What are the Required Conditions for Heavy Structure Buildings to be Thermally Effective in a Hot Humid Climate?

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We calculate the influence of thermal mass and night ventilation on the reduction of the maximum indoor temperature in summer in residential buildings without using air-conditioning. The results are given for different locations in the hot-humid Mediterranean climate of Israel. We found that the maximum obtained indoor temperature reduction depends linearly on the temperature difference between day and night at the site. The results obtained show that one can predict the indoor temperature decrease, due to the thermal mass and night ventilation, from the simple and available data of the long term average temperature swing of the site, which is a common available data. The conclusion is that in the hot-humid climate of the Mediterranean coast, high thermal mass with night ventilation is effective for residential buildings with no air-conditioning provided the temperature swing is above 5°C, which is in general the case in this climate. [DOI: 10.1115/1.1755242]

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Introduction

Heavy buildings built from concrete structure and concrete blocks, like the tradition in the Mediterranean countries, may have a twofold importance; in winter they allow to store passive solar radiation penetrating the room through the windows during daytime, to be used during night hours when external temperatures decline [1,2]. Such buildings can also store energy from one sunny winter day to the next cloudy one. On top of it, a properly cooled heavy building in summer during the night, maintains a low temperature during the day, provided the building is well thermally insulated [1,3–7]. This property is a result of the heavy external walls, which delay heat exchange between the outside and the inside spaces. If the building possesses a lot of internal mass there will be a slow increase in the air temperature, as the penetrating heat increases not only the air temperature, but also the temperature of the heavy thermal mass. The consequence is a slow heating of the building in summer and the maximal temperature in the building is reached only during the late hours when the outside air temperature is low. With good ventilation in the evening and night, the flowing heat from the heavy walls inside can be removed. In addition, energy can be saved if air conditioning unit is used [8–11] and the peak load can be reduced by preconditioning the building by night ventilation [12–14].

Cooling of heavy building by night ventilation is feasible in hot-dry places, where significant temperatures swing between day and night exists. In a hot-dry climate, like the Negev in Israel, the temperature swing is generally large and therefore it is very suitable to use thermal mass and night ventilations as a passive cooling strategy. However, in a hot-humid tropical climate, like Florida, the humidity is very high and it is widely believed that the use of thermal mass, as a passive cooling strategy, is not recommended [4]. Moreover, in the Psychrometric-Bioclimatic Chart, Milne and Givoni [15] present the line of 80% humidity as the upper humidity limit for thermal mass, with or without night ventilation, to be thermally efficient as passive cooling design strategy (see Fig. 1). Yet, in the coastal plane of Israel, although the relative humidity can exceed 80% for a long time, traditional architecture is to build with heavy thermal mass and experience shows that better thermal comfort conditions exist in such structures, than in light buildings.

Hence, for hot-humid climate the following questions arise:

- How heavy should the building be?
- Is night ventilation required and at what rate?
- Does the effectiveness of heavy structure buildings depend on the RH?
- Can energy conservation be achieved in heavy structure buildings when air-conditioning is used?
- What are the required conditions for heavy structure buildings to be thermally effective?

To answer the above questions a thorough analysis for the determination of the maximum indoor temperature obtained in summer was carried on by using an hourly simulation model ENERGY, which was first developed by Shaviv and Shaviv in the 70th [16–18] and extended by Shaviv in the 80th [1,19,20]. 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 [9]. The time-dependent equation for the heat flow through the walls is converted into an implicit finite differences scheme and solved numerically. The model allows the calculation of the temperatures inside the building without operating an air conditioning unit, as well as the required energy for keeping a pre-determined temperature and humidity in the building, once an air conditioning unit operates.

The climatic data includes the normal direct radiation, horizontal diffuse radiation, total and net radiation. The long wave radiation coming from the atmosphere and from the ground is elaborated from these data. The climatic data also includes the ambient temperature, relative humidity and wind velocity. The solar position at any moment is determined by the computer code. The radiation that falls on each particular wall according to its orientation is calculated. The amount of shortwave radiation that penetrates through each window is calculated for every hour accord-

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Table 1 Maximum reduction in indoor temperature (ΔTmax,in) in August in hot-humid zone for different thermal mass and night ventilation.

Tave – Daily Average Temperature in August
Tmax – Average Daily Maximum Temperature in August
Tmin – Average Daily Minimum Temperature in August
RHave – Daily Average Relative Humidity in August
RHmax – Average Daily Maximum Relative Humidity in August
RHmin – Average Daily Minimum Relative Humidity in August

The climatic data is averaged over a period of 10 years

		Nahariya	Geva Carmel	Tel Aviv	Gaza
Tave		25.4	25.4	25.8	25.4
Tmax		30.1	29.8	29.3	29.4
Tmin		20.6	21.0	22.4	21.5
ΔTout		9.5	8.8	6.9	7.9
RHave		76	71	71	73
RHmax		93	not available	82	85
RHmin		60	not available	60	63
ΔRH		33		22	22
Heavy	2 ac/h	4.1	3.8	2.9	3.3
	5 ac/h	4.7	4.3	3.3	3.8
	20 ac/h	5.9	5.4	4.1	4.8
	30 ac/h	6.2	5.7	4.3	5.0
Semi-Heavy	2 ac/h	3.5	3.2	2.3	2.7
	5 ac/h	4.3	3.9	2.8	3.3
	20 ac/h	5.5	5.0	3.7	4.4
	30 ac/h	5.7	5.2	3.9	4.6
Medium-Light	2 ac/h	2.0	1.7	0.9	1.3
	5 ac/h	2.7	2.4	1.5	2.0
	20 ac/h	3.5	3.1	2.0	2.6
	30 ac/h	3.6	3.2	2.1	2.7
Light	2 ac/h	-1.4	-1.5	-1.8	-1.7
	5 ac/h	-0.7	-0.8	-1.1	-1.0
	20 ac/h	0.1	0.0	-0.2	-0.1
	30 ac/h	0.1	0.1	-0.1	0.0

ing to the type of window glazing and shading coefficient. The simulation model predicts the radiation temperature of the sky and the surroundings.

The Simulation Study

To check the above questions we examined a test case apartment building with four external walls facing South, North, East and West, which has a square plan of 100 sqm and 2.5 m high, and is located in the upper floor of the building under the roof. The building walls and roof are insulated according to the Israeli standards and to the guidelines proposed by Shaviv and Capeluto [21], giving a U value of 0.755 and 0.717 W/sqm°C respectively. The apartment has a total window area of 9.0 sqm, in the four main facades distributed as follows: South 3 sqm, North, East and West 2 sqm. The windows are assumed to have clear single-glazing systems with external blinds which provide extra thermal insulation during night. Moreover, the blinds perform as a dynamic shading device providing good shading in the summer (SCdirect_rad=10%, SCdiffuse_rad=50%) while allowing the use of solar heating through the southern windows in winter (SCdirect_rad=90%, SCdiffuse_rad=90%).

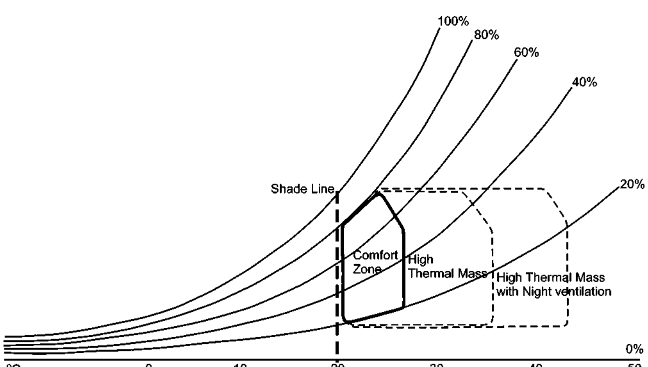

Fig. 1 Psychrometric-Bioclimatic Chart including the conditions for thermal mass cooling strategy (based on Givoni and Milne)

We define four levels of night ventilation, which are:

I. No night ventilation (2 ach)
II. Natural night ventilation (5 ach)
III. Forced night ventilation, achieved by using forced ventilation (20 ach)
IV. Forced night ventilation, achieved by using forced ventilation (30 ach).

We define four levels of thermal mass per sqm of apartment floor according to:

I. Light building: almost no thermal mass at all, like a mobile home (0.02 Wh/°C sqm).
II. Medium-light building: Light walls, ceiling and floor, but with cement tiles on the floor (22.27 Wh/°C sqm).
III. Semi-heavy building: Concrete floor with cement tiles on it, light ceiling, external walls and internal partitions (gypsum boards) (79.89 Wh/°C sqm).
IV. Heavy building: Concrete floor and ceiling, heavy external (20 cm concrete blocks) and internal walls (10 cm concrete blocks) (142.82 Wh/°C sqm).

We carried the simulation according to the climatic conditions

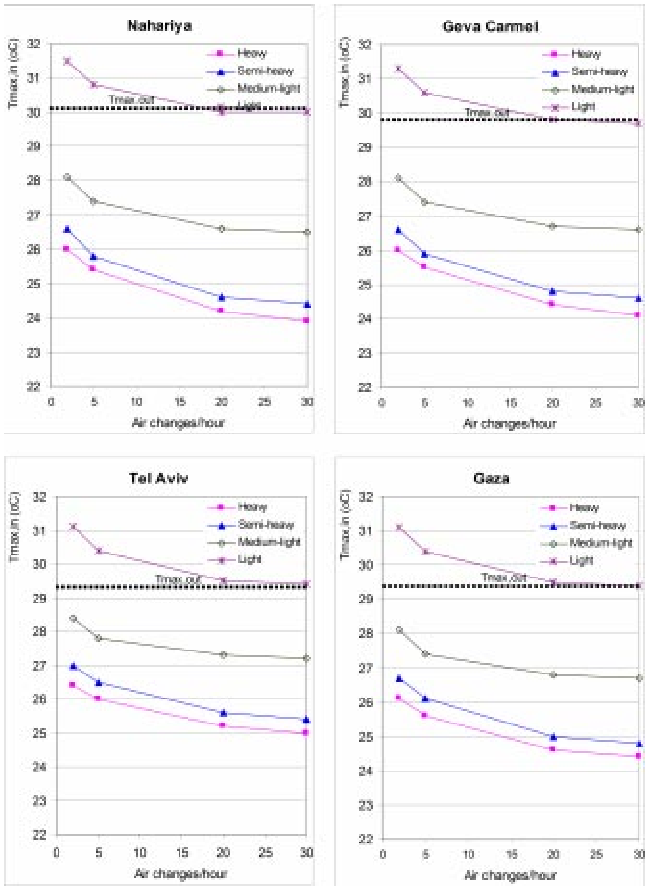

Fig. 2 Predicting the maximum indoor temperature in August in a residential building as a function of the thermal mass and night ventilation in different locations along the Mediterranean coastal plane

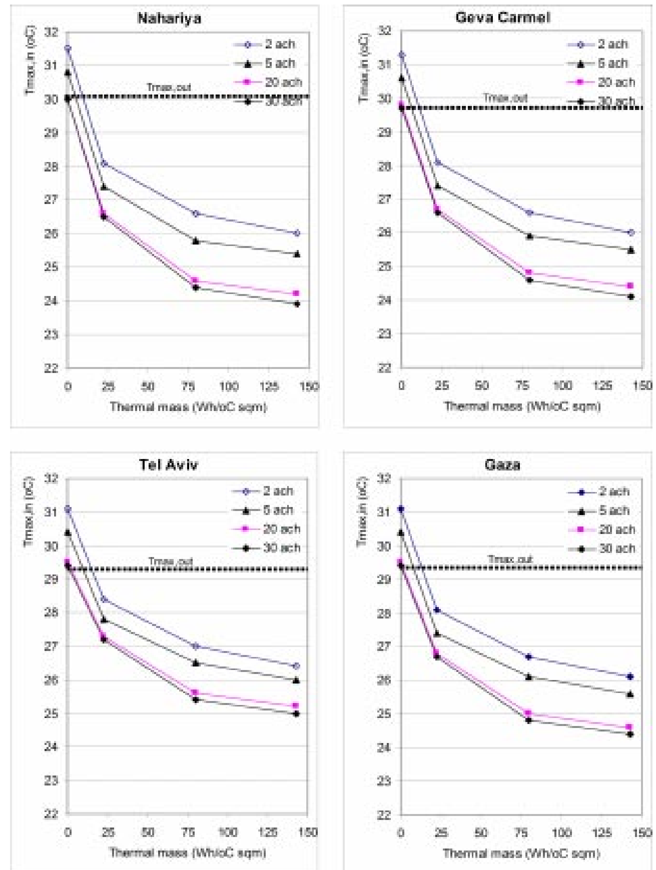

Fig. 3 Predicting the maximum indoor temperature in August in a residential building as a function of night ventilation and the thermal mass in different locations along the Mediterranean coastal plane of Israel

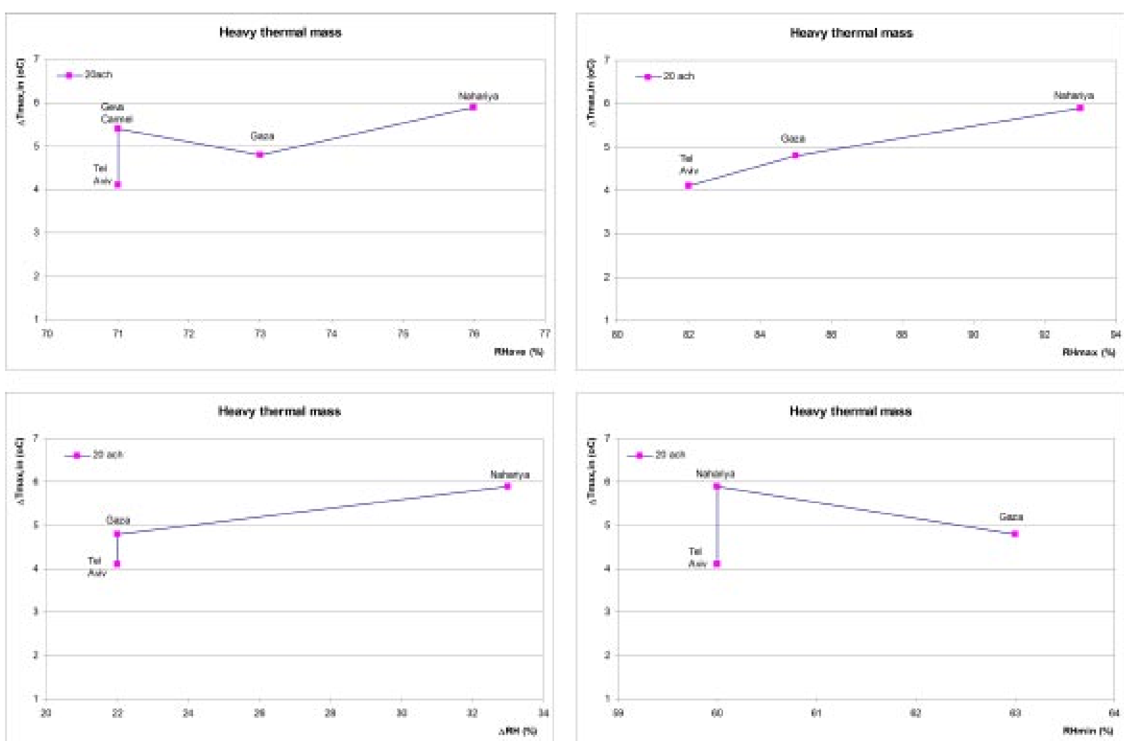

Fig. 4 The reduction in the maximum indoor temperature (ΔTmax,in), as a function of the relative humidity

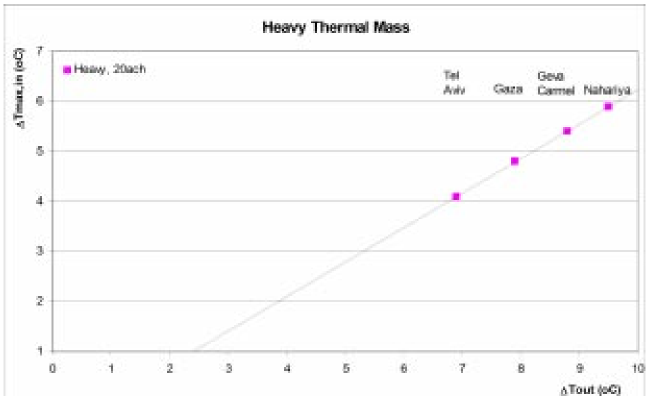

Fig. 5 The reduction in the maximum indoor temperature (ΔTmax,in), as a function of the temperature swing of the site (ΔTout)

of four places along the Mediterranean coastal plane of Israel according to the data given in the Climatic Atlas of Israel [22]. The places are presented from North to South:

I. Nahariya: Average Daily Temp. swing in August: 9.5°C. Daily Average RH in August: 76%.
II. Geva Carmel: Average Daily Temp. swing in August: 8.8°C. Daily Average RH in August: 71%.
III. Tel Aviv: Average Daily Temp. swing in August: 6.9°C. Daily Average RH in August: 71%.
IV. Gaza: Average Daily Temp. swing in August: 7.9°C. Daily Average RH in August: 73%.

We use the simulation model to calculate the maximum indoor temperature obtained in August, which is the hottest month in this region, and the value ΔTmax,in, which is the difference between the maximum indoor temperature obtained and the maximum outside temperature. The results are presented in Table 1 for the different case studies and for all types of buildings along with the climatic data of the different places, including ΔTout (the average daily temperature swing in August at the site) and the daily average relative humidity in August.

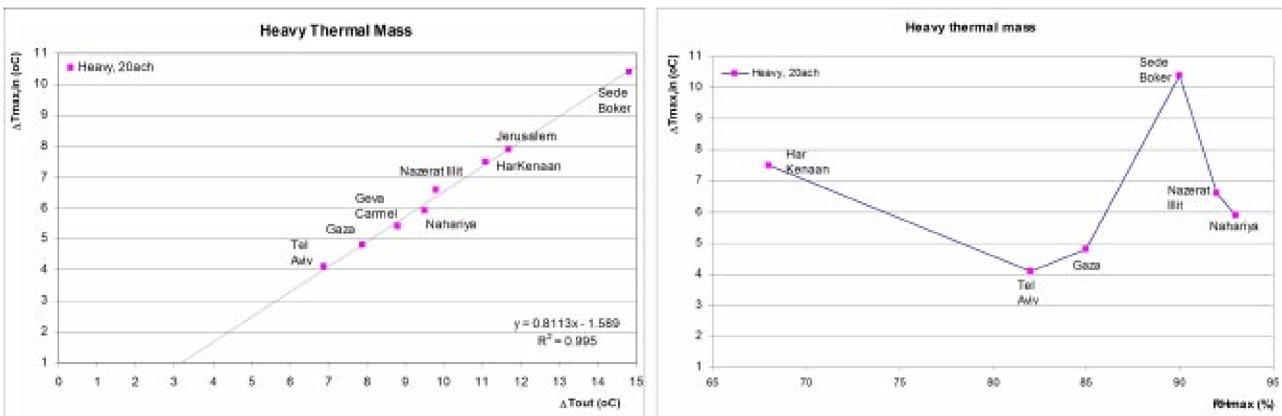

Fig. 6 The reduction in the maximum indoor temperature (ΔTmax,in), as a function of the temperature swing of the site (ΔTout) (left), and maximum relative humidity (RHmax) (right)

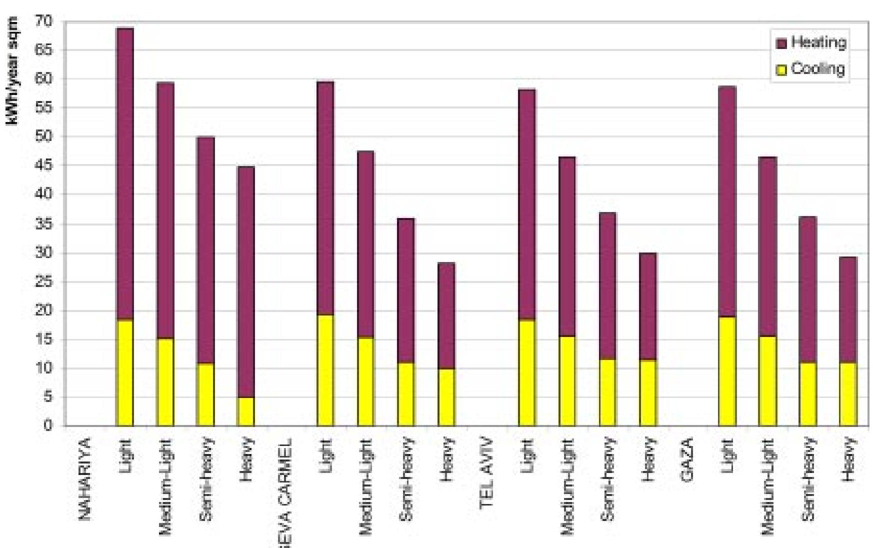

Fig. 7 Reduction in energy consumption during summer and winter as a function of thermal mass, in a well insulated 100 sqm apartment

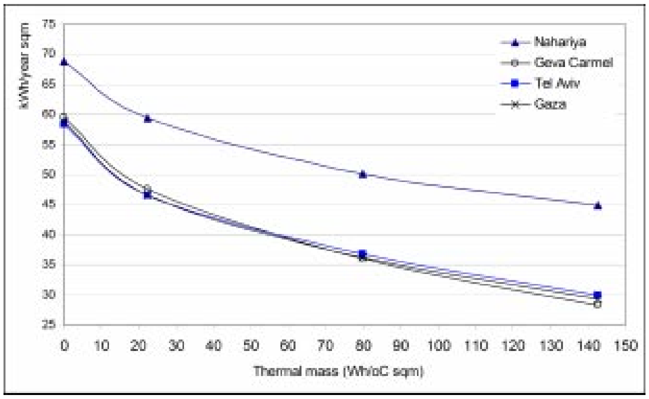

Fig. 8 Reduction in total energy consumption of buildings as a function of the thermal mass

How Heavy Should the Building be?

Comparing the performance of the different heavy and light structures we can observe (see Fig. 2) that the light structures behave like a heat trap. The temperature obtained in such buildings is even higher than the maximum temperature occurred outside. The medium light structure improved significantly the thermal behavior of the building, by reducing the maximum obtained indoor temperature. The semi-heavy structure further improved significantly the performance of the building and the improvement continues to the heavy structure, although this improvement is less significant.

There is no doubt that in summer, without air-conditioning, heavy structure buildings are thermally superior to light structures. However, semi-heavy structures (i.e. the internal partitions can be made of gypsum boards instead of concrete blocks, if this is a better solution from architectural and functional reasons) are sufficiently good as long as at least the floors or the ceilings are heavy.

Is Night Ventilation Required and at What Rate?

According to Fig. 3 we see that the maximum indoor temperature in all types of buildings, light or heavy, is reduced significantly with the introduction of night ventilation. However, towards the value of 30 ach the influence diminishes. Hence, no powerful vent for the forced night ventilation is required. Yet, achieving 20 ach is important. When it is not easy to achieve such a value of air exchanges by natural ventilation, forced night ventilation is recommended.

Does the Effectiveness of Heavy Structure Buildings Depends on the RH?

To answer the above question we plotted the values of ΔTmax,in, the maximum reduction in indoor temperature in August, obtained for heavy structure building and night ventilation of 20 ach, as a function of the daily average relative humidity in August (RHave, RHmax, RHmin, and ΔRH) (Fig. 4) and as a function of the average daily temperature swing in August (ΔTout) (Fig. 5), for the examined places along the Mediterranean coastal plane. It is generally assumed that the lower the humidity, the higher the outdoor temperature swings. However, one can clearly see that a linear relation exists between Tmax,in and ΔTout, but not between Tmax,in and RHave, RHmin, or ΔRH. Likewise, it seems that linear relation exists between Tmax,in and RHmax. To be sure about this conclusion, we decided to plot additional points to the graph, represented by the cities of Har Kennan, Nazerat Illit, Jerusalem and Sede Boker, which are in the temperate-cool region of Israel and have hot-dry climate in summer. Adding these last points to the graph shows, undoubtedly, that linear relation exists only between Tmax,in and ΔTout and not between Tmax,in and RHmax (Fig. 6). Therefore we can conclude that although we associate, in general, the thermal behavior of buildings with the level of the humidity, it is more accurate, in the case of examining the effectiveness of thermal mass and night ventilation, to associate it with the temperature swing of the place. This is in spite of the fact that the temperature swing, in general, depends inversely on the RH.

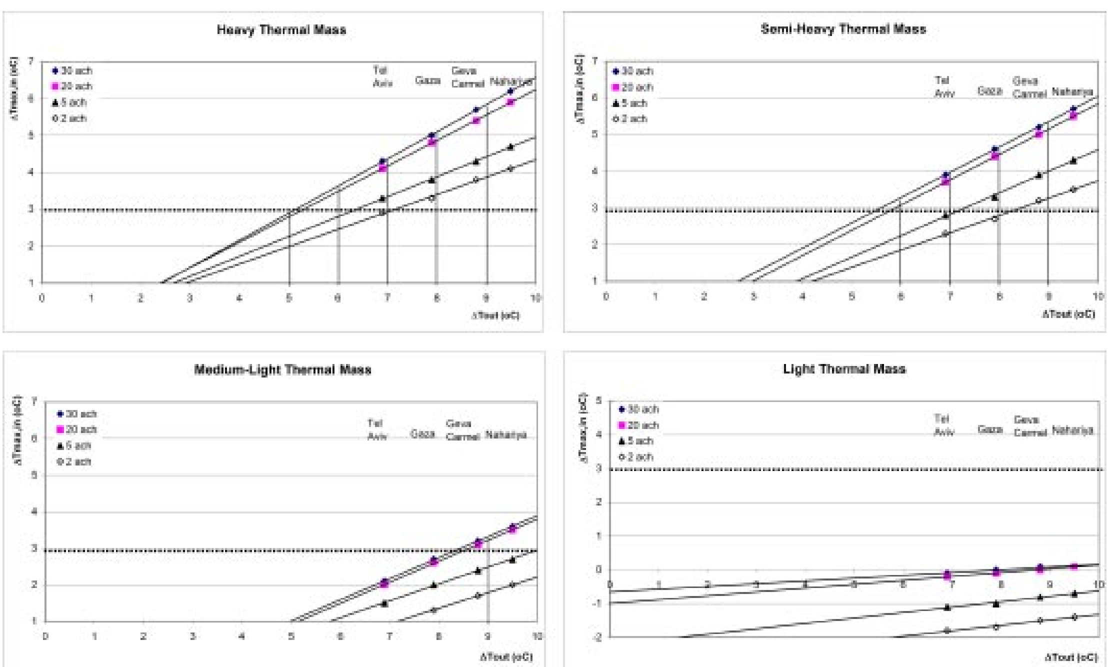

Fig. 9 The reduction in the maximum indoor temperature (ΔTmax,in) in the hot-humid climate of Israel, as a function of the temperature swing of the site (ΔTout)

Table 2 Required Conditions for Achieving Thermal Comfort without Air-conditioning Unit

ΔTout (°C)	Possible Solutions to achieve ΔTin of at least 3 °C						
	Heavy		Semi-heavy		Medium-light		Light
	Night ventilation (air changes/hour)						
	natural	artificial	natural	artificial	natural	artificial	
5	--	20, 30	--	--	--	--	--
6	--	20, 30	--	20, 30	--	--	--
7	2, 5	20, 30	5	20, 30	--	--	--
8	2, 5	20, 30	5	20, 30	--	--	---
9	2, 5	20, 30	2, 5	20, 30	--	20, 30	--

Can Energy Conservation be Achieved in Heavy Structure Buildings With Air-Conditioning?

As air-conditioning is used quite often in hot-humid climate, we checked also if energy conservation can be obtained in heavy thermal mass building, in comparison with a light one. According to Fig. 7 we see that the heavier the building is, the less energy is required for heating in winter and for cooling in summer. However, towards the value of 140 Wh/°C sqm an effective plateau is reached (Fig. 8). This means that there is no need for adding more thermal mass to traditional heavy structure Mediterranean buildings.

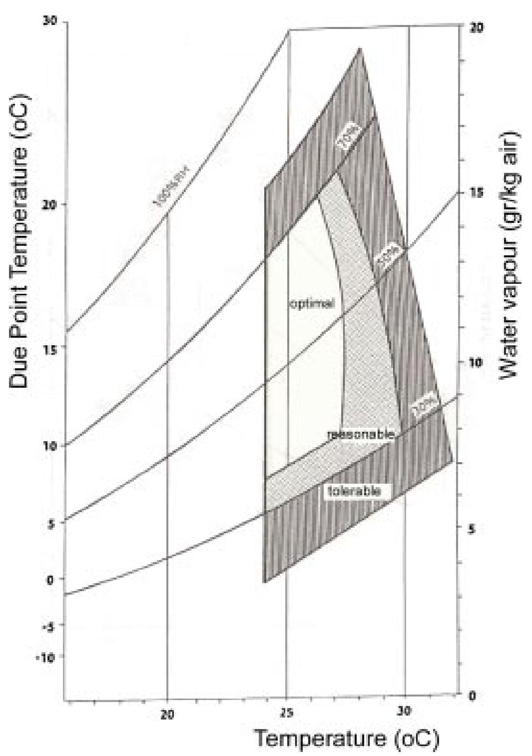

Fig. 10 Psychrometric-Bioclimatic Chart proposed by Shapiro, for an air movement of 0.5-0.8 m/sec

What are the Required Conditions for Heavy Structure Buildings to be Thermally Effective?

The above results show that thermal comfort with no air-conditioning can be obtained, in heavy, or semi heavy structures, in the hot-humid places along the Mediterranean climate, by proper implementation of night ventilation. On top of it, if air-conditioning is applied energy conservation is achieved in the heavy structure buildings. Therefore, we should ask why in many hot-humid climates heavy structure buildings are still not recommended, or better to ask: **what are the required conditions for heavy structure buildings to be thermally effective**?

Figure 9 presents, for all types of buildings and night ventilation, the reduction in the maximum indoor temperature (ΔTmax,in) in the hot-humid climate of Israel, as a function of the temperature swing of the site (ΔTout). According to Shapiro [23] is it possible to feel reasonable thermal comfort at a temperature of 27°C and relative humidity of 70%, provided air movement of 0.5-0.8 m/sec (see Fig. 10). In the studied cities the average daily maximum temperature in August is about 29.5-30.0°C, while at that time the RH is between 60% to 70% (see table 1). Therefore to achieve reasonable thermal comfort (i.e. temperature of 27°C and relative humidity below 70%), with no air-conditioning, ΔTmax,in should be greater than 3°C. As a result, we looked at all graphs presented in Fig. 9, to find the cases when such a condition is achieved. Table 2 summarizes the required conditions for achieving thermal comfort without an air-conditioning unit. From the results presented in Table 2, we can summarize that: in Tel-Aviv, heavy and semi-heavy buildings, with fan operating during the night, can be acceptable solutions. In Gaza and Geva Carmel, the conditions are the same as in Tel Aviv, but natural night ventilation is sufficient. In Nahariya, besides of what is adequate for the other places, also medium light buildings can be a solution, but with a fan operating during the night.

Summary and Conclusions

The reduction in the maximum indoor temperature (ΔTmax,in) in the hot-humid climate of Israel, was carried on by using an hourly simulation model ENERGY to predict the thermal performance of the building. We have tried to present the reduction in the maximum indoor temperature (ΔTmax,in) as a function of the relative humidity of the site. However, no simple relation was found, whether it is the maximum, minimum or average relative humidity. On the other hand a linear relation was found between ΔTmax,in and the temperature swing of the site (ΔTout). This means, that if the temperature swing of the location is known, which is usually a common available data, one can predict the maximum indoor temperature that will be obtained in the building, without running an hourly simulation model.

The results obtained show also that in the hot-humid climate along the Mediterranean coastal plane of Israel, it is possible to achieve a reduction in Tmax,in of about 3 to 6 degrees Centigrade in a heavy structure building with night ventilation, without operating an air-conditioning unit. The exact reduction achieved depends on the amount of the thermal mass, the rate of night ventilation, and the temperature swing between day and night at the site. The paper summarized the required conditions for achieving thermal comfort without air-conditioning unit in the examined places.

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