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Thermal mass and night ventilation as passive cooling design strategy

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Abstract

We calculated the influence of thermal mass and night ventilation on the maximum indoor temperature in summer. The results for different locations in the hot humid climate of Israel are presented and analyzed. The maximum indoor temperature depends linearly on the temperature difference between day and night at the site. The fit can be applied as a tool to predict from the temperature swing of the location the maximum indoor temperature decrease due to the thermal mass and night ventilation. Consequently, the fit can be implemented as a simple design tool to present the reduction in indoor temperature due to the amount of the thermal mass and the rate of night ventilation, without using an hourly simulation model. Moreover, this design tool is able to provide for the designer in the early design stages the conditions when night ventilation and thermal mass are effective as passive cooling design strategy.

Keywords: Thermal mass; Night ventilation; Passive cooling; Design strategies; Design tools; Hot humid climate

1. Introduction

It is well known that thermal mass with night ventilation can reduce the maximum indoor temperature in buildings in summer [1]. Hence, comfort temperatures may be achieved by proper application of the above. In addition, energy can be saved if an air conditioning unit is used [2]. The reason for this is that in summer, heavy external walls delay the heat transfer from the outside into the inside spaces. Moreover, if the building has a lot of internal mass the increase in the air temperature is

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slow. This is because the penetrating heat raises the air temperature as well as the temperature of the heavy thermal mass. The consequence is a slow heating of the building in summer and the maximal inside temperature is reached only during the late hours when the outside air temperature is already low. The heat that flows from the heavy walls inside can be removed with good ventilation in the evening and night. The capability to store energy also helps in winter, since energy can be stored in walls from one sunny winter day to the next cloudy one. But, it is also widely believed that in a hot humid climate, like Florida, it is not recommended to use thermal mass with night ventilation as a passive cooling design strategy. On the other hand in the hot-humid climate of Israel, traditional architecture is to build with heavy thermal mass, and experience shows that better thermal comfort conditions exist in heavy structures than in light buildings.

The questions therefore, addressed in this work are:

- Under what conditions are night ventilation and thermal mass effective as passive cooling strategy?
- Can a simple design tool to predict the reduction of the maximum indoor temperature due to the rate of night ventilation and the amount of the thermal mass be developed?

A thorough analysis was carried out with the purpose of providing a complete answer to the above questions. In this analysis, we used the hourly simulation model ENERGY [3] to calculate the maximum summer indoor temperature. This time-dependent model solves simultaneously the heat transfer equation through all exterior walls, taking into account the thermal mass in each external wall and in the internal partitions as well [2]. The model allows the calculation of the inside temperatures without operating an air conditioning unit, as well as the required energy for keeping a pre-determined inside air temperature, once an air conditioning unit operates.

2. The simulation study

The above questions were examined on a typical Israeli apartment building.

We defined four levels of night ventilation as follows:

1. No night ventilation (two air changes per hour)
2. Natural night ventilation (five air changes per hour)
3. Forced night ventilation (20 air changes per hour)
4. Forced night ventilation (30 air changes per hour)

We defined four levels of thermal mass as follows:

1. Light building: no thermal mass, like a mobile home
2. Medium-light building: light walls, but heavy floor, like cement tiles on concrete floor, and concrete ceiling

3. Semi-heavy building: heavy floor, ceiling and external walls (20 cm concrete blocks) but light internal partitions (Gibsum boards)
4. Heavy building: heavy floor, ceiling, external and internal walls (10 cm concrete blocks, with plaster on both sides)

We ran the simulation using the data of four locations along the coastal plane. The data were taken from the climatological data given in the Climatic Atlas of Israel [4]. The places are presented from North to South:

- Nahariya: T_{swing}=9.5°C, average RH in August 76%
- Geva Carmel: T_{swing}=8.8°C, average RH in August 71%
- Tel Aviv: T_{swing}=6.9°C, average RH in August 71%
- Gaza: T_{swing}=7.9°C, average RH in August 73%

where T_{swing} is the temperature swing from day to night at the site.

The prediction for the maximum temperature obtained in the hottest month in this region, August, is presented in Fig. 1 for the different case studies.

Analysis of the results showed that the reduction in the maximum indoor temperature as a function of the rate of night ventilation ($dT_{max,In}/d$ ach, where ach is the number of air changes per hour, and $T_{max,In}$ is the maximum indoor temperature) is vanishing towards the value 30 ach (see Fig. 1). An effective plateau is reached by the time the air changes reach 20 ach. This means that there is no need for a very powerful vent for the forced night ventilation. However, achieving 20 ach is important. If 20 ach are not achievable by natural means, forced night ventilation is recommended.

When the performance of the different heavy and light structures were compared, it was observed that the light structure behaves like a heat trap. The temperature obtained in such buildings is even higher than the maximum outside temperature. The medium light structure significantly improved the thermal behavior of the building, by reducing $T_{max,In}$. The semi-heavy structure further improved significantly the performance of the building and the improvement proceeds with the heavy structure, although this improvement is less significant.

3. A simple design tool

The above results show that a comfortable $T_{max,In}$ can be obtained in heavy structures in hot humid areas by proper application of night ventilation. However, to reply to both questions raised above, additional analysis is required. To this goal we summarized the results obtained for T_{max} (reduction in maximum indoor temperature compared with the maximum outside temperature $T_{max}=T_{max,Out}-T_{max,In}$). The results for heavy and medium light structures are presented in Table 1 along with the climatic data of T_{swing} (the temperature swing from day to night at the site) and the relative humidity in August.

Fig. 2 presents T_{max} as a function of T_{swing}. There are two groups of three lines

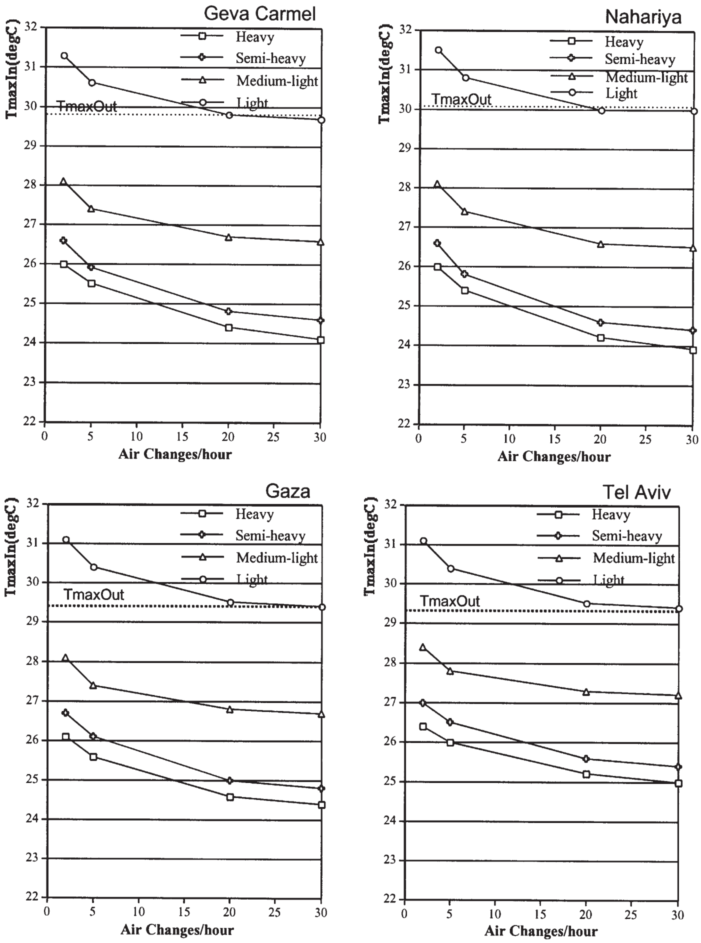

Fig. 1. The prediction of the maximum indoor temperature ($T_{\mathrm{max,In}}$) in August in a residential building along the Mediterranean coastal plane, as a function of the thermal mass and night ventilation.

each in the figure. The upper group is for heavy thermal mass and the lower group is for medium light thermal mass. The lines in each group represent the different rates of air changes per hour. We see that the relation between T_{max} and T_{swing} is linear. This relation allows us to predict the influence of the thermal mass and night ventilation in locations for which we do not have simulation results.

We have tried to present T_{max} as a function of the relative humidity. However, no simple relation was found, whether it was the maximum, minimum or average relative humidity.

We conclude that the answer to the first question is: thermal mass with night ventilation is effective as passive cooling strategy depending on the temperature swing at the site (T_{swing}). Moreover, it is not directly related to the relative humidity

Table 1
Maximum reduction in indoor temperature in August in the hot-humid zone for heavy structure (H) and medium light (M) structures

City		T_{max} (°C)									
	T_{swing}	20 ach		5 ach		2 ach		RH_{ave}	RH_{max}	RH_{min}	ΔRH
	(°C)	H	M	H	M	H	M	(%)	(%)	(%)	(%)
Nahariya	9.5	5.9	3.5	4.7	2.7	4.1	2.0	76	93	60	33
Geva Carmel	8.8	5.4	3.1	4.3	2.4	3.8	1.7	71			
Tel Aviv	6.9	4.1	2.0	3.3	1.5	2.9	0.9	71	82	60	22
Gaza	7.9	4.8	2.6	3.8	2.0	3.3	1.3	73	85	63	22

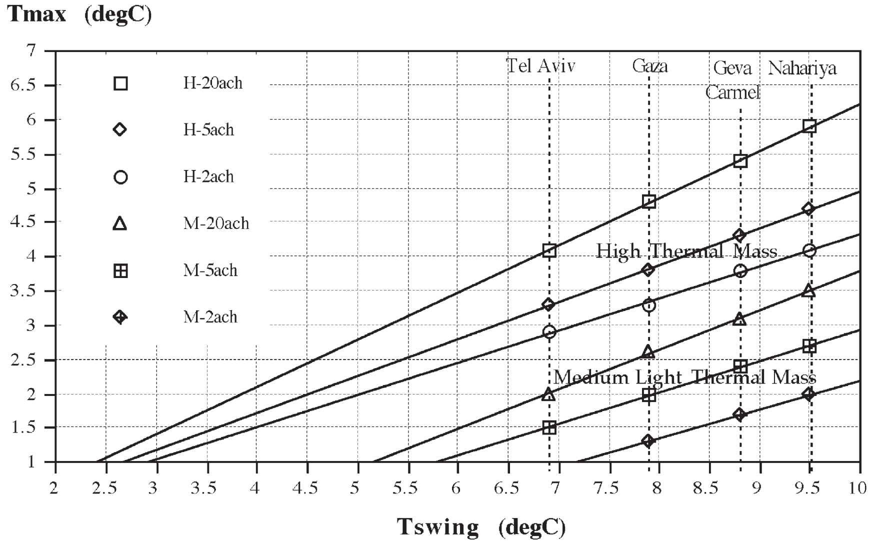

Fig. 2. The reduction in T_{max} in the hot-humid climate of Israel, as a function of T_{swing}.

of the site. Although in most cases, when the relative humidity is high, T_{swing} is small. Yet, exceptions are known (cf. the climatic data of Nahariya).

So far we found the linear relation for the range of T_{swing}=7–10°C. It is interesting to see to what extent the linear relation is preserved for still higher T_{swing} when the relative humidity is low. We added two more locations, Jerusalem and Sede Boker, which are located in another climatic zone, the mountain. In the mountain zone the average relative humidity is lower, and especially the relative humidity during daytime is much lower (see Table 2).

The corresponding graph with the two additional location data is presented in Fig. 3. One can see that the assumption of a linear relation between T_{max} and T_{swing} holds over r=0.996–0.999. When a new linear regression is carried out including the new points, only negligible changes in the fits constants occur.

The fitting lines in Fig. 3 can serve as a simple design tool for determining the effectiveness of the thermal mass and night ventilation as passive cooling design strategy. From Fig. 3 one can see that for heavy thermal mass and night ventilation

Table 2
5yMaximum reduction in indoor temperature in August in the cool dry zone for heavy structures

City	T_{swing}	T_{max} (°C)			RH_{ave}	RH_{max}	RH_{min}	ΔRH
	(°C)	20 ach	5 ach	2 ach	(%)	(%)	(%)	(%)
Jerusalem	11.7	7.9	6.4	5.4	63			
Sede Boker	14.8	10.4	8.7	7.6	60	90	30	60

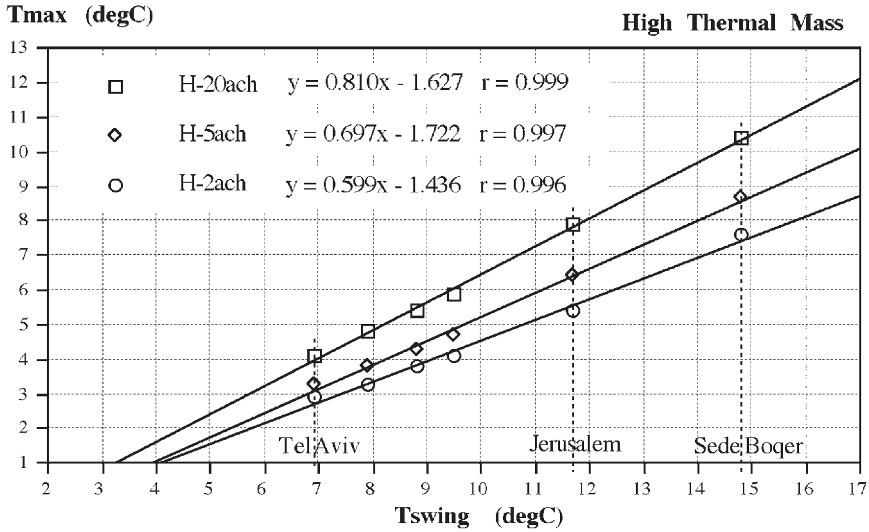

Fig. 3. The reduction in T_{max} in different climatic zones in Israel, as a function of T_{swing}.

of 20 ach, T_{swing} should be greater than 6°C, in order to achieve an effective T_{max} of about 3°C. This design is not effective for lower values of T_{swing}. When the rate of the night ventilation is smaller, or the building is lighter, even a higher value of T_{swing} is required for this design strategy to be effective.

4. Summary and conclusions

An analysis for the determination of the reduction in the maximum indoor temperature compared with the maximum outside temperature (T_{max}) was carried out using an hourly simulation model ENERGY to predict the thermal performance of the building. The results obtained show that in the hot humid climate of Israel it is possible to achieve a reduction of 3–6°C in a heavy constructed building without operating an air conditioning unit. The exact reduction achieved depends on the amount of thermal mass, the rate of night ventilation, and the temperature swing of the site between day and night. In addition, we have found a simple design tool to predict the reduction in indoor temperature as a function of the three above mentioned parameters. The simple design tool provides the conditions under which night ventilation and thermal mass are effective.

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