EFFECTS OF THERMAL MASS, WINDOW SIZE AND NIGHT-TIME VENTILATION ON PEAK INDOOR TEMPERATURE IN THE WARM-HUMID CLIMATE OF KUMASI, GHANA

By

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CHAPTER ONE
INTRODUCTION TO THE RESEARCH

1.1 Global Focus on Building Energy Use

Following increasing energy cost and negative environmental impacts of extraction, production and transportation, energy saving approaches are of utmost concern to the building industry (Singh et al, 2007). Approximately 70% of overall capital investment in the world goes into development of the built environment, which are buildings and urban infrastructucture (Rigg and Lahav, 1995). Construction is one of the most important economic sectors worldwide. The total world's annual output of construction is close to US$3 trillion and constitutes almost one-tenth of the global economy (CICA, 2002). This is the primary investment sector in development, and once made, the potential energy demand becomes largely fixed, with only minor future retrofit reductions possible. The majority of the energy consumption today is in the developed world, but will in the future apply to the presently developing world.

Building and for that matter shelter is one of the basic needs of human beings. All buildings, irrespective of their location, are expected to provide shelter for the various activities for which they were designed. Buildings make a major contribution to the quality of man's life because of the environment they provide for work, leisure and home life. However, buildings themselves can have an adverse environmental impact. Activities involved with the construction and operation of buildings consume materials and energy, emit pollutants and give rise to a lot of waste. Buildings use almost 40% of the world's energy, 16% of the fresh water and 25% of the forest timber, while it is responsible for almost 70% of emitted sulphur oxides and 50% of the carbon dioxide (CO_2) (Santamouris, 2010).

According to the International Energy Agency (IEA, 2007), statistics for energy balance for 2004-2005, the total final energy use globally accounts for 7209 Mtoe (Mega Tonnes Oil Equivalents). Although figures differ from country to country, buildings are responsible for about 30-40% of the total energy demand, which is a significant factor in the energy economy of many developing countries (Santamouris, 2005). This includes energy used for controlling the climate in buildings, appliances, lighting and other installed equipment (IEA, 2007).

Energy consumption is usually linked to economic growth and the development level of a country, so its consumption is unevenly distributed in the world. Developed market economies, which constitute one fifth of the world's population, consume almost 60 % of the world's primary energy (Sagar et al., 2006). But this proportion is likely to change with regions of developing countries having consumption patterns similar to those of developed market economies. This is a consequence of the rapid replacement of traditional energy sources by commercial sources, mainly fossil fuels. World energy consumption is projected to continue increasing strongly as a result of robust economic growth and expanding populations in the world's developing countries.

1.2 Ghana's Energy Sector

As a developing economy, Ghana's residential and industrial demand for electricity has long been relatively low, although increasing. The population of Ghana has increased over the years and economic growth rates have also increased steadily but the energy supply base has not caught pace with the growth. The total electricity consumption in Ghana increased from 782 GWh in 1970 to about 1328 GWh in 1980 at an average annual growth rate of 5.50%. The average annual GDP growth rate for this period was 0.2%. As a result of a drought in 1983, electricity consumption decreased from 1,361 GWh in 1981 to 1,007 GWh in 1984 at an average annual rate of negative 6.5%. During this period, the average annual GDP growth rate was negative 2%. Thereafter, total electricity consumption increased from 1,252GWh in 1995 to 5,286GWh in 2004 at a steady average annual growth of 8.86% with an average annual GDP growth of 4.46% (Ofosu-Ahenkorah, 2007).

As of 1966, the peak demand in Ghana was 100 MW which was less than 20% of the then installed capacity of 1020 MW of the Akosombo Hydro Electric Dam. For decades, Ghana's development has been fuelled by abundant inexpensive hydropower (Sackey, 2007).

The bulk of Ghana's electricity generation capacity is currently attributable to two hydro-projects, Akosombo (1,020 MW) and Kpong (160 MW) on the Volta Lake with the balance coming from two thermal plants in Takoradi (550 MW) and Tema (30 MW). This gave a total installed electricity generation capacity of 1760 MW as of 2006, with thermal sources contributing to 32.95%. The energy demand as of 2006 stood at 9,518 GWh with domestic demand of 7,200 GWh. The domestic demand was an increase of 12.2% over that of 2005. In 2010 the total electricity demand increased to 12,210 GWh, with a domestic demand component of 9,100 GWh (Sackey, 2007). Projections made by the Volta River Authority (VRA) of Ghana revealed that in 2012, Ghana's total electricity generation capacity will be 3,491MW, with contribution by thermal sources increasing to 55% (Sackey, 2007). The significant contribution by thermal sources to the national electricity generation capacity suggests that the component that will contribute carbon emissions into the atmosphere will increase.

It has been projected that Ghana will need more than 7 times its 2007 electric power capacity by 2020 if it should succeed in developing its economy into a middle income one (Ofosu-Ahenkorah, 2007).

1.3 Cooling Energy Needs of Buildings

Buildings are generally exposed to effects of solar radiation absorbed in the buildings' envelope and penetration through the openings, and internal heat gain generated by occupants (Gut and Ackerknecht, 1993). Electrical and mechanical equipment used in various processes of habitation such as cooking, washing, and use of electrical gadgets liberate heat into a space. Many other heat generating activities associated with cooking, which will normally take place outdoors at the traditional level are now indoor through the use of cooking stoves, microwave ovens, food processors and other supporting devices. The gradual increase in the use of information technology, employing personal computers and associated electrical gadgets, and the need for high illumination levels, also liberate heat into commercial and office buildings (IEA, 1995). The movement towards universal building designs that employ curtain walling that are poorly adapted to the local climatic conditions leads to high penetration of solar radiation (Santamouris, 2009). The above leads to higher average indoor temperatures than that of outdoor with a corresponding higher cooling load (Givoni, 1994)

The demand for thermal comfort, or tolerable internal environment, is resulting in an increasing demand for cooling in buildings for large parts of the year. Design of modern buildings continue to rely on mechanical cooling, usually based on vapour compression air-conditioning systems. Consequently, there is wider use of air conditioning (AC) in a great number of commercial and public office buildings and an expansion of the AC market (Santamouris, 2005). Santamouris in referring to the International Institute of Refrigeration (IIR), (IIR, 2002) reveals that there are more than 240 million AC units worldwide, and adds, the IIR study shows that AC use is responsible for about 15% of all electricity consumed worldwide (Santamouris, 2005).

The refrigerative cooling employed in mechanical cooling by AC can contribute directly to atmospheric ozone depletion through the leakage of harmful refrigerants which are powerful greenhouse gases. The production of chlorofluorocarbon (CFC), the main refrigerant employed in AC, was ended in 1995 under the Montreal Protocol because of the threat to the ozone layer. Since then, there has been heavy reliance on the use of hydro-chlorofluorocarbon 22 (HCFC 22) as an alternative to CFC. While HCFC 22 is far more ozone friendly than CFC, it is still a potent greenhouse gas (IPCC, 1995).

1.4 The Problem

There are well known principles to reduce cooling load for various climates. Reducing cooling loads depends on the building shape and orientation, the choice of building materials and a whole host of other decisions that are made in the early design stage by the architect and are highly sensitive to climate. Most of public office buildings in Ghana including those of the Ministries, Departments and Agencies (MDAs) were designed with features such as east-west orientation, and overhangs that reduce the impact of solar heat gain and therefore improves energy efficiency, they have openings with glazing that are of low mass and occupy about 55% of the total surface (EF, 2000). This permits easy transmission of heat from outdoors contributing to high cooling loads.

A study by Amos-Abanyie *et al.* (2009) involving climatic analysis of towns and cities in Ghana revealed climatic conditions predominantly fell outside the human comfort zone and as such uncomfortable conditions are experienced between 50 and 100% of the year. Figure 1.1 shows the Building Bioclimatic Chart for Kumasi showing the mean outdoor air temperature and relative humidity represented by the lines falling outside the comfort zone (shaded).

Based on the above observation, short term pilot monitoring was undertaken by installing sensors in selected office spaces on the KNUST Campus in Kumasi, Ghana to assess the indoor thermal conditions. These were done first for conditions when the offices remained closed day and night with an air conditioner (AC) working during the day, and then with the AC off. A simplification was obtained by eliminating the contribution of internal loads from people, lighting and equipment in order to isolate heat gains transmitted through the building envelope that is walls and windows. The indoor temperature patterns for the two scenarios are presented in Figure. 1.2.

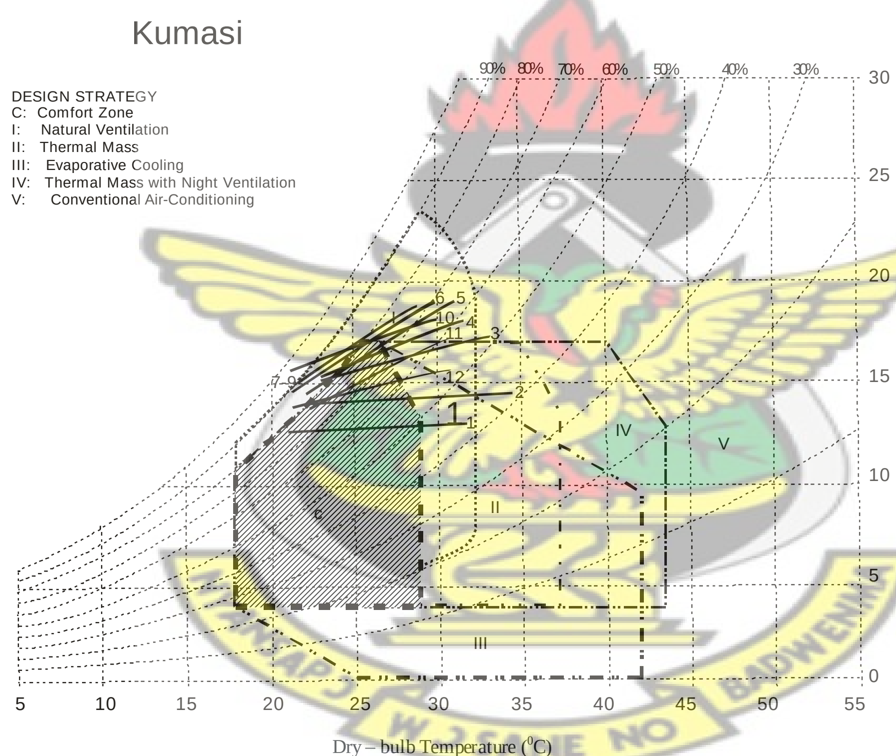


Figure 1.1: Building Bioclimatic Chart of Kumasi (Amos-Abanyie et al, 2009)

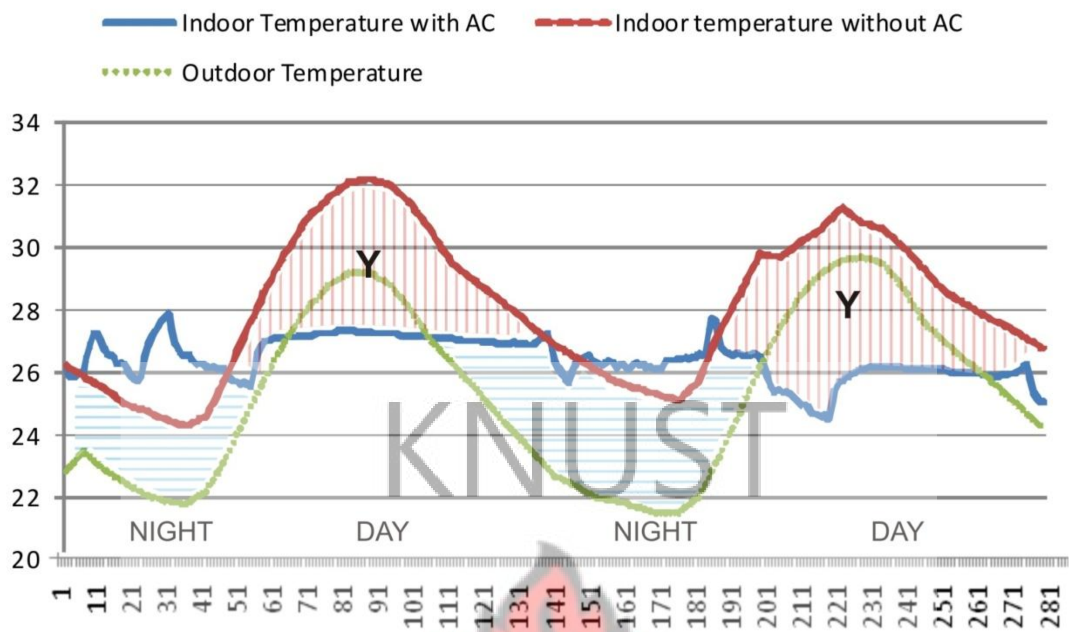


Figure 1.2: General pattern of indoor air temperature in office buildings in Kumasi

Figure 1.2 shows that in the non AC scenario, an average indoor peak temperature of as high as 31.5°C is reached. This can be attributed to the transmission of solar heat gain through the building envelope, that is the walls and the windows. On the other hand the AC works to maintain an otherwise high average indoor peak temperature of 31°C, at an average indoor temperature of 25°C (cooling setpoint temperature). The region shaded and marked Y represents the cooling load imposed on the AC during the day. This suggest that the higher the peak indoor air temperature, the higher the cooling load, and vice-versa. At night there is reasonably very low air temperature, however, because the windows remained closed, as it is in normal practice in office buildings at night, the cool night air does not contribute to cooling the thermal mass at night. The cooling of the mass at night from the outside is hampered by the thermal resistance of the mass, thus the inner layers are not cooled to provide a heat sink during the following day.

Much research has been carried out on integration of passive and low energy cooling techniques in the design of buildings to enhance thermal comfort in building. However, translating theoretical design improvements into ideas that can be readily accepted by building designers and builders is difficult (La Roche, 2004). One major demand on designers is to predict, at the design stage, how use of a passive and low energy cooling techniques in a building will perform in practice. Almost all manual methods are currently implemented using a computer simulation programs that have been developed based on data files of general thermo-physical properties of materials and their algorithmic representations of heat and mass transfer mechanisms. These can introduce errors as a result of differences from that of the actual materials and pertaining environmental conditions.

The above observations are worth investigating into to assess how the selection of thermal mass, window size and night-time ventilation to bypass the thermal resistance of the envelope can reduce the average indoor peak temperature during the day, so as to reduce the cooling load imposed on an air conditioner.

1.5 Aim of the Research

The primary aim of the research was to explore the integration of passive and low energy cooling techniques into the mode of building design in Ghana to enhance thermal comfort whilst reducing energy use in buildings.

1.6 Research Issues

From the situation presented in the research problem, the research issues, which have emerged are as listed below:

1. There is predominant use of low thermal mass materials (sandcrete block) for building envelopes in Ghana. No empirical study has been carried out to assess its performance with that of other known materials in Ghana.
2. There is a gradual movement towards poorly adapted universal building designed with extensive glazing that admits solar radiation into spaces.
3. The impact of cool night outdoor air in bypassing the thermal resistance of the mass of envelops of building in Ghana is not explored. Office buildings not designed as such, and remain closed at night.
4. Thermo-physical properties and algorithmic presentations of heat and mass transfer in predesign tools do not reflect localized conditions

1.7 Research Questions

In order to achieve the research objectives, the following specific questions were addressed:

1. How does the thermal mass level of materials used as building envelopes in Ghana affect the peak indoor air temperature?
2. How does the window size of a space affect the peak indoor air temperature?
3. How can night-time cooling of a space affect the peak indoor air temperature?
4. Do the thermo-physical properties and algorithmic presentations of heat and mass transfer in pre-design tools reflect localized conditions?

1.8 Research Objectives

On the basis of the research problems, the research issues and questions discussed, the following objectives were formulated for the study:

1. To investigate the effects of thermal mass on peak indoor air temperature.
2. To investigate the effects of window size on peak indoor air temperature.
3. To investigate the effects of night time ventilation on peak indoor air temperature.
4. To validate the simulation results by comparing predicted thermal conditions with the measured data from the outdoor experiments.

1.9 Scope of Research

Conceptually, the study focused on heat moderating effects of building envelope in suppressing peak indoor air temperature. Investigations carried out employed simulation models and experimental cells. Geographically, the simulations were done under the warm-humid climatic condition of the Ashanti Region of Ghana. Subsequent to the simulations, experimental test cells were constructed and monitored at the College of Architecture and Planning on KNUST Campus in the Ashanti Region of Ghana.

1.10 Significance of the Study

The relevance of the study is appreciated on two grounds. Firstly, findings from the study will guide the design of new buildings, refurbishment and retrofitting of existing buildings in warm-humid climates. Secondly, it is of interest to building investors, as it will lead to reduction in the required installed plant capacity.

1.11 Structure of the Thesis

The thesis is structured in such a way as to present a logical order to the investigation, findings and conclusions. Chapter One discussed the background of the proposed research topic as well as the purpose, objectives, scope and context of the research. A review of the literature on reduction of peak indoor air temperature in buildings by passive and low energy cooling techniques is presented in Chapter Two. The aim here was to provide insight into the current debate and areas of empirical weakness regarding the subject of the thesis. The methodology applied in this research is established in Chapter Three. It explains the data acquisition methods, the model development and the simulation process and the validation process employed. Chapter Four presents the procedure for the development of models and the results of the simulations, evaluation and discussion. The discussion of the experimental design, monitoring of the test cells and the calibration process of the input file involved in the validation of the simulation model are presented in Chapter Five. Chapter Six concludes the thesis with a summary of major insights into improving indoor temperature conditions by effects of thermal mass, window size and night-time ventilation in buildings in Ghana. This is followed by a synthesis of recommendations arising from the research. Each chapter of the thesis begins with an outline of the chapter's contents and concludes with a short summary of the key points in the chapter.

CHAPTER TWO

INDOOR TEMPERATURE REDUCTION BY PASSIVE AND LOW ENERGY COOLING TECHNIQUES

2.1 Chapter Outline

This chapter presents a review of both published and unpublished literature on reduction of indoor temperature by passive and low energy cooling techniques. The purpose is to provide the necessary background, to demonstrate the significance of the study and to identify the specific knowledge gaps associated with integration of passive and low energy cooling techniques in building design. The review provides current concepts, theories and data relevant to the subject of the study

2.2 Publications Reviewed

In order to demonstrate that all the main concepts and theories relevant to the topic have been identified, understood and critically evaluated, the review covered a rather wide scope. More than 100 documents including refereed journal papers, conference papers, as well as various project documentations were examined. The majority of the reports were published in such journals as the Energy and Buildings Journal, Solar Energy Journal, Energy Conversion and Management Journal, Building and Environment Journal, Applied Thermal Engineering Journal, Renewable Energy, IBPSA proceedings, PLEA proceedings and a number of academic theses. The review also sought to introduce and further explains the terms that appear most often in the thesis thereby giving a good background to the thesis.

2.3 Passive and low energy cooling techniques (PLECT) for warm-humid climates

The concept of passive and low energy cooling refers generally to the use of building design and choice of materials to provide cooling in an energy efficient manner to be able to avoid or minimize the use of conventional cooling systems that employ motorized mechanical components to move fluids and air (Huang, 2004). An intuitive definition to a passive cooling process is simply the process in which cooling takes place without the interaction of any externally powered system or parasitic power sources. A more technical definition is the use of renewable sources of energy to increase heat loss (Givoni, 2009).

Passive and low energy cooling techniques utilize natural resources to reduce the energy consumption of buildings and improve their thermal environment (Zhou et al, 2006). Lechner (2001) identified a three tier sustainable design approach for achieving thermal comfort in hot climates. The first tier consists of heat minimization. Some of the strategies employed in heat minimization include the appropriate use of shading, orientation, colour, vegetation, insulation, daylight, and the control of internal heat sources. The second tier of response is passive cooling and low energy cooling techniques. PLECT cooling includes the use of ventilation to shift the comfort zone to higher temperatures. In many hot climates, there are times when the combined effect of heat avoidance and PLECT is still not sufficient to maintain thermal comfort (Givoni, 1998). A third tier involving mechanical equipment is employed to eliminate remaining cooling load after application of heat minimization and PLECT. Activation of heat minimization and PLECT could reduce the capacity of the mechanical cooling system and thus consume modest amount of energy.

2.3.1 Classification of Passive Cooling Systems

Passive and low energy cooling techniques (PLECT) are capable of transferring heat from a building to various natural heat sinks (Givoni, 1994). Earlier studies by Cook (1989), Yannas (1995) and Givoni (1994) identified four natural heat sinks from which the cooling energy is derived by passive and low energy cooling techniques: the outdoor air (ambient air); the sky or the upper atmosphere; water and the earth (or undersurface soil). According to Yannas (1995) and Santamouris (2005), dissipation of excess heat by natural means depends on two conditions; (i) availability of a heat sink which is at a lower temperature than indoor air; and (ii) the promotion of heat transfer toward the sink. Passive and low energy cooling techniques are categorized into five major methods depending on the heat sinks that are employed (Givoni, 1994): 1) Radiative Cooling; 2) Evaporative cooling; 3) Ground Cooling; 4) Comfort Ventilation and 5) Nocturnal Ventilative Cooling. The passive and low energy cooling techniques discussed here are explained fully in Cook (1989) and Givoni (1994; 1998).

2.3.1.1 Radiative Cooling

Radiative cooling has been explained as the process whereby heat is absorbed by buildings in the daytime, and then radiated later to the cooler night sky in the form of infrared radiation (Cook, 1989). Radiant cooling is effective in providing daytime cooling in almost any region with low cloudiness at night, regardless of the air humidity levels. The mean climatic requirement is low cloudiness during the night. Under an overcast sky radiant losses to the upper atmosphere are reduced. The technique works best in arid climates where diurnal temperature swings are significant (Sreshthaputra, 2003). For hot-humid climates such as that of the Ashanti Region being examined under this research, high humidity and cloud cover will slow the rate of night-time radiation heat transfer, thus trapping heat inside the buildings that would have otherwise been radiated to the night sky.

2.3.1.2 Evaporative Cooling

Evaporative Cooling has been explained by Cook (1989) as the processes in which the sensible heat in an air stream is exchanged for the latent heat of water droplets or wetted surfaces. Evaporation uses the qualities of the local atmosphere to provide a heat rejection resource (Cook, 1989). According to Givoni (1994) evaporative cooling can be direct or indirect.

Evaporative cooling is direct when water is evaporated within a stream of air, the heat energy it requires (latent heat of vaporization) is taken from the air, as a result the temperature of the affected air is lowered while its moisture content (relative humidity) is increased (Yannas, 1995). According to Givoni (1994) direct evaporative cooling can only be applied when the WBT of the ambient air does not rise above about 22 °C (72 °F). This system is not applicable when the water vapour content in the air is already high such as in hot and humid regions. In more humid regions the efficiency of the system is reduced and the higher humidity may be undesirable from the comfort aspect.

Evaporative cooling is indirect when it is applied to cool a given element of a building, such as the roof or a wall. The cooled element, in turn, serves as the heat sink and absorbs through its interior surface, the heat inside the building.

In hot humid climates like the region under research, cooling with outdoor air without first removing moisture (such as with a desiccant cooler), causes the indoor air to be too humid or even to condense on surfaces, and this causes mold and mildew to form.

2.3.1.3 Ground cooling

Ground cooling occurs when heat is dissipated from the building to the ground, which during the cooling period has a temperature lower than the ambient air temperature of the interior spaces. The building may be thermally coupled to the earth mass under, around, and sometimes above a building. This is enhanced by constructing the building in such a way that a large area of the building is in contact with the ground. Another approach of ground cooling of the buildings is by earth to air heat exchangers. This becomes applicable when there is not enough surface of the building in contact with the ground, and then the ground properties can be used to indirectly cool the air inside the building. Use of earth cooling requires ground temperatures of within the comfort zone (18 to 29°C) for the ground to act as a heat sink (Labs, 1989). For the hot humid climate of Ashanti Region, the annual average ground temperature is in the range of 22.8 to 24.8°C (Koranteng et al, 2009). This is within the range of the comfort zone by Givoni and Milne (1979).

2.3.1.4 Comfort ventilation

Comfort ventilation is a technique that provides direct human comfort through the provision of a higher indoor air speed when still-air conditions seem to be too warm (Cook, 1989). Comfort ventilation is able to extend the upper limit of the comfort zone beyond that for still-air conditions but in a non linear fashion (Givoni, 1998). Applying comfort ventilations may be as simple as opening a window but “designing” the window or calculating available comfort from breeze has the difficulty of quantifying an opening system within the moving matrix of a changeable climate (Cook, 1989). This can make the determination of the necessary amount of air-flows and air change rates a very complex task (La Roche, 2004).

The limitation of comfort ventilation is that it does not lower indoor air temperature, but depends on increasing comfort by elevating sweat evaporation from the skin. When cross-ventilation is applied, indoor air temperature tends to follow the outdoor level (Givoni, 1998). The temperature up to which the body can still be comfortable for any region and season limits the applicability of comfort ventilation. Therefore, comfort ventilation can be applied only when indoor comfort can be experienced at the outdoor temperature with acceptable indoor airspeed. The maximum outdoor range of temperature that will ensure indoor comfort depends on the acclimatization and comfort expectations of the population and where the diurnal temperature range is less than about 10^oC (Givoni, 1998). These conditions are typical of the warm humid regions of Ghana.

In these regions the relatively small diurnal temperature range does not produce a significant reduction of the indoor daytime temperature below the outdoor. Therefore, daytime ventilation is needed to minimize the physiological effect of the high humidity and to enhance the convective heat loss from the body. Comfort ventilation can be applied to all types of buildings.

Until recently the typical building designed for comfort ventilation in humid climates was a low mass building with large windows, but Givoni (1998) asserts that even heavy-mass buildings that are continuously ventilated will have lower maximum temperatures than a low mass building even though thermal lag could be a problem. This problem with time lag makes the use of heavy-mass buildings in warm-humid climates more applicable in spaces used primarily in the day.

2.3.1.5 Night-time Ventilation Cooling (NVC)

This form of cooling occurs when an insulated high-mass building is ventilated with cool night outdoor air so that its structural mass is cooled by convection from the inside, thus bypassing the thermal resistance of the envelope (Cook, 1989). NVC works in two stages; at night natural ventilation or fans bring cool outdoor air in contact with the indoor mass, thereby cooling it, and the next morning the windows are closed to prevent the internal space of the building from being heated with outdoor air. The cooled mass acts as a heat sink during the daytime and absorbs the heat generated inside the building and that penetrating through walls into it, thus reducing the rate of indoor temperature rise. When natural ventilation through the windows at night is not sufficient, exhaust fans can be used.

NVC reduces the internal maximum temperatures, peak cooling loads, and overall energy consumption and has been well documented (Cook, 1989; Givoni, 1994; Stein and Reynolds, 1992).

Occupants' discretion and desirable comfort levels affect decisions such as opening or closing of the windows during the night. Nighttime opening of windows can expose buildings to safety and security risks; these will need to be considered at the design stage (Yannas, 1995).

There are three climatic parameters that determine the effectiveness of nocturnal ventilative cooling which are (1) the minimum air temperature; (2) the daily temperature swing; and (3) water vapour pressure level (Geros et al, 1999). The minimum air temperature determines the lowest temperature achievable. The daily temperature swing determines the potential for lowering the indoor maximum below the outdoor maximum. The potential for lowering the indoor daytime temperature below the outdoor level is proportional to the outdoors' diurnal temperature swing. The water vapour pressure level or humidity determines the upper temperature limit of indoor comfort with still air or with air movement. Since the outdoor daily temperature swing usually increases as the air humidity is reduced, the humidity of the air is one of the practical determinants of the applicability of this ventilation strategy.

This strategy is applicable mainly in regions with a diurnal temperature swing of more than 15 °C, especially arid regions where the daytime temperatures are between 32 and 36 °C and the night temperatures are about or below 20 °C (68 °F) to enable sufficient nocturnal cold storage. If the temperature is above this value, then other strategies should be applied during the hottest hours (Givoni, 1995). LaRoche and Milne (2004) cites Machado and La Roche (1999) and Szokolay (2000) to have explored the implementation of nocturnal ventilative cooling as a passive cooling option for buildings in warm humid climates. However, assess to the above articles have not been possible for review.

Chandra (1989) conducted test for hot-humid climates at the Passive Cooling Laboratory (PCL) in the Florida Solar Energy Centre using ceiling fan to raise the indoor convective heat transfer coefficient and increased the night ventilation rate. The study confirms that natural ventilation can be used to cool buildings in hot-humid climates. The results showed that with a constant air change rate of 15ACH, on the average, the indoor temperature could be maintained at 1.4°C above the ambient outdoor temperature. If the air exchange rate was increased to 30ACH, the indoor temperature could be maintained at the average ambient outdoor temperature. The study concluded that increasing the air exchange rate helps lower the average indoor temperature. Chandra (1989) also recommended using night-time ventilation at the rate of at least 30ACH for massive building in hot-humid climates. This suggest that ventilating the indoors at night with outdoor air at the rate recommended by Chandra can cool office spaces in the warm-humid climate of Ghana. No studies reports in literature on the mode of building design and construction in the tropical conditions of the sub-Saharan Africa. Besides, most air-conditioned office buildings are usually closed during the evening and night hours and therefore do not take advantage of night ventilation since they are not designed to run on night ventilation. This limits the access to measured data. This research investigated the effect of night ventilation for cooling the mass of air conditioned buildings that remain closed day and night using simulation methods.

2.4 Thermal Comfort and Adaptation in Hot-humid Climates

Several definitions of thermal comfort have been given by various authors. Thermal comfort has been defined by Hensen as ‘‘a state in which there are no driving impulses to correct the environment by the behaviour’’ (Hensen, 1991). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined thermal comfort as ‘‘the condition of the mind in which satisfaction is expressed with the thermal environment’’ (ANSI/ASHRAE, 2004). Givoni (1998), later provided one of the simplest definitions of thermal comfort and defined it operationally as the range of climatic conditions considered comfortable and acceptable to humans. This implied an absence of two basic sensations of discomfort: a thermal sensation of heat, and a sensation of skin wettedness (Givoni, 1998).

In 1962, Macpherson defined six factors as those affecting thermal sensation: four physical variables or environmental factors (air temperature, air velocity, relative humidity, mean radiant temperature), and personal variables (clothing insulation, state of health, acclimatization and activity level, i.e. metabolic rate) (Lin and Deng, 2008). The physical variables or environmental factors are the measurable tools for the designer and engineer and personal factors are those that come under the control of people. The main conditions allowing heat to be lost are temperature, humidity, air velocity and mean radiant temperature (Lechner, 2001). However, air temperature, relative humidity and air velocity are combined to form the thermal index to express their effect on man (Upadhyay et al, 2006).

2.4.1 Thermal Comfort Zone

Certain combinations of air temperature, relative humidity and air velocity result in what most people consider as thermal comfort (Lechner, 2001). Comfort standards define the acceptable temperatures, humidity, and air velocity conditions, usually inside buildings, and thus delineate the comfort zone (Givoni, 1998). Fanger (2003) asserts that, because of biological variance, establishing a condition that will satisfy everyone is not likely to be achieved. The standards define temperature ranges that should result in thermal satisfaction for at least 80% of occupants in a space (Charles, 2003).

Studies on thermal comfort in indoor environments have attracted authors for decades in the development of standards. Some of the significant ones include that of ASHRAE comfort charts since the 1920s (ASHRAE 1967; 1981; 1985; 2005), Olgyay's Bio-climatic Chart (Olgyay, 1963), Givoni's Building Bio-climatic Chart (Givoni, 1976), and Fanger's Predicted Mean Vote (Fanger, 1970). Various studies have involved establishing models (Fanger, 1970; De Dear, 1998) and indices (Gagge et al, 1986), carrying out experiments in climate chambers (Fanger, 1970; Nakano et al, 2002) and undertaking field surveys (Lin and Deng, 2008; Han et al, 2007), and establishing thermal comfort standards and evaluation methods (Olesen and Parsons, 2002; De Dear and Brager, 2002). The most important findings are now the basis of several national and international comfort standards such as the ASHRAE standards and the International Standards Organization (ISO).

A number of graphic "comfort standards" or "Comfort indices" that evaluates the combined effect of comfort of several climatic factors, and demarcating comfort zone, have been developed by various investigators (Olgyay,1963; Givoni, 1976; Szokolay, 2004; Fanger, 1972; Evans, 2003). Some of them such as Nicol and Humphreys (2002) aim at defining comfort zone, while others such as Olgyay (1967) and Givoni (1976, 1994, 1998) go beyond establishing the comfort zone to give climatic design advice. A comfort range of 23-29ºC with a relative humidity of 30-70% was suggested by Brooks, as cited in Olgyay (1963) for tropical conditions. Givoni (1998) suggested a comfort range for tropical climates: air temperature between 18°C and 29ºC, and the internal humidity varying between 4g/kg and 17g/kg and not exceeding the limit of 80%, and suggest that for comfort, the internal air velocity should not exceed 1.5m/s. The American Society of Heating, Refrigeration and Air-conditioning Engineering (ASHRAE) recommends 23-26ºC as temperature range for summer comfort within which the mechanical system has to maintain the indoor climate for sedentary activity (Stein and Reynolds, 2000).

According to Hyde (2000), the comfort zone is 2ºC above and below the neutral temperature (Equation 2.1). With the neutral temperature (adaptive model) being the temperature at which a person should be neither too hot nor too cold. On the other hand, Szokolay (2004) has set the comfort zone for 90% acceptability to be 2.5ºC above and below the neutral temperature after, Auliciems (1981).

$$Tn = 17.6 + 0.31 \times To.av \qquad \text{Equation 2.1}$$

Where To.av = the mean monthly outdoor temperature (ºC)
Tn = neutral temperature (ºC)

The narrow temperature range specified in the ASHRAE Handbook and others based on the neutral temperature (Szokolay, 2004; Hyde, 2000) suggest the need for cooling in situations where natural ventilation may provide acceptable indoor condition. People in hot climates such as Ghana, living in mostly un-air conditioned buildings, are likely to have acclimatized to and would tolerate higher temperatures. This can lead to problems associated with the application of the ASHRAE comfort standards in hot-humid places. This manifested when climatic data of Kumasi in Ghana, a not so-severe warm-humid city was plotted on a psychometric chart. In the rainy season in Kumasi, from April to October, even the minimum temperatures would be considered as uncomfortable by the ASHRAE comfort zone. This suggests that air conditioning is needed continuously, day and night, throughout the period. However, an interaction with faculty members residing in un-air conditioned buildings on the KNUST Campus during the pilot study revealed that the late hours of the nights and early mornings are experienced as comfortable, both outdoors and indoors. Some described the early mornings as chilly, apparently reflecting their acclimatization to the local climate.

2.4.2 Thermal comfort studies in Ghana and West Africa

Most of the reviewed comfort standards were developed based on mathematical models developed from special climate-controlled chamber experiments for mid-latitude climatic regions in North America and northern Europe (Ogbonna and Harris, 2008). Besides being suitable mainly for static, uniformly thermal conditions on the assumption that human beings are thought to feel comfortable in a narrow, well-defined range of thermal conditions, regardless of race, age and sex (Han et al, 2007), De Dear and Brager (2001) noted that ‘‘current thermal comfort standards and the models underpinning them purport to be equally applicable across all types of buildings, ventilation, occupancy pattern and climate zones’’.

Roaf and Hancock (1992) suggest that laboratory based predictions may not be entirely reliable, as they do not allow for people’s adaptive responses, such as taking off a shirt or drawing curtains or closing windows for example, or their need for some variety in the environmental conditions. Where appropriate, people will look for comfortable conditions (shade or sunshine, wind or shelter), and change their position, activity and clothing to make themselves more comfortable. Consequently, optimum temperatures prescribed in standards may result in over estimated heating and cooling requirements (Djongyan et al, 2010). In field studies, the range of temperatures which people report as comfortable is wider than might be expected. People accustomed to high temperatures report them to be acceptable, suggesting a degree of acclimatization which alters the level of thermal acceptability. It follows then from Roaf and Hancock (1992) assertion that there is no need for uniformity for indoor temperatures worldwide. A number of works have been carried out that are continuing to evaluate these indices in hot-humid climates.

Studies by Humphreys (1975) and Tanabe (1988) demonstrate that the building occupants are acclimatized to, and therefore able to tolerate both higher temperatures and humidity. Importantly, these studies showed significant differences in building design. For example, buildings in developing countries usually have less insulation, air tightness, and moisture controls than do buildings in developing countries.

Recently, a number of studies on human comfort have focused on developing countries in hot and humid climates where people are used to living in unconditioned buildings. Wu (1988) demonstrated that for people acclimatized to hot and humid climates in developing countries, the suggested upper temperature limit with indoor airspeeds of 2m/s would be higher and about 32^{o}C.

In 1968, the BRRI undertook a study of prevailing 10 year outdoor climatic data of ten representative stations from the Ghana Meteorological Agency to present it in a form directly applicable to building design for thermal comfort (Essien, 1968). The data was analysed to show a probability frequency of occurrence of discomfort conditions. The probable frequency of occurrence of hot discomfort was presented on the design temperature curve together with the severity of discomfort and the months during which various levels of discomfort may occur. Also available in the data was information on wind for designing to relieve thermal discomfort under hot humid conditions. For Kumasi, representing the warm-humid condition of the Ashanti Region, comfortable conditions were experienced for 180 days, and hot discomfort for 184.5 days. Varying wind speeds of between 6meter per minute and 130meters per minute were suggested for the periods of hot discomfort depending on the temperature levels.

Amos-Abanyie et al (2009) carried a study to assess the potential of passive and low energy techniques to improve thermal comfort in buildings for representative towns and cities of Ghana. A thirty-year (1976–2005) long term measured daily temperature and corresponding relative humidity data base for each of the ten towns and cities were obtained from the Ghana Meteorological Agency, from which the long term mean monthly minimum and maximum outdoor temperatures and corresponding relative humidity (06.00 and 15.00hrs) were determined. The data were plotted on the Building Bioclimatic chart of Milne and Givoni (1979) and used to evaluate the comfort conditions of the various regions of Ghana.

The study revealed that all the towns and cities experience uncomfortable conditions for a greater portion of the time of the year ranging between about 50 and 100%. In Kumasi, representing the Ashanti Region with the warm humid condition requires cooling for 69% of the time of the year with natural ventilation having a potential of applicability for 66% of the time of the year. This implies that with efficient design of buildings, employing passive and low energy cooling techniques can minimize the use of AC in achieving indoor thermal comfort. This can ensure a substantial saving of conventional energy needed for cooling. However for some periods natural ventilation will not be efficient requiring air-conditioning in buildings for 1% of the time of the year.

Koranteng et al (2010) studied indoor temperature and relative humidity conditions of five office buildings that were representative of existing low-rise buildings with different functions and locations in Kumasi, Ghana. The adaptive model based on the work of Auliciems (1981) and recommendations by Szokolay (2004) for 90% adaptability was used to derive the comfort zone for Kumasi. The generated mean maximum, minimum and hourly values during the working hours were then plotted on psychrometric charts to analyse the conditions pertaining in the office spaces in relation to the comfort zone. The indoor conditions in the office buildings in almost all the months fell outside the comfort zone. The study attributed the shift of the conditions in the spaces studied out of the comfort zone to high relative humidity values, even though the temperatures in some of the cases were below 29ºC. The study concluded that occupants were adapted to higher humidity levels and therefore found humidity levels of 80% comfortable, provided temperature were not above 29ºC. It also suggests that there is the need to adjust the comfort scale for the climatic context of Kumasi.

Adebamowo (2007) carried out a study to investigate the thermal characteristics of the outdoor and indoor spaces and the suitability of the predicted mean vote (PMV) and the adaptive models of naturally ventilated houses in the tropical climate using Lagos Metropolis in Nigeria as a case study. The study involved a survey of 3,490 residents selected randomly from the 349 urban communities during the dry and wet seasons in 2005 and 2006, between the hours of 8 a.m. and 8 p.m. Research Instruments used were basic electronic instruments (globe thermometer, whirling hygrometer, humidity slide rule and digital anemometer) for taking objective measurement and structured questionnaires for taking subjective measurements. Objective measurements were data on personal parameters (clothing and metabolic rate obtained from tables of ISO 7730) and environmental parameters (dry bulb temperature, mean radiant temperature, relative humidity and air velocity). Subjective measurements made use of ASHRAE 7-point scale of thermal sensation vote (TSV) and Bedford 7-point scale of thermal comfort vote (TCV). The study showed that design of houses in Lagos Metropolis is not thermally comfortable. Based on ASHRAE and Bedford scales, occupants of naturally ventilated houses show higher comfort level as compared to what PMV has predicted. The six factors taken into account by PMV cannot best describe thermal comfort and as such adaptive actions might have contributed to the higher level of thermal comfort. The above makes adaptive model more appropriate for thermal comfort assessment than the PMV.

A field survey was carried out by Ogbonna and Harris (2008) in Jos, Nigeria to obtain a broad understanding of occupants' thermal comfort sensations within buildings as a contributory factor to energy-services' demand and use. The adaptive thermal comfort paradigm was employed based on the theory that physiological and adaptive factors play equally central roles in the perception and interpretation of thermal comfort.

A total of 200 subjects in naturally-ventilated buildings (with occupant operable windows) provided 200 sets of cross-sectional thermal comfort data for the months of July and August 2006. Indoor climatic data were collected by hand-held portable laboratory-grade instruments, with accuracies and response times in tandem with the recommendations of ANSI/ASHRAE 55 and ISO 7726. Thermal neutrality, using the ASHRAE 7-point scale, occurred at 26.27°C. The thermal neutrality was in general agreement with most of the adaptive models, varying the least from Humphrey's 1981 model and the most from the Nicol and Roaf model by 0.33ºC and 0.72°C, respectively. The derived comfort range is between 24.88ºC and 27.66°C. The comfort range varies by about 1.39ºC on either side of the optimum temperature. This comfort range is less than the 2 to 3°C suggested by the standards, but may be due to the effects of elevated relative humidity. The PMV determined neutrality is much higher than the direct votes suggested. This appears to confirm the suggestion by previous researchers about the limitations of the PMV for predicting thermal comfort in naturally- ventilated buildings (Hensen, 1991). In comparison with the other scales, the seven-point Bedford comfort scale yielded very consistent and insightful information in relation to thermal neutrality. The plotting of votes on this scale closely estimated the thermal neutrality determined by the ASHRAE sensation votes. The scale appeared to capture the subjects' thermal preferences better than for instance the thermal preference and direct-acceptability scales.

In summary, the literature reviewed on thermal comfort reveals a conflicting advice for assessing and predicting comfort levels in buildings for different locations. It brings to the fore that, due to high humidity levels, high wind speeds, and acclimatization, no single universal comfort index has been developed for all people, all over the world, that does not need adjustment. The literature also reveals that most of the studies carried out in the tropical sub-Saharan Africa have been evaluation of human thermal comfort from the physiological, adaptive and convention paradigms.

2.5 Effect of thermal mass on indoor air temperature

In the most general sense, thermal mass describes the ability of any material to absorb heat, store it, and release it at a later time (Concrete Centre, 2001). Thermal mass can delay heat transfer through the envelope of a building, and help keep the interior cool during the day when the outside temperature is relatively higher. Moreover, when thermal mass is exposed to the interior, it absorbs heat from internal sources and dampens the amplitude of the indoor temperature swing (Chenvidyakarn, 2007). This is particularly beneficial during warm periods, when the internal heat gains during the day are absorbed, and help to prevent an excessive temperature rise and reduction in the risk of overheating (Yam et al, 2003).

In addition to reducing peak internal temperatures, a high thermal mass building can also delay its onset (Jacobs, 2009). In an office environment the peak indoor air temperature will typically occur in the late afternoon, or the evening after the occupants have left. At this point the cycle is reversed, with solar gains greatly diminished and little heat generated by occupants, equipment and lighting.

Chenvidyakarn (2007) asserts that, to optimize the daytime cooling capacity, thermal mass should be ventilated at night to allow relatively cool night air to remove heat absorbed during the day. Small scale experiments by Piriyasatta (1999) to assess the effects of wall colour and thermal mass to thermal conduction in buildings and computer modelling by Wand and Wong (2007) on impacts of ventilation strategies and facade on indoor thermal environment from naturally ventilated residential buildings in warm-humid climates of Singapore, suggest that materials of high thermal mass can make an appropriate envelope for spaces that are used primarily during the day.

2.5.1 Quantitative effect of thermal mass on indoor air temperature

The quantitative effect of the thermal mass of an envelope depends on its thickness and thermophysical properties (Givoni, 1976). The thermal mass level of a material depends on the combination of three basic thermophysical properties: i) High specific heat capacity; ii) High density; and iii) Moderate thermal conductivity (Concrete Centre, 2001). All materials have these properties at different levels. The varying levels make them absorb and release heat at different rates.

The combined effect of thermal conductivity and heat capacity of homogenous walls is expressed by the thermal diffusivity of the material (Givoni, 1976). Thermal diffusivity of a material is the ability of the material to adjust its temperature rapidly to that of their surroundings to reach thermal equilibrium. If the thermal environment around a material changes, heat must flow in or out of the material until thermal equilibrium is achieved, assuming the environment is constant after the change. Materials with a high thermal diffusivity will achieve thermal equilibrium faster than materials with low thermal diffusivity (Sakazar, 2003).

The main property of a building envelope affecting its response to internal cooling is the volumetric heat capacity (VHC). Volumetric heat capacity describes the ability of a given volume of a substance to store internal energy while undergoing a given temperature change. VHC of a substance is the product of the specific heat and the density of the substance (Brown and Marco, 1958). When this product is high, the envelope can absorb heat from internal surfaces more quickly and with a lower resultant temperature elevation. Envelopes with higher values of volumetric heat capacity are warmed slowly, but cool slowly after. The reverse happens with envelope of low volumetric heat capacity. High thermal mass building's ability to absorb heat and provide a cooling effect comes from the difference between the surface (radiant) temperature and that of the internal air. Consequently, the greatest cooling capacity is provided when the internal temperature peaks. The relatively stable radiant temperature provided by materials of high thermal mass is a significant factor in maintaining comfortable conditions (Concrete Centre, 2001). It enables higher air temperatures to be tolerated than in lighter-weight buildings, which are subject to higher radiant temperatures resulting from warmer internal surfaces.

Porous materials with low specific heat exhibits low thermal mass effects. Good thermal conductivity and low reflectivity are also required for effective passive cooling by thermal mass (Reardon, 2010). Therefore, reinforced concrete has a high thermal mass (2060 kJ/m^3.K) while earth adobe has a low thermal mass (1300 kJ/m^3.K).

2.5.2 Effect of thermal mass in warm humid climates

Most studies have been limited to either hot-dry or temperate climates where outdoor air has a lower humidity that allows buildings to take advantage of large diurnal temperature swings.

Traditionally, the effect of thermal mass in buildings in warm-humid climates has been more common in public buildings, such as place of worship. The heavy massing envelopes employed in such buildings also satisfy the need for durability. Appreciable reduction in indoor maximum of about 3°C below outdoor air maxima can be achieved in these buildings in studies by Sreshthaputra (2004) in thermal comfort studies in naturally ventilated buildings in hot humid climates of Thailand.

Achieving thermal comfort through passive means in hot-humid climates is very challenging. This is because these climates are characterized by relatively high temperatures and high relative humidities, making them require both cooling and dehumidification (Chenvidyakarn, 2007). This challenge leads to many official and public buildings relying completely on air-conditioning.

Computer simulations by Sreshthaputra (2003) and Shaviv et al (2001) suggest that thermal mass has potential in hot humid climates where night-time temperatures are relatively higher and diurnal temperature swings smaller. A reduction in the indoor temperature of about 3-6ºC below the exterior air may be achievable, depending on the local climate, the amount of mass, its distribution and the ventilation details.

Cheng and Givoni (2008) conducted experiments to investigate the effects of colour and building thermal mass in the hot humid climate of Hong Kong. The study revealed that the effect of envelope colour on thermal performance of buildings depends on various parameters, for example, the composition of the wall, the orientation of the building, the attribute of windows and the modes of ventilation. Higher thermal mass cuts down indoor maxima and at the same time brings up indoor minima and the influence on maxima is larger than on minima. The second aspect of the influence of thermal mass is the effect of time lag; heat storage properties of thermal mass can delay the occurrence of peak indoor temperature for several hours. Since the effect of thermal mass is not one way, its application much depends on the circumstances.

Ogoli (2003) carried out an architectural science inquiry on four environmental test chambers with different thermal mass level types in Nairobi, Kenya in which temperatures were simultaneously monitored during the warm period between January and March 1997. Walling for two of the test chambers were natural stone while the other two had timber paneling. Roofing for two test chambers with natural stone was heavy concrete tile while for the timber paneling wall was lightweight galvanized corrugated iron (GCI) sheets. The effect of thermal mass in lowering the maximum indoor daytime temperatures was evaluated. The low mass test chambers closely followed outdoor conditions and did not offer any significant thermal storage. All the light-mass test chambers without ceilings recorded small effect on the indoor maxima. However, high thermal mass was very effective in lowering indoor maximum temperatures below the high outdoor maxima. On a hot day in February, when maximum outdoor temperature was over 33°C, the indoor maximum temperature in high mass building was 25.4°C, which is within the comfort zone. The study concluded that materials with high thermal mass have long time lag and moderating effects to temperature swings.

Givoni (1998) evaluated the effect of mass in lowering the daytime indoor temperatures by monitoring buildings with different thermal mass levels under different ventilation and shading conditions during the summer of 1993 in Pala, South California in USA. This study revealed that the effect of night ventilation was very effective in lowering the indoor temperatures just for high but with very small effect on the indoor maxima of the low-mass building. It also reported that on an extremely hot day with outdoor maximum of 38°C, the indoor maximum temperature of the high mass building was only 24.5°C, which is well within the comfort zone for the humidity level of California.

Brown (1990) monitored an office building and compared data with simulations using variable levels of thermal mass in similar buildings, and found that an increase of the thermal mass from 21 to 201 kg/m2 of floor area, in closed and in ventilated buildings, can reduce the peak indoor temperature by approximately 1 and 2°C, respectively.

Hussein and Rahman (2009) carried out a study on the tropical climate in the warm-humid conditions of Malaysia to explore the indoor climate in mechanically ventilated buildings such as in classrooms of schools and to investigate occupants' perception of the accepted level of indoor thermal conditions. A ten-year period outdoor temperatures data was obtained from the Malaysian Meteorological Service. The most significant conclusion which was drawn from this study is that more than 80% of the respondents found their thermal indoor conditions acceptable, even though the thermal sensation votes exceeded acceptable thermal conditions set by the ASHRAE standard. It was also found in this study that respondents who felt neutral were not always satisfied with their thermal condition and most of them wanted their environment to be cooler. The neutral temperature of 28.4ºC with a comfort range of 26.0ºC to 30.7ºC was obtained by regression analysis of TSV's on operative temperature. The study also showed that respondents in the tropical environment such as Malaysia may have a higher heat tolerance since they accepted the thermal condition which exceeded the standard. It is proven that the respondents are able to adapt to the environment that they are used to. The study was carried out on three different days from morning until noon so as to get variation of temperatures, collecting a full set of objective physical measurements and subjective assessments through questionnaires. The measured environmental parameters were air temperature, relative humidity and air velocity. The subjective responses concern the judgment of the respondents about the thermal environment at the moment of measurements.

Sreshthaputra (2004) carried out a study to develop design and operational guidelines to improve thermal comfort in unconditioned buildings in hot humid climates of Thailand. To achieve this, a survey, measurements and data collection procedures combined with thermal and CFD simulations were employed. A simulation model of a Thai Buddhist Temple calibrated with measured data was created to represent the real building, and used as a base case for parametric studies. The study showed that thermal inertia plays an important role in reducing the diurnal temperature swings of the older Temple. However, during the night, the indoors were warmer than the outdoors because heat was trapped in the building's material inside the temple. It was made even worse because the building was completely closed off from the outside at night. The study also showed that night-time-only ventilation not only reduces the peak indoor temperature, but also the daily indoor temperature swings. The peak indoor temperature was slightly higher in the low-mass temples. This is because the low-mass temple has higher indoor temperature fluctuations than the high-mass temple, due to the thermal inertia effect normally found in most high-mass buildings.

2.6 Effect of window size on indoor air temperature

The windows of a building offers a very low resistance to heat flow from the outside even when it is closed, thus solar radiation penetrates and heats a space (Givoni, 1976). This can allow large quantities of heat to bypass the modifying influence of the rest of the envelope and heat up a space. Solar radiation that enters through glazed areas of a building is either reflected from the floor to the internal surfaces, or is absorbed by the floor, and elevates its temperature and subsequently heats the indoor air and other surfaces.

Bokel (2007) studied the effect of window position and window size on the energy demand for heating, cooling and electric lighting to assess the possibility of calculating the yearly energy demand for heating, cooling and electric lighting as a function of window position, window size and window shape for an office environment. The total energy demand was calculated with the dynamic thermal program Capsol which simulates the total yearly energy demand for lighting, heating and cooling. A reference model of an office room of 3.6 x 5.4 x 3.0 m^3 situated in the city of Groningen in the North of the Netherlands was used for the simulations. The external wall consisted of a south facing double glazed window (the window frame is not taken into account) and a reference size of 3.6 x 1.2 m^2 placed in the middle of the façade.The study concluded that from a technical point of view the ideal facade should have a window size of about 30 % of the façade area, where the window is positioned in the top half of the facade. A window size of 20 to 40% is also very acceptable. For larger window sizes, starting at 50 %, the advantage of a larger glass area on the lighting load is negligible. When the window position is considered, the window position does have a significant effect on the primary energy demand for lighting.

A study by La Roche and Milne (2004) also quantified the effects of modifying the amount of thermal mass and the window area on indoor comfort using a controller. The test confirmed that smaller windows performed better than larger windows. In all the series and with all indicators an increase in the unprotected window size was followed by a decrease in the performance of the system. The performance is inversely proportional to window size, and performance was consistently better when the smart ventilation system was used instead of the fixed infiltration. When the south window to floor ratio was higher than 11.1% the conditions inside the control cell, with a fixed infiltration rate, was worse than outdoors while with the smart controller the south window to floor area can be up to 26.6% before indoor temperature is higher than outdoor temperature.

For this research, the average window to floor ratio of office buildings in Ghana of 54% was used as the base case. This was compared in series with window to floor ratios of 27% and 0% (no window).

2.7 Predicting indoor temperature

Several theoretical and experimental methods have been developed to predict the characteristics of internal temperatures. Several authors have proposed calculation methods (Mackey and Wright, 1946), predictive equations (Givoni, 1992; Givoni, 1998; Shaviv et al., 2001; La Roche and Milne, 2004; Ogoli, 2003) or rules of thumb (Stein and Reynolds, 1992) to predict performance with different amounts of mass, ventilation rates, temperature swings or outdoor average temperature.

Mackey and Wright (1946) used a theoretical method and developed algorithms to determine the decrement and time lag under natural external conditions, as functions of the thermal diffusivity and thickness of the building components, and of the cycle period. However, this method was limited for steady-state conditions and is applicable to homogenous and to multi-layer walls with the indoor temperature assumed to be constant. The application of the formulae to multi-layer wall shown that in a wall (or roof) composed of a heavy and lightweight insulation layer, the location of the insulation has a pronounced effect on the decrement factor. For a composition of 10cm concrete and 4cm mineral wool, the placement of the insulation on external layer and internal layer resulted in decrement factors of 0.046 and 0.45 respectively.

For standard high mass materials such as bricks, concrete and stone, "the indoor temperature is closely related to the thickness of the walls and internal partitions" and has been observed that in many regions "maximum outdoor temperature vary more in summer than the minima, and the daily outdoor amplitude is to some extent related to the indoor maximum" (Givoni, 1976). Givoni (1976) cites that Drysdale (1961) and Raychaudhury and Chaudhury (1961) in Australia and India respectively, used these relationships to derive experimental formulae for prediction of the indoor maximum temperature, expressed as the reduction of the indoor air temperature below the outdoor maximum, as a function of the average weight of the building per unit external surface area. The formulae were developed on the assumption of a minimal ventilation effect and are therefore only applicable to dry regions.

In Australia, Drysdale (1961) suggested the following formula which applies to a building that is single storied and located in Australia (latitude 30◦S):

$$T\text{max-in}(^\circ F) = T\text{max-out} - 0.009W(T\text{max-out} - 68) \ldots\ldots\ldots\ldots \text{ Eqn. 2.2}$$

where Tmax-in is the indoor maximum temperature; Tmax-out the outdoor maximum temperature; and W is the average weight per unit area of the external walls.

In India (latitude 20◦N), Raychaudhury and Chaudhury (1961) suggested the following formula:

$$T\text{max-in}(^\circ F) = T\text{max-out} - 0.004W \times (T\text{max-out} - 60) \ldots\ldots\ldots \text{Eqn. 2.3}$$

where Tmax-in is the indoor maximum temperature; Tmax-out the outdoor maximum temperature; and W is the average weight of the whole structure, including roof, and the external walls, per unit area of the whole external surface (lb/ft2).

In Ogoli (2003) in Kenya, a formula was proposed to predict indoor maximum temperatures for closed high mass buildings and mean radiant temperatures (MRT) in low mass buildings at equatorial high altitudes. Materials with high thermal mass have long time lag and moderating effects to temperature swings. An analysis of the mean radiant temperatures (MRT) measured in low mass buildings was plotted with exterior air temperature.

For closed high mass buildings the formula is as follows:

$$T\text{max-in} = T\text{max-out} - 0.488(T\text{max-out} - T\text{min-out}) + 2.44 \ldots\ldots\ldots\ldots \text{ Eqn. 2.4}$$

where Tmax-in is the indoor maximum temperature; Tmax-out the outdoor maximum temperature; and Tmin-out is the outdoor minimum temperature.

The regression best fit for mean radiant temperatures (MRT) in low mass buildings is as follows:

MRT = 0.8372*(*exterior air temperature*)* + 5.3648…………. Eqn. 2.5

Givoni (1998) carried out studies on buildings with different mass levels during the summer of 1993 in Pala, South California under different rates of ventilation and shading conditions. Givoni states that the indoor maximum temperature in night ventilated buildings follows the outdoor average temperature and proposed a formulae to predict the expected indoor maximum temperature with different amounts of mass and insulation. However, the use of the formula is not extendable to structures different from those studied. This meant that specific studies need to be carried out for various structures and locations. The experimental approach also meant that various modes of the buildings were studied under different time periods. Use of simulation would ensure that same modes could be run for same time periods.

Shaviv et al (2001) carried out a study for different locations in the hot humid climate of Israel and analyzed the influence of thermal mass and night ventilation on the maximum indoor temperature. 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 analysis revealed that maximum indoor temperature depends linearly on the temperature difference between day and night at the site and also shown 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, Shaviv et al (2001) proposed a simple design tool to predict the reduction in indoor temperature from the diurnal temperature swing as a function of the night ventilation rate and the amount of mass, without using an hourly simulation model. The simple design tool is applicable under given conditions for night ventilation and thermal mass. 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.

La Roche and Milne (2004) developed a prototype microcomputer-controlled thermostat that was used to manage airflow according to cooling needs in a building and the resources in the environment. This intelligent control system measures both indoor and outdoor temperature and uses decision rules to control a whole-house fan, in addition to the furnace and air conditioner.

The maximum indoor temperatures inside these buildings were predicted using a two step process: the first involved the calculation of the TDR as a function of the south facing window to floor ratio; and the second was the calculation of the maximum indoor temperature with known TDR. The predictive equations for the test cells with a fixed infiltration rate of 0.7 ACH the smart ventilation system respectively are:

$$TDR = 20 - 1.8 * SWFR \quad \text{. . . . .} \quad \text{Eqn. 2.6}$$

$$TDR = 32 – 1.2 * SWFR \quad \text{. . . . .} \quad \text{Eqn. 2.7}$$

In both, TDR = temperature difference ratio, SWFR = south window to floor ratio.

After TDR is calculated for a building using Eqs. (2.6) and (2.7), it is possible to predict the indoor maximum temperature using Eq. (2.8) and solving for Tmaxin

$$Tmaxin = Tmaxout – [TDR * (Tmaxout \_ Tminout)] \ldots\ldots \text{ Eqn. 2.8}$$

where outdoor maximum and minimum temperatures, or daily temperature swing, must be known.

These results can be extrapolated to slab-on-grade houses that meet the California Energy Code. These equations could be used in buildings with lightweight walls, shaded north, east and west windows, and slab-on-grade construction to predict maximum temperatures with specific window sizes or to determine maximum window sizes that would achieve a specific performance. As one of the objectives of this study was to assess the effect of window size on peak indoor temperature, the work of La Roche and Milne (2004) was used as basis to develop the predictive expression.

2.8 Testing, analysis and modeling of building components

Approaches for testing of building components over the years has gone through several advances in procedures, analysis of measured data to extract performance characteristics, and has been linked with modeling and simulation (Strachan and Baker, 2008). One approach for testing building components has been the use of high quality laboratory facilities that are accurate. Examples of laboratory test facilities are hot-box facilities for measuring thermal transmittance, spectrophoto metric testing for optical properties of glazing, solar simulators and climate chambers for testing the output from photovoltaic modules. According to Strachan and Baker (2008) they tend to be steady state tests and do not take into account the dynamically varying conditions that the components are subjected to when used in the building envelope.

The other approach for testing building components has been the use of a dedicated full-scale building in a typical operational mode as done by Bloomfield (1999) and Swinton et al (2001). According to Bakker (2004) this has been shown to be highly complex and is difficult to measure all the required inputs such as constructional details, air movement, heating and cooling system operation, and external climatic conditions. This is difficult to achieve even in unoccupied buildings to the level needed to get reliable estimates of component performance. Studies carried to test and measure components performance in dedicated full-scale buildings show that results can still have significant uncertainties and the facilities are very expensive to construct and difficult to obtain the high levels of instrumentation and control necessary for accurate monitoring (Strachan and Baker, 2008).

In view of the above, outdoor testing cells with well-specified constructions and high level of instrumentation under high degree of control of the outdoor environment have been employed to fill the gap between laboratory testing and full-scale building testing approaches. Test cells allow the components to be tested in realistic, but controlled, conditions. Well-constructed test cells with a comprehensive set of sensors and data acquisition system can be used for a multiplicity of test components. Given that the establishment of such test facilities are expensive and time consuming, versatility is important. According to Strachan and Baker (2008), outdoor testing of cells reduces the chances of uncertainties than in laboratory test cells and has the ability to test over full operational range in dynamic and realistic climatic conditions. Test cells established to a common set of standards in different climate zones allows components to be tested for suitability to local climate conditions, as well as cross comparisons to ensure that the same performance characteristics can be determined (to a certain level of accuracy) irrespective of climate.

One limitation of the use of outdoor test cells is the small aperture size that can restrict the size of building components that can be tested. Although, it may be possible to test a smaller component and scale to the full size, this may require some detailed modelling in cases where, for example, there is natural ventilation through channels in the component. Another potential disadvantage for commercial tests is that the dynamic testing in the outdoor environment needs a longer testing period than for laboratory tests, although more information on dynamic performance is obtained. According to Strachan (2008) outdoor testing and analysis does not determine how the building component will perform when placed in a real building in a particular location and climate.

Simulation offers the bridge between the outdoor test and full-scale building performance predictions. Outdoor testing of cells has also been of significance in its link with simulation modeling. The EC PASSYS project employed simulations in its methodology in the assessment of performance of building components at full scale in outdoor testing of components such as advanced glazing by Clarke et al (1998) and PV-hybrid-PAS project on heat recovery by Vandaele et al (1997).

This study employed outdoor testing cells coupled with simulation since there are no laboratory facilities or buildings designed to run on night-time ventilation in Ghana. Besides no group of buildings have same and similar spatial dimensions and of different envelope materials that can provide measured data as required for this research.

2.9 Thermal Simulation Techniques in Building Design

Several thermal simulation computer programs have been developed worldwide for the purposes of new building design and existing building analysis. Simulation codes generally calculate dynamic heat transfer through building materials and evaluate overall building performance (Strachan, 2008). Boyer et al (1998) list numerous general-purpose, energy simulation tools such as DOE-2 (LBNL, 2001) BLAST (BSO 1993) TRNSYS (SEL, 1995), and ESPr (ESRU, 1997) that were initially developed for use on mainframe computers, which were available to government research centres in the 1970s and 1980s. However, during the last few decades, as the power of personal computers (PC) has increased, researchers have been able to translate general-purpose mainframe programs for use on PCs.

Other high performance, easy-to-use computer codes have been developed (Arastech et al, 1994) and OPAQUE (Abouella and Milne, 1990) for calculating heat transfer through fenestration systems. In addition, EnergyPlus and ESP-r, which are considered public domain simulation tools, and are recognized by researchers worldwide. In this research, EnergyPlus simulation programm was used as a design and analysis tool for the investigation.

2.10 The Energy Plus Simulation Programme

Energy Plus (DOE, 2008) is public domain software supported by the US Department of Energy that dynamically models the thermal performance of buildings: cooling, heating, ventilating, lighting; and their associated energy systems when they are exposed to different environmental and operational conditions. The program builds on the widely used features and capabilities of BLAST and DOE-2.

One of the strong points of Energy Plus is its fully integrated energy analysis and thermal load simulation approach where loads, systems and plant in the form of a collection of modules are solved simultaneously and allows capacity limits to be accurately modeled and investigated more realistically. The system and plant output are allowed to directly impact the building thermal responses rather than calculating all the loads first, then simulating system and plants.

EnergyPlus employs modularity that reflects in its actual filling in the details for the simulation in that each module is responsible for “getting” its own input and receives input from the input processor. No specific order is needed in the input data file because each module typically gets all its input the first time it is called and data that is not needed by a particular simulation is not processed. EnergyPlus implementes a “manager” philosophy that eliminates the interconnections between various program sections, as in other simulation programs such as DOE-2, and also the need to understand all parts of the code just to make an addition to a very limited part of the program.

Another useful feature is the interoperability between Energy Plus and CAD programs. Energy Plus has been designed to import a building’s geometry directly into the program.

Figure 2.1 provides an overview of the EnergyPlus program and shows two input files required by various modules for the simulation manager to run.

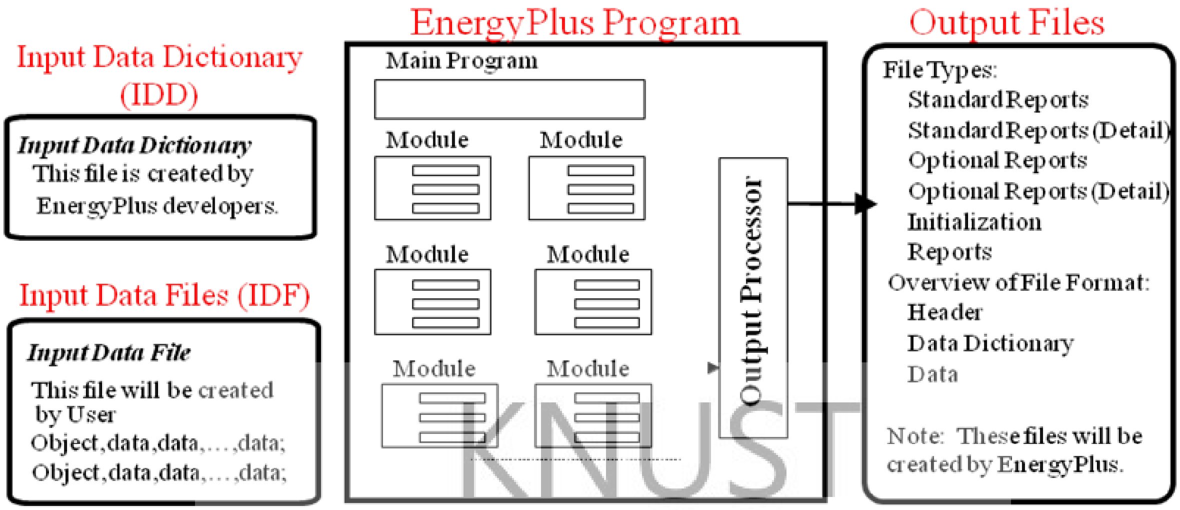


Figure 2.1: Overview of EnergyPlus Program
(Source: DOE, 2008)

The input files include the Input Data Dictionary (IDD) that is created by the developers and the Input Data Files (IDF) created by the user. Based on a user's description of a building's physical make-up, associated mechanical systems and loads can be calculated at a user-specified time step, and passed on to the building systems simulation module at the same time step. The output processor of EnergyPlus program provides output reports either at the summary or at the detailed (variable) level.

The application solves the sensible heat balance for a zone by setting up equations representing the individual energy balance for the air and each of the surrounding surfaces. These equations are then combined with further equations representing the energy balance at the external surfaces, and the whole equation set is solved simultaneously to generate air temperatures, surface temperatures and room loads. Conduction in the fabric of the building is treated dynamically using two methods for the analysis of wall heat flows. For state-representation finite difference methods are applied whereas conductive heat flows at the surfaces of walls and other building elements are calculated with response factor method. Convection is treated using a combination of empirical and theoretical relationships. Long-wave radiation exchange is modeled using the Stefan-Boltzmann law. Longwave radiation from the sky and the ground is treated using empirical relationships (EDSL 2007). For this research, the thermal performance analysis was done using Version 4.0 of the EnergyPlus simulation program.

2.11 Calibration and validation of simulation

There has been improvement in capability and validity of dynamic simulation programs for use with some confidence in predicting energy and environmental performance of buildings. Arguments have been advanced that simulation models can effectively replace the need for outdoor test cells (Littler, 1993). Empirical validation of thermal building simulation program using test room data by Lomas et al (1994) in the inter-program comparison by ANSI/ASHRAE 140 (2004) show significant differences exist in predictions between simulation programs on even simple buildings.

To ensure that simulation programs are capable of modeling building components, model predictions are calibrated with high quality datasets from outdoor experiment. Calibration involves creating a model of the test component and undertaking simulations using measured climatic data, and then compared to the measured test environment ensure that the model predictions align with the measured data over a realistic range of operating conditions spanning a period of several days to several weeks (Strachan, 2008). If successful, it gives confidence that the simulation program can correctly model the component characteristics when integrated into a full-scale building. The process can be improved by using simulation for the design of experiments, to ensure that all the main influencing factors are measured. A more pragmatic approach is to define the comparisons to be made and compare measurements with model predictions and modify the model if necessary. Once validated it is considered that the simulation program can then be used to model the performance of a component. When quantifying the thermal performance or providing data for comparisons with simulation predictions, it is important to undertake error analysis using statistical instruments that are checked to fall within allowable tolerances (Soebartoe, 1997).

For this research, the results of the experiments were used to calibrate the simulation model predictions. Considerable time and effort were devoted in the design, construction and monitoring of the test cells to ensure that accurate experimental test results were achieved to calibrate the simulation model to confirm that the simulation model of the tested component can accurately predict its performance.

2.12 Chapter Summary

The Chapter contains a review of both published and unpublished literature relevant to this research, and were organized around the following topics with respect to warm-humid climates: i) passive and low energy cooling techniques for warm humid climates; ii) concept of thermal comfort; iii) effect of thermal mass in space cooling in warm humid climates; iv) effect of window size, v) approaches to building components testing, analysis and thermal simulation and calibration techniques.

It was found that very few studies addressed passive cooling designs in warm-humid climates, especially in the hot developing sub-Saharan African countries. Moreover, only a few were concerned with the effects of thermal mass coupled with night ventilation in the warm-humid climates. There is no empirical information on thermal performance of available materials of various thermal masses used for building envelope.

With respect to thermal comfort, the previous studies demonstrated the historical development of the human comfort preferences. The review revealed that most of the well-documented efforts on the human thermal comfort have been developed in developed countries in cold and temperate climates, where people are used to living mostly in conditioned buildings. On the other hand, the limited studies carried out in the tropical sub-Saharan African countries have been evaluation of human thermal comfort from the psychological, adaptive and conventional paradigms. These studies show that due to high humidity levels, high wind speeds and acclimatization, no single universal comfort index has been developed for all people, and the world that does not need adjustments.

The limited literature reviewed generally asserts that NVC cannot eliminate the use of AC in space cooling in warm-humid climates. There is no information on the percentage of cooling energy that can be taken care of by activation of NVC of thermal mass in the in warm-humid climates.

Calibration of simulation results is necessary and important for the accuracy and usability of building simulation irrespective of the software being used. The base case results of simulation tools will have to be correctly calibrated with measured or past data to ensure that the virtual model of the building under analysis faithfully represents the thermal behaviour of that building. All previous studies used measured data from existing buildings that were designed with the techniques being tested to validate the simulation predictions. However, in the region of study no building is designed to run by night ventilation from which an experimental data could be obtained for the validation. It was also revealed that very limited study combined thermal simulation, measured data to perform an analysis of various envelope materials where thermal inertia plays an important role in peak indoor comfort conditions to reduce cooling load.

In summary, this research uses a computer simulation technique to analyse indoor air temperature conditions of simulation models representing the Ghanaian mode of building design in Ghana, and an experimental approach to achieve measured data to validate the predicted simulation results. Using these techniques, the effect of thermal mass, window size and NV on the thermal performance of building were evaluated.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Chapter Outline

This chapter discusses the methodology used in this research. It covers a discussion on the overall research design. It includes the data collection processes, development of the Energy Plus simulation model, experimental setup, data monitoring, the validation procedure for the Energy Plus predicted data.

3.2 Research Process

The literature review presented in Chapter 2 provided the relevant theoretical background to undertake this study. With a clear theoretical framework, the research was designed taking into consideration the philosophical viewpoint, the research approach, research strategy, time zone, and activities and methods. It was designed to meet the objectives of the research outlined in Section 1.9. These objectives were developed to achieve the aim of the research and since this involved modeling and simulation, the last stage of the research was devoted to the validation of the predicted results with measured data (Section 5.4).

3.3 Research Design

Research design is a plan of information required to answer research problems and how such information can be collected (Frazer and Lawley, 2000). It is essentially a logical sequence of steps linking the initial research questions to the data collected and ultimately to a series of conclusions arising from the study (Yin, 2003).

In choosing a research method for this study, the hierarchical model of research methodology by Saunders et al (2007) that describes the research process as the layers of the "onion", with the outer one being the research philosophy was adopted (Figure 3.1). The research philosophy guided the research approaches and lead into the research strategy. The research strategy paved way for the choice of time horizons and data collection and data analysis (Saunders et al, 2007). The following sections describes the research philosophy, research approaches, research strategy, choice of methods, time horizons and research technique for this research.

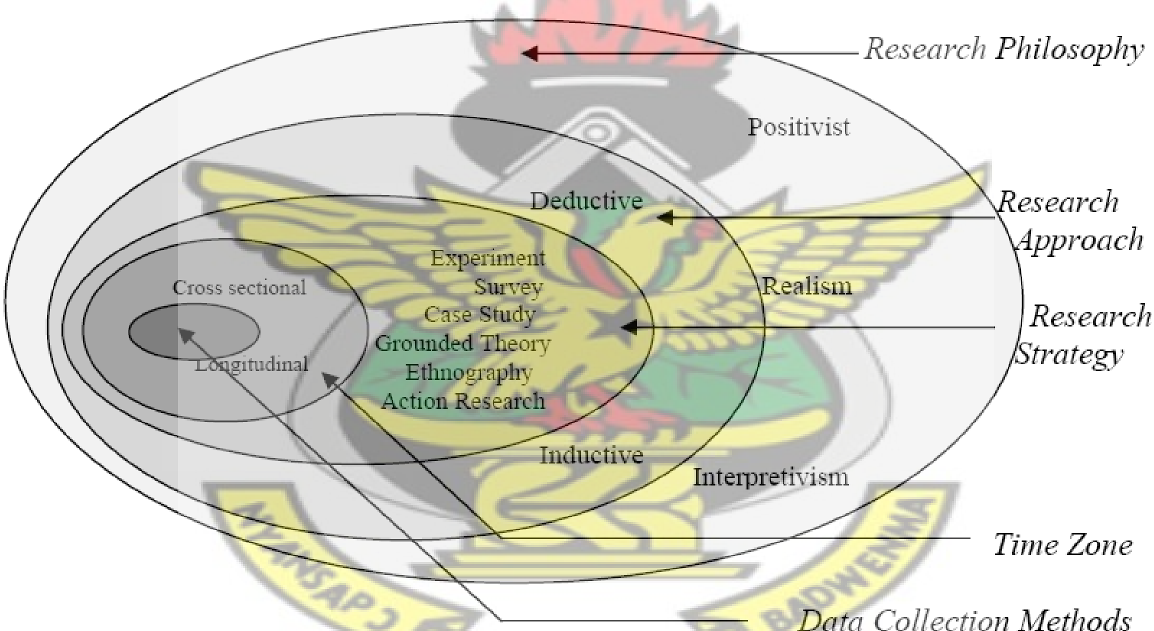


Figure 3.1: 'Onion' Research Process (Saunders et al, 2003)

3.3.1 Research Philosophy

Research philosophy basically concerns the assumptions that a researcher brings to an investigation. Numerous researchers have pointed out the importance of paying heed to the research philosophies. Easterby-Smith et al (2003) points out that failure to consider and think through philosophical issues can have a detrimental effect on the quality of the research outcome. Philosophical basis can help to determine the most suitable method to conduct the research at the very early stages. According to Easterby-Smith et al (2003), reference to research philosophies will enable the researcher to resolve the research question by identifying, adapting or even creating research design that projects beyond one's own experience and knowledge.

Sexton (2003) argues that research philosophies are characterized by contrasting views on the ontological, epistemological and axiological assumptions. This stage, for the purpose of positioning the research on the philosophical continuum, it was important to position the ontological, epistemological and axiological assumptions, before embarking on the research design.

As set out by the aim and objectives, this research shows a theory confirming attempt through deductive methods to observe causal relationship resulting from complex interaction between physical variables associated with building, climatic and technical parameters to impact on peak indoor air and mean radiant temperatures within controlled environments where the researcher directly, precisely and systematically manipulate the reality. The parameters involved in the study were transformed into observables or indicators to facilitate quantitative empirical testing. The research was subjected to a scientific rigor and the independence of the researcher was maintained. It does not involve human beings as such limits the research to the use of objective methods of gathering information. According to the above reasons, it could be argued that the research leans towards positivism and not social constructivism.

The research assumes that a reality pre-exists, in that the techniques being tested can reduce peak indoor temperature independent of the researcher and hence the job of the researcher was merely to identify the extent of this pre-existing reality. It also sought to explain the response of a building system by identifying fundamental laws through observable reality. The study did not require the researcher to be a part of the environment and no interaction was needed within the environment to assess the effect of the different building parameters; internal loads, airflow rates on peak indoor air and mean radiant temperatures. The research therefore bears a resemblance to realism assumptions (objectivism stance).

Further, the study did not require reasoning intuition, or perception to understand building characteristics and climatic parameters. The data required for the research involve physical properties of materials such as thickness, thermal conductivity of materials the values of which did not require the researcher to employ any sense of judgment, intuitive reasoning, or perception. In this sense, the research assumed a value-free stance than a value-laden one in its axiological positioning.

The analysis of philosophical assumptions and positions of the research above established a positivism stance in epistemological undertakings, an objectivism stance in ontological assumptions, with a value-free axiological position. This philosophical positioning influenced the selection of appropriate research approach and strategy which are described in the sections below.

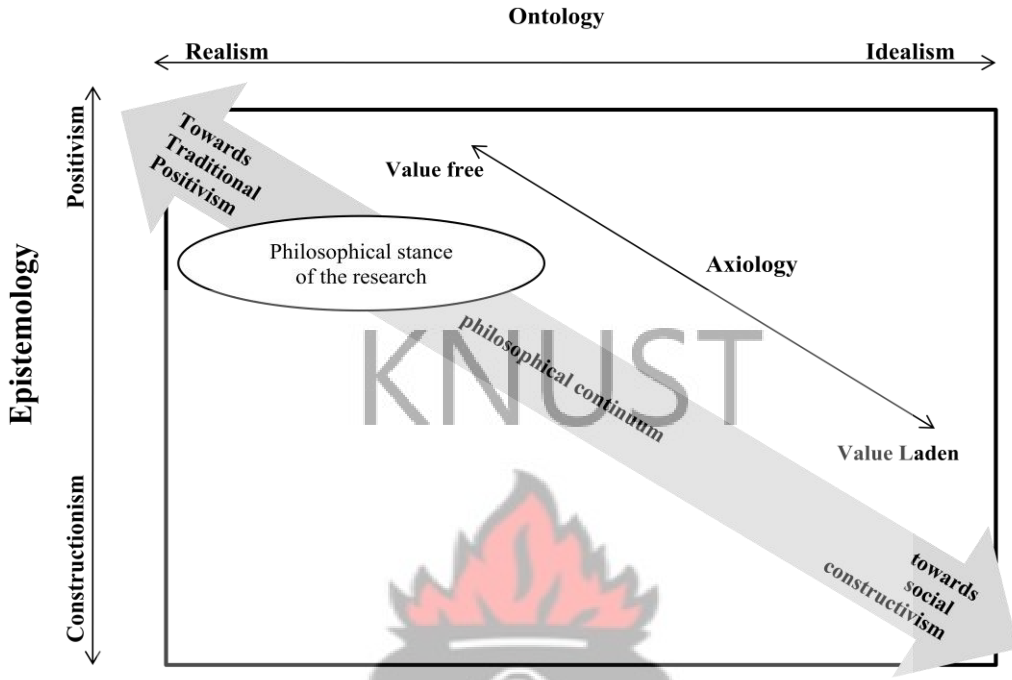


Figure 3.2: Continuum of Philosophical Assumptions (Sexton, 2004)

3.3.2 Research approach

As per the positivist stance established, the research is more biased towards deductive approach. Therefore the deductive research approach was adopted as the research investigates causal relationships between variables. By this approach the researcher had to first determine which concepts present important aspects of the theory or problem under investigation. After identifying these important concepts they were transformed into observables or indicators to facilitate quantitative empirical testing (Saunders et al, 2003).

3.3.3 Research Strategy

The literature on research methodology identifies experiments, survey, case study, grounded theory, and ethnography and action research as major research strategies within the spectrum from deductive to inductive research approaches (See Saunders et al, 2003; Yin 2003; Easterby Smith et al, 2002).

According to Easterby-Smith et al, (2002), five out of six key conditions in choosing appropriate research strategies closely relate to the basic dichotomy between the use of positivist and social constructionist approaches. Figure 3.3 shows how the research approach can be positioned within the epistemological, axiological and ontological continuums. It can be seen that experiments and surveys are governed by positivist, objectivism and value free stances whereas case study, action research, ethnography and grounded theory are towards interpretivism and subjectivism stances.

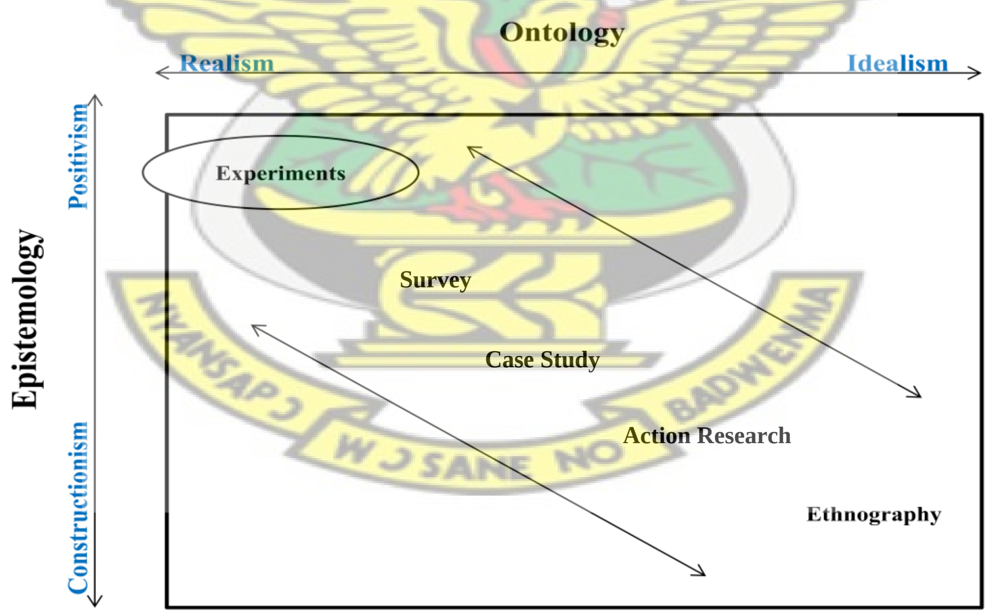


Figure 3.3: Continuum of Research Approaches (*Adapted from Sexton, 2004*)

As per the selection by philosophical positioning, this research takes positivism stance. Since it resides mainly in the positivism territory action research, ethnography and grounded theory strategies are incompatible. Again the ontological assumption of strong ‘pre-existing reality’ rules out case study, since case study requires no level of control over the environment where the investigator directly, precisely and systematically manipulates the reality (Yin, 2003), as required in this research. Case studies are carried out in a way that it incorporates the views of the “actors” in the case under observation (Zonabend, 1992). Moreover, case studies provide the opportunity of dealing with a full variety of evidence such as documents, interviews and observation (Yin, 2003).

Further to the above, case study, action research, ethnography and grounded theory cannot be conducted under controlled environments and also in a situation where the context is difficult to investigate as a result of limited number of variables set out (Yin, 2003).

Table 3.1: Research Design Selection Criteria

Strategy	Case study	Survey	Archival analysis	History	Experiment
Form of research question	How, Why	Who, What, Where, How many, How much	Who, What, Where, How many, How much	How, Why	How, Why
Control over behavioural events	No	No	No	No	Yes
Focus on contemporary events	Yes	Yes	Yes/No	No	Yes

Source: Yin (2003)

From the positioning of this research as captured in Figure 3.3, a choice has to be made between experiments and survey as suitable approaches. With respect to survey, it does not require high control over the environment and are conducted on a wider population using economical data collection methods such as questionnaires (Saunders et al, 2003).

Generally experiments are undertaken on the sample of the population and within a controlled environment to test whether there is causal relationship between the variables under investigation (Baker, 2001). Therefore, the most appropriate research strategy for this study is experiment.

3.4 Activities and Methods

The activities carried out to achieve the objectives of the study are the following: i) Data collection; ii) Development of simulation models using the EnergyPlus Input Data File; iii) Simulations and performance evaluation of models; iv) Experimental setup design; v) Monitoring of test cells; and vi) Validation (calibration) of predicted (simulated) results. Figure 3.4 presents a general overview of the activities carried out to achieve the objectives of the research.

3.4.1 Data collection

The data collected included climatic data, building and operational parameters. With the decision to undertake the investigation with the EnergyPlus simulation program, the first step was to develop the skill and knowledge in the use of the software. To be able to understand the mandatory input data library syntax of the program, a nine month period was spent to learn the program with the aid of the reference manual and tutorial lesson available on the EnergyPlus website.

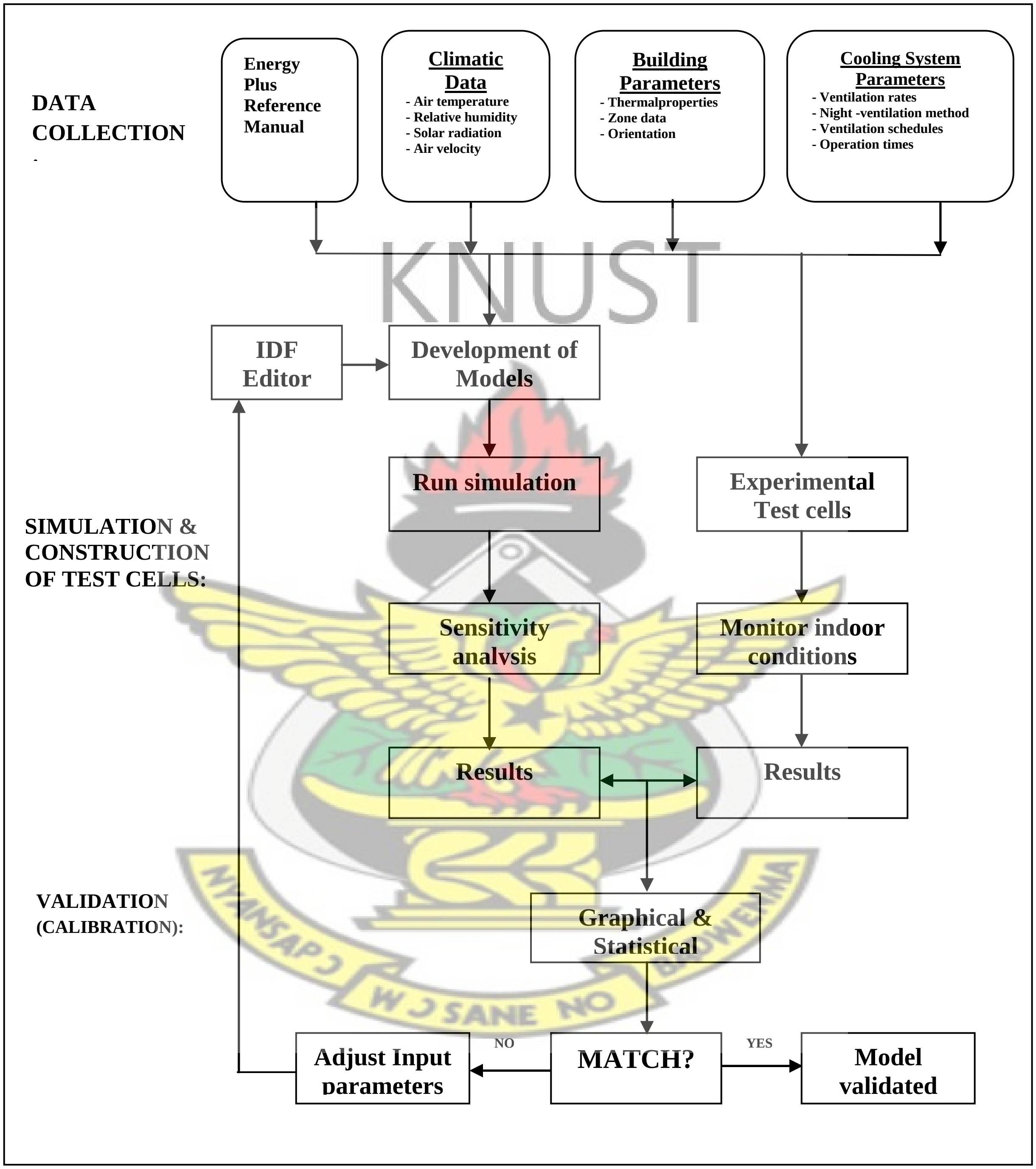


Figure 3.4: Flow chart of Research Activities (Author's Construct)

The E+ program is designed to calculate hourly building performance by using hourly climatic data in the *".epw"* extension file format. The climatic data used for the simulation included outdoor dry bulb temperature, relative humidity, wind speed, solar radiation, and ground (Appendix 1). Detailed and comprehensive recorded outdoor weather file comprising all the six climatic data was not available for Kumasi. Only daily maximum and minimum values of air temperature and relative humidity recorded at one hour interval were available from the Ghana Meteorological Agency. In previous studies by Koranteng et al (2009), sensors were mounted at specified points on the KNUST Campus in Kumasi to monitor outdoor air temperature and relative humidity. Segments of a synthetic weather data, generated via Meteotest 2008 file, that matches the outdoor measurements from the sensors were identified and used to run the simulation. This research used the data that were generated for the above study.

The building parameters included the thermo-physical properties of the basic building materials used for the model. Building parameters were obtained from the specifications and architectural drawings of the conventional mode of building design as specified in the Ghana building regulations. Building parameters helped to correctly dimension the model and specify zone data.

3.4.2 Development of Models

A series of comparative simulations were performed using the weather file of Kumasi. The Input Data File (IDF) of the EnergyPlus program was first used to develop a control model simulates of the conventional mode of building design and construction in Ghana. The control and test models had dimensions of 2.40m high, 1.2m wide and 2.4m deep. The floor was made of 150mm thick mass concrete and the roof was made of 150mm thick reinforced concrete slab. The wall of the control model was made of 150 mm thick solid sandcrete block which in this research represents the low mass material. The pilot survey stage established average window to floor ration of selected buildings to be 54%. This was used as the base case of the control model. A total window to floor ratio of 1.62m^2 of glazing area was obtained with a floor area of 2.44m^2 of the control model. The average window to floor ratio of buildings in Ghana of 54% was used to compute the total window area of the control model of 1.62m^2. The control model had windows closed 24 hours, with no night-time ventilation.

Three sets of treatments were made to the control model to obtain various test models that were used to carry out the investigations to achieve the objectives of the study. The first set of treatments was the variation of thermal mass for which of the solid sandcrete blocks of the control model was compared to that of baked bricks and concrete. The window to floor ratio of the control model of 54% was compared with that of 27% (window area of 0.82 m^2) and 0% representing no window.

To achieve objective one, three models were used, one with each of the three different thermal masses; solid sandcrete blocks (SSB), baked bricks (BB) and concrete (CONC) all with window to floor ratio of 54% as in Table 3.2. Nine models were used for objective two. There were three models made of each of solid sandcrete blocks (SSB), baked bricks (BB) and concrete (CONC). Among each of the three thermal masses, each had 54% (window area of 1.62m^2), 27% (window area of 0.82 m^2) and 0% window to floor ratios. In achieving objective three, the nine models used under objective two were each subjected to a night-time ventilation rate of 10 ACH. To assess the effect of varying night-time ventilation rate, the air change rates per hour was increased from 10ACH to 20ACH, then to 30ACH. The test models were subjected to night-time ventilation from 19:00 hours (evening) till 7:00 hours (next morning).

It is very common for night-time ventilation to be provided by natural ventilation. However, the site location of this research had irregular wind patterns and low night-time ventilation wind speeds. This may not be able to provide effective natural ventilation rates for effective night-time ventilation. For this reason, mechanical ventilation was adopted with the use of an intake and an exhaust fans to provide night-time ventilation. During the daytime periods the fans were provided with dampers to avoid internal heat gains by convection. An intake and exhaust ventilation fans were modelled for each model. Table 3.3 shows the characteristics of models used for objectives two and three.

Table 3.2: Treatments made to the Control Model

Thermal Mass	Solid Sandcrete Blocks (SSB)			Baked Bricks (BB)			Concrete (CONC)			Night Ventilation (NV)
W-F-R	54% (1.82m²)	27% (0.91m²)	0	54%	27%	0	54%	27%	0	
OBJECTIVE 1	√			√			√			Without NV
OBJECTIVE 2	√	√	√	√	√	√	√	√	√	Without NV
OBJECTIVE 3	√	√	√	√	√	√	√	√	√	With NV @ 10, 20, 30 ACH
	1	2	3	4	5	6	7	8	9	

Table 3.3: Characteristics of the models for objectives 2 and 3

Model	Model Characteristics	Difference from previous model
Control Model	1. Solid sandcrete blocks 2. Window size = 1.62m^2 3. No night-time ventilation	-
Test Model 1	1. Solid sandcrete blocks 2. Window size = 1.62m^2 3. Night-time ventilated	Night ventilation added (to control model)
Test Model 2	1. Solid sandcrete blocks 2. window size = 0.81m^2 3. Night-time ventilated	Window reduced by 50%
Test Model 3	1. Solid sandcrete blocks 2. No window 3. Night-time ventilated	Window eliminated
Test Model 4	1. Baked bricks 2. Window size = 1.62m^2 3. Night-time ventilated	mass added (medium) Window added - 100%
Test Model 5	1. Baked bricks 2. Window size = 0.81m^2 3. Night-time ventilated	Window reduced by 50%
Test Model 6	1. Baked bricks 2. No window 3. Night-time ventilated	Window eliminated
Test Model 7	1. Concrete 2. Window size = 1.62m^2 3. Night-time ventilated	mass added (heavy) Window added - 100%
Test Model 8	1. Concrete 2. Window size = 0.81m^2 3. Night-time ventilated	Window reduced – 50%
Test Model 9	1. Concrete 2. No window 3. Night-time ventilated	Window eliminated

3.4.2.1 Creation of Input Data File (IDF)

The process by which the model specifications were entered to create the IDF is presented in Figure 3.5. Variables were assigned to the following modules of the E+ IDF to develop the model for this study: i) Simulation Parameters; ii) Location, Climate and Weather File Access; v) Schedules; iv) Surface Construction Elements; v) Thermal Zone Description and Geometry; and vi) Air Flow Systems.

The models used in this research were all single zone. The zone of each model was defined by four exterior walls, a floor, and a roof with a ceiling below. Windows on the north and south walls have projecting horizontal shading devices. Input data were carefully inserted as accuracy of results related directly to it.

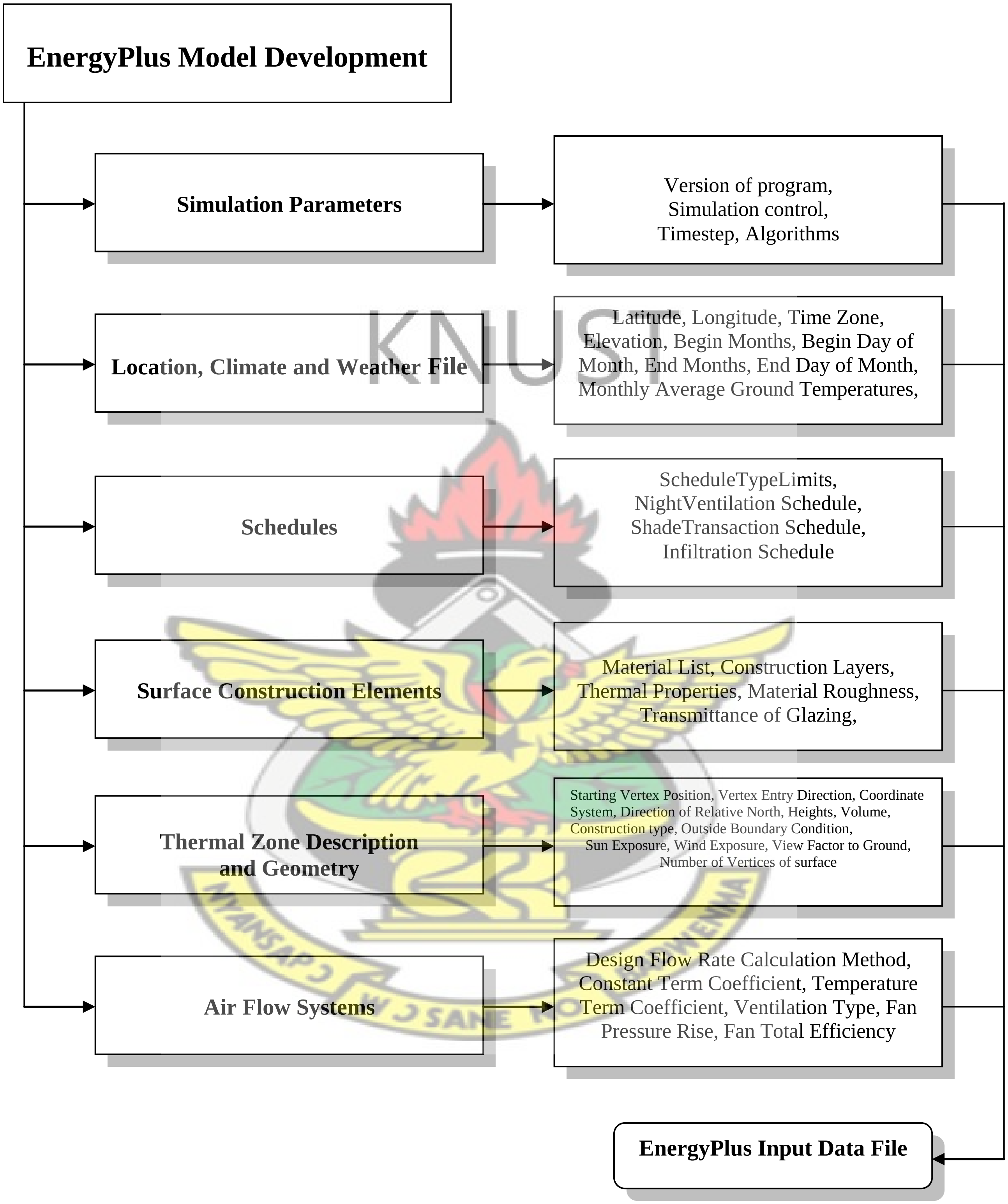


Figure 3.5: Input diagram of EnergyPlus of Input Data File (IDF)
(Author's Construct)

3.4.2.1.1 Simulation Parameters

For more accurate results, a zone timestep of six (6) was used to direct the program to generate results at a time interval of 10 minutes. The models were aligned to the true north-south with the north axis field specified as zero.

The conductive and radiative heat transfer through walls, roofs, windows, and doors were calculated separately by response factors. In addition, interior surface convection was computed based on specified convection coefficients, while the exterior convention coefficients were calculated by the program based on the specified surface roughness and exterior wind speed taken from the weather file.

3.4.2.1.2 Location, Climate and Weather File Access and Schedules

Site location parameters and exterior thermal environment play a critical role in determining the thermal performance of the models as far as sun angles and air properties are concerned (LBNL, 2009).

The site location parameters such as the latitude and longitude, time zone, elevation and the average monthly ground temperatures of Kumasi were specified in the IDF. Since the models are designed to be in contact with the ground, the ground temperatures were specified for use by Energy Plus as the outside temperatures for the floor slab in the heat transfer model. The specifications of the site location parameters and the ground temperatures for the various months are presented in Tables 3.4 and 3.5. The latitude and longitude of Kumasi are 6°75” North and -1°58” West respectively. The time zone is 0 hours and the elevation of Kumasi is 251 metres. The run period defining the months and days for which the simulation was run were scheduled and are shown in the IDF in Appendix 2. EP program does not assume an entire year simulation.

The ground reflectance determines the effect of ground cover on incident solar radiation on the surfaces of the models.

Table 3.4: Site Location Parameters for Kumasi

Name	KUMASI_ASH_GHA
Latitude {deg}	6.75
Longitude {deg}	-1.58
Time Zone {hr}	0
Elevation {m}	251

(Source: Kumasi Weather File, 2009)

Table 3.5: Ground Temperatures for Kumasi (°C)

Month	**Temperature**	**Month**	**Temperature**
January	26.6	July	25.5
February	27.0	August	25.1
March	27.2	September	25.0
April	27.0	October	25.1
May	26.6	November	25.5
June	26.1	December	26.1

(Source: Kumasi Weather File, 2009)

Schedules were specified to provide detailed description of the months of the year, days of the week and times of the day for which model functioning parameters such as zone night-time ventilation, shading and infiltration were activated. Separate schedules were defined for each of zone night-time ventilation, shading and infiltration. A transmittance schedule name was specified for each shading device.

3.4.2.1.3 Surface Construction Elements

The surface construction elements considered for the models are walls, roof, floor, door and windows. The specification of various surfaces defining a zone was done following a hierarchy of specifications shown in Figure 3.6. The first step was to create a database of the basic material types that were used to describe the layers within the various constructions elements.

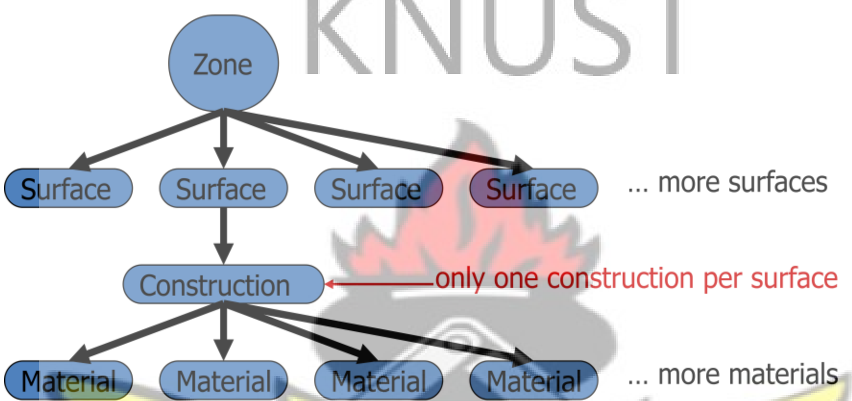


Figure 3.6: Hierarchy of envelope specification (LBNL, 2009)

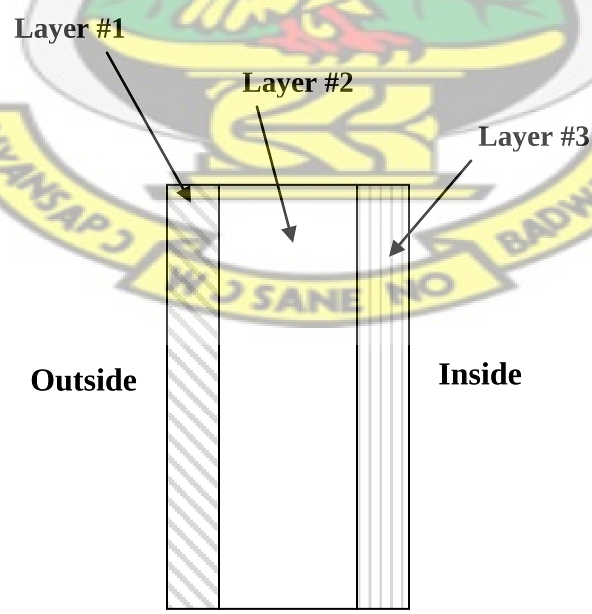


Figure 3.7: Material ordering in construction

The thermo-physical properties as well as the relative roughness of the basic materials used in the models are presented in Table 3.6. The roughness influences the convection coefficients, and more specifically the exterior convection coefficient. Basic materials that have their thickness, conductivity, density, and specific heat known, have been specified. Cement-sand plaster and ceiling air space do not have their four main properties known so only their thermal resistance has been specified.

The construction for each of the surface elements was defined by the composition of various basic material types. The layers of the construction materials were listed from "outside" to "inside", with outside being the layer furtherest away from the zone air (see Figure 3.7). Inside is the layer next to the zone air. For instance the roof construction has the inside layer being the plywood ceiling board, next is the air space and the outer layer is the concrete roof deck. Inside and outside air resistances were not provided as part of the construction definitions because Energy Plus calculates them automatically during the simulation.

The properties of the glass of the windows are shown in Tables 3.7. Solar diffusing was specified as 'No' because the glass is transparent and beam solar radiation incident on the glass is transmitted as beam radiation with no diffuse component. A dirt correction factor of 0.9 that corrects the presence of dust on the glass was specified because the glass is an outer layer of an exterior window. All the models had single pane, 3mm clear glass windows.

There were three types of constructions for the walls: solid sandcrete block walls, which had three layers; baked brick wall with two layers of basic materials; and concrete with three layers. The composition of various materials for the surface construction elements are shown in Table 3.8. All the models had mass concrete floor and reinforced concrete roof.

Table 3.6: Thermo-physical Properties of Basic Material Types (Source: LBNL, 2010)

Name	Thickness {m}	Conductivity {W/m-K}	Density {kg/m3}	Specific Heat {J/kg-K}	Thermal Resistance {m2-K/W}
Plywood Board	0.04	0.06	368	590	-
HEAVYWEIGHT CONCRETE	0.1016	1.95	2240	900	-
MASS-CONC	0.1524	1.95	2240	900	-
SAND-BLKS	0.1524	0.49	512	880	-
BRICKS- Fired Clay	0.102	1.02	2089	790	-
REINF-CONC	0.1524	1.95	2240	900	-
TIMBER-ODUM	0.0508	0.15	608	1630	-
Render: Cem/Sand - 20mm	-	-	-	-	0.026
Render: Cem/Sand - 50mm	-	-	-	-	0.052
Ceiling-air-space resistance	-	-	-	-	0.18

Table 3.7: Properties of Window Glazing

Property	Value
Name	CLEAR GLASS 3MM
Optical Data Type	SpectralAverage
Window Glass Spectral Data Set Name	0.003
Thickness {m}	0.837
Solar Transmittance at Normal Incidence	0.075
Front Side Solar Reflectance at Normal Incidence	0.075
Back Side Solar Reflectance at Normal Incidence	0.075
Visible Transmittance at Normal Incidence	0.898
Front Side Visible Reflectance at Normal Incidence	0.081
Back Side Visible Reflectance at Normal Incidence	0.081
Infrared Transmittance at Normal Incidence	0
Front Side Infrared Hemispherical Emissivity	0.84
Back Side Infrared Hemispherical Emissivity	0.84
Conductivity {W/m-K}	0.9
Dirt Correction Factor for Solar and Visible Transmittance	1
Solar Diffusing	No

Table 3.8: Order of Materials in Construction Elements

Name	Layer 1 (Outside Layer)	Layer 2	Layer 3	Layer 4	Layer 5
SINGLE-PANE WINDOW	CLEAR GLASS 3MM				
WALL-BLKS	Render: Cem/Sand - 20mm	SAND-BLKS	Render: Cem/Sand - 20mm		
WALL-BRICKS	BRICKS - Fired Clay	Render: Cem/Sand - 20mm			
WALL-CONC	Render: Cem/Sand - 20mm	MASS-CONC	Render: Cem/Sand - 20mm		
FLOOR	MASS-CONC	Render: Cem/Sand - 50mm			
DOOR	TIMBER - ODUM				
ROOF-1	Render: Cem/Sand - 20mm	REINF-CONC	Render: Cem/Sand - 20mm	Ceiling air space resistance	Plywood Board
ROOF	Render: Cem/Sand - 20mm	REINF-CONC	Render: Cem/Sand - 20mm		

3.4.2.1.4 Thermal Zone Description and Geometry

This section describes the thermal zone characteristics such as the physical make-up and orientation, as well as the geometry of each of the surfaces of the models.

The World Coordinate System (WCS) with zone origin values of (0,0,0) was used to facilitate use within the Computed Aided Design (CAD) system structure. The vertexes of surfaces of the models were specified as being viewed from outside of the zone air using a Three-Dimensional Cartesian Right-Hand coordinate system, where the X-axis points east, the Y-axis points north, and the Z-axis points up as shown in Figure 3.8. The vertexes were specified in a clockwise order starting with a vertex position in the top left corner as shown in Figure 3.9. This provided the surface translation in EnergyPlus an order and positional structure for each surface entry.

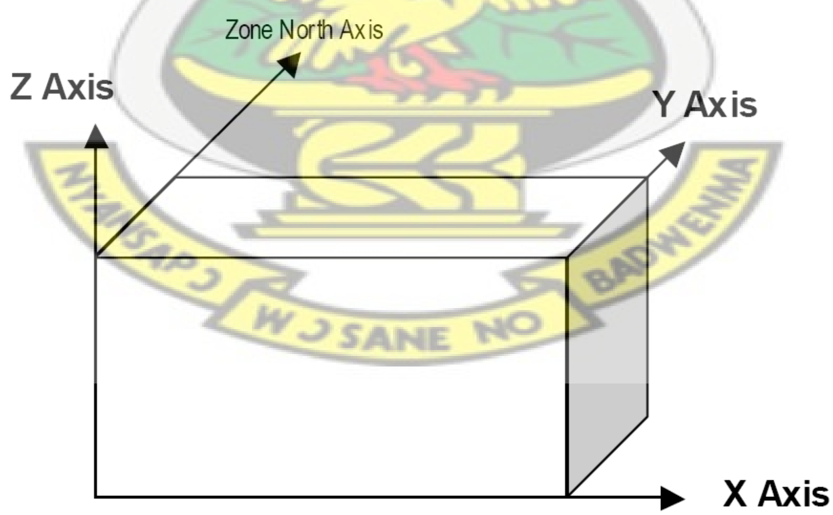


Figure 3.8: EnergyPlus Coordinate System

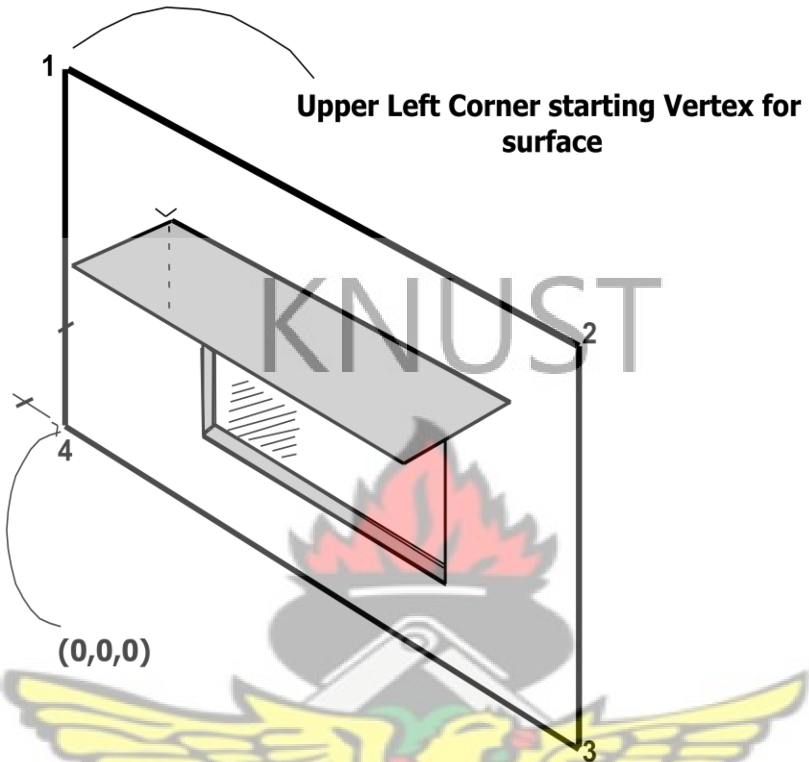


Figure 3.9: Illustration of Surface vertices

Six building surface construction elements were specified together with their properties and are shown in Table 3.9. A unique name that can be used as a reference in other modules was assigned to each surface. Since the models are of single zone, all the walls and the roof have outside boundary conditions being outdoor, and were therefore considered as being exposed to the sun and wind. The floor had its outside boundary condition being ground. The properties of the fenestration were specified. The shading devices were also specified and given names for reference. A transmittance schedule name was specified for each shading device. The angle of tilt of the surfaces were determined by Energy Plus based on their vertex coordinates.

The properties of the fenestration of the model outlined in Table 3.10. Five fenestration surfaces were defined. There were two each of north and south walls. Each wall had one window area of 1.62m^2 and another with window area of 0.81m^2. The properties of the door were also specified for the north wall. Two shading surfaces were defined for each of north and south walls. The number of vertices and coordinates, and other properties are outlined for each shading device in Table 3.11. The specification of the zone ventilation and zone infiltration parameters are presented in the IDF in Appendix 2.

Table 3.9: Surface Details

PARAMETER	EAST WALL	NORTH WALL	WEST WALL	SOUTH WALL	ROOF	FLOOR
Surface Type	Wall	Wall	Wall	Wall	Roof	Floor
Construction Name	WALL-BLKS	WALL-BLKS	WALL-BLKS	WALL-BLKS	ROOF-1	FLOOR
Zone Name	ZONE-CONTROL	ZONE-CONTROL	ZONE-CONTROL	ZONE-CONTROL	ZONE-CONTROL	ZONE-CONTROL
Outside-Boundary Condition	Outdoors	Outdoors	Outdoors	Outdoors	Outdoors	Ground
Sun Exposure	SunExposed	SunExposed	SunExposed	SunExposed	SunExposed	NoSun
Wind Exposure	WindExposed	WindExposed	WindExposed	WindExposed	WindExposed	WindExposed
View Factor to Ground	0.5	0.5	0.5	0.5	0	0
Number of Vertices	4	4	4	4	4	4
Vertex 1	4.44, 2, 2.44	4.44,3.22, 2.44	2, 3.22, 2.44	2, 2, 2.44	2, 2, 2.44	2, 2, 0
Vertex 2	4.44, 2, 0	4.44, 3.22, 0	2, 3.22, 0	2, 2, 0	4.44, 2, 2.44	2, 3.22, 0
Vertex 3	4.44, 3.22, 0	2, 3.22, 0	2, 2, 0	4.44, 2, 0	4.44, 3.22, 2.44	4.44, 3.22, 0
Vertex 4	4.44, 3.22, 2.44	2, 3.22, 2.44	2, 2, 2.44	4.44, 2, 2.44	2, 3.22, 2.44	4.44, 2, 0

Table 3.10: Properties of Fenestration Surfaces

PARAMETER	NORTH WINDOW 100%	SOUTH WINDOW 100%	NORTH DOOR	NORTH WINDOW 50%	SOUTH WINDOW 50%
Surface Type	Window	Window	Door	Window	Window
Construction Name	SINGLE PANE WINDOW	SINGLE PANE WINDOW	DOOR	SINGLE PANE WINDOW	SINGLE PANE WINDOW
Building Surface Name	NORTH WALL	SOUTH WALL	NORTH WALL	NORTH WALL	SOUTH WALL
View Factor to Ground	0.5	0.5	0.5	0.5	0.5
Shading Control Name	-	-		-	
Frame and Divider Name	-	-		-	
Multiplier	1	1	1	1	1
Number of Vertices	4	4	4	4	4
Vertex 1	4.29, 3.22, 1.7	3.39, 2, 1.7	2.79, 3.22, 1.7	4.07, 3.22, 1.7	3.61, 2, 1.7
Vertex 2	4.29, 3.22, 0.8	3.39, 2, 0.8	2.79, 3.22, 0	4.07, 3.22, 0.8	3.61, 2, 0.8
Vertex 3	3.39, 3.22, 0.8	4.29, 2, 0.8	2.15, 3.22, 0	3.61, 3.22, 0.8	4.07, 2, 0.8
Vertex 4	3.39, 3.22, 1.7	4.29, 2, 1.7	2.15, 3.22, 1.7	3.61, 3.22, 1.7	4.07, 2, 1.7

Table 3.11: Properties of Shading Surfaces

Parameter	SOUTH OVERHANG	WINDOW
Building Surface Name	SOUTH WALL	NORTH WALL
Transmittance Schedule Name	ShadeTransSch	ShadeTransSch
Number of Vertices	4	4
Vertex 1	4.44, 1.6, 1.7	2, 3.62, 1.7
Vertex 2	4.44, 2, 1.7	2, 3.22, 1.7
Vertex 3	3.24, 2, 1.7	4.44, 3.22, 1.7
Vertex 4	3.24, 1.6, 1.7	4.44, 3.62, 1.7

3.4.2.1.5 Air Flow Systems

The characteristics that affect the airflow system of the models such as design flow rate calculation method, ventilation type, fan pressure rise, fan total efficiency are described in this section. The number of air changes per hour (ACH) was adopted as the design flow rate calculation method. Flow systems for both zone ventilation and infiltration were modelled. Zone ventilation is the purposeful flow of air from the outdoor environment directly into a thermal zone to provide non-mechanical cooling.

For the exhaust ventilation type the conditions of the air entering the zone was assumed to be equivalent to the outside air conditions. For the intake ventilation, energy plus adds an appropriate amount of fan heat to the air stream. Energy Plus used the ACH in conjunction with zone volume to determine the maximum design flow rate. The ventilation and the infiltration were both controlled by a schedule

3.4.3 EnergyPlus Thermal Simulations

Separate simulations of the control and the test models were run using the weather file for Kumasi. The period for the simulation was from the month of November to March inclusive, a total of 212 days. The period represents the warmest months in Ghana (Amos-Abanyie, 2006). This period was chosen as the design assessment period to obtain results that represents a high percentage of the cooling requirements as done by Kolokotroni and Arronis (1999). In practice cooling takes place virtually the entire year in Ghana depending on the level of activity, thermal and operational characteristics of a building and the cooling setpoint temperature assumed. The inside surface temperatures and the zone air temperatures were generated at 10 minute interval for the entire simulation and the validation.

The predicted mean indoor air temperature and the mean radiant (surface) temperature of the control and the test models were generated in an HTML format to enhance their analysis. The mean indoor air temperature was used for the evaluation of the models. The mean radiant (surface) temperature together with the mean indoor air temperature was used for the validation of the predicted (simulation) results.

3.4.4 Performance evaluation of Simulation models

The performance of the test models was evaluated using that of the control model as a baseline. Performances of the different models were rated by evaluating three variables: (1) the maximum temperatures difference, (2) the temperature difference ratio (TDR) and (3) the percentage of overheated hours (La Roche/Milne, 2004).

3.4.4.1 Temperature Differences

An indication of reduction of cooling load was obtained by calculating the indoor air temperature reduction resulting from a given model. This is because energy gains due to night ventilation is mainly a function of the potential reduction of indoor air temperature compared to the case of none night ventilated model. When the temperature reduction is high, the peak demand is delayed, and thus cooling load of a building is lower (Geros et al., 1999). The temperature difference between a test model and the control model was indicative of the performance of the test model. A comparison of the drop in the peak indoor temperature between various test models and the control model was made. The higher the drop in the peak indoor temperature of a test model, the better was its performance.

3.4.4.2 Temperature Difference Ratio (TDR)

The test models were also compared with each other using the TDR. This concept was proposed by Givoni and has been used with good results to compare passive cooling systems with different configurations (La Roche and Givoni, 2002; La Roche and Milne, 2004). TDR was calculated using the following expression:

$$TDR = (T_{maxout} - T_{maxin}) / (T_{maxout} - T_{minout}) \quad \text{……………………… Eqn 3.1}$$

Where:

TDR = temperature difference ratio,
T_{maxout} = maximum temperature outside,
T_{maxin} = maximum temperature inside and
T_{minout} = minimum temperature inside.

The numerator is the difference between the indoor maximum temperature and the outdoor maximum, and the denominator is the outdoor temperature swing. The higher the value of the TDR, the better will be the performance of a test model. A higher value indicates that there is a larger temperature difference between outdoors and indoors and there is more cooling. TDR is expressed as a percentage and the value cannot be higher than 1.0. The relation between window-to-floor-ratio (WFR) and TDR was used to derive an expression to predict maximum indoor air temperature.

3.4.4.3 Percentage of overheated hours and thermal comfort

The number and percentage of overheated hours beyond the comfort band for each model was assessed. The comfort band proposed by Givoni (1992) of between 18 and 29°C was used. Mean maximum temperature for a given day that fell within the range of the comfort band was considered comfortable, and a mean maximum temperature above 29°C was considered hot or uncomfortable. The number of hot and comfortable hours and their distribution permitted the examination of the overall pattern of temperature in the experimental models. The most important of these factors is the number of hot hours in each model because they negatively affect comfort in the warmest period and subsequent higher cooling load requiring the operation of a mechanical cooling system.

A matrix made up of 24 rows that represent each hour of the day and a number of columns equal to the number of measured days in a series was prepared and used for the assessment of the performance of the models. Each of these cells indicated the average temperature for each hour of each day. The larger the difference in the number or percentage of overheated hours between a given test model and the control model the better was the performance of the model.

3.4.5 Experimental Design

An experiment setup was designed and run from October 2010 to March 2011 and data on indoor air and surface temperatures were monitored and used to validate the predicted (simulated) data. The experimental setup consisting of the following was designed by the author employing Version 2010 of Autodesk Architecture Program: i) two test cells; ii) an active ventilation system consisting of two SIKU FO7 100mm diameter wall fans; iii) HOBO H8 temperature data loggers that recorded indoor air temperature (Figure 3.10); iv) six external thermocouple-type sensors that recorded radiant (surface) temperature (Figure 3.11); and v) a laptop computer connected to the recording instruments which contained control programs that collected and stored experimental data. The layout of the experimental system is shown on Figure 3.12. The design guided the construction of the test cells with the aid of technicians on the premises of the College of Architecture (CAP) at the Kwame Nkrumah University of Science and Technology (KNUST) in Kumasi, Ghana.

Figure 3.10: HOBO H8 temperature sensor / data logger

Figure 3.11: External Thermocouple-Type Sensor for surface temperature measurement

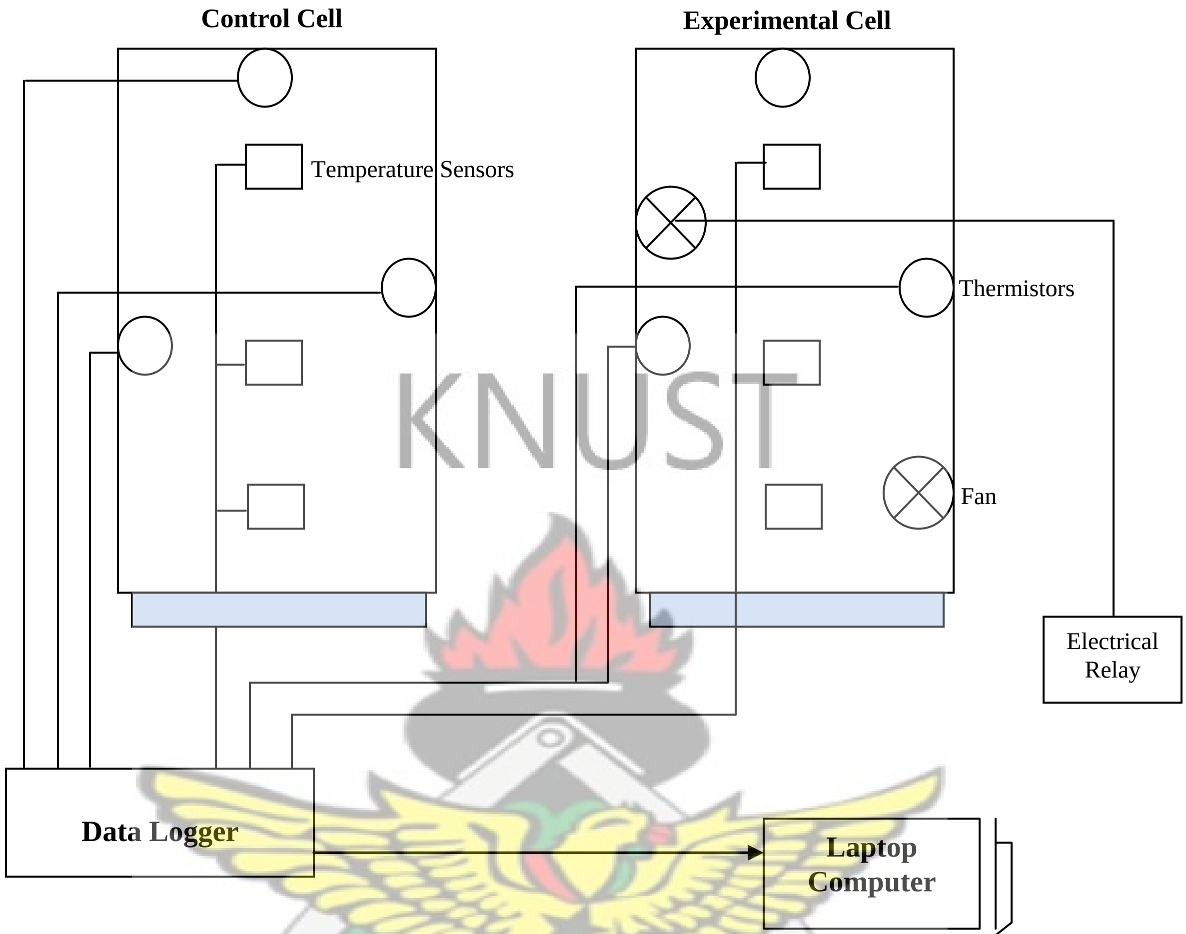


Fig. 3.12: Schematic drawing of the Experimental Setup

Two test cells of the same external dimension as used in the simulation were designed and built by the author, with the aid of technicians. One of the test cells was designed with the specifications of the control model used for the simulations and is referred to as "control cell" and the other with the specifications of the most well performed night ventilated test model (see Section 4.6.1) and is referred to as the "experimental cell".

Two SIKU FO7 100mm fans, one used as intake fan and the other an exhaust fan, were installed in the experimental cell which run to ventilate the cell at night. The intake fan was installed in the south facing wall of the experimental cell and the exhaust fan in the north facing wall. The fans were turned on at 19:00 hours (evening) of a day and turned off the following day at 07:00 hours (morning) by a research assistant who lived in a hostel close to the academic area of KNUST .

3.4.6 Air and radiant temperature data monitoring

Indoor air temperature in the cells were monitored with three HOBO H8 temperature data loggers that were placed at different heights in the middle of each cell (see Figure 3.13), as done by La Roche and Milne (2004). The radiant (surface) temperatures were monitored using external Thermocouple-Type Sensors mounted on the wall and ceiling surfaces of the test cells (Figure 3.14). Both the data loggers and External Thermocouple-Type Sensors were programmed to record data at 10 minutes intervals. The accuracy of the sensors are given in Table 3.12. All the measured data in HOBO format were transferred through a USB to the laptop computer. The data was then exported to Micro Soft Excel for analysis. The indoor air temperature of each test cell was computed as that of the average from the three data loggers. An area-weighted value for mean radiant temperature was calculated as follows (Finn et al., 2007):

$$T_{mr} = \frac{\sum_1^3 T_{sn} A_n}{\sum_1^3 A_n} \qquad \text{………… Eqn 3.2}$$

Where: T_{mr}: mean radiant temperature; T_{sn}: Temperature of a surface; and A_n: area of a surface

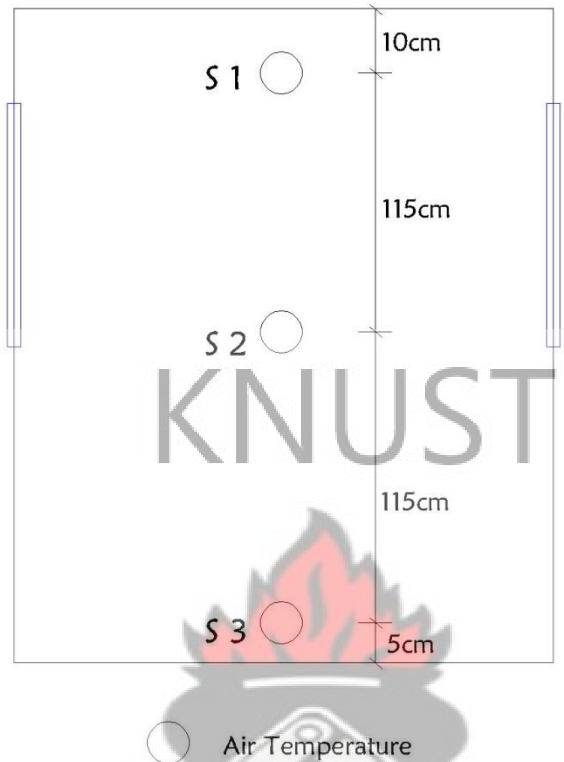


Fig. 3.13: Vertical positioning of Sensors to monitor indoor air temperature

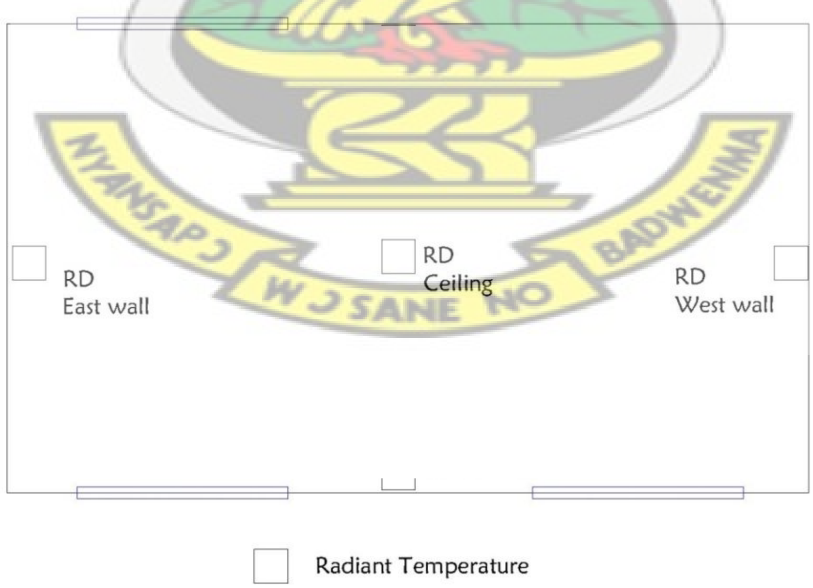


Figure 3.14: Positioning of External Thermocouple-Type Sensors for inside surface temperature

Table 3.12: Accuracy of Sensors (Hobo)

Snesors	Range	Error
Air Temperature	-20 to 70°C	± 0.4°C
External Thermocouple-Type	-40 to 100°C	± 0.7°C at 20°C

(Source: OCR, 2010)

3.4.7 Validation procedure

The measured air and mean radiant temperature were compared with their corresponding values from the simulation model for a satisfactory agreement. The simulated E+ hourly air temperature and mean radiant air temperature data were compared with their corresponding measured values from the experimental cells for a two week period in November 2010 (1^{st} to 14^{th}).

Statistical analysis using the root mean square difference (r^2) and the coefficient of variance of root-mean-squared-error (CV(RMSE)) were done and checked to fall within allowable tolerances. The coefficients of variation of the root mean squared error, CV (RMSE) (%) (Draper and Smith 1981) is essentially the root mean squared error divided by the measured mean of all the data, which is a convenient way of reporting a non-dimensional result. CV (RMSE) allows one to determine how well a model fits the data; the lower the CV (RMSE), the better the calibration.

$$CV(MSE) = [(\Sigma y_{pred,\, i} - \Sigma y_{data,\, i})^2 / (n - p)]^{1/2} / \acute{y}_{data} \times 100 \quad \text{.................Eqn 3.3}$$

where

y_{pred}, i	is a predicted dependent variable value for the same set of independent variables,
y_{data}, i	is a data value of the dependent variable corresponding to a particular set of the independent variables,
$\acute{y}_{data}$	is the mean value of the dependent variable of the data set,
n	is the number of data points in the data set,
p	is the total number of regression parameters in the model (arbitrarily assigned as 1 for all models).

The measured indoor air and radiant temperature from the test cells were used to calibrate the predicted (simulated) indoor air temperature and mean surface temperature. According to Kreider and Haberl (1994), the acceptable range considered appropriate for hourly CV(RMSE) of empirical models is 10 to 20%.

3.5 Chapter Summary

This chapter discussed the philosophical underpinning of the research and the choices made in research strategy, design and methods. In an attempt to better understand the issues at stake in this research, the overall approach to the design process from the theoretical underpinnings to the collection and analysis of the data was carefully done.

The chapter explains the overall process developed to create simulation models that were used for the investigation. To accomplish this, the EP simulation program was used with the reference manual providing a guide in observing mandatory input data syntax. Specification of parameters for model location, thermo-physical properties of basic building materials used and their geometrical configurations are also explained. The criteria employed in evaluating the simulation results to assess the effect of thermal mass, window size and night ventilation are discussed. In an attempt to validate the simulation results, which involve the use of measured data to calibrate the simulated data, an experimental design of test cells was undertaken. The processes involved in the design and construction of the experimental setup are explained. The indoor air temperature of the experimental test cell was measured using U12-006 HOBO H8 data logger and radiant temperature was measured with TMC6-HD external probe sensor.

CHAPTER FOUR

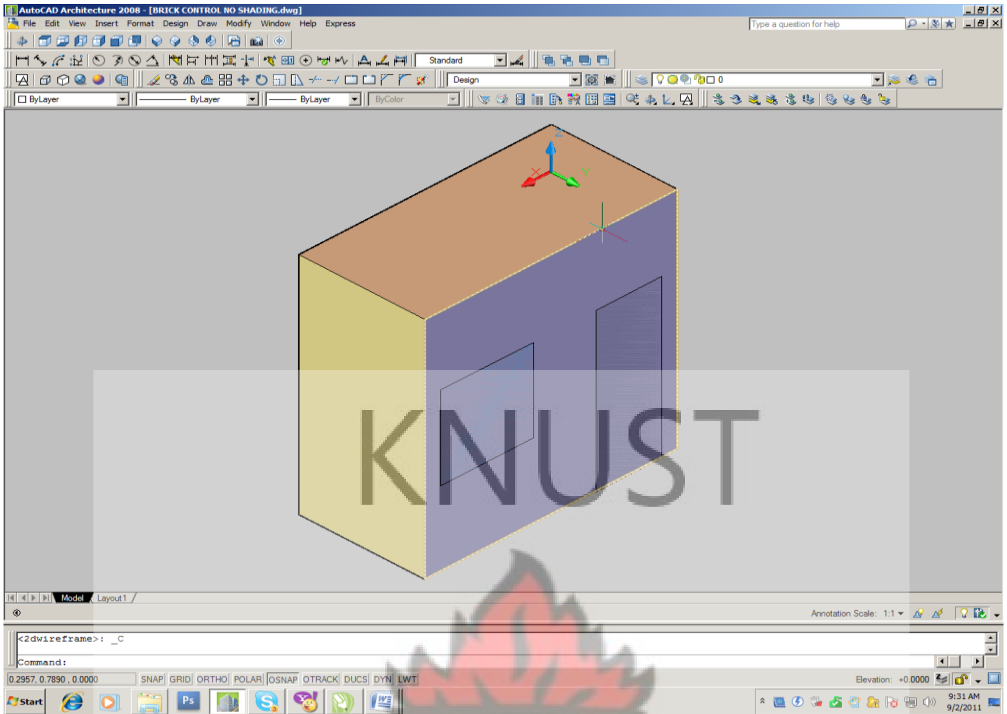
SIMULATION RESULTS, EVALUATION AND DISCUSSION OF FINDINGS

4.1 Chapter Outline

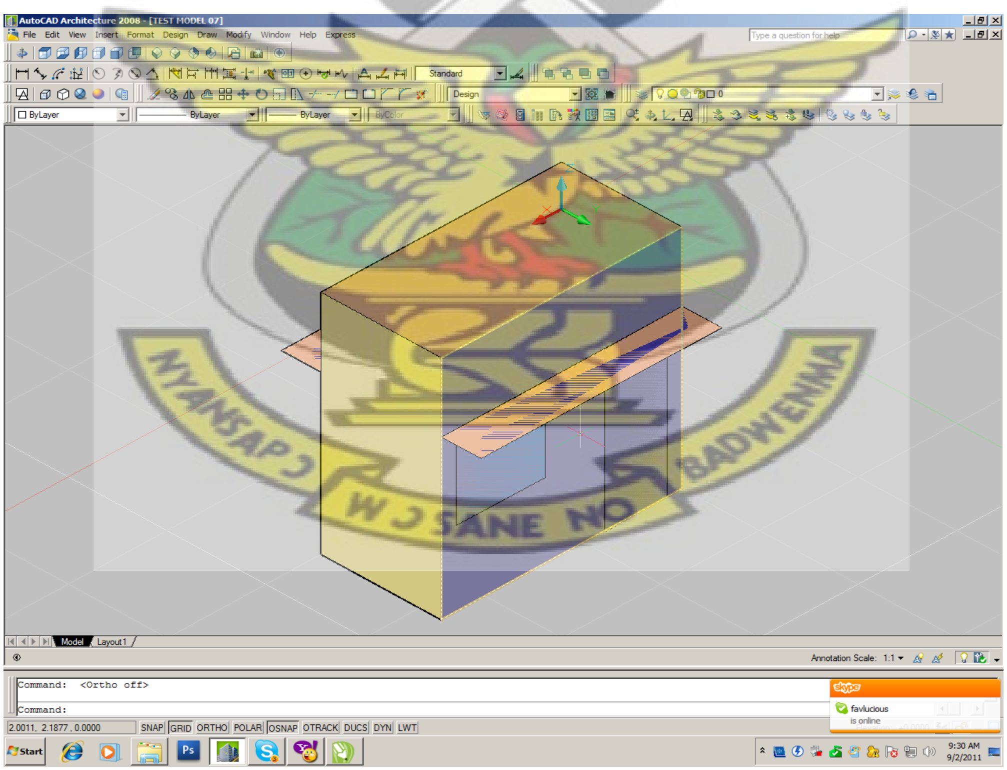
This chapter presents the results of the studies, including the results of the simulations to assess the impact of thermal mass, window size and night-time ventilation and the development of a empirical expression for the maximum indoor temperature of spaces. Results of maximum indoor air temperature, temperature difference ratio and number of overheated hours are also included in this chapter. The simulation results provided the basis for the selection of a test model for the experimental component to validate the simulation results.

4.2 Effect of Thermal Mass on Peak Indoor Air Temperature

The effect of thermal mass on peak indoor temperature was assessed under two scenarios, first with unshaded and closed windows, and then shaded and closed windows. This gave an indication of the effect of shading devices as they form a key element in the control of solar radiation and conductive heat transfer into a space. Each scenario was carried out with a set of three models each with different thermal mass for the walls; solid sandcrete blocks, baked bricks and concrete. The performance of the models was assessed by comparing their maximum indoor air temperatures. Figure 4.1 shows representative models for each of the two scenarios, one with the windows closed and unshaded, and the other closed and shaded.



(a)



(b)

Figure 4.1: CAD representative Model (a) Unshaded windows (b) Shaded windows

Figure 4.2 shows outdoor air temperature and the indoor air temperature patterns for the three models with windows closed and unshaded. The indoor maximum temperatures of all models are above the outdoor maxima of 30.1°C. The temperature elevation of solid sandcrete block model was about 6.9°C above the outdoors' maxima while that of baked brick was about 5.6°C, and that of concrete was about 3.2°C (Table 4.1). The results show a consistency in the temperature increase of the indoor average temperatures for the different mass levels with almost a parallel pattern to the changes in outdoor average temperature.

Table 4.1: Varying thermal mass and their maximum indoor temperature and differences

	MIT[a]		DAO[b]		DBL[c]	
Thermal Mass	unshaded	shaded	unshaded	shaded	unshaded	shaded
Low mass	37.1	35.6	6.9	5.5	-	-
Medium mass	35.8	34.9	5.6	4.8	2.3	0.7
Heavy mass	33.3	32.6	3.2	2.4	3.8	3.0

a = max. indoor –air temperature
b = difference above outdoor–air temperature
c = difference below control model

Figure 4.3 shows the indoor temperature patterns of the models, together with the outdoor temperature pattern and daily averages. With the shaded windows that are closed day and night the indoor maximum temperature of the solid sandcrete block model is about 5.5°C above the outdoors' maxima, while that of the baked brick model is about 4.8°C above the outdoors' maxima, and of the concrete model is about 2.4°C above the outdoors' maxima (Table 4.1). Thus, increased thermal mass with shaded windows has lowered the indoor maxima by about 3.1°C as compared with the conventional model of solid sandcrete block wall.

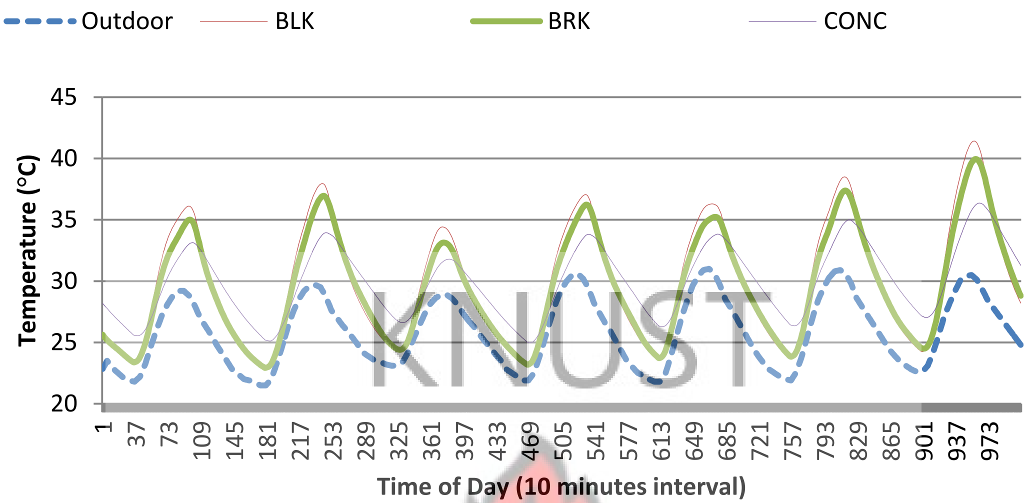


Figure 4.2: Daily outdoor and indoor temperature patterns of the models with windows closed and unshaded.

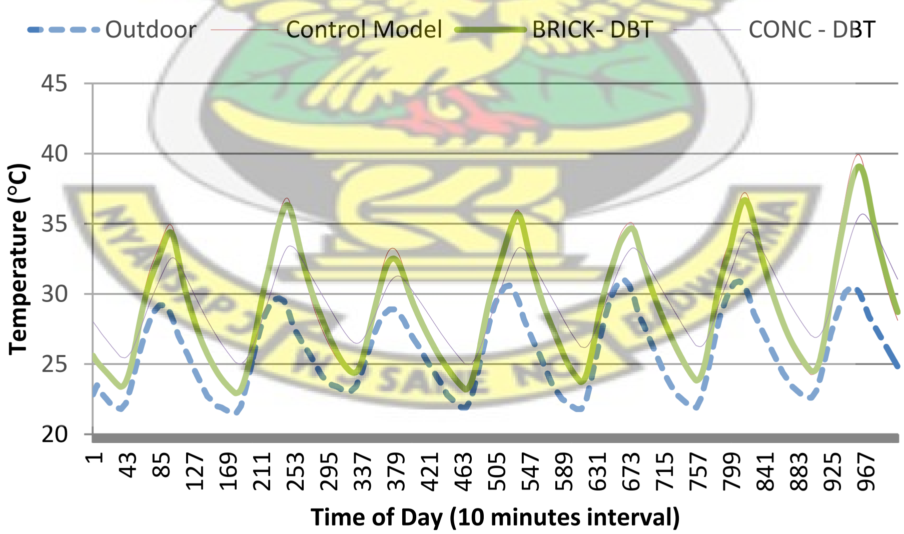


Figure 4.3: Daily outdoor and indoor temperature patterns of the models with windows closed and shaded

The above means that the fixed shading devices are effective in reducing the rise of the indoor temperature caused by penetrating solar radiation through the openings. The above also reveals that at the outdoor maximum of 30.1°C, common on hot days in Kumasi, the indoor temperatures in a high thermal mass building with shading devices will be lower and will therefore have a lower cooling load.

The pattern of the indoor maxima of the solid sandcrete blocks and the baked bricks follows closely the pattern of the outdoor averages as shown in Figure 4.4. However, the daily rate of change of the indoor maximum in the case of the concrete wall model is smaller than the rate of change of the outdoor averages.

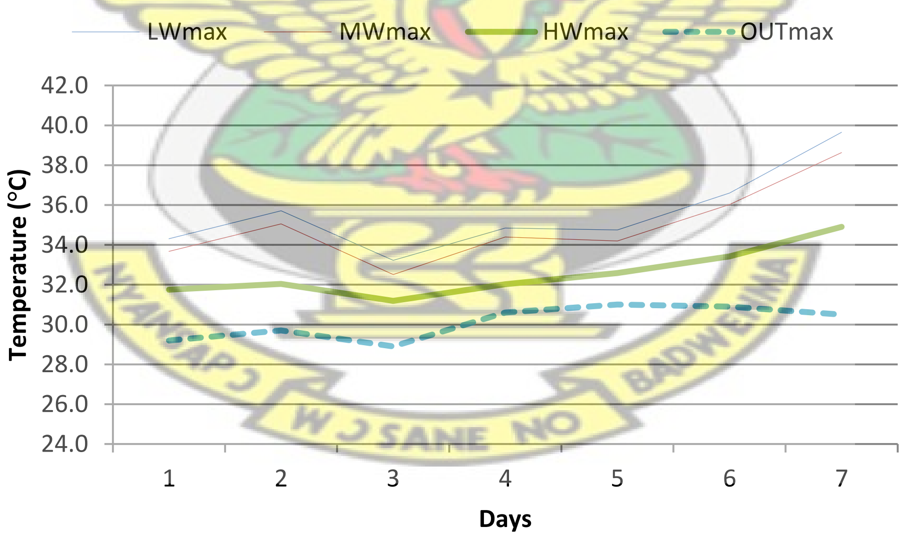


Figure 4.4: Daily maxima of outdoor and indoor air temperatures. Windows closed and shaded

4.3 Effect of window size on peak indoor air temperature

The performance of the different series was assessed by comparing their maximum indoor air temperatures with the maximum outdoor air temperatures over a seven day period (1st to 7th of November) as shown in Table 4.2.

In the solid sandcrete block series, models of window area of 1.62m^2 had a maximum indoor temperature of 35.58 with a difference of 5.44°C above the outdoor maximum temperature of 5.44°C, whilst models with window size of 0.81m^2 and with no window had differences of 4.66°C and 3.67°C respectively above the outdoor maximum temperature.

In the series with baked bricks and concrete walls, similar observations were made with reduced window size resulting in reduced maximum indoor temperature. The differences above the outdoor maximum temperature showed increasing trend with increased window sizes.

Table 4.2: Maximum indoor temperatures for varying window sizes

Window to floor	Solid Sandcrete Blocks			Baked Bricks			Concrete		
	Max Temp.	**DAO**	**DBL**	**Max Temp.**	**DAO**	**DBL**	**Max Temp.**	**DAO**	**DBL**
54%	35.58	5.44	0.00	34.93	4.82	0.66	32.56	2.45	3.03
27%	34.77	4.66	0.81	34.16	4.04	1.42	32.06	1.95	3.52
No window	33.78	3.67	1.80	33.63	3.52	1.95	31.52	1.41	4.06

DAO = Difference above outdoor maximum temperature
DBC = Difference below Control Model

4.4 Effect of night-time ventilation on peak indoor air temperature

The evaluation of the specific contribution of night ventilation in decreasing the maximum indoor air temperature is assessed in this section. The models developed and discussed in Section 3.4.2 were used in the simulations.

4.4.1 Model 1: Sandcrete block wall with 54% window to floor ratio

In this series, both the control and test models have solid sandcrete blocks and window size of 1.62m^2 or window to floor ratio of 0.54%. Windows of both models remained closed day and night; however, the test model was ventilated at night at a rate of 10ACH. Figure 4.5 shows the variation of the outdoor air temperature and the indoor air temperature of the models. Values of the daytime maximum temperature in the test model followed closely that of the control model. The difference in indoor air temperature between the control model and test models during both day and night were not significant because they both have the same amount of solar gain from same size of windows. The ventilation of the test model at night did not reduce the daytime maximum temperature significantly during the following day because of the low thermal inertia associated with the solid sandcrete blocks which is of low mass. At night the average minimum temperatures of the test model was about 0.8°C lower than that of the control model.

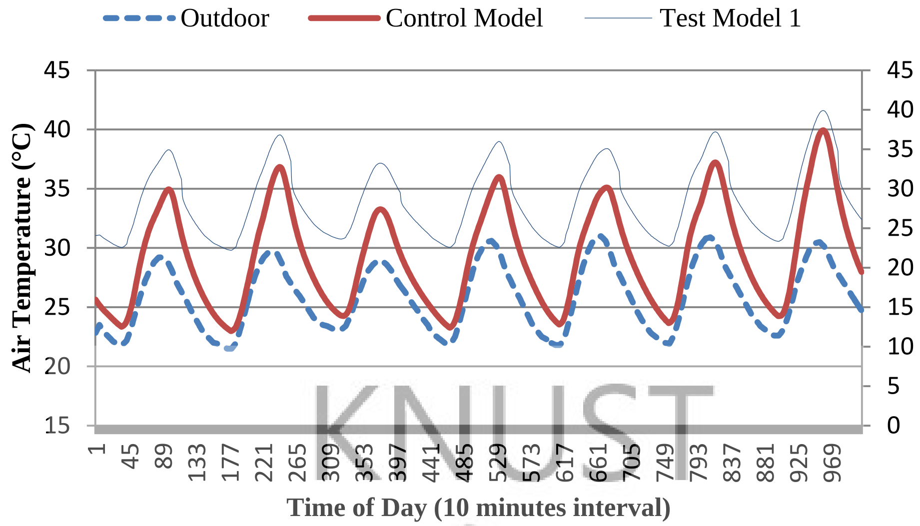


Figure 4.5: Outdoor and indoor air temperatures of model 1 and the control model

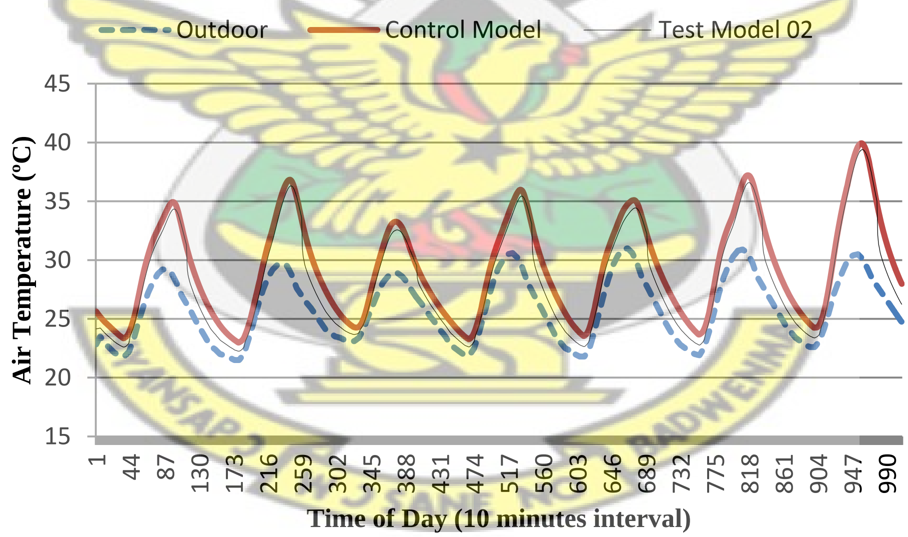


Figure 4.6: Outdoor and indoor air temperatures of model 2 and the control model

4.4.2 Model 2: Sandcrete block wall with 27% window to floor ratio

In this series, the window size of the test model was reduced by 50% of the original size with all other specifications remaining same. The low mass solid sandcrete block was maintained with a night ventilation rate of 10ACH. Figure 4.6 shows the variation of the outdoor air temperature and indoor air temperatures respectively. The maximum temperature in the test model was lower by a small margin of 0.9°C as compared to that of the control model. This could be attributed to the reduced solar heat gain as a result of the reduced size of the windows of the test model. At night the minimum temperature difference of 0.8°C.

4.4.3 Model 3: Sandcrete block with no window

In this series, the window was eliminated in the test model while maintaining the low mass solid sandcrete block and the night ventilation rate of 10ACH. Figure 4.7 shows the distribution of the outdoor air temperature and the indoor air temperatures of the models. Because there is no window in the test model, its maximum temperature was lower than that of the control model. The difference between the maximum temperatures in both test models increased to 1.9°C, compared to 0.9°C associated with model 2. However, the indoor air temperature of the test model was still above the range of the comfort zone.

At night, the minimum temperatures in the test model were lower than that in the control model.

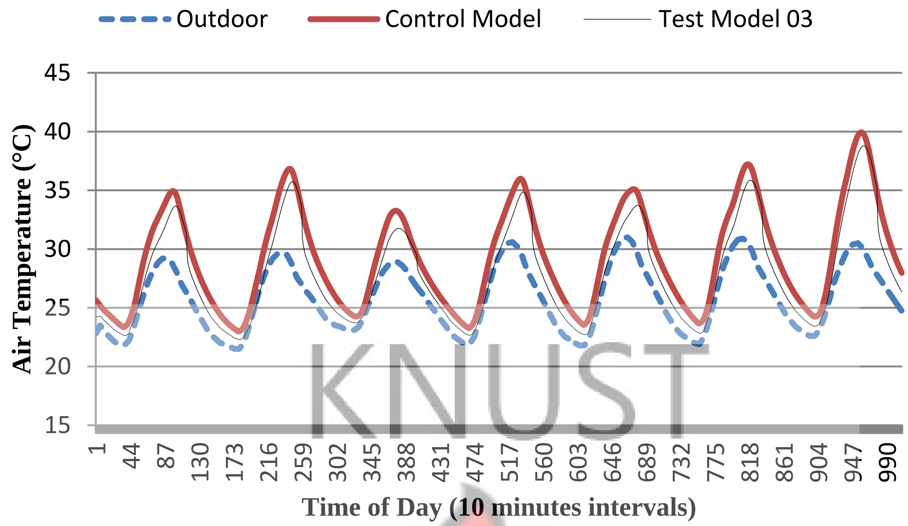


Figure 4.7: Outdoor and indoor air temperatures of model 3 and the control model

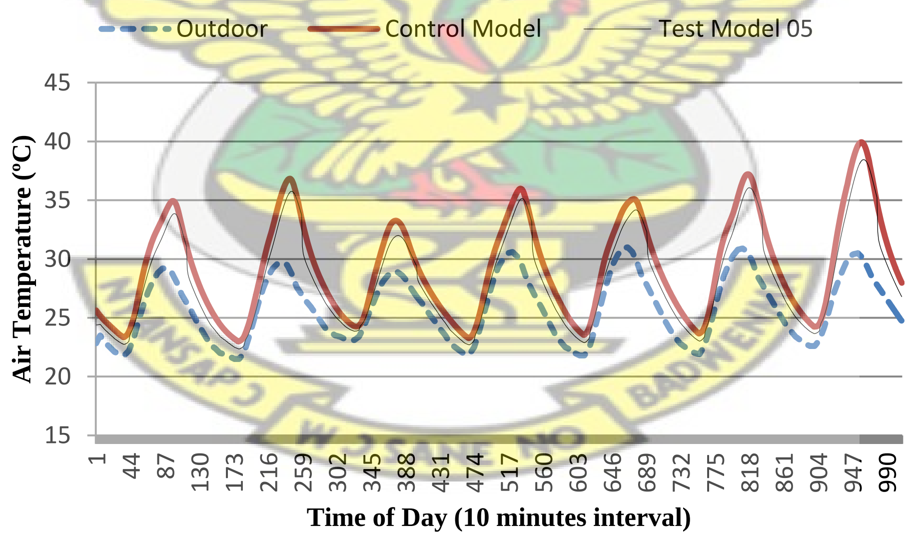


Figure 4.8: Outdoor and indoor air temperatures of model 4 and the control model

4.4.4 Test Model 4: Baked Bricks with 54% window to floor ratio

In this series the test model had medium mass of baked bricks with window to floor ratio of 0.54%. The difference between the maximum temperature in the control model and the test model was 1.0°C. The difference between the daytime maximum temperatures in the control model and the test model can be attributed to the effect of the thermal inertia of the additional mass, which is cooled at night by ventilation. Figure 4.8 shows the distribution of the indoor air temperature of the models in the series and the outdoor air temperature.

4.4.5 Test Model 5: Baked Bricks with 27% window to floor ratio

In this series the window of the test model was reduced to 50% of the original size while the extra mass provided by the medium weight mass was maintained and ventilated at night. Figure 4.9 shows the distribution of the outdoor air temperature and the indoor air temperature of the models. Because the window is smaller, the maximum temperature in the test model was lower than that in the control model and the difference between the maximum temperatures in the models increased to 1.5°C, compared to 1.0°C in the previous series. At night, the average minimum temperature in the test model is lower than that in the control model and closer to the outdoor minimum temperatures.

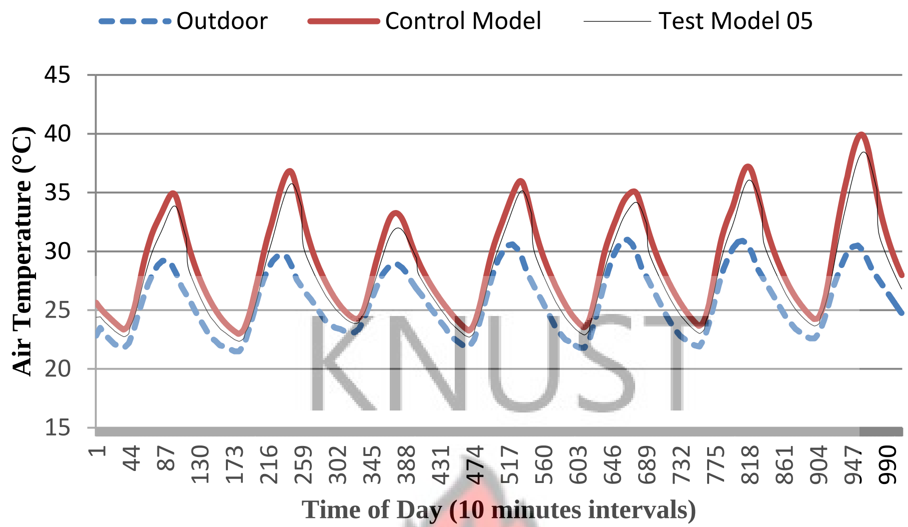


Figure 4.9: Outdoor and indoor air temperatures of model 5 and the control model

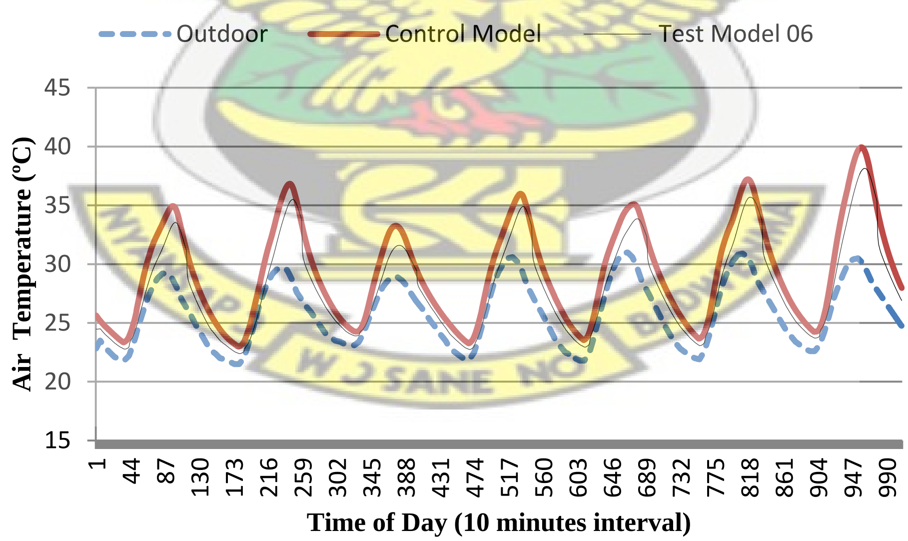


Figure 4.10: Outdoor and indoor air temperatures of model 6 and the control model

4.4.6 Test Model 6: Baked Bricks with no window

In this series the window was eliminated in the test model but was ventilated at night. Figure 4.10 shows the distribution of the outdoor air temperature and the indoor air temperature of the models. Because there were no windows in the test model, its maximum temperature was lower than that of the control cell. The difference between the maximum temperatures in the models increased to 1.9°C, compared to that of control model. At night, the mean minimum temperatures in the test model are lower than those in the control model, but not quite as low as the outdoor minimum temperature.

4.4.7 Test Model 7: Concrete with 54% window to floor ratio

In this series an extra mass was added to the test model by replacing the baked bricks with concrete wall which is a high mass. Both models have window to floor ratio of 0.54%. Figure 4.11 shows the distribution of the outdoor air temperature and indoor air temperature of the models. The maximum temperatures inside the models are wider apart (3.4°C) than in the previous series (1.9°C). Since both models have the same window to floor ratio, the difference between the daytime maximum temperatures in the control model and the test model could be attributed to the effect of the thermal inertia of the mass, which is ventilated at night.

An assessment of a specific day's (November 1) temperature distribution shows that the initial decrease of the indoor temperature combined with the thermal capacitance of the building causes a delay of the peak indoor temperature to about 5 hours after the peak outdoor temperature in the concrete wall models, while the corresponding peak in the control model was close to 2 hours late (Fig. 4.12).

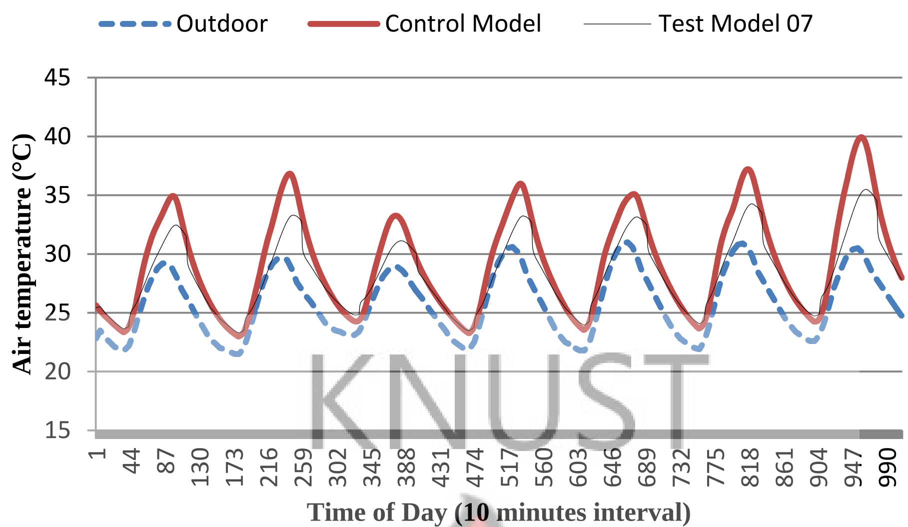


Figure 4.11: Outdoor and indoor air temperatures of model 7 and the control model

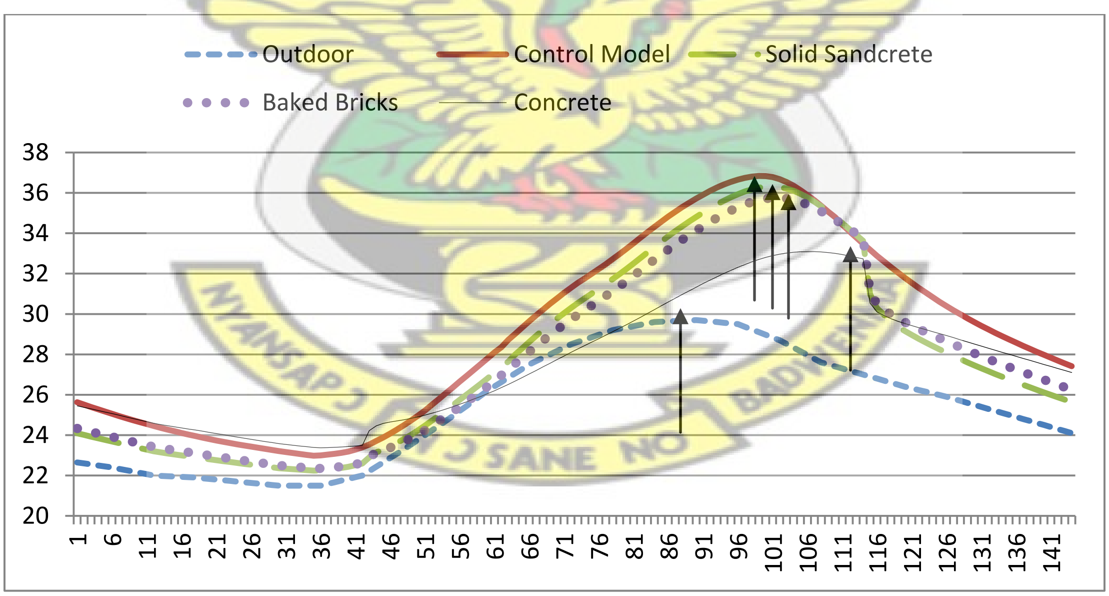


Figure 4.12: Time delay of the maximum indoor temperature by Model 7

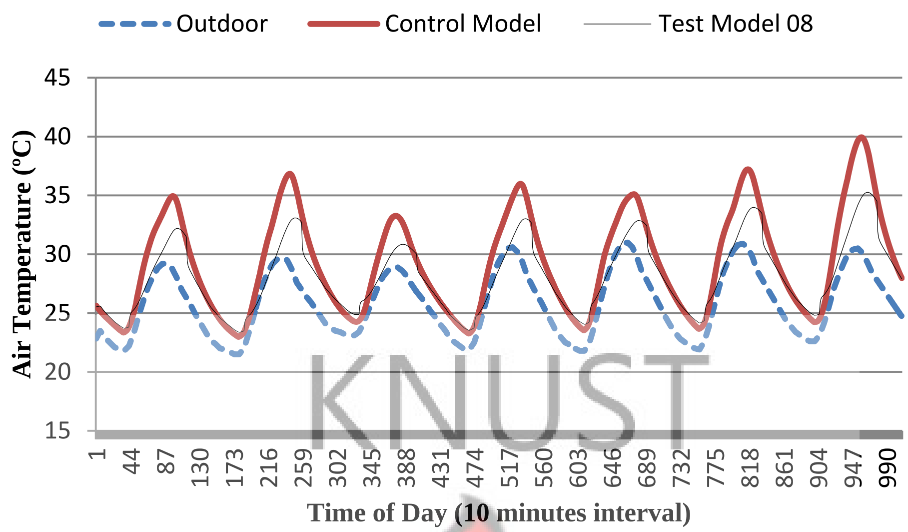


Figure 4.13: Outdoor and indoor air temperatures of model 8 and the control model

4.4.8 Test Model 8: Concrete with 54% window to floor ratio

In this series the window size of the test model is reduced to 50% of the original size while maintaining the extra mass. Figure 4.13 shows the distribution of the outdoor air temperature and the indoor air temperature of the models. Because the window is smaller, the maximum temperature in the test model is lower than in the control cell and the difference between the two models increases to 3.9°C, compared to 3.4°C in the previous series. At night, the minimum temperatures in the test model are always higher than those in the control model by a mean of 0.42°C.

4.4.9 Test Model 9: Concrete with no window

In this series the window was eliminated in the test model as was done for models 3 and 6. Figure 4.14 shows the distribution of the outdoor air temperature and the indoor air temperature of the models. The difference between the daytime maximum temperatures in the control model and the test model is 4.9°C, compared to the insignificant difference observed in the first series. At night the average minimum temperature inside the test model is about 0.5°C higher than in the control model.

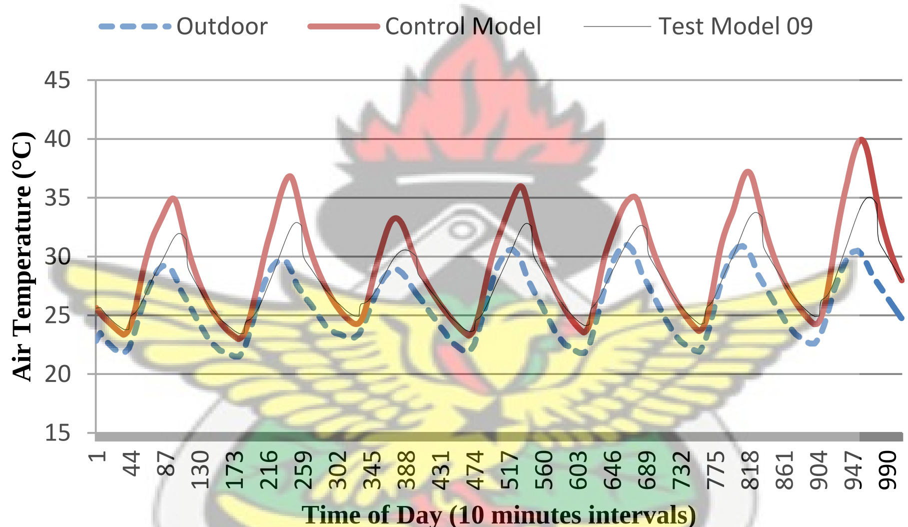


Figure 4.14: Outdoor and indoor air temperatures of model 9 and the control model

4.5 Analyses of Simulation Results

Performance of the simulation models was rated by evaluating three variables: (1) the maximum temperature, (2) the temperature difference ratio (TDR) and (3) the percentage of overheated hours (La Roche/Milne, 2004). In all the models the indoor temperature dropped compared to the control model, regardless of a model's mass, thus lowering also the indoor daily average temperature.

4.5.1 Temperature Difference

The difference between the average indoor maximum temperatures of test models and that of the control model are shown in Table 4.3.

Table 4.3: Average Maximum Temperature in Models and their difference below that of control model

Model	**Base Model**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Mean Max.		35.557	34.735	33.734	34.609	344.130	33.593	32.392	31.873	31.306
Difference*	0.000	0.026	0.849	1.849	0.975	1.453	1.990	3.191	3.710	4.278

*Difference with maximum temperature in control model

Maximum indoor temperatures in the test models were always lower than that of the control model. Therefore the larger the difference between the average maximum in a given test model and the control model, the better will be its performance. It can be seen that the indoor maximum temperature difference in the low mass sandcrete models are the lowest and therefore have lower performance.

The largest difference between the average maximum temperature of the control and a test model is 4.3°C which occurred in Model 9 that has no window and have walls made of concrete (Table 4.11). Test models 3, 6, 7 and 8 also have appreciable differences between their average maximum temperatures and that of the control model, indicating that features in these test models are significant. These features are reduced window size, high thermal mass, and night ventilation. But it is the combination of these features that achieves the improved performance.

4.5.1.1 Impact of varying night ventilation rates

To assess the impact of night ventilation rate, the test models were simulated considering 10, 20 and 30 ACH from 7pm to 7am each night for the period of the simulation. The resulting maximum indoor temperatures are presented in Table 4.4. The highest reduction of the indoor air temperature achieved in the test model due to increased night ventilation rate is close to 0.24ºC. An increase of the air change rate from 10 to 30 resulted in an average decrease of the peak indoor temperature of the building from 0.035 to 0.245°C, respectively.

Table 4.4: Average temperature difference of models with increased air change rate

ACH	Solid Sandcrete Blocks			Baked Bricks			Concrete		
	54%	27%	No Window	54%	27%	No Window	54%	27%	No Window
0	0.000	0.814	1.799	0.948	1.420	1.950	3.025	3.520	4.061
10	0.026	0.849	1.849	0.975	1.453	1.990	3.191	3.710	4.278
20	0.033	0.857	1.860	0.983	1.462	2.001	3.244	3.770	4.345
30	0.036	0.861	1.865	0.987	1.467	2.007	3.270	3.799	4.379

4.5.2 Temperature difference ratio (TDR)

The performance of the models was also compared using TDR. TDR was calculated for the different series and averaged for all the days in each series. Table 4.5 shows the TDR values for various models. All the experimental models had negative TDR values. This indicates that all of them have indoor average maximum temperature higher than that of the outdoors. For all the thermal masses, TDR increased with reduced window to floor ratios, and generally TDR increased for increased thermal mass. Model 9 had the smallest TDR with a performance of over four times that of the control model (Figure 4.15).

Table 4.5: TDR for models at night ventilation rate of 10ACH

Series	Solid Sandcrete Blocks	Baked Bricks	Concrete
Window /floor ratio 54%	-0.69	-0.57	-0.29
Window /floor ratio 27%	-0.59	-0.51	-0.23
No window	-0.46	-0.44	-0.16

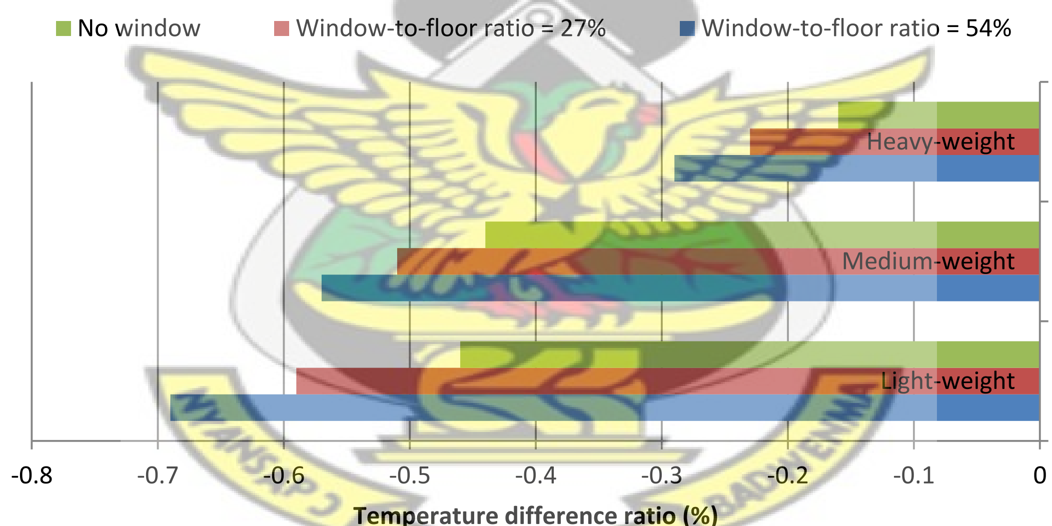


Figure 4.15: Temperature Difference Ratios

4.5.3 Empirical expression for predicting indoor maximum temperature

A common feature noticed from the research with high thermal mass was the tendency of similarity in pattern between the indoor maximum temperatures and the outdoor air temperature patterns. Similar observations were consistently made by Milne and La Roche (2004) in California and Roche (2005) in Lyle Centre in the Cal Poly Pomona.

The correlation between the temperature difference ratio and window to floor ratio for various building masses were determined. The correlation between TDR and window to floor ratio for the different thermal masses provided basis for the development of the predictive expression for the expected indoor maximum temperatures (Figure 4.16). One point for each percentage value of window size in each series is plotted. Each of these points is the average TDR for that percentage of window.

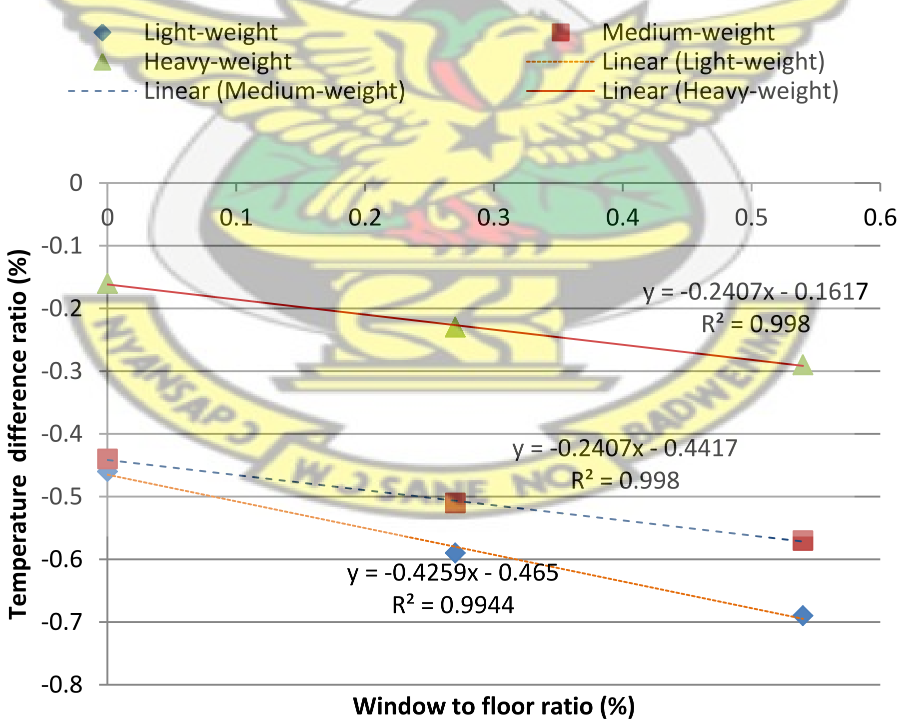


Figure 4.16: TDR as a Function of the Window to Floor Ratio

The correlation for the test model with solid sandcrete blocks at 10 air change rate per hour is:

TDR = -0.4259* SWFR - 0.465 . . . . Equation 4.1

In equation (2) $R^2 = 0.99$

The correlation for the test model with baked bricks at 10 air change rate per hour is:

TDR = -0.2407* SWFR - 0.4417 . . . . Equation 4.2

In equation (3) $R^2 = 0.98$

The correlation for the test model with concrete at 10 air change rate per hour is:

TDR = -0.2407* WFR - 0.1617 . . . . Equation 4.3

In equation (4) $R^2 = 0.998$

In all the above, TDR = temperature difference ratio, WFR = window to floor ratio (north and south window).

When TDR is calculated for a building using either of Equations (2), (3) or (4), it is possible to predict the indoor maximum temperature using Eq. (1) and solving for $Tmax_{in}$, where outdoor maximum and minimum temperatures, or daily temperature swing, must be known.

$$Tmax_{in} = Tmax_{out} - [TDR * (Tmax_{out} - Tmin_{out})]$$ ……………… Equation 4.4

For all thermal masses, as the north and south window to floor ratio increases, the TDR decreases. This implies that the large north and south facing windows reduce the performance of a system that cools with ventilation. These expressions could be used in buildings with the respective thermal masses with shaded north and south windows, of no east and west windows, mass concrete floor construction, and night ventilated at 10ACH to predict maximum temperatures with specific window sizes or to determine maximum window sizes that would achieve a specific performance.

4.5.4 Percentage of Overheated Hours and Thermal Comfort

The number of hours or cells with temperature above 29°C is calculated as the number of overheated hours as in Table 4.6. As presented, the achieved reduction of the overheating hours for solid sandcrete blocks due to night ventilation varies between 36% and 42% for air flow rate of 10 ACH. For baked bricks, the corresponding decrease varies between 37% and 39%, while for concrete, the reduction is between 35% and 39%.

Table 4.6: **Number and percentage of overheated hours for models night ventilated at 10 ACH**

	Solid Sandcrete Blocks		**Baked Bricks**		**Concrete**	
	NOH	POH	NOH	POH	NOH	POH
Control	81	48.2				
Window to floor ratio 54%	69	41.1	66	39.3	65	38.7
Window to floor ratio 27%	65	38.7	65	38.7	63	37.5
No window	62	36.9	63	37.5	60	35.7

4.6 Discussion of Results

4.6.1 Impact of thermal Mass

Analysis of the simulated results shows that increased mass generally led to an improved condition with reduced maximum indoor air temperatures. All the models, both control and test, have indoor maximum air temperatures above the outdoor air-temperature. However, all the test models had improved conditions than the control model, even though varied.

Models with solid sandcrete block walls, had peak indoor temperatures of between 3.58 and 5.38°C above the peak outdoor temperatures. In the test models with baked bricks, the peak indoor temperatures followed closely that of the solid sandcrete blocks with about 3.43 – 4.73°C above that of the peak outdoor temperature, and showed a better performance than the solid sandcrete blocks. The models with concrete walls had the peak indoor temperatures of between 1.32 and 2.36°C above the peak outdoor temperature.

The peak indoor temperatures in the concrete walled models, though still above the peak outdoor temperature, were below that of the control model made of solid sandcrete blocks by a mean of between 3.03 and 4.06°C.

For models with solid sandrete block walls, indoor temperature rises dramatically during the morning (early) hours and reached its maximum in late afternoons. It then cools down rapidly in the evening (late) hours, with a wider fluctuation in diurnal indoor temperature pattern. The temperatures in the solid sandrete block wall models closely followed that of the outdoor conditions and did not offer any significant thermal storage. This is because it is of a low mass material. This observation is similar to observations made by Ogoli (2003) in an architectural science inquiry on four environmental test chambers with different thermal mass level types in Nairobi, Kenya. The models with baked bricks walls have mean indoor patterns that follow closely that of the solid sandcrete blocks but with relatively smaller fluctuations.

In the test models with concrete walls, the moderating effect of thermal mass was noticeable. Because it is of a high mass material, the maximum indoor temperatures are suppressed at daytime and rises slowly to achieve a relatively lower maximum in the late afternoons. The stored heat in the high mass re-radiates back into the space at night and causes much higher minimum temperature during night hours. The observed trend is characteristic of high mass materials, and similar observations were made in Cheng and Givoni (2008) study to investigate the effects of colour and building thermal mass in the hot humid climate of Hong Kong. Indoor temperature fluctuations associated with baked bricks and concrete are kept to a minimum. Generally for this study, higher thermal mass reduced indoor maxima and at the same time brought up indoor minima. However, the influence on maxima was larger than on minima. The second aspect of the influence of thermal mass, in this study is the effect of time lag; heat storage properties of high mass concrete wall delayed the occurrence of peak indoor temperature by a number of hours.

The above indicates that walls made of concrete and baked bricks can maintain more steady indoor temperature with lower fluctuations and postpone the time of occurrence when peak indoor air temperature appears with a longer time lag than solid sandcrete blocks. However, with respect to indoor air temperature and delay of peak conditions, concrete performs better that bakes bricks.

The degree of thermal comfort is usually indicated by the peak indoor air temperature (Geros et al., 1999). With the base temperature of 29°C, the solid sandcrete block wall models had between 58 - 64% of the mean hourly indoor temperatures falling within the comfort zone and the baked brick wall models had between 61 - 63% of the hourly mean indoor temperature within the comfort zone. The concrete wall model, being of a high mass, performed better with 61 - 65% of the mean hourly indoor temperatures falling within the comfort zone.

4.6.2 Impact of window size on indoor air temeprature

The data show no remarkable change in peak indoor temperature for varied window size (window to floor ratio) for all the thermal masses investigated in this study. This can be attributed to the effect of shading devices on the test models which eliminates solar and conductive heat gains through the windows. The effective shading led to marginal effect of the varying window sizes. A study by La Roche and Milne (2004) to quantify the effects of modifying the amount of thermal mass and the window area on indoor comfort using a controller, revealed that an increase rather in the size of unprotected window could decrease the performance of the system. The study confirmed that smaller windows performed better than larger windows.

4.6.3 Impact of varying night-time ventilation rates

The impact of night ventilation was assessed for various air flow rates considering first 10 ACH, then 20 ACH and 30 ACH.. However, night ventilation of BB and CONC exposed them to cool outdoor air to offset the reradiated heat in to space. This provided a relatively lower minimum indoor air temperature at night. The attained low indoor air temperature and cooled mass provided a heat sink that suppressed the rate of indoor air temperature rise and as such the attainable maximum indoor temperature during the daytime.

Unlike a study by Chandra (1989) in the hot-humid climates at the Passive Cooling Laboratory (PCL) in the Florida Solar Energy Centre where increased air exchange rate could lower the average indoor air temperature, the difference in temperature as a result of night-time ventilation between the low mass and the high mass walls for this study was negligible. This could be explained by the relatively lower diurnal temperature range of Kumasi which does not effectively cool the building mass.

4.6.4 Maximum Indoor Temperature Predictive Expression

While the predictive expression developed for indoor maximum temperatures in this research is similar to that by Milne and La Roche (2004) in California and La Roche (2005) in Lyle Centre in the Cal Poly Pomona, differences exist in the gradient and the constants. The differences between the expression of this research and the others can be explained by the fact that i) the studies were done in different climates; ii) the study by Milne and La Roche (2004) was carried out using lightweight walls, shaded north, east and west windows, and slab-on-grade construction to predict maximum temperatures with specific window sizes; and the study by La Roche (2005) was carried out using slab on grade concrete floors with a thickness of 40mm with insulated green roof with different window dimensions.

The variation in the expressions for this study suggests that it is applicable to buildings of envelopes of the respective thermal masses of 150mm thick mass walls, with shaded north and south only windows, and 150mm mass concrete floor construction, and night ventilated at

10ACH in the warm humid climates similar to that of the Ashanti Region of Ghana. For all the expressions, as window to floor ratio increased, the temperature difference ratio decreased.

Figure 4.17 shows the measured data side by side with the results computed with the expression for predicting indoor maximum temperature in buildings with concrete wall in this study. The computed indoor maximum temperatures using the expressions and the measured data are close with a good agreement between the two.

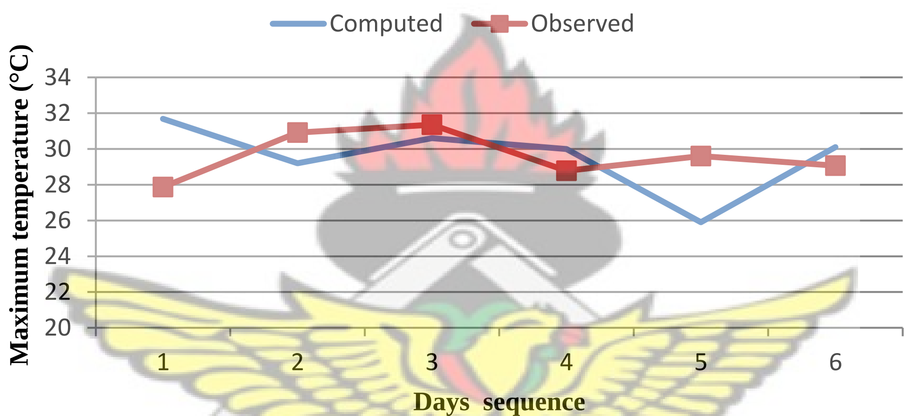


Figure 4.17: Measured and Computed Maximum Indoor Temperatures in cells with Concrete Wall

In LaRoche and Milne (2005) study when the south window to floor ratio was of a minimum of 11% and above the conditions inside the control cell, with a fixed infiltration rate, were the average indoor air temperature higher (worse) than that of the average outside air temperature. However, with this research no trend line strikes the positive window to floor area axis, it means that for all the wall envelope materials considered in this study, conditions inside the models would always be higher (or worse) and above the average outdoor temperatures even when there are no windows. This could be attributed to differences in thermal properties of the materials and climatic conditions associated with this study and that of LaRoche and Milne (2005).

4.7 Chapter Summary

The chapter presented the results obtained from investigations using the energy plus simulation program. The procedure used in creating models of varying thermal mass and window sizes have been presented. In creating the models, several carefully selected input parameters were used to obtain models that accurately represented the mode of building design and construction in Kumasi. Those parameters included that of simulation control, site location and climatic parameters, simulation schedules, surface construction elements with the thermo-physical properties of the basic construction elements that were used. Others were the zone geometrical descriptions such as the physical make-up and orientation of the surfaces of the models, and the zone air flow systems. The effect of thermal mass, window size and night ventilation were evaluated using three variables: (1) the maximum temperatures, (2) the temperature difference ratio (TDR) and (3) the percentage of overheated hours.

Based on the results of the simulations of this research, it was found that models of all thermal masses investigated have higher peak indoor air temperature than the outdoor air temperature. However, peak indoor air temperature generally dropped with increased thermal mass. Models with concrete wall achieved a delay in peak indoor air temperature of about 5 hours after the peak outdoor air temperature, while that of solid sandcrete blocks and baked bricks ranged between 2 to 3 hours. Using a base temperature of 29°C, the concrete walled model have 61 to 65% of the mean hourly indoor temperature fallen within the comfort zone, while that of solid sandcrete blocks and bake bricks were between 58 – 64 and 61- 63% respectively.

Peak indoor air temperature for all the thermal masses decreased with increased window sizes. However, the effect of varying window sizes was not remarkable when the windows were shaded from the effect of solar radiation. The above implies that with effective shading, windows size does not impact on peak indoor air temperature, as the impact of solar radiation transmitted through windows are eliminated.

The impact of night ventilation rates were negligible were assessed for various air flow rates considering 10, 20 and 30 ACH. The difference in temperature as a result of night-time ventilation between the low mass and the high mass walls was negligible.

The research revealed that thermal mass, window size and night-time ventilation have varied effects in reducing the peak indoor air temperature. However, the three provided a synergistic effect in reducing the peak indoor air temperature. The correlation between temperature difference ratio and window to floor ratio was used to develop an expression that can be used to predict the peak indoor temperature for a given thermal mass, when the peak outdoor temperature and temperature swings are known.

CHAPTER FIVE

VALIDATION OF PREDICTED (SIMULATED) RESULTS

5.1 Chapter Outline

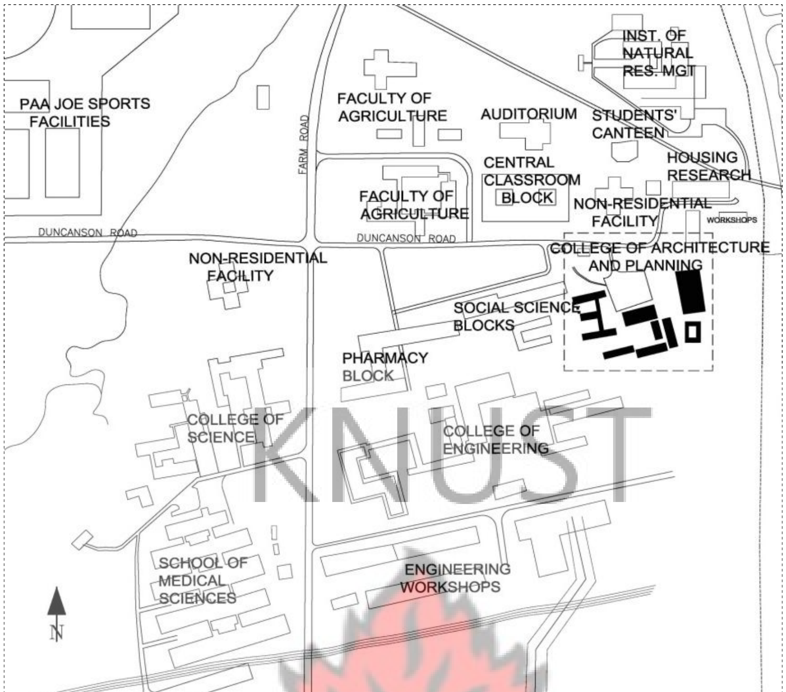
The chapter outlines the description of the experimental setup, data monitoring and validation of the simulation results.

5.2 Location of test cells

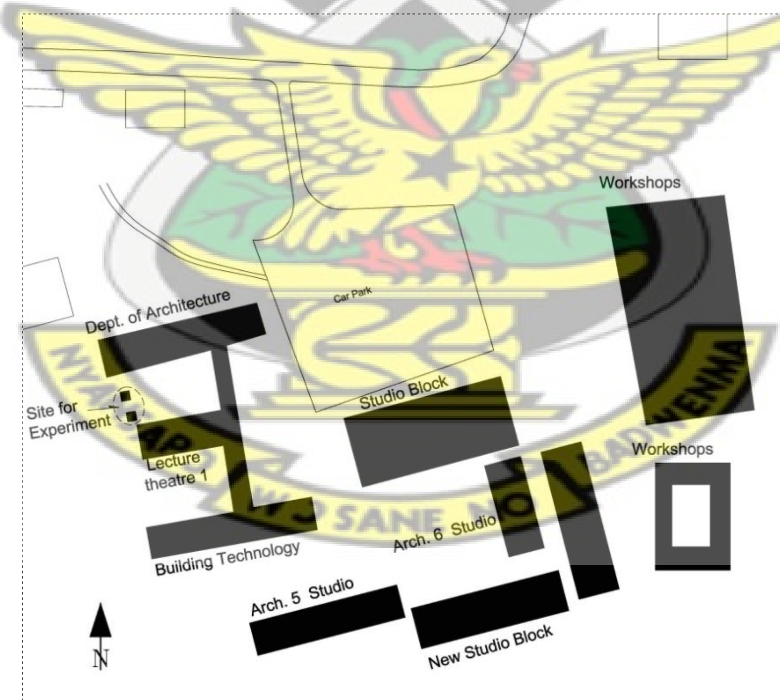
The experimental cells were constructed on the premises of the College of Architecture and Planning (CAP) at the Kwame Nkrumah University of Science and Technology (KNUST) in Kumasi, Ghana. Figure 5.1a is a location map showing the academic area of KNUST. Figure 5.1b shows a more detailed view of CAP with the experimental site. Figure 5.2 is a picture of the test cells taken from the top floor of the Administration Block of CAP. Attention was paid to the choice of location for the test cells to avoid over-shadowing by adjacent buildings which could affect the results of the study.

5.2.1 Design and Construction of Test Cells

Both test cells are oriented on the North-South azimuth (the east walls face due East, the north walls face due North, etc.). Orthographic projections of the test cells are shown in Figure 5.3(a-e). A horizontal shading device was placed above each bank of openings on the north and the south walls.



(a)



(b)

Figure 5.1: Location Map of Experimental Site. (a) Overview of Academic area of KNUST, (b) College of Architecture and Planning.

Figure 5.2: Picture of Experimental Test Cells

The walls of the control cell are composed of 25mm thick cement-sand external rendering, 150mm thick cement-sand-aggregate mix of 1:3:5 ratio mass concrete and a 25mm interior rendering as shown in Figure 5.4a.The walls of the experimental cell composed of 25mm thick cement-sand external rendering, 150mm thick cement-sand-aggregate mix of 1:3:5 ratio mass concrete and a 25mm interior rendering as shown in Figure 5.4b. The roof section in Figure 5.4c is constructed with a 25mm thick cement-sand exterior rendering, 150mm thick cement-sand-aggregate mix of 1:2:4 ratio reinforced concrete, and a dropped ceiling of acoustic panels for both cells. The floor consists of 50mm cement-sand screed on 150mm thick cement-sand-aggregate mix of 1:3:5 ratio mass concrete as shown in Figure 5.4d for both cells. Computed aided design generated three-dimensional views are presented in Figure 5.5. Figure 5.6 captures some of the construction activities of the test cells.

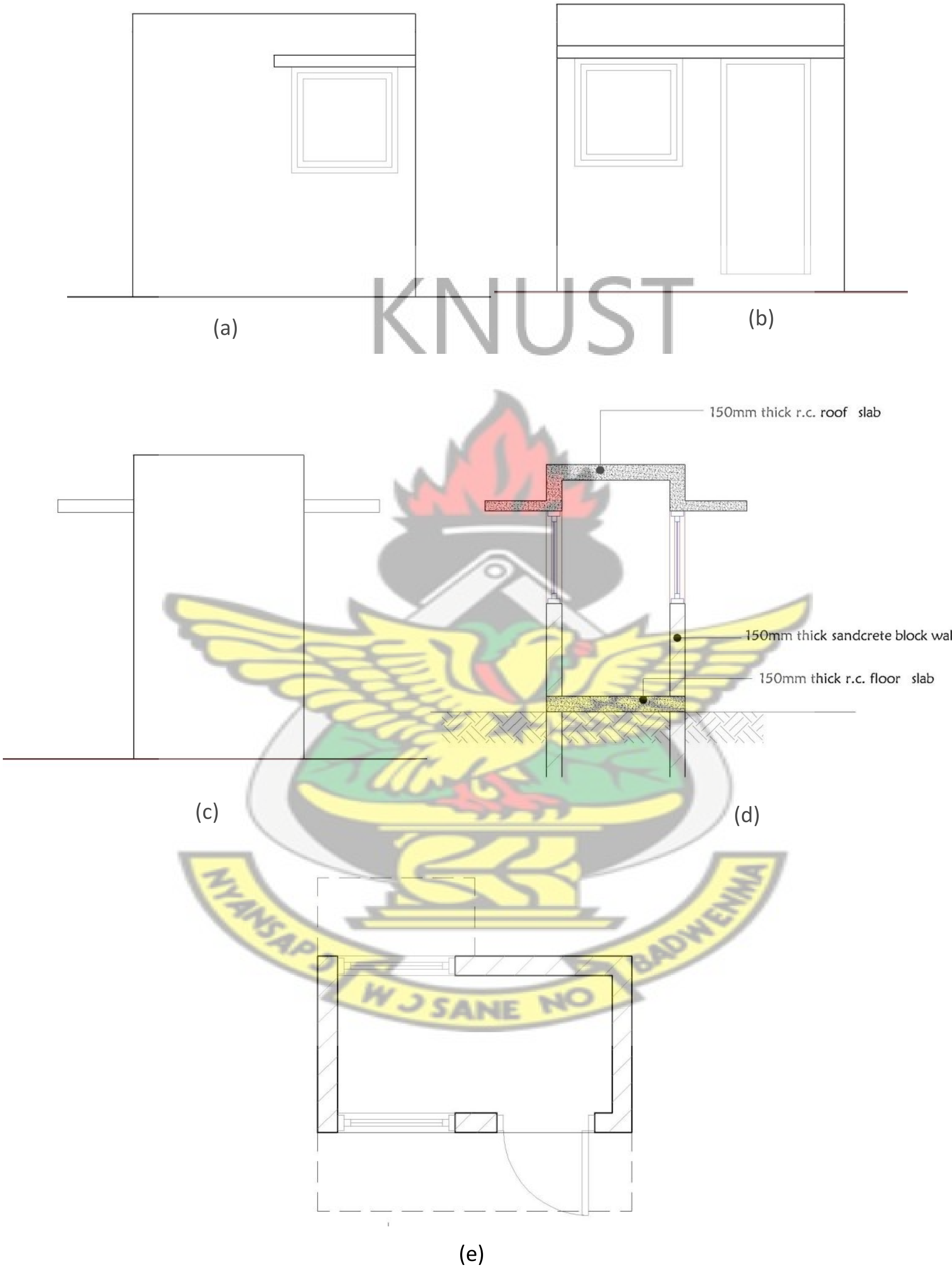


Figure 5.3: Orthographic Views. (a) South, (b) North, (c) East/West, (d) Section, (e) Plans

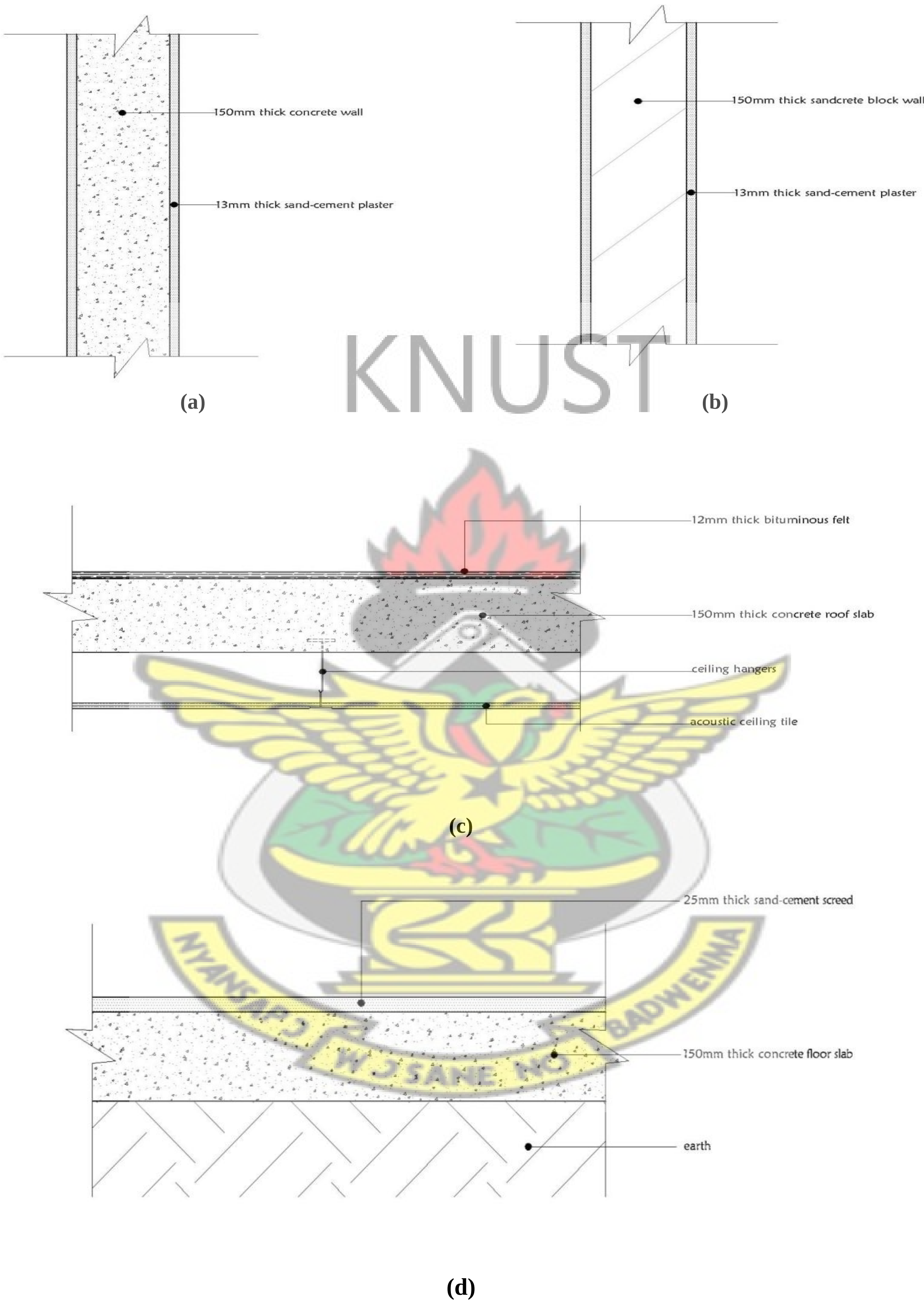


Figure 5.4: Construction Sections, (a) Concrete Wall Section, (b) Sandcrete Wall Section, (c) Roof Section, (d) Floor Section.

(a)

(b)

Figure 5.5: CAD generated 3D impressions of model. (a) North-east View, (b) South-west View

Figure 5.6: Construction of the Test Cells

5.2.2 Ventilation System and Schedule

An intake fan was installed in the south wall and an exhaust fan in the north wall of the experimental cell. The fans (Figure 5.7 and 5.8) were operated to ventilate the test cell each night from 7 p.m. till 7 a.m. (local time). The control cell was however not ventilated at night. The windows of both cells remained closed 24hours in a day as practiced in air conditioned office buildings.

Figure 5.7: Completed Test Cells with Installations

(a) (b)

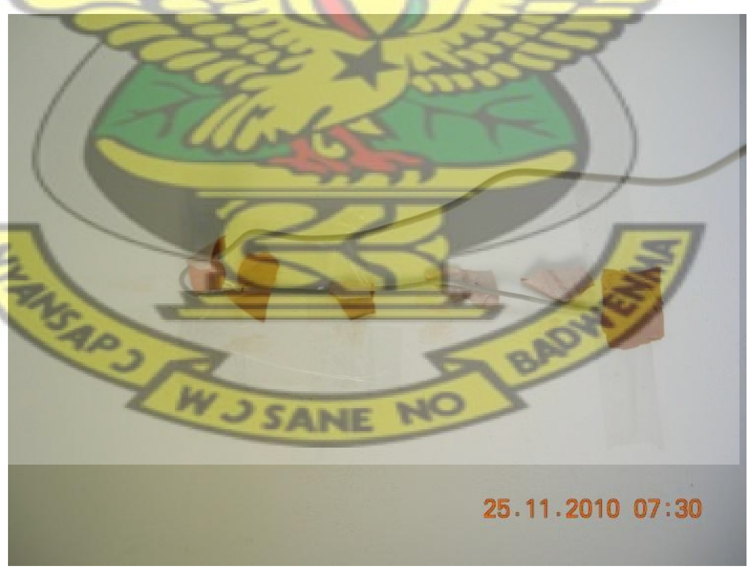
Figure 5.8: (a) Intake Fan and (b) Exhaust Fan

5.3 Air and radiant temperature data monitoring

Three sensors were positioned in the centre of each cell (control and experimental) to record air temperature at 10 minutes interval. In each cell the sensors (thermistors) were placed in the middle of the cell, but at different heights (La Roche/Milne, 2004). The lowest one was 5cm above the floor, the middle one at 1050 cm and the highest one at 2050cm, which is 10 cm below the ceiling. The indoor temperature data was calculated as the average of the readings of the three sensors measuring the indoor air temperature. Radiant temperature was obtained by recording the wall and ceiling surface temperatures by means of three External Thermocouple-Type sensors. Figures 5.9(a-c) illustrates the mounting of sensors, External Thermocouple-Type sensors and data loggers in the test cells.

(a)

(b)



(c)

Figure 5.9: Mounting of recorders (a) Sensors; (b) Data Loggers; (c) External Thermocouple-Type sensors

All the measured data were transferred through a USB to the laptop computer for the analysis. The data was then exported to Micro Soft Excel for analysis. The indoor air temperature of each test cell was computed as that of the average from the three data loggers. An area-weighted value for mean radiant temperature based on the three measured surfaces was calculated using equation 3.2 discussed in Section 3.7.1. The details are in Appendix 7.

5.4 Validation of the simulation results

Figures 5.10 and 5.11 illustrate segments of measured versus simulated indoor air temperature and mean radiant temperature respectively. In addition, Figures 5.12 and 5.13 provide an overview of the relationship between measured and simulated (in terms of regression lines) indoor air temperature and mean radiant temperature respectively. Predicted values of the simulation models compared well with the measured values. The respective correlation coefficient values are summarized in Table 5.1. In terms of statistic analyses, root mean square difference (r^2) were 0.8% and 0.83 for indoor air temperature and mean radiant temperature respectively; and Coefficient of Variation for the Root Mean Squared Error (CV (RMSE)) were 14.75% and 16.80% for indoor air temperature and mean radiant temperature respectively, and were statistically inappropriate.

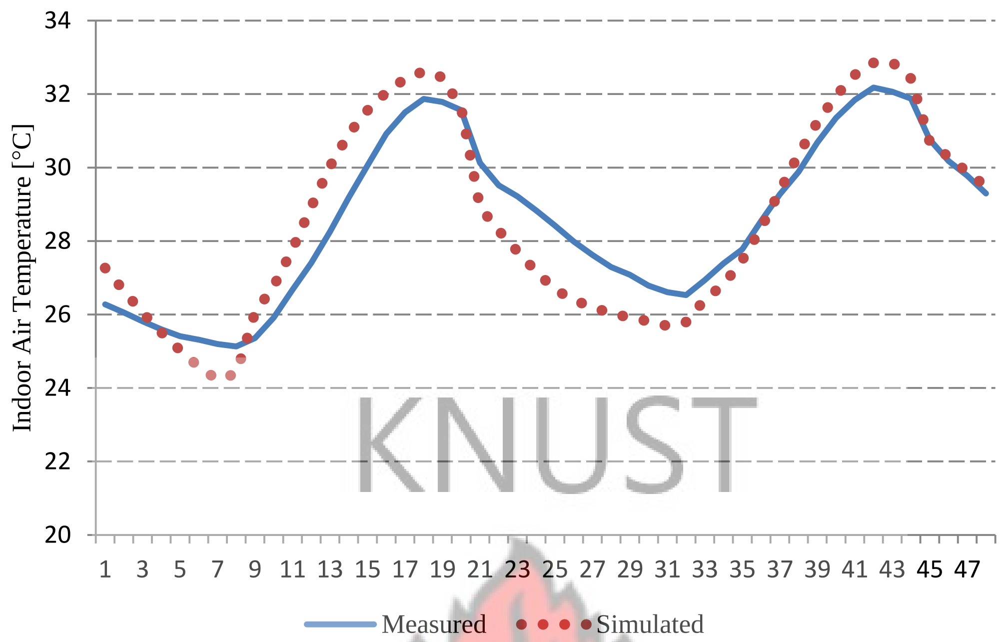


Figure 5.10: Measured versus simulated indoor air temperatures

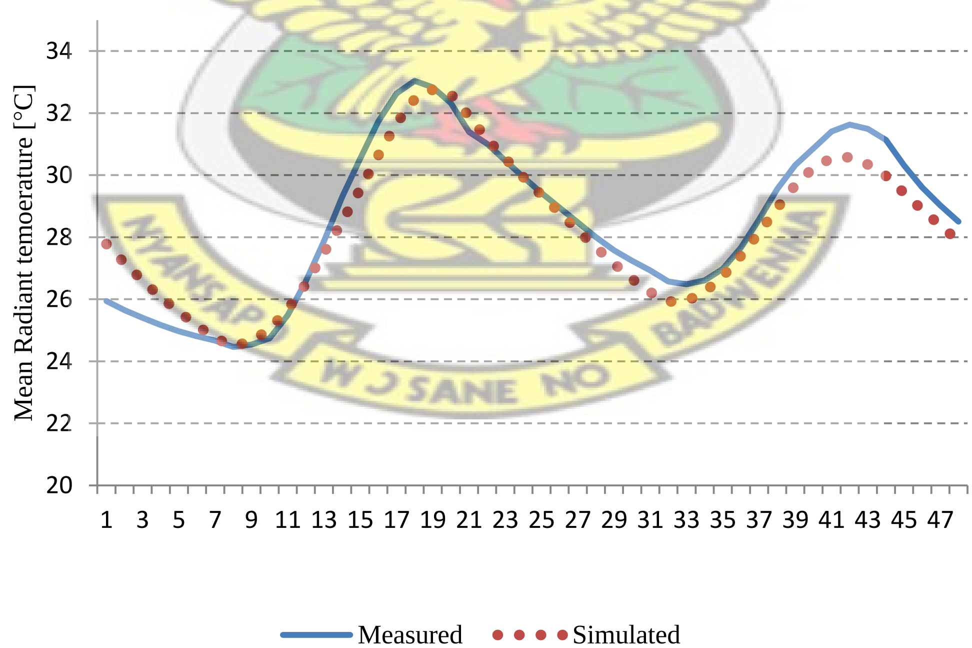


Figure 5.11: Measured versus simulated indoor air temperatures

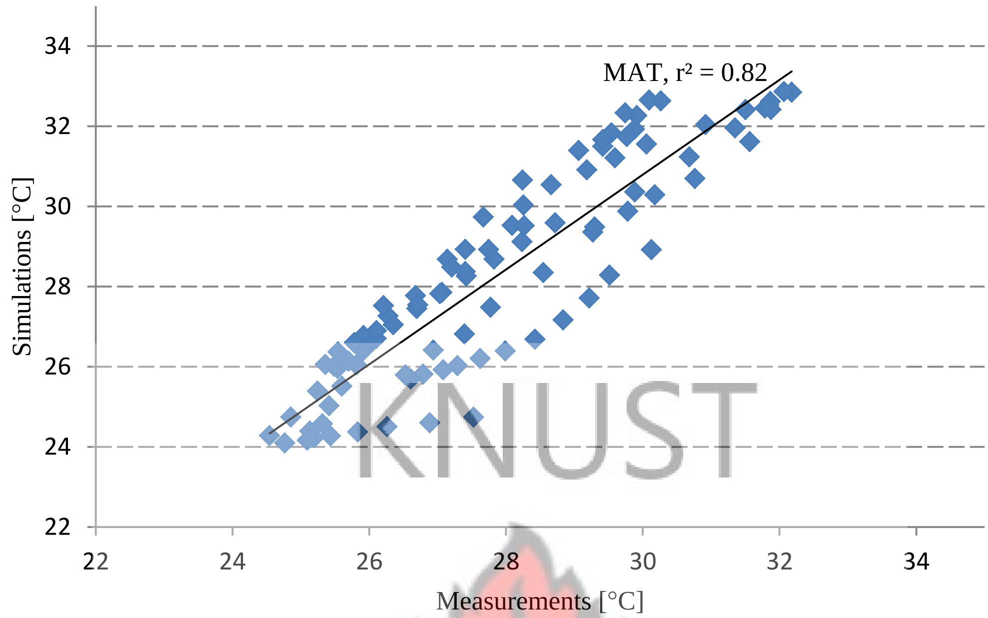


Figure 5.12: Relationship (regression lines) between measured and simulated indoor air temperatures

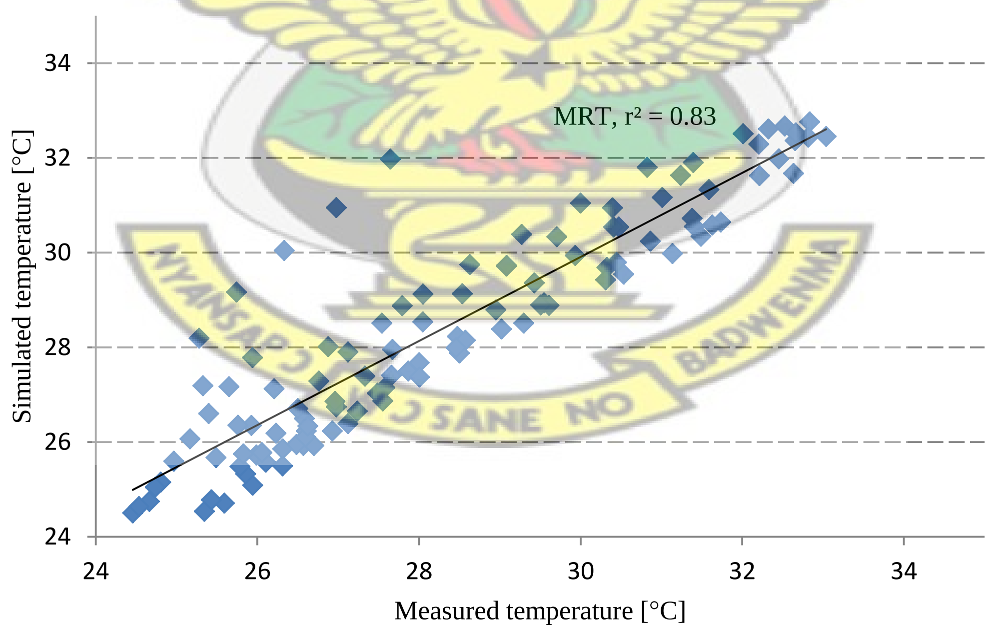


Figure 5.13: Relationship (regression lines) between measured and simulated mean radiant temperature

Table 5.1: Correlation Coefficient Values

	r^2	CV (RMSE)
Indoor Air Temperatures	0.82	14.75%
Mean Radiant Temperature	0.83	16.80 %

5.5 Chapter Summary

This Chapter has presented the results of the validation of the predicted and simulated results in Chapter 4. The chapter also described the activities involved in the experimental design of the test cells to obtain measured data for validating the simulation model. In order to verify the results from the simulation, the statistical method of the root mean square difference (r^2) and CV (RMSE) were used to compare the simulation results with the measured data from the test cell.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.0 Introduction

This research has examined the effect of thermal mass, window size and night-time ventilation in reducing peak indoor air temperature in buildings in Ghana. The research objectives presented in Section 1.7 were developed in order to achieve the aim of the research which was to explore the integration of passive and low energy cooling techniques into the mode of building design in Ghana to thermal comfort whilst reducing energy use for mechanical cooling. A methodology was developed employing experimentation and simulation. To accomplish this, the Energy Plus Simulation programm was used to develop a base model simulating the mode of building design and construction in Ghana. A series of treatments were made to the base model to achieve twenty-two (22) different models that were used to investigate the effects of thermal mass, window size and night-time ventilation on peak indoor air temperature. The performance of the models was evaluated using three variables: 1) the maximum temperatures difference, 2) the temperature difference ratio (TDR) and 3) the percentage of overheated hours. Following the simulations, an experimental system consisting of two test cells was designed based on the characteristics of selected simulation models. The test cells were constructed and indoor air and radiant temperatures were monitored to obtain measured data to validate the simulated results. Graphical and statistical analyses were employed in the validation to achieve a satisfactory agreement between simulated results and measured data.

This chapter, which is the final chapter of the study, presents the conclusions of the study and recommendations. The chapter discusses the achievements of the research objectives, implications of the research, and highlights the contributions of the research. The recommendations are disaggregated into two sub-sections; one aimed at policy formulation in the design and selection of materials for buildings and the other in respect of further research.

6.1 Study Findings

The major study findings discussed under the study objectives and research questions have been discussed under this sub-section. These findings provide the major highlights of the study and provide the basis for policy and future research

Objective One

Investigate the effects of thermal mass on peak indoor air temperature.

Research Question One: How does the thermal mass level of materials used as building envelopes in Ghana affect the peak indoor air temperature?

From the analysis, increasing the thermal mass by changing to materials of higher densities led to a reduction in peak indoor air temperature. The control model made of the solid sandcrete blocks had a peak indoor air temperature of 35.6°C. The test models of baked bricks and concrete envelopes had an average peak indoor air temperature of 34.9°C and 32.6°C. This means that BB reduced peak indoor air temperature (PIAT) by 0.7°C and concrete had the highest effect with a drop of 3°C below that of the control model.

Increased thermal mass also led to an increase in the number of hours of delay of PIAT occurrence after of peak outdoor air temperature (POAT). SSB, BB and CONC had number of hours of delay of 2, 3 and 5 hours respectively.

Objective Two

Investigate the effects of window size on peak indoor air temperature.

Research Question Two: How does the window size of a space affect the peak indoor air temperature?

From the analysis, the performance of models was found to be inversely proportional to window size. However, an effect of increased window size was marginal because of well protected windows as a result of shading from impacts of solar radiation. Even though the model with no windows exhibited the best performance, windows are important sources of natural light and views of nature and outdoor environment that should not be completely eliminated. All the models investigated exhibited negative TDRs with no trendline striking the positive axis of the TDR and window to floor ratio correlation. This meant that even with no window, PIAT will always be above or worse than the mean outdoor air temperature. In comparison with an earlier study by La Roche and Milne (2004), WFR had a threshold of 11% below which PIAT was below MOAT.

Objective Three

Investigate the effects of night time ventilation on peak indoor air temperature.

Research Question Three: How can night-time cooling of a space affect the peak indoor air temperature?

From the analysis on effect of activation of night-time ventilation, it was observed that PIAT reduced with ventilation rates of up to 10ACH for models of various window to floor ratios. The heavier model made of concrete resulted in decrease of PIAT of between 3°C and 4°C below that of the control model, as compared to differences of between 0.17°C and 0.19°C below the corresponding none night-time ventilated concrete models. Baked bricks with ventilation rates of 10ACH obtained a reduction on PIAT temperature of 1°C and 2°C below that of the control model, and between 0.32°C and 0.04°C below that of the baked bricks models with no night-time ventilation. Solid sandcrete blocks with ventilation rates of 10ACH obtained a reduction on PIAT temperature of 0.03°C and 1.9°C below that of the control model, and between 0.02°C and 0.05°C below the Solid sandcrete blocks models with no night-time ventilation. Activation of night time ventilation exposed the mass to cool night outdoor air to offset in part the heat that was re radiated at night. The attained low indoor air temperature and cooled mass provides a heat sink that suppressed the rate of rise of daytime temperature. On increasing night-time ventilation rate, it was observed that increasing ventilation rates beyond 10ACH did not lead to significant improvement. Increases of ventilation rates to 20ACH and 30ACH observed reduction in PIAT of average of below 0.06°C, 0.009°C and 0.008°C for concrete, baked bricks and solid sandcrete blocks respectively. This could be attributed to the relatively low diurnal temperature range of Kumasi which does not provide a sufficient drop of indoor maximum temperature below the outdoor maximum temperature.

Combined effects of thermal mass, window size and night-time ventilation

Even though the combined effects of thermal mass, window size and night-time ventilation maintained PIAT below that of the control model, they were all above the mean outdoor air temperature. Concrete, baked bricks and solid sandcrete blocks maintained average temperatures of 2.5°C, 4.8°C and 5.5°C respectively above the mean outdoor air temperature. The combined effects of thermal mass, window size and night-time ventilation also permitted a decrease in the next day's peak indoor air temperature, with a corresponding decrease in overheated hours. With a reference temperature of 29°C, expected reduction of the overheated hours varied between 35% and 39%, 37% and 39% and 36% to 42% for concrete, BB and SSB respectively.

Objective Four

Validate the simulation results by comparing predicted thermal conditions with the measured data from the outdoor experiments.

Research Question Three: Do the thermo-physical properties and algorithmic presentations of heat and mass transfer in predesign tools reflect localized conditions?

From the analysis, the thermo-physical properties of materials specified in the simulation program were found to be consistent with that of the local materials tested in this research. A high level of prediction accuracy was obtained in predicting the effects of thermal mass, window size and night-time ventilation with the E+ simulation program. The above observation suggests that the thermo-physical properties of materials specified in the simulation program are consistent with that of local materials tested in this research. The corresponding root mean square difference (r^2) were 0.82 and 0.83 between predicted and measured data observed for mean air temperature and mean radiant temperature respectively. Coefficient of variance of root mean square error (CV[RMSE]) of 14.75% and 16.80% between predicted and measured data observed for mean air temperature and mean radiant temperature respectively. The results compared favourably with validation exercise in earlier studies performed with other simulation packages, specifically TRNSYS with r^2 value higher than 0.90 by Geros et al. (1999) and DOE 2 by Bou Saada et al. (1994). Koranteng et al. (2009) observed r^2 value between predicted and measured data observed indoor air temperature for four buildings in Ghana to be between 0.80 and 0.90 using EDSL thermal simulation application. Kreider and Harbel (1994) identified a (CV[RMSE]) range of between 10% and 20% tolerance for calibration acceptance.

6.2 Research Implications

The conclusions reached by this study have implications for improving thermal performance of buildings and hence the amount of energy consumed in space cooling. There are implications for theories on energy efficient building design and implications for building design and architectural practice in Ghana.

6.2.1 Theory

The findings of this research have two implications on theory of application of passive cooling techniques. As shown by the literature review of this study, passive cooling techniques are able to reduce peak indoor air temperature below that of the outdoor without the use of mechanical cooling systems. However, the findings of this research reveals that the application of the techniques in the mode of building design under the warm humid conditions of Ghana assessed in this research cannot bring peak indoor air temperature below that of the outdoor. Another implication on theory of this research is that the effect of night-time ventilation of thermal mass in the warm-humid condition of sub-Saharan tropical climate is insignificant.

6.2.2 Practice

The study's implications for building design and architectural practice in Ghana are as follows:

1. Choosing the appropriate thermal mass and window-to-floor ratio can together reduce the peak indoor temperature of a building and thus the energy required for space cooling. Consideration should be given to extensive use and development of construction details to encourage use of heavy thermal mass materials such as concrete and baked bricks in the envelope of buildings.
2. The application of passive cooling techniques (thermal mass, window-to-floor ratio and NVC) cannot bring mean indoor temperature below that of the outdoor to eliminate the need for mechanical cooling in the warm-humid climate of Ghana.

6.3 Research Contributions

The research has made the following contributions to the body of knowledge on passive and low energy cooling techniques:

1. A significant contribution of this research to the body of knowledge is the provision of empirical evidence with respect to peak indoor air temperature drop to support the assertion that heavy thermal mass can improve the thermal performance of buildings in Ghana. Until this research, this assertion had not been supported by any empirical study from research findings in Ghana.
2. Night-time ventilation has been established as a technique that eliminates the need for mechanical cooling in hot-dry climates with wide diurnal temperature range. There is an assertion that night-time ventilation is not effective in all warm-humid climates. This research contributes further to the study of knowledge by providing sufficient evidence to

support earlier studies that night ventilation is not effective in some warm-humid environments with narrow diurnal temperature range. This evidence has not been sufficiently available in literature.

3. Calibrated simulation models are used in retrofit analysis for improvement in the thermal performance of buildings. Therefore another significant contribution of this research to the body of knowledge is the achievement of a validated simulation model for the mode of building design and construction in Ghana. This provides a reference point for future calibrated simulation studies in Ghana.
4. Another significant contribution of this research to the body of knowledge is the provision of sufficient evidence to confirm that thermo-physical properties of basic materials used for construction in Ghana are consistent with that used in international standard building simulation programs. Until this research there had been a widely held assertion that most building simulation programs are developed with thermo-physical properties of materials used in temperate developed countries and are not consistent with localized conditions as that of Ghana.

6.4 Recommendations

This section proposes two (2) sets of recommendations arising from this research. The first is applicable to policy decisions on developing institutional capacity for research in building thermal performance and encouragement of the use of building envelopes of higher thermal mass in building design in Ghana, whiles the second is for further research into passive and low energy cooling techniques.

6.4.1 Recommendations for Policy Makers

The following recommendations for policy makers on developing institutional capacity for research in building thermal performance and encourage the use of building envelops of higher thermal mass in building design in Ghana are made on the basis of this research work:

1. Specialized research units with focus on building thermal performance should be established in research institutions in Ghana.
2. Appropriate construction details should be developed to encourage the use of concrete and baked bricks in the envelope of buildings in Ghana.
3. There should be initiatives by policy makers to encourage mass production and use of baked bricks in the construction of buildings in Ghana.

6.4.1 Recommendations for Future Research

The following recommendations, based on the limitations of the scope of this study are made for further research into passive and low energy cooling techniques in Ghana:

1. This research considered only three envelope materials in Ghana. Other building materials are used in construction of buildings in Ghana albeit in limited numbers, such as timber, hollow concrete blocks, adobe blocks (sun-dried), hydra-foam blocks, stone, etc. Future research should be conducted to investigate the effect of thermal mass of other building envelope materials not tested in this study.
2. The climatic conditions of the various regions of Ghana have varying diurnal temperature range. However this study was limited to the climatic conditions of the Ashanti Region. Further research is required to investigate the potential of night-time ventilation in reducing cooling load on buildings for the other regions of Ghana.

3. This research tested a limited number of passive cooling techniques as described in the thesis. Further research should be carried out to test the performance of other passive cooling techniques such as Direct Evaporative, Indirect Evaporative Cooling, Radiant Cooling and ground Cooling in the various region of Ghana.
4. Building performance simulation employs detailed and reliable micro-climatic data of which there is limited monitoring equipment in Ghana. Research projects should be developed to encourage the acquisition and setting up of equipment to create banks of detailed and reliable climatic data in Ghana.
5. For simplification, this study investigated indoor air thermal conditions of unoccupied test models. It is recommended that future research be carried out in full scale buildings taking into consideration other factors such as internal loads.

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APPENDICES

1. CLIMATE CHARACTERISTICS OF KUMASI

2. INPUT DATA FILE OF SIMULATION MODELS

3. TEMPERATURE DIFFERENCE RATIOS

4. PERCENTAGE OF OVERHEATED HOURS

5. PREDICTED MEAN AIR TEMPERATURE OF MODELS

6. MEASURED AND SIMULATED MEAN AIR TEMPERATURE

7. MEASURED AND SIMULATED MEAN RADIANT TEMPERATURE

8. COEFFICIENT OF VARIANCE OF ROOT MEAN SQUARE ERROR

APPENDIX 1

CLIMATE CHARACTERISTICS AND WEATHER DATA OF KUMASI

Typical climate characteristics of Kumasi

Kumasi is the second largest city of Ghana and the capital of the Ashanti region. It is located on 6º43' N latitude and 1°36'W longitude with an elevation of 250 meters above sea level. As described by Dickson and Benneh (1988), this part of the country is hot and humid all year round. Generally, the climate is classified as tropical. Kumasi experiences two rain seasons: May/June and October. The hottest of the year in Kumasi is March just before the rainy first rainy season, while august is the coolest month. As the principal aim of this study is to provide guiding principles for design of building, prime importance is given to temperature and relative humidity since physiological comfort level depends on the two (Singh et al., 2007). The thermal effect of materials in buildings without mechanical air conditioning in a warm climate is also dependent on the diurnal temperature range, which also depends primarily on the vapour pressure level (Givoni, 1976). These make temperature and relative humidity interconnected in determining the type of climate. Conditions in Kumasi fall outside the human comfort band for more than 50 percent of the time of the year as shown in Figure 11.7 (Amos-Abanyie et al, 2009).

Based on weather data from the Ghana Meteorological Agency (GMA), the tropical climate characteristics of Kumasi are as follows:

Dry-bulb Temperature

The annual average dry-bulb temperature is 26.8ºC. The average maximum air temperature are between 27.4 to 32.1ºC and the average minimum air temperature is 21,3 to 22.8ºC. The diurnal temperature range is approximately 7 – 11ºC, with a mean of 9.1ºC.

Relative humidity

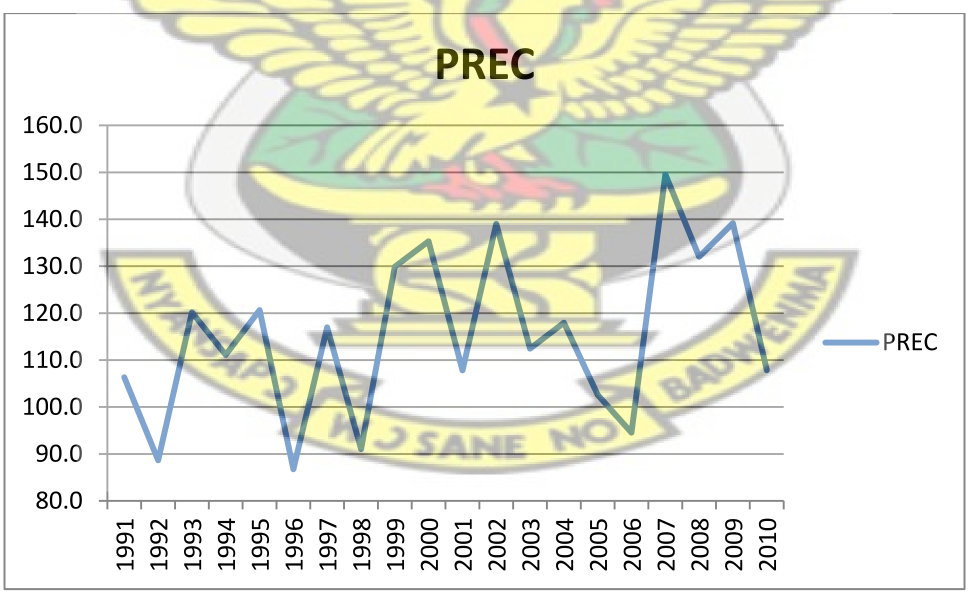
The annual relative humidity (RH) is 60%. The average maximum RH ranges from 89% and 96%. The average minimum RH is 42 and 73%.

Precipitation

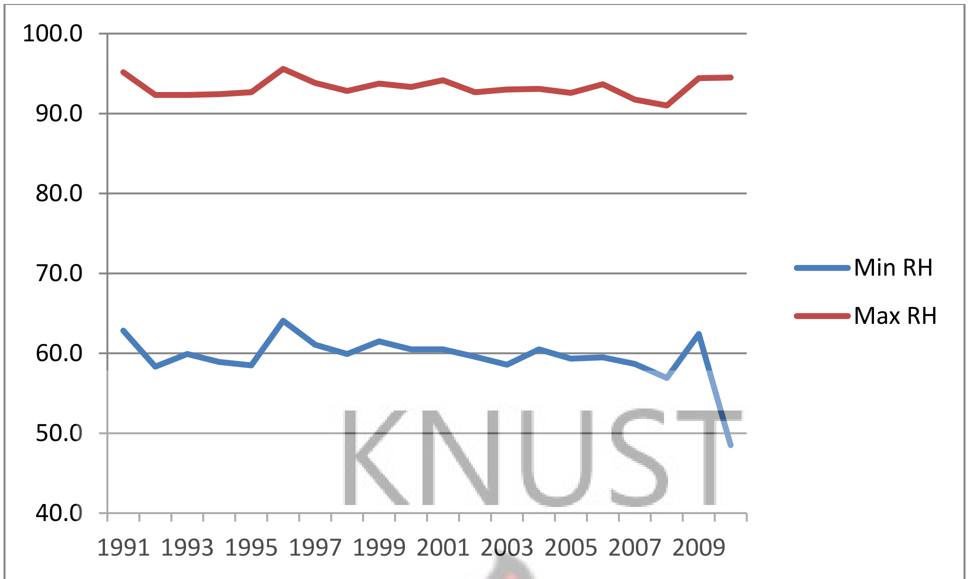
The climate of Kumasi is wet. The annual average precipitation is approximately 86.7 – 149.6 mm. in May / June and October the amount of rainfall may exceed 115,5mm per month.

Solar radiation

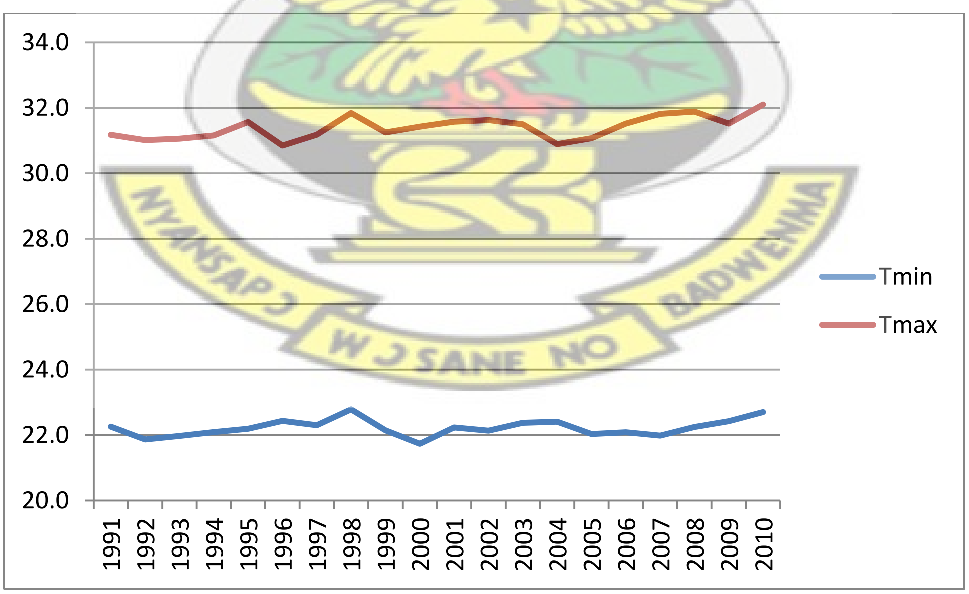
The monthly average daily solar radiation on the horizontal surface for April can be as much as 4.6kWh/m^2-day, causing this period to be the hottest month (Akuffo, 1991).



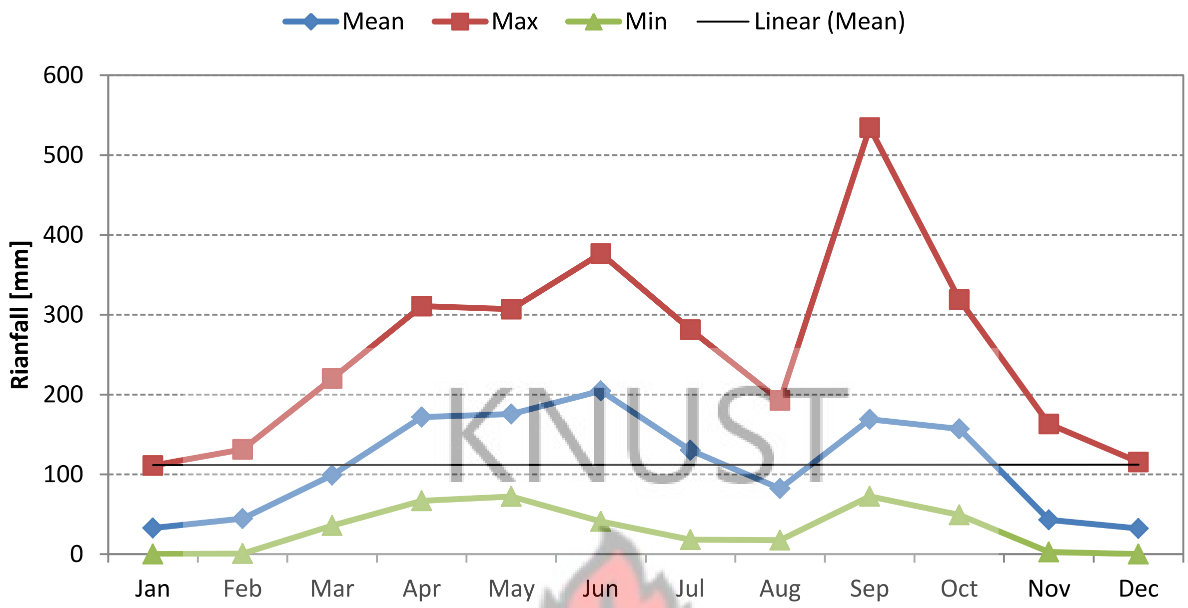
Annual Precipitation patterns for Kumasi



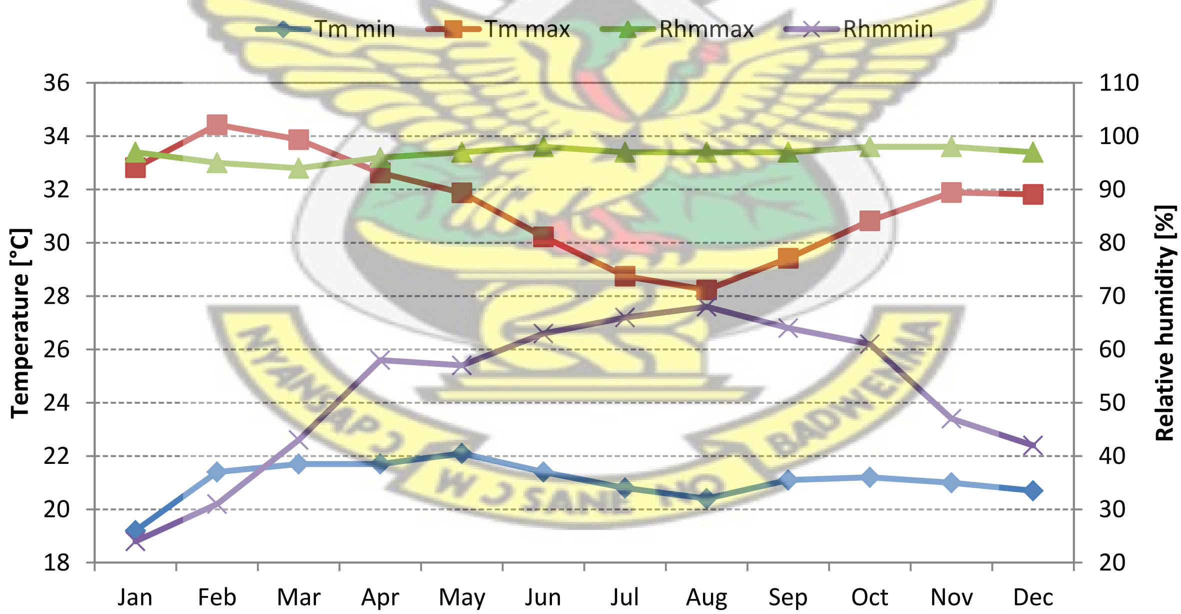
Annual Relative Humidity patterns for Kumasi



Annual Temperature Patterns for Kumasi



Monthly Rainfall Patterns for Kumasi



Monthly Temperature Patterns for Kumasi

Kumasi Weather Data

Weather data for Ghana are obtained from the Ghana meteorological agency or the US National Climatic Data Centre (NCDC). The latter provides on line access to the daily average weather data of all stations in countries that are members of the World Meteorological Organization (WMO). This is done to comply with the international agreement. The daily weather data can be downloaded from the NCDC's FTP server at http://ftp.ncdc.noaa.gov. However, in Ghana these data come from only one station - the Kotoka International Airport in Accra. The measurement generally include the daily dry-bulb temperature, dew pointy temperature, relative humidity, precipitation, wind speed, wind direction, cloudiness, visibility, atmospheric pressure, and various types of weather, occurrences such as hail, fog, thunder, glaze, etc. Detailed and comprehensive recorded outdoor weather data was not available for Kumasi. The weather data available from the GMA for Kumasi include monthly mean daily maximum and minimum values for dry bulb temperature and relative humidity.

To develop weather data for Kumasi, Koranteng et al (2009) mounted sensors at specified points on the KNUST Campus in Kumasi to monitor outdoor air temperature and relative humidity. Segments of a synthetic weather data, generated via Meteotest 2008 file that matches the outdoor measurements from the sensors were identified. This research used the weather data that was generated for the above study.

APPENDIX 2

INPUT DATA FILE OF SIMULATION MODELS

INPUT DATA FILES OF CONTROL MODEL

SIMULATION Parameters:

```
Version,4.0;
SimulationControl,
    No,                 !- Do Zone Sizing Calculation
    No,                 !- Do System Sizing Calculation
    No,                 !- Do Plant Sizing Calculation
    Yes,                !- Run Simulation for Sizing Periods
    No;                 !- Run Simulation for Weather File Run Periods
Building,
    CONTROL,            !- Name
    0,                  !- North Axis {deg}
    Suburb,             !- Terrain
    0.04,               !- Loads Convergence Tolerance Value
    0.4,                !- Temperature Convergence Tolerance Value {deltaC}
    FullExterior,       !- Solar Distribution
    25;                 !- Maximum Number of Warmup Days
SurfaceConvectionAlgorithm:Inside,Simple;
SurfaceConvectionAlgorithm:Outside,Simple;
HeatBalanceAlgorithm,ConductionTransferFunction,200;
ZoneCapacitanceMultiplier,1;
Timestep,6;
```

LOCATION, CLIMATE AND WEATHER FILE

```
Site:Location,
    KUMASI_ASH_GHA,     !- Name
    6.75,               !- Latitude {deg}
    -1.58,              !- Longitude {deg}
    0,                  !- Time Zone {hr}
    251;                !- Elevation {m}
SizingPeriod:WeatherFileDays,
    SIZING PERIOD,      !- Name
    11,                 !- Begin Month
    1,                  !- Begin Day of Month
    3,                  !- End Month
    31,                 !- End Day of Month
    Sunday,             !- Day of Week for Start Day
    No,                 !- Use Weather File Daylight Saving Period
    No;                 !- Use Weather File Rain and Snow Indicators
RunPeriod,
    ,                   !- Name
    11,                 !- Begin Month
    1,                  !- Begin Day of Month
    3,                  !- End Month
    31,                 !- End Day of Month
    UseWeatherFile,     !- Day of Week for Start Day
    Yes,                !- Use Weather File Holidays and Special Days
    No,                 !- Use Weather File Daylight Saving Period
    No,                 !- Apply Weekend Holiday Rule
```

```
        Yes,                    !- Use Weather File Rain Indicators
        No,                     !- Use Weather File Snow Indicators
        1;                      !- Number of Times Runperiod to be Repeated
Site:HeightVariation,
        0,                      !- Wind Speed Profile Exponent
        370,                    !- Wind Speed Profile Boundary Layer Thickness {m}
        0;                      !- Air Temperature Gradient Coefficient {K/m}
Site:GroundTemperature:
        BuildingSurface,24.4,24.8,25,24.8,24.4,23.9,23.3,22.9,22.8,22.9,23.3,23.9;
```

SCHEDULE

```
ScheduleTypeLimits,
        Temperature,            !- Name
        ,                       !- Lower Limit Value
        ,                       !- Upper Limit Value
        Continuous;             !- Numeric Type
ScheduleTypeLimits,
        Control Type,           !- Name
        0,                      !- Lower Limit Value
        4,                      !- Upper Limit Value
        Discrete;               !- Numeric T
ScheduleTypeLimits,
        Air Change per Hour,    !- Name
        0,                      !- Lower Limit Value
        30,                     !- Upper Limit Value
        Continuous;             !- Numeric Typ
ScheduleTypeLimits,
        Any Number;             !- Name
ScheduleTypeLimits,
        Fraction,               !- Name
        0,                      !- Lower Limit Value
        1,                      !- Upper Limit Value
        Discrete;               !- Numeric Type

ScheduleTypeLimits,
        On/Off,                 !- Name
        0,                      !- Lower Limit Value
        1,                      !- Upper Limit Value
        Discrete;               !- Numeric Type

Schedule:Compact,
        MinIndoor Temp,         !- Name
        Any Number,             !- Schedule Type Limits Name
        Through: 12/31,         !- Field 1
        For: AllDays,           !- Field 2
        Until: 24:00, 18;       !- Field 4

Schedule:Compact,
        MaxIndoor Temp,         !- Name
        Any Number,             !- Schedule Type Limits Name
        Through: 12/31,         !- Field 1
```

```
        For: AllDays,             !- Field 2
        Until: 24:00, 40;         !- Field 4
Schedule:Compact,
        MinOutdoor Temp,          !- Name
        Any Number,               !- Schedule Type Limits Name
        Through: 12/31,           !- Field 1
        For: AllDays,             !- Field 2
        Until: 24:00, 18;         !- Field 4
Schedule:Compact,
        MaxOutdoor Temp,          !- Name
        Any Number,               !- Schedule Type Limits Name
        Through: 12/31,           !- Field 1
        For: AllDays,             !- Field 2
        Until: 24:00, 40;         !- Field 4
Schedule:Compact,
        NightVent-SCH,            !- Name
        Fraction,                 !- Schedule Type Limits Name
        Through: 12/31,           !- Field 1
        For: AllDays,             !- Field 2
        Until: 7:00, 1.00,        !- Field 4
        Until: 19:00, 0.00,       !- Field 6
        Until: 24:00, 1.00;       !- Field 8
Schedule:Compact,
        ShadeTransSch,            !- Name
        Fraction,                 !- Schedule Type Limits Name
        Through: 12/31,           !- Field 1
        For: AllDays,             !- Field 2
        Until: 24:00, 0.00;       !- Field 4
Schedule:Compact,
        INFIL-SCHD,               !- Name
        Fraction,                 !- Schedule Type Limits Name
        Through: 12/31,           !- Field 1
        For: AllDays,             !- Field 2
        Until: 24:00, 0.00;       !- Field 4
Schedule:Compact,
        CONSTANT,                 !- Name
        Any Number,               !- Schedule Type Limits Name
        Through: 12/31,           !- Field 1
        For: AllDays,             !- Field 2
        Until: 24:00, 0.00;       !- Field 4
Schedule:Compact,
        MixingAvailSched,         !- Name
        Fraction,                 !- Schedule Type Limits Name
        Through: 3/31,            !- Field 1
        For: AllDays,             !- Field 2
        Until: 24:00, 1.00,       !- Field 4
        Through: 9/30,            !- Field 5
        For: Weekdays,            !- Field 6
        Until: 7:00, 1.00,        !- Field 8
        Until: 17:00, 1.00,       !- Field 10
        Until: 24:00, 1.00,       !- Field 12
        For: Weekends Holidays CustomDay1 CustomDay2,  !- Field 13
```

```
Until: 24:00, 0.00,      !- Field 15
For: SummerDesignDay WinterDesignDay,  !- Field 16
Until: 24:00, 1.00,      !- Field 18
Through: 12/31,          !- Field 19
For: AllDays,            !- Field 20
Until: 24:00, 1.00;      !- Field 22
```

SURFACE CONSTRUCTION ELEMENTS

```
Material,
    F16 Acoustic tile,       !- Name
    MediumSmooth,            !- Roughness
    0.0191,                  !- Thickness {m}
    0.06,                    !- Conductivity {W/m-K}
    368,                     !- Density {kg/m3}
    590;                     !- Specific Heat {J/kg-K}
Material,
    M14a 100mm heavyweight concrete,  !- Name
    MediumRough,             !- Roughness
    0.1016,                  !- Thickness {m}
    1.95,                    !- Conductivity {W/m-K}
    2240,                    !- Density {kg/m3}
    900,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance
Material,
    MASS-CONC.,              !- Name
    Rough,                   !- Roughness
    0.1524,                  !- Thickness {m}
    1.95,                    !- Conductivity {W/m-K}
    2240,                    !- Density {kg/m3}
    900,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance
Material,
    SAND-BLKS,               !- Name
    MediumRough,             !- Roughness
    0.1524,                  !- Thickness {m}
    0.49,                    !- Conductivity {W/m-K}
    512,                     !- Density {kg/m3}
    880,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance
Material,
    BRICKS- Fired Clay,      !- Name
    MediumRough,             !- Roughness
    0.102,                   !- Thickness {m}
    1.02,                    !- Conductivity {W/m-K}
    2089,                    !- Density {kg/m3}
    790,                     !- Specific Heat {J/kg-K}
```

```
        0.9,                    !- Thermal Absorptance
        0.7,                    !- Solar Absorptance
        0.7;                    !- Visible Absorptance
Material,
        REINF-CONC,             !- Name
        MediumRough,            !- Roughness
        0.1524,                 !- Thickness {m}
        1.95,                   !- Conductivity {W/m-K}
        2240,                   !- Density {kg/m3}
        900,                    !- Specific Heat {J/kg-K}
        0.9,                    !- Thermal Absorptance
        0.7,                    !- Solar Absorptance
        0.7;                    !- Visible Absorptance
Material,
        TIMBER-ODUM,            !- Name
        MediumSmooth,           !- Roughness
        0.0508,                 !- Thickness {m}
        0.15,                   !- Conductivity {W/m-K}
        608,                    !- Density {kg/m3}
        1630,                   !- Specific Heat {J/kg-K}
        0.9,                    !- Thermal Absorptance
        0.7,                    !- Solar Absorptance
        0.7;                    !- Visible Absorptance
Material:NoMass,
        Plaster: Cem/Sand - 20mm,       !- Name
        Smooth,                         !- Roughness
        0.026,                          !- Thermal Resistance {m2-K/W}
        0.9,                            !- Thermal Absorptance
        0.7,                            !- Solar Absorptance
        0.7;                            !- Visible Absorptance
Material:NoMass,
        Plaster: Cem/Sand - 50mm,       !- Name
        Smooth,                         !- Roughness
        0.052,                          !- Thermal Resistance {m2-K/W}
        0.9,                            !- Thermal Absorptance
        0.7,                            !- Solar Absorptance
        0.7;                            !- Visible Absorptance
Material:AirGap,
        F05 Ceiling air space resistance,       !- Name
        0.18;                                   !- Thermal Resistance {m2-K/W}
WindowMaterial:Glazing,
        CLEAR GLASS                 !- Name
        SpectralAverage,            !- Optical Data Type
        ,                           !- Window Glass Spectral Data Set Name
        0.003,                      !- Thickness {m}
        0.837,                      !- Solar Transmittance at Normal Incidence
        0.075,                      !- Front Side Solar Reflectance at Normal Incidence
        0.075,                      !- Back Side Solar Reflectance at Normal Incidence
        0.898,                      !- Visible Transmittance at Normal Incidence
        0.081,                      !- Front Side Visible Reflectance at Normal Incidence
        0.081,                      !- Back Side Visible Reflectance at Normal Incidence
        0,                          !- Infrared Transmittance at Normal Incidence
```

```
            0.84,                       !- Front Side Infrared Hemispherical Emissivity
            0.84,                       !- Back Side Infrared Hemispherical Emissivity
            0.9,                        !- Conductivity {W/m-K}
            1,                          !- Dirt Correction Factor for Solar and Visible Transmittance
            No;                         !- Solar Diffusing
    Construction,
            ROOF-1,                            !- Name
            Plaster: Cem/Sand - 20mm,          !- Outside Layer
            REINF-CONC,                        !- Layer 2
            Plaster: Cem/Sand - 20mm,          !- Layer 3
            F05 Ceiling air space resistance,  !- Layer 4
            F16 Acoustic tile;                 !- Layer 5

    Construction,
            SINGLE PANE WINDOW,         !- Name
            CLEAR GLASS 3MM;            !- Outside Layer
    Construction,
            ROOF,                       !- Name
            Plaster: Cem/Sand - 20mm,   !- Outside Layer
            REINF-CONC,                 !- Layer 2
            Plaster: Cem/Sand - 20mm;   !- Layer 3
    Construction,
            WALL-BLKS,                  !- Name
            Plaster: Cem/Sand - 20mm,   !- Outside Layer
            SAND-BLKS,                  !- Layer 2
            Plaster: Cem/Sand - 20mm;   !- Layer 3
    Construction,
            WALL-BRICKS,                !- Name
            BRICKS- Fired Clay,         !- Outside Layer
            Plaster: Cem/Sand - 20mm;   !- Layer 2

    Construction,
            WALL-CONC,                  !- Name
            Plaster: Cem/Sand - 20mm,   !- Outside Layer
            MASS-CONC.,                 !- Layer 2
            Plaster: Cem/Sand - 20mm;   !- Layer 3
    Construction,
            FLOOR,                      !- Name
            MASS-CONC.,                 !- Outside Layer
            Plaster: Cem/Sand - 50mm;   !- Layer 2
    Construction,
            DOOR,                       !- Name
            TIMBER-ODUM;                !- Outside Layer
```

THERMAL ZONE DESCRIPTION/GEOMETRY

```
    GlobalGeometryRules,
            UpperLeftCorner,            !- Starting Vertex Position
            Counterclockwise,           !- Vertex Entry Direction
            World,                      !- Coordinate System
            World,                      !- Daylighting Reference Point Coordinate System
            World;                      !- Rectangular Surface Coordinate System
```

```
Zone,
    ZONE-CONTROL,            !- Name
    0,                       !- Direction of Relative North {deg}
    0, 0, 0,                 !- X,Y,Z  {m}
    1,                       !- Type
    1,                       !- Multiplier
    autocalculate,           !- Ceiling Height {m}
    autocalculate;           !- Volume {m3}
BuildingSurface:Detailed,
    EAST WALL,               !- Name
    Wall,                    !- Surface Type
    WALL-BLKS,               !- Construction Name
    ZONE-CONTROL,            !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.5,                     !- View Factor to Ground
    4,                       !- Number of Vertices
    4.44, 2, 2.44,           !- X,Y,Z  1 {m}
    4.44, 2, 0,              !- X,Y,Z  2 {m}
    4.44, 3.22, 0,           !- X,Y,Z  3 {m}
    4.44, 3.22, 2.44;        !- X,Y,Z  4 {m}
BuildingSurface:Detailed,
    NORTH WALL,              !- Name
    Wall,                    !- Surface Type
    WALL-BLKS,               !- Construction Name
    ZONE-CONTROL,            !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.5,                     !- View Factor to Ground
    4,                       !- Number of Vertices
    4.44, 3.22, 2.44,        !- X,Y,Z  1 {m}
    4.44, 3.22, 0,           !- X,Y,Z  2 {m}
    2, 3.22, 0,              !- X,Y,Z  3 {m}
    2, 3.22, 2.44;           !- X,Y,Z  4 {m}
BuildingSurface:Detailed,
    WEST WALL,               !- Name
    Wall,                    !- Surface Type
    WALL-BLKS,               !- Construction Name
    ZONE-CONTROL,            !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.5,                     !- View Factor to Ground
    4,                       !- Number of Vertices
    2, 3.22, 2.44,           !- X,Y,Z  1 {m}
    2, 3.22, 0,              !- X,Y,Z  2 {m}
    2, 2, 0,                 !- X,Y,Z  3 {m}
```

```
        2, 2, 2.44;                      !- X,Y,Z  4 {m}
BuildingSurface:Detailed,
        ROOF,                            !- Name
        Roof,                            !- Surface Type
        ROOF-1,                          !- Construction Name
        ZONE-CONTROL,                    !- Zone Name
        Outdoors,                        !- Outside Boundary Condition
        ,                                !- Outside Boundary Condition Object
        SunExposed,                      !- Sun Exposure
        WindExposed,                     !- Wind Exposure
        autocalculate,                   !- View Factor to Ground
        4,                               !- Number of Vertices
        2, 2, 2.44,                      !- X,Y,Z  1 {m}
        4.44, 2, 2.44,                   !- X,Y,Z  2 {m}
        4.44, 3.22, 2.44,                !- X,Y,Z  3 {m}
        2, 3.22, 2.44;                   !- X,Y,Z  4 {m}
BuildingSurface:Detailed,
        FLOOR,                           !- Name
        Floor,                           !- Surface Type
        FLOOR,                           !- Construction Name
        ZONE-CONTROL,                    !- Zone Name
        Ground,                          !- Outside Boundary Condition
        ,                                !- Outside Boundary Condition Object
        NoSun,                           !- Sun Exposure
        WindExposed,                     !- Wind Exposure
        autocalculate,                   !- View Factor to Ground
        4,                               !- Number of Vertices
        2, 2, 0,                         !- X,Y,Z  1 {m}
        2, 3.22, 0,                      !- X,Y,Z  2 {m}
        4.44, 3.22, 0,                   !- X,Y,Z  3 {m}
        4.44, 2, 0;                      !- X,Y,Z  4 {m}
BuildingSurface:Detailed,
        SOUTH WALL,                      !- Name
        Wall,                            !- Surface Type
        WALL-BLKS,                       !- Construction Name
        ZONE-CONTROL,                    !- Zone Name
        Outdoors,                        !- Outside Boundary Condition
        ,                                !- Outside Boundary Condition Object
        SunExposed,                      !- Sun Exposure
        WindExposed,                     !- Wind Exposure
        autocalculate,                   !- View Factor to Ground
        4,                               !- Number of Vertices
        2, 2, 2.44,                      !- X,Y,Z  1 {m}
        2, 2, 0,                         !- X,Y,Z  2 {m}
        4.44, 2, 0,                      !- X,Y,Z  3 {m}
        4.44, 2, 2.44;                   !- X,Y,Z  4 {m}
FenestrationSurface:Detailed,
        NORTH WINDOW 100%,               !- Name
        Window,                          !- Surface Type
        SINGLE PANE WINDOW,              !- Construction Name
        NORTH WALL,                      !- Building Surface Name
        ,                                !- Outside Boundary Condition Object
```

```
        0.5,                    !- View Factor to Ground
        ,                       !- Shading Control Name
        ,                       !- Frame and Divider Name
        1,                      !- Multiplier
        4,                      !- Number of Vertices
        4.29, 3.22, 1.7,        !- X,Y,Z  1 {m}
        4.29, 3.22, 0.8,        !- X,Y,Z  2 {m}
        3.39, 3.22, 0.8,        !- X,Y,Z  3 {m}
        3.39, 3.22, 1.7;        !- X,Y,Z  4 {m}
FenestrationSurface:Detailed,
        SOUTH WINDOW 100%,      !- Name
        Window,                 !- Surface Type
        SINGLE PANE WINDOW,     !- Construction Name
        SOUTH WALL,             !- Building Surface Name
        ,                       !- Outside Boundary Condition Object
        0.5,                    !- View Factor to Ground
        ,                       !- Shading Control Name
        ,                       !- Frame and Divider Name
        1,                      !- Multiplier
        4,                      !- Number of Vertices
        3.39, 2, 1.7,           !- X,Y,Z  1 {m}
        3.39, 2, 0.8,           !- X,Y,Z  2 {m}
        4.29, 2, 0.8,           !- X,Y,Z  3 {m}
        4.29, 2, 1.7;           !- X,Y,Z  4 {m}
FenestrationSurface:Detailed,
        NORTH DOOR,             !- Name
        Door,                   !- Surface Type
        DOOR,                   !- Construction Name
        NORTH WALL,             !- Building Surface Name
        ,                       !- Outside Boundary Condition Object
        0.5,                    !- View Factor to Ground
        ,                       !- Shading Control Name
        ,                       !- Frame and Divider Name
        1,                      !- Multiplier
        4,                      !- Number of Vertices
        2.79, 3.22, 1.7,        !- X,Y,Z  1 {m}
        2.79, 3.22, 0,          !- X,Y,Z  2 {m}
        2.15, 3.22, 0,          !- X,Y,Z  3 {m}
        2.15, 3.22, 1.7;        !- X,Y,Z  4 {m}
Shading:Zone:Detailed,
        SOUTH WINDOW OVERHANG,  !- Name
        SOUTH WALL,             !- Base Surface Name
        ShadeTransSch,          !- Transmittance Schedule Name
        4,                      !- Number of Vertices
        4.44, 1.6, 1.7,         !- X,Y,Z  1 {m}
        4.44, 2, 1.7,           !- X,Y,Z  2 {m}
        3.24, 2, 1.7,           !- X,Y,Z  3 {m}
        3.24, 1.6, 1.7;         !- X,Y,Z  4 {m}
Shading:Zone:Detailed,
        NORTH OVERHANG,         !- Name
        NORTH WALL,             !- Base Surface Name
        ShadeTransSch,          !- Transmittance Schedule Name
```

```
4,                          !- Number of Vertices
2, 3.62, 1.7,               !- X,Y,Z  1 {m}
2, 3.22, 1.7,               !- X,Y,Z  2 {m}
4.44, 3.22, 1.7,            !- X,Y,Z  3 {m}
4.44, 3.62, 1.7;            !- X,Y,Z  4 {m}
```

AIR FLOW SYSTEMS

```
ZoneInfiltration:DesignFlowRate,
    ZONE Infil,                 !- Name
    ZONE-CONTROL,               !- Zone Name
    INFIL-SCHD,                 !- Schedule Name
    AirChanges/Hour,            !- Design Flow Rate Calculation Method
    ,                           !- Design Flow Rate {m3/s}
    ,                           !- Flow per Zone Floor Area {m3/s-m2}
    ,                           !- Flow per Exterior Surface Area {m3/s-m2}
    0.7,                        !- Air Changes per Hour
    0.606,                      !- Constant Term Coefficient
    0.03636,                    !- Temperature Term Coefficient
    0.1177,                     !- Velocity Term Coefficient
    0;                          !- Velocity Squared Term Coefficient

ZoneVentilation,
    ZONE Ventl-2,               !- Name
    ZONE-CONTROL,               !- Zone Name
    CONSTANT,                   !- Schedule Name
    AirChanges/Hour,            !- Design Flow Rate Calculation Method
    ,                           !- Design Flow Rate {m3/s}
    ,                           !- Flow Rate per Zone Floor Area {m3/s-m2}
    ,                           !- Flow Rate per Person {m3/s-person}
    10,                         !- Air Changes per Hour
    Exhaust,                    !- Ventilation Type
    400,                        !- Fan Pressure Rise {Pa}
    0.9,                        !- Fan Total Efficiency
    1,                          !- Constant Term Coefficient
    0,                          !- Temperature Term Coefficient
    0,                          !- Velocity Term Coefficient
    0,                          !- Velocity Squared Term Coefficient
    ,                           !- Minimum Indoor Temperature {C}
    MinIndoor Temp,             !- Minimum Indoor Temperature Schedule Name
    100,                        !- Maximum Indoor Temperature {C}
    ,                           !- Maximum Indoor Temperature Schedule Name
    -100,                       !- Delta Temperature {deltaC}
    ,                           !- Delta Temperature Schedule Name
    -100,                       !- Minimum Outdoor Temperature {C}
    ,                           !- Minimum Outdoor Temperature Schedule Name
    100,                        !- Maximum Outdoor Temperature {C}
    ,                           !- Maximum Outdoor Temperature Schedule Name
    40;                         !- Maximum Wind Speed {m/s}
ZoneVentilation,
    ZONE Ventl-1,               !- Name
    ZONE-CONTROL,               !- Zone Name
```

```
        CONSTANT,                        !- Schedule Name
        AirChanges/Hour,                 !- Design Flow Rate Calculation Method
        ,                                !- Design Flow Rate {m3/s}
        ,                                !- Flow Rate per Zone Floor Area {m3/s-m2}
        ,                                !- Flow Rate per Person {m3/s-person}
        10,                              !- Air Changes per Hour
        Intake,                          !- Ventilation Type
        400,                             !- Fan Pressure Rise {Pa}
        0.9,                             !- Fan Total Efficiency
        1,                               !- Constant Term Coefficient
        0,                               !- Temperature Term Coefficient
        0,                               !- Velocity Term Coefficient
        0,                               !- Velocity Squared Term Coefficient
        ,                                !- Minimum Indoor Temperature {C}
        MinIndoor Temp,                  !- Minimum Indoor Temperature Schedule Name
        100,                             !- Maximum Indoor Temperature {C}
        ,                                !- Maximum Indoor Temperature Schedule Name
        -100,                            !- Delta Temperature {deltaC}
        ,                                !- Delta Temperature Schedule Name
        -100,                            !- Minimum Outdoor Temperature {C}
        ,                                !- Minimum Outdoor Temperature Schedule Name
        100,                             !- Maximum Outdoor Temperature {C}
        ,                                !- Maximum Outdoor Temperature Schedule Name
        40;                              !- Maximum Wind Speed {m/s}
```

OUTPUT REPORTS

```
    Output:VariableDictionary,regular;
    Output:Surfaces:Drawing,DXF,RegularPolyline;

    Output:Table:SummaryReports,
        AllSummary;             !- Report 1 Name

    OutputControl:Table:Style,
        HTML;                   !- Column Separator

    Output:Diagnostics,
        DisplayExtraWarnings;   !- Key 1
```

OUTPUT VARIABLES

```
    Output:Variable,*,Outdoor Relative Humidity,Timestep;
    Output:Variable,*,Surface Inside Temperature,Timestep;
    Output:Variable,*,Zone Mean Radiant Temperature,Timestep;
    Output:Variable,*,Zone Mean Air Temperature,Timestep;
    Output:Variable,*,Outdoor Dry Bulb,Timestep;
```

FullInteriorAndExterior choice for solar distribution was used to account for how much of the beam radiation falling on the inside of the exterior window was absorbed by the window; how much if reflected back into the zone; and how much is transmitted to the outside. This also accounted for the effect of shading devices. The default maximum number of warm up days of 25 was used since it was more than sufficient for the simulation.

SCHEDULES

Infiltration, night Ventilation air flow and shading elements density of the model were scheduled using the objects from the schedule group. Schedule type limits were defined to validate portions of schedules. Schedule limits were either set as a range or as a numeric, with the numeric being either continuous or discrete. Each schedule type limit was assigned a name for reference and a lower and an upper limit values. A numeric type was specified to designate how the range values are validated. A continuous range allowed all numbers including fractional amounts within the range to be validated. Discrete type was used for integer values between the minimum and the maximum range values to be valid. Five schedules type limits were defined: control type; air change per hour; any number; fraction; and on/off.

The "through" element was used to specify the ending date expressing the month and day for the schedule period. In this study the ending date of 31st December is presented as 12/31. The "For" element specified the applicable days for the 24 hour period that must be described. This study involved simulating for all the days of the week therefore the "For" value was presented as "AllDays". The "Until" value specifies the ending time for the ending day and the day schedule being defined.

The view factor for each surface was also specified together with the number of vertices. The view factor from a surface to each other surface is the area of the receiving surface over the sum of areas that is visible to the sending surface. The fraction of the ground plane (assumed horizontal) that is visible from a heat-transfer surface. It is used to calculate the diffuse solar radiation from the ground that is incident on the surface. For example, if there are no obstructions, a vertical surface sees half of the ground plane and so View Factor to Ground = 0.5. A horizontal downward-facing surface sees the entire ground plane, so View Factor to Ground = 1.0. A horizontal upward-facing surface (horizontal roof) does not see the ground at all, so View Factor to Ground = 0.0.

APPENDIX 3

TEMPERATURE DIFFERENCE RATIOS

	MAX OUT	MIN OUT	SWING
DAY 1	29.2	21.8	7.4
DAY 2	29.7	21.5	8.2
DAY 3	28.9	23.1	5.8
DAY 4	30.6	21.9	8.7
DAY 5	31.0	21.8	9.2
DAY 6	30.9	21.9	9.0
DAY 7	30.5	22.6	7.9

Max in									
	MODEL 1	MODEL 2	MODEL 3	MODEL 4	MODEL 5	MODEL 6	MODEL 7	MODEL 8	MODEL 9
DAY 1	34.3	33.7	31.7	33.5	32.9	31.2	32.4	32.4	30.7
DAY 2	35.7	35.1	32.0	34.8	34.2	31.5	33.8	33.6	30.9
DAY 3	33.2	32.5	31.2	32.6	32.0	30.8	31.8	31.6	30.4
DAY 4	34.8	34.4	32.0	33.9	33.6	31.5	32.9	33.0	30.9
DAY 5	34.7	34.2	32.6	33.9	33.5	32.1	32.8	32.9	31.5
DAY 6	36.6	36.0	33.4	35.8	35.2	32.9	34.7	34.6	32.3
DAY 7	39.6	38.6	34.9	38.9	37.8	34.4	38.1	37.3	33.9

	MODEL 1	MODEL 2	MODEL 3	MODEL 4	MODEL 5	MODEL 6	MODEL 7	MODEL 8	MODEL 9
DAY 1	-0.69	-0.60	-0.34	-0.57	-0.50	-0.28	-0.44	-0.43	-0.20
DAY 2	-0.73	-0.65	-0.29	-0.63	-0.54	-0.22	-0.50	-0.47	-0.15
DAY 3	-0.75	-0.62	-0.39	-0.64	-0.54	-0.33	-0.50	-0.47	-0.27
DAY 4	-0.49	-0.44	-0.16	-0.38	-0.34	-0.10	-0.26	-0.28	-0.03
DAY 5	-0.41	-0.35	-0.17	-0.31	-0.27	-0.11	-0.20	-0.21	-0.05
DAY 6	-0.63	-0.57	-0.28	-0.54	-0.48	-0.22	-0.43	-0.41	-0.16
DAY 7	-1.16	-1.03	-0.56	-1.07	-0.92	-0.50	-0.96	-0.86	-0.43
TDR	**-0.69**	**-0.61**	**-0.31**	**-0.59**	**-0.51**	**-0.25**	**-0.47**	**-0.45**	**-0.18**

APPENDIX 4

PERCENTAGE OF OVERHEATED HOURS

Notes: The shaded cells of each matrix represent the hot hours of the day with average temperatures above the comfort range, while the plane cells represent the hours of the day with average temperature within the comfort range

COMFORTABLE AND HOT HOURS IN CONTROL MODEL FOR SEVEN DAYS

HOUR	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY6	DAY 7
1	25.4	25.3	27.0	25.6	26.6	26.6	27.1
2	24.9	24.7	26.3	25.0	25.8	25.9	26.4
3	24.5	24.2	25.6	24.5	25.1	25.2	25.8
4	24.1	23.7	25.1	24.1	24.5	24.7	25.2
5	23.7	23.3	24.7	23.7	24.0	24.2	24.7
6	23.4	23.1	24.4	23.3	23.6	23.8	24.4
7	23.6	23.2	24.3	23.6	23.8	23.9	24.3
8	24.5	24.0	24.7	24.6	25.0	24.9	25.1
9	26.1	25.4	25.8	26.2	26.8	26.8	26.9
10	28.0	27.1	27.5	28.0	28.8	29.0	29.3
11	29.8	28.9	29.1	29.7	30.5	31.0	31.8
12	31.2	30.6	30.6	31.1	31.7	32.4	34.1
13	32.2	32.1	31.9	32.2	32.7	33.5	36.0
14	33.1	33.6	32.9	33.3	33.7	34.7	37.8
15	33.9	35.2	33.2	34.4	34.5	36.1	39.2
16	34.7	36.3	33.0	35.4	35.0	37.0	39.9
17	34.8	36.8	32.2	35.9	35.0	37.0	39.4
18	33.6	36.0	31.0	35.3	34.2	35.9	37.8
19	31.9	34.3	29.9	33.7	32.8	34.2	35.6
20	30.3	32.5	29.0	32.0	31.4	32.5	33.7
21	29.0	31.0	28.1	30.6	30.2	31.1	32.0
22	27.9	29.7	27.4	29.4	29.2	29.9	30.7
23	26.9	28.7	26.7	28.3	28.2	28.9	29.5
24	26.1	27.8	26.1	27.4	27.4	27.9	29.5

COMFORTABLE AND HOT HOURS IN MODEL 1 FOR SEVEN DAYS

HOUR	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY6	DAY 7
1	24.1	23.8	25.2	24.6	24.7	24.9	25.4
2	23.9	23.3	24.7	24.0	24.1	24.3	24.8
3	23.5	22.9	24.4	23.5	23.6	23.8	24.3
4	23.1	22.7	24.1	23.2	23.2	23.4	23.9
5	22.8	22.4	23.8	22.8	22.8	23.0	23.6
6	22.6	22.2	23.7	22.6	22.6	22.8	23.4
7	22.8	22.5	23.7	22.9	22.9	23.0	23.5
8	24.2	23.7	24.4	24.3	24.6	24.6	24.8
9	25.9	25.2	25.6	26.0	26.6	26.6	26.6
10	27.9	27.0	27.4	27.9	28.6	28.9	29.1
11	29.7	28.8	29.0	29.7	30.3	30.9	31.7
12	31.1	30.6	30.5	31.0	31.6	32.3	34.0
13	32.2	32.1	31.9	32.2	32.7	33.4	35.9
14	33.0	33.6	32.9	33.3	33.7	34.7	37.7
15	33.9	35.1	33.2	34.4	34.5	36.1	39.2
16	34.7	36.3	33.0	35.4	34.9	37.0	39.8
17	34.8	36.8	32.2	35.9	35.0	37.0	39.4
18	33.6	36.0	31.0	35.3	34.2	35.8	37.8
19	31.9	34.3	29.9	33.7	32.8	34.2	35.6
20	28.3	29.8	27.9	29.7	29.6	30.2	30.8
21	27.0	28.4	27.1	28.3	28.3	28.9	29.3
22	26.0	27.4	26.4	27.2	27.3	27.9	28.3
23	25.2	26.6	25.7	26.3	26.4	27.0	27.4
24	24.4	25.8	25.2	25.4	28.3	26.1	27.4

COMFORTABLE AND HOT HOURS IN MODEL 2 FOR SEVEN DAYS

HOUR	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY6	DAY 7
1	24.2	23.9	25.3	24.7	24.8	25.0	25.5
2	24.0	23.4	24.8	24.1	24.2	24.4	24.9
3	23.6	23.0	24.4	23.6	23.7	23.9	24.4
4	23.2	22.7	24.1	23.2	23.3	23.5	24.0
5	22.9	22.5	23.9	22.9	22.9	23.1	23.7
6	22.7	22.3	23.7	22.7	22.7	22.8	23.4
7	22.8	22.4	23.7	22.8	22.9	23.0	23.5
8	23.9	23.4	24.3	23.9	24.3	24.2	24.5
9	25.3	24.6	25.2	25.4	26.0	26.0	26.1
10	27.1	26.1	26.8	27.1	27.9	28.1	28.3
11	28.8	27.8	28.3	28.8	29.5	30.0	30.8
12	30.2	29.6	29.7	30.1	30.7	31.5	33.1
13	31.3	31.1	31.0	31.3	31.8	32.5	35.1
14	32.1	32.6	32.1	32.4	32.8	33.7	36.9
15	33.0	34.2	32.5	33.4	33.6	35.2	38.4
16	33.9	35.5	32.4	34.5	34.1	36.3	39.3
17	34.3	36.2	31.9	35.3	34.4	36.5	39.1
18	33.5	35.8	30.9	35.1	33.9	35.7	37.8
19	31.9	34.4	29.9	33.7	32.8	34.2	35.9
20	28.4	29.9	27.9	29.8	29.6	30.3	31.0
21	27.1	28.5	27.1	28.4	28.4	29.0	29.5
22	26.1	27.5	26.4	27.3	27.4	27.9	28.4
23	25.3	26.7	25.8	26.4	26.5	27.1	27.5
24	24.5	25.9	25.2	25.5	27.9	26.2	27.5

COMFORTABLE AND HOT HOURS IN MODEL 3 FOR SEVEN DAYS

HOUR	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY6	DAY 7
1	24.3	24.0	25.4	24.7	24.9	25.1	25.6
2	24.0	23.5	24.9	24.2	24.3	24.5	25.0
3	23.6	23.1	24.5	23.7	23.8	24.0	24.5
4	23.3	22.8	24.2	23.3	23.3	23.5	24.1
5	23.0	22.5	23.9	23.0	23.0	23.2	23.7
6	22.7	22.3	23.8	22.7	22.8	22.9	23.5
7	22.7	22.4	23.7	22.8	22.8	23.0	23.5
8	23.5	23.0	24.1	23.5	23.9	23.9	24.2
9	24.7	23.9	24.8	24.7	25.3	25.3	25.5
10	26.2	25.2	26.1	26.2	27.0	27.2	27.5
11	27.8	26.8	27.4	27.8	28.5	29.1	29.9
12	29.2	28.5	28.7	29.1	29.7	30.4	32.1
13	30.2	30.0	30.0	30.2	30.7	31.5	34.1
14	31.1	31.5	31.1	31.2	31.7	32.6	35.9
15	32.0	33.1	31.7	32.3	32.5	34.1	37.5
16	33.0	34.5	31.7	33.5	33.1	35.3	38.5
17	33.6	35.5	31.4	34.5	33.6	35.8	38.7
18	33.2	35.5	30.7	34.7	33.6	35.4	37.8
19	31.9	34.3	29.9	33.7	32.7	34.2	36.0
20	28.4	30.0	27.9	29.8	29.6	30.4	31.1
21	27.2	28.6	27.2	28.4	28.4	29.0	29.6
22	26.2	27.6	26.5	27.4	27.5	28.0	28.5
23	25.4	26.8	25.9	26.5	26.6	27.2	27.6
24	24.6	26.0	25.3	25.6	27.5	26.3	27.6

COMFORTABLE AND HOT HOURS IN MODEL 4 FOR SEVEN DAYS

Test Model 4							
HOUR	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY6	DAY 7
1	24.3	24.0	25.8	24.7	25.2	25.4	25.9
2	24.1	23.6	25.3	24.2	24.5	24.7	25.2
3	23.7	23.2	24.8	23.7	24.0	24.2	24.7
4	23.3	22.9	24.4	23.3	23.5	23.7	24.3
5	23.0	22.6	24.1	22.9	23.1	23.3	23.9
6	22.8	22.4	23.9	22.7	22.9	23.0	23.7
7	22.9	22.5	23.9	22.9	23.1	23.2	23.7
8	24.1	23.5	24.5	24.1	24.6	24.6	24.9
9	25.4	24.8	25.4	25.5	26.2	26.1	26.3
10	27.1	26.3	26.8	27.2	27.9	28.1	28.3
11	28.7	27.9	28.2	28.8	29.5	29.9	30.5
12	30.1	29.6	29.6	30.2	30.7	31.3	32.6
13	31.2	31.1	30.9	31.4	31.8	32.4	34.4
14	32.1	32.6	31.8	32.5	32.9	33.7	36.2
15	33.0	34.1	32.3	33.6	33.7	35.1	37.7
16	33.8	35.3	32.2	34.7	34.2	36.1	38.6
17	34.1	35.9	31.6	35.3	34.4	36.3	38.5
18	33.1	35.5	30.7	34.9	33.9	35.5	37.4
19	31.6	34.3	29.7	33.7	32.7	34.1	35.8
20	28.3	30.1	27.9	29.9	29.7	30.5	31.2
21	27.2	29.0	27.2	28.7	28.7	29.3	29.9
22	26.3	28.0	26.5	27.7	27.8	28.4	28.9
23	25.4	27.2	25.9	26.8	26.9	27.5	28.0
24	24.6	26.5	25.3	26.0	28.0	26.6	28.0

COMFORTABLE AND HOT HOURS IN MODEL 5 FOR SEVEN DAYS

Test Model 5							
HOUR	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY6	DAY 7
1	24.4	24.1	25.9	24.8	25.3	25.5	26.0
2	24.2	23.6	25.3	24.2	24.6	24.8	25.3
3	23.8	23.2	24.9	23.7	24.1	24.3	24.8
4	23.4	22.9	24.5	23.4	23.6	23.8	24.4
5	23.1	22.6	24.1	23.0	23.2	23.4	24.0
6	22.8	22.4	23.9	22.8	23.0	23.1	23.7
7	22.9	22.5	23.9	22.9	23.1	23.2	23.8
8	23.9	23.3	24.4	23.9	24.4	24.3	24.7
9	25.1	24.4	25.2	25.1	25.8	25.8	26.0
10	26.7	25.8	26.5	26.8	27.5	27.6	27.9
11	28.2	27.4	27.8	28.3	29.0	29.4	30.0
12	29.6	29.1	29.1	29.7	30.2	30.8	32.1
13	30.7	30.5	30.4	30.8	31.3	31.9	33.9
14	31.5	32.0	31.4	32.0	32.4	33.2	35.6
15	32.5	33.6	31.9	33.1	33.2	34.6	37.2
16	33.4	34.8	31.9	34.2	33.8	35.7	38.2
17	33.8	35.6	31.5	35.0	34.1	36.0	38.3
18	33.1	35.4	30.6	34.9	33.8	35.4	37.5
19	31.7	34.3	29.8	33.7	32.8	34.2	35.9
20	28.4	30.2	27.9	30.0	29.8	30.5	31.3
21	27.3	29.0	27.2	28.8	28.7	29.4	30.0
22	26.3	28.1	26.6	27.8	27.8	28.4	29.0
23	25.5	27.3	25.9	26.9	27.0	27.6	28.1
24	24.7	26.6	25.3	26.1	27.8	26.7	28.1

COMFORTABLE AND HOT HOURS IN MODEL 6 FOR SEVEN DAYS

Test Model 6							
HOUR	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY6	DAY 7
1	24.5	24.2	26.0	24.8	25.4	25.6	26.1
2	24.2	23.7	25.4	24.3	24.8	24.9	25.4
3	23.8	23.3	25.0	23.8	24.2	24.4	24.9
4	23.5	23.0	24.5	23.4	23.7	23.9	24.5
5	23.1	22.7	24.2	23.1	23.3	23.5	24.1
6	22.9	22.5	24.0	22.8	23.0	23.2	23.8
7	22.8	22.5	23.9	22.8	23.0	23.2	23.8
8	23.7	23.1	24.4	23.6	24.2	24.1	24.6
9	24.7	24.0	24.9	24.7	25.5	25.4	25.7
10	26.2	25.3	26.1	26.2	27.0	27.2	27.4
11	27.7	26.8	27.3	27.8	28.5	28.9	29.5
12	29.0	28.5	28.6	29.1	29.7	30.2	31.5
13	30.1	29.9	29.8	30.2	30.7	31.3	33.3
14	31.0	31.4	30.9	31.4	31.8	32.6	35.1
15	31.9	33.0	31.5	32.5	32.6	34.0	36.6
16	32.9	34.3	31.6	33.7	33.3	35.2	37.8
17	33.5	35.3	31.3	34.6	33.8	35.7	38.1
18	33.0	35.3	30.6	34.8	33.7	35.3	37.4
19	31.7	34.3	29.8	33.8	32.8	34.2	36.0
20	28.4	30.2	28.0	30.0	29.8	30.6	31.4
21	27.3	29.1	27.3	28.8	28.8	29.5	30.1
22	26.4	28.2	26.6	27.9	27.9	28.5	29.2
23	25.6	27.4	26.0	27.0	27.1	27.7	28.2
24	24.8	26.7	25.4	26.2	27.6	26.8	28.2

COMFORTABLE AND HOT HOURS IN MODEL 7 FOR SEVEN DAYS

Test Model 7							
HOUR	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY6	DAY 7
1	25.5	25.2	26.8	25.5	26.3	26.4	27.0
2	25.2	24.7	26.3	25.0	25.7	25.8	26.4
3	24.8	24.3	25.9	24.5	25.2	25.3	25.9
4	24.3	24.0	25.5	24.1	24.7	24.9	25.5
5	24.0	23.6	25.2	23.8	24.3	24.5	25.1
6	23.7	23.4	24.9	23.5	24.0	24.2	24.8
7	23.7	23.4	24.8	23.6	24.1	24.2	24.8
8	25.1	24.7	26.0	24.9	25.8	25.8	26.3
9	25.9	25.3	26.4	25.6	26.6	26.7	27.1
10	26.8	26.1	27.1	26.6	27.6	27.7	28.1
11	27.8	27.1	27.9	27.6	28.6	28.8	29.3
12	28.7	28.1	28.7	28.7	29.5	29.8	30.6
13	29.6	29.2	29.6	29.6	30.4	30.8	31.8
14	30.5	30.3	30.3	30.6	31.3	31.8	33.1
15	31.3	31.5	30.9	31.5	32.1	32.8	34.2
16	32.0	32.4	31.1	32.4	32.7	33.7	35.1
17	32.4	33.1	31.0	33.1	33.1	34.2	35.5
18	32.3	33.3	30.7	33.2	33.0	34.1	35.3
19	31.7	33.0	30.2	32.9	32.7	33.7	34.8
20	28.8	29.9	28.4	30.0	30.1	30.7	31.2
21	27.9	29.2	27.8	29.1	29.2	29.8	30.3
22	27.2	28.5	27.2	28.4	28.5	29.1	29.6
23	26.4	27.9	26.6	27.6	27.8	28.4	28.9
24	25.7	27.3	26.1	26.9	27.9	27.7	28.9

COMFORTABLE AND HOT HOURS IN MODEL 8 FOR SEVEN DAYS

Test Model 8							
HOUR	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY6	DAY 7
1	25.6	25.3	26.8	25.6	26.3	26.5	27.1
2	25.3	24.8	26.4	25.1	25.8	25.9	26.5
3	24.8	24.4	26.0	24.6	25.3	25.4	26.0
4	24.4	24.1	25.6	24.2	24.8	25.0	25.6
5	24.1	23.7	25.2	23.9	24.4	24.6	25.2
6	23.8	23.4	25.0	23.6	24.1	24.3	24.9
7	23.8	23.4	24.9	23.7	24.1	24.3	24.9
8	25.0	24.6	25.9	24.7	25.7	25.7	26.3
9	25.6	25.0	26.3	25.4	26.4	26.4	26.9
10	26.4	25.7	26.8	26.2	27.2	27.3	27.8
11	27.3	26.6	27.5	27.2	28.2	28.4	28.9
12	28.3	27.7	28.3	28.2	29.1	29.4	30.1
13	29.2	28.7	29.1	29.1	29.9	30.3	31.3
14	29.9	29.8	29.9	30.0	30.8	31.2	32.6
15	30.7	30.9	30.5	31.0	31.6	32.3	33.7
16	31.5	31.9	30.8	31.9	32.2	33.2	34.7
17	32.1	32.7	30.8	32.7	32.7	33.8	35.2
18	32.1	33.1	30.6	33.0	32.8	33.9	35.2
19	31.7	32.9	30.2	32.8	32.6	33.7	34.8
20	28.8	29.9	28.4	30.0	30.1	30.7	31.2
21	28.0	29.2	27.8	29.1	29.2	29.9	30.4
22	27.2	28.6	27.2	28.4	28.5	29.2	29.7
23	26.5	28.0	26.7	27.7	27.8	28.5	29.0
24	25.8	27.4	26.2	27.0	27.7	27.8	29.0

COMFORTABLE AND HOT HOURS IN THE MODEL 1 FOR SEVEN DAY

Test Model 9							
HOUR	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY6	DAY 7
1	25.6	25.4	26.9	25.7	26.4	26.6	27.2
2	25.4	24.9	26.4	25.2	25.9	26.0	26.6
3	24.9	24.5	26.0	24.7	25.4	25.5	26.1
4	24.5	24.1	25.7	24.3	24.9	25.1	25.7
5	24.2	23.8	25.3	24.0	24.5	24.7	25.3
6	23.9	23.5	25.1	23.7	24.2	24.4	25.0
7	23.8	23.5	24.9	23.7	24.2	24.3	24.9
8	24.9	24.5	25.9	24.6	25.6	25.6	26.3
9	25.4	24.8	26.1	25.1	26.2	26.2	26.7
10	26.0	25.3	26.6	25.8	26.9	27.0	27.4
11	26.9	26.1	27.2	26.7	27.8	27.9	28.5
12	27.8	27.1	27.9	27.6	28.6	28.9	29.7
13	28.6	28.1	28.6	28.5	29.4	29.7	30.8
14	29.4	29.1	29.4	29.4	30.2	30.6	32.0
15	30.2	30.3	30.1	30.3	31.0	31.7	33.2
16	31.0	31.3	30.4	31.3	31.7	32.7	34.2
17	31.7	32.3	30.6	32.2	32.3	33.4	34.8
18	31.9	32.8	30.4	32.7	32.6	33.7	35.0
19	31.6	32.8	30.1	32.7	32.5	33.5	34.7
20	28.8	29.9	28.4	30.0	30.0	30.7	31.2
21	28.0	29.2	27.8	29.2	29.3	29.9	30.4
22	27.3	28.6	27.3	28.5	28.6	29.2	29.7
23	26.6	28.0	26.8	27.8	27.9	28.5	29.1
24	25.9	27.4	26.2	27.1	27.5	27.8	29.1

APPENDIX 5

PREDICTED MEAN AIR TEMPERATURE OF MODELS

PREDICTED MEAN AIR TEMPERATURE OF MODELS

Date/Time	Outdoor	Control Model	Test Model 01	Test Model 02	Test Model 03	Test Model 04	Test Model 05	Test Model 06	Test Model 07	Test Model 08	Test Model 09
11/01 00:10:00	22.833	25.638	24.068	24.157	24.250	24.316	24.394	24.475	25.433	25.523	25.610
11/01 00:20:00	22.967	25.535	24.077	24.161	24.249	24.323	24.397	24.474	25.452	25.539	25.622
11/01 00:30:00	23.100	25.437	24.089	24.168	24.252	24.332	24.402	24.474	25.470	25.554	25.634
11/01 00:40:00	23.233	25.345	24.105	24.179	24.258	24.343	24.409	24.476	25.487	25.568	25.644
11/01 00:50:00	23.367	25.258	24.126	24.195	24.269	24.359	24.420	24.487	25.507	25.584	25.657
11/01 01:00:00	23.500	25.179	24.153	24.217	24.290	24.384	24.442	24.504	25.529	25.603	25.673
11/01 01:10:00	23.400	25.097	24.100	24.164	24.234	24.326	24.383	24.443	25.464	25.538	25.607
11/01 01:20:00	23.300	25.015	24.022	24.082	24.151	24.238	24.295	24.355	25.369	25.443	25.514
11/01 01:30:00	23.200	24.938	23.945	24.007	24.074	24.154	24.212	24.273	25.276	25.352	25.425
11/01 01:40:00	23.100	24.864	23.870	23.933	24.001	24.078	24.137	24.197	25.187	25.264	25.339
11/01 01:50:00	23.000	24.794	23.794	23.858	23.926	24.002	24.061	24.122	25.098	25.177	25.253
11/01 02:00:00	22.900	24.725	23.718	23.782	23.851	23.925	23.984	24.046	25.009	25.089	25.167
11/01 02:10:00	22.833	24.659	23.653	23.718	23.787	23.859	23.919	23.981	24.933	25.015	25.094
11/01 02:20:00	22.767	24.594	23.593	23.657	23.727	23.797	23.857	23.921	24.862	24.945	25.026
11/01 02:30:00	22.700	24.530	23.532	23.597	23.667	23.735	23.796	23.859	24.792	24.875	24.957
11/01 02:40:00	22.633	24.466	23.471	23.536	23.607	23.673	23.734	23.798	24.721	24.805	24.888
11/01 02:50:00	22.567	24.401	23.410	23.475	23.546	23.611	23.672	23.736	24.653	24.736	24.820
11/01 03:00:00	22.500	24.338	23.349	23.415	23.486	23.548	23.610	23.674	24.586	24.670	24.752
11/01 03:10:00	22.433	24.273	23.288	23.354	23.425	23.486	23.547	23.612	24.518	24.604	24.688
11/01 03:20:00	22.367	24.209	23.227	23.293	23.364	23.423	23.485	23.550	24.450	24.537	24.623
11/01 03:30:00	22.300	24.145	23.166	23.232	23.304	23.360	23.422	23.488	24.381	24.469	24.557
11/01 03:40:00	22.233	24.081	23.105	23.171	23.243	23.297	23.360	23.426	24.313	24.402	24.491
11/01 03:50:00	22.167	24.017	23.044	23.110	23.182	23.234	23.296	23.363	24.245	24.335	24.425
11/01 04:00:00	22.100	23.953	22.982	23.048	23.120	23.170	23.233	23.299	24.176	24.268	24.359
11/01 04:10:00	22.067	23.890	22.933	22.998	23.070	23.118	23.180	23.246	24.120	24.212	24.304
11/01 04:20:00	22.033	23.829	22.888	22.953	23.024	23.070	23.132	23.197	24.069	24.160	24.252
11/01 04:30:00	22.000	23.769	22.843	22.907	22.978	23.022	23.083	23.148	24.017	24.108	24.200

Date/Time	Outdoor	Control Model	Test Model 01	Test Model 02	Test Model 03	Test Model 04	Test Model 05	Test Model 06	Test Model 07	Test Model 08	Test Model 09
11/01 04:40:00	21.967	23.709	22.799	22.862	22.932	22.974	23.034	23.098	23.965	24.056	24.148
11/01 04:50:00	21.933	23.650	22.755	22.818	22.887	22.927	22.987	23.050	23.913	24.004	24.096
11/01 05:00:00	21.900	23.592	22.712	22.775	22.843	22.880	22.940	23.002	23.862	23.953	24.044
11/01 05:10:00	21.883	23.541	22.676	22.738	22.805	22.841	22.899	22.961	23.817	23.907	23.998
11/01 05:20:00	21.867	23.491	22.643	22.703	22.770	22.804	22.861	22.923	23.774	23.864	23.955
11/01 05:30:00	21.850	23.441	22.611	22.670	22.736	22.768	22.825	22.885	23.731	23.821	23.912
11/01 05:40:00	21.833	23.393	22.579	22.638	22.703	22.733	22.789	22.848	23.689	23.779	23.870
11/01 05:50:00	21.817	23.346	22.548	22.606	22.670	22.698	22.753	22.812	23.648	23.737	23.828
11/01 06:00:00	21.800	23.365	22.562	22.598	22.638	22.701	22.738	22.776	23.642	23.714	23.786
11/01 06:10:00	21.867	23.406	22.610	22.622	22.636	22.735	22.752	22.771	23.664	23.719	23.773
11/01 06:20:00	21.933	23.455	22.670	22.660	22.650	22.780	22.781	22.782	23.692	23.732	23.771
11/01 06:30:00	22.000	23.513	22.736	22.706	22.673	22.830	22.817	22.802	23.718	23.746	23.772
11/01 06:40:00	22.067	23.595	22.817	22.765	22.708	22.894	22.866	22.834	23.751	23.765	23.776
11/01 06:50:00	22.133	23.704	22.912	22.838	22.755	22.971	22.926	22.877	23.791	23.790	23.785
11/01 07:00:00	22.200	23.835	23.019	22.922	22.813	23.057	22.997	22.929	23.836	23.820	23.800
11/01 07:10:00	22.383	23.993	23.486	23.303	23.090	23.515	23.396	23.266	24.662	24.613	24.554
11/01 07:20:00	22.567	24.172	23.849	23.595	23.290	23.829	23.668	23.493	24.946	24.897	24.836
11/01 07:30:00	22.750	24.370	24.091	23.778	23.425	24.011	23.808	23.605	25.113	25.046	24.964
11/01 07:40:00	22.933	24.578	24.309	23.950	23.560	24.174	23.939	23.712	25.227	25.132	25.020
11/01 07:50:00	23.117	24.797	24.545	24.142	23.717	24.359	24.096	23.849	25.322	25.201	25.060
11/01 08:00:00	23.300	25.031	24.797	24.367	23.892	24.563	24.272	24.009	25.419	25.273	25.106
11/01 08:10:00	23.533	25.282	25.063	24.610	24.084	24.781	24.479	24.185	25.525	25.355	25.162
11/01 08:20:00	23.767	25.569	25.359	24.866	24.292	25.012	24.702	24.377	25.642	25.447	25.228
11/01 08:30:00	24.000	25.844	25.642	25.141	24.516	25.263	24.941	24.584	25.775	25.551	25.304
11/01 08:40:00	24.233	26.218	26.028	25.428	24.755	25.539	25.189	24.806	25.914	25.663	25.390
11/01 08:50:00	24.467	26.540	26.361	25.723	25.008	25.824	25.448	25.041	26.058	25.782	25.487
11/01 09:00:00	24.700	26.869	26.700	26.022	25.272	26.109	25.712	25.288	26.201	25.906	25.593
11/01 09:10:00	24.917	27.200	27.041	26.285	25.545	26.398	25.984	25.544	26.353	26.039	25.709
11/01 09:20:00	25.133	27.536	27.385	26.651	25.825	26.693	26.262	25.805	26.513	26.180	25.832

Date/Time	Outdoor	Control Model	Test Model 01	Test Model 02	Test Model 03	Test Model 04	Test Model 05	Test Model 06	Test Model 07	Test Model 08	Test Model 09
11/01 09:30:00	25.350	27.870	27.728	26.960	26.106	26.990	26.541	26.069	26.680	26.327	25.963
11/01 09:40:00	25.567	28.196	28.061	27.272	26.388	27.281	26.817	26.333	26.846	26.477	26.099
11/01 09:50:00	25.783	28.513	28.386	27.576	26.667	27.566	27.091	26.596	27.014	26.631	26.239
11/01 10:00:00	26.000	28.820	28.699	27.872	26.942	27.845	27.360	26.855	27.183	26.787	26.383
11/01 10:10:00	26.200	29.114	28.999	28.153	27.211	28.115	27.623	27.111	27.350	26.944	26.530
11/01 10:20:00	26.400	29.390	29.288	28.427	27.473	28.377	27.881	27.361	27.517	27.103	26.678
11/01 10:30:00	26.600	29.655	29.559	28.694	27.728	28.632	28.134	27.606	27.683	27.264	26.828
11/01 10:40:00	26.800	29.912	29.818	28.955	27.976	28.879	28.381	27.845	27.849	27.425	26.978
11/01 10:50:00	27.000	30.159	30.070	29.208	28.216	29.119	28.622	28.079	28.014	27.586	27.128
11/01 11:00:00	27.200	30.398	30.314	29.453	28.448	29.353	28.856	28.306	28.179	27.748	27.278
11/01 11:10:00	27.350	30.627	30.547	29.689	28.673	29.578	29.083	28.528	28.342	27.907	27.428
11/01 11:20:00	27.500	30.850	30.775	29.916	28.891	29.799	29.304	28.743	28.505	28.066	27.577
11/01 11:30:00	27.650	31.068	30.996	30.136	29.100	30.014	29.517	28.950	28.669	28.223	27.725
11/01 11:40:00	27.800	31.275	31.207	30.345	29.300	30.219	29.720	29.149	28.830	28.378	27.871
11/01 11:50:00	27.950	31.470	31.405	30.543	29.491	30.413	29.913	29.339	28.988	28.530	28.015
11/01 12:00:00	28.100	31.653	31.592	30.729	29.670	30.596	30.096	29.519	29.142	28.679	28.156
11/01 12:10:00	28.217	31.824	31.766	30.903	29.839	30.768	30.267	29.688	29.292	28.824	28.294
11/01 12:20:00	28.333	31.984	31.930	31.067	29.998	30.931	30.430	29.849	29.438	28.965	28.429
11/01 12:30:00	28.450	32.137	32.086	31.222	30.149	31.088	30.587	30.004	29.581	29.103	28.561
11/01 12:40:00	28.567	32.284	32.235	31.371	30.294	31.240	30.738	30.156	29.721	29.238	28.690
11/01 12:50:00	28.683	32.428	32.382	31.514	30.436	31.392	30.887	30.304	29.860	29.370	28.818
11/01 13:00:00	28.800	32.570	32.527	31.654	30.575	31.542	31.034	30.452	29.999	29.501	28.944
11/01 13:10:00	28.867	32.711	32.670	31.790	30.712	31.690	31.177	30.597	30.136	29.630	29.070
11/01 13:20:00	28.933	32.850	32.811	31.924	30.847	31.837	31.319	30.741	30.272	29.757	29.196
11/01 13:30:00	29.000	32.989	32.953	32.057	30.982	31.983	31.461	30.886	30.407	29.884	29.321
11/01 13:40:00	29.067	33.130	33.095	32.192	31.118	32.132	31.606	31.032	30.542	30.012	29.446
11/01 13:50:00	29.133	33.272	33.239	32.331	31.257	32.283	31.755	31.182	30.677	30.142	29.572
11/01 14:00:00	29.200	33.419	33.387	32.476	31.402	32.439	31.909	31.336	30.813	30.273	29.700
11/01 14:10:00	29.200	33.566	33.536	32.625	31.552	32.596	32.067	31.496	30.947	30.406	29.830

Date/Time	Outdoor	Control Model	Test Model 01	Test Model 02	Test Model 03	Test Model 04	Test Model 05	Test Model 06	Test Model 07	Test Model 08	Test Model 09
11/01 14:20:00	29.200	33.716	33.688	32.780	31.709	32.755	32.231	31.661	31.082	30.540	29.962
11/01 14:30:00	29.200	33.870	33.843	32.940	31.871	32.918	32.398	31.831	31.217	30.676	30.096
11/01 14:40:00	29.200	34.016	33.990	33.099	32.039	33.075	32.564	32.004	31.345	30.810	30.233
11/01 14:50:00	29.200	34.160	34.136	33.260	32.211	33.232	32.732	32.179	31.473	30.944	30.371
11/01 15:00:00	29.200	34.305	34.282	33.422	32.386	33.389	32.900	32.355	31.602	31.080	30.511
11/01 15:10:00	29.133	34.442	34.420	33.581	32.562	33.539	33.064	32.530	31.727	31.214	30.651
11/01 15:20:00	29.067	34.569	34.548	33.735	32.737	33.680	33.223	32.702	31.846	31.346	30.791
11/01 15:30:00	29.000	34.686	34.667	33.883	32.908	33.812	33.374	32.869	31.962	31.475	30.930
11/01 15:40:00	28.933	34.787	34.768	34.016	33.071	33.928	33.511	33.025	32.069	31.598	31.067
11/01 15:50:00	28.867	34.866	34.848	34.132	33.222	34.025	33.630	33.166	32.167	31.714	31.199
11/01 16:00:00	28.800	34.923	34.906	34.227	33.356	34.100	33.730	33.290	32.257	31.823	31.326
11/01 16:10:00	28.667	34.948	34.931	34.296	33.469	34.147	33.804	33.392	32.333	31.921	31.446
11/01 16:20:00	28.533	34.929	34.914	34.331	33.558	34.155	33.847	33.471	32.387	32.003	31.557
11/01 16:30:00	28.400	34.882	34.868	34.337	33.621	34.137	33.862	33.522	32.431	32.075	31.658
11/01 16:40:00	28.267	34.796	34.782	34.308	33.654	34.083	33.844	33.541	32.457	32.132	31.747
11/01 16:50:00	28.133	34.667	34.654	34.241	33.654	33.988	33.787	33.526	32.464	32.172	31.822
11/01 17:00:00	28.000	34.498	34.485	34.136	33.619	33.856	33.694	33.476	32.452	32.195	31.881
11/01 17:10:00	27.833	34.286	34.274	33.991	33.550	33.683	33.563	33.390	32.418	32.198	31.924
11/01 17:20:00	27.667	34.042	34.030	33.812	33.447	33.480	33.399	33.270	32.368	32.185	31.950
11/01 17:30:00	27.500	33.760	33.749	33.598	33.312	33.242	33.202	33.118	32.298	32.152	31.958
11/01 17:40:00	27.333	33.477	33.467	33.371	33.149	33.000	32.990	32.940	32.231	32.113	31.949
11/01 17:50:00	27.167	33.189	33.179	33.127	32.960	32.749	32.762	32.738	32.158	32.063	31.924
11/01 18:00:00	27.000	32.896	32.887	32.872	32.750	32.492	32.522	32.520	32.079	32.002	31.883
11/01 18:10:00	26.883	32.602	32.593	32.608	32.525	32.232	32.277	32.291	31.993	31.930	31.828
11/01 18:20:00	26.767	32.308	32.299	32.340	32.290	31.972	32.029	32.058	31.898	31.849	31.762
11/01 18:30:00	26.650	32.016	32.008	32.072	32.051	31.716	31.782	31.824	31.797	31.760	31.687
11/01 18:40:00	26.533	31.730	31.722	31.806	31.811	31.464	31.540	31.592	31.691	31.666	31.605
11/01 18:50:00	26.417	31.451	31.444	31.544	31.573	31.219	31.303	31.365	31.582	31.567	31.518
11/01 19:00:00	26.300	31.180	31.173	31.289	31.339	30.981	31.072	31.144	31.470	31.465	31.427

Date/Time	Outdoor	Control Model	Test Model 01	Test Model 02	Test Model 03	Test Model 04	Test Model 05	Test Model 06	Test Model 07	Test Model 08	Test Model 09
11/01 19:10:00	26.183	30.918	29.193	29.274	29.316	29.091	29.154	29.203	29.465	29.467	29.450
11/01 19:20:00	26.067	30.663	28.655	28.731	28.776	28.625	28.683	28.732	29.036	29.044	29.035
11/01 19:30:00	25.950	30.418	28.372	28.448	28.497	28.376	28.435	28.486	28.844	28.857	28.854
11/01 19:40:00	25.833	30.181	28.090	28.166	28.219	28.157	28.217	28.271	28.676	28.693	28.695
11/01 19:50:00	25.717	29.952	27.862	27.940	27.997	27.967	28.029	28.084	28.532	28.553	28.559
11/01 20:00:00	25.600	29.731	27.667	27.746	27.806	27.794	27.857	27.915	28.403	28.427	28.438
11/01 20:10:00	25.467	29.515	27.473	27.555	27.619	27.620	27.686	27.746	28.269	28.298	28.314
11/01 20:20:00	25.333	29.304	27.282	27.366	27.435	27.448	27.516	27.579	28.134	28.168	28.189
11/01 20:30:00	25.200	29.099	27.097	27.183	27.256	27.280	27.350	27.416	28.001	28.039	28.065
11/01 20:40:00	25.067	28.899	26.918	27.006	27.082	27.114	27.186	27.255	27.868	27.910	27.941
11/01 20:50:00	24.933	28.704	26.742	26.832	26.912	26.950	27.024	27.095	27.736	27.783	27.818
11/01 21:00:00	24.800	28.513	26.570	26.661	26.744	26.787	26.863	26.937	27.604	27.655	27.695
11/01 21:10:00	24.683	28.327	26.408	26.500	26.586	26.633	26.709	26.785	27.480	27.534	27.578
11/01 21:20:00	24.567	28.147	26.251	26.344	26.432	26.481	26.559	26.636	27.358	27.415	27.462
11/01 21:30:00	24.450	27.971	26.097	26.191	26.280	26.332	26.410	26.487	27.235	27.295	27.346
11/01 21:40:00	24.333	27.798	25.946	26.040	26.131	26.183	26.262	26.340	27.113	27.175	27.230
11/01 21:50:00	24.217	27.628	25.798	25.892	25.984	26.036	26.116	26.195	26.991	27.056	27.113
11/01 22:00:00	24.100	27.462	25.652	25.746	25.839	25.892	25.971	26.051	26.868	26.936	26.996
11/01 22:10:00	23.983	27.301	25.509	25.603	25.697	25.750	25.829	25.910	26.747	26.817	26.880
11/01 22:20:00	23.867	27.144	25.368	25.463	25.557	25.610	25.690	25.770	26.626	26.698	26.764
11/01 22:30:00	23.750	26.990	25.230	25.324	25.419	25.472	25.552	25.633	26.506	26.580	26.647
11/01 22:40:00	23.633	26.840	25.094	25.188	25.283	25.336	25.416	25.498	26.386	26.462	26.532
11/01 22:50:00	23.517	26.694	24.960	25.054	25.150	25.203	25.283	25.365	26.267	26.345	26.417
11/01 23:00:00	23.400	26.552	24.828	24.922	25.018	25.072	25.152	25.234	26.149	26.229	26.302
11/01 23:10:00	23.283	26.412	24.702	24.792	24.889	24.943	25.024	25.106	26.031	26.112	26.188
11/01 23:20:00	23.167	26.274	24.579	24.669	24.761	24.816	24.897	24.980	25.913	25.997	26.075
11/01 23:30:00	23.050	26.140	24.456	24.547	24.640	24.696	24.772	24.856	25.797	25.882	25.963
11/01 23:40:00	22.933	26.008	24.335	24.426	24.521	24.578	24.656	24.739	25.681	25.768	25.852
11/01 23:50:00	22.817	25.879	24.215	24.306	24.402	24.460	24.540	24.623	25.565	25.655	25.741

APPENDIX 6

MEASURED AND SIMULATED MEAN AIR TEMPERATURE

TIME	AIR TEMP. BOTTOM	AIR TEMP. TOP	AIR TEMP. IDDLE	MEASURED MAT		SIMULATED MAT	
11/1/2010 1:00	27.456	27.407	27.333	27.399	27.576	25.53752507	25.564
11/1/2010 2:00	27.087	26.867	26.891	26.948	27.134	25.0147127	25.2232
11/1/2010 2:10	27.014	26.793	26.818	26.875		24.94492491	
11/1/2010 2:20	26.989	26.72	26.769	26.826		24.8751612	
11/1/2010 2:30	26.94	26.646	26.72	26.769		24.80530081	
11/1/2010 2:40	26.891	26.573	26.646	26.703		24.73570048	
11/1/2010 2:50	26.842	26.5	26.598	26.647		24.67000827	
11/1/2010 3:00	26.769	26.426	26.524	26.573	26.732	24.60367799	24.77246228
11/1/2010 3:10	26.695	26.329	26.426	26.483		24.53656775	
11/1/2010 3:20	26.646	26.256	26.378	26.427		24.46939631	
11/1/2010 3:30	26.598	26.207	26.329	26.378		24.40223991	
11/1/2010 3:40	26.549	26.134	26.28	26.321		24.33497353	
11/1/2010 3:50	26.5	26.061	26.207	26.256		24.26752999	
11/1/2010 4:00	26.451	26.012	26.158	26.207	26.345	24.21176004	24.37041126
11/1/2010 4:10	26.402	25.963	26.109	26.158		24.16006529	
11/1/2010 4:20	26.378	25.914	26.085	26.126		24.10811889	
11/1/2010 4:30	26.353	25.866	26.036	26.085		24.0559821	
11/1/2010 4:40	26.329	25.841	26.036	26.069		24.00412857	
11/1/2010 4:50	26.304	25.793	26.012	26.036		23.95265126	
11/1/2010 5:00	26.28	25.744	25.963	25.996	26.078	23.90703282	24.03132982
11/1/2010 5:10	26.256	25.695	25.939	25.963		23.86381185	
11/1/2010 5:20	26.231	25.671	25.914	25.939		23.82104288	
11/1/2010 5:30	26.182	25.623	25.866	25.890		23.77870618	
11/1/2010 5:40	26.158	25.598	25.841	25.866		23.73691126	
11/1/2010 5:50	26.158	25.574	25.817	25.850		23.71409312	
11/1/2010 6:00	26.158	25.55	25.817	25.842	25.892	23.71886934	23.7722391
11/1/2010 6:10	26.134	25.55	25.793	25.826		23.73240164	
11/1/2010 6:20	26.134	25.55	25.768	25.817		23.74635619	
11/1/2010 6:30	26.109	25.55	25.768	25.809		23.76517936	
11/1/2010 6:40	26.109	25.525	25.768	25.801		23.79013028	
11/1/2010 6:50	26.109	25.55	25.793	25.817		23.82048878	
11/1/2010 7:00	26.207	25.647	25.914	25.923	25.832	24.61279831	23.91122576
11/1/2010 7:10	26.378	25.841	26.061	26.093		24.89744353	
11/1/2010 7:20	26.426	25.866	26.085	26.126		25.04616188	
11/1/2010 7:30	26.451	25.89	26.109	26.150		25.13226168	
11/1/2010 7:40	26.451	25.914	26.134	26.166		25.20072144	
11/1/2010 7:50	26.5	25.963	26.182	26.215		25.27312305	
11/1/2010 8:00	26.5	26.036	26.231	26.256	26.168	25.3551891	25.15081678
11/1/2010 8:10	26.524	26.036	26.231	26.264		25.44679154	
11/1/2010 8:20	26.573	26.134	26.304	26.337		25.55138116	
11/1/2010 8:30	26.622	26.207	26.378	26.402		25.66348863	

TIME	AIR TEMP. BOTTOM	AIR TEMP. TOP	AIR TEMP. IDDLE	MEASURED MAT		SIMULATED MAT	
11/1/2010 8:40	26.671	26.304	26.475	26.483		25.78245937	
11/1/2010 8:50	26.72	26.402	26.573	26.565		25.90646797	
11/1/2010 9:00	26.793	26.573	26.72	26.695	26.458	26.03898185	25.73159509
11/1/2010 9:10	26.842	26.671	26.793	26.769		26.17982553	
11/1/2010 9:20	26.842	26.695	26.769	26.769		26.32707673	
11/1/2010 9:30	26.842	26.695	26.744	26.760		26.47745322	
11/1/2010 9:40	26.842	26.744	26.744	26.777		26.6309779	
11/1/2010 9:50	26.916	26.867	26.842	26.875		26.78675438	
11/1/2010 10:00	26.989	27.038	26.94	26.989	26.823	26.94406446	26.55769204
11/1/2010 10:10	27.038	27.186	27.014	27.079		27.10318008	
11/1/2010 10:20	27.136	27.382	27.21	27.243		27.26381146	
11/1/2010 10:30	27.308	27.85	27.554	27.571		27.42506048	
11/1/2010 10:40	27.358	27.974	27.604	27.645		27.58644633	
11/1/2010 10:50	27.382	27.998	27.604	27.661		27.74753434	
11/1/2010 11:00	27.456	28.196	27.677	27.776	27.496	27.90701527	27.50550799
11/1/2010 11:10	27.505	28.394	27.751	27.883		28.06554542	
11/1/2010 11:20	27.579	28.568	27.801	27.983		28.22322041	
11/1/2010 11:30	27.604	28.692	27.85	28.049		28.37819915	
11/1/2010 11:40	27.677	28.841	27.924	28.147		28.5301195	
11/1/2010 11:50	27.776	29.14	28.072	28.329		28.67902674	
11/1/2010 12:00	27.875	29.464	28.245	28.528	28.153	28.82395191	28.45001052
11/1/2010 12:10	28.023	29.84	28.468	28.777		28.96505198	
11/1/2010 12:20	28.072	29.941	28.518	28.844		29.10311935	
11/1/2010 12:30	28.147	30.066	28.568	28.927		29.23794367	
11/1/2010 12:40	28.245	30.293	28.642	29.060		29.37033883	
11/1/2010 12:50	28.221	30.217	28.568	29.002		29.50121104	
11/1/2010 13:00	28.32	30.419	28.667	29.135	28.958	29.62981844	29.30124722
11/1/2010 13:10	28.394	30.545	28.766	29.235		29.75707809	
11/1/2010 13:20	28.468	30.748	28.866	29.361		29.88405401	
11/1/2010 13:30	28.617	31.052	29.065	29.578		30.01198343	
11/1/2010 13:40	28.617	31.001	29.04	29.553		30.14162458	
11/1/2010 13:50	28.617	30.925	29.015	29.519		30.27320796	
11/1/2010 14:00	28.667	31.001	29.04	29.569	29.469	30.40566146	30.07893492
11/1/2010 14:10	28.742	31.128	29.115	29.662		30.5396154	
11/1/2010 14:20	28.866	31.382	29.29	29.846		30.67553695	
11/1/2010 14:30	28.941	31.51	29.389	29.947		30.80951114	
11/1/2010 14:40	29.09	31.842	29.64	30.191		30.94424335	
11/1/2010 14:50	29.24	32.124	29.84	30.401		31.08029542	
11/1/2010 15:00	29.19	31.97	29.715	30.292	30.056	31.21447938	30.87728027
11/1/2010 15:10	29.09	31.637	29.49	30.072		31.34600079	
11/1/2010 15:20	29.04	31.459	29.34	29.946		31.4748816	

TIME	AIR TEMP. BOTTOM	AIR TEMP. TOP	AIR TEMP. IDDLE	MEASURED MAT		SIMULATED MAT	
11/1/2010 15:30	29.04	31.433	29.34	29.938		31.59789481	
11/1/2010 15:40	29.09	31.382	29.315	29.929		31.71414875	
11/1/2010 15:50	29.065	31.255	29.29	29.870		31.82300943	
11/1/2010 16:00	29.065	31.128	29.24	29.811	29.928	31.92099026	31.64615427
11/1/2010 16:10	29.04	31.001	29.19	29.744		32.00317679	
11/1/2010 16:20	28.99	30.9	29.14	29.677		32.07521859	
11/1/2010 16:30	28.941	30.773	29.09	29.601		32.13207652	
11/1/2010 16:40	28.916	30.672	29.04	29.543		32.17195031	
11/1/2010 16:50	28.891	30.545	28.99	29.475		32.19473612	
11/1/2010 17:00	28.841	30.419	28.916	29.392	29.572	32.19798231	32.12919011
11/1/2010 17:10	28.816	30.293	28.866	29.325		32.1845458	
11/1/2010 17:20	28.766	30.167	28.791	29.241		32.1517728	
11/1/2010 17:30	28.717	30.041	28.717	29.158		32.11266635	
11/1/2010 17:40	28.667	29.916	28.642	29.075		32.06260251	
11/1/2010 17:50	28.593	29.765	28.568	28.975		32.00156689	
11/1/2010 18:00	28.518	29.64	28.493	28.884	29.110	31.93001428	32.07386144
11/1/2010 18:10	28.468	29.49	28.394	28.784		31.8489837	
11/1/2010 18:20	28.394	29.365	28.32	28.693		31.76021144	
11/1/2010 18:30	28.345	29.24	28.245	28.610		31.66557642	
11/1/2010 18:40	28.295	29.09	28.171	28.519		31.56669486	
11/1/2010 18:50	28.245	28.99	28.097	28.444		31.46483958	
11/1/2010 19:00	28.196	28.866	28.048	28.370	28.570	29.4673223	31.295605
11/1/2010 19:10	27.653	28.369	27.579	27.867		29.04377827	
11/1/2010 19:20	27.308	27.875	27.259	27.481		28.85699214	
11/1/2010 19:30	27.136	27.604	27.087	27.276		28.69277745	
11/1/2010 19:40	27.063	27.431	26.989	27.161		28.55258403	
11/1/2010 19:50	26.989	27.308	26.891	27.063		28.42706747	
11/1/2010 20:00	26.94	27.21	26.818	26.989	27.306	28.29828496	28.64524739
11/1/2010 20:10	26.891	27.087	26.769	26.916		28.16789199	
11/1/2010 20:20	26.867	27.014	26.72	26.867		28.03867204	
11/1/2010 20:30	26.842	26.916	26.671	26.810		27.91046765	
11/1/2010 20:40	26.793	26.842	26.622	26.752		27.78262363	
11/1/2010 20:50	26.744	26.769	26.573	26.695		27.65483825	
11/1/2010 21:00	26.695	26.695	26.5	26.630	26.778	27.53360191	27.848
11/1/2010 21:10	26.646	26.622	26.451	26.573		27.41458137	
11/1/2010 21:20	26.622	26.524	26.426	26.524		27.29520095	
11/1/2010 21:30	26.573	26.475	26.353	26.467		27.17549749	
11/1/2010 21:40	26.524	26.426	26.304	26.418		27.05580856	
11/1/2010 21:50	26.5	26.353	26.28	26.378		26.9362414	
11/1/2010 22:00	26.451	26.304	26.231	26.329	26.448	26.81711085	27.116
11/1/2010 22:10	26.426	26.231	26.182	26.280		26.69837384	

TIME	AIR TEMP. BOTTOM	AIR TEMP. TOP	AIR TEMP. IDDLE	MEASURED MAT		SIMULATED MAT	
11/1/2010 22:20	26.402	26.182	26.134	26.239		26.58003539	
11/1/2010 22:30	26.378	26.134	26.109	26.207		26.4622034	
11/1/2010 22:40	26.353	26.109	26.085	26.182		26.34500458	
11/1/2010 22:50	26.304	26.036	26.036	26.125		26.22868686	
11/1/2010 23:00	26.28	25.987	25.987	26.085	26.186	26.11243354	26.404
11/1/2010 23:10	26.256	25.963	25.963	26.061		25.99682735	
11/1/2010 23:20	26.207	25.914	25.939	26.020		25.88210756	
11/1/2010 23:30	26.182	25.866	25.89	25.979		25.76817919	
11/1/2010 23:40	26.134	25.793	25.841	25.923		25.65491125	
11/1/2010 23:50	26.085	25.744	25.793	25.874		25.54219956	

APPENDIX 7

MEASURED AND SIMULATED MEAN RADIANT TEMPERATURE

MEASURED AND SIMULATED MEAN RADIANT TEMPERATURE

Time, GMT+00:00	Temp 1, °C	Temp 2, °C	Temp 3, °C	T1*A	T2*A	T3*A	SUM_RT	MEASURED MRT		SIMULATED MRT	
11/1/2010 0:00	28.15	28.22	28.12	53.20	53.34	53.15	159.69	28.16			
11/1/2010 0:10	27.97	28.15	28.02	52.87	53.20	52.96	159.03	28.05		27.37	
11/1/2010 0:20	27.85	28.05	27.95	52.64	53.01	52.82	158.47	27.95		27.28	
11/1/2010 0:30	27.70	27.97	27.85	52.36	52.87	52.64	157.86	27.84		27.20	
11/1/2010 0:40	27.58	27.88	27.75	52.12	52.68	52.45	157.26	27.74		27.12	
11/1/2010 0:50	27.48	27.80	27.68	51.94	52.54	52.31	156.79	27.65		27.05	
11/1/2010 1:00	27.38	27.73	27.58	51.75	52.40	52.12	156.28	27.56	27.85	26.98	27.20
11/1/2010 1:10	27.28	27.65	27.51	51.57	52.26	51.98	155.82	27.48		26.91	
11/1/2010 1:20	27.16	27.55	27.41	51.33	52.08	51.80	155.21	27.37		26.84	
11/1/2010 1:30	27.06	27.51	27.33	51.15	51.98	51.66	154.79	27.30		26.76	
11/1/2010 1:40	26.97	27.41	27.24	50.96	51.80	51.47	154.24	27.20		26.68	
11/1/2010 1:50	26.87	27.33	27.16	50.78	51.66	51.33	153.77	27.12		26.61	
11/1/2010 2:00	26.77	27.28	27.09	50.59	51.57	51.19	153.35	27.05	27.30	26.53	26.76
11/1/2010 2:10	26.70	27.21	27.01	50.45	51.43	51.06	152.94	26.97		26.46	
11/1/2010 2:20	26.62	27.14	26.94	50.32	51.29	50.92	152.52	26.90		26.39	
11/1/2010 2:30	26.55	27.09	26.87	50.18	51.19	50.78	152.15	26.83		26.32	
11/1/2010 2:40	26.45	27.01	26.82	49.99	51.06	50.69	151.73	26.76		26.25	
11/1/2010 2:50	26.38	26.94	26.74	49.85	50.92	50.55	151.32	26.69		26.18	
11/1/2010 3:00	26.30	26.87	26.67	49.71	50.78	50.41	150.90	26.61	26.83	26.11	26.32
11/1/2010 3:10	26.21	26.79	26.60	49.53	50.64	50.27	150.44	26.53		26.05	
11/1/2010 3:20	26.13	26.74	26.52	49.39	50.55	50.13	150.07	26.47		25.98	
11/1/2010 3:30	26.06	26.67	26.48	49.26	50.41	50.04	149.70	26.40		25.91	
11/1/2010 3:40	25.99	26.60	26.40	49.12	50.27	49.90	149.29	26.33		25.84	
11/1/2010 3:50	25.91	26.55	26.35	48.98	50.18	49.81	148.96	26.27		25.77	
11/1/2010 4:00	25.87	26.50	26.28	48.89	50.09	49.67	148.64	26.22	26.40	25.70	25.91
11/1/2010 4:10	25.79	26.43	26.23	48.75	49.95	49.58	148.27	26.15		25.63	

Time, GMT+00:00	Temp 1, °C	Temp 2, °C	Temp 3, °C	T1*A	T2*A	T3*A	SUM_RT	MEASURED MRT		SIMULATED MRT	
11/1/2010 4:20	25.72	26.38	26.18	48.61	49.85	49.48	147.95	26.09		25.56	
11/1/2010 4:30	25.67	26.30	26.13	48.52	49.71	49.39	147.63	26.04		25.50	
11/1/2010 4:40	25.62	26.28	26.09	48.43	49.67	49.30	147.40	26.00		25.43	
11/1/2010 4:50	25.62	26.23	26.04	48.43	49.58	49.21	147.21	25.96		25.37	
11/1/2010 5:00	25.55	26.18	26.01	48.29	49.48	49.16	146.94	25.91	26.05	25.30	25.50
11/1/2010 5:10	25.53	26.13	25.96	48.24	49.39	49.07	146.71	25.87		25.24	
11/1/2010 5:20	25.50	26.09	25.91	48.20	49.30	48.98	146.48	25.83		25.17	
11/1/2010 5:30	25.45	26.04	25.89	48.11	49.21	48.93	146.25	25.79		25.11	
11/1/2010 5:40	25.43	25.99	25.84	48.06	49.12	48.84	146.01	25.75		25.05	
11/1/2010 5:50	25.40	25.99	25.84	48.01	49.12	48.84	145.97	25.74		24.99	
11/1/2010 6:00	25.40	25.94	25.82	48.01	49.02	48.79	145.83	25.72	25.80	24.97	25.11
11/1/2010 6:10	25.40	25.91	25.77	48.01	48.98	48.70	145.69	25.70		24.93	
11/1/2010 6:20	25.38	25.89	25.77	47.97	48.93	48.70	145.60	25.68		24.91	
11/1/2010 6:30	25.40	25.87	25.74	48.01	48.89	48.66	145.56	25.67		24.89	
11/1/2010 6:40	25.38	25.84	25.74	47.97	48.84	48.66	145.46	25.66		24.87	
11/1/2010 6:50	25.40	25.82	25.72	48.01	48.79	48.61	145.42	25.65		24.87	
11/1/2010 7:00	25.70	25.91	25.87	48.56	48.98	48.89	146.43	25.83	25.67	24.88	24.89
11/1/2010 7:10	25.60	25.84	25.77	48.38	48.84	48.70	145.92	25.74		24.90	
11/1/2010 7:20	25.60	25.82	25.77	48.38	48.79	48.70	145.88	25.73		25.03	
11/1/2010 7:30	25.62	25.82	25.77	48.43	48.79	48.70	145.92	25.74		25.11	
11/1/2010 7:40	25.65	25.82	25.79	48.47	48.79	48.75	146.02	25.75		25.17	
11/1/2010 7:50	25.72	25.82	25.79	48.61	48.79	48.75	146.15	25.78		25.23	
11/1/2010 8:00	25.77	25.79	25.79	48.70	48.75	48.75	146.20	25.78	25.75	25.31	25.09
11/1/2010 8:10	25.84	25.79	25.82	48.84	48.75	48.79	146.38	25.82		25.39	
11/1/2010 8:20	25.96	25.79	25.87	49.07	48.75	48.89	146.71	25.87		25.47	
11/1/2010 8:30	26.11	25.82	25.89	49.35	48.79	48.93	147.07	25.94		25.58	
11/1/2010 8:40	26.23	25.84	25.91	49.58	48.84	48.98	147.39	26.00		25.68	
11/1/2010 8:50	26.40	25.84	25.96	49.90	48.84	49.07	147.81	26.07		25.80	
11/1/2010 9:00	26.60	25.89	26.04	50.27	48.93	49.21	148.41	26.17	25.94	25.91	25.58

Time, GMT+00:00	Temp 1, °C	Temp 2, °C	Temp 3, °C	T1*A	T2*A	T3*A	SUM_RT	MEASURED MRT		SIMULATED MRT	
11/1/2010 9:10	26.74	25.91	26.06	50.55	48.98	49.26	148.78	26.24		26.04	
11/1/2010 9:20	26.87	25.91	26.06	50.78	48.98	49.26	149.01	26.28		26.17	
11/1/2010 9:30	26.99	25.94	26.06	51.01	49.02	49.26	149.29	26.33		26.31	
11/1/2010 9:40	27.21	25.99	26.13	51.43	49.12	49.39	149.94	26.44		26.46	
11/1/2010 9:50	27.43	26.04	26.21	51.84	49.21	49.53	150.58	26.56		26.60	
11/1/2010 10:00	27.65	26.06	26.28	52.26	49.26	49.67	151.19	26.66	26.37	26.75	26.32
11/1/2010 10:10	27.88	26.13	26.35	52.68	49.39	49.81	151.88	26.79		26.90	
11/1/2010 10:20	28.17	26.21	26.48	53.24	49.53	50.04	152.81	26.95		27.05	
11/1/2010 10:30	28.67	26.30	26.67	54.18	49.71	50.41	154.30	27.21		27.20	
11/1/2010 10:40	28.77	26.33	26.62	54.37	49.76	50.32	154.45	27.24		27.36	
11/1/2010 10:50	29.04	26.38	26.72	54.89	49.85	50.50	155.24	27.38		27.51	
11/1/2010 11:00	29.39	26.48	26.79	55.55	50.04	50.64	156.22	27.55	27.11	27.67	27.21
11/1/2010 11:10	29.74	26.55	26.89	56.21	50.18	50.82	157.21	27.73		27.82	
11/1/2010 11:20	30.07	26.65	26.97	56.82	50.36	50.96	158.15	27.89		27.98	
11/1/2010 11:30	30.29	26.70	26.99	57.25	50.45	51.01	158.72	27.99		28.13	
11/1/2010 11:40	30.70	26.82	27.19	58.02	50.69	51.38	160.08	28.23		28.28	
11/1/2010 11:50	31.10	26.94	27.31	58.78	50.92	51.61	161.31	28.45		28.43	
11/1/2010 12:00	31.51	27.04	27.46	59.55	51.10	51.89	162.55	28.67	28.06	28.57	28.13
11/1/2010 12:10	31.97	27.16	27.60	60.42	51.33	52.17	163.93	28.91		28.71	
11/1/2010 12:20	32.25	27.24	27.63	60.96	51.47	52.22	164.65	29.04		28.85	
11/1/2010 12:30	32.69	27.36	27.78	61.79	51.71	52.50	165.99	29.28		28.99	
11/1/2010 12:40	33.03	27.43	27.75	62.42	51.84	52.45	166.72	29.40		29.12	
11/1/2010 12:50	33.31	27.55	27.85	62.96	52.08	52.64	167.68	29.57		29.25	
11/1/2010 13:00	33.68	27.65	27.95	63.65	52.26	52.82	168.74	29.76	29.24	29.38	28.98
11/1/2010 13:10	33.94	27.78	28.05	64.15	52.50	53.01	169.65	29.92		29.50	
11/1/2010 13:20	34.20	27.90	28.17	64.64	52.73	53.24	170.61	30.09		29.63	
11/1/2010 13:30	34.47	28.02	28.30	65.14	52.96	53.48	171.58	30.26		29.75	
11/1/2010 13:40	34.52	28.12	28.30	65.24	53.15	53.48	171.87	30.31		29.88	
11/1/2010 13:50	34.62	28.20	28.32	65.44	53.29	53.52	172.25	30.38		30.01	

Time, GMT+00:00	Temp 1, °C	Temp 2, °C	Temp 3, °C	T1*A	T2*A	T3*A	SUM_RT	MEASURED MRT		SIMULATED MRT	
11/1/2010 14:00	34.86	28.35	28.44	65.89	53.57	53.76	173.22	30.55	30.19	30.14	29.75
11/1/2010 14:10	34.89	28.42	28.49	65.94	53.71	53.85	173.50	30.60		30.27	
11/1/2010 14:20	35.02	28.54	28.62	66.19	53.95	54.09	174.22	30.73		30.40	
11/1/2010 14:30	35.13	28.67	28.79	66.39	54.18	54.41	174.99	30.86		30.54	
11/1/2010 14:40	35.29	28.77	28.97	66.69	54.37	54.74	175.81	31.01		30.66	
11/1/2010 14:50	35.42	28.89	29.07	66.95	54.60	54.93	176.48	31.13		30.80	
11/1/2010 15:00	35.26	28.92	28.84	66.65	54.65	54.51	175.81	31.01	30.86	30.93	30.53
11/1/2010 15:10	35.24	28.94	28.82	66.59	54.70	54.46	175.75	31.00		31.06	
11/1/2010 15:20	35.21	29.02	28.82	66.54	54.84	54.46	175.84	31.01		31.18	
11/1/2010 15:30	35.05	29.07	28.87	66.24	54.93	54.56	175.73	30.99		31.31	
11/1/2010 15:40	34.65	29.12	28.87	65.49	55.03	54.56	175.07	30.88		31.42	
11/1/2010 15:50	34.23	29.12	28.84	64.69	55.03	54.51	174.23	30.73		31.53	
11/1/2010 16:00	33.86	29.12	28.79	64.00	55.03	54.41	173.44	30.59	30.92	31.63	31.30
11/1/2010 16:10	33.57	29.07	28.74	63.45	54.93	54.32	172.71	30.46		31.72	
11/1/2010 16:20	33.31	29.04	28.69	62.96	54.89	54.23	172.08	30.35		31.79	
11/1/2010 16:30	33.05	29.02	28.62	62.47	54.84	54.09	171.39	30.23		31.85	
11/1/2010 16:40	32.82	28.97	28.57	62.03	54.74	53.99	170.77	30.12		31.90	
11/1/2010 16:50	32.56	28.92	28.49	61.54	54.65	53.85	170.05	29.99		31.93	
11/1/2010 17:00	32.28	28.89	28.42	61.01	54.60	53.71	169.32	29.86	30.23	31.94	31.84
11/1/2010 17:10	32.02	28.82	28.35	60.52	54.46	53.57	168.55	29.73		31.93	
11/1/2010 17:20	31.77	28.77	28.27	60.04	54.37	53.43	167.83	29.60		31.91	
11/1/2010 17:30	31.54	28.72	28.20	59.60	54.28	53.29	167.17	29.48		31.86	
11/1/2010 17:40	31.31	28.64	28.15	59.17	54.13	53.20	166.50	29.37		31.82	
11/1/2010 17:50	31.10	28.59	28.05	58.78	54.04	53.01	165.84	29.25		31.77	
11/1/2010 18:00	30.90	28.52	27.97	58.40	53.90	52.87	165.17	29.13	29.48	31.71	31.86
11/1/2010 18:10	30.67	28.44	27.90	57.97	53.76	52.73	164.46	29.01		31.64	
11/1/2010 18:20	30.47	28.39	27.83	57.59	53.66	52.59	163.84	28.90		31.56	
11/1/2010 18:30	30.27	28.32	27.75	57.21	53.52	52.45	163.18	28.78		31.47	
11/1/2010 18:40	30.09	28.25	27.68	56.87	53.38	52.31	162.56	28.67		31.38	

Time, GMT+00:00	Temp 1, °C	Temp 2, °C	Temp 3, °C	T1*A	T2*A	T3*A	SUM_RT	MEASURED MRT		SIMULATED MRT	
11/1/2010 18:50	29.89	28.17	27.63	56.49	53.24	52.22	161.95	28.56		31.28	
11/1/2010 19:00	29.62	28.15	27.60	55.97	53.20	52.17	161.34	28.46	28.78	31.18	31.46
11/1/2010 19:10	29.24	27.73	27.19	55.26	52.40	51.38	159.05	28.05		31.08	
11/1/2010 19:20	28.92	27.60	27.14	54.65	52.17	51.29	158.11	27.89		30.77	
11/1/2010 19:30	28.64	27.51	27.04	54.13	51.98	51.10	157.22	27.73		30.59	
11/1/2010 19:40	28.42	27.41	26.97	53.71	51.80	50.96	156.47	27.60		30.46	
11/1/2010 19:50	28.20	27.31	26.89	53.29	51.61	50.82	155.73	27.47		30.33	
11/1/2010 20:00	28.02	27.24	26.82	52.96	51.47	50.69	155.12	27.36	27.75	30.21	30.65
11/1/2010 20:10	27.83	27.16	26.77	52.59	51.33	50.59	154.52	27.25		30.08	
11/1/2010 20:20	27.70	27.06	26.70	52.36	51.15	50.45	153.96	27.15		29.96	
11/1/2010 20:30	27.55	27.01	26.65	52.08	51.06	50.36	153.49	27.07		29.84	
11/1/2010 20:40	27.43	26.94	26.60	51.84	50.92	50.27	153.03	26.99		29.72	
11/1/2010 20:50	27.28	26.87	26.55	51.57	50.78	50.18	152.52	26.90		29.61	
11/1/2010 21:00	27.16	26.79	26.48	51.33	50.64	50.04	152.01	26.81	27.07	29.49	29.84
11/1/2010 21:10	27.06	26.74	26.43	51.15	50.55	49.95	151.64	26.74		29.37	
11/1/2010 21:20	26.97	26.67	26.40	50.96	50.41	49.90	151.27	26.68		29.26	
11/1/2010 21:30	26.84	26.60	26.33	50.73	50.27	49.76	150.76	26.59		29.14	
11/1/2010 21:40	26.74	26.55	26.28	50.55	50.18	49.67	150.39	26.52		29.02	
11/1/2010 21:50	26.67	26.50	26.26	50.41	50.09	49.62	150.12	26.48		28.91	
11/1/2010 22:00	26.60	26.45	26.21	50.27	49.99	49.53	149.79	26.42	26.60	28.79	29.14
11/1/2010 22:10	26.50	26.40	26.18	50.09	49.90	49.48	149.47	26.36		28.67	
11/1/2010 22:20	26.43	26.33	26.13	49.95	49.76	49.39	149.10	26.30		28.56	
11/1/2010 22:30	26.35	26.30	26.09	49.81	49.71	49.30	148.82	26.25		28.44	
11/1/2010 22:40	26.30	26.23	26.06	49.71	49.58	49.26	148.55	26.20		28.33	
11/1/2010 22:50	26.23	26.18	26.01	49.58	49.48	49.16	148.22	26.14		28.22	
11/1/2010 23:00	26.18	26.13	25.99	49.48	49.39	49.12	147.99	26.10	26.25	28.11	28.45
11/1/2010 23:10	26.11	26.09	25.96	49.35	49.30	49.07	147.72	26.05		28.00	
11/1/2010 23:20	26.04	26.04	25.91	49.21	49.21	48.98	147.39	26.00		27.89	
11/1/2010 23:30	25.96	25.99	25.87	49.07	49.12	48.89	147.07	25.94		27.78	

APPENDIX 8

COEFFICIENT OF VARIANCE OF ROOT MEAN SQUARE ERROR

TIME	MEASURED MAT	SIMULATED MAT	TIME	Measured	Simulated
11/8/2010 0:00	25.785	28.198	11/2/2010 0:00	25.942	27.781
11/8/2010 1:00	25.470	27.600	11/2/2010 1:00	25.650	27.166
11/8/2010 2:00	25.147	27.027	11/2/2010 2:00	25.399	26.600
11/8/2010 3:00	24.902	26.524	11/2/2010 3:00	25.166	26.067
11/8/2010 4:00	24.688	26.104	11/2/2010 4:00	24.968	25.593
11/8/2010 5:00	24.500	25.728	11/2/2010 5:00	24.805	25.151
11/8/2010 6:00	24.330	25.460	11/2/2010 6:00	24.665	24.743
11/8/2010 7:00	24.257	25.716	11/2/2010 7:00	24.458	24.501
11/8/2010 8:00	24.535	27.266	11/2/2010 8:00	24.536	24.637
11/8/2010 9:00	24.815	28.139	11/2/2010 9:00	24.739	25.045
11/8/2010 10:00	25.193	29.130	11/2/2010 10:00	25.490	25.668
11/8/2010 11:00	25.907	30.767	11/2/2010 11:00	26.582	26.493
11/8/2010 12:00	26.733	32.035	11/2/2010 12:00	27.868	27.497
11/8/2010 13:00	27.147	32.965	11/2/2010 13:00	29.297	28.510
11/8/2010 14:00	27.525	33.667	11/2/2010 14:00	30.534	29.542
11/8/2010 15:00	27.870	34.211	11/2/2010 15:00	31.735	30.642
11/8/2010 16:00	27.872	34.486	11/2/2010 16:00	32.636	31.671
11/8/2010 17:00	27.922	34.434	11/2/2010 17:00	33.039	32.450
11/8/2010 18:00	27.833	34.094	11/2/2010 18:00	32.835	32.758
11/8/2010 19:00	27.702	33.189	11/2/2010 19:00	32.325	32.609
11/8/2010 20:00	27.186	30.188	11/2/2010 20:00	31.394	31.900
11/8/2010 21:00	26.880	29.380	11/2/2010 21:00	31.011	31.163
11/8/2010 22:00	26.680	28.630	11/2/2010 22:00	30.472	30.537
11/8/2010 23:00	26.500	27.918	11/2/2010 23:00	29.934	29.937
11/9/2010 0:00	26.275	27.268	11/3/2010 0:00	29.428	29.359
11/9/2010 1:00	26.056	26.650	11/3/2010 1:00	28.953	28.789
11/9/2010 2:00	25.814	26.045	11/3/2010 2:00	28.475	28.226
11/9/2010 3:00	25.598	25.514	11/3/2010 3:00	28.003	27.674
11/9/2010 4:00	25.412	25.028	11/3/2010 4:00	27.581	27.145
11/9/2010 5:00	25.315	24.578	11/3/2010 5:00	27.238	26.652
11/9/2010 6:00	25.195	24.228	11/3/2010 6:00	26.929	26.230
11/9/2010 7:00	25.132	24.393	11/3/2010 7:00	26.570	25.926
11/9/2010 8:00	25.358	26.06	11/3/2010 8:00	26.485	25.947
11/9/2010 9:00	25.916	26.776	11/3/2010 9:00	26.606	26.232
11/9/2010 10:00	26.678	27.775	11/3/2010 10:00	26.979	26.742
11/9/2010 11:00	27.404	28.929	11/3/2010 11:00	27.662	27.405
11/9/2010 12:00	28.255	30.036	11/3/2010 12:00	28.575	28.146
11/9/2010 13:00	29.181	30.915	11/3/2010 13:00	29.549	28.936
11/9/2010 14:00	30.054	31.556	11/3/2010 14:00	30.326	29.684

11/9/2010 15:00	30.920	32.044	11/3/2010 15:00	30.864	30.239
11/9/2010 16:00	31.503	32.414	11/3/2010 16:00	31.409	30.550
11/9/2010 17:00	31.868	32.618	11/3/2010 17:00	31.631	30.579
11/9/2010 18:00	31.787	32.454	11/3/2010 18:00	31.491	30.342
11/9/2010 19:00	31.565	31.618	11/3/2010 19:00	31.137	29.978
11/9/2010 20:00	30.127	28.922	11/3/2010 20:00	30.311	29.425
11/9/2010 21:00	29.515	28.287	11/3/2010 21:00	29.609	28.884
11/9/2010 22:00	29.217	27.716	11/3/2010 22:00	29.023	28.381
11/9/2010 23:00	28.835	27.169	11/3/2010 23:00	28.502	27.877
11/10/2010 0:00	28.425	26.683	11/4/2010 0:00	28.007	27.370
11/10/2010 1:00	27.989	26.394	11/4/2010 1:00	27.554	26.866
11/10/2010 2:00	27.621	26.206	11/4/2010 2:00	27.123	26.385
11/10/2010 3:00	27.291	26.027	11/4/2010 3:00	26.700	25.924
11/10/2010 4:00	27.081	25.923	11/4/2010 4:00	26.313	25.496
11/10/2010 5:00	26.788	25.813	11/4/2010 5:00	25.942	25.085
11/10/2010 6:00	26.607	25.693	11/4/2010 6:00	25.594	24.707
11/10/2010 7:00	26.531	25.794	11/4/2010 7:00	25.346	24.537
11/10/2010 8:00	26.938	26.414	11/4/2010 8:00	25.432	24.778
11/10/2010 9:00	27.393	26.817	11/4/2010 9:00	25.856	25.325
11/10/2010 10:00	27.774	27.484	11/4/2010 10:00	26.597	26.103
11/10/2010 11:00	28.545	28.351	11/4/2010 11:00	27.487	27.028
11/10/2010 12:00	29.271	29.361	11/4/2010 12:00	28.460	27.988
11/10/2010 13:00	29.884	30.363	11/4/2010 13:00	29.507	28.894
11/10/2010 14:00	30.681	31.235	11/4/2010 14:00	30.444	29.793
11/10/2010 15:00	31.351	31.959	11/4/2010 15:00	31.381	30.721
11/10/2010 16:00	31.844	32.524	11/4/2010 16:00	32.214	31.624
11/10/2010 17:00	32.179	32.849	11/4/2010 17:00	32.655	32.365
11/10/2010 18:00	32.065	32.864	11/4/2010 18:00	32.528	32.669
11/10/2010 19:00	31.876	32.42	11/4/2010 19:00	32.013	32.510
11/10/2010 20:00	30.763	30.699	11/4/2010 20:00	30.826	31.801
11/10/2010 21:00	30.177	30.291	11/4/2010 21:00	29.999	31.042
11/10/2010 22:00	29.780	29.881	11/4/2010 22:00	29.272	30.383
11/10/2010 23:00	29.296	29.489	11/4/2010 23:00	28.630	29.745
11/11/2010 0:00	27.527	24.742	11/5/2010 0:00	28.051	29.123
11/11/2010 1:00	26.885	24.601	11/5/2010 1:00	27.543	28.509
11/11/2010 2:00	26.261	24.506	11/5/2010 2:00	27.122	27.901
11/11/2010 3:00	25.831	24.374	11/5/2010 3:00	26.762	27.287
11/11/2010 4:00	25.432	24.273	11/5/2010 4:00	26.501	26.704
11/11/2010 5:00	25.094	24.166	11/5/2010 5:00	26.233	26.182
11/11/2010 6:00	24.765	24.097	11/5/2010 6:00	25.989	25.723
11/11/2010 7:00	24.542	24.281	11/5/2010 7:00	25.786	25.482

11/11/2010 8:00	24.852	24.744	11/5/2010 8:00	25.829	25.747
11/11/2010 9:00	25.244	25.392	11/5/2010 9:00	25.928	26.350
11/11/2010 10:00	25.542	26.369	11/5/2010 10:00	26.207	27.123
11/11/2010 11:00	26.210	27.524	11/5/2010 11:00	26.878	28.011
11/11/2010 12:00	27.143	28.683	11/5/2010 12:00	27.794	28.877
11/11/2010 13:00	27.668	29.735	11/5/2010 13:00	29.083	29.710
11/11/2010 14:00	28.241	30.659	11/5/2010 14:00	30.410	30.539
11/11/2010 15:00	29.063	31.395	11/5/2010 15:00	31.590	31.329
11/11/2010 16:00	29.543	31.834	11/5/2010 16:00	32.454	31.978
11/11/2010 17:00	29.88	31.928	11/5/2010 17:00	32.819	32.435
11/11/2010 18:00	29.767	31.745	11/5/2010 18:00	32.663	32.527
11/11/2010 19:00	29.594	31.213	11/5/2010 19:00	32.207	32.290
11/11/2010 20:00	28.718	29.592	11/5/2010 20:00	31.239	31.628
11/11/2010 21:00	28.235	29.121	11/5/2010 21:00	30.396	30.943
11/11/2010 22:00	27.826	28.685	11/5/2010 22:00	29.707	30.332
11/11/2010 23:00	27.419	28.261	11/5/2010 23:00	29.085	29.729
11/12/2010 0:00	27.062	27.853	11/6/2010 0:00	28.538	29.129
11/12/2010 1:00	26.695	27.45	11/6/2010 1:00	28.049	28.534
11/12/2010 2:00	26.352	27.047	11/6/2010 2:00	27.673	27.953
11/12/2010 3:00	26.101	26.703	11/6/2010 3:00	27.331	27.391
11/12/2010 4:00	25.908	26.392	11/6/2010 4:00	26.963	26.855
11/12/2010 5:00	25.698	26.136	11/6/2010 5:00	26.625	26.334
11/12/2010 6:00	25.536	25.958	11/6/2010 6:00	26.316	25.853
11/12/2010 7:00	25.486	26.010	11/6/2010 7:00	26.105	25.573
11/12/2010 8:00	25.782	26.600	11/6/2010 8:00	26.057	25.776
11/12/2010 9:00	26.107	26.899	11/6/2010 9:00	25.760	26.351
11/12/2010 10:00	26.709	27.542	11/6/2010 10:00	25.328	27.188
11/12/2010 11:00	27.208	28.484	11/6/2010 11:00	25.280	28.192
11/12/2010 12:00	28.090	29.526	11/6/2010 12:00	25.744	29.163
11/12/2010 13:00	28.660	30.543	11/6/2010 13:00	26.334	30.043
11/12/2010 14:00	29.415	31.500	11/6/2010 14:00	26.978	30.949
11/12/2010 15:00	29.914	32.266	11/6/2010 15:00	27.646	31.972
11/12/2010 16:00	30.095	32.655	11/6/2010 16:00	28.095	32.925
11/12/2010 17:00	30.266	32.633	11/6/2010 17:00	28.223	33.526
11/12/2010 18:00	29.743	32.335	11/6/2010 18:00	28.090	33.605
11/12/2010 19:00	29.415	31.667	11/6/2010 19:00	27.809	33.332
11/12/2010 20:00	28.268	29.518	11/6/2010 20:00		
11/12/2010 21:00	27.746	28.926	11/6/2010 21:00		
11/12/2010 22:00	27.404	28.374	11/6/2010 22:00		
11/12/2010 23:00	27.033	27.822	11/6/2010 23:00		
11/13/2010 0:00	26.978	27.73			

11/13/2010 1:00	26.921	27.638			
11/13/2010 2:00	26.863	27.546			
11/13/2010 3:00	26.800	27.454			
11/13/2010 4:00	26.734	27.362			
11/13/2010 5:00	25.094	24.166			
11/13/2010 6:00	24.765	24.097			
11/13/2010 7:00	24.542	24.281			
SUM	2683.105	2723.286		3388.473	3440.224
DIFF(DATA-PRED)	40.181			51.751	
DIFF SQUARED (A)	1614.512761			2678.191103	
DATA SETS (n)	96			120	120
p	1			1	1
n-p	95			119	
MEAN DATA	27.949			28.237	
DIFF SQD/(n-p)	16.99487117			22.50580759	
SQRT	4.122483617			4.744028625	
CV(MRSE)/100	0.147500164			0.168005907	
CV(MRSE)[%]	14.75001639			16.8005907	

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis submission is my own work towards the PhD and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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Certified by:

PROF. JOSUAH AYARWAH
…………………………… ……………………..…. ….…..………………….
Head of Department's Name Signature Date

DEDICATION

Dedicated with the deepest love and respect to my family:

Mrs. Esi Botsewa Amos-Abanyie, Mr.Papa Mbeah Amos-Abanyie, Mr. Joojo Mbeah Amos-Abanyie, Mr.Yookow Mbeah Amos-Abanyie and Mrs. Francesca Amos-Abanyie (Mummy)

For their love and support

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ABSTRACT

There is lack of empirical data and practical advice on thermal performance of building envelope materials used in Ghana in figures readily appreciated by building designers, prospective builders and facility managers. There is predominant use of low mass sandcrete blocks and adoption of universal building designs with extensive use of glazing that is characterized by high solar and conductive heat gains. Relatively lower night-time outdoor air temperatures are not harnessed to contribute in maintaining thermal comfort in buildings.

This research aimed to advance knowledge in passive cooling of buildings in warm-humid climates by exploring the integration of passive and low energy cooling techniques in building design in Ghana to enhance thermal comfort and reduce energy use for space cooling. Adopting building performance simulation and experimental approaches, the effects of thermal mass, window size and night-time ventilation on peak indoor air temperature (PIAT) were evaluated using three variables: (1) the maximum temperatures, (2) the temperature difference ratio (TDR) and (3) the percentage of overheated hours. Following the simulations, experimental cells were designed and constructed based on the specifications of the best performing simulation models. Measured data from the experiments were used to validate the simulated results employing both graphical and statistical analyses.

From the study it was observed that an increase in thermal mass by changing to materials of higher densities led to a reduction in peak indoor air temperature. Baked bricks (BB) and concrete (CONC) reduced peak indoor air temperature (PIAT) below that of solid sandcrete blocks (SSB) by 0.7°C and 3°C respectively. Increased thermal mass also led to an increase in the number of hours of delay of PIAT occurrence after of peak outdoor air temperature (POAT), with SSB, BB and CONC having delays of 2, 3 and 5 hours respectively.

From the analysis, the study also revealed that reduction in window size lead to a reduction in PIAT. Even though the model with no windows exhibited the best performance, windows are important sources of natural light and views of nature and outdoor environment that should not be completely eliminated.

From the study, activation of night-time ventilation at a rate of up to 10ACH, PIAT was reduced for all the thermal masses of various window to floor ratios tested. Concrete resulted in a decrease of PIAT of between 0.17°C and 0.19°C below that of the corresponding none night-time ventilated concrete models. With a ventilation rate of 10ACH, BB obtained a reduction on PIAT temperature of between 0.32°C and 0.04°C below that of the baked bricks

models with no night-time ventilation. Solid sandcrete blocks with ventilation rates of 10ACH obtained a reduction on PIAT temperature of between 0.02°C and 0.05°C below the Solid sandcrete blocks models with no night-time ventilation. Increases of ventilation rates to 20ACH and 30ACH observed reduction in PIAT of average of below 0.06°C, 0.009°C and 0.008°C for concrete, baked bricks and solid sandcrete blocks respectively.

Even though the combined effects of thermal mass, window size and night-time ventilation maintained PIAT below that of the control model, they were all above the mean outdoor air temperature. Concrete, baked bricks and solid sandcrete blocks maintained average temperatures of 2.5°C, 4.8°C and 5.5°C respectively above the mean outdoor air temperature. With a reference temperature of 29°C, expected reduction of the overheated hours varied between 35% and 39%, 37% and 39% and 36% to 42% for concrete, BB and SSB respectively.

From the analysis, the thermo-physical properties of materials specified in the simulation program were found to be consistent with that of the local materials tested in this research. A high level of prediction accuracy was obtained in predicting the effects of thermal mass, window size and night-time ventilation with the E+ simulation program. The corresponding root mean square difference (r^2) were 0.82 and 0.83 between predicted and measured data observed for mean air temperature and mean radiant temperature respectively. Coefficient of variance of root mean square error (CV[RMSE]) of 14.75% and 16.80% between predicted and measured data observed for mean air temperature and mean radiant temperature respectively.

The study has made a number of contributions to the body of knowledge on passive and low energy cooling techniques regarding the development of Ghana. A significant contribution of this research to the body of knowledge is the provision of empirical evidence with respect to peak indoor air temperature drop to support the assertion that heavy thermal mass can improve the thermal performance of buildings in Ghana. Until this research, this assertion had not been supported by any empirical study from research findings in Ghana. Calibrated simulation models are used in retrofit analysis for improvement in the thermal performance of buildings. Therefore another significant contribution of this research to the body of knowledge is the achievement of a validated simulation model for the mode of building design and construction in Ghana. This provides a reference point for future calibrated simulation studies in Ghana. Another significant contribution of this research to the body of knowledge is the provision of sufficient evidence to confirm that thermo-physical properties

of basic materials used for construction in Ghana are consistent with that used in international standard building simulation programs. Until this research there had been a widely held assertion that most building simulation programs are developed with thermo-physical properties of materials used in temperate developed countries and are not consistent with localized conditions as that of Ghana.

Keywords: Buildings envelop, Thermal mass, Night-time ventilation, Peak indoor temperature, passive cooling techniques, Warm-humid climates.

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ABBREVIATIONS

AC	:	Air Conditioner
ACH	:	Air Change Rate
ANSI	:	American National Standards Institute
ASHRAE	:	American Society of Heating Refrigeration and Air-conditioning Engineers
BSO	:	Blast Support System
CAD	:	Computer Aided Design
CFC	:	Chloro-Fluoro Carbon
CFD	:	Computational Fluid Dynamics
CICA	:	Confederation of International Contractors Association
CO2	:	Carbon Dioxide
DOE	:	United States Department of Energy
E+	:	Energy Plus Simulation Software
EC	:	European Commission
EF	:	Energy Foundation of Ghana
ESDL	:	Environmental Design Solutions Limited
ESRU	:	Energy Systems Research Unit of the University of Strathclyde, Glasgow, UK
GCI	:	Galvanized Corrugated Iron
HCFC2	:	Hydro Fluorocarbon Two
HVAC	:	Heating Ventilation and Air Conditioning
IBPSA	:	International Building Performance Simulation Association
IDD	:	Input Data Dictionary
IDF	:	Input Data File
IEA	:	International Energy Agency
IIR	:	International Institute of Refrigeration

ISO	:	International Standards Organization
KNUST	:	Kwame Nkrumah University of Science and Technology
LBNL	:	Lawrence Berkeley National Laboratory
MDA	:	Ministries Departments and Agencies
MRT	:	Mean Radiant Temperature
NVC	:	Night Ventilative Cooling
PC	:	Personal Computer
PCL	:	Passive Cooling Laboratory
PLEA	:	Passive and Low Energy Architecture
PLECT	:	Passive And Low Energy Cooling Techniques
PMV	:	Predicted Mean Vote
PV	:	Photovoltaic System
TCV	:	Thermal Comfort Vote
TSV	:	Thermal Sensation Vote
VHC		Volumetric Heat Capacity
WBT	:	Wet Bulb Temperature

LIST OF PUBLICATIONS

1. Amos-Abanyie, S**.,** Akuffo, F.O., Oteng-Sefa, S. and Kutin-Sanwu, V. (2011) **"Parametric study of effect of thermal mass, window size and night-time ventilation**

on peak indoor temperature in the warm-humid climate of Ghana". 7th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2011). Organized by the Tongji University. 6-9th November 2011, Shanghai, China [Accepted for Presentation, Manuscript Number: 0474].

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