilation was assisted by the fans.

Fig. 13 shows the daily temperature patterns of the two buildings during this period. The indoor daytime temperatures of the low mass building were close to the outdoor's maxima. Those of the high mass building were consistently below the outdoor's, and below the temperatures of the low mass building, by 2 to 4°.

The outdoor temperature swing exhibited a wide variation during this period, from about 10 to 20°. Visual inspection of the figure suggests that the difference between the maxima of the low mass and the high mass buildings are correlated with the outdoor swing.

It was found that the depressions of the indoor maxima below the outdoor's, d_{max}, can be related to the outdoor swing by the following formulae: For the low mass building:

$$d_{max} = 0.12 \times \text{Swing}$$

and for the high mass building:

$$d_{max} = 0.3 \times \text{Swing}$$

Fig. 14 shows the measured and the computed indoor maxima during the period when the windows were open and the buildings were ventilated day and night.

4.4. Comparison with previous studies under different test conditions

While in Israel at Ben Gurion University of the Negev the author conducted extensive research at the University Campus in Sede-Boqer on the performance of two full-size (3×4 m) 'stand alone' rooms with much higher mass than the Pala high-mass building (walls of 20 cm concrete, insulated externally). The exterior color was off-white. One room was closed day and night (as control room). The second room was cooled at night by natural ventilation (through an open door). The boundary conditions of the rooms were similar to the buildings in the Pala research.

Fig. 15 shows the measured indoor maximum and minimum temperatures in the two rooms, together with the outdoor maximum and minimum temperatures, during a 13-day period. It can be seen that, when the buildings have white envelope color, night ventilation has lowered the maximum temperature by about 2°C.

The indoor maximum temperatures were computed by the formula developed above, with modified constants for the white envelope color, as will be described in the second phase report, when the Pala experiments with white color will be reported.

Fig. 16 shows the measured and the computed maximum temperatures in the two rooms. It can be seen that the formula developed on the basis of the experiments in Pala predicts rather well also the maximum temperatures measured in a different climate in a different building configuration.

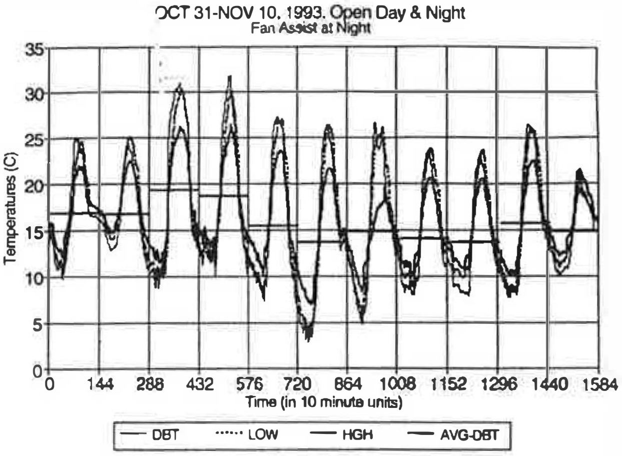

Fig. 13. Daily temperatures of the test buildings when the windows were open day and night. Ventilation at night assisted by the fans.

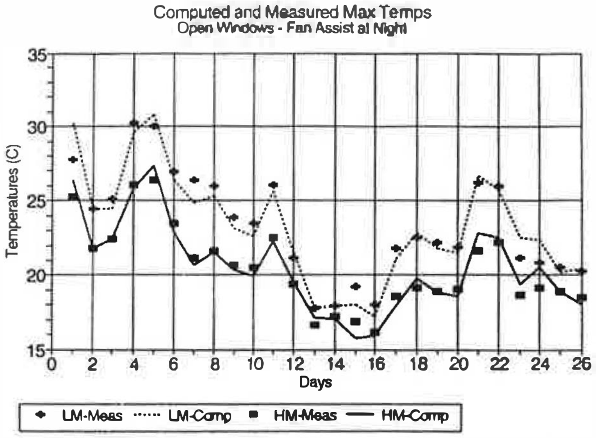

Fig. 14. Measured and calculated indoor maximum temperatures of the two test buildings when the windows were open day and night. Ventilation at night assisted by the fans.

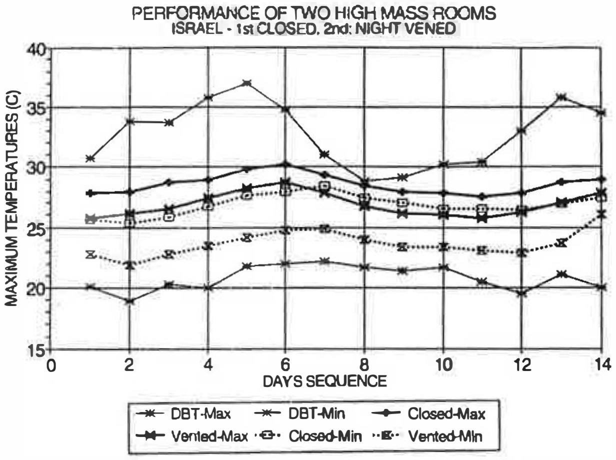

Fig. 15. Study in Sede-Boqer, Israel. Measured indoor maximum and minimum temperatures in two full size high mass, white colored rooms, one closed and the other night vented, during a 13-day period.

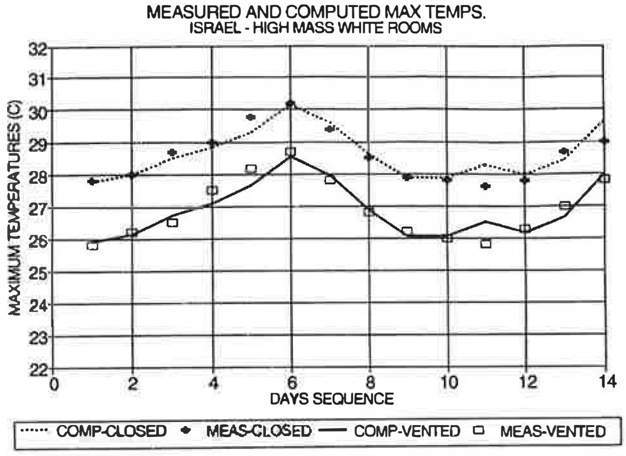

Fig. 16. Measured and computed maximum temperatures in the two rooms shown in Fig. 15.

4.5. Discussion

The formula at its present stage enables prediction of the expected indoor temperatures only of buildings with the ratios of heat capacity to the building's heat gain coefficient similar to the buildings tested in Pala.

In the pala buildings the ceiling height (8 ft) was the same as is common in full size houses. However, the walls' length and the floor area (23 m^2) were smaller than in ordinary houses. Previous studies of the author ([2]) has demonstrated that, as long as the envelope elements of thermal models have the same materials and thickness as real buildings, and infiltration, or ventilation, is expressed in terms ACH, the indoor temperatures in the models and the buildings are very similar, provided the edge effect at the corners are small. This requires a minimum linear dimension of about 1.5–2 m for wall 20 cm thick. Thus, buildings of 5 × 5 m are expected to have, under the same climatic conditions, similar indoor temperatures as full size buildings.

From the climatic aspect, as the formula is based on general climate parameters, and as the climate in Pala during the monitoring period (solar radiation, average temperature and temperature swing) was very variable, the formula is applicable to a wider range of climatic conditions.

Acknowledgements

I want to express my thanks to Mr. Tarek Labib, my Research Assistant, who was in charge of installing the data acquisition system and collecting all the experimental data. I want to thank the California Institute of Energy Efficiency (CIEE) for funding this experimental study. Thanks are due also to San Diego Gas and Electric for enabling us to use the Pala research facility for this study.

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