OPTIMIZING PASSIVE COOLING SYSTEMS IN RESIDENTIAL BUILDINGS: A CASE STUDY OF AKURE, NIGERIA

By

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Abstract

The provision of thermal comfort within the building interior in hot and humid climatic regions is a great challenge, especially when there is the need to reduce energy consumption in order to achieve environmental sustainability. This paper analyzes optimization of passive cooling systems in residential buildings as a contribution to sustaining the environment through reduction in cooling loads within building interiors, using Akure as a case study. The paper discusses passive (natural) cooling systems including radiant night cooling, radiant cooling with specialized radiators, convective cooling, evaporative cooling and roof ponds. The procedure for design of passive cooling systems is also discussed. The paper uses long-term climatic data to determine the comfort conditions (thermal stress) in Akure and it also discusses the relationship between the climate, the comfort conditions and the building cooling loads which indicate how much cooling is required to achieve thermal comfort. The various methods of calculating cooling loads are compared. The optimization of passive cooling systems involves the balancing of many components: the microclimate, the building design (including materials, components, layout and fenestration), the positioning of the building, the equipment and usage of the building and landscaping. Finding an optimum mix that will have the minimum carbon footprint in the specific context of Nigerian technological and socio-economic circumstances will require extensive and detailed studies using computer models.

Keywords: Optimization, Passive Cooling Systems, Residential Buildings, Thermal Comfort, Thermal Stress.

1. INTRODUCTION

Akure, the capital of Ondo State in Nigeria, popularly called the Sunshine State, is blessed with long hours of sunshine all year round, with lush green vegetation nourished by evenly spread rainfall. This warm and humid climate is moderate in many respects, and over the ages, traditional buildings have provided reasonable comfort with minimalist design and equipment. The rising standard of living, the proliferation of new work profiles and equipment that require air conditioning, and 'peer' pressure from other modern cities have however led to increasing
demand for higher standards of comfort which is promptly met with the installation of air-conditioning systems by eager vendors and opportunists. These air conditioners then boost the growth of other businesses: supply of imported generators, supply of imported fuel, and supply of imported spare parts to maintain both the air conditioners and the generators. This cycle is repeated every few years as the air conditioners and generators break down and need to be replaced.

This booming business, the reliance on imported technology and the green house gas emissions produced by air-conditioning technology and generators is roundly condemned by both politicians and scientists from the comfort of their fully air-conditioned offices powered by stand-by generators that supply 90% of their energy needs. Even most of the national grid is powered by fossil fuels. With growing urbanization and the lip-service paid to alternative technologies, the vicious circle is complete. The result is global warming, depletion of non-renewable resources and the attendant natural disasters: floods, drought, heat waves, flash floods, erosion, et cetera.

Yet Man has, over millennia, mastered the provision of comfort, even in hostile desert climates, with little or no reliance on mechanical gadgets. These techniques are well known but now rarely applied - it is much easier to turn to technology and consumerism, irrespective of the cost to future generations. Natural ventilation is now old-fashioned; the facade of buildings is no longer determined by adaptation to climatic conditions, rather they have become expressions of the owners' wealth and profligacy.

While an appeal to conscience may slow down this trend, it can only be reversed when science, technology and ecology merge to produce alternative solutions that are not only more effective, but more economical and sustainable. An obvious starting point is turning to Mother Nature for solutions - a search for balance, for minimization of effort, for maximization of benefit. Passive cooling systems in residential buildings aim to minimize solar heat gain and the energy required for cooling while maximizing human comfort conditions - all in a sustainable and environment friendly way.

2. PASSIVE COOLING OF RESIDENTIAL BUILDINGS

Passive cooling refers to technologies or design features used to cool buildings without power consumption (Wikipedia, 2010b). It is called passive (and not active) because it does not involve the use of mechanical and electrical devices. The key to designing a passive solar building is to best take advantage of the local climate. Elements to be considered include window placement and glazing type, thermal insulation, thermal mass, and shading. Passive solar design techniques can be applied most easily to new buildings, but existing buildings can be adapted or retrofitted (Wikipedia, 2010c).

Passive cooling is achieved by using two sometimes complementary approaches (Wikipedia, 2010b):

1. Slowing down the transfer of heat into the building. This reduces the amount of heat that enters the building, thus reducing the amount of heat that must be removed for cooling (cooling loads). Cooling loads can usually be avoided through good design involving the judicious use of shading devices, vegetation, colours and insulation.
2. Removing unwanted heat from a building by ventilation or some type of solar air conditioning.

3. PASSIVE COOLING THROUGH REDUCTION OF COOLING LOADS IN RESIDENTIAL BUILDINGS

Passive cooling systems are used for cooling and ventilation of buildings. The first concern in passive cooling is however how to avoid cooling loads and not how to cool down the building. If
excessive heating can be minimized, then the problem of providing sufficient cooling will be half-solved. Externally generated cooling loads are due to sunshine through windows or on the outside of walls or roofs, hot air entering the building or heat conducted from hot outside air to the inside (Ogunsote, 1991).

The need for passive cooling in building is becoming more relevant now than ever as a result of the increased amount of energy required to cool the interiors of buildings mechanically, especially in the tropics. Solar radiation received in the tropics is very high and the proportion of diffuse radiation is also very high due to high humidity and cloud cover in the region. This affects the thermal conditions of building (Nyuk & Yu, 2009, p. 5). The excessive utilization of mechanical devices to cool buildings takes its toll on the environment because of the high rate of urbanization in the tropics, in which almost half of the world population lives (Nyuk & Yu, 2009, p. 17). Passive cooling strategies must necessarily be based on the interaction of the building and the local climate. Some of the strategies used to achieve passive cooling in residential buildings include the following:

1. Proper building orientation
2. Proper landscaping
3. Shading using trees and shrubs, trellises, overhangs and shading devices
4. Use of high thermal mass to reduce heat absorption
5. Use of high thermal mass with night cooling
6. Roof, ceiling and attic insulation
7. Use of reflective roofs and light wall colours

3.1. Proper Building Orientation

Proper building orientation plays an important role in reducing cooling loads in tropical climates where there is a high level of radiation from the sun. This can be achieved by reducing exposure of buildings to the sun, with the longer axis of the building facing the East-West direction. This will not only minimize the hot radiation received from the sun by building walls, but also enhance cooling breeze penetration.

3.2. Proper Landscaping

Landscaping is an effective means of protecting the building from unwanted solar gains and redirecting wind flow to enter the house for natural ventilation. A well planned landscape and strategically planted trees around the building can provide shade and reduce the temperature of the air surrounding the house. Plants prevent most solar radiation from striking surfaces made of concrete, bricks and asphalt. Modification of the surrounding climate and irradiance reduction achieved by plants is an efficient means of lowering energy usage for space cooling and it has been shown that about 25-80% savings on air conditioning can be achieved with proper landscaping (Nyuk & Yu, 2009, p. 86).

3.3. Shading using Trees and Shrubs, Trellises, Overhangs and Shading Devices

Shading is the first line of defence to reduce the ingress of solar gain, and it can also reduce the effective temperature experienced by an occupant by up to 8°C (Nick and Koen, 2005, p. 72). Large trees can provide shading for walls which can reduce outside wall temperatures and also provide shading for windows. Windows can be shaded with overhangs to prevent direct solar radiation from penetrating the building (Plate 1). Overhangs are not effective on Eastern and Western elevations because the sun is too low in the morning and afternoon for an overhang to provide any effective shade. Other external shading devices that can be used include horizontal, vertical and egg-crate sun-shading devices; awnings, trellises and roof eaves. Awnings work like the visors on baseball caps by blocking high-angle sunlight. On buildings, awnings can cover individual windows or sections of outside walls (Oikos, 1994b). Trellises are permanent
structures that partially shade the outside of a building (Plate 2). Clinging vines and climbing plants growing over the trellis add more shade and evaporative cooling (Plates 3 and 4). Fast growing vines and climbers create shade quickly, while trees can take years to provide useful shade.

Plate 1: Robie House, Chicago. The use of large overhangs is one of the characteristics of the architecture of Frank Lloyd Wright. Source: Photograph by the authors, 2005.

Plate 2. Hotel Mayaland, Chichen Itza, Mexico. The use of trellises to control the microclimate of a courtyard. Source: Photograph by the authors, 2010.
Plate 3: Rockhurst University, Kansas City, USA. The use of climbers and trees to reduce penetration of solar heat. Source: Photograph by the authors, 2005.

Plate 4. Apartment Building on George Street, Sydney, Australia. The use of plants to control the microclimate of a flat in the city centre. Source: Photograph by the authors, 2010.
3.4. **Use of High Thermal Mass to Reduce Heat Absorption**

Some materials absorb heat during the day, and release this heat in the night. This property of materials is defined by the thermal capacity and time lag. Residential buildings are considered to have average mass when the exposed mass area is equal to the floor area - for every square meter of floor area there is one square meter of exposed thermal mass (Oikos, 1997). High mass buildings have up to a ratio of 3:1 for area of exposed thermal mass to floor area. To be effective, thermal mass must be exposed to the living spaces.

3.5. **Use of High Thermal Mass with Night Cooling**

This relies on the daily heat storage of thermal mass combined with night ventilation that cools the mass. The building must be closed during the day and opened at night to flush the heat away (Oikos, 1997).

3.6. **Roof, Ceiling and Attic Insulation**

Ceiling (and roof) insulation is usually associated with attic insulation. In hot and warm climates insulation may also include reflective insulation for the roof (besides ceiling-attic insulation). The reflective materials used under the roofs (in hot climates) are usually a layer of reflective foil laminate (RFL) sarking or foil batts. Sarking is wood, plywood, boarding, felt, waterproofing material, foil sheet or other material placed under the shingles of a roof in order to provide support or insulation, or to assist with preventing water intrusion. Batt insulation are pre-cut sections of insulation (fibreglass, mineral fibre or rock wool) designed to fit between studs. When installing a reflective material, make sure that there is a minimum gap (of about 3cm) between the roof and the RFL. In the case of sarking, just install it between the battens and the rafters, with its shiny side facing down. Fibreglass is a common and cheap insulating material, but cellulose and mineral wool are good alternatives for attics. Cellulose is a truly 'green' insulator, with a high thermal and acoustical performance. Attics and roofs with cathedral ceilings demand higher R-values than walls. In hot climates, an R-value of R-19 in ceilings below ventilated attics is recommended. (House-Energy, 2010a; 2010b). The R-Value is the reciprocal of U-value, and is a measure of insulation’s ability to resist heat travelling through it. The higher the R-Value, the better the thermal performance of the insulation.

3.7. **Use of Reflective Roofs and Light Wall Colours**

Reflective roof coatings and membranes are an easy and cheap way of reducing roof overheating, improving roof reflectivity and lowering high air-conditioning costs (House-Energy, 2010c). They comprise elastomeric white roof and acrylic coatings, aluminium coatings, polyurethane foam coatings, synthetic rubber, bitumen, etc. Reflective coatings have both waterproof and reflective properties, and some of them are applied over common asphalt and fibreglass shingles or metal roofs. Using light-coloured polymers reduces cooling loads.

The amount of solar radiation absorbed by a surface is referred to as the absorptivity and is dependent on the colour of the surface (Ogunsote and Prucnal-Ogunsote, 2004). The absorptivity of colours is shown in Table 1. Boundary walls and screen walls should be in dark colours, browns, greens and blues so as not to reflect heat and glare. Hard landscaping (paving) should preferably be in dark colours, or if light, should have a broken surface to avoid reflecting heat and glare. Walls should be in light colours to reflect heat.
### Table 1: Absorptivity of colours.

<table>
<thead>
<tr>
<th>Colour</th>
<th>Absorptivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfectly black</td>
<td>100</td>
</tr>
<tr>
<td>Ordinary black</td>
<td>85</td>
</tr>
<tr>
<td>Dark green, Dark grey</td>
<td>70</td>
</tr>
<tr>
<td>Light green, Light grey</td>
<td>40</td>
</tr>
<tr>
<td>White oil paint</td>
<td>20</td>
</tr>
<tr>
<td>New whitewash</td>
<td>12</td>
</tr>
<tr>
<td>White emulsion paint</td>
<td>12 - 20</td>
</tr>
</tbody>
</table>


## 4. PASSIVE COOLING THROUGH REMOVAL OF EXCESS HEAT FROM RESIDENTIAL BUILDINGS

There are two types of solar cooling systems - the passive cooling systems known as natural cooling systems and active cooling systems.

**Natural cooling systems** are passive solar cooling systems that depend solely on natural means for the cooling of buildings. **Radiant night cooling** directly cools the roof mass from longwave net heat loss to the night sky. The benefits of this type of cooling increases if the roof is covered with insulating materials during the day to prevent heat gain. **Radiant cooling with specialized radiators** makes use of metallic plate radiators for longwave radiation. The heat storage mass consisting of the walls and the roof may be cooled at night by **convective cooling** using the cool outdoor air. In the day time the structural mass can then be used as a heat sink with interior ventilation deliberately kept low to avoid heat gain. **Evaporative cooling** of buildings may be either direct or indirect. It employs the latent heat of evaporation of water for cooling. The wind force is used to produce natural air flow through moist elements installed in windows and openings. The air is humidified while the dry bulb temperature falls thus causing evaporative cooling. **Roof ponds** also lower the temperature of the building structure through evaporation. **Earth cooling** uses the earth as a heat sink to lower the temperature of buildings while encouraging heat loss from the earth's surface. Heat loss is achieved by covering the ground with a layer of gravel and irrigating it. **Comfort ventilation** uses ambient air for cooling (Ogunsote, 1991; Oikos, 1994a).

### 4.1. Natural Ventilation

Ventilation is the replacement of used inside air by outside air and it has three major functions: supply of fresh air, body cooling and structural cooling (Ogunsote, 1991, p. 77). Natural ventilation can be generated by wind pressure or thermal buoyancy (stack effect), depending on prevailing wind strength and temperature conditions (Walker, 2010).

Natural ventilation systems rely on pressure difference to move fresh air through buildings. Pressure difference can be caused by wind or the buoyancy effect created by temperature difference or differences in humidity. In either case, the amount of ventilation will depend critically on the size and placement of openings in the building (Walker, 2010). Taking advantage of natural wind currents and convention to cool spaces are very effective ways of reducing the cooling load. Windows and corridors can direct air flow using natural ventilation principles.

Natural ventilation can be counterproductive in hot humid climates during seasons when the temperature of the external air at night is high (above the limit for thermal comfort).
5. DESIGN OF PASSIVE COOLING SYSTEMS IN RESIDENTIAL BUILDINGS

The design of buildings incorporating effective passive solar systems and energy conservation principles is a complex one and much depends upon the architect and his understanding of solar energy. It is important to understand that each house should be a solar house - the rule rather than the exception (Ogunsote, 1991). In this wise, all houses, even those made from conventional building materials and using conventional construction should take maximum advantage of environmental conditions to enhance thermal comfort. Many houses may be kept comfortable throughout the year by applying these principles. There are however climates where this is not achievable - cooling or heating devices have to be installed.

The following steps are usually involved in the design of passive cooling systems (Ogunsote, 1991):

5.1. Data Collection

This involves the collection and analysis of climatic data for the specific site including outdoor air temperatures, humidity or vapour pressure, wind speed and direction, global radiation on a horizontal plane, hours of sunshine, cloudiness and precipitation.

5.2. Bioclimatic Analysis

This involves the determination of the thermal stress and comfort conditions using an appropriate thermal index. The aim is to determine the nature of thermal stress and how to relieve it. For design of passive cooling systems, the most important is hot discomfort.

5.3. Solar Geometry

The bioclimatic analysis would have shown us when in the year there is hot discomfort and how it should be relieved. The position and movement of the sun at this period is determined and used to design sun-shading devices to block the sun and prevent overheating. This information is also used for landscape design, and as input into computer software for solar analysis.

5.4. Thermal Analysis

This is an analysis of the heat balance of the building. The first analysis is done on the basis of the climatic and site data to produce sketch design guides. The performance of the building is checked continuously as amendments are made. At the end of the design process the whole building will be analyzed to confirm its performance.

5.5. Choice of Passive Cooling System

The choice of a passive solar or conventional system of cooling is based on many factors such as client demand, cost effectiveness, fashion, tradition, availability and maintenance.

The integration of the chosen system into the building will cause a change in the existing thermal balance. New calculations need to be made, thus bringing us back to the thermal analysis stage. The results of this analysis may necessitate an adjustment of the solar system parameters. This process is repeated until an optimal solution is found.

6. THE CLIMATE OF AKURE

Akure city lies on latitude 7 degrees and 15 minutes North of the Equator and on longitude 5 degrees and 12 minutes East at an altitude of 370m above sea level. It is one of the major cities in Nigeria and also the capital of Ondo State. The vegetation of Akure city is equatorial rain forest. Two seasons are experienced by the city - the wet or rainy season from April to October
and the dry or harmattan season from November to March. From the data available, Akure enjoys a moderate tropical climate with maximum temperatures rarely rising above 33°C and minimum temperatures rarely falling below 20°C. Relative humidity is also moderate with maximum relative humidity rarely rising above 86% and minimum relative humidity rarely falling below 40%. There is some form of precipitation throughout the year, even though there are distinct wet and dry seasons. The approximate annual precipitation is 1410mm with double maxima occurring in June/July and September/October. There is usually more than six hours of sunshine, even during the rainy season. See table 2.

Table 2: Average Climatic Conditions in Akure (1983-2004).

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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Monthly Maximum Temperature (°C)</td>
<td>32.1</td>
<td>33.5</td>
<td>33.4</td>
<td>32.3</td>
<td>31.6</td>
<td>29.0</td>
<td>29.0</td>
<td>28.2</td>
<td>29.1</td>
<td>30.4</td>
<td>32.2</td>
<td>31.4</td>
<td>31.0</td>
</tr>
<tr>
<td>Mean Monthly Minimum Temperature (°C)</td>
<td>17.9</td>
<td>20.0</td>
<td>21.7</td>
<td>22.0</td>
<td>21.1</td>
<td>20.8</td>
<td>20.2</td>
<td>20.1</td>
<td>20.2</td>
<td>20.6</td>
<td>21.2</td>
<td>19.8</td>
<td>20.5</td>
</tr>
<tr>
<td>Mean Daily Maximum Relative Humidity (%)</td>
<td>66.3</td>
<td>65.1</td>
<td>75.9</td>
<td>78.4</td>
<td>79.6</td>
<td>83.2</td>
<td>86.6</td>
<td>85.8</td>
<td>84.6</td>
<td>79.2</td>
<td>75.2</td>
<td>70.7</td>
<td>77.6</td>
</tr>
<tr>
<td>Mean Daily Minimum Relative Humidity (%)</td>
<td>43.6</td>
<td>40.0</td>
<td>48.2</td>
<td>54.0</td>
<td>56.5</td>
<td>59.1</td>
<td>62.8</td>
<td>64.1</td>
<td>61.4</td>
<td>60.3</td>
<td>50.0</td>
<td>43.2</td>
<td>53.6</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
<td>10.9</td>
<td>33.5</td>
<td>65.6</td>
<td>79.1</td>
<td>154.4</td>
<td>169.5</td>
<td>209.9</td>
<td>245.7</td>
<td>178.8</td>
<td>180.3</td>
<td>49.0</td>
<td>34.1</td>
<td>1410</td>
</tr>
<tr>
<td>Hours of Sunshine</td>
<td>7.9</td>
<td>8.1</td>
<td>7.4</td>
<td>8.4</td>
<td>8.1</td>
<td>7.5</td>
<td>6.9</td>
<td>6.3</td>
<td>7.6</td>
<td>7.6</td>
<td>8.0</td>
<td>7.6</td>
<td>7.6</td>
</tr>
<tr>
<td>Mean Wind Velocity (m/s)</td>
<td>0.9</td>
<td>1.1</td>
<td>1.2</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Source: Analysis of data collected from weather stations in Akure by FUTA students.

7. THE COMFORT CONDITIONS (THERMAL STRESS) IN AKURE

Studies conducted by Ogunsote & Prucnal-Ogunsote (2003) indicate that the comfort limits and the method proposed by Evans (1980) are the most effective for the determination of thermal stress for the Nigerian climate. This method uses the air temperature and the relative humidity to establish the thermal stress. See Table 3.

Table 3. Comfort limits proposed by Evans.

<table>
<thead>
<tr>
<th>Relative humidity (%)</th>
<th>Day comfort limits (°C)</th>
<th>Night comfort limits (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 30</td>
<td>29.5 – 32.5</td>
<td>27.5 – 29.5</td>
</tr>
<tr>
<td>30 – 50</td>
<td>28.5 – 30.5</td>
<td>26.5 – 29</td>
</tr>
<tr>
<td>50 – 70</td>
<td>27.5 – 29.5</td>
<td>26 – 28.5</td>
</tr>
<tr>
<td>70 – 100</td>
<td>26 – 29</td>
<td>25.5 – 28</td>
</tr>
</tbody>
</table>

Source: Evans (1980).

These limits were used to determine the comfort conditions (thermal stress) in Akure. The day thermal stress was obtained by comparing the mean monthly maximum temperature with the day comfort limits using the mean monthly minimum relative humidity. Note that the maximum temperature is used with the minimum relative humidity because both readings are taken in the early afternoon. The night thermal stress is obtained by comparing the mean monthly minimum temperature with the night comfort limits using the mean monthly maximum relative humidity. The thermal stress is categorised as shown in Table 4:
Table 4. Categories of thermal stress.

<table>
<thead>
<tr>
<th>Category of thermal stress</th>
<th>Conditions</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very cold</td>
<td>Temperature less than 5 degrees below the lower comfort limit</td>
<td>--</td>
</tr>
<tr>
<td>Cold</td>
<td>Temperature below the lower comfort limit but more than 5 degrees below the lower comfort limit</td>
<td>-</td>
</tr>
<tr>
<td>Comfortable</td>
<td>Temperature within the comfort limits</td>
<td>0</td>
</tr>
<tr>
<td>Hot</td>
<td>Temperature above the upper comfort limit but less than 5 degrees above the upper comfort limit</td>
<td>+</td>
</tr>
<tr>
<td>Very Hot</td>
<td>Temperature more than 5 degrees above the upper comfort limit</td>
<td>++</td>
</tr>
</tbody>
</table>

Source: Data analysis by the authors.

The climatic data, comfort limits proposed by Evans (1980) and this categorization were used to determine the thermal stress in Akure as shown in table 5.

Table 5. Human Comfort Conditions (Thermal Stress) in Akure.

<table>
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<tbody>
<tr>
<td>Mean Monthly Maximum Temperature (°C)</td>
<td>32.1</td>
<td>33.5</td>
<td>33.4</td>
<td>32.3</td>
<td>31.6</td>
<td>29.0</td>
<td>29.0</td>
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</tr>
<tr>
<td>Mean Monthly Minimum Temperature (°C)</td>
<td>17.9</td>
<td>20.0</td>
<td>21.7</td>
<td>22.0</td>
<td>21.1</td>
<td>20.8</td>
<td>20.2</td>
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<td>20.2</td>
<td>20.6</td>
<td>21.2</td>
<td>19.8</td>
</tr>
<tr>
<td>Mean Daily Maximum Relative Humidity (%)</td>
<td>66.3</td>
<td>65.1</td>
<td>75.9</td>
<td>78.4</td>
<td>79.6</td>
<td>83.2</td>
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<td>70.7</td>
</tr>
<tr>
<td>Mean Daily Minimum Relative Humidity (%)</td>
<td>43.6</td>
<td>40.0</td>
<td>48.2</td>
<td>54.0</td>
<td>56.5</td>
<td>59.1</td>
<td>62.8</td>
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<td>61.4</td>
<td>60.3</td>
<td>50.0</td>
<td>43.2</td>
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<tr>
<td>Day Thermal Stress</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Night Thermal Stress</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
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</table>

Source: Data analysis by the authors.

From this analysis, human comfort conditions in Akure are satisfactory and there are no extremes of cold or hot discomfort. Hot discomfort in the day is often followed by cold or very cold discomfort in the night, thereby giving room for amelioration of thermal stress through the use of building materials with high thermal capacity and long time lag. This analysis however does not take many variables, such as the globe temperature and wind speed, into consideration. There is need for a more detailed and accurate estimation of the thermal stress.

8. CALCULATION OF COOLING LOADS

The cooling load is the amount of cooling required to keep the interior of a building at a temperature that will prevent hot discomfort, usually at a temperature below the upper comfort limit, regardless of the temperature outside the building. Space cooling load is the rate at which heat is removed from the conditioned space to maintain a constant space air temperature. Cooling loads can be divided into external and internal cooling loads.

External cooling loads are heat gains that originate outside the building (or enclosure) and they comprise of:

1. Solar heat gain through fenestration areas.
2. Conduction heat gain through fenestration areas.
3. Conduction heat gain through roofs and external walls
4. Conduction heat gain through floors; and in the case of enclosures, also through interior partitions and ceilings.
Internal cooling loads on the other hand are heat gains that originate within the building and they comprise of:
1. Heat gain from electric lighting.
2. Sensible and latent heat released by occupants of the building or space (usually human beings).
3. Heat gain from all heat-producing equipment and appliances.
4. Heat gain from infiltration and ventilation (both sensible and latent cooling loads). Infiltration load is a space cooling load due to the infiltrated air flowing through cracks and openings and entering into a conditioned room under a pressure difference across the building envelope (Chan, 2010).

External cooling loads depend on both the environment (climate) and the building. By modifying the design and positioning of a building, the cooling load attributable to the building can be controlled.

There are several methods for calculating cooling loads (The Commission of the European Communities, 1980). They include:

8.1. **The Cooling Degree Day (CDD) Method**
The cooling load is obtained by multiplying the degree day figures by the total energy heat gain per day. The disadvantage of this method is the use of the degree day base temperature which is often rather arbitrarily set.

8.2. **The Bin Method**
The cooling load is obtained by multiplying the adjusted degree day figures by the total energy heat gain per day. The disadvantage is the difficulty of obtaining the adjusted degree day figures (Lebens, 1980).

8.3. **The Los Alamos Solar Load Ratio (SLR) Method**
The solar load ratio method was developed by Balcomb and McFarland (1978) at the Los Alamos National Laboratory, Los, Alamos, New Mexico, USA. The monthly Solar Load Ratio (SLR) is a dimensionless correlation parameter defined by:

\[
SLR = \frac{\text{Monthly solar energy absorbed on the thermal storage wall surface}}{\text{Monthly building load}}
\]

\[
\text{(including the wall steady – state losses in the absence of solar gain)}
\]

The monthly solar energy absorbed on the thermal storage wall surface is given by the product of the total solar collection wall area and the monthly energy transmitted through a unit area of (south) glazing and the wall absorbance. The monthly building load is equal to the building loss coefficient (including the steady state conduction through south solar collection wall) multiplied by the monthly heating degree days. The monthly SLR method provides an insight into the month-by-month behaviour of the system, and there is flexibility in adjusting the monthly values of solar energy absorbed by the building (Balcomb, 1983; Wray, Biehl & Kosiewicz, 1982).

8.4. **Finite Difference Thermal Network Software**
This method makes it possible to incorporate the diurnal temperature variations into the calculation (McFarland, 1978; Chapman, Burns and Winn, 1979). It is the most accurate but has the limitation imposed by the difficulty of predicting occupant behaviour.
9. THE COOLING DEGREE DAY METHOD OF CALCULATING ENVIRONMENTAL COOLING LOADS

Degree days are a specialist type of weather data, calculated from readings of outside air temperature. There are three main types of degree days: heating degree days, cooling degree days, and growing degree days. Heating degree days (HDD) are a measure of how much (in degrees), and for how long (in days), the outside air temperature was below a certain level while cooling degree days (CDD) are a measure of how much (in degrees), and for how long (in days), the outside air temperature was above a certain level. In effect, the higher the cooling degree days, the more the energy required to cool the building. The distribution of the cooling degree days over the weeks and months give a good approximation of the fluctuation in energy required for cooling a building (Google Knol, 2010). Growing degree days (GDD), also known as growing degree units (GDU) are used to estimate the growth and development of plants and insects during the growing season. They are a measure of heat accumulation used by horticulturists, gardeners, and farmers to predict the date that a flower will bloom or a crop reach maturity (Wikipedia, 2010a).

9.1. Calculation of Cooling Degree Days

The calculation of the cooling degree days involves two steps.

1. Determination of the days (usually in a month) during which the maximum air temperature is above the base temperature, and the number of degrees by which the base temperature is exceeded on each such day. The base temperature is the temperature above which the building needs heating or cooling. This is usually fixed for the whole year, for example, the base temperature for heating is 18°C in the USA. Thus on a day when the highest air temperature is 30°C, the cooling degree days will be 12. When the maximum air temperature is equal to or below the base temperature, the cooling degree day is zero.

2. The addition of the cooling degree days for the period under consideration, usually one month. This monthly figures can be further added to give the cooling degree days for the whole year.

Calculation of the energy required to cool the building can be determined by multiplying the energy required to lower the temperature of the building by one degree Celsius by the total of the cooling degree days.

Given the advances in modelling tools and computation, it is now feasible to calculate more accurate degree days by introducing the following refinements.

1. Using a different (and higher) base temperatures for calculating cooling degree days and not the same base temperature used for heating degree days. This compensates for the comfort zone, that is the range of temperatures in which neither cooling nor heating is required. Some authorities however argue that cooling should start as soon as the temperature rises to the lower comfort limit.

2. Fixing different base temperatures for each day based on sensation of comfort by combining the effects of air temperature, globe temperature, relative humidity and wind speed. This may necessitate using a measurement of thermal comfort, such as the effective temperature or heat index, instead of the air temperature as the base reference.

The only weather station in Nigeria for which cooling degree days are available (and only from November 2009), is the Murtala Mohammed International Airport, Ikeja, Lagos. The cooling degree days for Lagos are shown in table 6. Cooling degree days for other locations, including Akure, will need to be calculated to determine the amount of energy required for cooling and the distribution of this cooling load over the year.
Table 6: Celsius Based Cooling Degree Days for Lagos Using a Base Temperature of 20°C

<table>
<thead>
<tr>
<th>Month</th>
<th>Cooling Degree Days</th>
<th>Error margin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 2009</td>
<td>228</td>
<td>0</td>
</tr>
<tr>
<td>December 2009</td>
<td>267</td>
<td>0</td>
</tr>
<tr>
<td>January 2010</td>
<td>249</td>
<td>0</td>
</tr>
<tr>
<td>February 2010</td>
<td>277</td>
<td>0</td>
</tr>
<tr>
<td>March 2010</td>
<td>297</td>
<td>0</td>
</tr>
<tr>
<td>April 2010</td>
<td>263</td>
<td>0</td>
</tr>
<tr>
<td>May 2010</td>
<td>253</td>
<td>0</td>
</tr>
<tr>
<td>June 2010</td>
<td>203</td>
<td>10</td>
</tr>
<tr>
<td>July 2010</td>
<td>183</td>
<td>0</td>
</tr>
<tr>
<td>August 2010</td>
<td>183</td>
<td>0</td>
</tr>
<tr>
<td>September 2010</td>
<td>185</td>
<td>3</td>
</tr>
</tbody>
</table>


10. OPTIMIZATION OF PASSIVE COOLING SYSTEMS IN RESIDENTIAL BUILDINGS

Optimization is the maximization of the effectiveness of a system. Process optimization involves adjustment of a process so as to optimize some specified set of parameters without violating some constraint. The optimization of passive cooling systems involves the balancing of many parameters: the microclimate, the building design (including materials, components, layout and fenestration), the location and positioning of the building, landscaping, the equipment installed, usage of the building and occupant behaviour. This is done while minimizing the energy requirements for maintaining thermal comfort of occupants. In the specific context of this paper, it is also required that the carbon footprint of the building be minimized.

While the climate is given, the microclimate can be controlled by site selection and landscaping. Most other parameters are easily amenable to manipulation through building design and specifications. Even the landscaping is subject to design. The usage of the building and occupant behaviour, while predictable to some extent, is far less amenable to control by the building designer. Optimization in this scenario should be based on flexible boundary conditions to achieve any practically meaningful result.

The preferred approach to solving this type of problem is through computer modelling. This modelling is made even more complex by variations in thermal stress (comfort conditions) over the hours of each day, of each week, of each month of any given year even for a single location. This variation is a direct result of weather fluctuations, thus making the use of reliable climatic models a sine qua non for effective optimization.

11. CONCLUSIONS AND RECOMMENDATIONS

Optimization of passive cooling systems for residential buildings in Akure is highly desirable and such optimization will contribute significantly to the design of green buildings in hot humid climates such as is found in the southern part of Nigeria. This will however require a delicate balance between elements for microclimate control (landscaping), the building design (materials, components, layout and fenestration), the location and positioning of buildings, cooling equipment installed, usage of the building and occupant behaviour. Finding an optimum mix that will have the minimum carbon footprint in the specific context of Nigerian technological and socio-economic circumstances will require extensive and detailed studies using computer models.
It is recommended that research in this area be encouraged through grants and conferences. The collation and analysis of climatic data; and studies about thermal stress patterns, user preferences and behavioural patterns, building materials properties and usage as well as building technologies will contribute significantly to this discourse.

12. ACKNOWLEDGEMENTS

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13. REFERENCES


