The Role of Thermal Mass in Humid Subtropical Climate: Thermal Performance and Energy Demand of CSET Building, Ningbo

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ABSTRACT
The role of thermal mass in humid subtropical climate has always been intriguing. Located on the eastern coast of China, in humid subtropical climate zone, the Centre for Sustainable Energy Technology (CSET) building, Ningbo, is the first of its kind in the country. It is developed as an exemplar building which displays various energy efficient techniques to increase user comfort and reduce energy demand. Although, the use of heavyweight construction has always been controversial in such climates due to small diurnal range (10°C) and high humidity (65%-95%), the building possesses high thermal mass in the form of 300mm thick concrete walls and 400mm thick concrete slab. The objective of this study was to analyse the thermal performance of CSET building, Ningbo in terms of thermal comfort and energy demand, with respect to the high thermal mass. Through this study, it was also aimed to establish the role of thermal mass in humid subtropical climate zone. Parametric analysis was performed on the building using computer simulations, carried out on TAS Thermal Analysis Simulation Software, to obtain comparative results with and without night ventilation, for four cases: (i) As-designed case, (ii) Reduced building mass, (iii) Heavyweight building materials substituted with lightweight materials and (iv) Omission of the building’s glass envelope. Results indicated that the as-designed case i.e high thermal mass coupled with night ventilation performs the best in terms of thermal comfort and energy demand and hence plays a vital role in the thermal performance of CSET building. It was further established that in humid subtropical climates, night ventilation, proper shading, controlled daytime ventilation and moderate internal gains could improve the performance of heavyweight buildings, such that they perform better than the traditionally accepted lightweight buildings.

Keywords: humid subtropical climate, thermal mass, night ventilation, thermal comfort, energy demand

INTRODUCTION
Thermal mass is said to function as a climate moderator as massive building envelopes can attenuate the temperature fluctuation and reduce the indoor peak temperature. Thermal mass has been defined by Yannas (1994) as the capacity of a building to store and release heat at different times of the day. Thermal capacity is expressed as “the energy required to raise the temperature of a layer of material”. Usually, “higher the density of a material, higher is the resulting thermal capacity” (ibid).
Therefore, buildings with high thermal capacity are termed as heavyweight and include all masonry construction, while buildings with low thermal capacity are thermally lightweight and include timber or steel frame construction (ibid). It is often believed that using thermal mass is a universally ‘good thing’ (Baker & Steemers, 2000). However, the benefits of the effect of thermal mass depend on several parameters such as climate conditions, building thermal properties, ventilation, thermal insulation, occupancy and internal heat gains.

Traditionally, it was believed that the use of thermal mass did not have any benefits in humid subtropical or warm-humid climates. According to Szokolay (2000), up to the mid 1980s it was considered preferable to have elevated, lightweight, cross-ventilated buildings in such climates. However, these traditional design principles were being questioned by researchers like Szokolay (2000) and Soebarto (1999) who have investigated the role played by thermal mass in warm-humid climates. Their studies suggested that the debate between the performance of heavyweight and lightweight buildings in such climates was futile as both constructions performed equally well, with heavyweight performing slightly better than lightweight buildings (see Figure 1).

![Performance of lightweight and heavyweight buildings in warm-humid climate](image)

Figure 1  Performance of lightweight and heavyweight buildings in warm-humid climate,  
Source: Szokolay, 1985 cited by Baker & Steemers, 2000

Although much work has been done till date, more studies need to be conducted to ascertain the effects of the much debated use of thermal mass in humid subtropical climate. For the purpose of this study, an exemplar building (using high thermal mass), located in humid sub-tropical climate was selected.

The Centre for Sustainable Energy Technology (CSET) building is situated in Ningbo (28°51’-30°33’N and 120°55’-122°16’E) which is located on the eastern coast of China, to the South of the Yangtze River Delta (see Figure 2.1) (Lau et. al. 2006). According to the most widely used world climate classification done by Köppen-Geiger (Kottek et. al. 2006), Ningbo lies in the humid subtropical zone. The building is developed as an exemplar building which displays various energy efficient techniques to increase user comfort and reduce energy demand. The building incorporates high thermal mass i.e. it is thermally heavyweight.

The climatic analysis of Ningbo revealed a diurnal range of about 10°C and a relative humidity of 65-95%. Due to the small diurnal swing and high humidity in summer, it was felt that the thermal mass may not perform as expected. Lau et al. (2006) also suggested that night ventilation may not be very effective in providing pre-cooling in summer. Due to these reasons, it was considered essential to analyse the role of thermal mass in CSET building. Through this analysis, it was aimed to re-establish the role of thermal mass in humid subtropical climate zone so that this study can be referred to by designers designing in similar climate all over the world.

CSET BUILDING, NINGBO

The CSET building, developed as a climate integrated design, promotes energy efficiency, generates its own energy from renewable sources, uses locally available materials with low embodied
energy and harvests rainwater (Lau et al., 2006). Along with other climate responsive strategies, the building has internally exposed 300mm thick concrete walls and 400mm thick concrete slab. This implies that the building uses internally exposed thermal mass to minimize temperature fluctuations in summer & winter. The architectural drawings of the building are presented in Figure 2 (a), 2 (b) and 3.

The section shown in Figure 3 depicts the building functions. The laboratory, a workshop and an exhibition space are located in the semi-basement floor. While the research and teaching areas for post graduate students are situated on the second and third floor. The offices, a meeting room with staff kitchenette are all distributed on the fourth and fifth floor (see Figure 3).

Figure 2  (a) Ground floor plan (b) Third floor plan, Source: MCA

Figure 3  Building function, Source: MCA

Figure 4  The building envelope, Source: (MCA, SBE, 2006)

The opaque parts of the building are made of externally insulated concrete and have openings for natural ventilation. The transparent parts of the building are made of high performance glass which in
combination with the external façade provides thermal insulation while optimising daylight penetration into the internal spaces. The second skin makes an external envelope around the building. This external envelope is made of silk screen laminated glass in order to avoid direct solar penetration into the internal spaces (refer Figure 4). The double skin on the south side is sealed providing a thermal buffer, passive pre-heating in winter and exhausting unwanted warm air in summer. The skin on east and west walls is open and provides solar protection and vents excess solar gains.

METHODOLOGY

This research was based on thermal performance analysis of parametric variations in the building envelope which could be tested by performing computer simulations. The parametric analysis was performed for the following cases:

**Case I: Base Case**
1 - a: Base Case without Night Ventilation
1 - b: Base Case with Night Ventilation

**Case II: Reduction in Mass**
2 - a: Reduced Mass without Night Ventilation
2 - b: Reduced Mass with Night Ventilation

**Case III: Lightweight Construction**
3 - a: Lightweight Walls without Night Ventilation
3 - b: Lightweight Walls with Night Ventilation
3 - c: Lightweight Walls and Suspended Ceiling without Night Ventilation
3 - d: Lightweight Walls and Suspended Ceiling with Night Ventilation

**Case IV: Omitting the Glass Envelope**
4 - a: Omitting the Glass Envelope without Night Ventilation
4 - b: Omitting the Glass Envelope with Night Ventilation

The comparative analysis of the above mentioned cases helped in answering the much debated question about the difference in the performance of heavyweight and lightweight buildings in humid subtropical climate. The following considerations / assumptions were made for performing the dynamic thermal simulations on the software.

**Comfort Range / Energy Demand.** As per the climate analysis of Ningbo as well as review of available literature regarding comfort range, 19°C to 27°C was classified as the thermal comfort range for CSET building. Similarly, based on Pasivhaus and Keller Technology’s standards, the benchmarking for heating and cooling demand for Ningbo is taken in the range of 30 KWh/m² to 40 KWh/m².

**Building Analysis Software.** The Building Thermal Analysis Program used for performing the analysis, the New Generation TAS v. 9.1.3a developed by Environmental Design Solutions Ltd. (EDSL). TAS, is a dynamic thermal simulation tool. It allows the user to model, zone and subsequently simulate the building to predict its energy consumption, CO2 emissions, operating costs and occupant comfort.

**Model Geometry.** The geometry of the model was created in accordance with the information provided on the architectural drawings. Due to the limitations of the software, the façades were modelled based on the assumption that they are vertical i.e. they were modelled without the inclination indicated in the drawings (See Figure 5 (a) and (b)).

![Figure 5](image-url) **Figure 5** (a) South-west view of model (b) South-east view of model (the tilt on the south is not considered), Source: Created by author using TAS
Weather Data. The weather file used for the analysis was sourced from Energyplus and the nearest available location to Ningbo was Shanghai. After reviewing the two weather files, the difference between their temperature profiles were considered negligible. Therefore, the weather file of Shanghai was used for all simulations (refer Lau et al., 2006).

Building Elements. Information regarding construction materials to be applied to the various building elements like external wall, internal walls, floor, roof, glass etc. was obtained from Lau et al. (2006). Some of the specified materials were not available in TAS construction database; hence the closest to the specified were selected. For this reason, a slight variation occurred in the U-values of some of the building elements. The details of the building elements are as given in Table 1.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Building Element</th>
<th>Building Material</th>
<th>U-Value (W/m²°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Externally insulated wall</td>
<td>300mm concrete with 120mm insulation</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
<td>Internal wall</td>
<td>200mm concrete</td>
<td>1.9</td>
</tr>
<tr>
<td>3</td>
<td>Floor</td>
<td>400mm concrete</td>
<td>1.4</td>
</tr>
<tr>
<td>4</td>
<td>Basement floor</td>
<td>Concrete Slab with cavity insulation</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>Roof</td>
<td>Concrete</td>
<td>0.24</td>
</tr>
<tr>
<td>6</td>
<td>Openings in external wall</td>
<td>High performance clear glass</td>
<td>1.5</td>
</tr>
<tr>
<td>7</td>
<td>External glass envelope</td>
<td>Silk screen laminated glass</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Internal Conditions. Based on the use of the space, assumptions were made regarding occupancy, equipments and lighting gains in the building and the same are presented in Table 2. These assumptions were kept constant throughout the study.

<table>
<thead>
<tr>
<th>Floor</th>
<th>Space</th>
<th>Occupancy (@ 80W/person)</th>
<th>Equipment</th>
<th>Lighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-basement</td>
<td>Reception, exhibition, lab, workshop</td>
<td>15 persons</td>
<td>No equipment</td>
<td>None in summer, 6W/m2 in winter</td>
</tr>
<tr>
<td>Ground Floor</td>
<td>Expo area</td>
<td>3 persons</td>
<td>No equipment</td>
<td>None in summer, 6W/m2 in winter</td>
</tr>
<tr>
<td>First Floor</td>
<td>Teaching room</td>
<td>30 persons</td>
<td>30 laptops @ 80W per laptop</td>
<td>None in summer, 6W/m2 in winter</td>
</tr>
<tr>
<td>Second Floor</td>
<td>Resource room</td>
<td>15 persons</td>
<td>No laptops</td>
<td>None in summer, 6W/m2 in winter</td>
</tr>
<tr>
<td>Third Floor</td>
<td>Offices</td>
<td>10 persons</td>
<td>10 PCs @ 100W per PC</td>
<td>None in summer, 6W/m2 in winter</td>
</tr>
<tr>
<td>Fourth Floor</td>
<td>Meeting room</td>
<td>10 persons</td>
<td>No equipment</td>
<td>None in summer, 6W/m2 in winter</td>
</tr>
</tbody>
</table>

As mentioned earlier, the comfort range was classified as 19°C to 27°C. Simple natural ventilation was simulated for all cases. The aperture settings were such that the apertures began to open if the dry bulb temperature in the adjacent zone exceeded 23°C, and were fully open if the dry bulb temperature reached 26°C. The apertures began to close when the internal temperature exceeded the external temperature. The building is occupied from 8:00am to 6:00pm and for incorporating night ventilation, all windows were opened from 7:00pm to 8:00am, for all seasons except winter. The maximum wind speed was assumed to be 10m/s, beyond which the apertures began to close regardless of the temperature. An infiltration rate of 0.2 ach was considered.

No heating or cooling was modeled, as the intent of the study was to test the performance of the building with or without thermal mass, isolated from all heating and cooling strategies. For the purpose
of calculating heating and cooling demand, another set of simulations were run for which the heating set point was taken at 19°C and the cooling set point was taken at 27°C.

**Data Selection.** For evaluating thermal comfort, firstly the dry bulb temperature was observed over a period of a week in summer (17th – 23rd July, warmest week), mid-season (15th – 21st October) and winter (18th – 24th December, coldest week). Secondly, the total number of occupied hours from the whole year, when the temperature exceeded 27°C was extracted for every zone for each case. As the occupied time for this building is 8:00am to 6:00pm, the total annual occupied hours is 3650. Finally, the energy demand was observed in terms of the total annual heating and cooling demand of the building. The internal gains due to equipments, lighting and occupancy were expressed in KWh/m² and remained constant throughout the study. The solar gains varied according to the building fabric.

**COMPARATIVE ANALYSIS**

The parametric analysis conducted for the specified cases revealed that the performance of the building deteriorates upon reduction in building mass. It was identified that the main benefit of a heavyweight building was that the variation in internal temperature was smaller and closer to the average external temperature than a lightweight building. In the lightweight substitute of the building, the fluctuations in internal temperature were larger and presented higher peaks than the heavyweight building as well as the ambient temperature (refer Figure 6). From the comparison of the building with and without the glass envelope, it was found that the thermal mass became more effective when it received lower solar gain since the low transmittance glass acted as a shading device for the building.

![Figure 6 Indoor summer temperature profile: Basecase v/s Lightweight Construction, Source: Author](image)

In general, for all cases, night ventilation (NV) enhanced the performance of the building. In summer, during the warmest week, the condition "with night ventilation" was found to perform better than "without night ventilation" for the Ground Floor, while the upper floor temperatures for the two conditions, were almost coinciding with "with night ventilation" performing better. Even though night ventilation assists in lowering the temperatures, they were still found to be above 27°C during the occupied hours implying that extreme summer conditions would result in overheating unless cooling is provided. During mid-season, all the temperatures lay in the comfort zone i.e. 19°C to 27°C. Although both lower as well as upper floors benefited from the effect of night ventilation, the benefits were more visible in in the lower floors. In extreme winter conditions, the internal temperatures lay out of the comfort range i.e. they were below 19°C.
During the 3650 occupied hours, the building was found to experience comfortable temperatures in mid-seasons. The number of hours when the ambient temperature exceeded 27°C, the upper limit of the specified comfort range, is 760. Even during the warmest summer days the building exhibited stable indoor temperatures, though at temperatures above the thermal comfort range i.e. 27°C. The graph shown in Figure 7 reveals that for all the cases, without night ventilation, the number of hours exceeding 27°C during occupied hours is similar in each zone. Night ventilation enhances the building performance and there is variation in the results for this condition among the various cases. For every zone, the Base-case, a combination of thermal mass and night ventilation works best. Floor wise analysis revealed that the first floor was the worst performing floor, probably due to very high gains from occupancy and equipments. The performance became better with night ventilation. The semi-basement floors performed the best as they had low occupancy and high thermal mass. The ground floor performed better than the upper floors in all cases. The ground floor experienced about 770 hours exceeding 27°C, i.e. similar to ambient, while for the upper floors the number was about 1010 (refer Figure 7).

Figure 7  Hours exceeding 27°C during occupied hours: Comparison between all cases, Source: Author

Figure 8  Annual loads: Comparison between all cases, Source: Author
In terms of energy demand, although the annual cooling load reduced with the incorporation of night ventilation, the annual heating load increased (refer Figure 8). Due to the limitation of the software, for some days in spring and autumn when the ambient temperature was very low, although night ventilation was not required, the apertures were still open. This might have resulted in an over-estimate of the heating loads. The total annual heating and cooling load for the building was found to be 39 KWh/m² and 42 KWh/m² for Base-case without night ventilation and with night ventilation respectively. These values are higher than the Passivhaus standard of 30 KWh/m²; however the values lie in or slightly above the specified range of 30 KWh/m² to 40 KWh/m² for heating and cooling. This implies that there is scope for improvement in the thermal performance of CSET building.

The lower floors (semi-basement and ground) in the building perform well due to low occupancy and equipment gain, while the upper floors (1st to 4th) suffer due to higher gains and lesser openings. Therefore it is strongly believed that reducing the gains and provision of more openings in the upper floors would improve the performance of the building.

CONCLUSION

From the above analysis, a broader conclusion can be drawn that a heavyweight building i.e. a building with high thermal mass, when coupled with night ventilation, appropriate shading and moderate internal gains from occupancy, lighting and equipments, performs better than a lightweight building in a humid subtropical climate even though this climate has small diurnal range and high humidity. This conclusion is in conjunction with the results of the studies conducted by Szokolay (2000) and (Soebarto, 1999) on the role of thermal mass in warm- humid climate.

Although, this research was contextually bound to one building in Ningbo, China, the inferences made would be helpful in establishing the general performance of thermal mass in humid subtropical climate which would assist building designers designing in this climate anywhere in the world. However, as the design and microclimate of each building plays a very important role in its performance, there are limits to the generalisability of the results. For this reason, it will not be advisable to prepare design guidelines based on the analysis of only one building. Based on a similar methodology as followed in this research, further research may look at thermal performance analysis of more intitutional buildings in this climate zone. Due to high relative humidity associated with humid sub-tropical climate, there is risk of condensation occurring due to contact of moist air with cold internal surfaces in buildings. As an extention to this study, further research may test the risk of condensation associated with lightweight and heavyweight construction in humid sub-tropical climate zone.

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