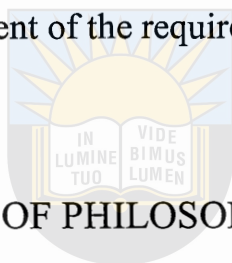


**THERMAL CHARACTERIZATION OF A PASSIVE SOLAR HOUSE IN
ALICE, EASTERN CAPE PROVINCE,
SOUTH AFRICA**



University of Fort Hare
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A Thesis submitted in fulfillment of the requirements for the degree of



**DOCTOR OF PHILOSOPHY
IN PHYSICS**

University of Fort Hare
Together in Excellence

By

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Promoters: Professor E L Meyer
Professor G Makaka

October 2018

DECLARATION

I, the undersigned, hereby declare that the work contained in this dissertation is my own original work and that I have not previously in its entirety or part submitted it at any other University for a degree.

Name



Signed

Date

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DEDICATION

To my late father; Mr Alfred Overen

“...Always be the best in whatever you are doing...”

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EXECUTIVE SUMMARY

A passive solar house was designed and constructed as a prototype low-cost energy efficient house to avert the underperforming low-cost housing plaguing the rural communities in South Africa. Thermal performance characterisation of the passive solar house and developing a thermal load model of a single-family house was the aim of this research.

The net thermal energy change in the inner space of a house is equal to the difference between the total heat gain and the total heat loss from the inner space. This is given by the first law of thermodynamics and serve as the basic principle of a house thermal load evaluation. To this effect, the various contributor of heat gain and loss of the passive solar house were identified. Typically, heat gain in a house occurs in the form of solar heat gain, heat transmission through the building envelope, ventilation/infiltration and internal heat gain. Whereas, heat loss occurs in the form of conductive (building envelope) heat transfer and ventilation/infiltration. As such, the indoor and ambient weather parameters over a year period were monitored. Monitored parameters include air temperature, global horizontal irradiance, and global irradiance at the various elevations of the house. The surface temperature of the building envelope components such as the floor, perimeter walls (inner and outer surface) and the inner surface of the roof was also monitored. At the same time, the occupancy daily activities and operation of the house were closely observed. The occupancy activities refer to the number of occupancies, type of appliances used, lighting, time in and out, as well as their operation of the ventilation components.

The measured meteorological parameters were analyzed in term of data integrity, seasonal distribution and thermal implication. It was found that 5% of the total measured data were lost due to the mechanical error of the data acquisition system. The obtained 95% of data was found sufficient to present tangible thermal behavior of the house. Hence, working with the available data, the measured meteorological data were further presented in typical summer and winter days.

In term of operations of the house, a typical working-class family was occupying the house during the monitoring period. As a result, the house had a minimum occupancy during the day and maximum at night time. It was also found that during the weekends, the house was usually unoccupied. Also, during the monitoring period, all appliances were located in the living room/ kitchen (zone 1). Although, only the 7.70 kW stove and 0.78 kW refrigerator were taken into consideration for the internal heat gain analysis. A total heat gain of 2.10 kW was obtained with both appliances in used, and the refrigerator alone generates 0.25 kW. The daily cumulative heat energy without the influence of other heat sources or sink was 0.58 kWh/m². Another aspect of internal heat gain taken into consideration was electrical lighting fixtures. A total of five 11 W CFLs were installed in the house. Three of the installed lamps were located in zone 1 and one each in the north and south facing bedrooms (zone 2 and 3, respectively). The lighting daily cumulative heat energy was found to be 1.33 Wh/m², 0.71 Wh/m² and 0.88 Wh/m² in zone 1, 2 and 3, respectively. Also, the air exchange rate of each zone with different scenarios of the ventilation components operation was performed upon completion of the house. The findings of the air exchange testing were used to evaluate ventilation/infiltration air heat transfer of the house. The daily cumulative heat energy due to ventilation and infiltration was 0.196 kWh/m², 0.033 kWh/m², and 0.080 kWh/m² in zone 1, 2, and 3, respectively. Based on the indoor and ambient air temperature difference, the said heat energy indicates the amount of heat loss. As such, the daily cumulative internal heat energy in zone 1 was reduced by 0.38 kWh/m².

Transmission heat transfer through the components of the building envelope was analyzed in the form of opaque and transparent components. Opaque components further comprise the walls and roof. The south wall was found to have the maximum heat loss with a daily average of 161.95 W in the summer season and 147.14 W in the winter season. The north wall was found to have the maximum heat gain with 153.43 W and 201.60 W in summer and winter seasons, respectively. In both seasons, the solar irradiation on the perimeter walls was reduced by more than 95%. Based on the roof design, the house ceiling was classified into crawlspace and skillion ceiling

design. Whereby, the skillion ceiling covers the southern floor area, while the crawlspace ceiling dominates the northern floor area. In both seasons, heat loss through the crawlspace ceiling was approximately 54% higher than that of the skillion ceiling. However, the average daily heat loss and gain through the ceiling of the whole building were 0.19 and 0.45 kW, respectively in the summer season. In the winter season, the daily average heat loss was 0.18 kW and a gain of 0.44 kW.

The windows were the only components considered under transparent components. The north facing windows which include the north perimeter and clerestory windows had the maximum heat gain in both seasons. Both windows had an average daily heat gain of 408.16 W in summer and 712.82 W in winter. The south windows with the least heat gain had 76.19 W and 50.85 W in summer and winter, respectively. In summer, their daily average heat loss ranges from 59.58 to 67.43 W. Whereby, the south windows had the least heat loss and the clerestory windows were maximum. A daily average heat loss of 57.65 to 64.33 W was obtained through the windows during the winter season. Although in winter, the west and clerestory windows had the minimum and maximum heat loss, respectively. Also, the east windows had a daily average of 28.74 W in summer and 29.13 W in winter. Furthermore, solar heat gain through the windows was found to be relatively higher than other components of the building envelope. The clerestory windows admit 96% of summer and 101% winter generated heat energy on their respective outer surfaces.

Heating and cooling load model which made up the thermal load of a house were developed. Whereby the heating load model cater for the rate at which heat must be added in the inner space of a house to maintain a desirable air temperature while cooling load is the rate at which heat must be removed to achieve a similar target. The worst-case scenario was assumed in order to develop both models. Therefore, heating load covers the period during the absence of the sun while cooling load concentrate on the period in which the sun is present. The indoor air temperature influencing factors considered under the heating load model was the conductive and infiltration heat

transfer. In designing the cooling load model, internal heat gain and solar heat gain were the indoor air temperature influencing factors taken into consideration. A combination of the influencing factors in the respective load gives the heating and cooling load models. However, the developed models at their initial stage were found suitable in predicting the thermal load of an existing house. However, for non-existing house whereby indoor air temperature and global irradiance at the various elevations of the house cannot be measured, the models at their initial stage were not applicable. As such as the indoor air temperature and global irradiance were predicted from other outdoor meteorological data. These include air temperature, wind speed, wind direction, relative humidity, and global horizontal irradiance.



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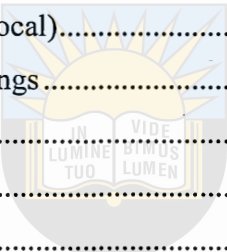
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INTRODUCTION

1.1 Background

Over the years, building design, occupants behavior, choice of technology usage, manufacturing and construction processes, has resulted in the increasing energy consumption as well as the release of greenhouse gases (GHG) in the building sector [Blok *et al.*, 2007]. Globally the building sector consumes over 30% of the total final energy, having increased by more than 35% since 1990. At the same time, accounting for 30% of CO₂ gas emission. The building sector also accounts for half of the world electricity demand, with some region electricity consumption increased by 500% [International Energy Agency, 2016]. In the residential sector, energy is consumed for space heating, cooling, domestic activities, lighting, etc. Residential energy consumption is however affected by, energy price, availability of energy sources, household income level, energy-related policies building, and household characteristic, etc. [Klunne, 2000; González-Eguino, 2015]. Hence, residential energy consumption varies across regions and countries. According to International Energy Outlook (IEO) 2016, residential energy consumption in Organisation for Economic Cooperation and Development (OECD) nations is predicted to increase at an average of 0.6% per annum from 2012 to 2040. For the same period, non-OECD nation's residential energy usage is expected to grow faster, at an average of 2.1% per annum. Also, residential energy consumption is responsible for 80% of all growth in the world's residential energy consumption over the 28-year period [U.S. Energy Information Administration, 2016].

Energy efficiency is said to be the most economical and readily available means of improving energy security and reducing GHG [International Energy Agency, 2008]. Energy efficiency in the residential sector involves the use of passive and active solar design for space heating, lighting, and energy for domestic purposes. Passive solar design involves the design of a house to utilize solar energy through its orientation and the components of building envelope. On the other hand, the active solar design is the

use of solar technology to convert solar energy into electricity and heat energy for hot water production.

Through effective implementation and practice of energy efficiency in the building sector, most countries are targeting enhanced building performance and GHG reduction in the near future. In the United States, the Energy Independence and Security Act of 2007 calls for newly constructed buildings to achieve Net-zero energy (NZE) by 2030 and for all buildings to be NZE by 2050. Also, a new energy efficiency initiatives for buildings in New York city to accelerate deep retrofits with the aim of 80% GHG emission reduction by 2050 [Brain *et al.*, 2016]. The European Union targets 20% building energy consumption and GHG emission reduction through the EPBD. As well as an NZE target for all new buildings in Europe by 2021 [Ferreira *et al.*, 2016]. Likewise, Australia is also projecting a 19% GHG reduction by 2020 [Climate Change Authority, 2014].

1.1.1 Overview of building heat transfer and thermal load evaluation

The first law of thermodynamics is the basic principle of building thermal load evaluation. In the building context, it can be expressed as the net thermal energy change in an enclosed environment is equal to the difference between the total heat gain and the total heat loss from the environment [Masuda and Claridge, 2014]. Heat gain occurs in a building in the form of solar heat gain, conductive heat transfer, ventilation/infiltration, and internal heat gain. Where internal heat gain comprises of heat generated by occupants, appliance/ equipment, lightings, and domestic activities. In this regard, heat gain can be classified as sensible and latent heat gain. The direct release of heat to the environment due to temperature change is known as sensible heat gain while heat gain due to phase change, e.g., evaporation in an environment is referred to as latent heat gain. Heat loss, on the other hand, occurs in the form of conductive heat transfer and ventilation/infiltration [Kalogirou, 2014].

Most forms of heat gain or loss occur through the building envelope. The building envelope components are the component of the building such as walls, windows, floor, doors, and roof that protect the habitable space of the building from the ambient weather conditions. Hence the rate of heat gain and loss of a building is a factor of the thermophysical (thermal and physical) properties of the building envelope and average ambient weather conditions. The heat gained and lost in a building are responsible for cooling and heating loads of the building, respectively. Where, heating or cooling load is the rate at which heat energy must be added or removed from an enclosed environment to offset the heat losses or gains, respectively to maintain a desirable indoor temperature [Bradshaw, 2010]. Therefore, a cumulative sum of all form heat gains in the building can be used to determine the whole building cooling load while the sum of all form of heat losses give the whole building heating load.

1.2 Problem statement

Since the initiation of Reconstruction Development Programme in South Africa, over 1.2 million Low-cost Housing (LCH) have been built. These houses were designed with no consideration of thermal energy efficiency, as they cannot utilize solar energy for space heating. Also, uncontrollable heat exchange between the inner and outer space of the house due to openings and cracks on the building envelope; leaves the inner space extremely cold in winter. Hence low-cost households consume a significant amount of energy to achieve indoor thermal comfort [Makaka, Meyer and McPherson, 2008]. Also, the recent energy crisis faced by the country has seen an increase in the cost of electricity. Low-cost households tend to carry the burden of the energy crisis, considering that majority of them live on social grants and limited Free Basic Electricity (FBE) tokens. Therefore, most households that cannot afford electrical energy resort to the use of firewood, coal, paraffin heaters or thick clothing as alternative sources of energy for heating [Overen, Meyer and Makaka, 2017]. The use of paraffin heater could result in poor indoor air quality, cold-related illness, early child motility, and other respiratory diseases. [Dear and McMichael, 2011; Sustainable

Energy Africa, 2014]. Provision of low-cost housing is a positive approach to development in the country, but in cooperating passive solar design will improve the welfare of occupants, and minimize the rate of carbon emission in the country.

1.3 Aim and objectives

A passive solar house was designed and constructed at the University of Fort Hare, Alice in the Eastern Cape of South Africa. The house was built as a prototype of energy efficient single-family low-cost housing. The aim of this research is to evaluate the thermal load of the house and develop thermal load model of a house. The following objectives were set out to achieve the aim,

- To monitor the seasonal indoor and outdoor meteorological conditions of the passive solar house.
- To determine the house air exchange rate and the resultant air heat transfer.
- To determine the internal heat gain of the house.
- To determine the heat transfer through the various building envelope components of the house.
- To develop a heating and cooling load models for an existing and non-existing house.

1.4 Research questions

Based on the abovementioned activities, this research tends to answer the following questions;

- What is the influence of the ambient weather conditions on the indoor air temperature and relative humidity of the passive solar house?
- What is the internal heat gain of the passive solar house concerning the occupancy operation and activities?

- What are the air exchange rate of the passive solar house and its thermal impact?
- What is the respective thermal contribution of the various building envelope components?
- What are the limitations and applications of the developed thermal load models?

1.5 Research methodology

An experimental based methodology was adopted in this research. Whereby, a passive solar house used as a case study was identified and secured. Indoor and outdoor meteorological parameters such as air temperature, global horizontal irradiance, wind speed, and direction were monitored over a year period. The considered period was to capture the seasonal behavior of the house. The monitored parameters also included solar irradiance at the various elevations of the house as well as the perimeter walls inner and outer surface temperatures. The behavior and activities of the occupants were also observed, as to establish operation of the house. During the monitoring period, the rate at which the air indoor was exchanged with the ambient air was determined. Due to the cost of performing the air exchange rate testing, the testing was only conducted for two days in the summer season. The obtained findings were however used to establish a typical air exchange rate of the house.

1.6 Rationale of study

As stated earlier, the house used as a case study was designed as a remedy to the poorly performing low-cost housing in South Africa. This research, however, brings to light the thermal benefit of replacing low-cost housing with passive solar housing. In other words, quantifying the thermal performance of the passive solar house. Also, there is currently no reference thermal load for evaluating the thermal performance of houses in South Africa [South African Bureau of Standards, 2011]. As a result, houses in

South Africa are built with no thermal load target. Thermal evaluation and rating of buildings in South Africa are limited to commercial and public buildings [Green Building Council South Africa, 2017]. The findings of this research will provide a reference thermal load of houses in South Africa. Also, a model that can be used to predict the thermal load of a house is presented in the research. The model is not limited to the house used as a case study but other existing and non-existing houses.

1.7 Delineation and limitations

The holistic thermal performance of a single-family passive solar house is the main findings of this research. Based on the methods adopted in computing the thermal performance of the house, a consolidated thermal load model was developed. Given that only one house was used in the research, the findings are limited to a single-family passive solar house. Also, due to the climatic zoning of the house, the findings are applicable to passive solar houses in the temperate interior (Zone 2) climate of South Africa.

1.8 Definition of terms

The following terms should be used and understood as defined in this section unless the context suggests otherwise:

1. **BEAS:** Building energy analysis software; refer to a software package accredited by Agreement South Africa according to SANS 10400-X: 2011, Part XA, Clauses 4.2.1 a and c, used to evaluate the performance of a building.
2. **Building envelope:** refers to those components of a house enclosing the habitable space from the ambient weather factors. These include walls, floor, roof, external doors, and windows.
3. **Conditioned space:** refers to a room or living space that is heated or cooled by either mechanical or natural means to an occupant thermal comfort level.

4. **Energy efficiency:** refers to the act of minimizing the whole building energy consumption without compromising the comfort of the occupants.
5. **Heat gain:** this is the flow or transfer of heat to the inner space of a house due to solar, transmission, ventilation/infiltration or internal means.
6. **Heat loss:** this is the flow or transfer of heat from the inner space of a building due to transmission and ventilation/infiltration.
7. **Heating or cooling energy:** the amount of energy consumed by a heating or cooling system.
8. **Inner space:** refers to the habitable area of a house such as the living room and bedroom, but excluding the storage and bathroom.
9. **Internal heat gain:** refers to the heat generated in the inner space of a house due to appliances and occupant activities.
10. **Laws of thermodynamics:** The *first law* of thermodynamics; the principle of conservation of energy, states that energy cannot be created or destroyed but only converted from one form to another. In any system, the energy output must equal the energy input unless there is a $\pm$ storage component. The *second law* of thermodynamics states that heat flow from higher to lower temperature region.
11. **Multi-family house:** refers to a building that contains multi separate household
12. **Natural/ mechanical ventilation:** Natural ventilation is the ventilation of the inner space of a house by the operation of the doors and windows, while, mechanical ventilation is ventilation of the inner space using a mechanical or electrical system.
13. **Opaque building component:** refers to the components of the building envelope which light cannot travel through. These components are typically the walls, roof, and floor.
14. **Orientation:** refer to the geographical direction of a house façade.
15. **Reference building:** is a hypothetical building that is used to determine the maximum allowable loads for a proposed building.
16. **SABS:** South African Bureau of Standards.

17. **SANS:** South Africa National Standard.
18. **Single-family house:** refer to a house occupied by a single household.
19. **Solar heat gain:** refer to the heat generated by solar radiation penetrating through the transparent components or on the outer surface of the opaque components of a house.
20. **Space heating or cooling:** is the adding or removing of heat from the inner space of a house using a mechanical system.
21. **Thermal comfort zone:** this is the recommended indoor air temperature or relative humidity whereby space heating or cooling is not required to achieve thermal comfort.
22. **Thermal energy efficiency:** this is the act of minimizing the amount of heating or cooling energy required in a house without compromising the comfort of the occupants.
23. **Thermal load (heating and cooling load):** refers to the amount of heating or cooling a house required to maintain the indoor air temperature within the thermal comfort level.
24. **Thermal zoning (zone):** refers to the partitioning of the condition spaces of a house into different zones, with separate thermal energy calculation for each zone.
25. **Transparent building component:** are the components of the building envelope which light can travel through. The window is the major transparent building component.
26. **Ventilation/infiltration:** ventilation is the intentional introduction of ambient air into the inner space of a house to improve in air quality or regulate air temperature. Whereas, the unintentional flow of air into or out of the inner space of a house is referred to as infiltration.

1.9 Envisaged outcomes

The following outcomes are expected:

- The indoor air temperature and relative humidity response to the ambient weather condition of a passive solar house.
- The internal heat generated by major appliances in the house concerning the occupant's operation.
- The air exchange rate of the house and its resultant heat transfer.
- The thermal impact of each component of the building envelope of the passive solar house.
- A model that can be used to predict the heating and cooling load of an existing or non-existing house.

1.10 Layout of the thesis

A theoretical review of the methods used in evaluating the thermal load of the house was given in Chapter two (*Building Thermal Load Evaluation*). It also contains other methods of evaluating thermal load of a building. Chapter three (*Description of House and Meteorological Measurements*) presents a detailed description of the house used in the research. The house design and materials used, as well as its compliance with SANS 204 recommendations, were presented. The sensors and data acquisition system used in the meteorological monitoring were also discussed. Chapter three ended with the house air exchange rate evaluation procedure.

Measured data in the research was presented and discussed in Chapter four (*Analysis of Measured Data*). This chapter deals with the integrity of the measured data. It has also presented thermal implications of the measured data. In Chapter five (*Operation of the House and Ambient Air Heat Transfer*), operations of the house regarding the occupant activity and internal heat gain were presented and analyzed. Also, the ventilation/ infiltration heat transfer due to the air exchange rate of the house was given and discussed. In Chapter six (*Building Envelope Heat Transfer*), the heat transfer in the various components of the building envelope is assessed and analyzed. Simplified models for evaluating the heating and cooling load of an existing or non-existing house

were presented in Chapter seven (*Residential Thermal Load Evaluation Toolkit*). This chapter also contains a comparative analysis of the developed method and the existing methods.

Conclusions drawn from all findings obtained in this research and recommendations are presented in Chapter eight (*Conclusion, Contributions, and Recommendations*). The contributions and significance of the research study are highlighted in this chapter.

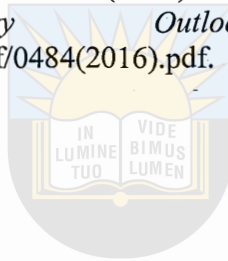


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REFERENCES

- Blok, K., Geng, L., Harvey, D., Lang, S., Levermore, G., *et al.* (2007) 'Residential and commercial buildings', *Climate Change 2007: Working Group III: Mitigation of Climate Change*, pp. 387–446.
- Bradshaw, V. (2010) *The building environment: Active and passive control systems*. John Wiley & Sons.
- Brain, D., John, D., Ksenia, P. and Peter, G. (2016) *Towards Zero-Emission Efficient and Resilient Buildings: Global Status Report 2016*. Paris.
- Climate Change Authority (2014) *Reducing Australia's Greenhouse Gas Emissions: Targets and Progress Review—Final Report*, Climate Change Authority, Melbourne. Sydney. Available at: <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Reducing+Australia+?+s+Greenhouse+Gas+Emissions+?+Targets+and+Progress+Review+final+Report#4>.
- Dear, K. B. G., and McMichael, A. J. (2011) 'The health impacts of cold homes and fuel poverty.', *BMJ (Clinical research ed.)*, 342, p. d2807. doi: 10.1136/bmj.d2807.
- Ferreira, M., Almeida, M., Rodrigues, A. and Silva, S. M. (2016) 'Comparing cost-optimal and net-zero energy targets in building retrofit', *Building Research & Information*. Taylor & Francis, 44(2), pp. 188–201.
- González-Eguino, M. (2015) 'Energy poverty: An overview', *Renewable and Sustainable Energy Reviews*, 47, pp. 377–385. doi: 10.1016/j.rser.2015.03.013.
- Green Building Council South Africa (2017) *Certified Projects | GBCSA, GBCSA*. Available at: <https://www.gbcsa.org.za/projects/certified-projects/> (Accessed: 1 August 2017).
- International Energy Agency (2008) *Worldwide Trends in Energy Use and Efficiency*, Iea.Org. Available at: http://iea.org/efficiency/CD-EnergyEfficiencyPolicy2009/1-Cross-sectoral/1-Indicators_2008.pdf.
- International Energy Agency (2016) *Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems*. Paris. Available at: [WWW.iea.org](http://www.iea.org).
- Kalogirou, S. A. (2014) *Solar Space Heating and Cooling, Solar Energy Engineering*. Academic Press. doi: 10.1016/B978-0-12-397270-5.00006-6.
- Klunne, B. W. (2000) 'Improved quality of life through passive solar design', (Irrah), pp. 2000–2003.
- Makaka, G., Meyer, E. L. and McPherson, M. (2008) 'Thermal behavior and ventilation efficiency of a low-cost passive solar energy efficient house', *Renewable Energy*, 33(9), pp. 1959–1973. doi: 10.1016/j.renene.2007.11.014.
- Masuda, H. and Claridge, D. E. (2014) 'Statistical modeling of the building energy balance variable for screening of metered energy use in large commercial

- buildings', *Energy and Buildings*. Elsevier B.V., 77, pp. 292–303. doi: 10.1016/j.enbuild.2014.03.070.
- Overen, O. K., Meyer, E. L. and Makaka, G. (2017) 'Thermal, Economic and Environmental Analysis of a Low-Cost House in Alice, South Africa', *Sustainability*. Multidisciplinary Digital Publishing Institute, 9(3), p. 425.
- South African Bureau of Standards (2011) *SANS 10400-XA: The application of National Building Regulations, Part X: Environmental sustainability, Part XA: Energy usage in buildings*. South Africa.
- Sustainable Energy Africa (2014) *Tackling Urban Energy Poverty in South Africa*. Cape Town.
- U.S. Energy Information Administration (2016) *International Energy Outlook 2016, International Energy Outlook 2016*. doi: [www.eia.gov/forecasts/ieo/pdf/0484\(2016\).pdf](http://www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf).



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Chapter 2

BUILDING THERMAL LOAD EVALUATION

2.1 Introduction

The components of the building envelope, ambient weather conditions, and occupant activities must be taken into consideration to evaluate the thermal load of a building. The components of the building envelope which comprises the walls, roof, floor, windows, and doors are examined base on their thermophysical properties. Many studies [Antretter, Klingenberg and Pazold, 2013; Eurac and Academy, 2015; Korniyenko, 2015; Romani, Draoui and Allard, 2015; Yaghoobian and Srebric, 2015] only takes into consideration the wall, roof, and windows when evaluating building thermal load. Hence, the building envelope components are sub-divided into opaque and transparent components. Based on the second law of thermodynamics, the average ambient weather conditions tend to influence the direction of heat flow through the building envelope. Heat gain or loss through ventilation or infiltration is also influenced by ambient weather condition. Furthermore, occupants and their domestic activities also contribute to the heat gain in a building.

Due to the variation of factors required, building thermal load calculation can be very complicated when a detailed analysis is required. The complexity of thermal load analysis often requires that heating and cooling energy usage be calculated in hourly increments for a year's time. At the same time accounting for heat storage, natural lighting, ventilation, hourly solar intensities, and various shading effects [De Boeck *et al.*, 2015]. Consequently, Building Energy Analysis Software (BEAS) are often used to perform building thermal load evaluation. Nevertheless, the findings of a BEAS are a mere estimate of the thermal load. Given that the variability of construction materials, average weather conditions, occupant activities, and others. are approximated in the software algorithm [Brain *et al.*, 2016].

In this regard, this chapter presents a theoretical review of building thermal loads evaluation. The review presents a hand-tractable thermal load evaluation method and takes all components of building envelope into consideration. Various methods of evaluating building thermal load are also discussed and presented.

2.2 Thermal load

The building envelope which serves as a border between the inner and outer space protects the occupants from the ambient weather factors. As such, the building envelope is in constant interaction with the various elements of weather. Due to construction deficiency and occupant needs at a given time, thermal energy is transferred into or out of the building; resulting in an increase or decrease of the indoor air temperature. It should be noted that as much as the weather elements create harsh thermal conditions indoors, they also serve as the only natural source of thermal energy in a building. Therefore, a balance between the amount of energy admitted and prevented is required to maintain indoor thermal comfort. Moreover, human activities, metabolism, and appliance also generate thermal energy indoors. A schematic of a building thermal load is given in Figure 2.1.



Figure 2.1: Schematic of a building thermal load

As seen in Figure 2.1, some of the building thermal load are distributed throughout the building while other take place around the borders of the building envelopes. Thermal load due to internal heat gain and ventilation are distributed all over the building, depending on where the source is located. Conductive heat transfer loads, as well as thermal loads associated with infiltration, occurs at the perimeter walls [Bradshaw, 2006]. To maintain indoor thermal comfort, the equivalent amount of heat gained must be removed, this is referred to as a cooling load, while the amount of heat that must be added to the inner space to offset the heat lost is referred to as a heating load. Table 2-1 gives a summary of the relationship between the building heat transfer and thermal load.

Table 2-1: Various heating and cooling load in a building.

Thermal load	Heat transfer	
	Sensible	Latent
Heating	Conductive heat loss through a building envelope.	
	Ambient air heat loss: ventilation/ infiltration.	
Cooling	Conductive heat gain through a building envelope.	
	Solar heat gain through windows.	
	Ambient air heat gain: ventilation/ infiltration.	
	Internal heat gain: occupant, lights, and appliance.	

Source: Bradshaw, (2006) The Building Environment: Active and Passive Control Systems. John Wiley & Sons

As shown in Table 2-1, heating loads use simple worst-case assumptions. Solar and internal heat gain is not taken into consideration since extreme heating load occurs at night. Hence, heat losses are treated instantaneously and simple heat transfer equation; $UA\Delta t$ can be used to determine cooling load, heat storage is not considered [ASHRAE,

2009]. Also, if no humidification is considered, latent load during the heating season is zero. However, considering humidification, uncertainties in the value of the outdoor humidity have little effect on the latent load since the absolute humidity of outdoor air in winter is very low [Kreider, Curtiss and Rabl, 2009]. In contrast, cooling loads require more complex calculation, as one needs to consider both sensible and latent heat gain. Heat storage due to thermal mass material has to be taken into consideration. Several thermal loads evaluation method was developed due to the complexity of a cooling load calculation [Van Dijk, Spiekman and De Wilde, 2006; Antretter, Klingenberg and Pazold, 2013]. In general, to calculate cooling and heating loads all forms of heat transfer in a building has to be considered.

2.2.1 Conductive heat transfer

Heat transfer in a conductive medium occurs due to the temperature difference between two bodies that are in contact. In this context, conductive heat transfer occurs in opaque and transparent components of the building envelope.

2.2.1.1 Opaque components

The walls and roof are considered as the opaque components of a building. Both components are in contact with the indoor and ambient air. Thus, due to the temperature difference between the indoor and ambient air, heat tends to flow from one environment to another. However, the rate of heat flow across the components depends on their thermal properties and exposed surface area (thermophysical properties). Heat transfer through opaque components is the sum of the relatively steady-state and unsteady-state heat transfer [Chartered Institution of Building Services Engineers, 2000]. The steady-state heat transfer which does not take heat storage of the components (wall) into account, is given as;

$$Q_c = \sum AU(T_o - T_i) \quad (2.1)$$

where $\sum AU$ is the sum of the product of the surface area, (m^2) and thermal transmittance coefficient, (W/m^2K) of the whole building opaque components. T_i and T_o represent indoor and ambient air temperature, ($^{\circ}C$), respectively. Q_c is the heat transfer through opaque components, (W), a negative Q_c , which is a result of a lower ambient air temperature implies heat loss; higher ambient air temperature will result in a positive Q_c , indicating heat gain.

Equation 2.1 is not viable for calculating heat gain through opaque components of a building. The effect of solar radiation on the air film around the components (perimeter walls) was not considered. Given that solar radiation plays a significant role in heat gain through the building envelope [Ulgen, 2002; Kontoleon and Eumorfopoulou, 2008]. The ambient air temperature T_o in Equation 2.1 is replaced with sol-air temperature T_{eo} to indicate the effect of solar radiation on the heat gain through the opaque components, and it's given as;

$$Q_{c\theta} = \sum AU(T_{eo} - T_i) \quad (2.2)$$

$Q_{c\theta}$ is the heat transfer considering the effect of the sun or (solar heat gain), (W) through opaque components. It must be said that Equation 2.2 is only valid between sunrise and sunset, and outside this period, the air film temperature of the components is equal. Hence Equation 2.1 can be used to calculate heat transfer. T_{eo} is sol-air temperature, ($^{\circ}C$) and it is defined as the effect of the ambient temperature on the indoor thermal condition of a house in the present of solar radiation; which is expressed mathematically as [ASHRAE, 2005];

$$T_{eo} = T_o + \frac{\alpha I}{h_o} - \frac{\Delta q_{ir}}{h_o} \quad (2.3)$$

h_o represent the surface (convective and radiative) heat transfer coefficient ($\text{W/m}^2\text{K}$), I is global solar irradiance on the surface of the opaque components (W/m^2), and α is the absorptance of the surface for solar radiation. Δq_{ir} is the correction to infrared radiation transfer between a surface and the environment, if the sky temperature is different from T_o , (W/m^2). On an average basis, the mean heat gain Q_{cm} , through the opaque components can be written as;

$$Q_{cm} = \sum AU(T_{eo,avg} - T_i) \quad (2.4)$$

$T_{eo,avg}$ is the mean sol-air temperature over 24 hours.

So far, the thermal capacity of the opaque components was not considered in Equation 2.1 and 2.2 as well as 2.4. Thermal capacity which depends on the thickness and thermophysical properties of material reduces the time and amount of heat transferred through the building component [Asan and San, 1998; Jin *et al.*, 2012]. Hence, ignoring thermal capacity may result in overestimated cooling load. Since thermal capacity is a factor of the thickness of a material, it is mainly considered for the heat transfer through the walls, with regard to opaque components. Over the years, studies [Asan, 1998; Kontoleon and Eumorfopoulou, 2008; Aste, Angelotti and Buzzetti, 2009; Wang and Wang, 2016] have expressed the effect of building walls thermal capacity using time lag and decrement factor. Heat gain can be obtained by introducing the time lag and decrement factor of the wall, taking the thermal capacity of a building wall into consideration, heat gain is given as [Kaşka and Yumrutaş, 2009];

$$Q_{cd+\phi} = \sum AU \left((T_{eo,avg} - T_i) + (T_{eo+\phi} - T_{eo,avg}) f \right) \quad (2.5)$$

$T_{eo+\phi}$ is the sol-air temperature time lag hours ago while f is decrement factor. Time lag is defined as the time required for a heat wave to propagate through a wall from the outer to the inner surface. Whereas, decrement factor is the decreasing ratio of its

temperature amplitude during the transit process of a wave penetrating through the wall [Asan, 2000]. The time lag ϕ is given as;

$$\phi = \theta_{T_{i,\max}} - \theta_{T_{o,\max}} \quad (2.6)$$

while f is expressed as,

$$f = \frac{A_o}{A_i} = \frac{T_{i,\max} - T_{i,\min}}{T_{o,\max} - T_{o,\min}} \quad (2.7)$$

where $\theta_{T_{i,\max}}$ and $\theta_{T_{o,\max}}$ represent the times when the wall inner and outer surface temperatures were at their maximum, respectively. While, $T_{i,\min}$, $T_{i,\max}$, $T_{o,\min}$ and $T_{o,\max}$ are the minimum and maximum temperature on the wall inner and outer surfaces, respectively.

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Heat transfer through partition walls, floors and ceilings can be calculated using Equation 2.1. In this case, whenever a conditioned space is adjacent to other spaces at different temperatures, the heat transfer through the partition is given as;

$$Q_{c, \text{int}} = \sum AU(T_{\text{adj}} - T_i) \quad (2.8)$$

The air temperature of the adjacent space T_{adj} is constant, or variations of this temperature are small compared to the difference of the adjacent space and indoor temperature difference.

2.2.1.2 Transparent components

Transparent components of the building envelope refer to glazing, windows or any component of the building envelope where radiative heat transmission occurs. Similar to opaque components, conductive heat transfer occurs whenever temperature difference exists. For a single pane of glass and in the absence of solar radiation the

heat transfer through windows can be calculated by Equation 2.1. In this case, u is the glass heat transfer coefficient ($\text{W/m}^2\text{K}$). Heat transfer through the frames was not considered in the formula [Rubin, 1982].

2.2.2 Solar heat gain through glazing

Glazing thermal load comprises of conductive heat transfer and solar heat gain. Conductive heat transfer as indicated in the previous section involves the heat loss or gain due to indoor and ambient air temperature difference. Whereas, solar heat gain is due to radiative heat transfer through the glazing to the inner space of a building. In other words, solar heat gain is the heat flow through the window in the presence of solar radiation. The solar irradiance I incident on glazing, a portion ρI is reflected, αI is absorbed and τI is transmitted to the inner space. Due to the conservation of energy, the sum of reflectivity ρ , absorptivity α , and transmissivity τ , equal to unity [Kreider, Curtiss and Rabl, 2009; Duffie and Beckman, 2013].

$$\rho + \alpha + \tau = 1 \quad (2.9)$$

Hence, in the presence of solar radiation Equation 2.1 can be rewritten as;

$$Q = \sum AU(T_o - T_i) + \tau I + h_i \Delta T_{sol} \quad (2.10)$$

h_i is the surface heat transfer coefficient to the indoor air and ΔT_{sol} is the temperature rise of the glass due to absorption of solar radiation. The right-hand side of Equation 2.10 represents conductive heat transfer (without solar radiation), solar heat gain and extra heat gain due to solar radiation absorbed by the glass.

Assuming a linear approximation for all relevant heat transfer equations and given that ΔT_{sol} is independent of T_i and T_o are zero, by setting the absorbed solar flux equal to the sum of the heat flow to inside and outside;

$$\alpha I = h_i \Delta T + h_o \Delta T_{sol} \quad (2.11)$$

After solving for ΔT , one obtains

$$\frac{Q}{A} = U(T_o - T_i) + \tau I + \frac{\alpha h_i}{h_i - h_o} \quad (2.12)$$

The two rightmost terms of Equation 2.12 can be combined as the total solar heat gain Q_{sol} through a window;

$$Q_{sol, tot} = AFI \quad (2.13)$$

where F is *solar heat gain coefficient* and it is given as;

$$F = \tau + \alpha \frac{U}{h_o}, \text{ with } U = \frac{h_i h_o}{h_i + h_o} \quad (2.14)$$

Equation 2.14 is valid only for single pane glass windows. Double pane glass window is given as;

$$F = \tau + \alpha_o \frac{U}{h_o} + \alpha_i U \left(\frac{1}{h_s} + \frac{1}{h_o} \right), \text{ with } U = \frac{h_i h_o}{h_i + h_o} \quad (2.15)$$

where h_s represent the heat transfer coefficient of the space between the two panes; while α_i and α_o are the absorptivity of the inner and outer panes, respectively. Apart from the properties of the glass, F depends on the surface heat transfer coefficients and angle of incidence.

The relationship between F and the *shading coefficient* (SC) of a window is given as;

$$SC = \frac{F}{F_{ref}} \quad (2.16)$$

F_{ref} is a reference solar heat gain coefficient of a double-strength (DSA) glazing and it is equal to 0.87. The SC values for single and double glazing as specified by ASHRAE are given in Table 2-2 [Robert, 2001b].

Table 2-2: Typical windows glazing shading coefficient and transmissivity in winter and summer condition

Type of Glazing	Nominal Thickness per pane		τ	SC	
	mm	inches		Winter	Summer
Single glazing clear	3	$\frac{1}{8}$	0.86	1.00	1.00
	6	$\frac{1}{4}$	0.78	0.94	0.95
	10	$\frac{3}{8}$	0.72	0.90	0.92
	13	$\frac{1}{2}$	0.67	0.87	0.88
	3	$\frac{1}{8}$	0.64	0.83	0.85
Heat absorbing	6	$\frac{1}{4}$	0.46	0.69	0.73
	10	$\frac{3}{8}$	0.33	0.60	0.64
	13	$\frac{1}{2}$	0.24	0.53	0.58
Double glazing clear out, clear in	3	$\frac{1}{8}$	0.71	0.88	0.88
	6	$\frac{1}{4}$	0.61	0.81	0.82
Heat absorbing out, clear in	6	$\frac{1}{4}$	0.36	0.55	0.58

Source: Robert, A. P. (2001) 'Cooling Load Calculation', in ASHRAE Handbook-Fundamentals. SI. New York: ASHRAE, pp. 1-106

Thus, the instantaneous solar heat gain through a window is given as;

$$Q_{sol} = A \times SC \times SHGF \quad (2.17)$$

Where $SHGF$ is the solar heat gain factor, and the relationship of $SHGF$ and F is given as;

$$SHGF = F_{ref} I \quad (2.18)$$

Equation 2.17 does not account for the thermal capacity of glazing; hence it is suitable for heating load calculation. A correction factor called the *thermal lag factor* (TLF) is introduced in Equation 2.17 to consider thermal capacity;

$$Q_{sol} = A \times SC \times SHGF \times TLF \quad (2.19)$$

TLF was designed as a function of maximum $SHGF$ at any given latitude, month, and exposure. Considering the solar intensity with time, the mass of structure and internal shading.

2.2.3 Internal heat gain

Like solar heat gain, internal heat gain is another sources of heat that influence the cooling load of a house. Internal heat gain refers to heat generated inside a house due to occupant's activities, lighting, and electrical appliances. Heat generated by these sources can be classified into sensible and latent heat gain.

2.2.3.1 Occupant

Heat is generated in the human body by a metabolic process, which is released through radiation, convection, and evaporation from the skin or clothing. Also by convection and evaporation in the respiratory tract. Heat released by the human body due to radiation and convection is considered as sensible heat gain, while latent heat gain is due to evaporation. The form (sensible or latent) at which the heat is released depends on the temperature of the surrounding. The total amount of heat released to the surrounding is a factor of the number of people, their duration, and activity. The

instantaneous sensible ($Q_{s,occ}$) and latent ($Q_{l,occ}$) heat generated by a person or people is given by ASHRAE as [ASHRAE, 2005]:

$$Q_{s,occ} = N(SHG_p) \quad (2.20)$$

And

$$Q_{l,occ} = N(LHG_p) \quad (2.21)$$

Where N is the number of people, while SHG_p and LHG_p are sensible and latent heat gain per person, respectively. Latent heat from the moisture of occupants goes directly into the air with no delay, while a fraction of the sensible heat is absorbed and stored by the surrounding structure and furnishings. The absorbed heat is later released into the surrounding. Hence, to account for this delay, the building storage factor is taken into consideration [Bradshaw, 2006].

2.2.3.2 Lighting

Lighting is a major internal load component. The heat generated from lighting, comes from the light-emitting element or lamps. Most of the heat is emitted in the form of radiation, directly heating the space. Some are absorbed by the building masses and furnishings, later released into space by convection. The manner in which the lights are installed, the type of air distribution system, and the mass of the building determine the heat gain at any given moment. Instantaneous sensible heat gain from electrical lighting Q_{lit} is given as;

$$Q_{lit} = W_l F_e \quad (2.22)$$

where W_l is the total installed light wattage (W); this is obtained from the rating on all the lamps installed in the building zone in consideration. It does not include ratings

of ballast. The ratio of experimental heat output of the bulb to the actual electrical wattage is given by the heat emission coefficient F_e [Suszanowicz, 2017].

2.2.3.3 Electrical appliances

Sensible heat gain from appliances is often listed on the nameplate of the appliance. This value can be overestimated compared to the actual heat gain. However, the sensible heat gain from appliances can be determined as a function of usage factor F_u , radiation fraction F_R and the nameplate rated energy input q_{input} [Gordon, Parvin and Horton, 1994; Smith, Swierczyna and Claar, 1995]

$$Q_{s,app} = q_{input} F_u F_R \quad (2.23)$$

2.2.4 Ambient air heat transfer

Ventilation is the intentional introduction of ambient air to the inner space of a building. Infiltration or exfiltration (air leakage) on the other hand, is the unintentional flow of ambient air into or out, respectively from the building. Ventilation can be subdivided into natural and mechanical ventilation. Natural ventilation occurs due to the intentional opening of the ventilation components of a building. Ventilation components include windows, doors, grilles, etc. Likewise, infiltration and exfiltration are driven by natural and/or artificial mechanism. Also, natural ventilation and infiltration are driven by the pressure difference across the building envelope due to the ambient wind. As well as air density difference as a result of indoor and outdoor air temperature difference [Robert, 2001a].

Both ventilation and infiltration are as a result of air exchange (or change) rate (N) of a building. Hence, air exchange rate is often used to determine the natural ventilation and infiltration rate of a building and it is given as;

$$N = \frac{\omega}{V} \quad (2.24)$$

where, ω is the volumetric flow rate of air into and out of the inner space of a building, (m^3/s) and V is the volume of the space, (m^3). The unit of N is 1/time, usually h^{-1} when the time is in hours, the air exchange rate is called *air change per hour* (ACH). However, several methods have been used to measure the air exchange rate of a building. These include fan pressurized, tracer gas, air velocity, and anemometer, light and laser measurement, surface temperature measurements/thermography, etc. [Allard, Olofsson and Hassan, 2012].

Tracer gas technique is the most commonly used in detecting air exchange and linkage in an enclosed single or multiple zones [Manzeis *et al.*, 2000; Weeks, Boelter and Simmons, 2006]. The ASTM E741 outlines the procedure of using tracer gas to measure N in a single zone. These methods are concentration decay, concentration injection and constant injection [ASTM Standard, 2011]. Depending on the method, N is evaluated by the measurement of the concentration or volume of gas injected into the zone. The method selection is based on the stability of air flow, quality of the measured and limitation of the method. The choice of gas varies from hydrogen, Helium, Carbon Monoxide, Carbon Dioxide, Methane, etc. Ideal tracer gas should possess the following properties; detectability, non-reactivity, safety (non-toxic, non-flammable), buoyancy, relatively low concentration in ambient air, and low cost [Sherman, 1990].

The principle of all tracer gas measurement techniques is the mass balance of the tracer gas in the building or zone. If the ambient concentration is zero and indoor air is well mixed, the total balance takes the form [ASHRAE, 2009];

$$V \left(\frac{dC}{d\theta} \right) = I(\theta) - \omega(\theta)C(\theta) \quad (2.25)$$

where $I(\theta)$ represent the tracer gas injection rate, (m^3/s) at the time θ , (s) and $C(\theta)$ is the tracer gas concentration at the time θ . Equation 2.25 is based on the following assumptions;

1. The tracer gas is uniformly mixed within the building zone or space.
2. The dominant means of removing the tracer gas from the zone or space is airflow out of the building.
3. No other or unknown tracer gas sources are in the building zone or space.

The concentration decay technique is the simplest and straightforward method. In this method, a specific amount of tracer gas is injected into the zone to obtain a uniform tracer gas concentration. Since the decay curve of the tracer gas concentration C follows an exponential course, $I(\theta)$ equal zero after injection and assuming a zero outdoor concentration. The gas concentration $C(\theta)$ is given as [Persily, 1997; Laussmann and Helm, 2011];

$$C(\theta) = C_o e^{-N\theta} \quad (2.26)$$

where C_o is the tracer gas concentration at θ equal to zero. Measurements in concentration decay test are usually analyzed by taking the natural logarithm of Equation 2.26 to give;

$$\ln C(\theta) = \ln C_o - N\theta \quad (2.27)$$

The value of N can be determined from the slope of the logarithm linear regression of the gas concentration measurements over time;

$$N = \frac{[\ln C(\theta_2) - \ln C(\theta_1)]}{(\theta_2 - \theta_1)} = \frac{\Delta \ln C(\theta)}{\Delta \theta} \quad (2.28)$$

From Equation 2.28, the ventilation or infiltration rate ($\dot{h}$) can be expressed as [Szokolay, 2008];

$$\dot{h} = N \times V \text{ or } \dot{h} = ach \times \frac{V}{3600} \quad (2.29)$$

where $\dot{h}$ is the ventilation or infiltration rate (m^3/s). The 3600 is used to convert hours to seconds. Hence, the specific ventilation heat flow rate or ventilation conductance of a building is given as;

$$q\dot{h} = 1200 \times N \times V \text{ or } q\dot{h} = 0.33 \times ach \times V \quad (2.30)$$

$q\dot{h}$ is the specific ventilation heat flow rate (J/s K), and the 0.33 was obtained from the volumetric heat capacity of moist air ($1200 \text{ J/m}^3\text{K}$) divide by 3600. Therefore, the instantaneous sensible $Q_{s,air}$ and latent $Q_{l,air}$ heat gain or loss due to ambient air are

$$Q_{s,air} = q\dot{h}(T_o - T_{in}) \quad (2.31)$$

while

$$Q_{l,air} = \omega \times \rho(\varpi_o - \varpi_i)\gamma \quad (2.32)$$

where $\Delta\varpi$ represent humidity ratios of indoor and outdoor air, ρ is equal to the density of air (Kg/m^3) and γ is the specific heat of vaporization of water (J/kg). At standard conditions $\rho\gamma$ is equivalent to $3.010 \text{ W/ (m}^3/\text{s)}$. [Kreider, Curtiss and Rabl, 2009].

2.3 Other methods of evaluating building thermal load

In the quest for accurate prediction, a various method for evaluating building thermal load has been established. Some of the methods share the same principle with the

above-listed method, while others have a relatively different concept. An overview of some of the method for building thermal load calculation is presented in this section.

2.3.1 Heat balance

This method is based on the first law of thermodynamics. The heat transfer through the building envelope is considered to be the main influence of the building thermal energy balance. As a result, heat transfer by an individual component of the building envelope has to be obtained to evaluate the whole building thermal load. With respect to the previous section, combining all terms of heat loss in the building and subtracting the heat gains, the whole building sensible thermal load is given as [Chwieduk, 2014];

$$Q_s = Q_c + Q_{s,air} + Q_{floor} - Q_{gain} \pm Q_{stor} \quad (2.33)$$

where,

$$Q_{gain} = Q_{sol} + Q_{lit} + Q_{s,app} - Q_{s,occ} \quad (2.34)$$

The effect of heat storage due to the thermal mass of the building envelope was indicated by adding Q_{stor} . Therefore, Q_c can be obtained by calculating the individual heat loss through the wall, roof and windows (absence of solar radiation) using Equation 2.1. Similarly, Equation 2.2 and 2.17 can be used to calculate the solar heat gain through the opaque and transparent components, respectively to obtain Q_{sol} .

However, Q_{stor} can be obtained by

$$Q_{stor} = C_{eff} \times \dot{T} \quad (2.35)$$

C_{eff} is *effective heat capacity*, which is defined as the periodic heat flow into and out of a body divided by the surface temperature swing (J/K) [Sonderegger, 1978], and $\dot{T}$ is the rate of temperature increase (K/h), it is expressed as;

$$\dot{T} = \frac{\Delta T}{\Delta \theta} = \frac{T_2 - T_1}{\theta_2 - \theta_1} \quad (2.36)$$

From Equation 2.33, a positive Q_s indicates heating load while a negative implies cooling load. However, the whole-building thermal load is the sum of the sensible and latent thermal load. As shown in Table 2-1, the latent heat components are ambient air, electrical appliances, and occupants. Hence, the whole-building latent heat is;

$$Q_l = Q_{l,air} + Q_{l,occ} + Q_{l,app} \quad (2.37)$$

Latent heat transfer is only significant in a building that uses humidification. Given that the indoor humidity cannot be controlled in buildings without humidification. In this regard, a negative Q_l shows that the whole-building thermal load is greater than the sensible heating load alone [Masuda and Claridge, 2014]

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2.3.2 TETD/ TA

Total Equivalent Temperature Difference/ Time-average (TETD/TA) method was developed to deal with the transient effect of solar radiation and thermal storage in a building envelope. In this regard, the response factor technique was used with several wall and roof assemblies sample. In order to derive data used to calculate TETD value as a function of sol-air temperature and maintained room temperature [Yumrutaş, Kaşka and Yildirim, 2007]. Heat gain through the walls and roofs depend on inner surface temperatures, indoor air temperature, and convection heat transfer coefficient. The inner surface temperature varies with time which is a factor of solar irradiation, ambient air temperature, and thermophysical properties of the walls and roof [Kaşka and Yumrutaş, 2009]. Therefore, the heat gain was obtained by

$$Q_{TETD} = T_{eo,avg} - T_i + (DF)(T_{eo+\phi} - T_{eo,avg}) \quad (2.38)$$

where,

$$TETD = T_{eo,avg} - T_i + (DF)(T_{eo+\phi} - T_{eo,avg}) \quad (2.39)$$

The heat gain is converted to an instantaneous space cooling load by the time-averaging (TA) technique. This technique averages the radiant portions of the heat gain components for the current hour with related values from an appropriate period of immediately preceding hours. Due to the complexity of this method, it is best solved by a computer program.

2.3.3 CLTD/SCL/CLF

The Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) method was developed by ASHRAE, 2001 to address the complexity of thermal capacity [Robert, 2001b]. The simplified, hand-tractable arithmetic method was developed using a detailed computer model and/or data. Data obtained were used to generate CLTD values for direct one-step calculation of cooling load. In order to deal with conduction heat gain via sunlit walls and roof as well as conduction through exposed glazing. Thus, conductive heat transfer through walls and roof can be determined by

$$Q_{c,\theta} = U \times A \times CLTD \quad (2.40)$$

The subscript θ represents the hour of the day. The CLTD values for the roof were adjusted by:

$$CLTD_{roof} = CLTD + (78 - T_{i,des}) + (T_{am} - 85) \quad (2.41)$$

where $T_{i,des}$ is the actual inside design air temperature ($^{\circ}\text{C}$), and $T_{i,am}$ is the average ambient design air temperature ($^{\circ}\text{C}$), it can be estimated by;

$$T_{am} = T_{o,des} - \frac{T_{\max-\min}}{2} \quad (2.42)$$

$T_{o,des}$ represent the ambient design air temperature (°C) and $T_{max-min}$ is the daily temperature range. On the other hand, conductive heat gain through a window can be expressed as

$$Q_{C,glaz,\theta} = U \times A \times CLTD_{glaz,\theta} \quad (2.43)$$

Similarly, solar heat gain through glazing and internal heat source were developed using SCL and CFL. The radiative solar heat gain through any glass surface in a building is given as

$$Q_{sol,glaz,\theta} = A \times SC \times SCL \quad (2.44)$$

Using SCL values, one has to know the number of walls, floor covering, inside shading, and some other variables in the zone. Furthermore, heat gain by occupants was also proposed, and it is given as

$$Q_{occ,\theta} = N \times F_d (Q_{s,occ} \times CLF_{\theta} + Q_{l,occ}) \quad (2.45)$$

$Q_{s,occ}$ and $Q_{l,occ}$ are sensible and latent heat gain, respectively, while $Q_{occ,\theta}$ is the resultant cooling load at the hour, θ . The latter is immediately translated into cooling load while the former undergoes time delay subjected to the mass of the room and released in later time. F_d represent the diversity factor. It takes into account the variability of the number of occupants in the space. Typical F_d values are given in Table 2-3 [Kreider, Curtiss and Rabl, 2009].

Table 2-3: Typical occupants' diversity factor values in buildings

Type of building	F_d values
Industrial	0.85-0.95
Retail	0.80-0.90
Accommodation	0.40-0.60
Office	0.75-0.90
Hotel	0.40-0.60

Source: Kreider, Curtiss, and Rabl. (2009) *Heating and cooling of buildings: design for efficiency*. Second edition. Edited by F. Kreith and R. Mahajan. Denver: CRC Press.

Heat generated due to lighting and appliance were also proposed in this method. The heat gain due to lighting at any given hour can be determined by

$$Q_{lit,\theta} = W_l \times F_d \times F_{sa} \times CLF_{\theta} \quad (2.46)$$

Whereas the sensible heat gain due appliance is given as

$$Q_{app,\theta} = Q_{s,app} \times CLF_{\theta} \quad (2.47)$$

$Q_{s,app}$ and $Q_{app,\theta}$ represent the sensible heat generated and corresponding cooling load at the hour, θ . Equation 2.47 is applicable only to appliance/ equipment that generates heat due to resistive heating.

The CLFD/SCL/CLF values are determined and given by ASHRAE, 2001. Similar to SCL values selection, the building type, room location, floor covering must be known to determine the zone type. Once the zone type has been obtained the occupants, lighting and appliance CFL values can be found.

2.3.4 Radiant time-series

Radiant time series (RTS) derived from the heat balance method for performing design cooling load evaluation. This method was aimed to replace all other simplified

methods such as the transfer function, CLTD/SCL/CLF and TETD/TA. In addition, it was developed to offer a rigorous method without iterative calculation and yet quantifies the contributions of each component to the whole building cooling load [Robert, 2001b; Spitler, 2014]. Hence surface conductive heat transfer is determined by

$$Q_{cond,\theta} = A \sum_{j=0}^{23} Y_{pj} (T_{eo-j\delta} - T_i) \quad (2.48)$$

where A serves as the surface area, Y_{pj} is the j th response factor, with the response factor for walls and roof given by ASHRAE, 2001. $T_{eo-j\delta}$ represent the sol-air temperature from j hours ago, T_i is the indoor air temperature, assumed to be constant. After calculating conductive heat gain, solar heat gain, internal heat gain and ambient air heat transfer are calculated the same as with transfer function method.

2.3.5 Degree-days

A degree-day is one of the simplest and fast methods for evaluating building thermal load [Kalogirou, 2014]. This method is based on the difference between a base temperature (T_b) and the average ambient air temperature (T_{av}). The base temperature is a range of temperatures at which the inner space of a building requires no heating or cooling to achieve thermal comfort. When the ambient air temperature is below or above the base temperature, it is assumed that heating or cooling is needed to regulate the indoor temperature; since heat losses from a building are directly proportional to the indoor-to-outdoor air temperature difference. It follows that the energy consumption of a heated building over a period of time is related to the sum of the temperature differences over the period [Day, 2006]. Degree-days in hourly average temperature are given by [De Rosa *et al.*, 2015]; numbers of heating (HDH) degree-hours is;

$$HDH = \sum_m (T_b - T_{av})^+ \quad (2.49)$$

While cooling (CDH) degree-hours is determined by;

$$CDH = \sum_m (T_{av} - T_b)^+ \quad (2.50)$$

The positive sign implies that only positive values are considered. Also, m indicates monthly degree-hours or the sum of daily degree-hours in a given month. It could also be extended or reduced to yearly or daily degree-hours, respectively. The base temperatures vary from country to country. For example, in the UK heating degree days are based on an outside dry bulb temperature of 15.5°C, whereas Australia uses 18°C and the United States uses 18.3°C. From Equation 2.49 and 2.50, the monthly or seasonal thermal load can be determined by [Büyükalaca, Bulut and Yilmaz, 2001; Overen, Meyer and Makaka, 2017].

$$q_{h,c} = U \times DH_{h,c} \quad (2.51)$$

where $q_{h,c}$ is cooling or heating load (kWh/m²) and $DH_{h,c}$ is the total heating or cooling degree-hours (°C·h). The corresponding heating or cooling energy required to maintain a stable indoor thermal condition is given by:

$$\phi_{h,c} = \frac{UA}{\eta_{h,c}} \times DH_{h,c} \quad (2.52)$$

where $\phi_{h,c}$ is the monthly heating or cooling energy (kWh), A is the total floor surface area of the building and $\eta_{h,c}$ is the efficiency of the heating or cooling system.

2.4 Summary

The fundamentals of thermal load have been discussed. The discussion covers the various form of heat transfer in a building envelope as well as the internal heat gain. In this regard, conductive heat transfer in the opaque and transparent components of the building envelope was discussed. Also, the method of evaluating the solar heat gain through glazing (window) was also considered. Internal heat gain which is due to occupants (domestic activities), lightings and electrical appliances was elaborated in this chapter. The various formulas required to calculate the sensible and latent heat gain in each of the components were given. Discussions of the fundamental of thermal load ended with the ambient air heat transfer. In which, the sensible and latent heat transfer due to air exchange rate of a building were explained. The formulas of heat transfer were given in the steady and unsteady state. In the steady state, the thermal capacity of the building envelope or indoor mass were not taking into consideration. Heat storage in the unsteady state was taken into consideration by introducing a time lag and decrement factor. Also, it was indicated that steady-state heat transfer is sufficient for calculating the heating load, whereas, the effect of thermal capacity has to be accounted for in cooling load calculations.

Furthermore, other various thermal load calculation methods were briefly discussed. These methods include heat balance, TETD/TA, CLTD/SCL/CLF, radiant time-series, and degree-days. While heat balance is the fundamental of thermal load calculation, TETD/TA was introduced to deal with the transient effect of solar radiation and heat storage in the building envelope. On the other hand, CLTD/SCL/CLF was developed to simplify the thermal capacity issue in cooling load calculations. Whereas, radiant time series was recently developed to replace TETD/TA, CLTD/SCL/CLF, and other simplified thermal load calculation methods. Beside, degree-day is an unrelated thermal load calculation method. It uses the difference between the ambient air and a base temperature to determine the thermal load of a building.

REFERENCES

- Allard, I., Olofsson, T. and Hassan, O. A. B. (2012) 'Methods for air tightness analysis for residential buildings in Nordic countries', *WIT Transactions on Ecology and the Environment*, 165, pp. 311–322. doi: 10.2495/ARC120281.
- Antretter, F., Klingenberg, K. and Pazold, M. (2013) 'All-in-One Design Tool Solution for Passive Houses and Buildings — Monthly Energy Balance and Hygrothermal Simulation.'
- Asan, H. (1998) 'Effects of wall's insulation thickness and position on time lag and decrement factor', *energy and buildings*. Elsevier, 28(3), pp. 299–305.
- Asan, H. (2000) 'Investigation of wall's optimum insulation position from maximum time lag and minimum decrement factor point of view', *energy and buildings*. Elsevier, 32(2), pp. 197–203.
- Asan, H. and San, Y. S. (1998) 'Effects of Wall 's thermophysical properties on time lag and decrement factor', *Energy and Buildings*, 28, pp. 159–166. doi: 10.1016/S0378-7788(98)00007-3.
- ASHRAE (2005) 'ASHRAE Handbook: Fundamentals', *American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta*, 32, p. TC 4.7, Energy Calculations. doi: 10.1039/c1cs15219j.
- ASHRAE (2009) *ASHRAE Handbook–Fundamentals*. SI Edition. Edited by M. S. Owen. Atlanta, GA: the American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.
- Aste, N., Angelotti, A. and Buzzetti, M. (2009) 'The influence of the external walls thermal inertia on the energy performance of well insulated buildings', *Energy and Buildings*. Elsevier, 41(11), pp. 1181–1187.
- ASTM Standard (2011) 'Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution.' ASTM International West Conshohocken, PA.
- De Boeck, L., Verbeke, S., Audenaert, A. and De Mesmaeker, L. (2015) 'Improving the energy performance of residential buildings: A literature review', *Renewable and Sustainable Energy Reviews*. Elsevier, 52, pp. 960–975. doi: 10.1016/j.rser.2015.07.037.
- Bradshaw, V. (2006) *The Building Environment: Active and Passive Control Systems*. Third. New Jersey: John Wiley & Sons.
- Brain, D., John, D., Ksenia, P. and Peter, G. (2016) *Towards Zero-Emission Efficient and Resilient Buildings: Global Status Report 2016*. Paris.
- Büyükalaca, O., Bulut, H. and Yilmaz, T. (2001) 'Analysis of variable-base heating and cooling degree-days for Turkey', *Applied Energy*, 69(4), pp. 269–283. doi: 10.1016/S0306-2619(01)00017-4.

- Chartered Institution of Building Services Engineers (2000) 'Minor factors influencing solar gains', 5(3), pp. 170–184.
- Chwieduk, D. (2014) *Solar Energy in Buildings: Thermal Balance for Efficient Heating and Cooling*. Elsevier.
- Day, T. (2006) *Degree-days: theory and application*. First edit, Tm41. First edition. Edited by K. Butcher. London: Chartered Institution of Building Services Engineers. doi: 1903287766.
- Van Dijk, H., Spiekman, M. and De Wilde, P. (2006) 'A Monthly Method for Calculating Energy Performance in the Context of European Building Regulations', pp. 255–262.
- Duffie, J. A. and Beckman, W. A. (2013) *Solar engineering of thermal processes*. Fourth. New Jersey: John Wiley & Sons.
- Eurac, G. D. and Academy, E. (2015) 'Holistic method for energy renovation of buildings: focus on users involvement Pre-prints of BSA 2015 - Building Simulation Application Pre-prints of BSA 2015 - Building Simulation Application', *Building Simulation Application*, pp. 1–8.
- Gordon, E. B., Parvin, F. A. and Horton, D. J. (1994) *Development and application of a standard test method for the performance of exhaust hoods with commercial cooking appliances*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA (United States).
- Jin, X., Zhang, X., Cao, Y. and Wang, G. (2012) 'Thermal performance evaluation of the wall using heat flux time lag and decrement factor', *Energy and Buildings*. Elsevier B.V., 47, pp. 369–374. doi: 10.1016/j.enbuild.2011.12.010.
- Kalogirou, S. A. (2014) *Solar Space Heating and Cooling, Solar Energy Engineering*. Academic Press. doi: 10.1016/B978-0-12-397270-5.00006-6.
- Kaşka, Ö. and Yumrutaş, R. (2009) 'Experimental investigation for total equivalent temperature difference (TETD) values of building walls and flat roofs', *Energy Conversion and Management*, 50(11), pp. 2818–2825. doi: 10.1016/j.enconman.2009.06.027.
- Kontoleon, K. J. and Eumorfopoulou, E. A. (2008) 'The influence of wall orientation and exterior surface solar absorptivity on time lag and decrement factor in the Greek region', *renewable energy*. Elsevier, 33(7), pp. 1652–1664.
- Korniienko, S. (2015) 'Evaluation of Thermal Performance of Residential Building Envelope', *Procedia Engineering*. Elsevier B.V., 117(8 442), pp. 191–196. doi: 10.1016/j.proeng.2015.08.140.
- Kreider, J. F., Curtiss, P. S. and Rabl, A. (2009) *Heating and cooling of buildings: design for efficiency*. Second edition. Edited by F. Kreith and R. Mahajan. Denver: CRC Press.
- Laussmann, D. and Helm, D. (2011) 'Air Change Measurements Using Tracer Gases',

- Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality*, pp. 365–404. doi: 10.5772/1030.
- Manzeis, R., K, S., V, L. and J, P. (2000) ‘Measuring Air Changes per Hour with Carbon Dioxide’, *Critical Care Medicine*, 1, pp. 1–11.
- Masuda, H. and Claridge, D. E. (2014) ‘Statistical modeling of the building energy balance variable for screening of metered energy use in large commercial buildings’, *Energy and Buildings*. Elsevier B.V., 77, pp. 292–303. doi: 10.1016/j.enbuild.2014.03.070.
- Overen, O. K., Meyer, E. L. and Makaka, G. (2017) ‘Thermal, Economic and Environmental Analysis of a Low-Cost House in Alice, South Africa’, *Sustainability*. Multidisciplinary Digital Publishing Institute, 9(3), p. 425.
- Persily, A. K. (1997) ‘Evaluating building IAQ and ventilation with indoor carbon dioxide’, *ASHRAE Transactions*, pp. 193–204.
- Robert, A. P. (2001a) *ASHRAE Handbook-Fundamentals*. SI. Edited by ASHRAE. New York: ASHRAE.
- Robert, A. P. (2001b) ‘Cooling Load Calculation’, in *ASHRAE Handbook-Fundamentals*. SI. New York: ASHRAE, pp. 1–106.
- Romani, Z., Draoui, A. and Allard, F. (2015) ‘Metamodeling the heating and cooling energy needs and simultaneous building envelope optimization for low energy building design in Morocco’, *Energy & Buildings*. Elsevier B.V., 102, pp. 139–148. doi: 10.1016/j.enbuild.2015.04.014.
- De Rosa, M., Bianco, V., Scarpa, F. and Tagliafico, L. A. (2015) ‘Historical trends and current state of heating and cooling degree days in Italy’, *Energy Conversion and Management*. Elsevier Ltd, 90, pp. 323–335. doi: 10.1016/j.enconman.2014.11.022.
- Rubin, M. (1982) ‘Calculating heat transfer through windows’, *Energy Research*, 6(August 1981), pp. 341–349.
- Sherman, M. H. (1990) ‘Tracer-gas techniques for measuring ventilation in a single zone’, *Building and Environment*, 25(4), pp. 365–374. doi: 10.1016/0360-1323(90)90010-O.
- Smith, V. A., Swierczyna, R. T. and Claar, C. N. (1995) *Application and enhancement of the standard test method for the performance of commercial kitchen ventilation systems*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA (United States).
- Sonderegger, R. (1978) ‘Diagnostic Tests Determining the Thermal Response of a House’, *ASHRAE Transactions*. Atlanta, GA, 84(pt.1), p. 691.
- Spitler, J. D. (2014) *Load Calculation Applications Manual*. Second. Edited by S. O. Mark. Atlanta: ASHRAE. doi: 978-1-933742-72-4.

- Suszanowicz, D. (2017) 'Internal heat gain from different light sources in the building lighting systems', in *E3S Web of Conferences 19*. Singapore: EDP Sciences, pp. 1–5. doi: 10.1051/e3sconf/20171901024.
- Szokolay, S. V. (2008) *Introduction to architectural science: the basis of sustainable design*. Second, *Journal of the American College of Radiology: JACR*. Second. Edited by C. Brisbin. Oxford: Elsevier. doi: 10.1016/j.jacr.2010.08.020.
- Ulgen, K. (2002) 'Experimental and theoretical investigation of effects of wall's thermophysical properties on time lag and decrement factor', *energy and buildings*. Elsevier, 34(3), pp. 273–278.
- Wang, T. P. and Wang, L. B. (2016) 'The effects of transparent long-wave radiation through glass on time lag and decrement factor of hollow double glazing', *Energy and Buildings*. Elsevier B.V., 117, pp. 33–43. doi: 10.1016/j.enbuild.2016.02.009.
- Weeks, M. T., Boelter, F. W. and Simmons, C. E. (2006) 'Practicalities in Applying the ASTM Tracer Gas Method to Measure Air Change Rates', in *American Industrial Hygiene Conference and Exposition Philadelphia*. Pennsylvania.
- Yaghoobian, N. and Srebric, J. (2015) 'Influence of plant coverage on the total green roof energy balance and building energy consumption', *Energy and Buildings*. Elsevier B.V., 103, pp. 1–13. doi: 10.1016/j.enbuild.2015.05.052.
- Yumrutaş, R., Kaşka, Ö. and Yildirim, E. (2007) 'Estimation of total equivalent temperature difference values for multilayer walls and flat roofs by using periodic solution', *Building and Environment*, 42(5), pp. 1878–1885. doi: 10.1016/j.buildenv.2006.02.020.

Chapter 3

DESCRIPTION OF HOUSE AND METEOROLOGICAL MEASUREMENTS

3.1 Introduction

Building thermal load can be divided into conductive heat transfer, glazing solar heat gain, internal heat gain, and ambient air heat transfer. Conductive and ambient heat transfer is mainly driven by indoor and outdoor air temperature difference. Due to the varying intensity of solar radiation on the perimeter walls, conductive heat transfer is further determined by introducing sol-air temperature. Sol-air temperature accounts for the air film temperature around the perimeter walls concerning the incident solar radiation. It also caters for other parameters such as surface absorbance, colour, orientation (vertical or horizontal) of the surface [Kaşka and Yumrutaş, 2009; Kalogirou, 2014]. Sol-air temperature is also applicable to conductive heat transfer through a roof in the present of solar radiation.

Similarly, unsteady state conductive heat transfer accounts for thermal capacity of the building envelope using time lag and decrement factor. Thermal capacity depends on the thermophysical properties of the building material and determines the rate as well as the amount of heat transfer [Asan, 2000; Ulgen, 2002]. Thus, inner and outer surface temperatures of the building envelope components are required to determine the time lag and decrement factor.

On the other hand, ambient air heat transfer occurs due to air flow through intentional and unintentional openings on the building envelope. The influencing factors of ambient air heat transfer are wind speed and direction, and ambient and indoor air temperature difference. Furthermore, glazing solar heat gain result from penetrated sun rays through fenestrations. As a result, the solar irradiance incident on glazing is a major factor of solar heat gain. Occupants, lighting and appliance which can be quantified by the operation of the house, resulting in the internal heat gain.

In this regard, to effectively evaluate the thermal load of the passive solar house, the above-listed parameters influencing the heat transfer of the house have to be measured. This chapter focus on the technique and sensors used in measuring the thermal load influencing parameters of the house. The chapter, however, starts by describing the house and its site. This was followed by a discussion on the sensors and method used in measuring the meteorological parameters of the house. Lastly, the experimental methodology of the air exchange rate of the house was given.

3.2 Site and house description

A passive solar house designed and constructed in the University of Fort Hare SolarWatt Park was used in this research [Ziuku and Meyer, 2011]. The University of Fort Hare is located in latitude 32.8° south and longitude 26.8° east at an altitude of 540 m in Alice, Eastern Cape South Africa. The Google Earth view of the University of Fort Hare Alice campus indicating SolarWatt Park and a photo of the passive solar house is given in Figure 3.1. *Together in Excellence*



Figure 3.1: Satellite image of the University of Fort Hare, SolarWatt Park [Google Earth] and a photo of the house

According to the Köppen-Geiger climate classification, Alice is in the BSh Arid, Steppe, Hot arid climate. Such a climate is characterized with annual precipitation greater than 5 Pth. The annual temperature is greater than or equal to +18°C [Conradie, 2012]. Locally, Alice is classified in the temperate interior (Zone 2) climate of South Africa [South African Bureau of Standards, 2011b]. The climatic location of Alice is indicated by the red arrow in Figure 3.2.

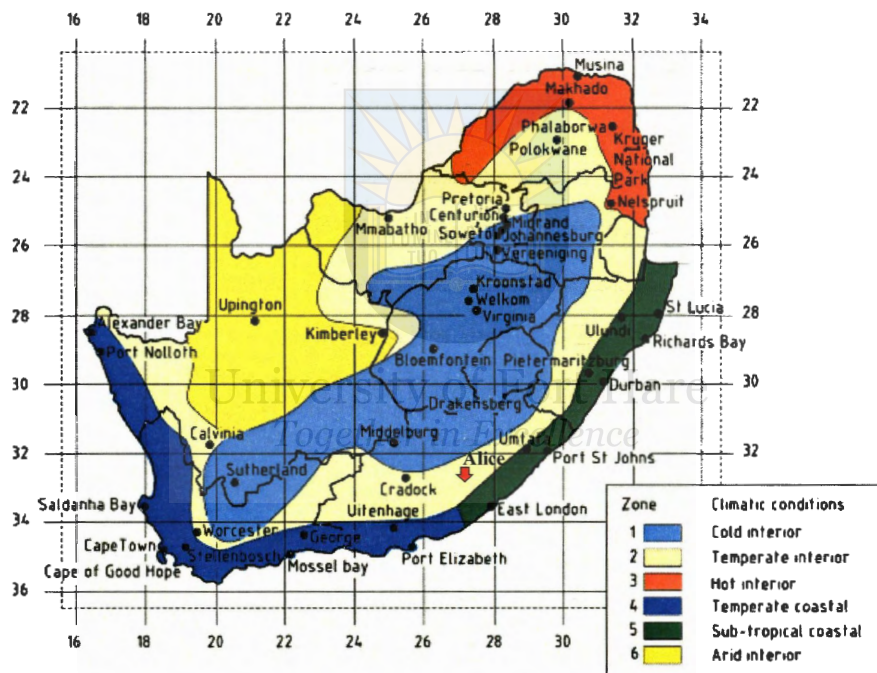


Figure 3.2: Climatic zone map of South Africa [SANS 204, 2011]

The climatic of Alice is characterized by a hot summer and mild (no snow) winter, with an average dry bulb temperature of 29°C and 15°C, respectively. The east wind is predominant in summer while the winter is dominated by the west wind. An average wind speed of 2.5 m/s is experienced in Alice throughout the year [Overen, Meyer and Makaka, 2017; South Africa Weather Service, 2017].

3.2.1 Orientation and floor plan

The site was found suitable for the house due to its clear north side with no sun rays' obstacle such as tall trees, mountains, and high rise buildings. In line with the energy efficient building design recommendation by SANS 204 and 10400-XA [South African Bureau of Standards, 2011a, 2011b], the house was designed with its major glazing area facing north. A simulated daily sun path of the house concerning its orientation is shown in Figure 3.3.



Figure 3.3: A 3D view sun path simulation of the house

The selected orientation of the house is to ensure maximum penetration of solar radiation during the winter season. At the same time, the 1 m long eaves prevent solar radiation from the inner space in summer. Thereby, preventing overheating during the summer season and providing passive heating in winter. The clerestory windows were installed to release indoor warm air due to convection current to achieve passive cooling. To this effect, sufficient space was ensured at the southeast side of the house, to allow the free flow of summer prevailing wind. Deciduous trees planted at the west side provide late afternoon shading and prevent the cold winter wind during the winter season.

The 10 m x 8 m (80 m²) floor area of the house comprises of three rooms. These include an open plan living room/kitchen, stretching from north to south elevation of the house. Also, north and south facing bedrooms as well as a bathroom. The rooms

were arranged in the house to ensure optimum and uniform admittance of solar radiation. The floor plan of the house indicating the floor arrangement is shown in Figure 3.4.



Figure 3.4: The house floor plan and arrangement

The two north-facing windows admit solar radiation to the north floor areas, while the clerestory windows channel solar radiation to the south areas. As a result, the living room/kitchen receives solar radiation from morning to mid-day through the east and north facing windows, while the north-facing bedroom enjoys solar access during mid-day. At the same period, the south facing bedroom receives solar radiation via the clerestory windows. As such, irrespective of the floor arrangement, even solar distribution is achieved indoor.

3.2.2 Structure details

The floor of the house is made of 90 mm thick concrete slab, laid on a 250 micron damp-proof. The damp-proof was used to ensure that no moisture percolates from the ground through the floor into the house. As shown in Figure 3.4, a double brick 15 mm air cavity structure served as the walls of the house. The air cavity which acts as a thermal insulator reduces the rate of heat transfer through the walls. However, the perimeter walls were made of face bricks. Hence the outer surfaces were not plastered while the inner surfaces were plastered and painted. Similarly, both side of the partition walls were plastered and painted. As shown in Figure 3.5, the north and south walls were raised to a height of 3.0 m, and the east and west walls were built to a height of 3.9 m at the pitch of the roof. Measuring from the north floor area indoors, the distance between the floor and the ceiling was 2.6 m. Elevation plans and interior rendering of the house, detailing the dimension of the building envelope components are given in Figures 3.5 and 3.6, respectively.

Furthermore, the house roof was designed to accommodate photovoltaic (PV) panels and solar water heater (SWH) collectors, as shown in Plate 3.7. Therefore, the south half of the roof area was covered with galvanized corrugated zinc metal sheet. On the east and west wings of the north half of the roof, 20 sets 1.4 m x 0.8 m PV panel was evenly spread. In between the wings, was occupied by two 1.3 m x 2 m high-pressure SWH collectors. A photo of the house is shown in Plate 3.7.

At the south half of the roof, the ceiling was fastened under the branding running from the south walls to the pitch. As such, the ceiling assumed the slope of the roof, forming a skillion ceiling, thereby allowing direct access through the clerestory windows to the inner space of the house. At the north half of the roof, a crawl space was design under the roof area. Thus the ceiling boards were fastened to the ceiling joist. The ceiling of the house was made of 9 mm rhino plastered board in bedrooms and 12 mm pine ceiling at the living/kitchen. Openings between the walls and ceiling, around plumbing pipes, window frames and doors were properly sealed to minimize air leakage. The

house was found suitable as a thermal load reference house due to its passive solar features.

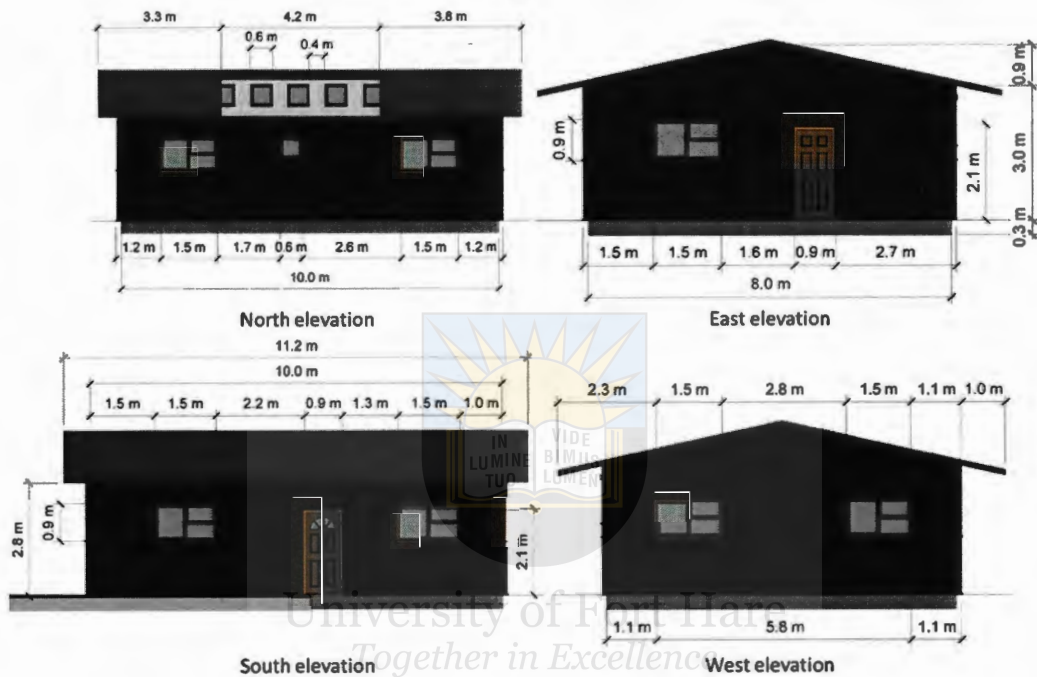


Figure 3.5: Elevation plan of the house



Figure 3.6: West view interior rendering of the house



Plate 3.1: Photo of the passive solar house

Also, the house possesses a major energy efficiency design feature of house requirements in the climate zone 2 according to SANS 204 [South African Bureau of Standards, 2011b]. These features include the true north orientation, 1 m long eaves, longest façade stretching from east to west, and so forth. Although the floor arrangement does not place major active area (living room) at the northern side, the clerestory windows complement the purpose of the north facing windows in this regard.

3.3 Meteorological Measurements

Besides the physical properties of the building envelope, thermal behavior of the house plays a crucial role in thermal load. Thermal behavior deals with the response of the indoor thermal conditions of a house to the ambient weather conditions with respect to the building envelope. Having discussed the physical properties of the building envelope, this session focus on the thermal parameters. As well as the methods and sensors used in measuring them.

3.3.1 Indoor/ outdoor air temperature and relative humidity

HMP60 temperature and relative humidity probe were used to measure the indoor as well as the outdoor air temperature and relative humidity. The HMP60 probe uses a

platinum resistance temperature (PRT) detector to measure air temperature. The PRT detector sensed temperature by measuring the electrical resistance of a noble metal such as platinum. The resistance of the platinum wire is measured by passing a direct current through it and obtaining its voltage. The measured voltage is converted into temperature, using a calibrated equation [Jumo GmbH & Co., 2005; Moser and Gijs, 2007], whereas air relative humidity is measured by a capacitive relative humidity sensor. This sensor is a capacitor of hygroscopic dielectric material between a pair of electrode. At equilibrium conditions, the amount of moisture present in the hygroscopic material depends on both ambient air temperature and water vapor pressure.

Given that relative humidity is also a function of air temperature and water vapor pressure, a relationship exists between relative humidity, the moisture present in the sensor, and sensor capacitance. This relation is based on the operation of the capacitive humidity instrument [Yamazoe and Shimizu, 1986; Rontronic Measurement Solutions, 2016]. The measurement specifications of HMP 60 probe temperature and relative humidity sensor are given in Table 3-1 [Campbell Scientific INC, 2010].

Table 3-1: HPM 60 temperature and relative humidity sensors specification

Parameters	Measurement range	Accuracy ($\pm$)
Temperature ($^{\circ}\text{C}$)	-40 to +60	0.6
Relative humidity (%)	at 0°C to 40°C	0 to 90 3
		90 to 100 5
	at 0°C to 40°C	0 to 90 5
	and $+40^{\circ}\text{C}$ to $+60^{\circ}\text{C}$	90 to 100 7

Source: Campbell Scientific INC (2010) HMP60 Temperature and Relative Humidity Probe. Utah

To measure the indoor air temperature and relative humidity, three sets of HMP60 probes were used. In the living room/kitchen, south and north facing bedrooms one HMP60 probe was suspended at a height of 0.8 m to ensure that the measured air

temperature is nearest to the temperature felt by the occupants. At the same time, the probe does not obstruct the activities of the occupants. The locations of the HMP60 probe in the house are indicated in Figure 3.7.

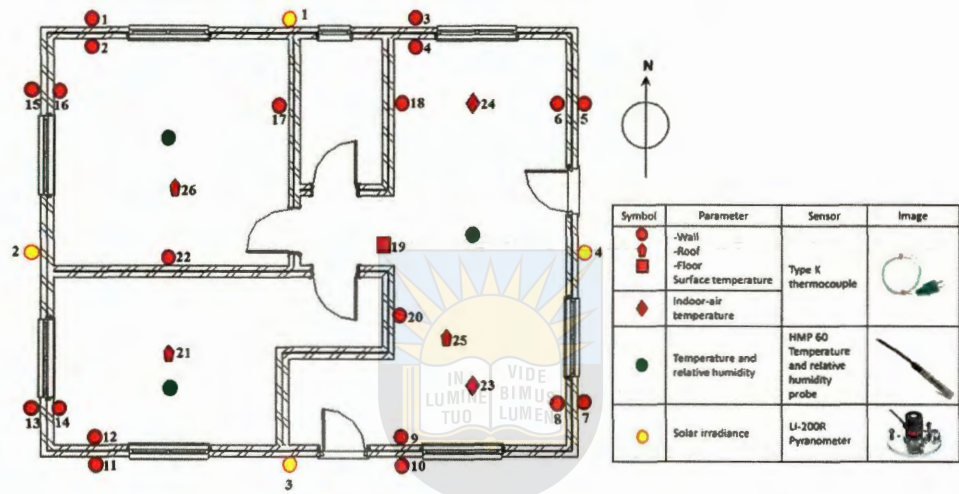


Figure 3.7: The house floor plan indicating locations of the meteorological sensor

Furthermore, the outdoor air temperature and relative humidity measuring probe was housed in a 6-plate natural aspirated radiation shield. A setup outdoor weather station consisting of the natural aspirated radiation shield and other sensors are shown in Plate 3.2.



Plate 3.2: Setup outdoor weather station

The white painted radiation shield enables it to reflect solar radiation. At the same time, the louver allows natural free flow of air through the shield. Thereby keeping the probe close as possible to the ambient air temperature (eliminating solar effect) and water vapor [Campbell Scientific INC, 2015]

3.3.2 Building envelope surface temperature

The surface temperature of the building envelope components of the house was measured with a total of 24 thermocouples. Thermocouples are made of two dissimilar metal (p and q) wires; one predesigned as negative while the other as positive. The wires were joined to form two junctions; measurement (hot) and reference (cold) junction. Schematics of a standard and commonly used thermocouple are given in Figures 3.8 and 3.9, respectively.

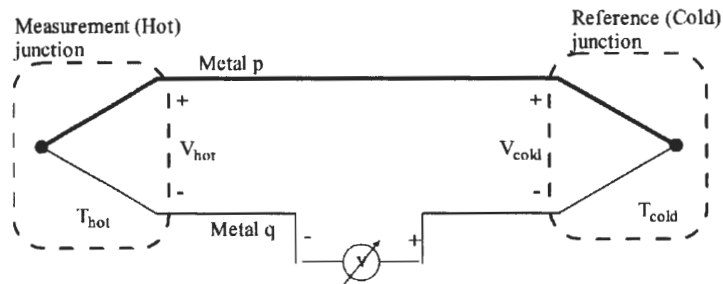


Figure 3.8: Schematic of a standard thermocouple

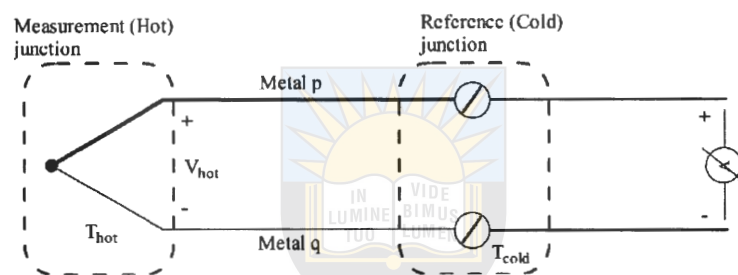


Figure 3.9: Schematic of commonly used thermocouple

According to the Seebeck effect, the voltage output of a thermocouple circuit is a function of the temperature difference between the two junctions [Maxim integrated, 2007]. In the commonly used thermocouple, a third metal is introduced into the circuit. This metal is known as an intermediate metal. It does not influence the output voltage, as long as the same temperature is maintained at the two junctions. This configuration allows the thermocouple to be used without a separate reference junction.

Type K (commonly used) thermocouple with a temperature measurement range of -200 to 1250°C and error of 2.20°C , [Montgomery, 1992] was used in this research. As shown in Figure 3.7, the inner and outer surface temperatures of the perimeter walls of the passive solar house were measured with Type K thermocouples. As well as, the temperature of the inner surfaces of the roof, floor, and surface of the partition walls. The thermocouples were mounted such that the measurement junction has direct contact with the surface of the building envelope components. On the perimeter walls, the thermocouples were installed such that the outer and inner surfaces measurement

junction are aligned. As a result, a height of 1.8 m (half the distance between the ceiling and floor) was maintained on all walls, including the partition walls.

3.3.3 The various elevations global solar irradiance

The influence of solar radiation on their respective ambient air film temperature was taken into consideration to evaluate heat transfer through the perimeter walls, roof, and windows of the house. In this regard, the solar irradiance at the north, east, south and west elevations of the house were measured with Li-Cor (LI-200R) pyranometer. Li-Cor pyranometer uses a silicon photovoltaic sensor mounted in a cosine-corrected head to measure solar irradiance. Together, a variable shunt resistor circuit in the cable is used to convert the measured current to voltage signal [Kerr, Thurtell and Tanner, 1967]. A cosine-corrected sensor operates base on the principle of Lambert's cosine law. Its state that the radiation observed from an ideal diffusely reflecting surface is directly proportional to the cosine of the angle θ between an observer's line of sight and the surface normal. Figure 3.10 shows Lambertian surface which the cosine-corrected head of a Li-Cor pyranometer is based.

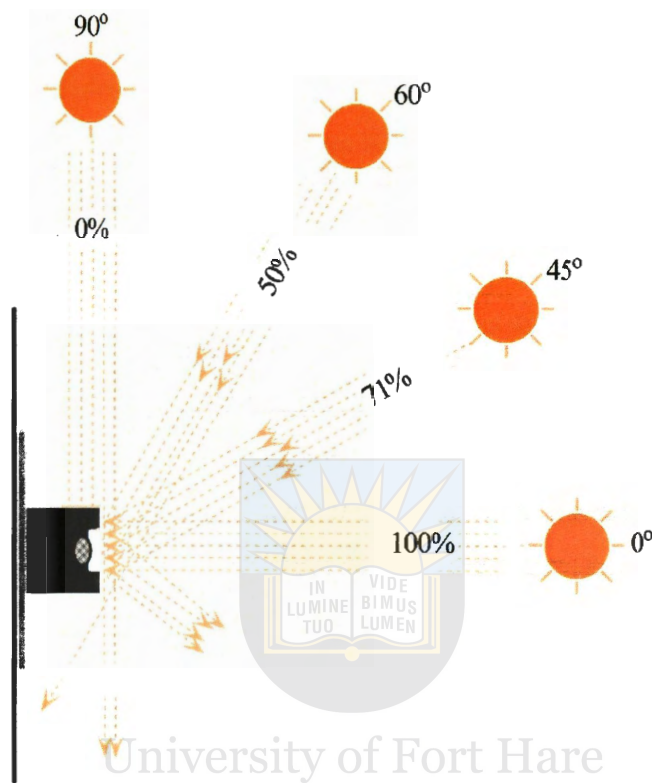


Figure 3.10: Li-Cor pyranometer cosine-corrected head principle of operation

The correction (Lambert surface) provide a uniform diffusion of the incident radiation. As such, irradiance is the same in all direction from which it can be measured [Biggs, 2015]. Typically, LI-200R pyranometer has a sensitivity of $75 \mu\text{A}$ per 1000 Wm^{-2} . In a 2 m cable configuration, terminated into 147 Ohm load, the response time is less than $1 \mu\text{s}$. LI-200R pyranometer is specifically designed with a high stability silicon photovoltaic sensor (blue enhanced). It is calibrated for a daylight spectrum of 400 to 1100 nm with as an error of $\pm 3\%$, within $\pm 60^\circ$ angle of incidence. Also, the default cable length can be extended up to 50 m [Li-COR GmbH, 2015].

As shown in Figure 3.7, four sets of LI-200R pyranometer was used to measure the solar irradiance of the four elevations of the house. Hence, one pyranometer was mount vertically on the outer surface of each of the perimeter wall. They were mounted at an even height of 1.8 m. By so doing, the solar radiation received by the air film

around the walls and windows at each elevation were measured. The measured global horizontal irradiance covered in the next section were used to analyze the solar effect on the air firm temperature above the roof.

3.3.4 Ambient global horizontal irradiance, wind speed, and direction

A Kipp & Zonen CMP 11 pyranometer was used to monitor the global horizontal irradiance (GHI) of the house. CMP 11 pyranometer is made up of 32-junction thermopile as a sensing element. The thermopile consists of thermocouple junction pairs connected in series. The measurement (hot) junction of one of the thermocouple absorbs thermal radiation, increasing its temperature. The difference between the measurement and a fixed temperature reference (cold) junction produces a voltage directly proportional to the differential temperature created. The principle of operation of the thermopile is known as the thermoelectric effect [Tang *et al.*, 2010].

The sensitivity of the CMP series radiometers depends on the individual physical properties of the thermopile and its construction. Hence the sensitivity of CMP series radiometer varies. The sensitivity of the CMP 11 used in this research is $8 \mu\text{V}/\text{m}^2$ with a spectral range of 285 to 2800nm. Its response time is less than 1.7sec (63%) and 5sec (95%) [Kipp & Zonen, 2015].

The CMP 11 pyranometer was placed on a plane surface as shown in Plate 3.2 in order to measure the GHI of the house. As per requirement, the outdoor weather station was elevated by 1 m above the roof, thereby providing an unobstructed space for the radiometer. The radiometer was properly leveled on the platform to ensure accurate measurement. The levelling of the radiometer was achieved by adjusting the adjustable feet of the sensor until the bubble was within the ring mark of the spirit level. Figure 3.11 shows a photo of the CMP 11 Pyranometer, indicating the position of the bubble in the ring of the spirit level.

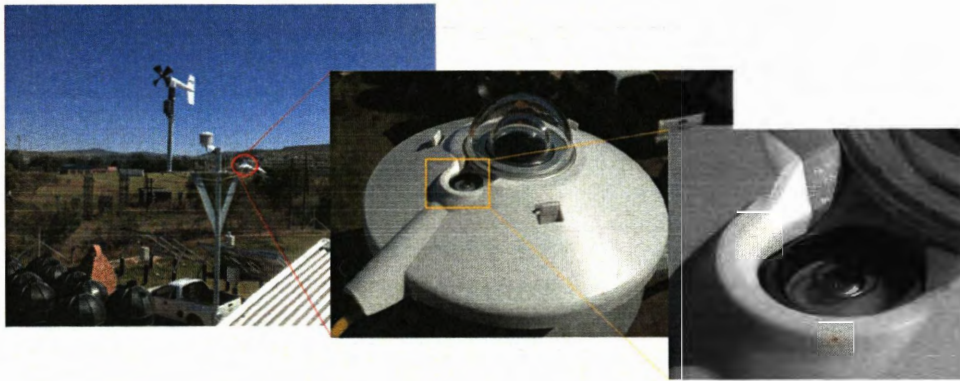


Figure 3.11: CMP 11 pyranometer setup

As per recommended routine maintenance, the dome of the radiometer was cleaned with micro-cleaner, a minimum of twice per week. The cleaning frequency, however, depends on the daily weather conditions. This is to ensure that the dome is clear of dew, dust, frost, birds' excreta, and any substance that may obstruct the transmission of solar radiation through the dome. On a monthly basis, the desiccant was checked and replaced if the color changes from its default orange color to clear (transparent). The self-indicating silica-gel desiccant is used to absorb humidity within the radiometer. When fresh it has an orange color, and a clear silica-gel desiccant indicates that it is fully saturated.

Also, ambient wind speed and direction were monitored with a Young 05103 wind monitor. The wind speed sensor is a four blade helicoid propeller. The propeller rotation produces an AC sine wave voltage signal with frequency directly proportional to wind speed. The wind direction sensor is a lightweight vane with a sufficiently low aspect ratio to assure good fidelity in fluctuating wind condition. The wind direction is sensed by a 10 k Ω precision conductive plastic potentiometer which uses a regulated excitation voltage. With a constant voltage, the potentiometer outputs an analog voltage signal which is directly proportional to the angle of the wind direction [Park *et al.*, 2012; Amin *et al.*, 2016]. Table 3-2 contain a summary of Young 05103 wind monitor specifications [R.M. Young Company, 2005].

Table 3-2: Young 05103 wind monitor specifications

Specification	Wind speed (m/s)	Wind direction (degree)
Range	0 to 100	355° electrical (5° open)
Accuracy	±0.3	±3°
Threshold sensitivity	1.0	1.1 m/s at 10° displacement

Source: R.M. Young Company (2005) *High performance Wind Sensor*. Michigan.
Available at: [http://www.youngusa.com/Brochures/05103\(0106\).pdf](http://www.youngusa.com/Brochures/05103(0106).pdf).

3.3.5 Data acquisition system

Data acquisition system (DAS) was set up to monitor the sensors, retrieve and store data. The DAS comprises of Campbell Scientific CR1000 and AM16/32 relay multiplexer. CR1000 is a precision instrument for demanding and low-power measurement applications. Its operation is based on the internal clock, onboard CPU, operating system, data storage, support software, and user-developed program. Users used the support software to create CR Basic program which instructs the CR1000. The operating system and user-developed program use the internal clock for scheduling operations. Operations include monitoring, periodic retrieving data from installed sensors and saving to the data storage. Data stored can be later retrieved by users with a personal computer via the support software. The support software program varies from PC 200, 400 and LoggerNet [Campbell Scientific INC, 2013]. For this research, LoggerNet support program was used.

CR1000 wire panel provides terminals for connecting sensor, power and communication device. The terminals are the measurement inputs, voltage outputs, groundings, the power I/O, and communication ports. Regarding the measurement inputs, the amount of the channel depends on the type of sensor. Thus, there are 16 single-ended, 8 differential, 2 pulses and 8 digital I/O channels. However, the measurement inputs terminals can be increased using AM16/32 relay multiplexer. The AM16/32 uses mechanical relays to connect each of the sensor channels in turn to a common output destined for the data logger (CR1000). The user developed program

access the sensor channels through the multiplexer to measure and store data into the CR1000. Similarly, the maximum number of sensor that can be accommodated in the AM16/32 depends mainly on the type of sensors. Although the AM16/32 is made up of 32 single-ended and 16 differential channels, more than one AM16/32 multiplexer can be connected to a CR1000 data logger to increase the channel further [Campbell Scientific INC, 2008]. Plates 3.3 and 3.4 shows a photo of the DAS(s) used in this research.



Plate 3.3: Data acquisition system (A): the passive solar house sensors

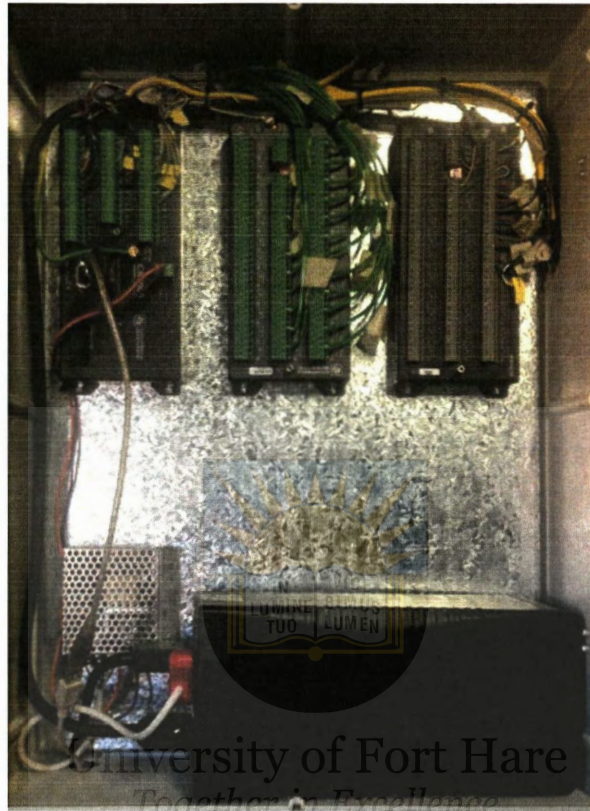


Plate 3.4: Data acquisition system (B): outdoor weather station sensors

DAS (A) was set up to monitor meteorological sensors of the house. As such, the CR1000 directly monitors the four Li-Cor pyranometer installed on the perimeter walls and the three HMP 60 air temperature and relative humidity probes. As well as, the AM16/32, used to multiplex the thermocouples measuring the building envelope surface temperature.

DAS (B) on the other hand, was set up for a broader and long-term research purpose. However, it performs continuous monitoring of the outdoor weather sensors and other sensors outside the scope of this research. Hence, the GHI CMP 11 pyranometer and Young 05103 wind monitor were connected to the CR1000. It also accommodates the outdoor air temperature and relative humidity HMP 60 probe.

Both DAS(s) CR1000 and AM16/32 were instructed via a developed program to scan each sensor in 10 minutes' interval and store the data every 30 minutes. At the same time, the stored data should be processed in average, maximum and sample order. That is for every stored data an average table containing the average value of three scanned cycles was created. The maximum table contains only the maximum value among the three scanned cycles, while the last (third) value obtained from three scan cycles was recorded as the sample. A 12 Volt DC power supply was used to power the CR1000, complemented with a 12 Volt rechargeable battery and uninterruptible power supply (UPS) in DAS (A) and (B), respectively.

3.4 Air exchange rate experiment methodology

The ASTM E741-00 concentration decay method was used to determine the air change rate of the house [ASTM Standard, 2011; Laussmann and Helm, 2011]. CO₂ gas was used as the tracer gas since it is cheap and readily available. Also, in less than 0.5%, CO₂ is harmless, not explosive and easily detectable [Sherman, 1990]. The gas was injected into the zone and its rate of decay over time was monitored. The CO₂ gas concentration decay was monitored using a Non-Dispersive Infrared gas sensor. The sensor was placed at a height of 0.45 m above the floor. For even mixture of the gas, a fan was used to circulate the gas. Plate 3.5 shows the gas sensors and laptop computer running Campbell Scientific PC400 as used in the experiment.

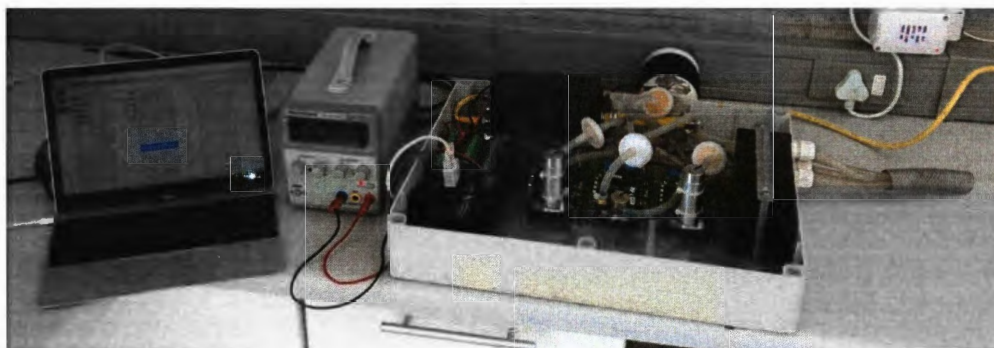


Plate 3.5: Air exchange rate experimental setup

In line with the adopted standard (ASTM E741), the floor area of the house was partitioned into zones. In this context, a zone is a space wherein the tracer gas concentration is maintained uniformly throughout and only exchange air with the ambient surrounding. As such, Plate 3.12 shows the various zones of the house.

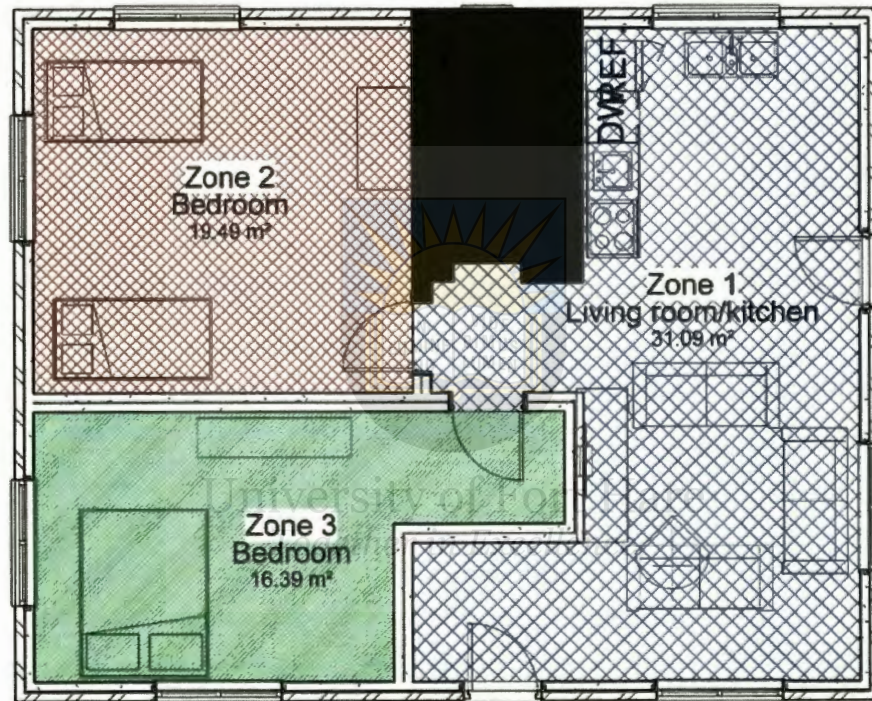


Figure 3.12: Floor plan indicating the various thermal zones of the house

The floor plan was partitioned into three thermal zones. Zone 1 marked with blue diagonal cross-hatch lines filled region is the living room/kitchen. The red diagonal up lines filled region used to indicate the north-facing bedroom is zone 2. While the south-facing bedroom is zone 3, represented by the green vertical lines filled region. The bathroom was blacked out since it is not considered as a thermal zone.

The air exchange rate experiment was performed in each of the zones. In each zone, different scenarios to inspect the effect of the air exchange rate of the house were assumed. The various scenarios assumed are summarized in Table 3-3.

Auxiliary data which caters for parameters that influence the air exchange rate of the house were obtained from DAS (A) and (B), discussed in the previous section. However, auxiliary parameters in this context refer to indoor/outdoor air temperature, wind speed, and relative humidity.

Table 3-3: Assumed ventilation components operation scenario

Zone	Scenario	Ventilation component and operation
1	1	All doors and windows open
	2	All doors closed and windows open
	3	All doors open and windows closed
	4	All doors and windows closed
2 and 3	5	All windows open
	6	All window closed

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3.5 Summary

Details of the house and its meteorological parameters required for the thermal load evaluation were the focus of this chapter. In this regard, the site description of the passive solar house, detailing its geographical location and local climatic conditions were given. The physical description regarding the floor plan, orientation and structural details of the house were also given. The thermal implications of the building design and choice of materials used were highlighted. These include the two-large north facing windows for optimum solar radiation admittance and clerestory windows for channeling solar radiation to the south floor area of the house. At the same time, the clerestory windows also provide passive cooling mechanism due to convection current. The air cavity brick walls were used to minimize heat transfer between the inner and outer space of the house. Also, detailed dimensions of the building envelope components were given.

Meteorological measurement, on the other hand, dealt with the sensors and methods used to monitor typical weather parameters influencing the thermal load of a house. These parameters are air temperature and relative humidity (indoor/outdoor), building envelope surface temperature, solar radiation, wind speed, and direction. Hence, the principle of operation and installation method of the following sensor were discussed. HMP 60 temperature and relative humidity probe, thermocouple, Li-Cor pyranometer, CMP 11 pyranometer, and Young 05103 wind monitor. The data acquisition systems used in monitoring and retrieving the data were also discussed. They comprise of Campbell Scientific CR1000 data logger and an AM16/32 multiplexer.

Lastly, the experimental method of air exchange rate of the house was discussed. The discussion includes a description of the experimental setup, thermal zoning of the house, and the various ventilation component operation considered.

REFERENCES

- Amin, M. R., Mishu, M. K., Al Faysal, A. and Nizam, M. R. (2016) 'Design and implementation of optoisolator based low cost digital anemometer with wind direction monitoring system', in *Informatics, Electronics and Vision (ICIEV), 2016 5th International Conference on*. Dhaka: IEEE, pp. 133–138.
- Asan, H. (2000) 'Investigation of wall's optimum insulation position from maximum time lag and minimum decrement factor point of view', *energy and buildings*. Elsevier, 32(2), pp. 197–203.
- ASTM Standard (2011) 'Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution'. ASTM International West Conshohocken, PA.
- Biggs, W. W. (2015) *Principles of radiation measurement*, Li-Cor, Inc. Lincoln. Available at: <https://www.licor.com/documents/liuswfuvtn7e9loxaut>.
- Campbell Scientific INC (2008) *AM16/32 relay multiplexer*. Utah. Available at: [https://www.uvm.edu/bwrl/.../Campbell literature .../AM416 multiplexer.pdf](https://www.uvm.edu/bwrl/.../Campbell%20literature%20.../AM416%20multiplexer.pdf).
- Campbell Scientific INC (2010) *HMP60 Temperature and Relative Humidity Probe*. Utah.
- Campbell Scientific INC (2013) *CR1000 Measurements and control system, Revision 5*. Utah. Available at: <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:CR1000+Measurement+and+Control+System#0>.
- Campbell Scientific INC (2015) *Solar Radiation Shields: For Temperature/Relative Humidity Sensors*. Utah. Available at: <http://campbellsci.com/solar-radiation-shields>.
- Conradie, D. C. U. (2012) 'South Africa's climatic zones: Today, tomorrow', *International Green Building Conference and Exhibition, Future*, pp. 1–9.
- Jumo GmbH & Co. (2005) *Construction and Application of Platinum Temperature Sensors*. Fulda. Available at: <https://www.jumo.net/attachments/JUMO/attachmentdownload?filename=t90.6000gb.pdf&id=3008>.
- Kalogirou, S. A. (2014) *Solar Space Heating and Cooling, Solar Energy Engineering*. Academic Press. doi: 10.1016/B978-0-12-397270-5.00006-6.
- Kaşka, Ö. and Yumrutaş, R. (2009) 'Experimental investigation for total equivalent temperature difference (TETD) values of building walls and flat roofs', *Energy Conversion and Management*, 50(11), pp. 2818–2825. doi: 10.1016/j.enconman.2009.06.027.
- Kerr, J., Thurtell, G. and Tanner, C. (1967) 'An integrating pyranometer for climatological observer stations and mesoscale networks', *Journal of Applied*

- Meteorology*, 6(4), pp. 688–694. doi: 10.1175/1520-0450(1967)006<0688:aipfco>2.0.co;2.
- Kipp & Zonen (2015) *Instruction manual - pyranometer and albedometer*. Delft. Available at: <http://www.kippzonen.com/Download/72/Manual-Pyranometers-CMP-series-English>.
- Laussmann, D. and Helm, D. (2011) 'Air Change Measurements Using Tracer Gases', *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality*, pp. 365–404. doi: 10.5772/1030.
- Li-COR GmbH (2015) *Light Measurement*. Lincoln. doi: 10.4135/9781412972000.n167.
- Maxim integrated (2007) *Implementing Cold-Junction Compensation in Thermocouple Applications*. San Jose. Available at: <http://www.maximintegrated.com/an4026>.
- Montgomery, K. K. (1992) 'Type N versus type K thermocouple comparison in a brick kiln', *Temperature: its Measurement and Control in Science and Industry*, 6, pp. 601–605.
- Moser, Y. and Gijs, M. A. M. (2007) 'Miniaturized flexible temperature sensor', *Journal of Microelectromechanical Systems*. IEEE, 16(6), pp. 1349–1354.
- Overen, O. K., Meyer, E. L. and Makaka, G. (2017) 'Thermal Behavior of a Low-Cost House Coated with Transparent Infrared Reflective Paint', in *World Sustainable Built Environment Conference 2017*. Hong Kong: SBE, pp. 758–764. Available at: <https://www.conftool.com/wsbe17hongkong>.
- Park, J. W., Jung, H.-J., Jo, H. and Spencer, B. F. (2012) 'Feasibility study of micro-wind turbines for powering wireless sensors on a cable-stayed bridge', *Energies*. Molecular Diversity Preservation International, 5(9), pp. 3450–3464.
- R.M. Young Company (2005) *High performance Wind Sensor*. Michigan. Available at: [http://www.youngusa.com/Brochures/05103\(0106\).pdf](http://www.youngusa.com/Brochures/05103(0106).pdf).
- Rontronic Measurement Solutions (2016) *The capacitive humidity sensor – How it works & attributes of the uncertainty budget*. New York. Available at: https://www.rotrotron.com/media/productattachments/files/c/a/capacitive_humidity_sensor_final.pdf.
- Sherman, M. H. (1990) 'Tracer-gas techniques for measuring ventilation in a single zone', *Building and Environment*, 25(4), pp. 365–374. doi: 10.1016/0360-1323(90)90010-O.
- South Africa Weather Service (2017) *Climate South Africa*. Available at: <ftp://ftp.weathersa.co.za> (Accessed: 1 January 2017).
- South African Bureau of Standards (2011a) *SANS 10400-XA: The application of National Building Regulations, Part X: Environmental sustainability, Part XA: Energy usage in buildings*. South Africa.

- South African Bureau of Standards (2011b) *SANS 204: Energy efficiency in buildings*. South Africa.
- Tang, W., Yang, K., He, J. and Qin, J. (2010) 'Quality control and estimation of global solar radiation in China', *Solar Energy*. Elsevier, 84(3), pp. 466–475.
- Ulgen, K. (2002) 'Experimental and theoretical investigation of effects of wall's thermophysical properties on time lag and decrement factor', *energy and buildings*. Elsevier, 34(3), pp. 273–278.
- Yamazoe, N. and Shimizu, Y. (1986) 'Humidity sensors: principles and applications', *Sensors and Actuators*. Elsevier, 10(3–4), pp. 379–398.
- Ziuku, S. and Meyer, E. (2011) *Energy Efficient Building Integrated Photovoltaic Housing*. University of Fort Hare.



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Chapter 4

ANALYSIS OF MEASURED DATA

4.1 Introduction

The meteorological monitoring of the house covers the four seasons in South Africa. These include summer (1 December to 29/28 February), autumn (1 March to 31 May), winter (1 June to 31 August) and spring (1 September to 30 November) [Conradie, 2012; South Africa Weather Service, 2012]. Though, for thermal performance and energy consumption analysis, the four seasons are often classified into two groups. 1 June to 31 August remain as winter season, whereas 1 September to 31 May is considered as summer season [Eskom, 2016].

The measured meteorological parameters of the house are indoor and outdoor air temperature and relative humidity, global horizontal irradiance, and wind speed and direction. The surface temperatures of the building envelope were also monitored. Given the monitoring period and the number of sensors involved, data acquisition system (DAS) failure and malfunction of sensors were inevitable; leading to data loss and abnormal measurements.

Against this backdrop, a qualitative and quantitative analysis of measured data is presented in this chapter. The chapter covers the integrity, demography and descriptive statistical analysis of the data. The thermal implication of the measured data was also discussed.

4.2 Ambient weather condition

The measured meteorological parameters can be divided into ambient weather parameters, building envelope surface temperature, and indoor weather parameters. In the context of this research, the ambient weather parameter comprises of solar

radiation, wind speed, and direction. As well as ambient air temperature and relative humidity. This section focuses on solar radiation, wind speed, and direction. Ambient air temperature and relative humidity were discussed with the corresponding indoor air temperature and relative humidity in a later section.

4.2.1 Global horizontal irradiance

Data collection was initiated in September 2016 and continued until September 2017. As a result, a disordered GHI distribution was obtained; placing June, July and August profile at the extreme of the graph as shown in Figure 4.1. However, a total of 17937 data entries were logged during the entire monitoring period. Uncontrollably, 944 data entries were missed; amounting to 5% of missing data. The missing data occurs in November 2016, December 2016, February 2017 and March 2017. The period of missing data in the affected months was excluded in data analysis and descriptive statistic going forward

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In line with Paulescu *et al.*, 2013 and Olmo *et al.*, 1999 the position of the CMP 11 pyranometer as shown in Plate 3.2 and 3.13 was targeted to measure global horizontal irradiance (GHI). Direct and diffuse solar radiation measured on a plane surface on the earth is referred to as GHI. Whereby the instantaneous radiative power is known as irradiance (W/m^2). While the radiative energy over a certain period such as an hour, day, month or year is known as irradiation (J/m^2 or Wh/m^2) [Szokolay, 2004; Kreider, Curtiss and Rabl, 2009]. The latter is used to quantify the thermal energy of the sun at a given location. Figure 4.1 shows the measured solar irradiance and monthly average solar irradiance.

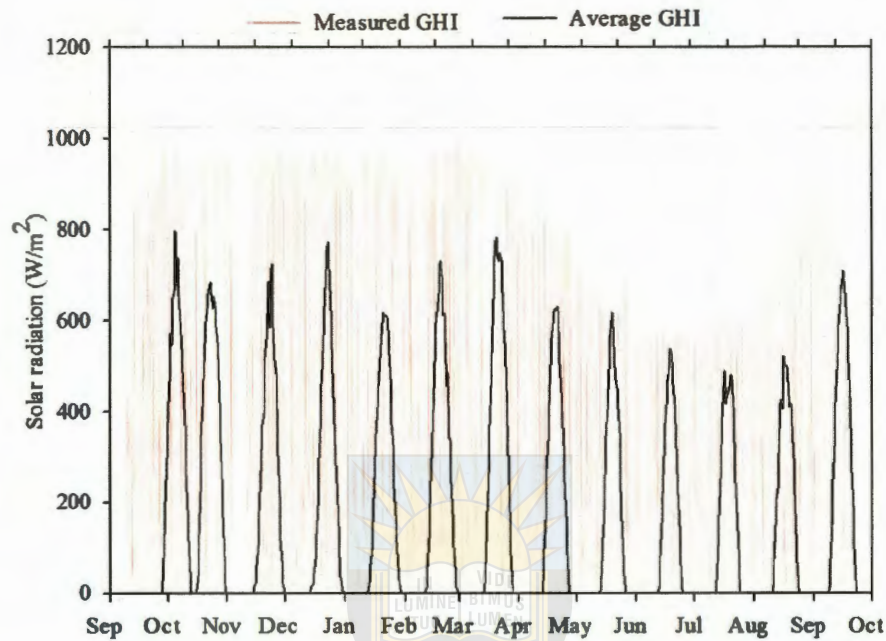


Figure 4.1 Measured and monthly average global horizon

In agreement with theory [Hinrichs and Kleinbach, 2013], the measured GHI as shown in Figure 4.1 ranges from 0 to 996.0 W/m², and periods with the absence of the sun produces 0 W/m². The maximum solar irradiance of 996.0 W/m² was logged in February 2017 at 12h30. Furthermore, to portray a typical annual sequential distribution of the measured GHI, a monthly average irradiance and total irradiation were developed. Also, Gaussian solar irradiance and irradiation distribution using the measured data is given in Figure 4.2. The trend of the chart tends to correspond with the solar radiation distribution in the southern hemisphere [Marzo *et al.*, 2017]. In other words, a relatively lower solar irradiance of an average of 140.5 W/m² were observed in June, July, and August. Whereas, the rest of the months had an average of 192.8 W/m².

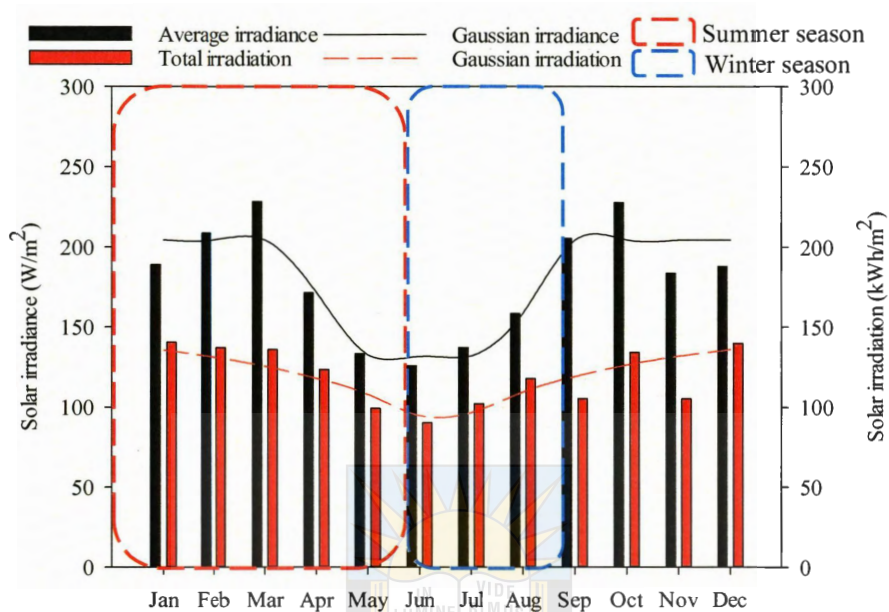


Figure 4.2: Seasonal solar irradiance and irradiation

However, due to data loss and sky formation, an irregular distribution of solar irradiance was observed in January, February, November, and December. Hence, the red and blue dash regions were used to indicate periods considered as summer and winter seasons, respectively. The seasonal classification of the data is also applicable to other parameters analyzed going forward.

4.2.1.1 Global irradiance with respect to building orientation

Due to the daily movement of the sun, solar irradiance varies across each elevation of a house. As a result, the average ambient air temperature does not justify the rate of heat transfer through the perimeter walls and windows [Oral and Yilmaz, 2003]. Hence, a film of air temperature (sol-air temperature) developed based on the solar irradiance at the various elevations of a house is rather used to determine the heat transfer. Therefore, this section deals with the measured solar irradiance at each elevation of the passive solar house. The sol-air temperature will be discussed in Chapter 6 of this document. With that been said, Figure 4.3 and 4.4 shows the solar irradiance and corresponding irradiation at the various elevations of the house on a typical summer and winter day, respectively.

Practically, the sun travels daily from east to west through the north elevation in the southern hemisphere and the south elevation in the northern hemisphere [Szokolay, 2008; Kaşka and Yumrutaş, 2009]. The measured solar irradiance at the various elevations of the house in Figures 4.3 and 4.4 concurs with the above concept. Hence the north elevation receives a significant amount of solar radiation during the day, while the south elevation receives minimum daily solar radiation. Nevertheless, the solar irradiance at the north, south elevations and GHI peak at approximately the same time (mid-day).

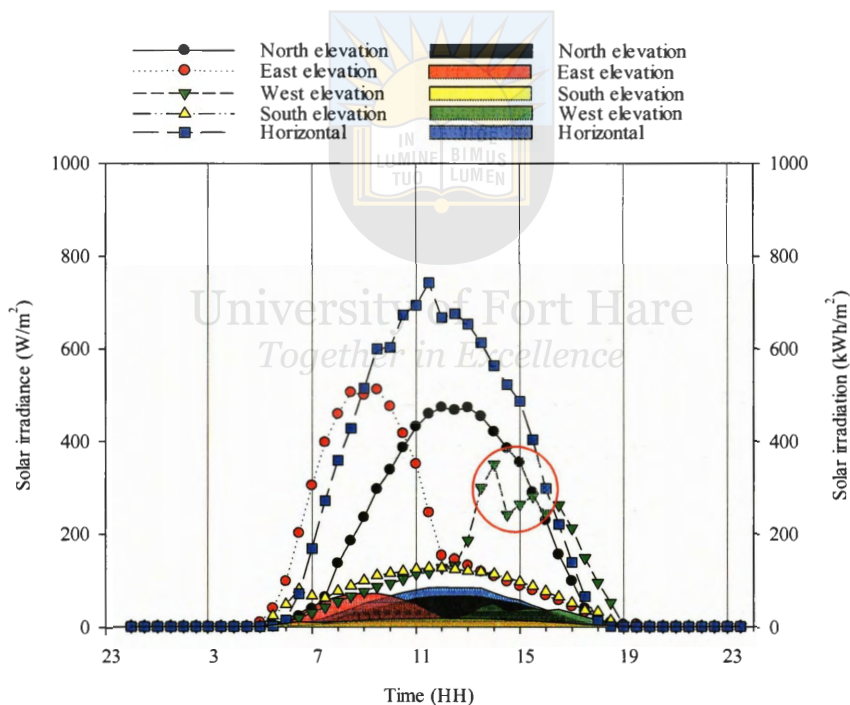


Figure 4.3: Typical summer day solar radiation at the various elevations

In winter, however, the solar irradiance at the north elevation was higher than the GHI as well as the north irradiance obtained in summer. The high winter solar irradiance was expected, and it was as a result of the low angle sun experienced during the winter season. In this regard, it must be said that the Li-Cor pyranometer was strategically placed on the perimeter walls (north facing) such that the shadow of the eaves does not fall on them.

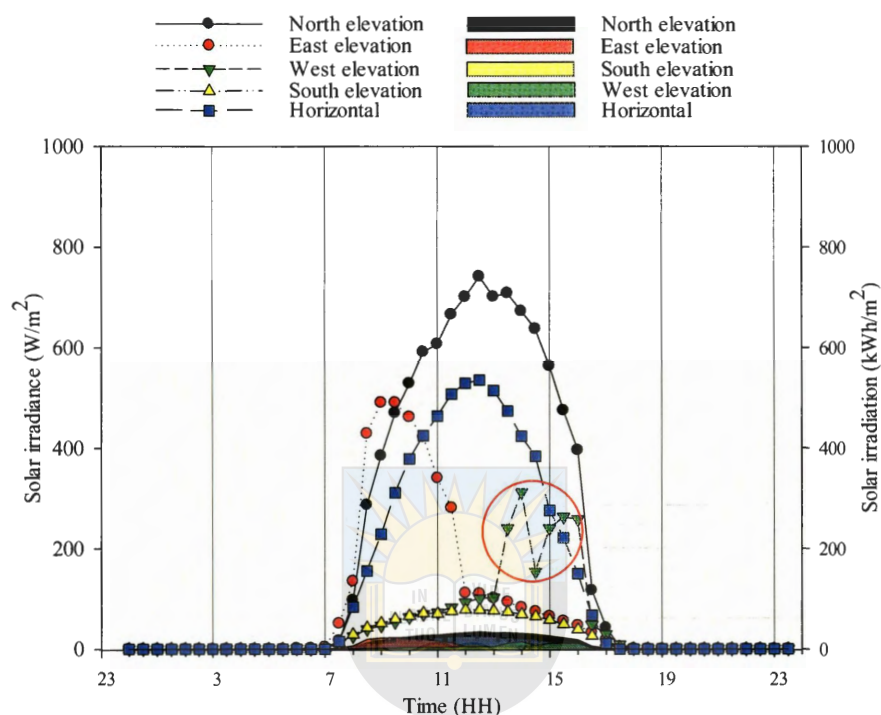


Figure 4.4: Typical winter day solar radiation at the various elevations

Additionally, the solar irradiance at the east and west elevations were also observed to peak in the early and late hours of the day, respectively. The sharp dip found in the west irradiance distribution, indicated by the red circle was due to deciduous trees planted at the west side of the house. As mentioned in Chapter 3, the trees shade the late afternoon sun and prevent cold winter wind. Further analysis of the solar irradiance at the building elevations are given in Tables 4-1 and 4-2.

Table 4-1: Summary of typical summer day solar radiation at the building elevations

Building elevation	Average (W/m ²)	Maximum (W/m ²)	Peak time	Daily irradiation (kWh/m ²)
North	215.1	472.4	12h00	3.23
East	188.4	510.7	09h30	2.83
West	123.4	349.6	14h00	1.85
South	76.6	126.7	11h00	1.15

Table 4-2: Summary of typical winter day solar radiation at the building elevations

Building elevation	Average (W/m ²)	Maximum (W/m ²)	Peak time	Daily irradiation (kWh/m ²)
North	376.4	741.5	12h30	4.71
East	156.0	490.6	9h30	1.95
West	92.7	311.7	14h00	1.16
South	44.2	78.0	12h00	0.55

Comparing Tables 4-1 and 4.2, the winter solar irradiance at the north elevation is approximately twice that observed in the summer. The daily irradiation of the north elevation in both seasons follows the same suit. It must be said that this seasonal behavior of the sun at the various elevations of a house, constitute the principle of passive solar design. Further discussions on the principle of passive solar design concerning the solar irradiance at the north elevation in winter are covered in the next chapter. Nonetheless, the irradiation generated at each of the building elevations was proportional to their respective irradiance regardless of the season.

4.2.2 Wind speed and direction

The heating aspect of ambient weather condition which has to do with the solar irradiance and irradiation was discussed in the previous section. The cooling element can be traced to wind and precipitation. Given that precipitation was not monitored in this research, this section deals with the ambient wind distribution of the house.

Wind is often used to describe air in motion. Air movement produces physiological cooling by dissipation of heat and increases evaporation from the skin [Reardon and Clarke, 2013]. The physiological cooling of wind depends on the speed. There is, however, a degree of tolerance to wind speed by individuals. At certainty speed, occupancy might perceive wind as discomforting. The ambient summer and winter wind speed frequency distribution of the house are shown in Figure 4.5.

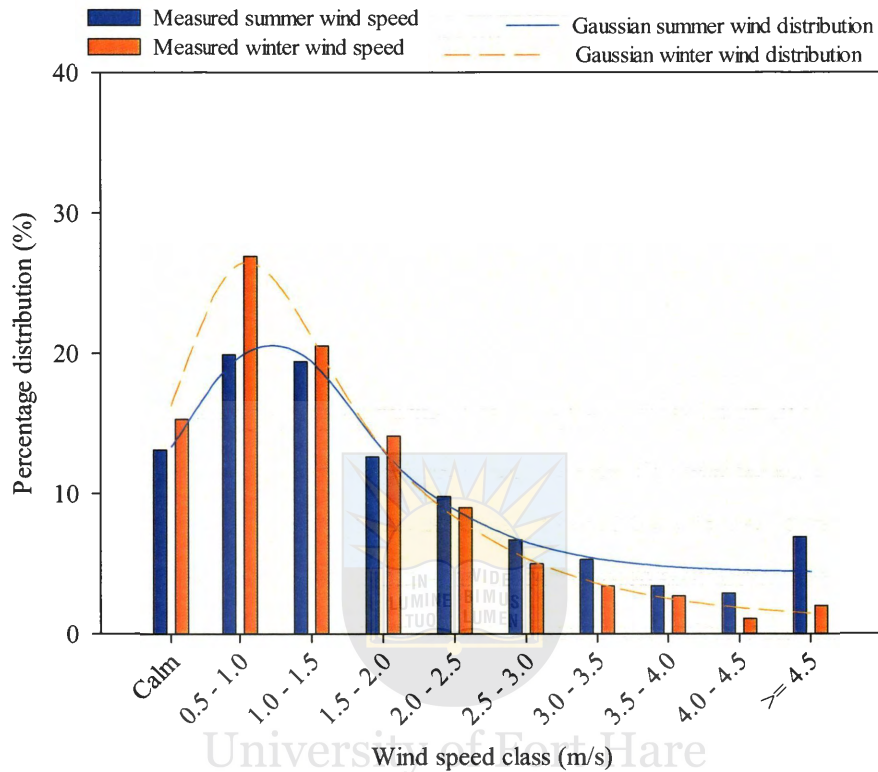


Figure 4.5: Summer and winter seasons wind speed distribution

The bar chart was developed by grouping the measured seasonal wind speed into 10 classes, with each class made of 0.5 widths. Calm represent wind speed lesser than 0.5 m/s. As seen in Figure 4.5, the seasonal wind speed distribution is asymmetrical. In other words, the wind speed is not normally distributed, and positively skewed to the left. The pattern of the wind distribution implies that majority of the observed wind speed was greater than 1.0 m/s but occurs less frequent. According to Bradshaw [Bradshaw, 2006], the wind speed of 0.5 to 1.0 m/s that occupants perceive to be thermally comfortable was the most occurring in both seasons.

Furthermore, the wind speed distribution concerning the time of the day was also developed. The summer and winter daily average wind speed was determined and given in Figure 4.6.

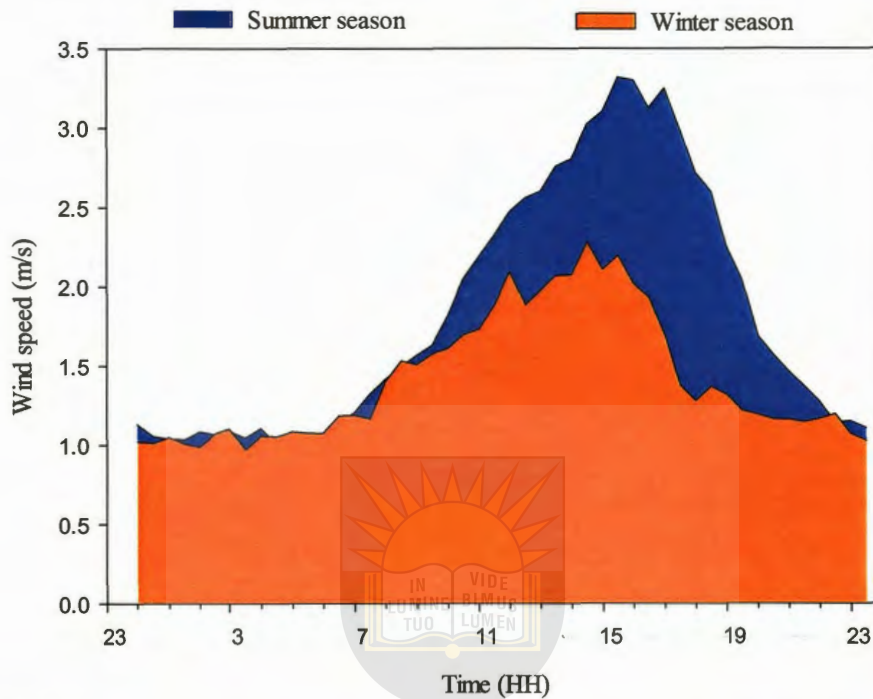


Figure 4.6: Typical average summer and winter days wind speed distribution

On average, the minimum wind speed in both seasons was approximately 0.9 m/s, as seen in Figure 4.6. A maximum wind speed of 3.3 m/s was observed at 16h00 in summer, while the maximum wind speed in winter was 2.3 m/s at 14h30. As observed in Figure 4.6, wind speed greater or equal to 1.5 m/s was observed from 8h30 to 21h00 and 8h30 to 17h30 in summer and winter, respectively. Wind blowing at this speed (greater or equal to 1.5 m/s) result in draughty, movement of hair, particles, papers and other annoyances [Epstein and Moran, 2006]. Hence, with a typical winter day having a relatively lesser wind speed, an occupant will respond comfortably with the wind during winter than in the summer season. The ambient and indoor air temperature, as well as relative humidity, are the most significant factors to be taken into consideration since air temperature determines the convective heat dissipation of the body. Relative humidity, on the other hand, influence the rate of evaporation from the skin. Thus, both factors influence the perception of an individual response to wind speed. However, the wind speed given in Figure 4.6 was obtained from the ambient

environment. Shutting of the ventilation components will significantly reduce the effect of the wind indoors.

In addition to air temperature and relative humidity, the direction also influences the effect of wind perceived by occupants indoors. The annual wind direction of a house location needs to be considered for effective utilization of wind for space cooling and reducing infiltration heat losses in the winter season. This information is required to determine the location of windows for wind channeling or full block/brick wall. The effect of wind channels and blockers of the house is analyzed in details in the next chapter. The wind rose profiles in Figures 4.7, and 4.8 shows the seasonal wind direction of the house with respect to wind speed.

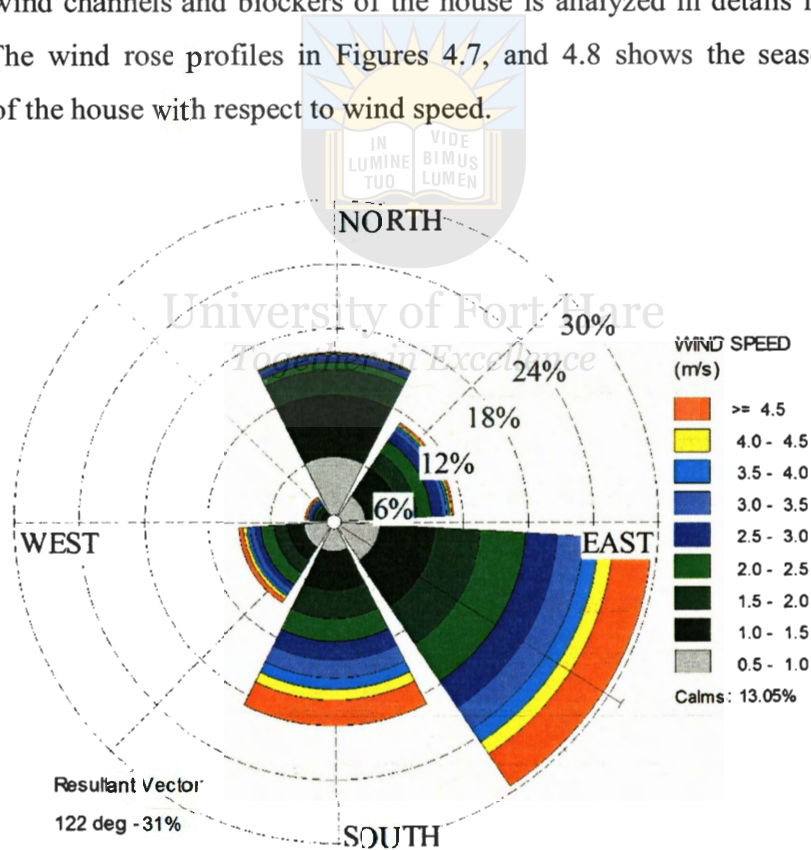


Figure 4.7: Summer season wind rose profile

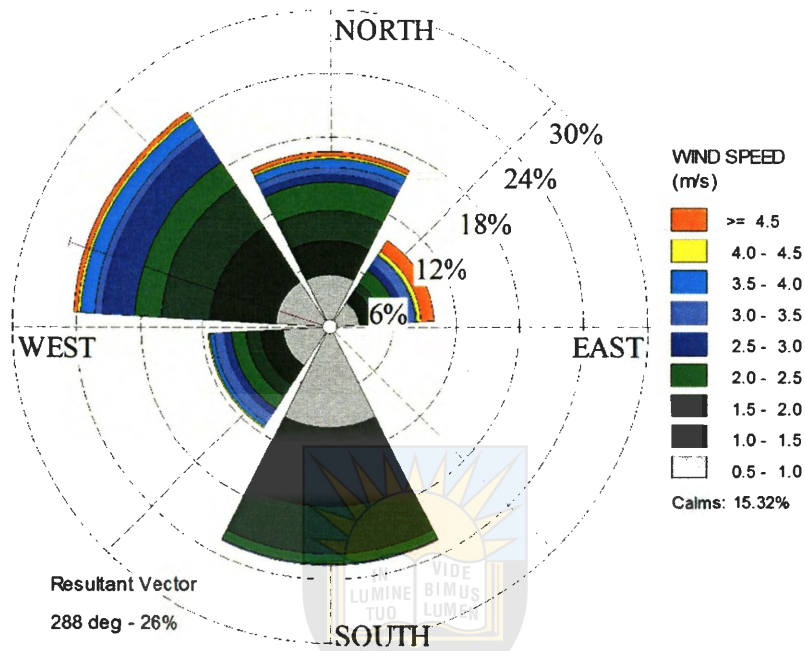


Figure 4.8: Winter season wind rose profile

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Measured wind speed and direction data were integrated into an hourly interval and was used to develop the wind rose profile. The prevailing wind is indicated by the resultant vector which was determined by the frequency count of the mean wind direction. From Figure 4.7, 31% of the wind with a mean direction of 122° was observed to blow from the southeast; serving as the prevailing wind. Wind speed greater than 4.5 m/s was mostly blowing from the same direction, representing 4% of the total speed. Wind speed ranging from 1.0 to 1.5 m/s was the dominant speed in the southeast direction with 5%. Besides, the wind speed class of 0.5 to 1.0 m/s with 8% of the total speed blowing from the north was observed to be most frequent in the summer season.

Contrarily, the same wind speed class with 9% of the south wind was dominant in winter season as seen in Figure 4.8. However, the northwest (288°) wind was the prevailing wind, with 26%. Wind speed class of 1.0 to 1.5 m/s was the most frequent with 6% in this direction. Wind speed greater than 4.5 m/s was only 0.4% in the northwest direction but was maximum with 1.2% in the northeast direction.

4.3 Building envelope surface temperature distribution

The ambient weather conditions which include solar radiation, wind speed and direction were discussed in the previous sections. Their influence however on occupants indoor also depends on the thermal performance of the building envelope. This section deals with the measured surface temperature of the building envelope. The components of the building envelope considered are the walls (perimeter and partition), floor and roof. Thermal performance of the windows is analyzed in Chapter 6 of this document.

4.3.1 Perimeter walls

Excluding the roof and floor, the perimeter walls enclose 64% of the surface area of the house. In this regard, interactions between the ambient weather condition and the walls tend to influence the indoor thermal behavior of the house significantly. Also, measurement at a spot is arguably insufficient to quantify the surface temperature distribution of the perimeter walls, since the floor area of the house is 10 m × 8 m. Thus, two spots on the inner and outer surfaces of each of the perimeter wall were measured as shown in Figure 3.7. The seasonal daily average outer and inner surface temperature of the perimeter walls are given in Figures 4.9 and 4.10.

In Figures 4.9 and 4.10, the line and scatter plots represent the wall inner and outer surfaces. On each surface, the measurement spots were located at the east and west ends of the south and north facing walls also at the north and south ends of the west and east facing walls. The vertical bar chart represents the percentage difference of the temperature measured at both spots (ends) on the inner and outer surface of the wall. The percentage difference was obtained by the absolute value of the difference between the spot temperatures, divided by their average multiplied by 100.

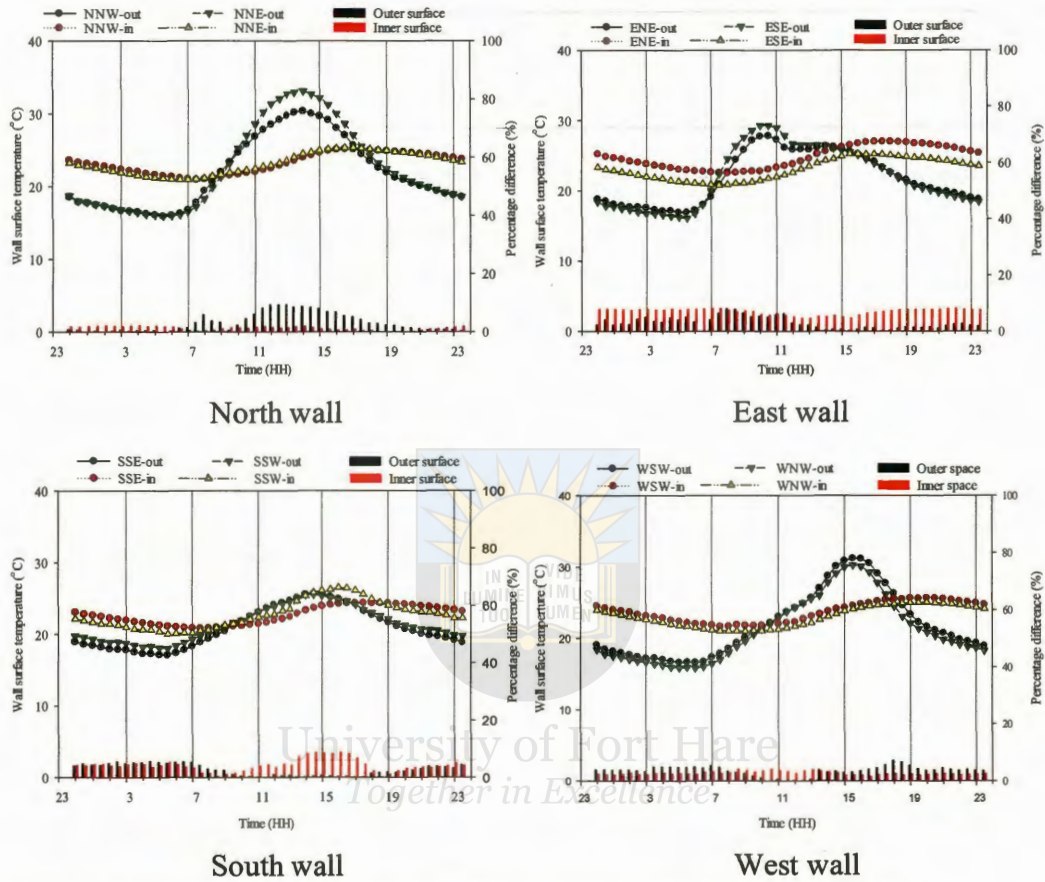


Figure 4.9: Average summer daily surface temperature of perimeter walls

In Figure 4.9, a fairly constant inner surface temperature of an average of 2.3°C was observed in all walls regardless of the various measuring spot. On the outer surface, the north and east walls had an average temperature of 22.0°C , while 21.0°C was the temperature observed on the west and south walls. Among all walls considered, the maximum temperature of 31.7°C at 14h00 was measured on the north wall outer surface with a resultant inner surface temperature of 24.3°C . The south wall outer surface was found to have the smallest temperature of 25.6°C at 14h30, while the inner surface temperature was 24.8°C .

In winter (Figure 4.10), the north and east walls inner surface temperature had 17.7°C each, while the south and west walls inner surface temperatures were lower by approximately 1.0°C . The average outer surface temperature of all four walls was

different, with the north wall having the highest temperature of 17.7°C and the lowest temperature of 13.6°C on the south walls.

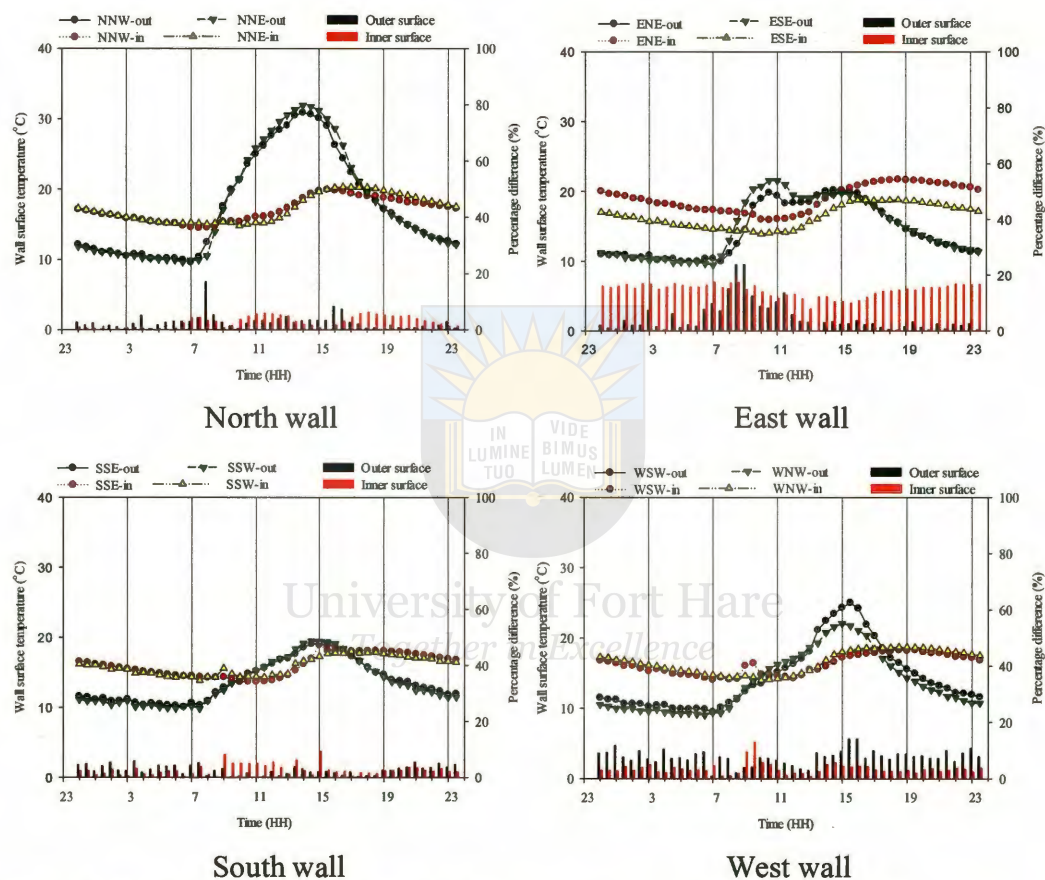


Figure 4.10: Average winter daily surface temperature of perimeter walls

Considering all four walls, the north walls outer surface also had the maximum temperature of 31.4°C at 14h00 with a corresponding inner surface temperature of 18.6°C. Likewise, the south wall outer and inner surfaces with 19.3 and 16.9°C at 14h30 were the minimum temperatures measured.

In both seasons, the walls surface temperature measured at the various spots has no significant difference. Given that 15% observed at the east wall inner surface in the winter season was the maximum average percentage difference, which is equivalent to a temperature difference of 2.6°C ± 1.5°C. It must be said that the north end inner

surface of the east wall is where the kitchen is located. Cooking and other heat generated appliances were performed in that region of the house. Specifically, a 780 W refrigerator was placed in front of the area of the wall, where the thermocouple was located. Thereby, increasing the north end inner surface temperature of the east wall. The seasonal temperature distribution of the perimeter walls concerning the various measurement spots are summarized in Table 4-3. The average spots temperature on the inner and outer surface will be used to represent the respective wall surface temperature going forward.

Comparing Tables 4-1, 4-2 and 4-3, the outer surface temperature peak time of each wall correspond to their respective solar irradiance peak time with approximately two and a half hours delay. A comparative chart of Table 4-1, 4-2 and 4.3 is presented in Figure 4.11.

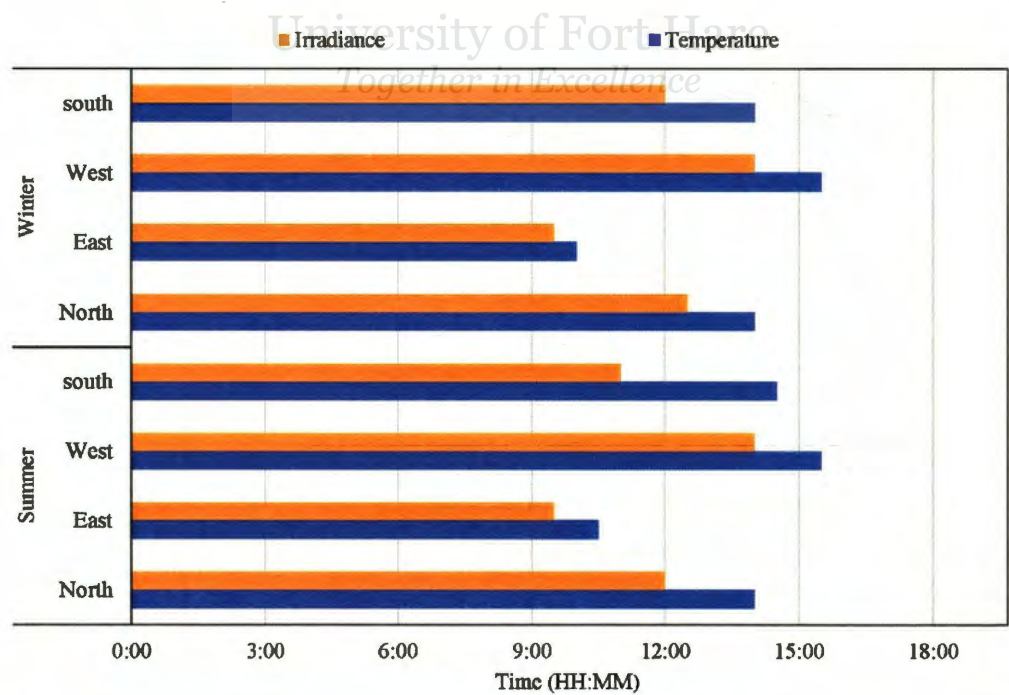


Figure 4.11: Surface temperature and solar irradiance peak time at the house four walls

The two and a half hours delay was due to ambient weather factors such as wind speed, air relative humidity, air temperature as well as the intensity of solar radiation. Wind

speed dissipates heat from the wall surface, resulting in cooling [Offerle *et al.*, 2007; Zhang, Zhong and Liu, 2016], while low air temperature increases air relative humidity around the wall surface.

Table 4-3: Seasonal surface temperature distribution of perimeter walls

Wall	Measured spot (surface)	Summer season				Winter season			
		Avg. (°C)	Max. (°C)	Peak time	% Diff.	Avg. (°C)	Max (°C)	Peak time	% Diff.
North	NNW (out)	22	30	14h00	3	12	31	14h00	3
	NNE (out)	23	33	14h00		18	32	14h00	
	NNW (in)	23	25	16h30	1	17	20	15h00	3
	NNE (in)	23	25	17h00		17	20	16h30	
East	ENE (out)	22	28	10h30	3	14	20	15h00	5
	ESE (out)	22	29	10h30		15	22	10h00	
	ENE (in)	24	27	17h30	7	19	22	18h30	15
	ESE (in)	23	25	16h00		16	19	16h00	
South	SSE (out)	21	26	14h30	3	14	19	14h30	3
	SSW (out)	21	26	14h30		14	19	14h30	
	SSE (in)	23	24	17h30	4	16	19	15h30	3
	SSW (in)	23	27	16h00		16	18	17h00	
West	WSW (out)	22	31	15h30	4	14	25	15h30	8
	WNW (out)	21	30	15h30		14	22	15h00	
	WSW (in)	23	26	20h00	3	16	18	19h30	4
	WNW (in)	23	25	20h00		17	19	18h30	

Hence, higher solar radiation is required to overcome the abovementioned weather factors which is evident at the south wall surface temperature distribution. As shown in Figures 4.3 and 4.4, the south building elevation had the least solar radiation intensity. At the same time, the minimum surface temperature and maximum time delay were observed at the south wall as shown in Table 4-3.

Regarding temperature variation across the wall, decrement factor and time lag are often used to analyze this behavior. As mention in Chapter 2, time lag deals with the time taken for heat to be transmitted to the inner surface, while the decrement factor provides the amount of heat transmitted through the wall. Both concepts treat heat in terms of the surface temperature of the wall. Also, decrement factor and time lag depends on the wall thermophysical properties. In the context of this study, thermophysical properties refer to heat transmission concerning the wall surface area. Base on Fourier’s law, heat transmission is a factor of thermal conductivity of the wall and ambient weather condition which serves as applied heat. The amount of surface area exposed to the applied heat is directly proportional to the heat transmission. The time lag and decrement factor of the perimeter walls were determined using Equations 2.6 and 2.7; the findings are given in Table 4-4.

Table 4-4: Perimeter walls thermophysical properties in both seasons

Wall	Surface area (m ²)	Summer		Winter	
		Decrement factor	Time lag (h)	Decrement factor	Time lag (h)
North	16.6	0.27	3	0.24	2
East	14.6	0.38	6.5	0.49	8
South	15.9	0.61	2	0.45	0.5
West	13.0	0.28	4.5	0.31	3

In Table 4-4, apart from the east and south walls, the outer surface contribute approximately 30% of the inner surface temperature variation of the perimeter walls. The impact of the walls on the indoor air temperature can be attributed to the superstructure perimeter walls of the house. As highlighted in Chapter 3, the 15 mm air cavity of the perimeter walls, tend to reduce the amount of heat transfer from the outside to the inner wall and vice versa. Consequently, reducing the decrement factor and increasing the time lag. This implies that 70% of the walls inner surface temperature variation is due to other sources of heat indoors.

Vis-à-vis Figure 4.3 and 4.4, the south elevation of the house do not receive direct solar radiation during summer and winter season. As a result, a minimum temperature variation exists between the inner and outer surface. Hence, the south wall had the maximum decrement factor of 0.61. The relatively high decrement factor observed on the east wall, was due to the indoor thermal load as indicated earlier.

4.3.2 Partition walls and floor

Besides heat transfer through the perimeter walls, internal heat transfer from one room to the other occurs through partition walls. Varying indoor air temperature due to a different activity in the rooms and the orientation of their respective fenestration and perimeter walls may lead to the heat transfer. On the other hand, the inner space of a house loses heat to the floor. Given that typical floor has no external sources of heating. It, however, serves as a heat sink of a house. Also, partition walls and floor serve as thermal storage for the inner space of a house. Based on the thermal flywheel effect, heat absorbed and stored by the walls and floor during the day are released at night to warm the inner space. However, as shown in Figure 3.7, the surface temperature of the partition walls and floor were monitored to examine the thermal behavior of the walls and floor concerning internal heat transfer and thermal storage. Figures 4.12 and 4.13 shows the surface temperature distribution of the partition walls and floor of the house.

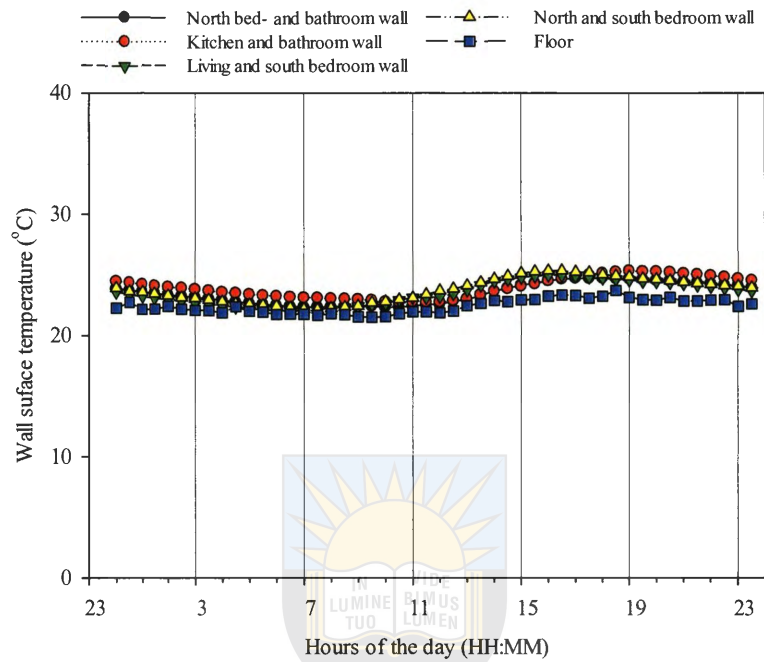


Figure 4.12 Partition walls and floor surface temperature distribution on a typical summer day

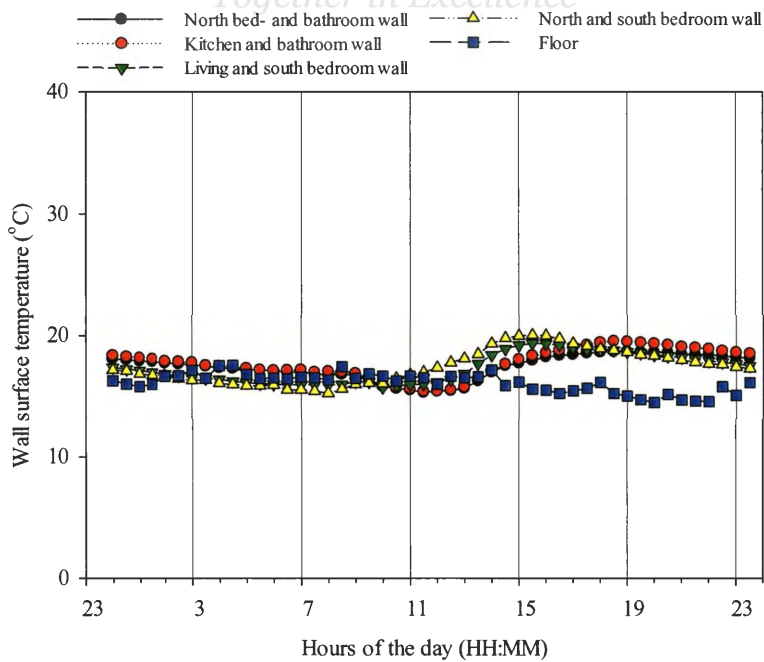


Figure 4.13: Partition walls and floor surface temperature distribution on a typical winter day

The thermal behavior of the partition walls and floor was characterized by their surface temperature change rate since the surface temperature change rate is proportional to the rate of heat transfer through both components. As shown in Figure 4.12 and 4.13, a fairly constant temperature was observed on the partition walls and floor compared with the perimeter walls. The summer average daily temperature change rate was 0.1 °C/h for each wall, while the floor was 0.2 °C/h. In the winter season, a relatively higher surface temperature change rate was observed. The walls had an average of 0.2 °C/h while the floor was 0.4 °C/h. Based on the findings, it can be said that the walls and floor of the house had a high heat capacity. Hence heat transfer through partition walls and floor were minimal.

4.3.3 Roof

Unlike the floor, the roof of a house receives a significant amount of solar radiation which serves as a heating source. Thus the temperature difference between the floor and roof create a vertical indoor air temperature variation. However, ceiling boards were fitted in the house to prevent direct heating from the roof. This section deals with the surface temperature distribution of the roof and ceiling of the house.

Due to the design of the south half of the roof (Figure 3.6), the temperature measurement was constrained to the north half. As mentioned in Chapter 3, the roof north half were covered with 20 Photovoltaic (PV) panels. The array of PV panels was made of 10 PV panels on the east and west wing of the north half of the roof. Each wing comprises five rows, with two PV panels per row. For the surface temperature measurement of the roof, each wing was visually split into three levels; the top, middle, and bottom level. The inner surface temperature of the solar panel was measured at each level at both wings of the roof. Hence, the average temperature of the six levels represents the whole building roof temperature. Furthermore, the inner surface temperatures of all three rooms ceiling were also measured separately. Whereby the average temperature of the three rooms ceiling serves as the whole building ceiling

temperature. The seasonal inner surface temperature of the whole building roof and ceiling are given in Figures 4.1 and 4.15.

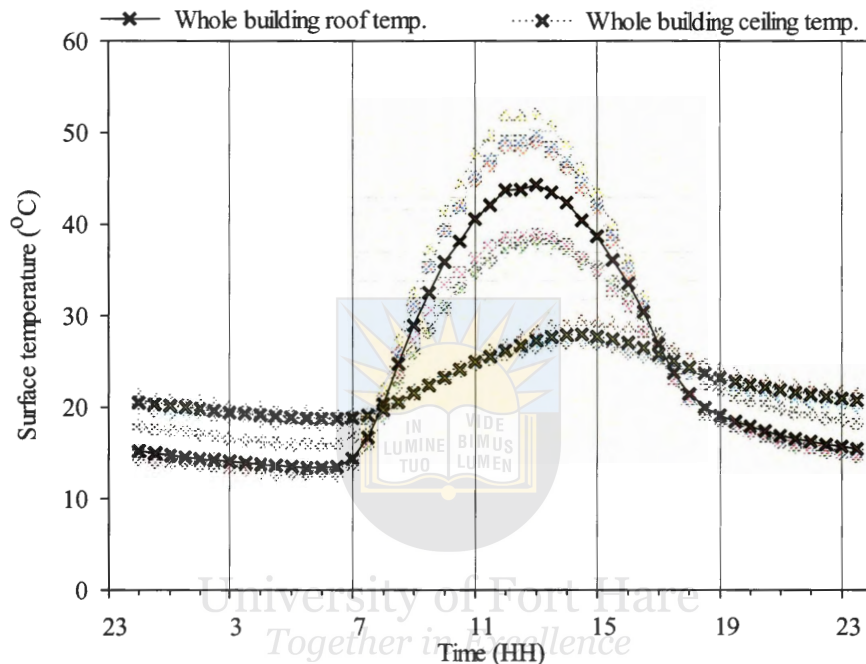


Figure 4.14: Typical summer day roof and ceiling surface temperature distribution.

From Figures 4.14 and 4.15, the surface temperature distribution of the roof follows the global horizontal irradiance trend given in Figures 4.3 and 4.4. Hence the thermal behavior of the roof and ceiling can be addressed in two periods; a period in the present of the sun and the period in the absence of the sun. The period in the present of the sun stretches from approximately 07h00 to 18h00, while periods in the absence of the sun were 00h00 to 06h30 and 18h30 to 23h30. In this regard, the roof surface temperature was at its peak value of 44.3°C at 13h00 in summer and 39.3°C at 12h00 on a typical winter day. Relative to the ceiling, the roof surface temperature was minimal during the absence of the sun, with an average of 15.4°C and 8.8°C on a typical summer and winter days, respectively.

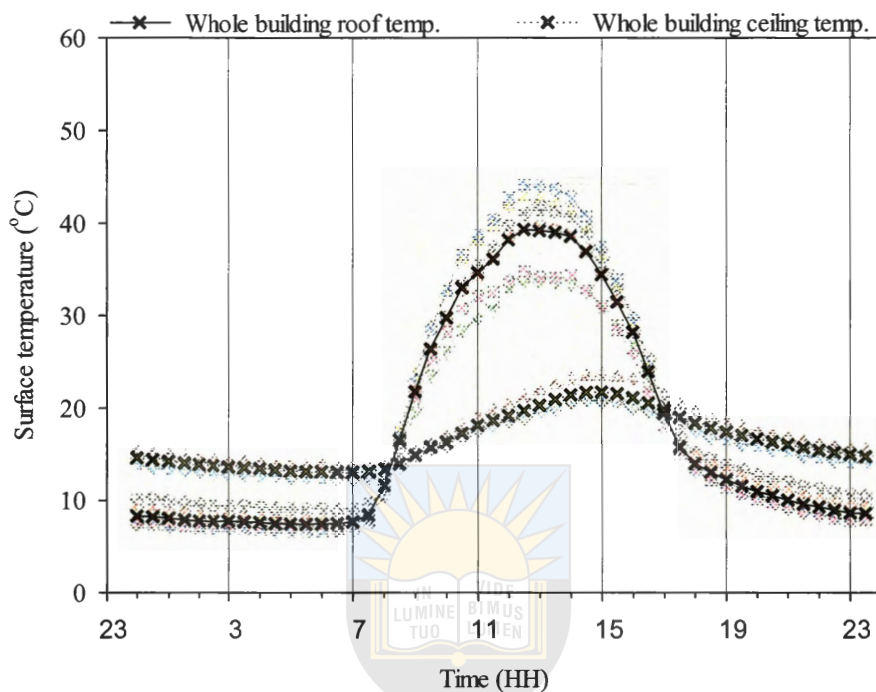


Figure 4.15: Typical winter day roof and ceiling surface temperature distribution

Further findings of the roof and ceiling surface temperature measurements are given in Table 4-5.

Table 4-5: Thermal behavior of the roof and ceiling in both seasons.

Building envelope	Summer					Winter		
	Max. Temp. (°C)	Peak time	Avg. Temp. Sun present (°C)	Avg. Temp.: Sun absent (°C)	Max. Temp. (°C)	Peak time	Avg. Temp.: Sun present (°C)	Avg. Temp. Sun absent (°C)
Roof	44.3	13h00	33.1	15.4	39.3	12h30	28.0	08.8
Ceiling	27.9	14h30	25.4	20.3	21.7	15h30	19.9	15.0

The ceiling surface temperature was found to follow the same trend as the roof. Though, a peak temperature difference of 16.4°C and time lag of one and the half hours were observed in the summer season, while the peak temperature difference in winter was 17.6°C with a corresponding time lag of two and a half hours.

4.4 Indoor weather parameters

The last set of measured data to be considered is the indoor temperature and relative humidity. Both parameters will be discussed alongside the ambient air temperature and relative humidity.

4.4.1 Horizontal air temperature variation in zone 1

As indicated in Figure 3.7, two thermocouples and an HMP 60 temperature and relative humidity probe were used to monitor the living room/ kitchen (zone 1) air temperature and corresponding relative humidity. The three sets of the thermal sensor were installed to capture the horizontal air temperature variation in zone 1 since the zone stretches from the north to south elevation. Thus, two sets of Type K thermocouples were suspended at a height of 0.8 m above the living room and kitchen floor area. An HMP 60 probe was also hung at the same height in between (center) the living room and kitchen thermocouples. Approximately 2 m gaps were maintained between all three sensors. The summer and winter average daily air temperature and relative humidity profile of the above-measured floor area of zone 1 are given in Figures 4.16 and 4.17. The graphs also contain the percentage difference of the measured air temperature at the floor area. Regarding the statistical standard deviation, the percentage difference of a given variable in this context is the percentage deviation of the air temperature from the average air temperature measured at the various floor area.

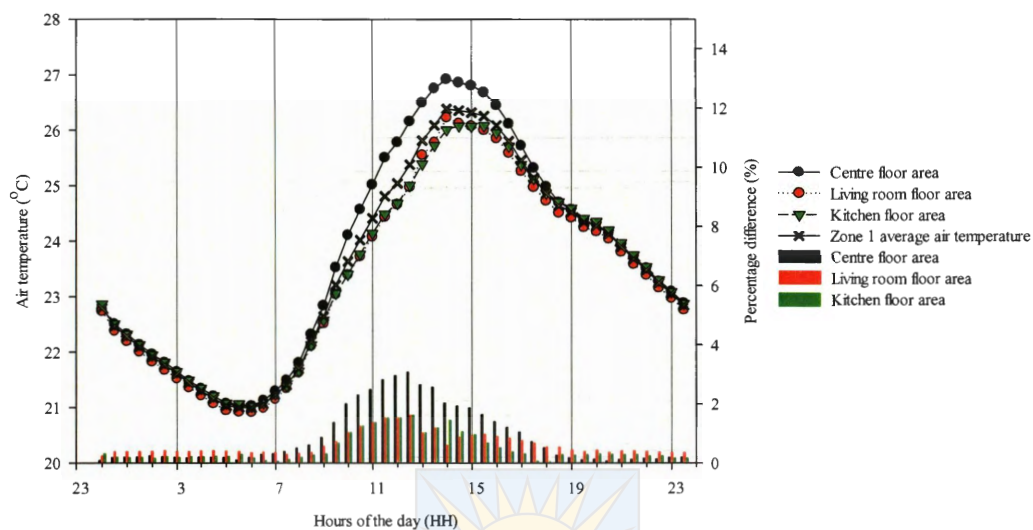


Figure 4.16: Average summer day profile of various floor area air temperature of zone 1

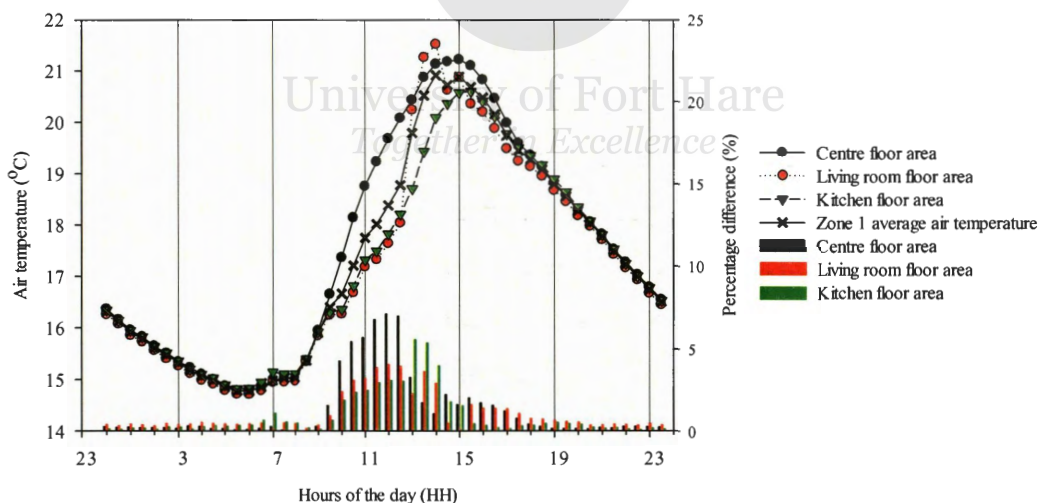


Figure 4.17: Typical winter day profile various floor area air temperature of zone 1

The inconsistent and small-scale selected in Figures 4.16 and 4.17 were used to magnify the air temperature variation. Like the surface temperature of the roof, zone 1 air temperature can be analyzed using periods with the sun present and absent. Whereby, 00h00 to 09h30 and 17h00 to 23h30 made up periods during which the sun was absent and was present between 10h00 and 17h00. As shown in both Figures, a fairly constant air temperature was obtained at the three measured floor area during

the absence of the sun. The living room floor area had the maximum average percentage difference with 0.5% which is equivalent to an average deviation of $0.1^{\circ}\text{C} \pm 1.5^{\circ}\text{C}$ from the average air temperature in zone 1. A relatively higher temperature deviation was observed during the presence of the sun. The center floor area had the maximum average percentage difference of 2% and 3.4% in summer and winter seasons, respectively. These were equivalent to a temperature deviation of $0.5^{\circ}\text{C} \pm 0.6^{\circ}\text{C}$ in the summer and $0.6^{\circ}\text{C} \pm 0.6^{\circ}\text{C}$ in winter.

Based on the accuracy of the sensors and the deviation obtained, it could be said that there was no significant air temperature variation from the kitchen to the living room floor area. The average air temperature of the living room, center and kitchen floor areas will serve as zone 1 air temperature, going forward.

4.4.2 Zonal air temperature and relative humidity variation

Similarly, to monitor the thermal influence of the various activities and orientation of the rooms, the indoor air temperature and relative humidity of the individual zones in the house were measured separately. As shown in Plate 3.12, the main floor areas of the house which include the living room/kitchen, north and south facing bedrooms were classified into zones. With the living room/kitchen represented by zone 1, the north and south facing bedroom were signified by zone 2 and 3, respectively. Hence the seasonal daily indoor air temperature and relative humidity profiles of the various zones in the house are given in Figures 4.18 and 4.19.

In Figure 4.18 and 4.19, the vertical bar charts; below and above represent the air temperature and relative humidity percentage difference, respectively of the three zones in the house. The typical summer day air temperature and relative humidity percentage difference were minimal. In both days, zone 3 had the maximum air temperature and relative humidity percentage difference.

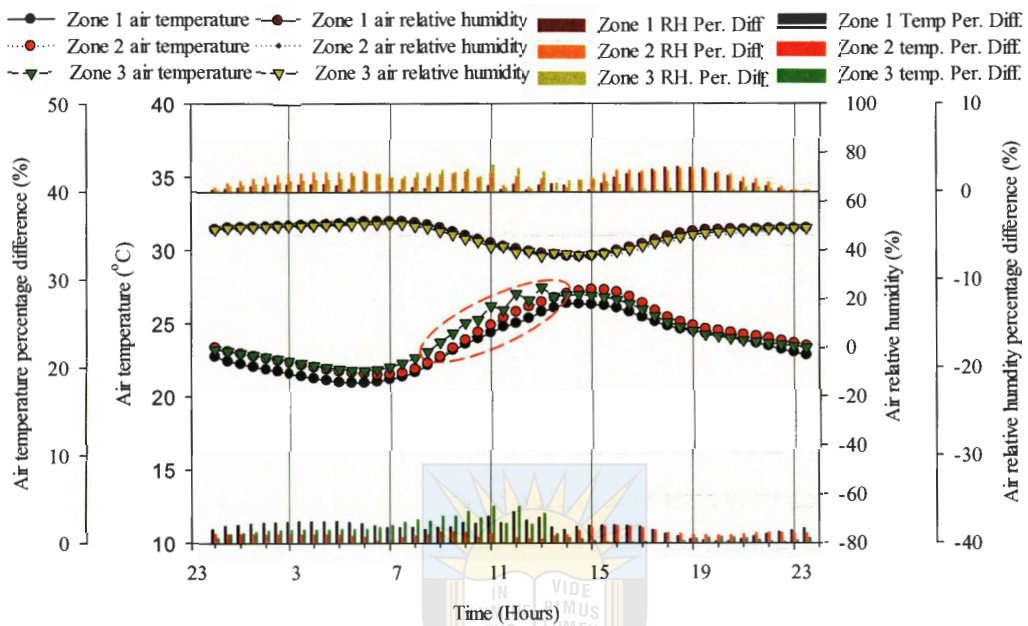


Figure 4.18: Typical summer day air temperature and relative humidity distribution in the various zone

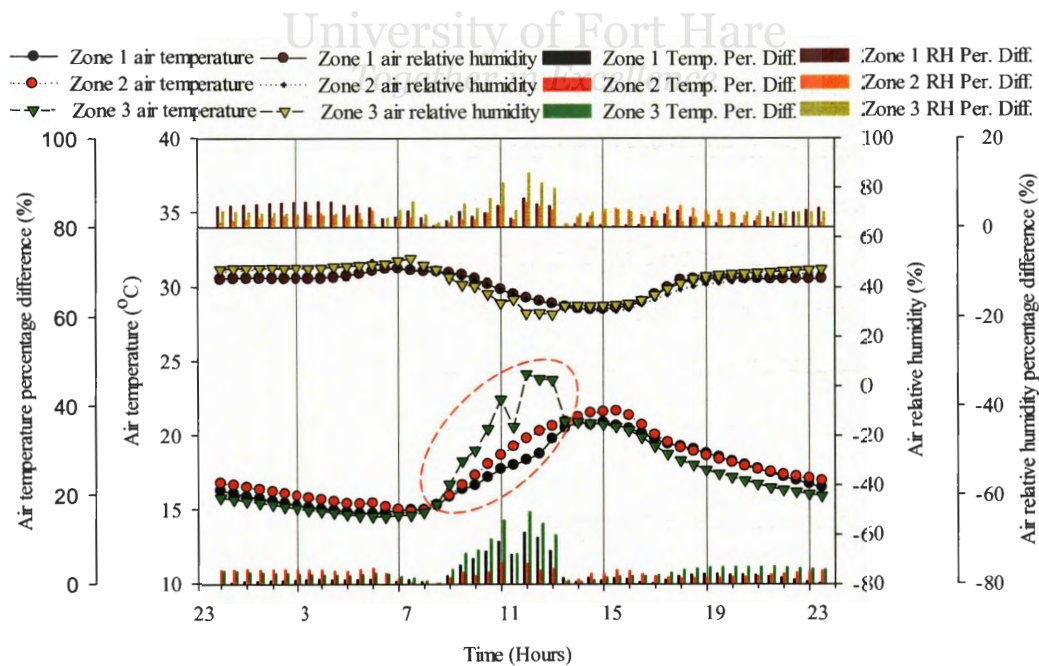


Figure 4.19: Typical winter day air temperature and relative humidity distribution in the various zone

In a typical summer day, the air temperature percentage difference was 4% at 12h00. Its corresponding relative humidity was 3% at 11h00. While, the typical winter day air temperature and relative humidity percentage difference were 16% and 12%, respectively. Further findings are populated in Table 4-6 and Table 4-7.

Table 4-6: Typical summer day indoor air temperature and relative humidity variation in the house zones

Zone	1		2		3	
Indoor weather parameter	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)
Daily swing	5.4	14.4	5.8	16.1	5.7	13.5
Max. Per. Diff. (%)	4	2.9	2	2.7	4	3.1
(Equiv. Temp.)	(0.9°C)	(1.3%)	(0.5°C)	(1.2%)	(1.1°C)	(1.3%)
Peak Time	12h00	18h30	16h00	18h30	11h00	11h00
Average Per. Diff. (%)	2	0.9	1	1.7	1	1.1
(Equiv. Temp.)	(0.4°C)	(0.4%)	(0.2°C)	(0.8%)	(0.3°C)	(0.5%)

Table 4-7: Typical winter day indoor air temperature and relative humidity variation in the house zones

Zone	1		2		3	
Indoor weather parameter	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)
Daily swing	6.1	16.3	6.7	20.0	9.6	22.2
Max. Per. Diff. (%)	11.6	6.5	4.8	5.7	16.2	12.2
(Equiv. Temp.)	(2.4°C)	(2.2%)	(0.9°C)	(1.9%)	(3.4°C)	(4.1%)
Peak Time	12h00	12h00	11h00	12h00	12h00	12h00
Average Per. Diff. (%)	2.2	3.1	2.3	2.5	3.9	3.6
(Equiv. Temp.)	(0.4°C)	(1.3%)	(0.4°C)	(1.0%)	(0.7°C)	(1.5%)

In both Tables, the daily swing refers to the difference between the daily maximum and minimum air temperature and relative humidity obtained. In Table 4-6, a fairly constant daily air temperature swing of an average of 5.6°C was observed, although the relative humidity swing in each zone varies. The different pattern of distribution of the air temperature and relative humidity was expected given that the presence and activities of occupants in a room are a contributing factor to the relative humidity.

Furthermore, varying air temperature and relative humidity were observed in each zone in the typical winter day. This implies that a relatively high diurnal temperature variation was experienced during the winter season. Also, zone 3 had the maximum daily air temperature swing of 9.6°C . This was as a result of the north facing clerestory windows. Recall that the house was designed to optimize even air temperature indoors. Hence, the clerestory windows were installed to distribute solar radiation to the south floor area of the house. The red highlighted dash circle in Figure 4.18 and 4.19, indicates air temperature increase in zone 3 (south facing room) due to penetrated solar radiation. Consequently increases the day and night air temperature difference in the zone. Zone 3 air temperature tend to increase more in winter due to the low angled sun experienced during the season, considering only the red circled area in both figures.

4.4.3 Whole building weather response to ambient air temperature and relative humidity

The average air temperature and relative humidity of all zones were obtained to examine the demography and distribution of the zones air temperature and relative humidity within the thermal comfort. The examination also includes the ambient air temperature and relative humidity. The average air temperature of all zones was represented by the whole building air temperature while whole building relative humidity is the average relative humidity of the three zones. Summer season frequency distribution of the whole building and ambient air temperature, as well as their corresponding relative humidity, are shown in Figure 4.20 and 4.21, respectively.

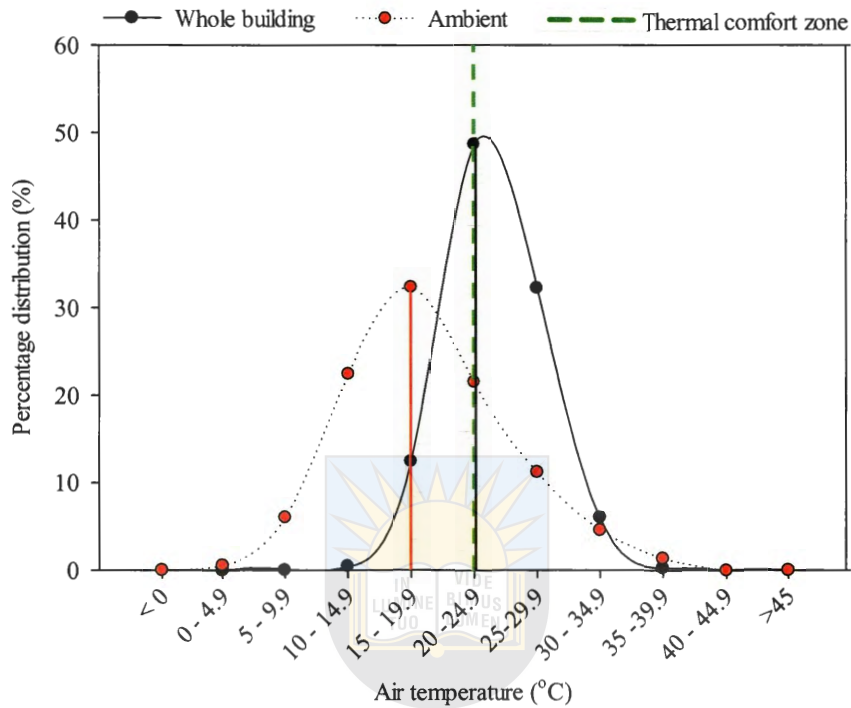


Figure 4.20: Whole building and ambient air temperature summer season profile

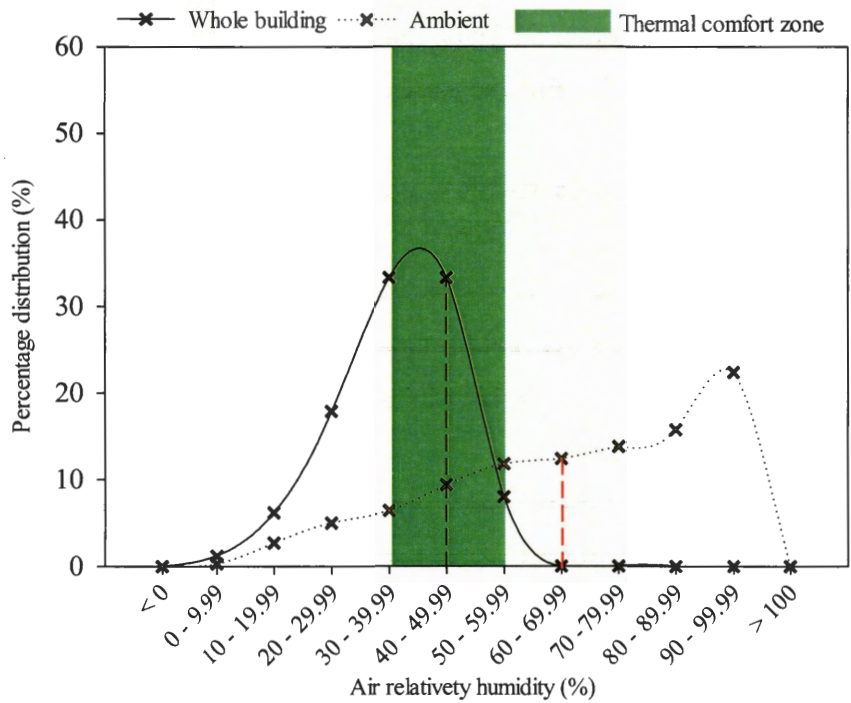


Figure 4.21: Whole building and ambient air relative humidity summer season profile

A total of 12607 data entries were used to develop the whole building and ambient summer season air temperature and relative humidity distribution profile. As seen in Figure 4.20, the whole building and ambient air temperature distributions were divided into nine classes of 4.9°C width. While the air relative humidity frequency distribution curve in Figure 4.21, is made of 11 classes of 9.99% width. Statistically, the whole building and ambient air temperature were not normally distributed. The whole building temperature skewness was 0.20 with a standard error (S.E) of 0.02, whereas a skewness of 0.41 (S.E 0.02) was obtained for the ambient temperature. Although both whole building and ambient air relative humidity in Figure 4.21 were also not normally distributed, an opposite skewness was obtained. The whole building and ambient relative humidity had a skewness of -23.32 and -23.68, respectively, both with a S.E of 0.02.

This implies that the measured air temperature and relative humidity deviate away from their mean toward the positive and negative side, respectively. Where the whole building and ambient mean values are indicated by the solid black (24°C) and red (19°C) line in their respective classes. The broken black line (47%) is used to identify the mean value of the whole building relative humidity while the broken red line signifies the mean ambient relative humidity of 68%.

Thermally, in both figures, the broken green line and band indicate the indoor air temperature (20°C and 24°C) and relative humidity (30% and 60%) thermal comfort zone, respectively [SABS, 2011]. In this regards, 49% of the whole building air temperature as well as approximately 85% of its corresponding relative humidity were found within the thermal comfort. Whereas, only 21% and 28% of the ambient air temperature and relative humidity, respectively were in the thermal comfort zone.

In the winter season, a total of 4386 data entries were used to develop the whole building thermal condition, ambient air temperature, and relative humidity distribution profile. Nonetheless, a similar behavior of the whole building, ambient air

temperature, and relative humidity were observed. Figure 4.22 shows the measured ambient and whole building air temperature as well as the resultant relative humidity in Figure 4.23 during the winter season.

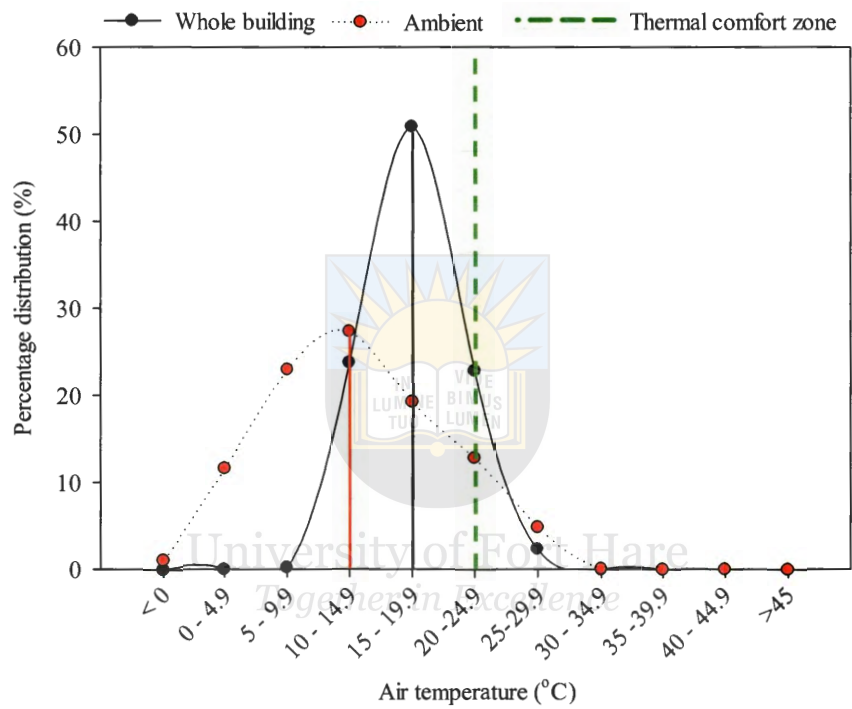


Figure 4.22: Winter season whole building and ambient air temperature profile

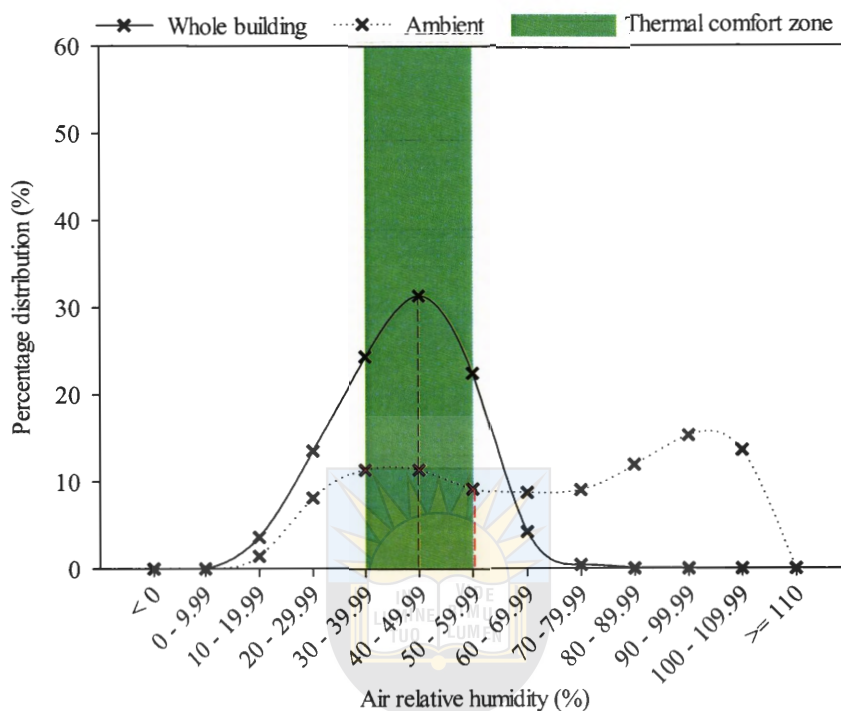


Figure 4.23: Winter season whole building and ambient air relative humidity profile

In Figures 4.22 and 4.23, the whole building temperature and relative humidity skewness were 0.22 and -0.21, respectively with a S.E of 0.04. Meanwhile, a skewness of 0.22 was observed for the ambient air temperature while the relative humidity skewness was -0.15, both with a S.E of 0.04. Hence, the whole building, ambient air temperature, and relative humidity curves are asymmetric. Specifically, the mean of the whole building air temperature drifts away from the thermal comfort zone, leaving only 23% of the whole building temperature distribution in the thermal comfort zone. However, the percentage of the ambient air temperature in the thermal comfort zone deviate by 10%. Whereas, approximately 78% and 29% of the whole building and ambient air relative humidity, respectively were inside the thermal comfort zone.

Considering Figure 4.20 to 4.23, it could be said that the whole building air temperature to a certain degree is influenced by the ambient air temperature. Given that both distributions follow the same trend in both season. Nevertheless, the same cannot be said for the whole building and ambient air relative humidity. In both

seasons, the whole building relative humidity distribution tends to follow the whole building air temperature.

Theoretically, relative humidity is a measure in percentage the amount of water vapor in the air compared to the amount of water vapor the air can hold at a given temperature. Considering that the amount of water vapor the air can hold primarily depend on the air temperature, an increase in air temperature increases the capacity of water vapor the air can hold. At a fixed amount of water vapor, an increase in air temperature results in a decrease of the air relative humidity and vice versa. Therefore, the measured air temperature and relative humidity are shown in Figures 4.20 to 4.23 are in line with theory [Hardwick *et al.*, 2015].

An average summer and winter day profile is given in Figures 4.24 and 4.25, to further illustrate the whole building thermal conditions response to the ambient air temperature and relative humidity vis-à-vis the thermal comfort zone. The difference between the ambient air temperature, relative humidity, the resultant whole building temperature, and relative humidity in terms of daily change rate is also included in both figures.

The average daily seasonal whole building and ambient air temperature and relative humidity shown in Figures 4.24 and 4.25 agree with theory [Hardwick *et al.*, 2015]. An inverse relationship was observed between the whole building air temperature and its corresponding relative humidity. The same relationship was found between the ambient air temperature and relative humidity.

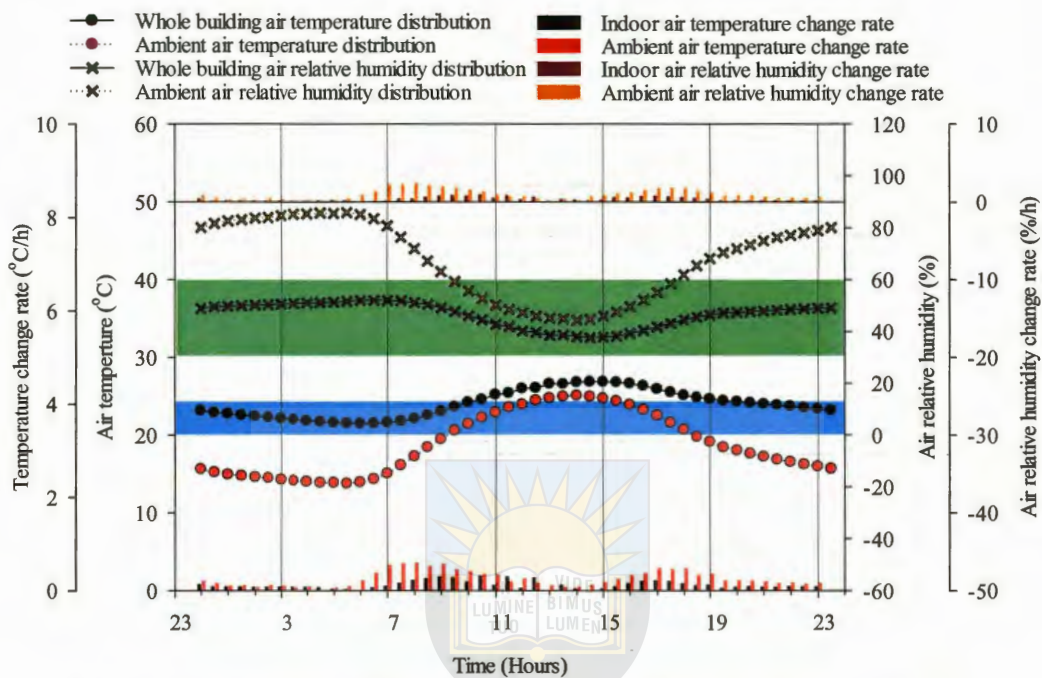


Figure 4.24: Average summer day whole building indoor weather condition response to ambient air temperature and relative humidity

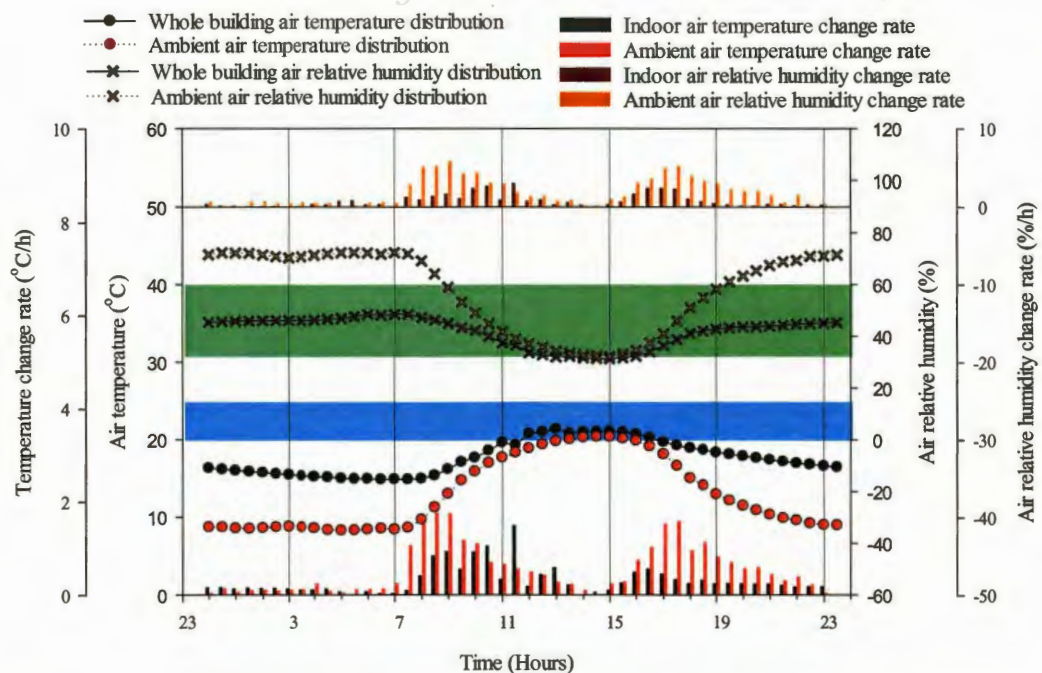


Figure 4.25: Average winter day whole building indoor weather condition response to ambient air temperature and relative humidity

From Figure 4.24, the whole building and ambient air temperature were found to be out of the thermal comfort zone 46% and 77% of the day, respectively. However, the whole building relative humidity was entirely within the thermal comfort zone, while the ambient air relative humidity was in the thermal comfort zone for only 38% of the day. The whole building air temperature was mostly above the thermal comfort zone between 10h00 and 12h00 with an average air temperature of 25.6°C. Nevertheless, a more stable indoor air temperature and relative humidity was observed, their respective average change rates were half of the ambient air temperature and relative humidity average change rates. The daily whole building air temperature change rate was 0.22 °C/h while that of the ambient air temperature was 0.47 °C/h. The daily change rates of 0.61 and 1.74 %/h were found for the indoor and ambient air relative humidity, respectively.

On an average winter day (Figure 4.25), the ambient air temperature was found to be in the comfort zone for only 5% of the day, whereas the indoor air temperature was in the thermal comfort zone for 21% of the day. On the other hand, the whole building relative humidity was completely in the thermal comfort zone, although, 21% of the distribution was found to occupy the lower (30 to 35%) level of the thermal comfort zone. The ambient air relative humidity was however within the thermal comfort zone 44% of the day. Regarding the daily air temperature and relative humidity variation, a relatively vigorous behavior was observed in the average winter day. The average winter day had the maximum daily temperature and a relative humidity change rate of 0.59 °C/h and 1.48 %/h, respectively. The ambient temperature change rate was 1.03 °C/h while its corresponding relative humidity was 3.53 %/h. Regardless of the seasons, the ambient temperature and relative humidity change rate were found to be approximately twice the whole building temperature and relative humidity, respectively.

4.5 Summary

The measured meteorological parameters that affect the thermal load of a house were discussed in term of data integrity, seasonal distribution and thermal implication. The meteorological parameters covered in research, include solar radiation, air temperature (indoor and ambient), air relative humidity (indoor and ambient), wind speed and direction. Besides the meteorological parameters, the surface temperature distribution of the building envelope components was also taken into consideration. All parameter were presented in relation to its summer and winter season performance. Due to uncontrollable data lost which account for 5% of the total collected data, 16993 data entries per parameter were obtained. Although summer and winter seasons profile were obtained, the majority of the lost were observed in the summer season.

Nonetheless, the maximum global horizontal irradiance (GHI) of 996.0 W/m^2 was obtained during the summer season, in the month of February. The resultant solar irradiation, which depicts the amount of heat generated was 12.0 kWh/m^2 . The average GHI in summer was found to be 192.8 W/m^2 and 140.5 W/m^2 in winter. In addition to the GHI, the global irradiance at the various elevation of the house was monitored. In both seasons, the north and south elevations of the house had the maximum and minimum irradiance, respectively. On the other hand, the maximum wind speed distribution in summer and winter were found to be between 0.5 to 1.0 m/s . The mean wind direction obtained from wind rose chart indicates a southeast (122°C) and northwest (288°C) prevailing wind in summer and winter, respectively.

Furthermore, the horizontal surface temperature difference of the perimeter walls was seen to lesser than 2.6°C . The maximum surface temperature difference was observed on the east wall. Also, the outer surface temperature of the perimeter walls was found to follow the global irradiance on their respective elevation irrespective of the season. The ceiling and roof surface temperature had a peak value of 44.3°C and 27.9°C ,

respectively on a typical summer day. On an average winter day, the roof surface temperature was 39.3°C and the ceiling was 21.7°C.

There was no significant temperature deviation observed between the north and south floor area of zone 1 in both seasons. However, a significant temperature difference was observed among the three zones during the winter season. Zone 3 was found to have the average maximum air temperature deviation of 3.4°C while its corresponding relative humidity deviation was 4.1%. In addition, the whole building air temperature and relative humidity were compared to the ambient air temperature and relative humidity. Their respective distribution within the thermal comfort zone was also examined. It was found that 49% and 23% of the whole building summer and winter season air temperature distributions, respectively were within the thermal comfort zone. But only 21% of the ambient summer season air temperature was in the thermal comfort zone and 10% during the winter season. In terms of air relative humidity distributions, 85% of the whole building and 28% of ambient were in the thermal comfort zone in summer. Though in winter season 78% and 29% of the whole building and ambient, respectively were in the thermal comfort zone. Regardless of the season, a relatively stable air temperature was observed indoor.

REFERENCES

- Bradshaw, V. (2006) *The Building Environment: Active and Passive Control Systems*. Third. New Jersey: John Wiley & Sons.
- Conradie, D. C. U. (2012) 'South Africa's climatic zones: Today, tomorrow', *International Green Building Conference and Exhibition*, Future, pp. 1–9.
- Epstein, Y. and Moran, D. S. (2006) 'Thermal Comfort and the Heat Stress Indices', *Industrial Health*, 44(3), pp. 388–398. doi: 10.2486/indhealth.44.388.
- Eskom (2016) *Tariff and charges booklet*, Eskom Holdings SOC LTD. Pretoria. Available at: <http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/tariffbookletproof1.pdf>.
- Hardwick, S. R., Toumi, R., Pfeifer, M., Turner, E. C., Nilus, R., *et al.* (2015) 'The relationship between leaf area index and microclimate in tropical forest and oil palm plantation: Forest disturbance drives changes in microclimate', *Agricultural and Forest Meteorology*. Elsevier, 201, pp. 187–195.
- Hinrichs, R. and Kleinbach, M. (2013) *Energy: Its use and the environment*. Fifth. Edited by C. Harford, E. Dodd, and B. Kirkey. New York: BROOKS/COLE.
- Kaşka, Ö. and Yumrutaş, R. (2009) 'Experimental investigation for total equivalent temperature difference (TETD) values of building walls and flat roofs', *Energy Conversion and Management*, 50(11), pp. 2818–2825. doi: 10.1016/j.enconman.2009.06.027.
- Kreider, J. F., Curtiss, P. S. and Rabl, A. (2009) *Heating and cooling of buildings: design for efficiency*. Second. Edited by F. Kreith and R. Mahajan. Denver: CRC Press.
- Marzo, A., Trigo, M., Alonso-Montesinos, J., Martínez-Durbán, M., López, G., *et al.* (2017) 'Daily global solar radiation estimation in desert areas using daily extreme temperatures and extraterrestrial radiation', *Renewable Energy*, 113, pp. 303–311. doi: 10.1016/j.renene.2017.01.061.
- Offerle, B., Eliasson, I., Grimmond, C. S. B. and Holmer, B. (2007) 'Surface heating in relation to air temperature, wind and turbulence in an urban street canyon', *Boundary-Layer Meteorology*, 122(2), pp. 273–292. doi: 10.1007/s10546-006-9099-8.
- Olmo, F. ., Vida, J., Foyo, I., Castro-Diez, Y. and Alados-Arboledas, L. (1999) 'Prediction of global irradiance on inclined surfaces from horizontal global irradiance', *Energy*, 24(8), pp. 689–704. doi: 10.1016/S0360-5442(99)00025-0.
- Oral, G. K. and Yilmaz, Z. (2003) 'Building form for cold climatic zones related to building envelope from heating energy conservation point of view', *Energy and Buildings*. Elsevier, 35(4), pp. 383–388.

- Paulescu, M., Paulescu, E., Gravila, P. and Badescu, V. (2013) *Weather Modeling and Forecasting of PV Systems Operation, Green Energy and Technology*. doi: 10.1007/978-1-4471-4649-0.
- Reardon, C. and Clarke, D. (2013) 'Passive Cooling', in Paul, D. and DCCEE (eds) *Your Home*. Second. sydney: Department of the Environment, Water, Heritage and the Art, pp. 135–148. doi: 10.1016/0038-092X(84)90205-6.
- SABS (2011) *SANS 204:2011 - SOUTH AFRICAN NATIONAL STANDARD: Energy efficiency in buildings*.
- South Africa Weather Service (2012) *How are the dates of the four seasons worked out?*, *WeatherSA*. Available at: <http://www.weathersa.co.za/learning/weather-questions/82-how-are-the-dates-of-the-four-seasons-worked-out> (Accessed: 4 May 2013).
- Szokolay, S. V. (2004) *Introduction to architectural science: the basis of sustainable design*. First Edit, Elsevier. First Edit. Edited by C. Brisbin. Oxford: Architectural Press.
- Szokolay, S. V. (2008) *Introduction to architectural science: the basis of sustainable design*. Second, *Journal of the American College of Radiology: JACR*. Second. Edited by C. Brisbin. Oxford: Elsevier. doi: 10.1016/j.jacr.2010.08.020.
- Zhang, H., Zhong, K. and Liu, J. (2016) 'Effects of wind conditions on heat dissipation from surfaces of walls for isolated low-rise building subject to winter solar radiation', in *Power and Renewable Energy (ICPRE), IEEE International Conference on Power and*. IEEE, pp. 653–658

Chapter 5

OPERATION OF THE HOUSE AND AMBIENT AIR HEAT TRANSFER

5.1 Introduction

Besides the ambient and indoor weather conditions, the operation of the house has a significant impact on the overall thermal load. Operation of the house takes into consideration the basic occupant daily activities that influence the indoor thermal behavior of the house. These include the number of occupants, gender, age, time spent indoor, appliances and lighting fixtures. Due to human metabolism, occupants release heat as a by-product into the inner space of a house. Heat released by occupants depend on occupancy density, clothing, and collective level of activity. However, due to relatively low-density space, occupant heat gain is often ignored in residential thermal load calculations. [Bruning, 2012; Feng *et al.*, 2016] Likewise, appliances and lighting fixtures in a house contribute to the heat generated indoors through the electrical and mechanical process. The rate of heat generation by appliance and lighting are often specified by manufactures. On the other hand, ambient air heat transfer is a direct consequent of occupants operation of the ventilation components and defect on the building envelope. Daily operation (opening and closing) of windows and doors for ventilation and exit purposes, result in heat transfer. Heat transfer due to air exchange between the inner and outer spaces also occur in openings in the building envelope. This is referred to as infiltration.

This chapter deals with the operation of the house with respect to the internal heat gain due to appliances used and lighting fixtures. However, an overview of the occupant activities as per usage of the appliances and lighting fixtures was given. The lighting of the house was analyzed in terms of natural and electrical lighting. The heat transfer due to air exchange rate of the house was also analyzed. This was treated in terms of ventilation and infiltration of sensible air heat transfer.

5.2. The basic operation of the house

During the thermal performance monitoring period of the house, the occupant activities, as well as appliance and lighting usage, were observed. The observation includes the number of family members, daily routine activities and occupancy period. Ratings of lighting fixtures and appliances were also observed. In addition, a brief interview section with the occupants was conducted to clarify their daily activities. This section analyses the internal load gain of the house. The analyses only consider the sensible heat gain.

5.2.1 Overview of occupant activities

The house was occupied by one of the University staff and his immediate family during the monitoring period. It was observed that the family comprises of his wife, two children (boy and girl) between the age of 6 and 10 years and an infant. In addition, an adult female housekeeper was part of the occupants of the house. During the weekdays, the infant remains at home with the housekeeper, and the other family members go out for their daily activities. On a daily average, the father and two children were found to leave home at 8h00, and the children return at 15h00. The father, however, returns at 18h00. The wife was observed to work and live out of town. Hence over the weekend, the entire family often travel out to spend time with her. Occasionally (public holiday), extended family members were found to visit and spend a couple of days with the family in the house. It was also observed that no mechanical heating or cooling system was used in the house during the monitoring period.

The occupancy density was found to be 0.075 person/m²; equivalent to 13.4 m²/person, since the whole building encloses a floor area of 67 m². Due to the relatively low occupancy density, occupant heat gain was ignored. Also, during peak cooling period (mid-day) the house is often occupied by an adult and infant, further reducing the space density.

5.2.2 Thermal impact of appliances

As observed during the monitoring period, a liquid crystal display television and 110 W stereo system were the major appliances in the living room, and the kitchen comprising of an electric hot-top range with oven. The stove has no hood nor vent. In addition, a 20 L microwave oven and 0.8 m³ interior space refrigerator were part of the kitchen appliances. The floor area of the house and interior photos indicating the appliance setup are given in Plate 5.1.

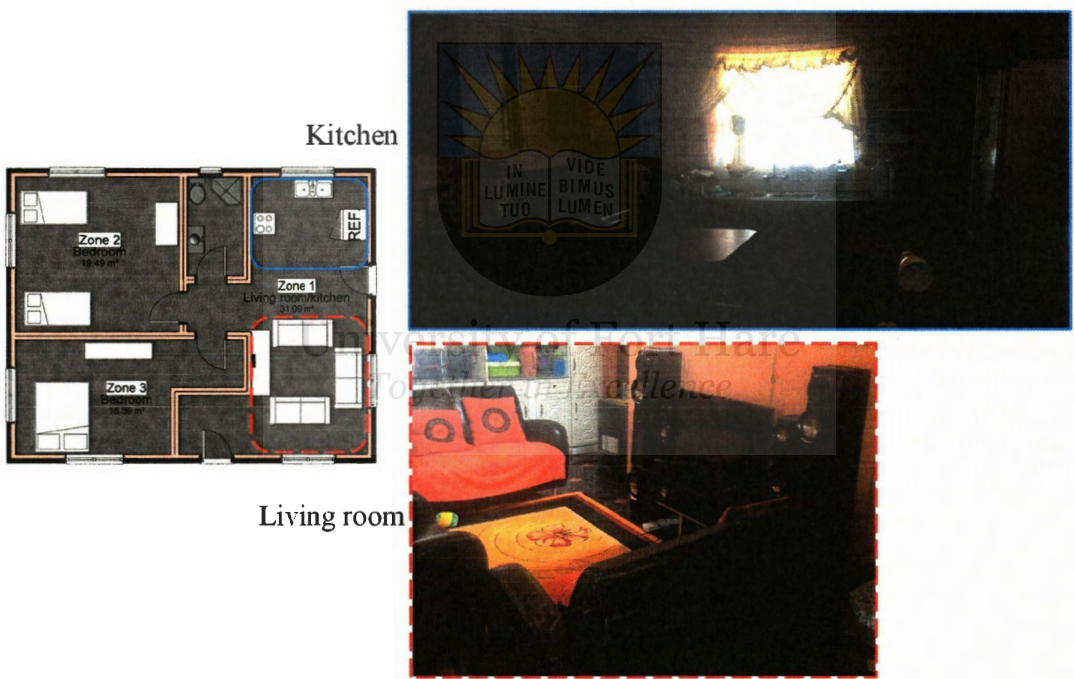


Plate 5.1: Photo of the living room and kitchen settings

There were no fixed appliances in the bedrooms as seen in Plate 5.1. However, the living room appliances heat gain are relative insignificant [Bradshaw, 2006; Ahmed *et al.*, 2017]. Due to the inconsistent use of the microwave oven, internal heat gain of the appliance took into consideration the refrigerator and stove. The instantaneous sensible heat gain of the stove was determined using Equation 2.23 and given in Table 5-1. Also, Table 5-1 contain the typical instantaneous sensible heat gain of the refrigerator given by ASHRAE [ASHRAE, 2001].

Table 5-1: Appliance sensible heat gain

Appliance	Power rating (W)	Heat gain (W)
Stove	7700	1848
Refrigerator	780	248

The power rating was obtained from the nameplate in order to estimate the heat gain of the stove. A usage factor of 0.50 and a radiation factor of 0.48 was assumed [Alereza and Breen, 1984]. The refrigerator has an internal volume of 0.8 m³, which falls in the category of 0.71 to 2.1 m³ refrigerators in the ASHRAE standard. The recommended sensible heat gain in this category was used as the heat gain of the refrigerator.

In the entire monitoring period, the refrigerator was found operational. However, the operation of the stove was intermittent. Based on discussions with the occupants, between 06h00 and 07h00, the housekeeper prepares breakfast. Alongside her daily activities, she cooks between 11h00 and 13h00, preparing lunch. Some portion of the food prepared during lunchtime was often reserved for dinner. Occasionally, she, however, cooks a fresh meal for dinner from 16h00 to 18h00. The daily heat gain of the house due to appliances was simulated and given in Figure 5.1.

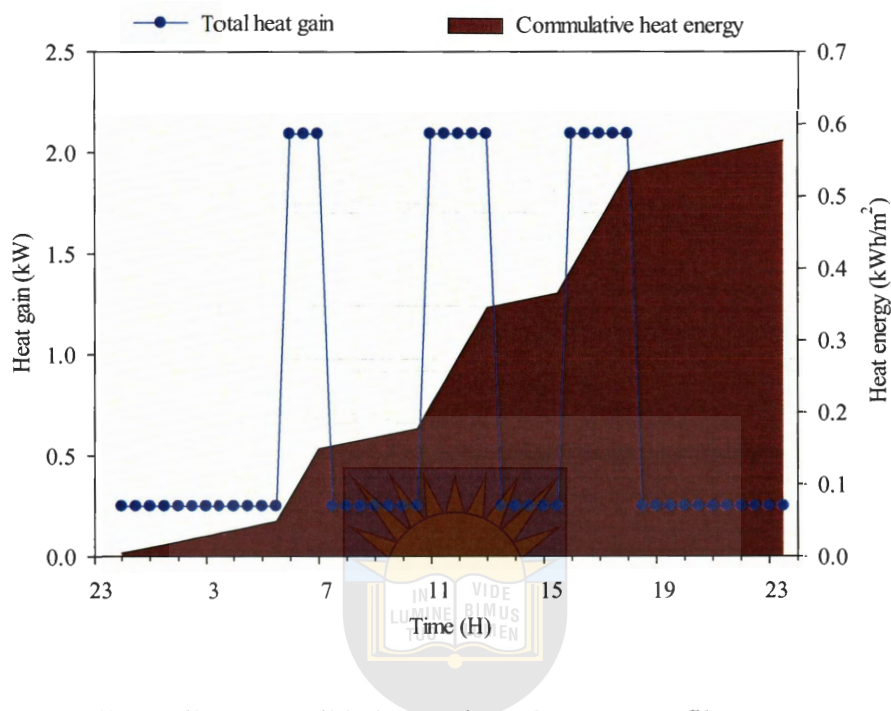


Figure 5.1: Daily appliance sensible heat gain and energy profile

Figure 5.1 was simulated based on the following assumption; the effect of refrigerator thermostat was ignored, and the housekeeper maintains the same cooking routine and cooks fresh meals for dinner daily (worst case scenario). The average daily appliances heat gain was 0.37 kW. Although, during the periods of cooking the total heat gain were 2.10 kW and 0.25 kW with the stove off as shown in Figure 2.5. The area under the heat gain curve represented the heat energy of the appliances and was found to be 7.98 and 57.4 Wh/m² with the stove off and on, respectively. Whereas, the appliances cumulative daily heat energy was 0.58 kWh/m².

It must be said that the cumulative heat energy is only a simulated performance of appliances, as it does not take into consideration the heat transfer of other components of the house. Given that no fixed appliances were used in the bedroom (zone 2 and 3), the estimated sensible heat gain only applies to the living room and kitchen (zone 1).

5.2.3 Thermal impact of lighting

Lighting fixtures are other contributors to the internal heat gain of the house. Like appliances, the rate of lighting heat gain depends on the amount, operation period, power rating, design, and installation. It was observed that a total of five 11W Compact Fluorescent Lamps (CFL) were installed in the house. Excluding the bathroom, each of the CFLs was fitted in an uplighter frosted glass sconce. A photo of the lighting fitting is shown in Plate 5.2.

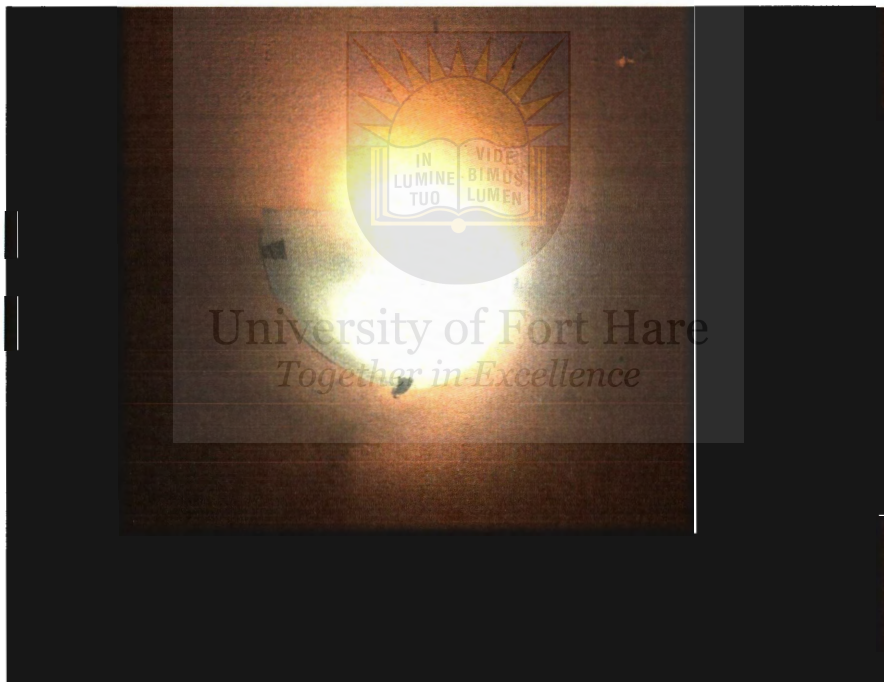


Plate 5.2: Photo of the lighting fixture in the living room

A total of three light fittings were installed in zone1, and one each in the north (zone 2) and south (zone 3) facing bedroom. In addition to the electrical lighting, the natural lighting of the house was also monitored. The house design enhances the indoor daylighting through the transmission of the sun's rays via the clerestory windows to the southern floor area. In the same vein, the two large north facing windows provide solar radiation to the north facing area. Together the north-facing windows increase the indoor illuminance of the house without electrical lighting during the day. Plate

5.3 shows the clerestory windows stretching through zone 1 to 3 and resultant penetrated sun rays.



Plate 5.3: Photo of clerestory windows and sun rays providing daylighting

The illuminance level which includes electrical and natural lighting of the house was measured using a Li-Cor photometric sensor. The sensor was placed on a 0.7 m high reading table in the living room. Hence, the illuminance level perceived by occupants performing any activity at table level was measured. For the purpose of the research, arrangements were made with the occupants to switch off all lamps during the day

(presence of the sun) and switch them on at night (absence of the sun) when necessary. The indoor illuminance level monitored over a week period is shown in Figure 5.2.

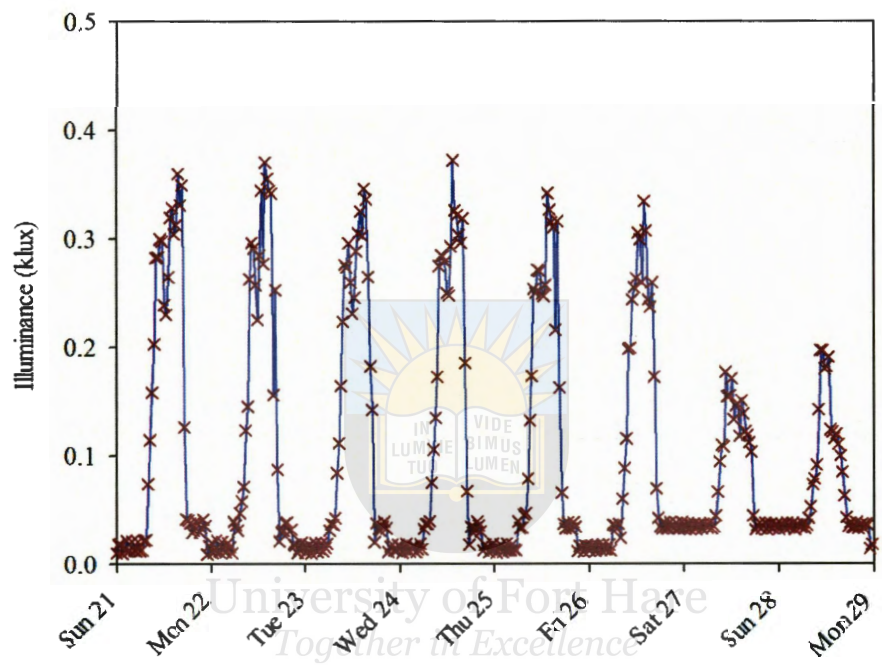


Figure 5.2: Indoor illuminance level

From Figure 5.2, the average illuminance level of the house can be classified into clear and cloudy sky days. The classification was based on the maximum daily illuminance obtained. In other words, days with maximum illuminance greater than 0.2 klux were considered as clear sky days, while days with maximum illuminance less than 0.2 klux were cloudy sky days. In line with the above assumptions, 21 to 26 May were clear sky days. Their average maximum illuminance was 0.30 klux. Whereas, 27 and 28 May with average maximum illuminance equal to 0.19 klux were considered as cloudy sky days. The average maximum illuminance obtained during the cloudy sky day was equivalent to the recommended illuminance for an occupant in the kitchen, dining room, and reading at table level [Szokolay, 2008]. Furthermore, the average illuminance before and after the peak illuminance in both cloudy sky days was 0.04 klux. Whereas during the clear sky days, the average illuminance before and after the

peak illuminance was 0.01 klux. It should be noted that both cloudy sky days were weekend. As stated earlier, the occupants often spend the weekend away from the house. It was observed that during such period while they were away, the lamps were switched on throughout the night for security reasons. Therefore, to further illustrate the natural and electrical lighting performance of the house, an average day profile base on the weekdays was developed. Figure 5.3 shows a typical day profile of the indoor illuminance of the house.

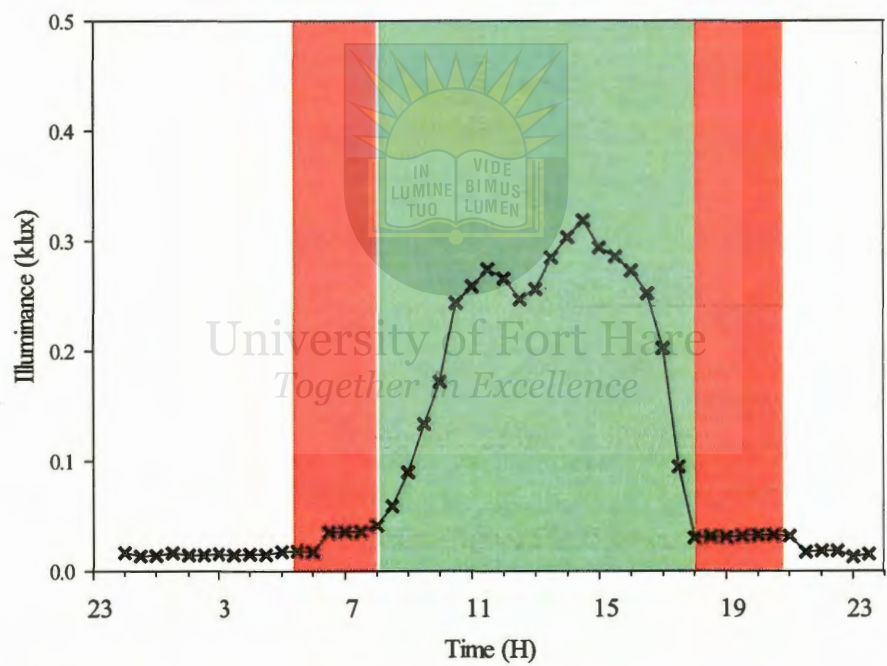


Figure 5.3: Typical day indoor illuminance distribution

As shown in Figure 5.3, the daily illuminance profile is subdivided into three periods. The green band area indicates period with daylight (all lamps off), and the red bands are period with all the lamps on. Period with all lamps off and absence of the sun is indicated by the white regions. The average daylight illuminance was 0.2 klux. The said illuminance is applicable to zone 1 and 3. With all lamps on, the average illuminance in zone 1 was 0.03 klux. The relatively high indoor daylight illuminance is attributed to the design (clerestory windows) of the house.

Based on the daily indoor illuminance profile, it can be said that the occupants adhered to the arranged lighting routine, excluding the weekends. A worst-case scenario was assumed in order to estimate the electrical lighting heat gain. All lamps in the house (conditional space) were switched on and off at the same period. Also, the heat emission coefficient of CFL lamps is 0.31 [Suszanowicz, 2017]. Vis-à-vis the above assumption, Equation 2.22 was used to estimate the electrical lighting heat gain and given in Figure 5.4.

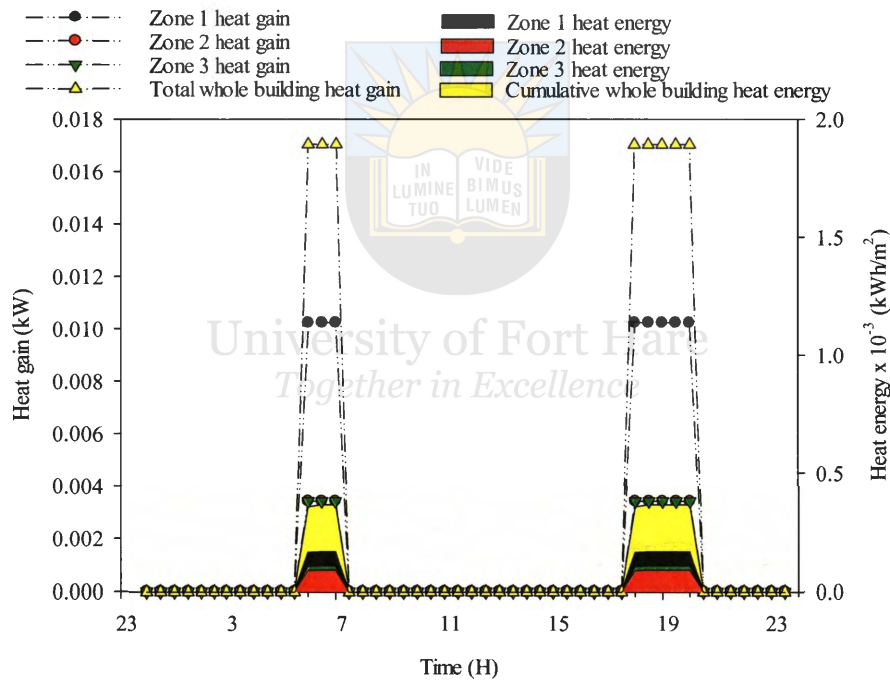


Figure 5.4: Daily electrical lighting heat gain and energy profile

From Figure 5.4, the lamps in the house were on between 6h00 and 7h00 as well as from 18h00 to 20h00 during the weekdays. As a result, the lighting heat gain for zone 1 was 10W and 3.4W for zone 2 and 3. Their corresponding daily cumulative heat energy was 1.33 Wh/m², 0.71 Wh/m², and 0.85 Wh/m² in zone 1, 2 and 3, respectively. The resultant whole building cumulative heat energy was 2.90 Wh/m².

5.3 Analysis of ambient air heat transfer

The heat energy indicated in the previous section varies with other forms of heat transfer in the house, which includes the ambient air heat transfer and heat transfer through the building envelope. The ambient air heat transfer is a factor of the indoor and outdoor air exchange rate. That occurs through the ventilation components and opening (cracks) on the building envelope. This section focus on the air exchange rate of the house as well as the resultant ventilation and infiltration air heat transfer.

5.3.1 Overview of air exchange rate of the house

ASTM E741-00 concentration method was adopted to determine the zonal air exchange rate, see section 3.4 for more details. According to ASTM E741-00 standard, a zone is a space wherein a uniform air concentration is maintained and only exchange with the ambient air [ASTM Standard, 2011]. Based on the above definition, Table 5.2 summarized the scenario assumed during the experiment.

Table 5-2: Assumed ventilation components operation

Zone	Scenario	Ventilation component and operation
1	1	All doors and windows open
	2	All doors closed and windows open
	3	All doors open and windows closed
	4	All doors and windows closed
2 and 3	5	All windows open
	6	All window closed

At a height of 3 m, the occupants rarely operate the clerestory windows. Nevertheless, to carter for worst case scenario, the windows operation include the clerestory windows. The entire air exchange testing process took a period of two days. In both days, indoor and ambient air temperatures together with wind speed and direction were

simultaneously monitored. The whole building and ambient air temperature during the entire period of the experiment are presented in Figure 5.5.

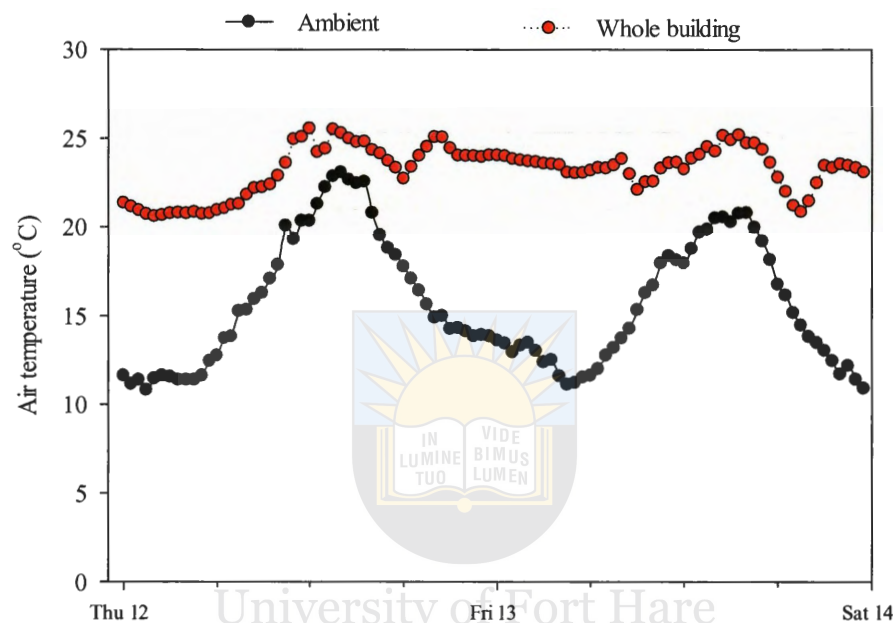


Figure 5.5 Indoor and outdoor air temperature response

From Figure 5.5, the average ambient air temperature was 16°C with a corresponding indoor temperature of 23°C. The experiment was usually conducted between 10h00 and 20h00 daily. Within this period, the average ambient and indoor air temperature were 19°C and 24°C, respectively. Hence, the opening of the ventilation components will result in an outward flow of warm air. However, the speed or pressure of the air flow depends on the ambient wind speed and direction. The two days measured wind data was converted into hourly data and used to generate the wind rose profile in Figure 5.6.

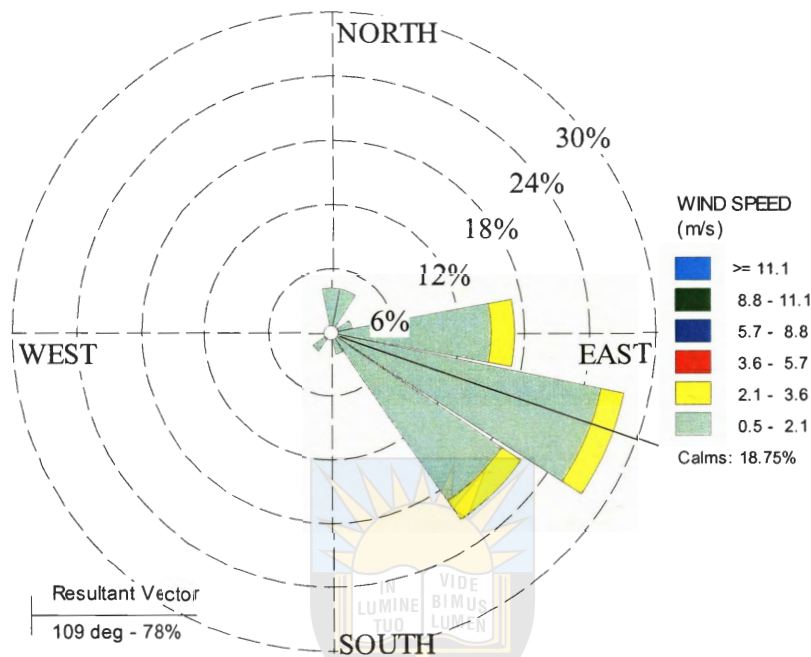


Figure 5.6: Wind speed and direction profile

As indicated by the resultant vector in Figure 5.6, prevailing east of south wind was experienced during the experimental period. In other words, the majority of the wind was blowing from the east of south to west of north orientation of the house. The average wind speed was 1.1 m/s with 19% calm. Theoretically, the opening of all windows in zone 1 will create a positive pressure at the south-facing windows. At the same time, a negative pressure at the north facing windows. The pressure difference between both windows results in a cross-ventilation in the zone. Thereby, increasing the air exchange rate with all ventilation components open. A typical airflow pattern during the period of the experiment is shown in Figure 5.7.

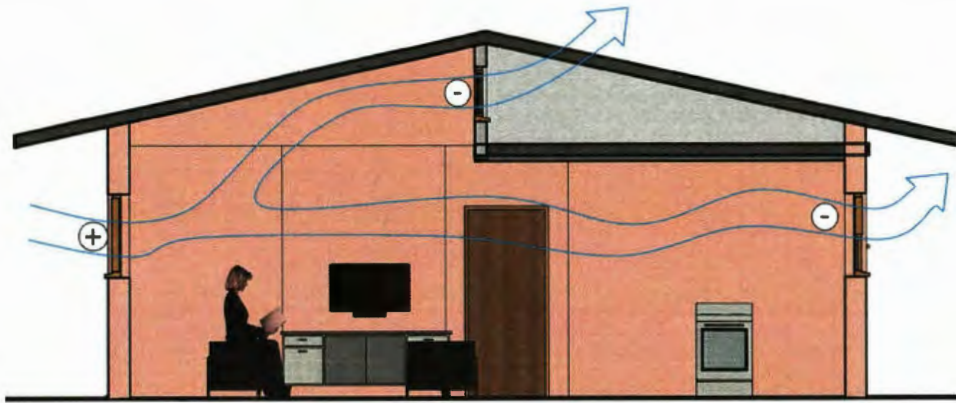


Figure 5.7: Wind effect; cross ventilation and stack effect of the house

The opening of the clerestory windows creates an additional wind effect known as stack effect. Stack effect is as a result of the temperature difference between the indoor and ambient air with respect to the vertical positions of the inlet and outlet. Due to the density difference between warm and cold air, warm air in the zone tends to rise and escape through the clerestory windows. The stack of escaping air is replaced by ambient cold air through the south-facing window. Continuous escape and replacement of air indoors result in a flow of fresh air through the house. The air flow rate increases with an increase in the height between the clerestory and south-facing windows.

As mentioned in section 3.4, the tracer gas was CO_2 , and a Non-Dispersive Infrared (NDIR) was used as the gas sensor. The whole building indoor CO_2 baseline concentration was determined by placing the gas sensor in the house over a 24 hours period. The sensor was placed at a height of 0.5 m above the floor. All internal doors of the unoccupied house were fully opened with all windows and external doors closed. The CO_2 baseline concentration was found to 0.24%. In all scenarios given in Table 5-2, the CO_2 gas tank valve was opened for about 20 seconds to allow CO_2 discharge into the respective zones. The CO_2 concentration in the air was logged at 1-minute intervals until the baseline CO_2 concentration level was reached. It should be

noted that during the entire experimental period the occupants were not indoors. The CO₂ gas rate of decay in each of the zones is shown in Figures 5.8 to 5.10.

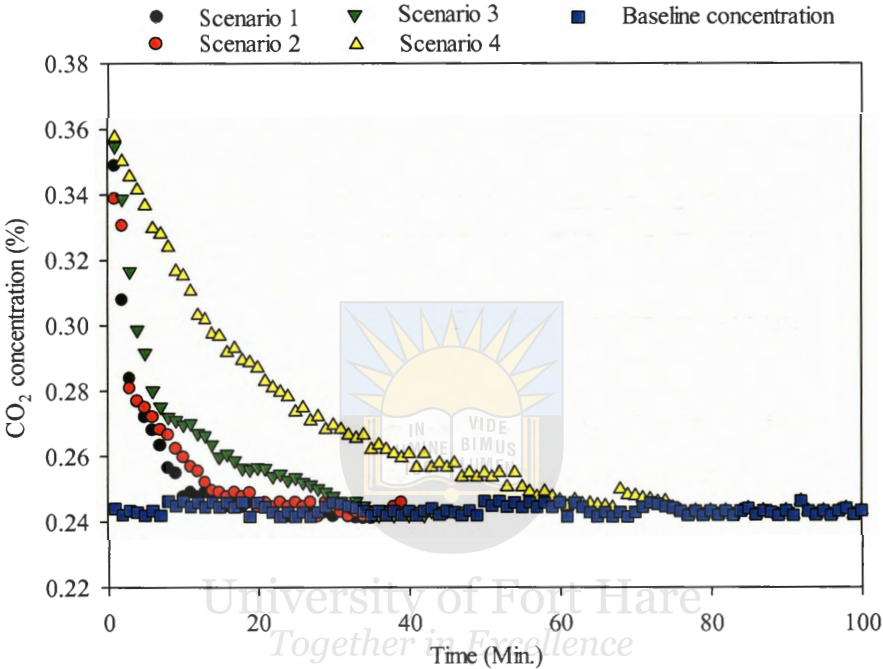


Figure 5.8: CO₂ gas decay rate in zone 1

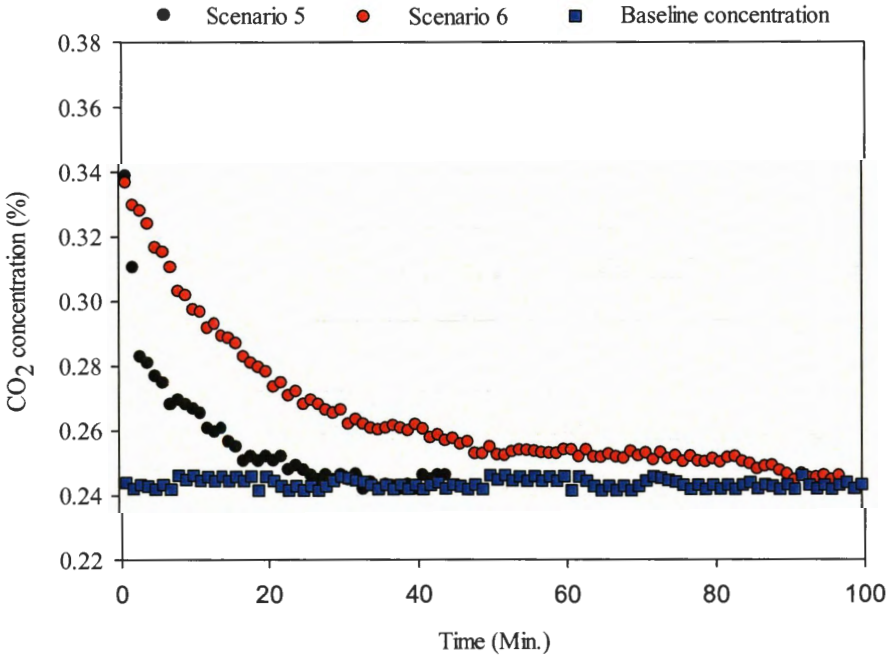


Figure 5.9: CO₂ gas decay rate in zone 2

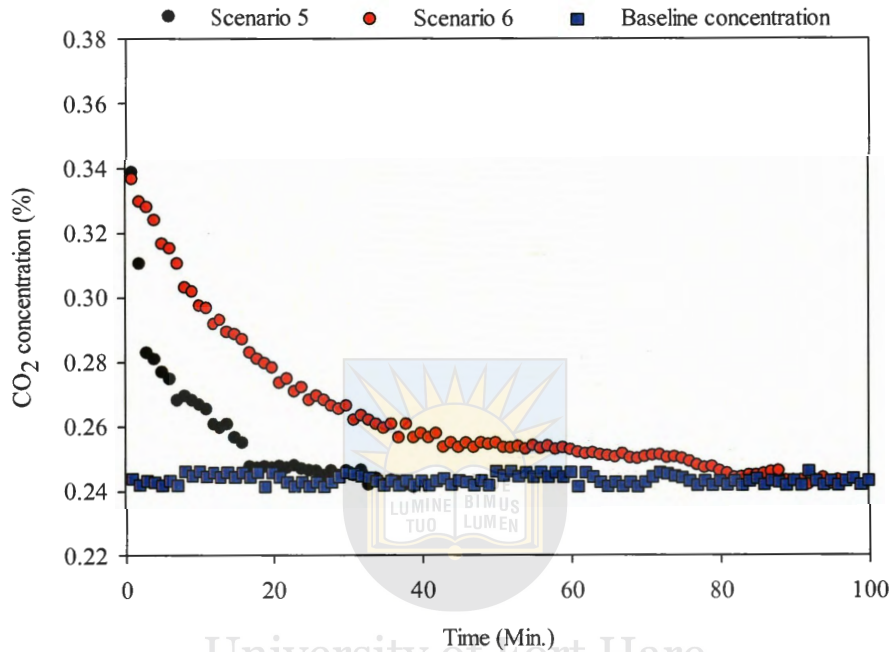


Figure 5.10: CO₂ gas decay rate in zone 3

The time taken for the CO₂ gas concentration to decay from the maximum dosage to the baseline concentration is referred to as the decay period. In Figure 5.8, all assumed scenarios were observed. The opening of all the ventilation components indicated by scenario 1 resulted in the shortest CO₂ decay period with 10 minutes. The opening of the windows only (scenario 2) in zone 1 increases the decay period by 4 minutes and by 19 minutes with the doors open and windows closed (scenario 3). The longest decay period of 56 minutes was observed in scenario 4 which represent all ventilation components closed. Although the doors have a larger surface area (1.89 m²) than the windows (1.35 m²), the windows accounted for faster removal of CO₂ from the zone. The direction of the wind during the experiment period is responsible for the effective removal of the CO₂ from the zone. The prevailing east of south wind observed during the experiment tend to produce a rush of air flow from the south windows (windward) through the inner space of zone 1 to the north facing windows (leeward). Thus, a high

rate of CO₂ removal occurs in the zone with all the windows open as compared to the doors.

Zone 2 with a relatively smaller floor area of 19.49 m², the rate of CO₂ removal of the windows was also smaller. The CO₂ decay period with the windows open and closed in zone 2 was 23 and 85 minutes, respectively. As indicated in section 3.2.1, zone 2 is the north-facing bedroom and comprised of only the north- and west of north-facing windows. Therefore, the prevailing east of south wind during the experiment had minimal effect on the CO₂ decay rate with all the windows open in the zone.

Despite zone 3 (Figure 5.9) had the smallest surface area of 16.13 m², a higher rate of CO₂ removal was observed in the zone with respect to zone 2. Similarly to zone 2, the rate of CO₂ decay through the doors was not taken into consideration in zone 3. The opening of the windows in the zone resulted in a decay rate of 17 and 76 minutes with the windows closed. The respective positive and negative air pressure at the south- and north-facing open windows which resulted in the rate of CO₂ removal in zone 1, is also experienced in zone 3 with all windows open. However, zone 1 has a larger floor area and a number of windows compared to zone 3. Hence, a higher rate of CO₂ removal was observed in zone 1.

Furthermore, the CO₂ concentration in all of the measurements was divided by the maximum concentration/dose logged to give a normalized CO₂ concentration. This, however, does not affect the results since we are interested in the tracer decay rates. After which, the logarithm of CO₂ concentration in each of the zone was obtained. Thence the air exchange rate was obtained from the slope of the linear regression. The normalized logarithmic CO₂ decay in the zones was obtained, considering the line of best fit and given in Figures 5.11 to 5.13.

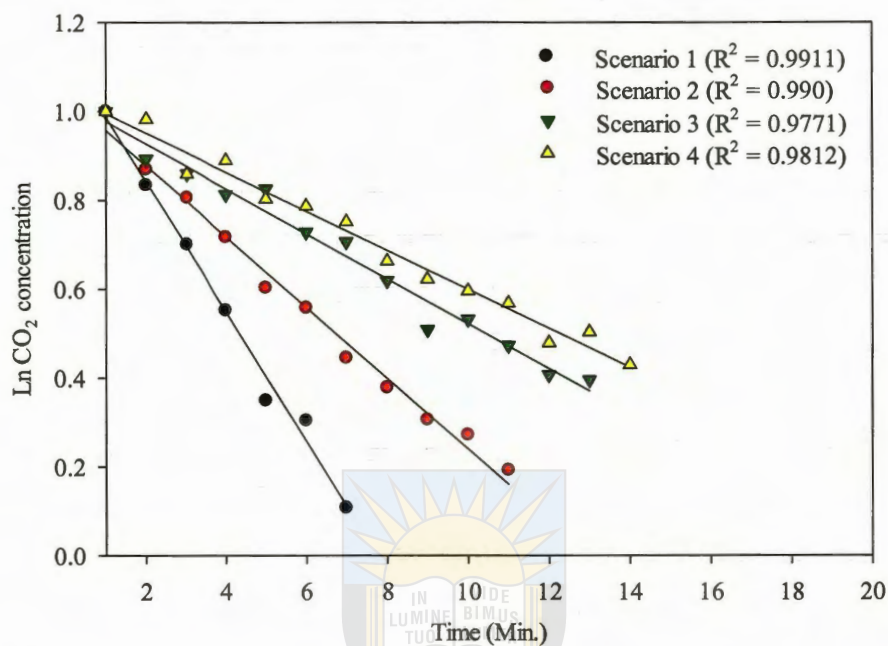


Figure 5.11: Zone 1 normalized logarithmic CO₂ gas decay

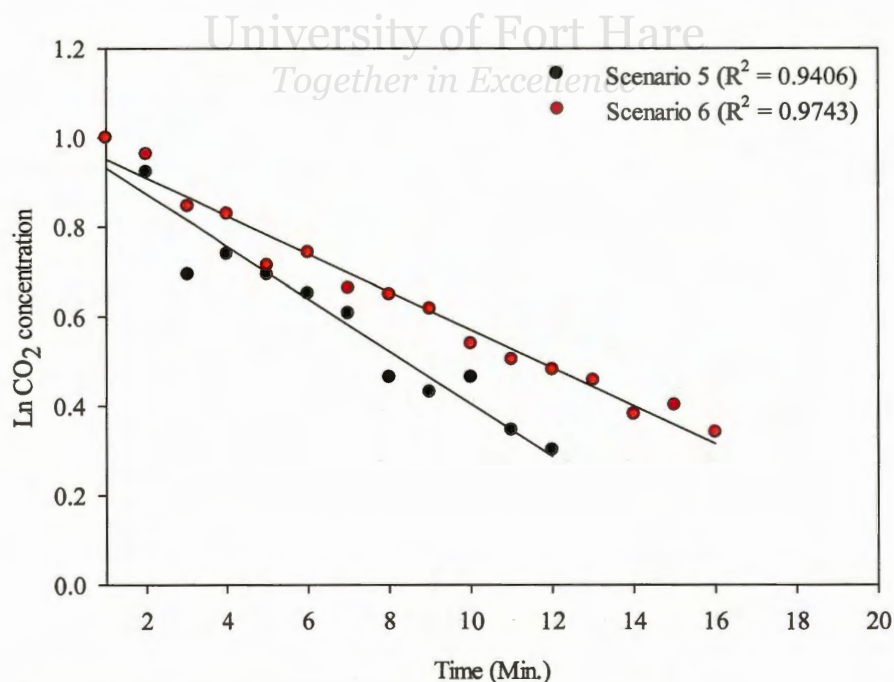


Figure 5.12: Zone 2 normalized logarithmic CO₂ gas decay

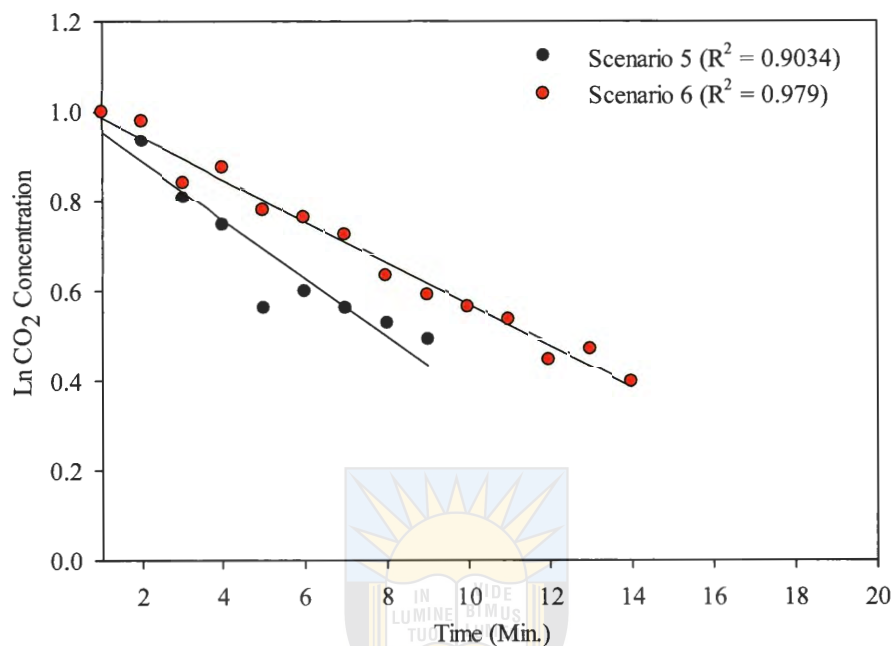


Figure 5.13: Zone 3 normalized logarithmic CO₂ gas decay

From Figures 5.11 to 5.13, the normalized logarithmic CO₂ was observed to follow the trend of the concentration decay rate given in Figures 5.8 to 5.10. The computed air change rate of the zones relative to the various scenarios are summarized in Table 5-3.

Table 5-3: Zonal air change rate of the house

Zone	Scenario	Decay period (min.)	Air change rate (h)
1	1	10	2.27
	2	14	1.86
	3	29	0.90
	4	56	0.60
2	5	19	1.07
	6	85	0.43
3	5	17	1.84
	6	76	0.50

The computed air change rate given in Table 5-3 agrees with the theoretical concept. The opening of the windows in each of the zone resulted in an increase of the indoor and ambient air exchange rate. It resulted in a higher air exchange rate compared to the opening of the door or with all ventilation components closed. However, with the windows opened, zone 1 and 3 was above the recommended air change rate of domestic rooms by 0.86% and 0.84%, respectively. In all zones, the air change rate was found to be within the recommendation with all ventilation components closed.

5.3.2 Ventilation and infiltration air heat transfer analysis

The previous section deals with the investigation and analysis of the air exchange rate of the house. It was analyzed in terms of the percentage of air exchanged per hour. The specific volume and volumetric heat capacity of air are required to express the computed air exchange rate in ventilation and infiltration heat transfer. Specific volume in this context refers to the volume of a particular zone that is occupied by air. Enclosed furniture such as cupboard and wardrobe some appliances like refrigerator and stove reduces the actual volume of a room. Therefore the specific volume of each of the zone was obtained by subtracting the total volume of enclosed furniture and appliance in the zones from the actual volume of the zone.

The dimension of furniture in the various zones was measured. In zone 1, the kitchen cabinet occupied a total of 4.84 m^3 . This includes the volume of the stove. The external volume of the refrigerator was found to be 1.14 m^3 . On the other hand, the living room had a 1.27 m^3 cupboard. Like a typical bedroom, zones 2 and 3 has a wardrobe and a bed as the major furniture with no appliances. Both pieces of furniture had a total volume of 3.42 m^3 in zone 2 and 4.18 m^3 in zone 3. Based on the above volume of furniture and appliance, also considering a height of 2.6 m indoors, the whole building volume is populated in Table 5-4.

Table 5-4: Actual and specific volume of the various zones

Zone	Actual volume (m ³)	Specific volume (m ³)
1	80.83	73.58
2	50.67	47.25
3	42.61	38.43

Only enclosed furniture with regular shapes was considered. Beside the irregularly shaped furniture such as a couch, have the ability to absorb and release air. As indicated in Table 5-4, the considered furniture reduces the actual volume of zone 1 by 9%, 7% in zone 2 and 10% in zone 3. Hence, the obtained specific volume and Equations 2.29 to 2.31 were used to compute the volumetric air flow rate, specific ventilation rate, and sensible air heat transfer, respectively. Table 5-5, contains the above-computed values.

Table 5-5: Computed zonal ventilation rate and sensible heat transfer

Zone	Scenario	Volumetric air flow rate $\times 10^{-3}(\text{m}^3/\text{s})$	Specific ventilation heat rate (J/s K)	Sensible air heat transfer (W)
1	1	46.40	55.12	275.59
	2	38.01	45.16	225.82
	3	18.40	21.85	109.27
	4	12.26	14.57	72.84
2	5	14.44	16.68	83.42
	6	5.64	6.71	33.52
3	5	19.64	23.34	116.67
	6	5.34	6.34	31.71

In Table 5-5, specific ventilation heat rate which deals with air flow through the ventilation component only applies when the doors and/or windows were opened. When the ventilation components were closed, indicated by scenarios 4 and 6, specific infiltration heat rate was rather experienced. The resultant sensible air heat transfer due to infiltration was relatively smaller. Although, indoor and ambient air

temperature difference of 5°C observed during the experiment period (10h00 to 20h00) was used. The instantaneous sensible air heat transfer and the corresponding energy are given in Figure 5.14.

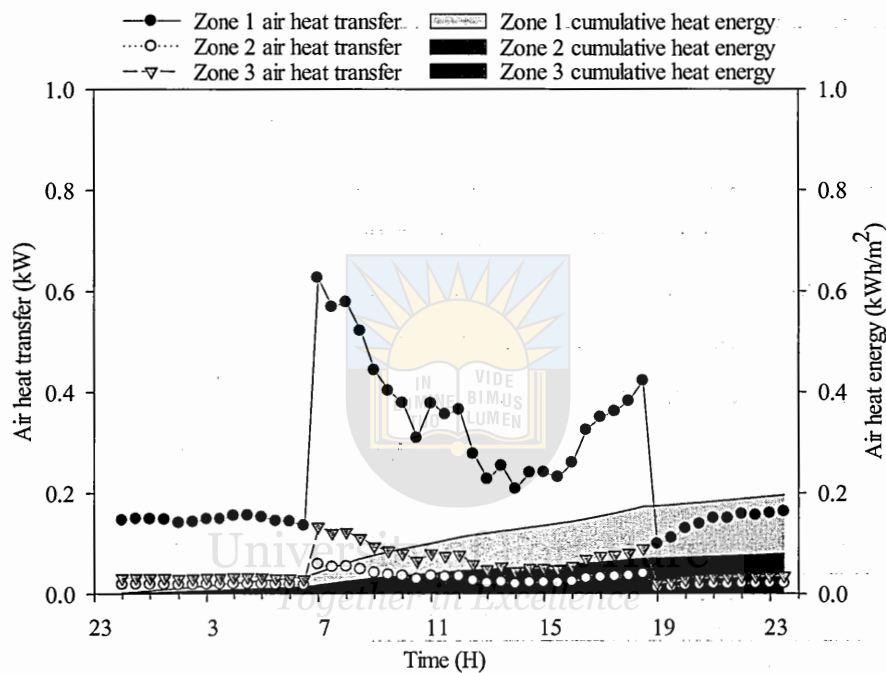


Figure 5.14: Daily sensible ambient air heat transfer and energy profile

From Figure 5.14, to simulate the daily air heat transfer in zone 1, worst case scenarios were assumed. It was easy to assign a fix operation time for the window. But the intermittent operation of the doors made it difficult to assign a fixed schedule. Hence, it was assumed that all windows and doors were opened at the same time, and closed after a given period. The assumptions correspond to scenarios 1 and 4 in Table 5-5. Whereas, scenarios 2 and 3 were assumed in zones 2 and 3. The sum of the sensible air heat transfer of both assumed scenarios in each zone was represented by air heat transfer in Figure 5.14. In all zones, it was also assumed that all ventilation components (including the external door in zone 1) were opened at 07h00 and closed at 18h00 daily.

Based on the above assumptions, the daily average air heat transfer in zone 1 was 253.91 W. Opening of the ventilation components result in an average air heat transfer of 362.89 W and 144.93 W while they were closed. The daily cumulative heat energy in zone 1 was found to be 0.196 kWh/m². Zones 2 and 3 had a relatively smaller sensible air heat transfer, due to the ventilation components and floor area considered. The average air heat transfer with the windows open were 34.23 and 77.35 W in zones 2 and 3, respectively. However, with the windows closed, the average air heat transfer was reduced by 18.75 W in zone 2 and 31.57 W in zone 3. The daily average air heat transfer was found to be 26.49 W and 54.46 W in zone 2 and 3, respectively. The resultant daily cumulative heat energy was 0.033 kWh/m² in zone 2 and 0.080 kWh/m² in zone 3.

The daily indoor and ambient air temperature difference used in computing the sensible air heat transfer results in positive values. This implies at all that time throughout the day; the indoor air temperature was greater than the ambient air temperature (Figure 5.5). According to the second law of thermodynamics, the above sensible air heat flows from the inner to the ambient space of the house. As a result, the internal heat generated by appliances and lighting in zone 1 was reduced by 66%. Whereas, zones 2 and 3 were dominated by the sensible air heat energy loss. Given that the lighting heat energy generated in both zones were relatively insignificant.

5.4 Summary

The house was occupied by a typical working-class family during the monitoring period. As a result, the house had a minimum occupancy during the day and maximum at night time. It was also found that during the weekends, the house was usually unoccupied. The observed activities of the occupants were used to simulate the appliances and lighting internal heat gain of the house. During the monitoring period, all appliances were located in zone 1. Although, only the 7.70 kW stove and 0.78 kW refrigerator were considered. A total heat gain of 2.10 kW was obtained with both

appliances in used, the refrigerator alone generates 0.25 kW. The daily cumulative heat energy without the influence of other heat sources or sink was 0.58 kWh/m². On the other hand, a total of five 11 W CFLs were installed in the house. Three of the installed lamps were located in zone 1. The indoor illuminance level of the house provided by the clerestory windows was found to be within the recommendation for domestic rooms. Daylighting of the house was 0.20 klux while at night, with all lamp on the illuminance was 0.03 klux. The resultant daily cumulative heat energy was found to be 1.33 Wh/m², 0.71 Wh/m² and 0.88 Wh/m² in zones 1, 2 and 3, respectively.

In addition, the ambient air heat transfer due to the air exchange rate of the house was also analyzed. The highest air exchange rate of 2.27 per hour was observed in zone 1 with all doors and windows opened. The direction wind during the experiment period was found to be a contributing factor to the relatively high air exchange rate. Zone 2 with all windows closed had the least air exchange rate of 0.43 per hour. Furthermore, the ventilation and infiltration air heat transfer was computed. The daily cumulative heat energy due to ventilation and infiltration was 0.196 kWh/m², 0.033 kWh/m², and 0.080 kWh/m² in zones 1, 2, and 3, respectively. Based on the indoor and ambient air temperature difference, the said heat energy indicates the amount of heat loss. As such, the daily cumulative internal heat energy in zone 1 was reduced by 0.38 kWh/m². Whereas, due to the relatively insignificant heat gain of the CFLs, zones 2 and 3 were dominated by the air heat loss.

REFERENCES

- Ahmed, K., Akhondzada, A., Kurnitski, J. and Olesen, B. (2017) 'Occupancy schedules for energy simulation in new prEN16798-1 and ISO/FDIS 17772-1 standards', *Sustainable Cities and Society*. Elsevier, 35(July), pp. 134–144. doi: 10.1016/j.scs.2017.07.010.
- Alereza, T. and Breen, J. P. (1984) 'Estimates of recommended heat gains due to commercial appliances and equipment', *ASHRAE Transactions*. American Society of Heating, Refrigerating and Air-conditioning Engineers, 90(2), pp. 25–58.
- ASHRAE (2001) 'Nonresidential Cooling and Heating Load Calculation Procedures', in *ASHRAE Handbook-Fundamentals*, pp. 8–13.
- ASTM Standard (2011) 'Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution'. ASTM International West Conshohocken, PA.
- Bradshaw, V. (2006) *The Building Environment: Active and Passive Control Systems*. Third. New Jersey: John Wiley & Sons.
- Bruning, S. F. (2012) 'Load calculation spreadsheets: Quick answers without relying on rules of thumb', *ASHRAE Journal*, 54(1), pp. 40–46.
- Feng, W., Marnay, C., Zhou, N., Ding, Y. and Wang, Z. (2016) *Influence of occupancy - oriented interior cooling load on building cooling load*, *Applied Thermal Engineering*. doi: 10.1016/j.applthermaleng.2015.11.096.
- Suszanowicz, D. (2017) 'Internal heat gain from different light sources in the building lighting systems', in *E3S Web of Conferences 19*. Singapore: EDP Sciences, pp. 1–5. doi: 10.1051/e3sconf/20171901024.
- Szokolay, S. V. (2008) *Introduction to architectural science: the basis of sustainable design*. Second, *Journal of the American College of Radiology: JACR*. Second. Edited by C. Brisbin. Oxford: Elsevier. doi: 10.1016/j.jacr.2010.08.020.

Chapter 6

BUILDING ENVELOPE HEAT TRANSFER

6.1 Introduction

The occupant operation of the house in terms of appliances and lighting fixtures generates the internal heat. Although, heat generated by lighting fixtures was observed to be insignificant. Due to indoor and ambient air temperature difference, the opening of the ventilation components, as well as openings in the building envelope, resulting in heat loss from the inner space of the house. Besides, the above-mentioned heat sources and sink, the building envelope is a major component of heat transfer in a house. As stated earlier, the building envelope comprises the walls, roof, door, windows, and floor. In the context of building thermal load evaluation, the components of the building envelope are classified into opaque and transparent components. Opaque component heat transfer is often treated in terms of conductive heat transfer, due to indoor and ambient air temperature difference. As well as the thermophysical properties of the building envelope. The walls and roof made-up the opaque components, while the glazing (windows) is referred to as the transparent component. Radiative heat transfer is the major form of heat transfer in the transparent components.

This chapter deals with heat transfer through the opaque and transparent components of the building envelope. Thus, heat transfer through the walls, roof, and windows of the house was analyzed. Given that the average air temperature difference of the house zones was 0.3°C in summer and 0.5°C in winter (Tables 4-6 and 4-7). A constant whole building air temperature was assumed. Therefore, internal heat transfer between zones was ignored. Also, considering that the house does not have adjacent space (basement) beneath the floor. Heat transfer evaluation of the house did not include the floor.

6.2 Opaque component heat transfer

From the previous chapters (Four and Five) the average indoor air temperature was higher than the ambient air temperature at all time of the day. This was however interpreted as an outer flow of heat from the inner space of the house based on the second law of thermodynamics. As indicated in chapter 3, the said ambient air temperature was measured by a solar shielded HMP 60 temperature and relative humidity probe. That is the effect of the sun was minimal in the measured air temperature. However, the solar radiation plays a significant role in the heat transfer through opaque components [Bekkouche *et al.*, 2011; Overen, Meyer and Makaka, 2017]. Therefore, a parameter that in cooperate the ambient air temperature and solar radiation was introduced to evaluate the heat transfer through the opaque components. This is known as the sol-air temperature. Sol-air temperature also caters for convective and radiative heat transfer between the opaque components surface and ambient air film. The summer and winter daily average sol-air temperature at the perimeter walls and roof of the house were determined using Equation 2.3, and Figures 4.5 and 4.6, respectively. The roof and perimeter walls sol-air temperature on an average summer and winter days are given in Figures 6.1 and 6.2, respectively.

In computing the opaque components sol-air temperature, longwave radiation factor

$\left(\frac{\Delta q_{lr}}{h_o} \right)$ was assumed to be -3.9°C for the roof and 0°C for the perimeter walls surface.

In terms of solar absorption of the surfaces, the roof was assumed to be a light-coloured surface with $0.026 \text{ m}^2\text{K/W}$ absorptance, and a dark coloured the perimeter walls surface with $0.053 \text{ m}^2\text{K/W}$ [Kaşka, Yumrutaş and Orhan, 2008].

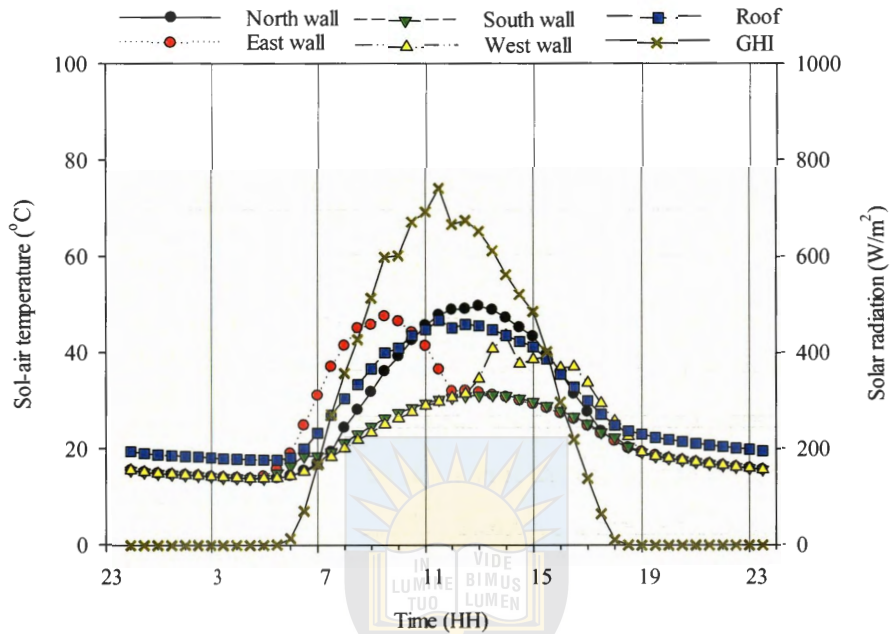


Figure 6.1: Opaque components sol-air temperature on a typical summer day

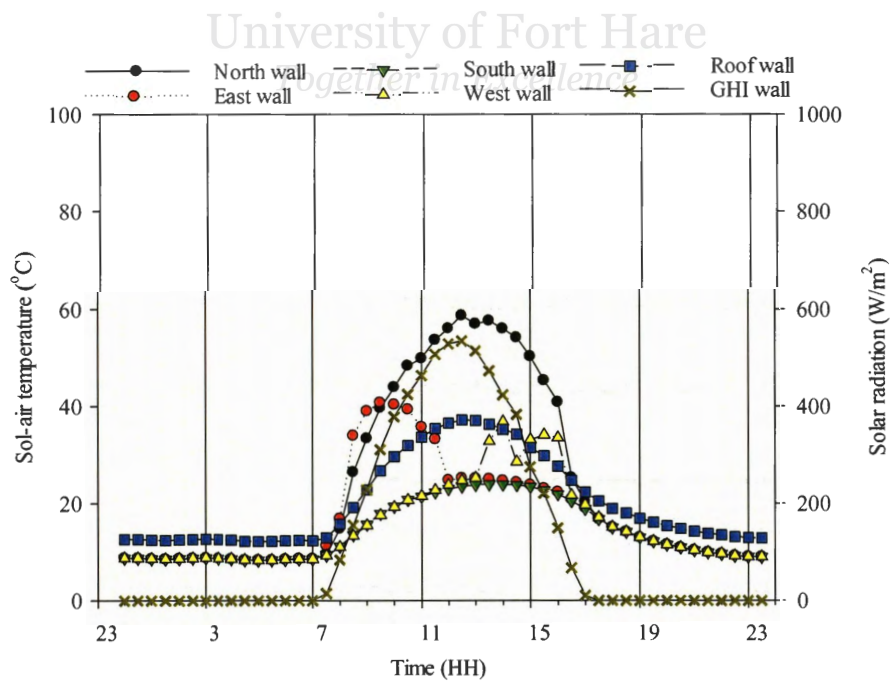


Figure 6.2: Opaque components sol-air temperature on a typical winter day

The roof sol-air temperature was relatively smaller with respect to the perimeter walls as shown in Figures 6.1 and 6.2. In practice, the roof is assumed as a horizontal surface.

As such, it only receives longwave radiation from the sky, while vertical or tilted surfaces (perimeter walls) receive a combination of longwave and shortwave radiation. The combined radiation received on a vertical surface, resulting in the high sol-air temperature at the perimeter walls. Moreover, the intensity of solar radiation at the respective parameter wall determines the resultant sol-air temperature. In both Figures, the peak sol-air temperature at the east and north walls were found to be greater than that of the roof. Comparing Figures 6.1 and 6.2 to Figures 4.3 and 4.2, the sol-air temperature at the perimeter walls correspond with their respective solar radiation. Both parameters were observed to follow the same trend and peaks at the same time. However, during the absence of the sun; the sol-air temperature at the perimeter walls was found to be approximately equal.

6.2.1 Walls

As mentioned earlier, heat transfer in building walls is a sum of steady- and unsteady state heat transfer. Whereby, steady-state heat transfer ignores thermal storage of the walls material. Unsteady-state on the other hand, take into consideration the thermal capacity of the wall. The steady- and unsteady-state heat transfer of the perimeter walls were computed from Equations 2.4 and 2.5 combined with Table 4-4. The summer and winter average daily profile of the steady- and unsteady-state heat transfer of the perimeter walls are shown in Figures 6.3 and 6.4, respectively.

In both figures, unsteady-state heat transfer curves represent the actual heat transfer through the perimeter walls. The regions above and below the red line were assumed to be heat gain and loss. As such, the south wall had the maximum heat loss in both seasons. A daily average heat loss of 161.95 W was observed in the summer season and 147.14 W in the winter. In terms of heat gain, the north wall was found to be the most active. The daily average heat gain was 153.43 and 201.60 W during the summer and winter seasons, respectively.

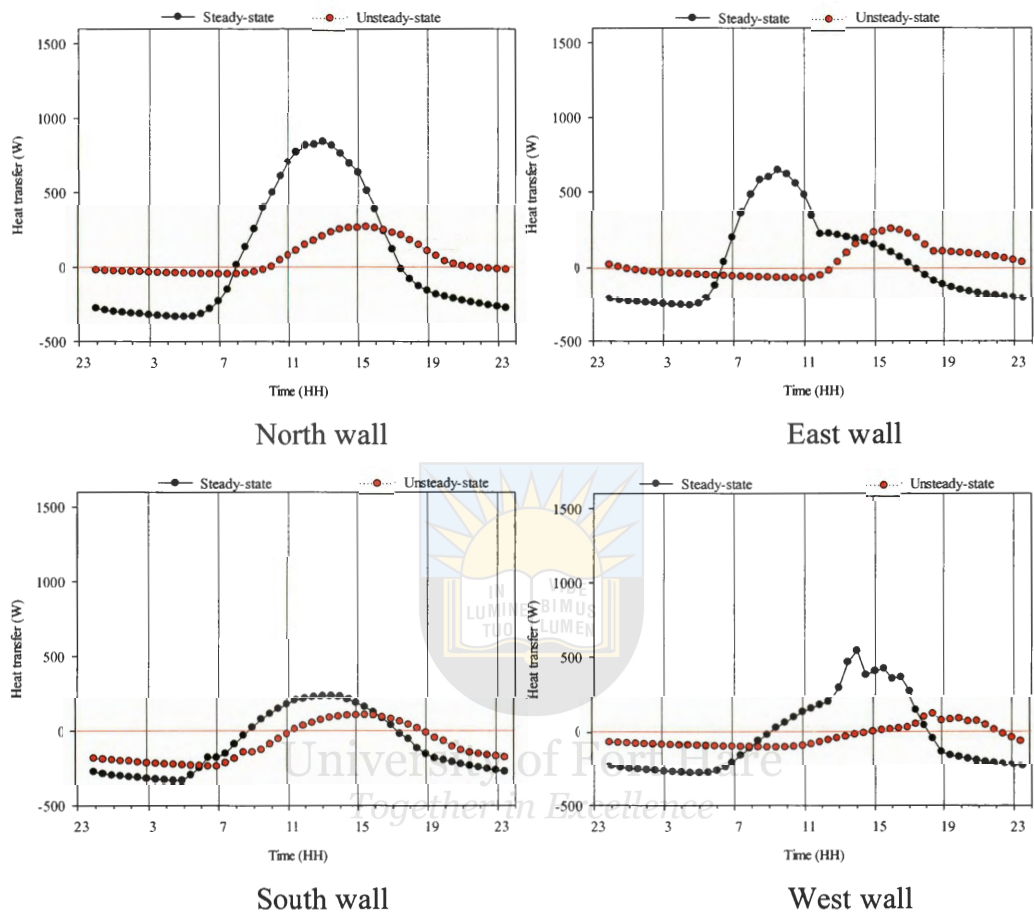


Figure 6.3: Typical summer day steady and unsteady state heat transfer

Furthermore, a varying peak time was observed in both curves. This was initiated by the time lag and decrement factor of the perimeter walls given in Table 4-4. As such, the heat transfer time lag in Figures 6.3 and 6.4 correspond with the temperature and time lag given in chapter four. It can be said that steady-state heat transfer results in overestimated values. Going forward, the heat transfer of the perimeter walls will only consider the unsteady-state.

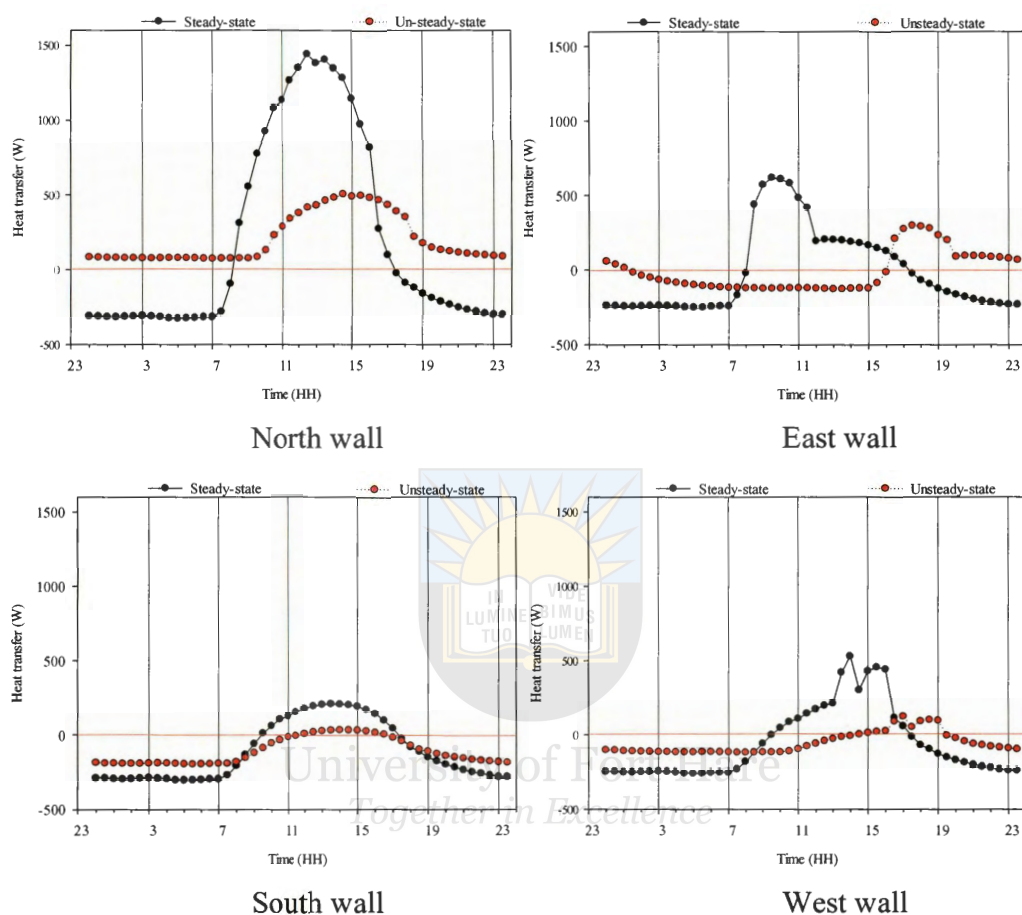


Figure 6.4: Typical winter day steady and unsteady state heat transfer

Besides the observed heat transfer estimation difference between the steady- and unsteady state, Figures 6.3 and 6.4 depict the thermophysical properties of the perimeter walls. This was indicated by the time lag observed between both states of heat transfer. However, the actual heat reduction of the walls cannot be obtained from Figures 6.3 and 6.4. Given that un-steady state is a mere hypothetical heat transfer that ignores the thermal capacity of the wall. Therefore, to further evaluate the thermal properties of the perimeter walls, a comparative analysis of the inner and outer surface of the walls were performed.

The area of the unsteady-state curve below and above the red line in Figures 6.3 and 6.4, represents the heat energy loss and gain, respectively on the inner surface. The

resultant solar irradiation of the perimeter walls serves as the heat energy on the outer surface. Since solar irradiation is zero (see chapter 4) during the absence of the sun, heat energy gained through the walls were only considered. This is also referred to as solar heat gain. Thus, the solar heat energy gain of the perimeter wall on an average summer day is given in Figure 6.5 and average winter day in Figure 6.6.

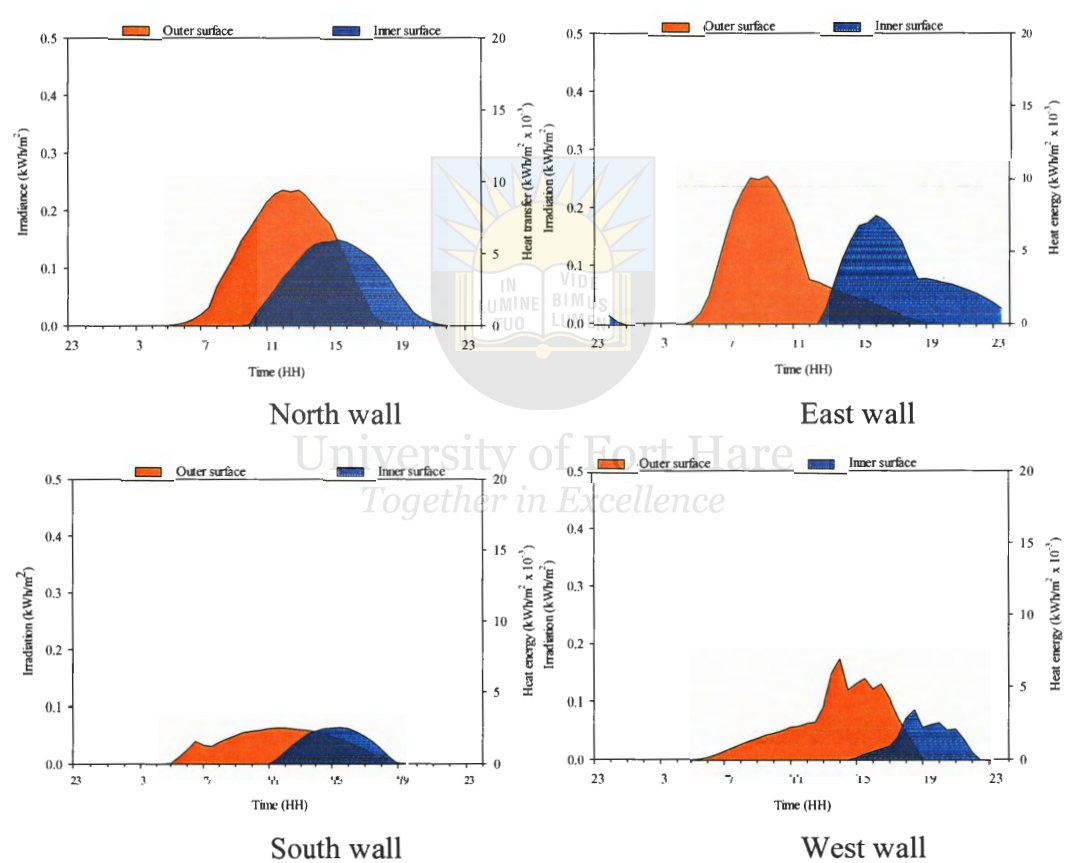


Figure 6.5: Perimeter walls solar heat energy gain on an average summer day

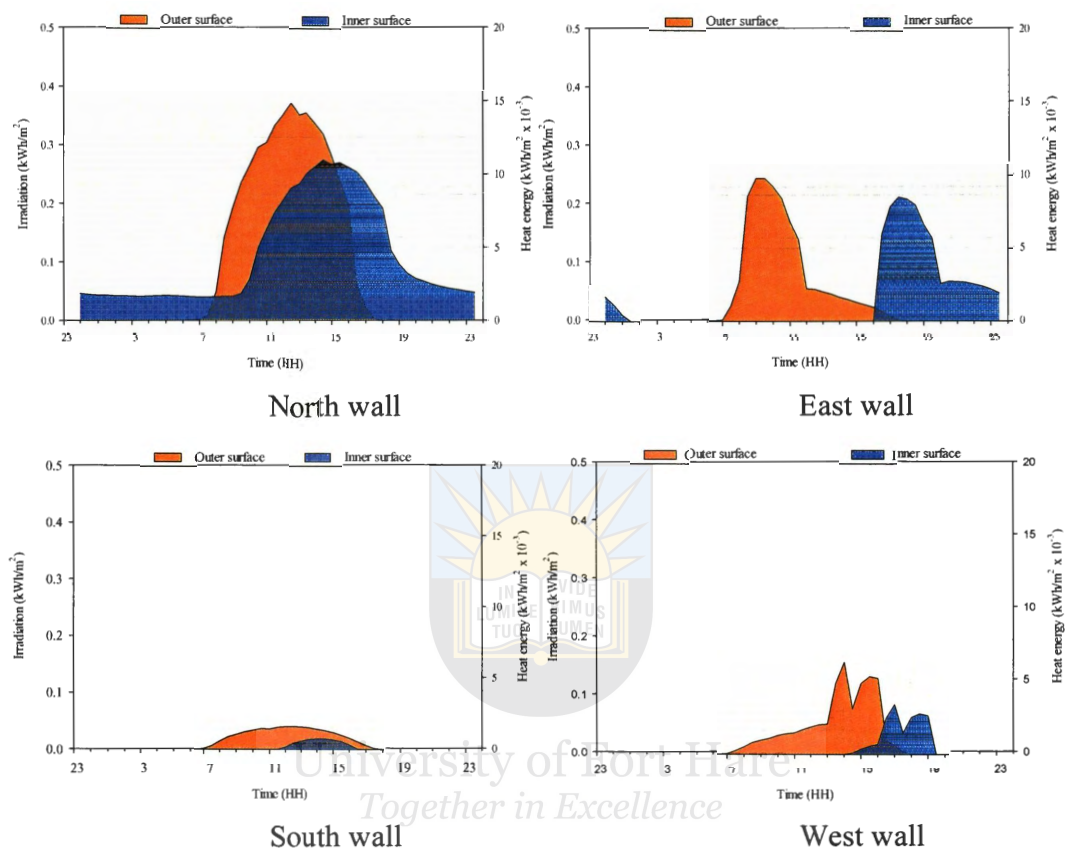


Figure 6.6: Perimeter walls solar heat energy gain on an average winter day

The inner and outer surface peak energy time lag corresponds with Table 4-4. However, the heat energy generated on the inner surface of the perimeter wall was found to be insignificant with respect to their individual irradiation. From Figure 6.5, the north and south walls had the maximum and minimum daily cumulative irradiation of 3.23 and 1.15 kWh/m^2 , respectively. Although, approximately only 2% of the resultant heat energy was transmitted to the inner surface of both walls. Similarly, the north and south walls had the maximum and minimum solar irradiation during the winter season. However, 4% of the 4.71 kW/m^2 irradiation of the north wall was transmitted to the inner surface. Whereas, only 1% of the 0.55 kWh/m^2 was transmitted on the south wall. Findings regarding the other walls are given in Table 6-1

Table 6-1: Perimeter walls seasonal solar heat gain

Wall	Summer season			Winter season		
	Outer surface (kWh/m ²)	Inner surface (kWh/m ²)	Percentage reduction. (%)	Outer (kWh/m ²)	Inner (kWh/m ²)	Percentage reduction. (%)
North	3.23	0.08	98	4.71	0.21	96
East	2.83	0.09	97	1.95	0.07	96
South	1.15	0.03	97	0.55	0.01	99
West	1.85	0.02	99	1.16	0.02	99

The relatively high heat reduction indicated in Table 6-1, is a positive attribute of the perimeter walls. As mentioned in chapter three, one of the energy efficiency features of the passive solar house is its superstructural walls. The walls were specifically designed to minimize heat transfer between the inner and outer space. Another passive solar attribute of the house observed from Table 6-1, is the comparatively north wall high irradiation during the winter season. This is due to the shading of the high angle Sun rays in the summer season, as a mechanism to avoid overheating. Whereas, the winter low angle Sun rays are utilized for indoor space heating. It must be highlighted that the high percentage reduction observed in the south and west walls do not equate to the optimum thermal performance of both walls. As indicated in Figures 4.3 and 4.4 both wall receives the least amount of solar radiation daily. Therefore, thermal equilibrium between the inner and outer surface results in minimal heat transfer.

6.2.2 Roof

Recalling from chapter three, in order to utilize the clerestory window two sets of ceiling design was adopted in the house. The conventional crawlspace ceiling design is occupying the northern floor area, and a major part of the southern floor area was covered by the skillion ceiling design. Figure 6.7 contains various views of the house with the majority of the building envelope hidden, indicating the house ceiling structure.

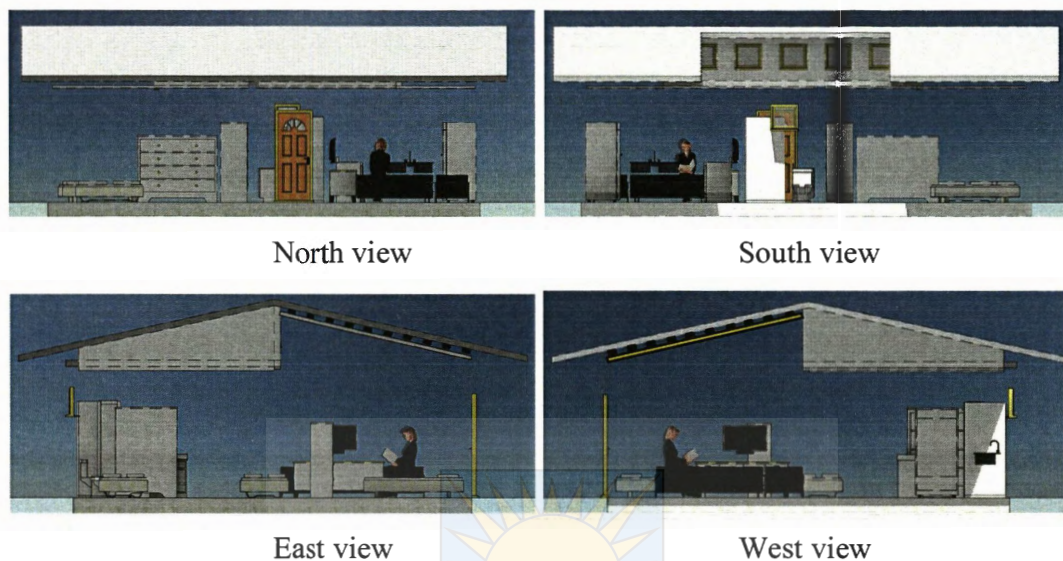


Figure 6.7: Passive solar house indoor rendering indicating roof structure

The skillion ceiling covers the entire floor area of the living room and south facing bedroom as shown in Figure 6.7. The floor area covered by the skillion ceiling was 5.5 m^2 in the south-facing bedroom and 17.1 m^2 in the living room. At the southern floor area, approximately 54% and 53% of the kitchen and north facing bedroom floor area, respectively were covered by crawlspace ceiling. The estimated volume of the kitchen crawlspace was 4.3 m^3 and 3.9 m^3 for the north facing bedroom. It must be said, during the monitoring period, no mechanical or natural ventilation system was installed in the crawlspace.

Besides the multiple ceiling designs, the roof heat transfer was analyzed with regard to the indoor and crawlspace air temperature difference. Therefore, the heat transfer analysis focus on the ceiling materials only. Given that the space in the skillion designed ceiling assumed the space of the combined 230 mm thick purlin, rafter and branding used in the roof construction. The sol-air temperature at the roof surface was assumed as the air temperature in the skillion ceiling. Whereas, the inner surface temperature of the roof was assumed as the crawlspace air temperature. Ignoring vertical air temperature variation between the roof and ceiling, since the maximum

distance was 910 mm. The thermal resistive elements in both ceiling design are given in Table 6.2.

Table 6-2: R-value of the house ceiling

Design	Ceiling material	Thickness (mm)	Thermal resistive element	R-value (m ² K/W)
Skillion	Pinewood	12	Indoor air film	0.61
			Wood siding	0.14
			Crawlspace air film	0.92
Crawlspace	Plasterboard	9	Indoor air film	0.61
			Plasterboard	0.06
			Crawlspace air film	0.92

From Table 6.2, the U-value of the ceiling in summer and winter seasons was found to be 0.63 W/m²K. Based on the obtained surface area and the U-value of the ceiling, Equation 2.8 was used to compute the ceiling heat transfer. Figures 6.8 and 6.9 shows the heat transfer through both ceiling designs in summer and winter seasons, respectively.

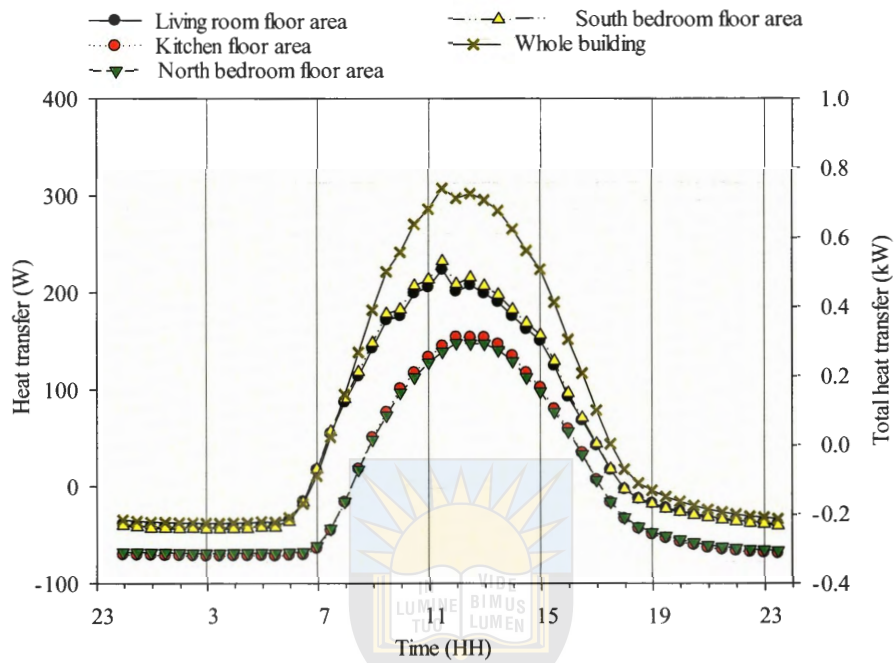


Figure 6.8 Average summer daily roof heat transfer

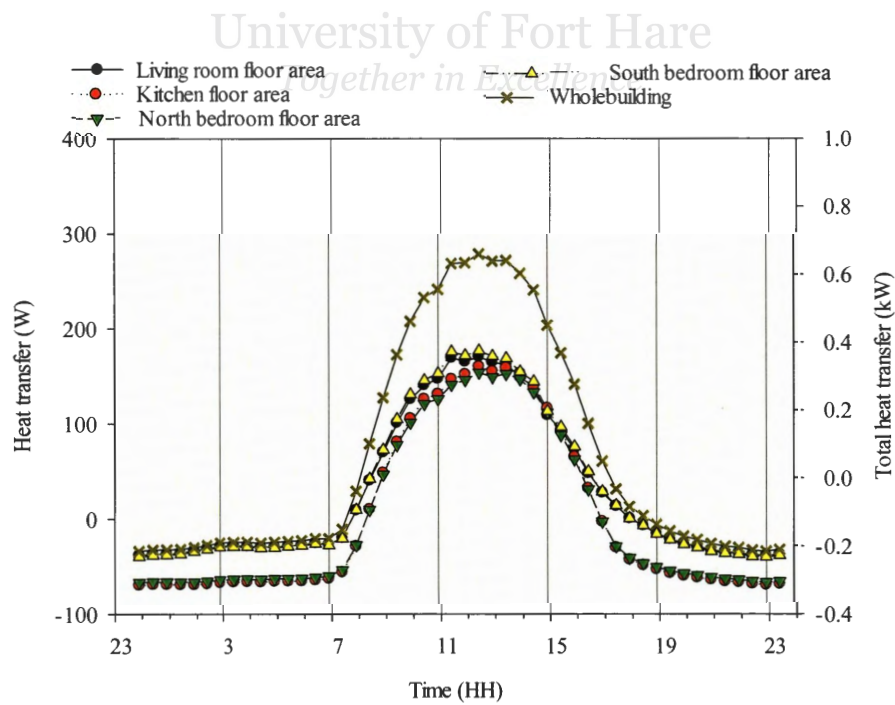


Figure 6.9: Average winter daily roof heat transfer

As shown in Figures 6.8 and 6.9, the skillion designed ceiling had the minimum heat loss in both seasons. The average daily heat loss was 66.98 W during the summer season and 61.39 W in the winter season. These were however 44% and 48% lesser than the heat loss through the crawlspace ceiling design, respectively. In terms of heat gain, the crawlspace ceiling design had the maximum during the winter season, with an average daily heat gain was 215.37 W. The skillion roof design had a relatively higher heat gain of 281.22 W in the summer season. The Whole building average daily heat loss in the summer season was 0.19, and 0.45 kW gained. In the winter season, the daily average heat loss and gain were 0.18 and 0.44 kW, respectively.

Due to the space difference between both ceiling designs, the crawlspace tends to contain more volume of air than the skillion ceiling. As such, the crawlspace serves as a buffer. Depending on the ambient and indoor air temperature with respect to the crawlspace air temperature, the heat in the crawlspace is absorbed from either environment. While the skillion roof transfer heat between the inner and ambient space of the house with minimal storage. The above phenomena are further illustrated by the generated heat energy of the ceilings. The daily cumulative heat energy of the ceiling designs in both seasons are given in Figure 6.10.

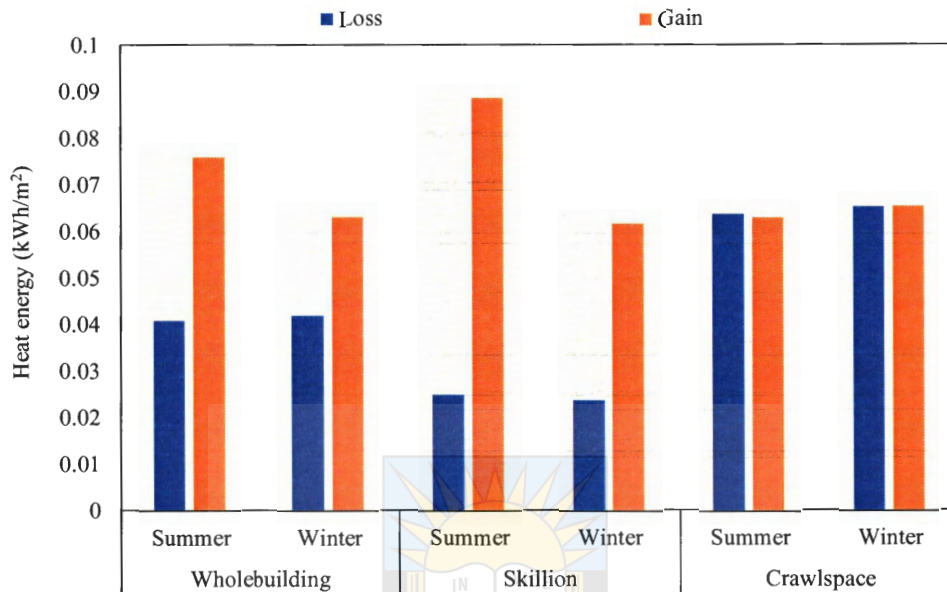


Figure 6.10: Seasonal daily heat energy chart of the house roof

In the summer season, the daily cumulative heat energy loss through the crawlspace ceiling was 60% greater than that of the skillion ceiling. The daily cumulative heat energy gained through the crawlspace ceiling was 29% lesser in the same season. The crawlspace ceiling was dominant during the winter season. Heat energy gain and loss through the crawlspace ceiling were 6% and 64% greater than that of skillion ceiling, respectively.

Furthermore, the thermal resistance of the roof assembly was also analyzed. The analysis was based on the amount of global horizontal irradiation obtained at the roof level and heat energy (solar heat gain) gain through both ceiling designs. Hence, Figures 6.11 and 6.12 shows the seasonal daily solar irradiation and whole building ceiling heat energy gained.

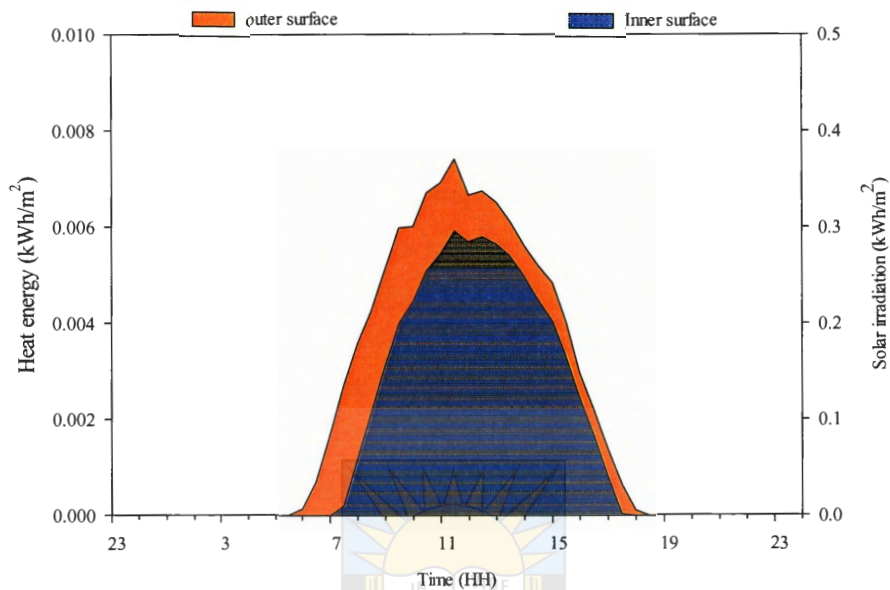


Figure 6.11: Roof solar heat gain and irradiation on a typical summer day

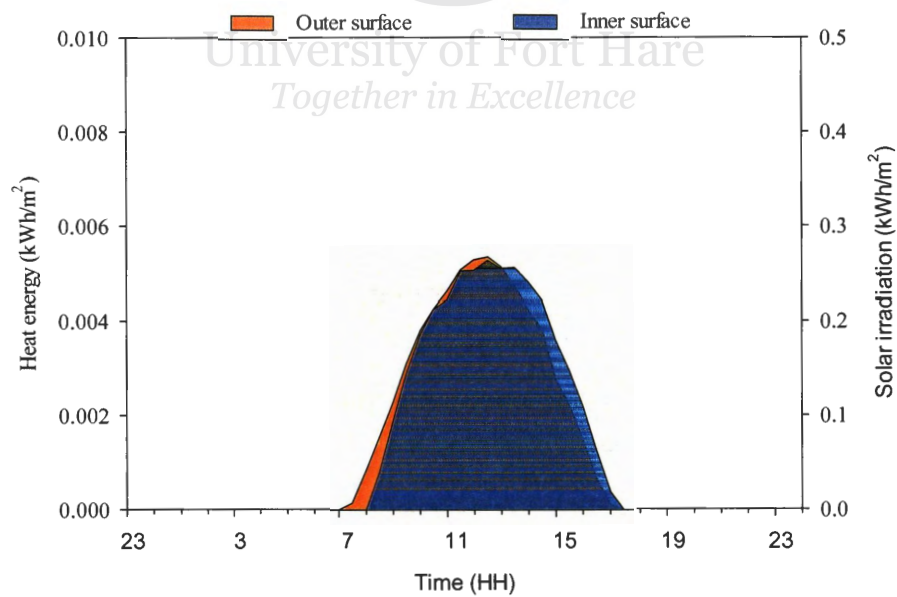


Figure 6.12: Roof solar heat gain and irradiation on a typical winter day

The average irradiation at the roof level was 0.19 kWh/m^2 in the summer season and 0.14 kWh/m^2 during the winter season, as seen in Figures 6.11 and 6.12. These result in daily cumulative irradiation of 5.22 and 3.08 kWh/m^2 , respectively. The resultant

daily cumulative heat energy gain through the whole building ceiling was 0.08 kWh/m² in the summer and 0.06 kWh/m² in the winter season. In other words, only 1% of the summer irradiation was transmitted into the inner space of the house and 2% in the winter season.

6.3 Transparent component heat transfer

Transparent components are those components that allow the direct transmission of radiation in the form of heat or light. In building context, transparent components include; the area of the windows or walls covered with glass. They are often referred to as glazing. Based on the structural detail of the house given in chapter three, windows are the only transparent components in the house. Hence this section deals with the heat transfer through the windows of the house.

6.3.1 Windows

According to Szokolay, windows are the most important components in a passive solar house [Szokolay, 2008]. They are used to admit and distribute solar radiation in the house for space heating. Per se, the house used in the study had windows in all elevations, as shown in Figure 3.5. It includes the clerestory windows. Whereby, the north facing windows were design for optimum solar admittance, and the other windows were used for passive solar cooling. The windows orientation and arrangement are in line with passive solar design in the southern hemisphere [Klunne, 2002]. Wooden frame windows were adopted in the house to minimise conductive heat transfer. In terms of sizes, the windows can be classified into large and small windows. The 1.35 m² (0.80 m² excluding frame) surface area windows located on the perimeter walls are referred to as large windows. The small windows with a surface area of 0.36 m² (0.20 m² excluding frame) were used as the bathroom and clerestory windows.

Based on the house design, the direct gain passive solar strategy was adopted [National Renewable Energy Laboratory, 2001]. Whereby the north facing windows were the direct gain glass area. This strategy in cooperates the window (north facing) sizes and thermal mass of a house floor and walls to provide suitable passive heating. However, according to the Passive Solar Industries Council; to avoid overheating, visual glare and fabric fading; north facing windows should not exceed 12% of the floor area [Passive Solar Industries Council, 2009]. Hence the window to floor area proportion of the house in the research was determined. The findings are given in Tables 6.3 and 6.4.

In both Tables, the bathroom floor area was not taken into consideration. Given that the bathroom was not considered as a thermal condition space. In addition, the area of the glass does not include the frame. The north facing windows were found to be within the recommended floor area proportion of passive solar design, as shown in Table 6-3. Zone 3 with 6 small north facing windows had the maximum windows to floor area percentage with 7%. *Together in Excellence*

Table 6-3: Direct solar gain glass to floor area

Zone	Floor area (m ²)	Window size	Glass area (m ²)	Window to floor proportion (%)
1	31.09	1 large	1.4	5
		3 small		
2	19.49	1 large	0.8	4
3	16.39	6 small	1.2	7
Whole building	66.97	2 large	3.4	5
		9 small		

Table 6-4: Proportion of windows to floor area

Windows	Floor area (m ²)	Window size	Glass area (m ²)	Window to floor proportion (%)
North	50.58	2 large	1.6	3
East	31.09	1 large	0.8	3
South	47.48	2 large	1.6	3
West	35.88	2 large	1.6	4
Clerestory	47.48	9 small	1.8	4

As indicated in Figure 3.4, Zone 3 is the south facing bedroom. Thus, the relatively high proportion of windows to floor area is required to channel the sun rays to the southern floor area, providing an even solar distribution indoors. The north facing bedroom, on the other hand, had the least windows to floor percentage. Zone 1, as well as the whole building, were found to within the recommended percentage by 7%. In terms of the windows at the various elevations of the house, the clerestory window was among the highest windows to floor area proportion. While the north, east and south elevations had 3% window to floor area proportion each.

The above findings, however, do not indicate the heat transfer of the windows. Heat transfer through the windows was addressed in the form of conduction and radiation. Conductive heat transfer occurs through a window in the present and absent of the sun. Whereas, radiative heat transfer transpires due to the presence of the sun. Therefore, heat transfer through the house windows was computed by combining Equations 2.2 and 2.17. Since global irradiance at the four elevations of the house was measured, Solar Heat Gain Factor (SHGF) in Equation 2.17 was replaced with Solar Heat Gain Coefficient (SHGC) and global irradiance. The relationship between all three parameters was given in Equation 2.18. The daily seasonal heat transfer through the windows at the four elevations of the house are shown in Figures 6.13 and 6.14.

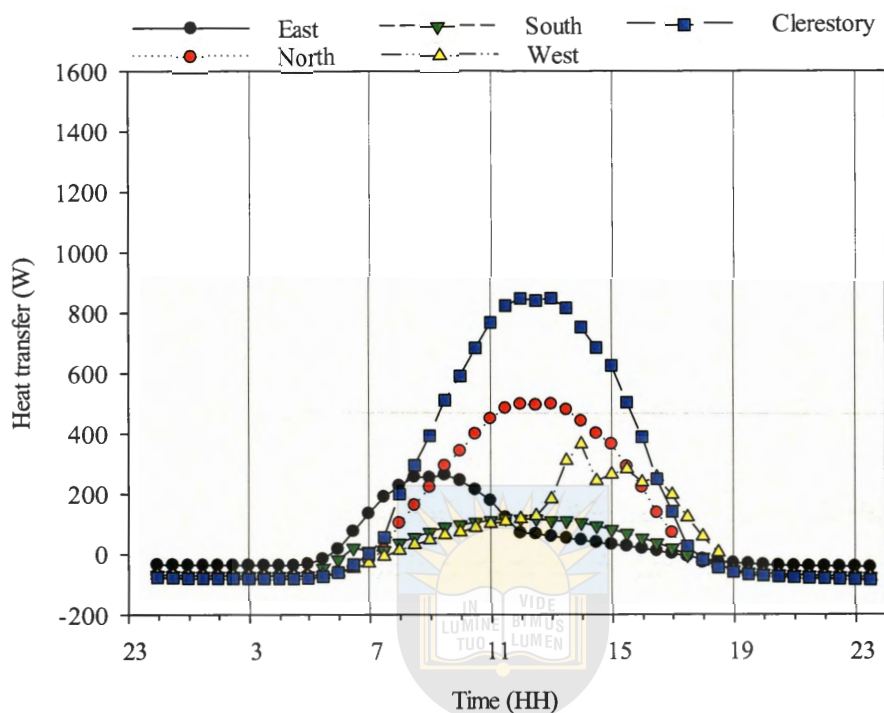


Figure 6.13: Windows heat transfer on a typical summer day

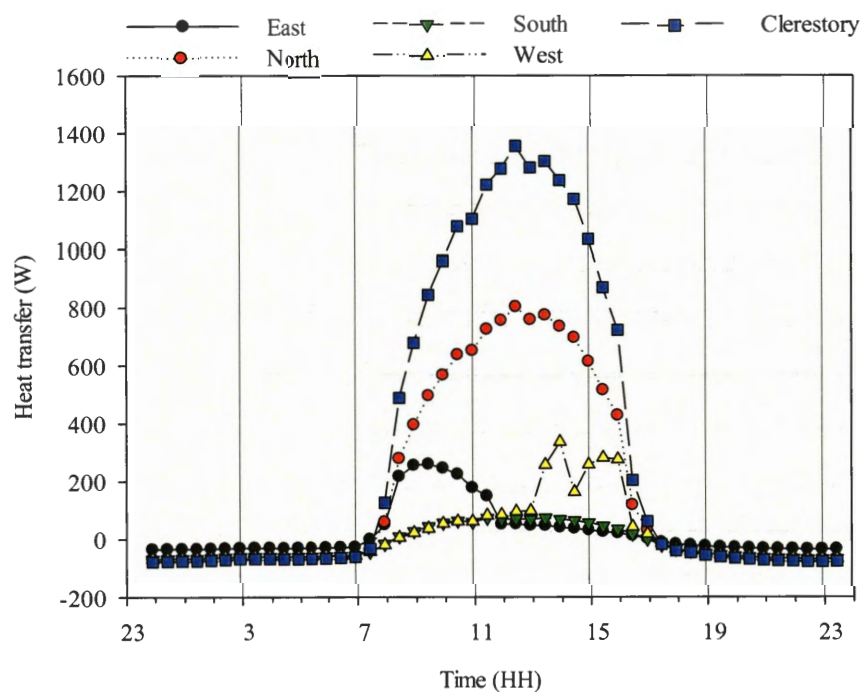


Figure 6.14: Windows heat transfer on a typical winter day

The following assumptions were made to obtain the profile given in Figures 6.13 and 6.14. The SHGC and U-value of a timber frame window are 0.77 and 5.6 W/m² K, respectively [South African Bureau of Standards, 2011]. In all windows excluding the clerestory windows, semi-open weave and medium colour single drape were used. Hence, the Shading Coefficient (SC) of the windows is 0.51. On the other hand, no drapes were used in the clerestory windows, resulting in a SC of 0.95 [Robert, 2001]. The area of the frame and thermal lag factor of the windows were ignored. In term of operation, all windows were closed at all time.

In both Figures, the north facing windows had the maximum heat gain. This includes the clerestory and north perimeter windows. Heat gain through the clerestory windows was found to be maximum with 759 W at 14h00 and 1356.50 W at 12h30, in summer and winter season, respectively. The daily average heat gain through the same windows was 507.72 W in the summer season and 896.51 W in the winter season. The north perimeter windows heat transfer follow the same trend but 79% and 41% lesser in summer and winter, respectively. The least heat gain was obtained at the south perimeter windows. Their daily average heat gain was 76.29 W in summer and 50.85 W in winter. Heat transfer through the south windows was 85% lesser than that of the clerestory windows in summer and 94% lesser in the winter season. The clerestory windows also had the maximum heat loss. The daily average heat loss difference between the clerestory windows and the other perimeter windows were 15.62 and 14.42 W in summer and winter seasons, respectively.

Furthermore, the daily cumulative heat energy through the windows in summer and winter season are given in Figure 6.15.

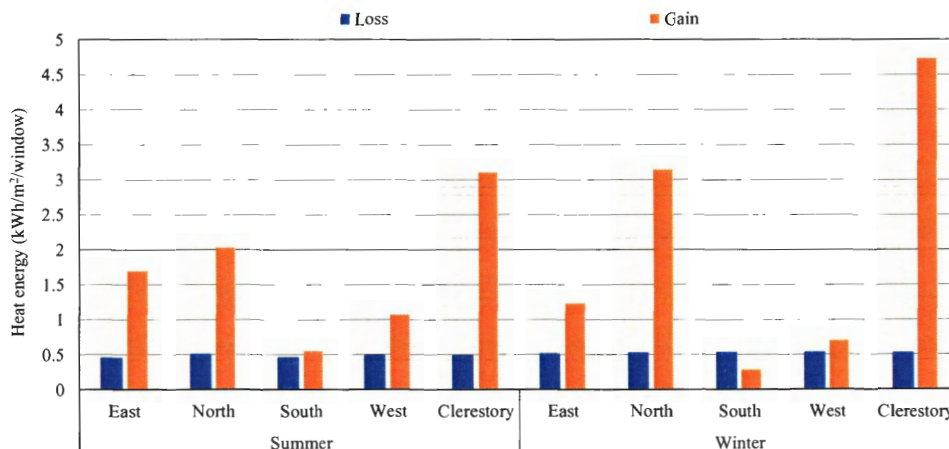


Figure 6.15: Seasonal daily windows cumulative heat energy

The clerestory windows generate 3.10 kWh/m²/window in the summer season and 4.73 kWh/m²/window in winter. This result in 9.30 and 18.6 kWh/m² daily cumulative heat energy generated in the living room and south facing bedroom in the summer season. As well as, 14.19 kWh/m² in the living room and 28.38 kWh/m² in the south facing bedroom during the winter season. Once again, the south perimeter windows were the most underperforming. The daily cumulative heat energy gain through the south windows were 82% and 94% lesser than that of the clerestory windows in summer and winter, respectively. An average daily cumulative heat energy loss of 0.48 kWh/m²/window was obtained in all windows in the summer season. Also in winter, 0.52 kWh/m²/window was obtained. Besides, the east perimeter windows had the maximum heat energy loss with 0.45 kWh/m²/window in summer and 0.51 kWh/m²/window in winter.

The clerestory windows show significant heat contribution to the inner space of the house. It clearly indicates that the clerestory windows were able to offset the underperforming south perimeter windows from the finding. Also, irrespective of size (glass surface area), the clerestory windows outperformed the other windows in both seasons in terms of heat gain. It can be said that the performance of the windows is a factor of the orientation of the house rather than the surface area of the windows (glass).

Additionally, the solar heat gain through the windows was examined. The summer and winter daily average irradiation solar on the outer surface of the house windows and the resultant heat energy gain are given in Figures 6.16 and 6.17, respectively.

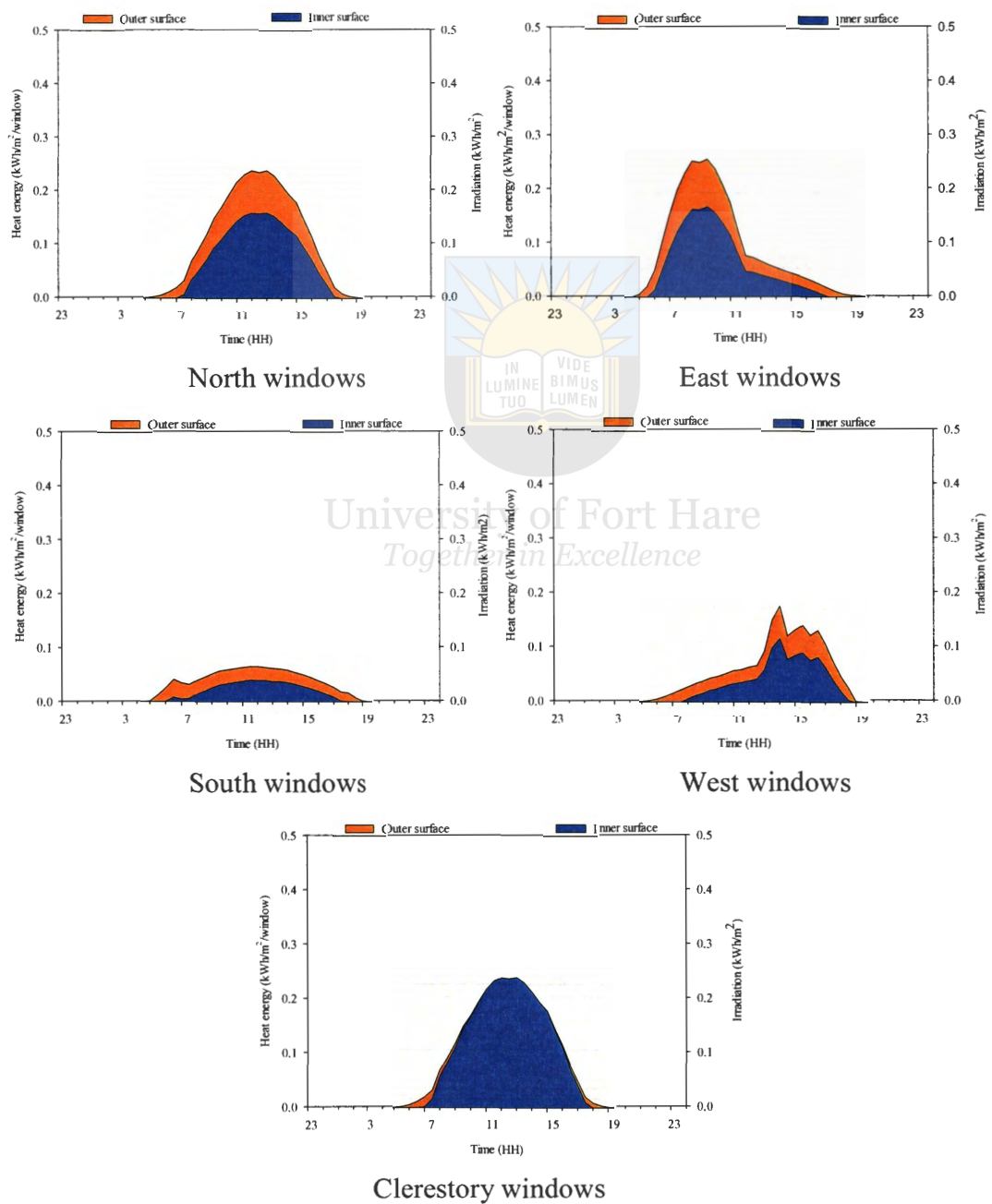


Figure 6.16: Daily summer solar heat gain of the house windows

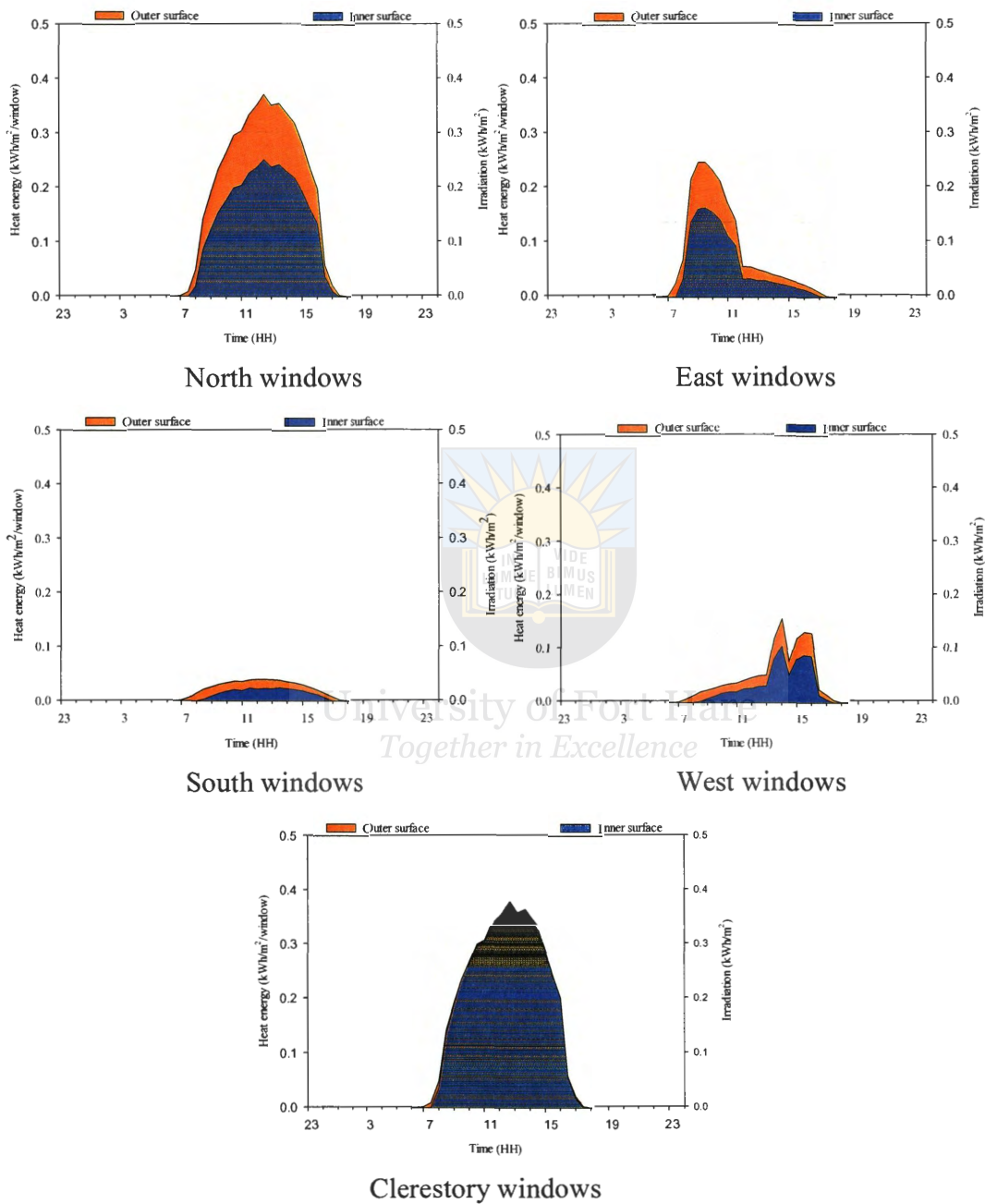


Figure 6.17: Daily winter solar heat gain of the house windows

Compared with other components of the building envelope, significant heat energy was transmitted through the windows. From Figure 6.16, the south perimeter windows had the minimum heat energy transmission. It was found that 48 %/window of solar irradiation was transmitted through the south perimeter windows. The clerestory

windows, on the other hand, had the maximum heat energy transmission with 96 %/window, similar behavior was observed in Figure 6.17. The south perimeter and clerestory windows heat energy transmission with respect to their solar irradiation were 52 %/window and 101 %/window, respectively. Detailed findings of the solar irradiation of the house windows and the resultant heat energy transmission are given in Table 6-5.

Table 6-5: The seasonal proportion of solar irradiation transmitted through the windows

Windows	Summer		Winter	
	Solar irradiation (kWh/m ²)	Transmitted heat energy (%/window)	Solar irradiation (kWh/m ²)	Transmitted heat energy (%/window)
North	3.23	63	4.71	67
East	2.83	60	1.95	63
South	1.15	48	0.55	52
West	1.85	57	1.16	61
Clerestory	3.23	96	4.71	101

As stated earlier, the heat energy transmitted through the windows (glass area) is due to simultaneous conductive and radiative heat transfer. Although, the above comparative analysis only took into consideration the radiative energy generated on the outer surface of the window. Hence, during the winter season, more than 100% of heat energy was transmitted through the clerestory windows. It should, therefore, be said that the transmitted heat energy through the windows includes conductive and radiative.

6.4 Overall thermal load (daily heat energy) analysis of the house

The heat transferred (internal heat gain) due to appliances and lightings usage in the house was presented and analyzed in chapter 5. The chapter also covers the resultant sensible air heat due to typical occupants operation of the ventilation components, such

as closing and opening of the doors and windows. Furthermore, the building envelope heat transfer was the main focus in chapter 6, whereby heat transferred through the perimeter walls, roof and windows were computed and discussed. This section focus on the consolidated impact of the daily heat energy from the abovementioned mode of heat transfer in the house.

A combined daily cumulative heat energy of all form of heat transfer in the house was performed in order to show the overall thermal load of the house. However, two sets of combined daily cumulative energy for heat gain and another loss through the perimeter walls and windows were computed. A whole building roof daily cumulative heat energy gain and loss were deduced and used for all zones in the house. As shown in Chapter 5, internal heat gains considered in the study were heat released from appliances (stove and refrigerator) in zone 1 (living room/ kitchen) and electric lamp in the various zones of the house. The sensible air heat transfer due to air exchange between the inner and ambient environment resulted in a daily cumulative heat energy loss in each zone since a higher indoor air temperature was observed during the ventilation testing period. The overall heating and cooling loads of the various zones in the house is given in Figure 6.18.

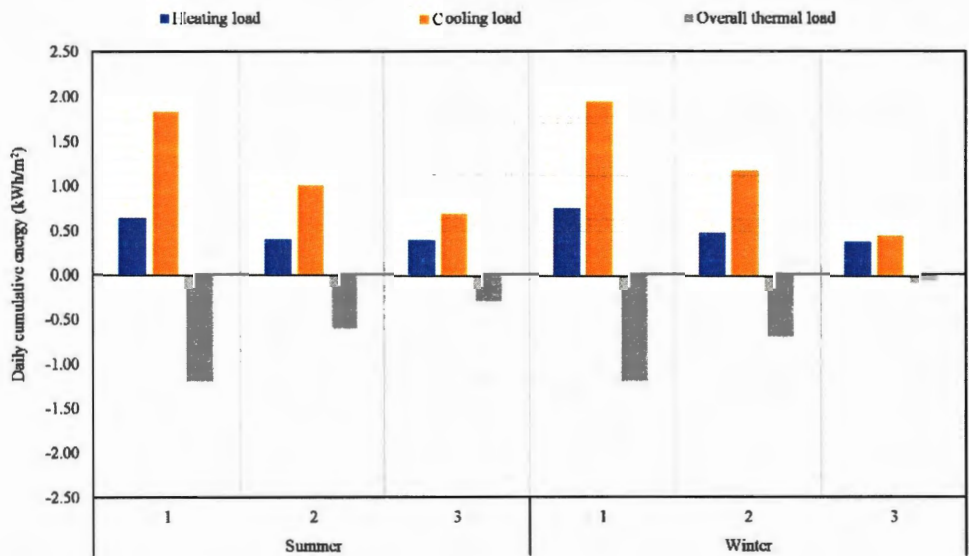


Figure 6.18: An overall thermal load of the house

In Figure 6.18, the daily cumulative heat energy loss serves as the heating load, while the cooling load is the daily cumulative heat energy. The overall thermal load of the house is the difference between the heating and cooling loads. Therefore, a negative thermal load as obtained above implies all zones in the house were not thermally balanced in both seasons, and cooling energy is required indoors to achieve thermal comfort. Zone 1 tend to require the most cooling energy in summer with an excess cooling load of 1.19 kWh/m², while zone 3 during the winter season was the most thermally balanced with 0.07 kWh/m². The excess cooling load in zone 2 were 0.60 and 0.70 kWh/m² in summer and winter, respectively.

From Figure 6.18, a further breakdown of the heating and cooling load of the house was conducted to analyse the impact of the overall thermal load on the indoor thermal condition. Figure 6.19 presents the percentage impact of the heat transfer components in the various zones of the house.

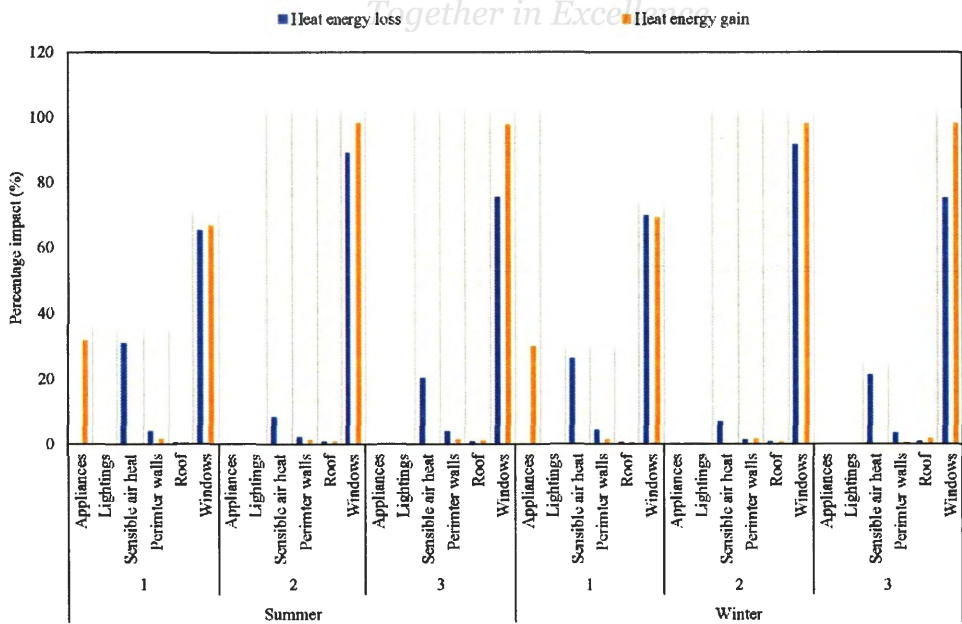


Figure 6.19: Heat transfer components percentage impact in the various zone of the house

In summer, the windows were found to generate the highest heat energy gained with 66.6% in zone 1, 98.0% in zone 2 and 97.6% in zone 3. In zone 1, internal heat generated by appliance was the second highest with 31.6%, whereas lighting heat contributions with 0.1% in all zones in the house can be considered insignificant. Also from Figure 6.19, it was observed that the windows are responsible for the highest heat energy lost, accounting for 65.5%, 89.0%, and 45.4% in zones 1, 2, and 3, respectively. Sensible air heat transfer follows the windows in terms of heat losses with 30.5% in zone 1, 8.2% in zone 2 and 20.0% in zone 3.

The winter heat gain and loss distribution tend to follow a similar pattern, with the windows responsible for approximately 70.0% of heat energy lost and gained in zone 1. In zones 2 and 3, approximately 97.9% heat gain are to the heat transfer through the windows, while the windows are also responsible for 91.55 heat loss in zone 2 and 75.1% in zone 3. Appliances heat contribution in zone 1 was reduced by 2.1%, and lighting heat contribution was also insignificant with 0.1% heat gain. Besides the windows, sensible air heat has the highest source of energy lost, responsible for 25%, 6.8%, and 21.0% heat losses in zones 1, 2, and 3, respectively

It can, therefore, be said that the windows are the main cause of the excessive cooling load in both seasons as shown in Figure 6.18. Moreover, solar heat gain through the windows occurs between 05h00 and 19h30 in summer and 06h00 and 18h30 in winter. Also, the appliances heat gain was simulated with the stove (67.0% of appliances heat) on from 6h00 to 7h00, 11h00 to 13h00, and 16h00 to 18h00, while the refrigerator (33% of appliances heat) was on throughout the day. Hence, overheating due to excess cooling load could be experienced in the house (zone 1) in the summer season during the day (presence of the sun) and while the stove is used. It is evident in Figure 6.18 that opening of the windows was not sufficient in the complete removal of the heat generated by the appliances and windows in zone 1.

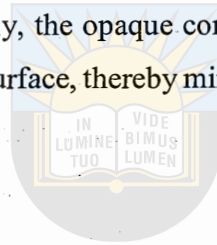
6.5 Summary

The components of the building envelope were analyzed in the form of opaque and transparent components. Opaque components further comprise the walls and roof. The south wall was found to have the maximum heat loss with a daily average of 161.95 W in the summer season and 147.14 W in the winter season. On the other hand, the north wall was found to have the maximum heat gain of 153.43 W and 201.60 W in summer and winter seasons, respectively. In both seasons, the solar irradiation on the perimeter walls was reduced by more than 95%. Based on the roof design, the house ceiling was classified into crawlspace and skillion ceiling design. Whereby, the skillion ceiling covers the southern floor area, and the crawlspace ceiling dominates the northern floor area. In both seasons, heat loss through the crawlspace ceiling was approximately 54% higher than that of the skillion ceiling. However, the average whole building daily heat loss and gain through the ceiling were 0.19 and 0.45 kW, respectively in the summer season. In the winter season, the daily average heat loss was 0.18 kW and a gain of 0.44 kW.

The windows were the only components considered under transparent components. The proportion of the house windows to floor area were found to be within the recommended proportion of 12%. Within this proportion, overheating and other consequences associated with excessive solar radiation will be avoided. The west elevation and clerestory windows had the maximum area of window per floor area with 4% each. The north facing windows which include the north perimeter and clerestory windows had the maximum heat gain in both seasons. The average daily heat gain of both windows was 408.16 W in summer and 712.82 W in the winter season. The south windows with the least heat gain had 76.19 W and 50.85 W in summer and winter seasons, respectively. Heat loss among the north, south, west and clerestory windows were found to be relatively equal. In summer, their daily average heat loss ranges from 59.58 to 67.43 W. whereby, the south windows had the least heat loss and the clerestory windows were maximum. A daily average heat loss of 57.65 to

64.33 W was obtained through the windows during the winter season. Although in the winter season, the west and clerestory windows had the minimum and maximum heat loss, respectively. Also, the east windows had a daily average of 28.74 W in summer and 29.13 W in winter.

Furthermore, solar heat gain through the windows was found to be relatively higher than other components of the building envelope. However, the clerestory windows admit 96% and 101% of summer and winter heat energy on its outer surface. As such, the clerestory windows can be said to be the most significant component for heating in the passive solar house. Conversely, the opaque components show minimum heat transfer between the inner and outer surface, thereby minimizing heat loss in the house.



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References

- Bekkouche, S. M. A., Benouaz, T., Yaiche, M. R., Cherier, M. K., Hamdani, M., *et al.* (2011) 'Introduction to control of solar gain and internal temperatures by thermal insulation, proper orientation and eaves', *Energy and Buildings*. Elsevier B.V., 43(9), pp. 2414–2421. doi: 10.1016/j.enbuild.2011.05.018.
- Kaşka, Ö., Yumrutaş, R. and Orhan, A. (2008) 'Theoretical and experimental investigation of total equivalent temperature difference (TETD) values for building walls and flat roofs in Turkey', *Energy Conversion and Management*, 50(11), pp. 2818–2825. doi: 10.1016/j.enconman.2009.06.027.
- Klunne, W. E. (2002) 'Energy efficient housing to benefit South African households', *Boiling point*, 48(48), pp. 27–29. Available at: https://practicalaction.org/our-work/docs/energy/docs48/bp48_pp27-29.pdf.
- National Renewable Energy Laboratory (2001) 'Passive Solar Design for the Home'. Merrifield: U.S. Department of Energy (DOE), pp. 1–8.
- Overen, O. K., Meyer, E. L. and Makaka, G. (2017) 'Perimeter Walls Solar Heat Gain, a Mechanism for Building Design', in *11 Built Environment Conference*. Durban: ASOCSA, pp. 680–691.
- Passive Solar Industries Council (2009) 'Passive Solar Design Strategies: Guidelines for Home Building'. Washington: Charles Eley Associates, pp. 1–96.
- Robert, A. P. (2001) 'Cooling Load Calculation', in *ASHRAE Handbook-Fundamentals*. SI. New York: ASHRAE, pp. 1–106.
- South African Bureau of Standards (2011) *SANS 204: Energy efficiency in buildings*. South Africa.
- Szokolay, S. V. (2008) *Introduction to architectural science: the basis of sustainable design*. Second, *Journal of the American College of Radiology: JACR*. Second. Edited by C. Brisbin. Oxford: Elsevier. doi: 10.1016/j.jacr.2010.08.020.

Chapter 7

RESIDENTIAL THERMAL LOAD EVALUATION TOOLKIT

7.1 Introduction

In the previous sections, the internal load and heat transfer of the building envelope components were analyzed. The internal load was based on the appliances and occupant operation of the house. Whereby, the components of the building envelope were analyzed with respect to the indoor and ambient air temperature. Internal load, on the other hand, represent the thermal load due to day to day running of the house. The thermal load due to thermophysical properties of the house structure was represented by the building envelope heat transfer. A consolidation of the individual internal load and heat transfer serves as an overall thermal load of the house. The obtainable values can be used as a thermal rating performance of the house.

This chapter deals with the design and development of residential thermal load prediction model. The model was based on the thermal energy balance of a house. In other words, the model put together all aspect of thermal load in a building into a single equation. Hence, the model is applicable to existing and non-existing residential buildings. The basic concept and assumption of the model were discussed. Thereafter, the heating and cooling load models of a typical residential building were given. Application and limitation of the models were also discussed.

7.2 Model structure

7.2.1 Definition of residential thermal load model

As stated earlier, thermal load is the rate at which heat must be added or removed from the inner space of a building in order to maintain a desirable air temperature. Figure 7.1 shows a graphical schematic of the thermal load of a house.

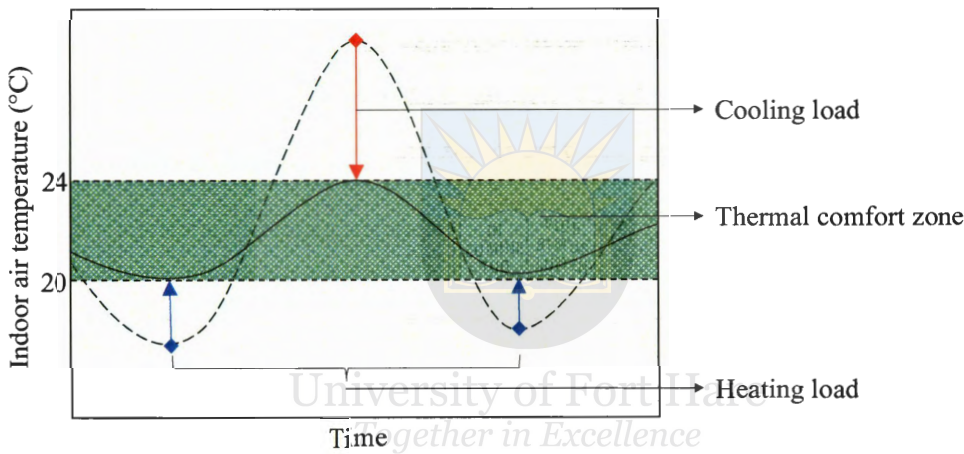


Figure 7.1: Graphical schematic of the thermal load of a house

From Figure 7.1, the rate at which heat is removed from the building to maintain the indoor air temperature within the thermal comfort zone is, therefore, the cooling load. Whereas, heating load deals with the adding of heat into the building. The thermal comfort zone is also referred to as indoor desirable or design air temperature. However, to cool the inner space to thermal comfort, heat must be removed at the same rate it is generated. Likewise, to maintain indoor thermal comfort via heating, heat must be added in the same rate it is lost.

Furthermore, from the basic thermal energy calculation, the amount of heat required to change air temperature by 1°C is given by;

$$q = mc_p (T_f - T_i) \quad (7.1)$$

where; m is the mass of air, c_p is specific heat capacity of air. The initial and final temperature of the air is represented by T_i and T_f . In the building context, m is expressed as, ρ ; the density of air and V ; the volume of the room occupied by air. T_i is the indoor air temperature measured at any instance, and T_f is the indoor design temperature or indoor thermal comfort air temperature. This temperature is often given in a range of 20 to 24°C. It is assumed that between these temperatures, the inner space of a house is thermally comfortable [South African Bureau of Standards, 2011]. If the air temperature is above 24°C or below 20°C, cooling or heating is required respectively to return the indoor air temperature to the thermal comfort zone. As such, Equation 7.1 can be rewritten as,

$$q_h = \rho V c_p (T_{\alpha_l} - T_{in-air})^+ \quad (7.2)$$

$$q_c = \rho V c_p (T_{in-air} - T_{\alpha_h})^+ \quad (7.3)$$

where q_h and q_c are the respective heating and cooling load required to maintain the indoor air temperature of a house within the thermal comfort zone. T_{α_l} and T_{α_h} represent the lower and upper limit of the thermal comfort zone. The + sign indicates that only positive values are accepted. Volume in Equations 7.2 and 7.3 refers to the occupiable airspace in the house. That is the volume of solid and regular shaped materials such as furniture and appliances (refrigerators) are not included.

7.2.2 Model assumptions

A constant whole building indoor air temperature was assumed to simplify the model structure. Hence, internal heat transfer between zones is insignificant. Also, heat transfer through the floor is negligible. This is practically viable in a house without a basement. The coefficient of heat transfer (*U-value*) of the respective building envelope components is constant. This implies that the influence of ambient weather

conditions such as wind speed was ignored. Furthermore, the air exchange rate through the ventilation component and infiltration are the only source of indoor air cooling and heating. In other words, no mechanical heating or cooling systems are used. Likewise, no humidification was applied to the indoor space. The influence of relative humidity was not taking into consideration.

7.3 Residential heating load model

Heating load often occurs at the extreme (peak-winter) weather conditions or at night and early hours of the morning. During these periods, the sun is usually absent so is the solar heat gain. Internal heat gain from occupants, appliances, and lighting are relatively insignificant. Indoor air temperature during heating load period is mainly influenced by infiltration and conductive heat loss. Therefore, the rate of heat lost indoors can be expressed as;

$$\rho V c_p T_{in-air} = Q_{cond} + Q_{s,air} \quad (7.4)$$

Q_{cond} and $Q_{s,air}$ are conductive, and infiltration heat transfer and are given in Equations 2.1 and 2.31, respectively. Combining Equations 2.1 and 2.31 into Equation 7.4 to give;

$$\rho V c_p T_{in-air} = \sum AU(T_{in} - T_o) + qh(T_{in} - T_o) \quad (7.5)$$

Substituting Equation 7.5 into 7.2;

$$q_h = \rho V c_p T_{a_h} - \left(\sum AU(T_{in} - T_o) + qh(T_{in} - T_o) \right) \quad (7.6)$$

$$q_{ht} = \rho V c_p T_{a_h} - \sum AU - qh(T_{in} - T_o) \quad (7.7)$$

In terms of the volumetric air flow rate, specific air flow rate in Equation 7.7 can be written as;

$$q_h = \rho V c_p T_{\alpha_h} - \sum AU - \rho N c_p (T_{in} - T_o) \tag{7.8}$$

$$q_h = \rho V c_p \left(T_{\alpha_h} - \frac{\sum AU}{\rho V C_p} - \frac{N}{V} (T_{in} - T_o) \right)^+ \tag{7.9}$$

where N is the volumetric air exchange rate. While $\frac{\sum AU}{\rho V C_p}$ represent the thermophysical properties and floor area of the house, T_o is the ambient air temperature. For existing houses, the instantaneous indoor air temperature (below the desired temperature) can be measured directly and inserted into Equation 7.9. For the non-existent house, the indoor air temperature (T_{in}) can be predicted based on the ambient weather perimeters. The parameters, therefore, include air temperature, relative humidity, wind speed, and direction. Given the assumption made in the build-up of the model, global horizontal irradiance was not included. Thus, only data during the absence of the Sun were considered. However, forward stepwise linear regression technique was employed to select the parameters that best predict the indoor air temperature. The selected parameters that best predict the summer and winter indoor air temperature, as well as their respective coefficient, are given in Table 7-1.

Table 7-1: Heating load indoor air temperature predictors and coefficient

Parameter	Summer season coefficient	Winter season coefficient
Forcing constant	8.32	8.96
Outdoor temperature	0.72	0.543
Outdoor relative humidity	0.040	0.035
Wind direction		-0.002

From Table 7.1, statistically, the wind speed was found not suitable to predict the heating load indoor air temperature. The P-value of wind speed in summer and winter season were 0.325 and 0.048, respectively. For the selected parameters, P-values were less than 0.001. The standard error of summer season indoor air temperature estimated

parameters was 1.57 and 1.56 for that of winter season parameters. Further validation of the model was performed and given in Figures 7.2 and 7.3.

As shown in Figures 7.2 and 7.3, selected summer and winter days representing clear, partly cloudy and cloudy sky days were used in the model validation. It must be said that data from the selected days were not included in the development of the model; specifically for validation purposes. Hence, 12, 13 and 14 November 2017 data were used as summer clear, cloudy and partly cloudy sky day indoor air temperature validation, respectively. While for winter indoor air temperature validation, 17th serve as cloudy sky day, 18th as partly cloudy sky day and clear sky day was 19th. Data from the above said days were obtained in August 2017. The shape of the solar irradiance distributions was used to classify the various sky formation.

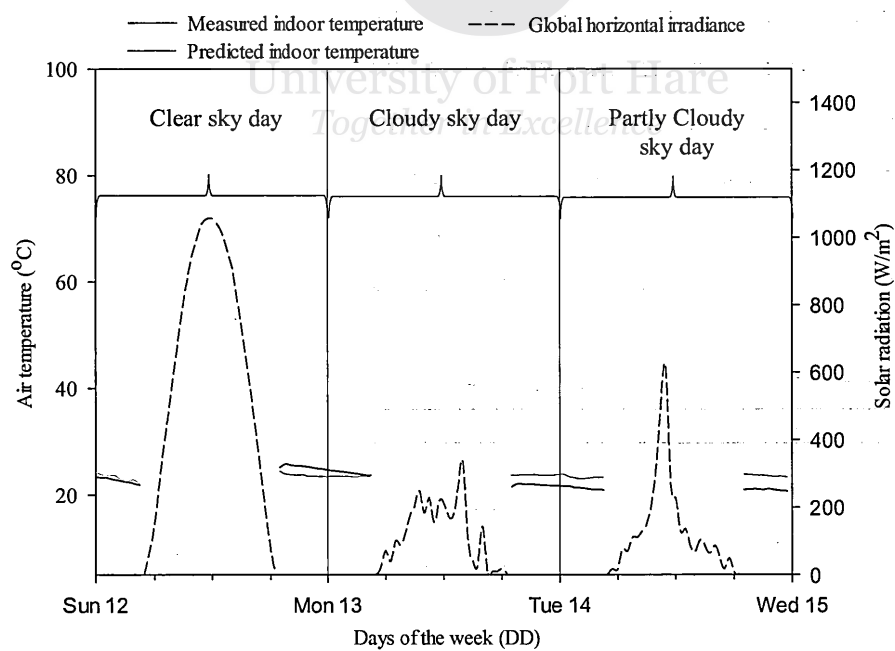


Figure 7.2: Heating load measured and predicted indoor air temperature on selected summer days

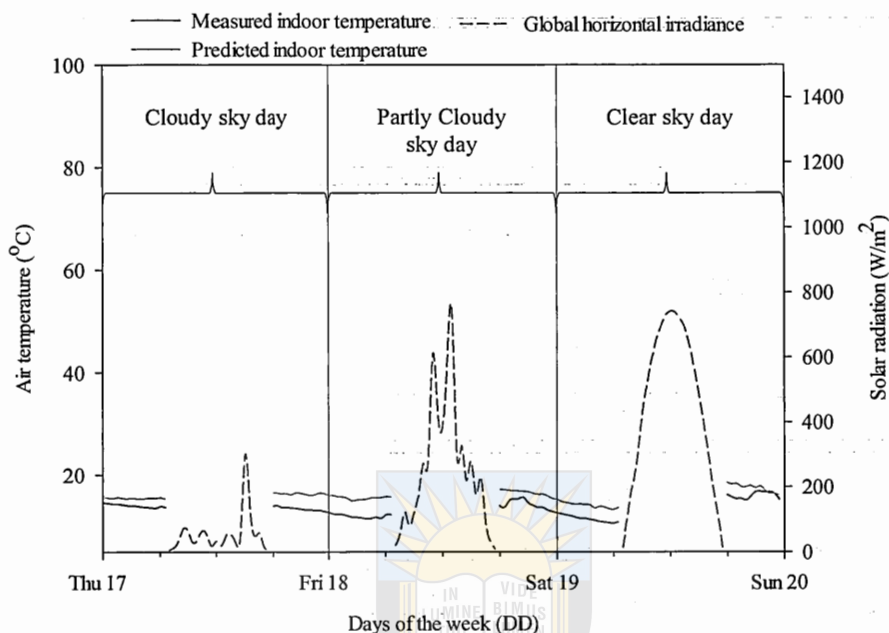


Figure 7.3: Heating load measured and predicted indoor air temperature on selected winter days

Furthermore, a typical clear sky day heating load indoor air temperature prediction was more accurate as shown in Figure 7.2. The average percentage error was 2%. This corresponds to a difference of 0.5°C between the average predicted and measured indoor air temperature. Whereas, the Root Mean Square Error (RMSE) was 1.17. Table 7.2 provides more findings of the model validation.

Table 7-2: Heating load indoor air temperature model validation

Daily sky formation	Summer season			Winter season		
	RMSE	Avg. Per. error (%)	Temp. Diff. (°C)	RMSE	Avg. Per. error (%)	Temp. Diff. (°C)
Clear	1.17	2	0.5	2.31	16	2.1
Cloudy	1.42	3	0.6	2.27	16	2.1
Partly cloudy	2.34	11	2.3	3.07	23	3.0

In the winter season, the clear and cloudy sky days' indoor air temperature prediction share the same level of accuracy as seen in Table 7-2. Both days are having an average percentage error of 16%. Their corresponding measured and predicted average indoor

air temperature difference was 2.1°C each. In both seasons, the model had the worst accuracy in the partly cloudy sky days. The RMSE and average percentage error in the summer season were 2.34 and 11%, respectively. An average percentage error of 23% was obtained in the winter season and a RMSE of 3.07.

7.4 Residential cooling load model

Contrary to heating load, cooling load occurs during typical summer (sunny) days or at mid-day. The sun is a very crucial factor in a house cooling load. The thermal contribution of the sun in a house cooling load consists of solar heat gain through transparent and opaque components. Other factors which influence the cooling load indoor air temperature of a house are occupants, appliances, and lighting. These are classified as internal heat gain. As indicated in chapter five, ventilation and infiltration result in heat loss from a house. Therefore both parameters were not considered as an influencing factor of the cooling load of a house. Thus the rate at which heat is gain indoor can be expressed as;

$$\rho V c_p T_{in-air} = Q_{int} + Q_{sol} \quad (7.10)$$

whereby Q_{int} refers to the internal load such as occupancy, appliance, and lighting in a house. The internal load was assumed as a constant K , due to the diversity of internal load in houses. The constant K , however, varies with occupancy, type of appliances and lighting used in a given house. On the other hand, Q_{sol} is a combination of solar heat gain through the walls and roof as well as the windows (glazing). In other words, Q_{sol} is the sum of solar heat gain through the opaque and transparent components of the building envelope and given as;

$$Q_{sol} = Q_{trs} + Q_{op} \quad (7.11)$$

where,

$$Q_{irs} = \sum A \times SHGC \times SC \times I \quad (7.12)$$

and A is the area of the window excluding the frames. The Solar Heat Gain Coefficient ($SHGC$), is the fraction of solar energy that is transmitted directly or indirectly into the house. $SHGC$ varies with the type of glazing, frame, and angle of incidence of the Sun rays. While, Shading Coefficient (SC), represent the fraction of solar radiation reduced by shading materials (blinds, drapes, etc.). Lastly, I is the global radiation at the various elevations of a house. On the other hand, instantaneous solar heat gain through opaque components of a house is given in Equation 2.2. The ambient air temperature (T_o) in Equations 2.2 and 2.3, was replaced by sol-air temperature (T_{eo}). This was done in order to incorporate the thermal influence of solar radiation at the various elevations of a house. Whereby, the sol-air temperature is given as;

$$T_{eo} = T_o + \frac{I\alpha}{h_o} - \frac{\Delta q_{ir}}{h_o} \quad (7.13)$$

T_o representing ambient air temperature and I is the global irradiance at various elevations of a house, and $\frac{\alpha}{h_o}$ varies from approximately 0.026 m²K/W for a light-coloured surface to a 0.053 m²K/W for a dark surface. Likewise, $\frac{\Delta q_{ir}}{h_o}$ ranges from 0°C for vertical surfaces to -3.9°C for horizontal surfaces. Whereby, vertical surface is applicable to walls and typical windows; horizontal surfaces serve as roof. However, if both parameters $\frac{\alpha}{h_o}$ and $\frac{\Delta q_{ir}}{h_o}$ are kept as constant C and P, respectively; Equation 7.13 can be rewritten as;

$$T_{eo} = T_o + IC - P \quad (7.14)$$

Substitute Equations (7.14) into (2.2) to give;

$$Q_{op} = \sum Au(T_o + IC - P - T_{in}) \quad (7.15)$$

$$Q_{op} = \sum Au(T_o - T_{in} + IC - P) \quad (7.16)$$

Therefore, Equation (7.11) can be written as;

$$Q_{sol} = \sum Au(T_o - T_{in} + IC - P) + \sum A \times SHGC \times SC \times I \quad (7.17)$$

Substituting Equations 7.17 into 7.10 and replacing Q_{int} with k , the heat gain in the house can be rewritten as;

$$\rho V c_p T_{in-air} = k + \sum Au(T_o - T_{in} + IC - P) + \sum (A \times SHGC \times SC \times I) \quad (7.18)$$

Furthermore, substituting Equations 7.18 into 7.3, the cooling load of a house is given by;

$$q_c = k + \sum Au(T_o - T_{in} + IC - P) + \sum (A \times SHGC \times SC \times I) - \rho V c_p T_a \quad (7.19)$$

$$q_c = \rho V c_p \left(\frac{k}{\rho V c_p} + \frac{\sum Au(T_o - T_{in} + IC - P)}{\rho V c_p} + \frac{\sum (A \times SHGC \times SC \times I)}{\rho V c_p} - T_{a_h} \right) \quad (7.20)$$

From Equation 7.20, $\frac{k}{\rho V c_p}$ deal with the occupancy density, appliances and lighting

used in a house with respect to internal heat gain. To the right-hand side of the

Equation, $\sum \frac{Au}{\rho V c_p}$ serves as the thermophysical properties in terms of conductive

heat gain through the building envelope (opaque and transparent). The thermophysical

properties of the transparent component are addressed by; $\sum \frac{(A \times SHGC \times SC)}{\rho V c_p}$. For an

existing house, Equation 7.20 can be used to determine the cooling load. Nevertheless,

for a non-existing house whereby the global irradiance, I at the various elevations and

indoor air temperature, T_i cannot be obtained, Equation 7.20 is not suitable to determine the cooling load. However, global irradiance and indoor air temperature can be predicted from the global horizontal irradiance and ambient weather parameters, respectively.

Forward stepwise linear regression technique was also employed to predict the cooling load indoor air temperature. The parameters that best predict the summer and winter indoor air temperatures are given in Table 7-3.

Table 7-3: Cooling load indoor air temperature predictors and coefficient

Parameter	Summer season coefficient	Winter season coefficient
Forcing constant	13.93	0.0026
Outdoor temperature	0.64	0.88
Outdoor relative humidity		0.095
Global horizontal irradiance	-0.0011	0.0014
Wind direction	-0.023	-0.030

Based on the cooling load assumption in the model structure, only data obtained during the presence of the Sun were used in developing the indoor air temperature in both seasons. The selected parameters in Table 7.3, predicts the summer indoor air temperature with an R^2 value of 0.99 in summer and winter season. The standard error of estimation were 0.18 and 0.32 in summer and winter seasons, respectively. Selected days with various sky formation as shown in Figure 7.2 and 7.3 were used to validate the indoor air temperature model further. Figure 7.4 and 7.5 compared the measured and predicted indoor air temperature with respect to various sky formation in summer and winter seasons, respectively.

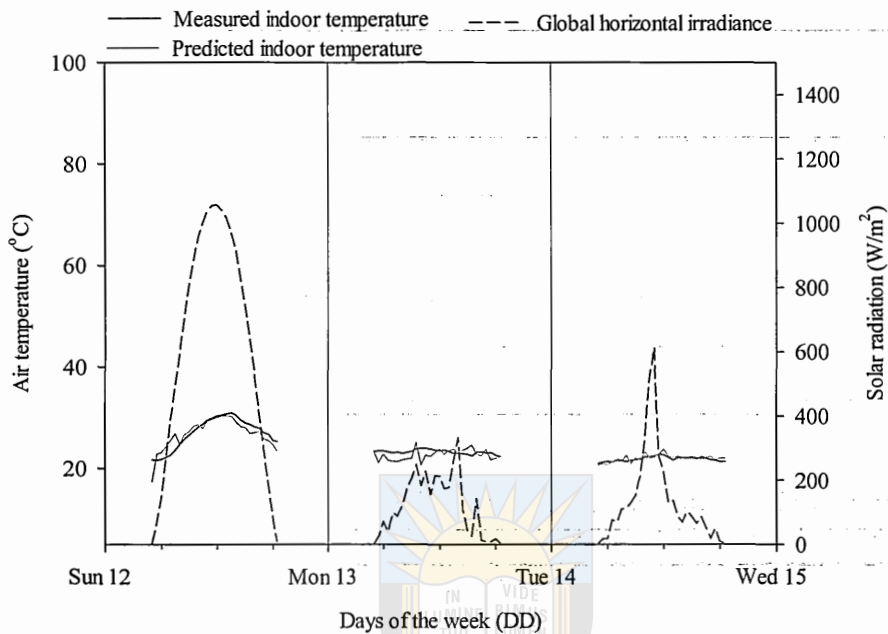


Figure 7.4: Cooling load measured and predicted indoor air temperature on selected summer days

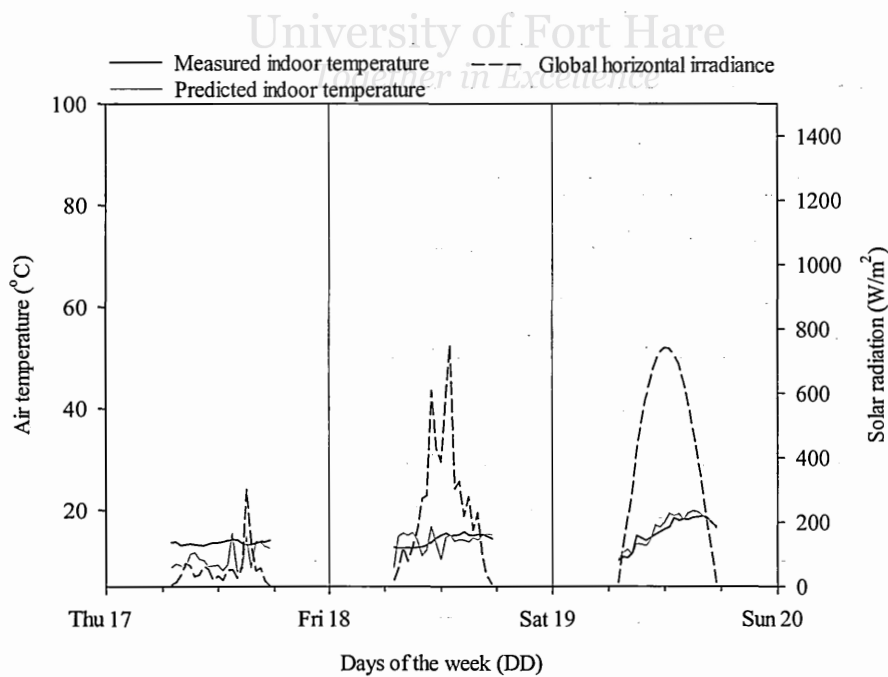


Figure 7.5: Cooling load measured and predicted indoor air temperature on selected winter days

Unlike the heating load indoor air temperature model, the clear and partly cloudy sky days were relatively more accurate as shown in Figure 7.4 and 7.5. In Figure 7.4, the clear and partly sky cloudy days had an average percentage error of 1% each. Corresponding to a temperature difference of 0.2°C and 0.1°C in clear and partly cloudy sky days, respectively. More details of the cooling load indoor air temperature model validation are given in Table 7.4.

Table 7-4: Cooling load indoor air temperature model validation

Daily sky formation	Summer season			Winter season		
	RMSE	Avg. Per. error (%)	Temp. Diff. (°C)	RMSE	Avg. Per. error (%)	Temp. Diff. (°C)
Clear		1.52	1	0.2	1.12	3
Cloudy		1.30	2	0.5	3.70	22
Partly cloudy		0.49	1	0.1	2.07	1

In the winter season, partly cloudy sky days had a RMSE of 2.07. Although it was not the least RMSE obtain among the selected days, it had the least average percentage error of 1%. The resultant temperature difference was 0.2°C. In both seasons, cloudy sky days had the least accuracy with 2% error in the summer season and 22% in winter.

Additionally, the non-linear regression curve fitting technique was used to develop the model to predict the global irradiance of the various elevations of the house. This technique is an iterative process that finds the equation that best predicts the curve of a given (dependent) variable from a set of (independent) variable (s). It begins by guessing the equation that fits the dependent curve; it continues until a fix residual sum of square is obtained. At this point, the R^2 value is maximum. As such, the north and south global irradiance were predicted by the Gaussian equation, while a 3-dimensional Lorentzian equation best predict the east and west global irradiance. Equations 7.21 and 7.22 show the north and south as well as the east and west global irradiance prediction models, respectively.

$$I_{N,S} = y + ae^{\left[-0.5 \left| \frac{I_o - x}{b} \right|^c \right]} \quad (7.21)$$

$$I_{E,W} = \frac{a}{\left[\left(1 + \left(\frac{t-x}{b} \right)^2 \right) \left(1 + \left(\frac{I_o - y}{c} \right)^2 \right) \right]} \quad (7.22)$$

where $I_{N,S}$ and $I_{E,W}$ are north or south and east or west global irradiance, respectively.

I_o represents global horizontal irradiance while t is the time of the day in decimal.

Table 7-5 gives the coefficient of x , y , a , b , and c for summer season global irradiance model and 7-6 for the winter season.

Table 7-5: Parameters coefficient for global irradiance model in summer season

Parameter	I_N	I_s	I_E	I_W
x	1289.28	-81.93	43049.28	43049.72
y	-30.29	139.80	939.47	909.58
a	609.41	-167.45	6597.68	4773.32
b	323.86	184.18	-0.043	0.048
c	1.32	1	237.22	-265.02

Table 7-6: Parameters coefficient for global irradiance model in winter season

Parameter	I_N	I_s	I_E	I_W
x	1.93	-25.81	42964.35	-1.44
y	801.18	84.20	676.02	166.69
a	-832.31	-92.97	8485.85	2775.99
b	205.62	118.59	0.025	0.031
c	1.35	0.70	126.76	98.77

The R^2 values of the predicted north and south global irradiance in the summer season were 0.95 each. Whereas, a relatively higher R^2 value of 0.99 was obtained in the

winter season at the same elevations. In the summer season, R^2 values of 0.90 and 0.89 were obtained in the predicted east and west global irradiance, respectively. The predicted winter global irradiance R^2 value in the east elevation was 0.89 and 0.92 at the west elevation. Further validation of the models was done based on measured and predicted global irradiance. A comparison of the seasonal predicted and measured global irradiance is given in Figures 7.6 and 7.7.

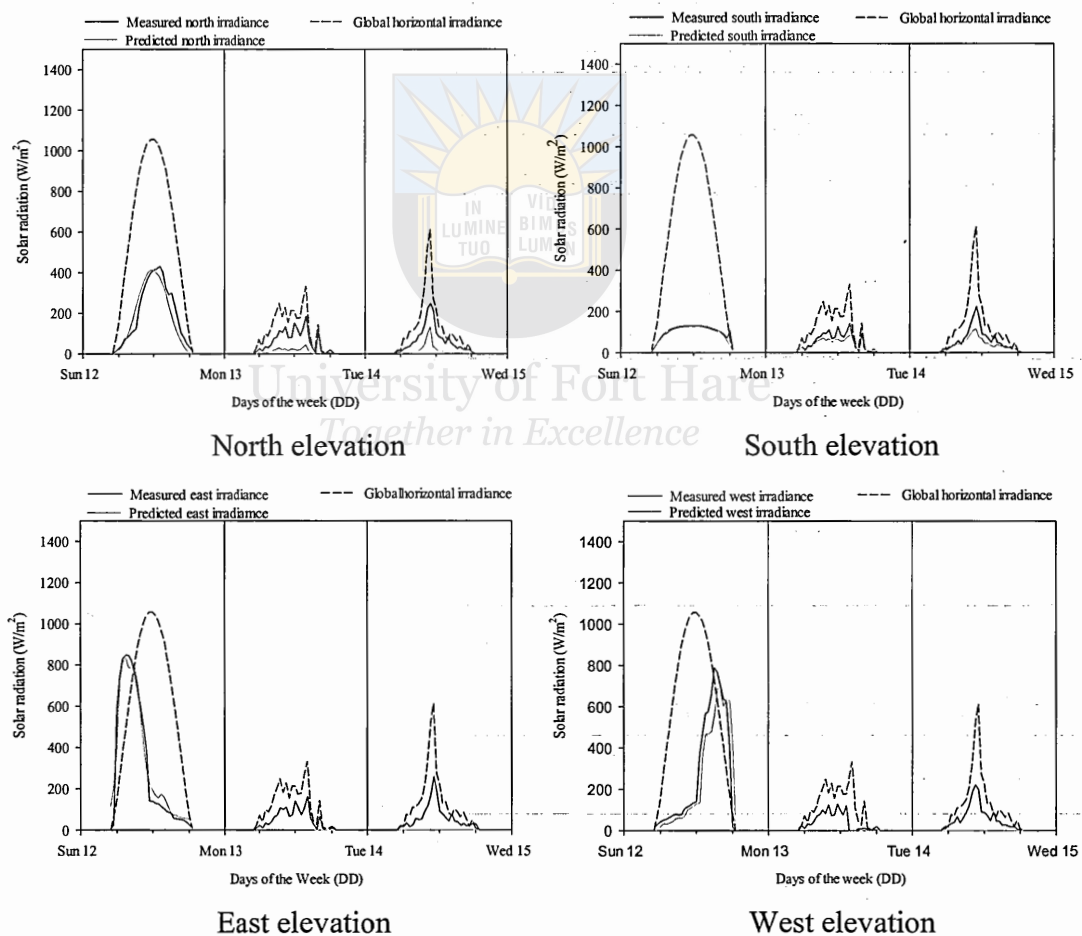


Figure 7.6: Measured and predicted global irradiance of the various elevation on selected summer days

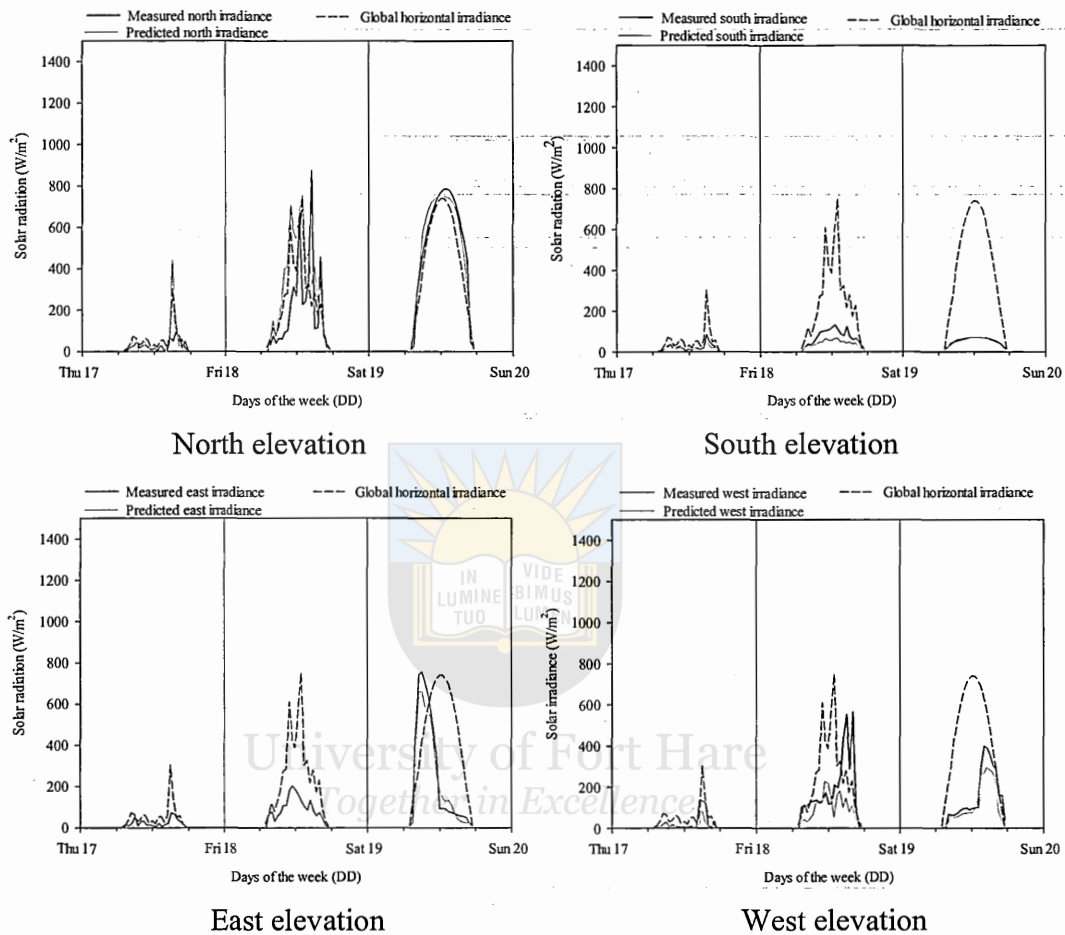


Figure 7.7: Measured and predicted global irradiance of the various elevation on selected winter days

From Figures 7.6 and 7.7, the models were verified in selected days with respect to typical sky formation. The various sky formation considered are shown in Figures 7.2 and 7.3. In both seasons and regardless of the elevation, the clear sky days has the most accurate global irradiance prediction. On the other hand, cloudy, and partly cloudy sky days share the worst global irradiance prediction. In terms of elevation, the north and south global irradiance models prove to be more reliable in predicting the north and south global irradiance than that of the east and west models. More findings of the validation of the model are given in Table 7-7.

The relatively low accuracy of the predicted global irradiance achieved in the cloudy and partly cloudy sky days was mainly due to the irregular distribution of the global horizontal irradiance. As shown in Figures 7.6 and 7.7, the measured global irradiance has no morning and evening peaks in cloudy and partly cloudy sky days.

Table 7-7: Validation of global irradiance predicting model

Global irradiance	Sky formation	Summer season			Winter season		
		RMSE	Avg. Per. error (%)	I Diff. (W/m ²)	RMSE	Avg. Per. error (%)	I Diff. (W/m ²)
I_N	Clear	48.12	6	10.58	67.90	0.5	2.33
	Cloudy	64.77	81	49.94	88.67	36	9.68
	Partly cloudy	65.64	76	50.62	249.47	58	116.52
I_S	Clear	15.37	0.4	0.35	3.90	5	2.66
	Cloudy	23.98	25	13.29	10.06	9	1.85
	Partly cloudy	34.96	30	17.75	38.17	42	30.21
I_E	Clear	69.30	4.14	13.00	48.18	5	13.24
	Cloudy	69.44	99	52.39	29.22	100	21.93
	Partly cloudy	83.20	100	59.45	104.10	99	88.15
I_W	Clear	104.44	10	17	64.14	24	36.43
	Cloudy	31.16	98	42	35.36	46	11.61
	Partly cloudy	30.78	100	60	167.23	47	85.91

Wherein, the morning and evening global irradiance peaks are a consequence of east and west global irradiance, respectively. As such, the models fail to predict the east and west global irradiance during both days. This, however, resulted in an average percentage error of above 90% in the east and west global irradiance predictions in cloudy and partly cloudy days.

7.5 Application and limitation of the models

Based on the structure of the models, they are applicable to any building, especially residential buildings. As indicated in Equations 7.9 and 7.20, the heating and cooling load models contain parameters that distinctively distinguish a building from the other. These include the occupant behavior and thermophysical properties of the building. The occupant behavior deals with the occupancy density, appliances and lighting used in a particular building. The thermophysical properties, on the other hand, deals with the thermal and physical properties of building envelope components with regard to the materials used. This properties specifically deals with the rate at which heat is transfer between the inner and outer space of a building through the building envelope components. Both parameters were treated in the models with regard to the floor area of any given building. Lastly, the models have been designed to evaluate the thermal load of existing and non-existing buildings.

As highlighted in the assumptions of the models, the models are limited to a sensible thermal load of a house. Also, the model is suitable for evaluating peak thermal load. The models can further be limited by the findings of the validation. In the heating and cooling load models, optimum accuracy in predicting the indoor air temperature as well as the global irradiance at the various elevations was obtained in clear sky days. This applies to summer and winter season. Hence, it can be said that the models are not reliable on a cloudy or partly cloudy sky day.

7.6 Summary

A consolidated model for evaluating the thermal load of a house was discussed in this chapter. The thermal load model consists of heating and cooling load. Heating load carter for the rate at which heat must be added in the inner space of a building to maintain a desirable air temperature. Whereas, cooling load is the rate at which heat must be removed to achieve a similar target. The worst-case scenario was assumed in

order to develop both models. Therefore, heating load covers the period during the absence of the sun while cooling load concentrate on the period in which the sun is present.

The indoor air temperature influencing factor considered in terms of the heating load was conductive and infiltration heat transfer. In designing the cooling load model, internal heat gain and solar heat gain were the indoor air temperature influencing factor taken into consideration. Internal heat gain involves heat generated indoors by the occupant, appliance, and lighting. Solar heat gain, on the other hand, consist of conductive heat gain through transparent and opaque components. A combination of the influencing factors in the respective load gives the heating and cooling load models. However, the developed models at their initial stage were found suitable in predicting the thermal load of an existing house. But for non-existing house whereby indoor air temperature and global irradiance cannot be measured, the models at their initial stage were not applicable. As such, the indoor air temperature and global irradiance were predicted from other outdoor meteorological data. These include air temperature, wind speed, wind direction, relative humidity, and global horizontal irradiance.

The heating and cooling load indoor air temperature models were developed by forward stepwise linear regression technique. The global irradiance only applies to the cooling load, since heating load occurs during the absence of the sun. The global horizontal model was developed using non-linear curve-fitting techniques. The developed heating and cooling load indoor air temperature models, as well as the global irradiance, were found to be more reliable on sunny days in winter and summer season.

REFERENCES

South African Bureau of Standards (2011) *SANS 204: Energy efficiency in buildings*. South Africa.



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Chapter 8

CONCLUSION, CONTRIBUTIONS, AND RECOMMENDATIONS

8.1 Conclusion

A holistic approach was taken to evaluate the thermal load of a passive solar house. The house was designed and constructed as a prototype of an energy-efficient low-cost house. This involves indoor and outdoor meteorological parameters as well as the surface temperatures of the building envelope. Internal heat gain due to the operations of appliances and lightings were also taken into consideration. The thermal load evaluation also covers sensible air heat transfer between the inner and outer space of the house. Among the above mentioned thermal load contributing components of the house, the windows were found to be the most influencing component in terms of heat gain. The north-facing clerestory windows had a daily heat transfer of 0.51 kW in summer and 0.90 kW in winter. The windows in the north facing perimeter wall follow the same trend with 0.31 and 0.53 kW heat transfer in summer and winter, respectively. The opening of the ventilation components in zone 1 posed the highest rate of heat loss with 0.25 kW. This was followed by heat loss during the summer season through the walls and roof with 0.16 and 0.19 kW, respectively.

The findings of the research tend to agree with the South African National Standard; floor arrangement with the active area at the north side of the house enjoys passive solar heating during the winter season. This is however accompanied by a large north facing windows. In addition, the integration of clerestory windows in a house as observed in the findings of the research, yield even solar distribution indoor due to the channelling of the low angle winter sun rays to the southern floor area. Therefore, the thermal underperforming low-cost housing in South Africa can be improved by the integration of clerestory windows into the design.

8.2 Contributions

The key contribution of this research was the development of a simplified method of evaluating the thermal load of a house in South Africa. Predicting or evaluating the thermal load of a house provide the performance of the house with respect to the building materials used and its local climate. The developed thermal load evaluation model is applicable to housing before and after construction. As such the thermal load of a house can be forecast based on the building materials used, orientation and local climate. This, however, provides room for improvement at the earlier stage of the building. Furthermore, adopting the model in South Africa can be used to set a benchmark thermal load for housing and its resultant energy consumption. Setting a high thermal performance benchmark for housing, i.e., reducing the heating and cooling load can also serve as a scheme to alleviate energy poverty and enhance social-economic development in rural communities in South Africa. In this regard, the model can be used as a tool to ensure that local buildings adhere to South African National Standards.

8.3 Recommendation

The developed model which is the key contribution of this research study is limited to the sensible heat gain of a house. In other words, heat gain due to phase changes was not taken into consideration. Since both sensible and latent heat gain occurs simultaneously in a house, a research study that in co-operating both parameters in a single thermal load model is recommended. This will provide a more realistic thermal load of a house. Furthermore, peak thermal load prediction is the strength of the model. Although a peak thermal load can be used to quantify the performance of a house, an instantaneous thermal load will provide a real-time thermal behavior of the house. Also, a theoretical and data-driven thermal load model of a house was presented in this research. Validation of the model in its entirety was not performed due to the limited resources required for the process. Whereas the data-driven aspect of the model

was validated and the necessary limitations established. Therefore, a house or room fitted with indoor air temperature controlled air condition system is recommended to validate and provide the necessary adjustment for the developed thermal load model.



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APPENDIX A

DATA ACQUISITION SYSTEM A

CR1000 datalogger wiring text

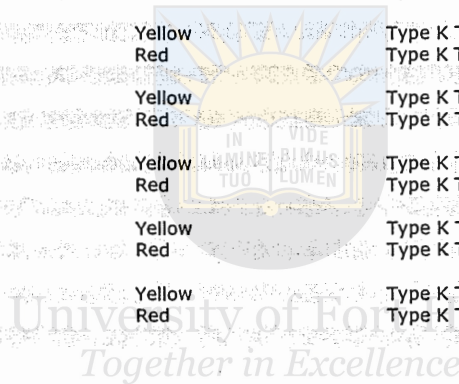
CR1000	Attached Sensor/Device		
Terminal	Wire/Terminal	Name	Measurements
1H	Red	LI200S (1)	SlrW_Nth, SlrkJ_Nth
1L	Black	LI200S (1)	SlrW_Nth, SlrkJ_Nth
	Jumper to Ground	LI200S (1)	SlrW_Nth, SlrkJ_Nth
⏏ (Ground)	Clear	LI200S (1)	SlrW_Nth, SlrkJ_Nth
	Jumper to 1L	LI200S (1)	SlrW_Nth, SlrkJ_Nth
2H	Red	LI200S (2)	SlrW_Est, SlrkJ_Est
2L	Black	LI200S (2)	SlrW_Est, SlrkJ_Est
	Jumper to Ground	LI200S (2)	SlrW_Est, SlrkJ_Est
⏏ (Ground)	Clear	LI200S (2)	SlrW_Est, SlrkJ_Est
	Jumper to 2L	LI200S (2)	SlrW_Est, SlrkJ_Est
3H	Red	LI200S (3)	SlrW_Wst, SlrkJ_Wst
3L	Black	LI200S (3)	SlrW_Wst, SlrkJ_Wst
	Jumper to Ground	LI200S (3)	SlrW_Wst, SlrkJ_Wst
⏏ (Ground)	Clear	LI200S (3)	SlrW_Wst, SlrkJ_Wst
	Jumper to 3L	LI200S (3)	SlrW_Wst, SlrkJ_Wst
4H	Red	LI200S (4)	SlrW_Sth, SlrkJ_Sth
4L	Black	LI200S (4)	SlrW_Sth, SlrkJ_Sth
	Jumper to Ground	LI200S (4)	SlrW_Sth, SlrkJ_Sth
⏏ (Ground)	Clear	LI200S (4)	SlrW_Sth, SlrkJ_Sth
	Jumper to 4L	LI200S (4)	SlrW_Sth, SlrkJ_Sth
VX1 or EX1			
⏏ (Ground)	Clear	HMP50/HMP60 (1)	RT_LVRM, Rh_LVRM
	Clear	HMP50/HMP60 (2)	RT_BDRM, Rh_BDRM
	COM Ground	AM16/32 (2x32 mode)	
	Clear	HMP50/HMP60 (3)	RT_BDRM2, Rh_BDRM2
P1			
⏏ (Ground)			
P2			
⏏ (Ground)			
5H	Black	HMP50/HMP60 (1)	RT_LVRM, Rh_LVRM
5L	White	HMP50/HMP60 (1)	RT_LVRM, Rh_LVRM
⏏ (Ground)			
6H	Black	HMP50/HMP60 (2)	RT_BDRM, Rh_BDRM
6L	White	HMP50/HMP60 (2)	RT_BDRM, Rh_BDRM
⏏ (Ground)			
7H	COM ODD H	AM16/32 (2x32 mode)	
7L	COM ODD L	AM16/32 (2x32 mode)	
⏏ (Ground)			
8H	Black	HMP50/HMP60 (3)	RT_BDRM2, Rh_BDRM2
8L	White	HMP50/HMP60 (3)	RT_BDRM2, Rh_BDRM2
⏏ (Ground)			
VX2 or EX2			
⏏ (Ground)			
VX3 or EX3			
G	Blue	HMP50/HMP60 (1)	RT_LVRM, Rh_LVRM
	Blue	HMP50/HMP60 (2)	RT_BDRM, Rh_BDRM
	G or GND	AM16/32 (2x32 mode)	
	Blue	HMP50/HMP60 (3)	RT_BDRM2, Rh_BDRM2
5V			
G			
SW-12			
G			
12V	Brown	HMP50/HMP60 (1)	RT_LVRM, Rh_LVRM
	Brown	HMP50/HMP60 (2)	RT_BDRM, Rh_BDRM
	12V	AM16/32 (2x32 mode)	
	Brown	HMP50/HMP60 (3)	RT_BDRM2, Rh_BDRM2
12V			
G			
C1	CLK	AM16/32 (2x32 mode)	
C2	RES	AM16/32 (2x32 mode)	

AM 16/32 relay multiplexer wiring text

AM16/32 (2x32 mode)		Attached Sensor/Device	
Terminal	Wire/Terminal	Name	Measurements
1H	Yellow	Type K TC (1)	Temp_C(1)
1L	Red	Type K TC (1)	Temp_C(1)
⌵ or $\perp$ (Ground)			
2H	Yellow	Type K TC (2)	Temp_C(2)
2L	Red	Type K TC (2)	Temp_C(2)
⌵ or $\perp$ (Ground)			
3H	Yellow	Type K TC (3)	Temp_C(3)
3L	Red	Type K TC (3)	Temp_C(3)
⌵ or $\perp$ (Ground)			
4H	Yellow	Type K TC (4)	Temp_C(4)
4L	Red	Type K TC (4)	Temp_C(4)
⌵ or $\perp$ (Ground)			
5H	Yellow	Type K TC (5)	Temp_C(5)
5L	Red	Type K TC (5)	Temp_C(5)
⌵ or $\perp$ (Ground)			
6H	Yellow	Type K TC (6)	Temp_C(6)
6L	Red	Type K TC (6)	Temp_C(6)
⌵ or $\perp$ (Ground)			
7H	Yellow	Type K TC (7)	Temp_C(7)
7L	Red	Type K TC (7)	Temp_C(7)
⌵ or $\perp$ (Ground)			
8H	Yellow	Type K TC (8)	Temp_C(8)
8L	Red	Type K TC (8)	Temp_C(8)
⌵ or $\perp$ (Ground)			
9H	Yellow	Type K TC (9)	Temp_C(9)
9L	Red	Type K TC (9)	Temp_C(9)
⌵ or $\perp$ (Ground)			
10H	Yellow	Type K TC (10)	Temp_C(10)
10L	Red	Type K TC (10)	Temp_C(10)
⌵ or $\perp$ (Ground)			
11H	Yellow	Type K TC (11)	Temp_C(11)
11L	Red	Type K TC (11)	Temp_C(11)
⌵ or $\perp$ (Ground)			
12H	Yellow	Type K TC (12)	Temp_C(12)
12L	Red	Type K TC (12)	Temp_C(12)
⌵ or $\perp$ (Ground)			
RES	C2	CR1000	
CLK	C1	CR1000	
G or GND	G	CR1000	
12V	12V	CR1000	
COM ODD H	7H	CR1000	
COM ODD L	7L	CR1000	
COM BGround			
COM EVEN H			
COM EVEN L			
COM BGround			
13H	Yellow	Type K TC (13)	Temp_C(13)
13L	Red	Type K TC (13)	Temp_C(13)
⌵ or $\perp$ (Ground)			
14H	Yellow	Type K TC (14)	Temp_C(14)
14L	Red	Type K TC (14)	Temp_C(14)
⌵ or $\perp$ (Ground)			
15H	Yellow	Type K TC (15)	Temp_C(15)
15L	Red	Type K TC (15)	Temp_C(15)
⌵ or $\perp$ (Ground)			
16H	Yellow	Type K TC (16)	Temp_C(16)
16L	Red	Type K TC (16)	Temp_C(16)
⌵ or $\perp$ (Ground)			
17H	Yellow	Type K TC (17)	Temp_C(17)
17L	Red	Type K TC (17)	Temp_C(17)
⌵ or $\perp$ (Ground)			
18H	Yellow	Type K TC (18)	Temp_C(18)
18L	Red	Type K TC (18)	Temp_C(18)
⌵ or $\perp$ (Ground)			
19H	Yellow	Type K TC (19)	Temp_C(19)
19L	Red	Type K TC (19)	Temp_C(19)
⌵ or $\perp$ (Ground)			
20H	Yellow	Type K TC (20)	Temp_C(20)
20L	Red	Type K TC (20)	Temp_C(20)
⌵ or $\perp$ (Ground)			
21H	Yellow	Type K TC (21)	Temp_C(21)

AM 16/32 relay multiplexer wiring text (continue)

Terminal	Wire/Terminal	Name	Measurements
21L ⏏ or $\perp$ (Ground)	Red	Type K TC (21)	Temp_C(21)
22H	Yellow	Type K TC (22)	Temp_C(22)
22L ⏏ or $\perp$ (Ground)	Red	Type K TC (22)	Temp_C(22)
23H	Yellow	Type K TC (23)	Temp_C(23)
23L ⏏ or $\perp$ (Ground)	Red	Type K TC (23)	Temp_C(23)
24H	Yellow	Type K TC (24)	Temp_C(24)
24L ⏏ or $\perp$ (Ground)	Red	Type K TC (24)	Temp_C(24)
25H	Yellow	Type K TC (25)	Temp_C(25)
25L ⏏ or $\perp$ (Ground)	Red	Type K TC (25)	Temp_C(25)
26H	Yellow	Type K TC (26)	Temp_C(26)
26L ⏏ or $\perp$ (Ground)	Red	Type K TC (26)	Temp_C(26)
27H	Yellow	Type K TC (27)	Temp_C_2(1)
27L ⏏ or $\perp$ (Ground)	Red	Type K TC (27)	Temp_C_2(1)
28H	Yellow	Type K TC (28)	Temp_C_2(2)
28L ⏏ or $\perp$ (Ground)	Red	Type K TC (28)	Temp_C_2(2)
29H	Yellow	Type K TC (29)	Temp_C_2(3)
29L ⏏ or $\perp$ (Ground)	Red	Type K TC (29)	Temp_C_2(3)
30H	Yellow	Type K TC (30)	Temp_C_2(4)
30L ⏏ or $\perp$ (Ground)	Red	Type K TC (30)	Temp_C_2(4)
31H	Yellow	Type K TC (31)	Temp_C_2(5)
31L ⏏ or $\perp$ (Ground)	Red	Type K TC (31)	Temp_C_2(5)
32H	Yellow	Type K TC (32)	Temp_C_2(6)
32L ⏏ or $\perp$ (Ground)	Red	Type K TC (32)	Temp_C_2(6)



DATA ACQUISITION SYSTEM B

CR1000 datalogger wiring text

CR1000 Terminal	Wire/Terminal	Attached Sensor/Device Name	Measurements
1H	Black	HMP50/HMP60 (1)	Rt_CNRM, Rh_CNRM
1L	White	HMP50/HMP60 (1)	Rt_CNRM, Rh_CNRM
⏏ (Ground)	Clear	HMP50/HMP60 (1)	Rt_CNRM, Rh_CNRM
	Clear	HMP50/HMP60 (2)	Rt_WKSH, Rh_WKSH
	Clear	HMP50/HMP60 (3)	Rt_DKRM, Rh_DKRM
	Clear	HMP50/HMP60 (4)	Rt_OUDR, Rh_OUDR
2H	Black	HMP50/HMP60 (2)	Rt_WKSH, Rh_WKSH
2L	White	HMP50/HMP60 (2)	Rt_WKSH, Rh_WKSH
⏏ (Ground)	COM Ground	AM16/32 (2x32 mode) (2)	
	COM Ground	AM16/32 (2x32 mode) (1)	
	Clear	CMP3/CMP6/CMP11	Sol_Glo, SlrkJ
3H	Black	HMP50/HMP60 (3)	Rt_DKRM, Rh_DKRM
3L	White	HMP50/HMP60 (3)	Rt_DKRM, Rh_DKRM
⏏ (Ground)			
4H	Black	HMP50/HMP60 (4)	Rt_OUDR, Rh_OUDR
4L	White	HMP50/HMP60 (4)	Rt_OUDR, Rh_OUDR
⏏ (Ground)			
VX1 or EX1			
⏏ (Ground)			
P1			
⏏ (Ground)			
P2			
⏏ (Ground)			
5H	COM ODD H	AM16/32 (2x32 mode) (2)	
5L	COM ODD L	AM16/32 (2x32 mode) (2)	
⏏ (Ground)			
6H	COM ODD H	AM16/32 (2x32 mode) (1)	
6L	COM ODD L	AM16/32 (2x32 mode) (1)	
⏏ (Ground)			
7H	White	CMP3/CMP6/CMP11	Sol_Glo, SlrkJ
7L	Black	CMP3/CMP6/CMP11	Sol_Glo, SlrkJ
	Jumper to Ground	CMP3/CMP6/CMP11	Sol_Glo, SlrkJ
⏏ (Ground)	Jumper to 7L	CMP3/CMP6/CMP11	Sol_Glo, SlrkJ
8H			
⏏ (Ground)			
VX2 or EX2			
⏏ (Ground)			
VX3 or EX3			
G	Blue	HMP50/HMP60 (1)	Rt_CNRM, Rh_CNRM
	Blue	HMP50/HMP60 (2)	Rt_WKSH, Rh_WKSH
	Blue	HMP50/HMP60 (3)	Rt_DKRM, Rh_DKRM
	Blue	HMP50/HMP60 (4)	Rt_OUDR, Rh_OUDR
5V			
G	G or GND	AM16/32 (2x32 mode) (2)	
	G or GND	AM16/32 (2x32 mode) (1)	
SW-12			
G			
12V	Brown	HMP50/HMP60 (1)	Rt_CNRM, Rh_CNRM
	Brown	HMP50/HMP60 (2)	Rt_WKSH, Rh_WKSH
	Brown	HMP50/HMP60 (3)	Rt_DKRM, Rh_DKRM
	Brown	HMP50/HMP60 (4)	Rt_OUDR, Rh_OUDR
	12V	AM16/32 (2x32 mode) (2)	
	12V	AM16/32 (2x32 mode) (1)	
12V			
G			
C1	CLK	AM16/32 (2x32 mode) (2)	
	CLK	AM16/32 (2x32 mode) (1)	
C2	RES	AM16/32 (2x32 mode) (2)	
C3	RES	AM16/32 (2x32 mode) (1)	
C4			
G			
C5			
C6			

APPENDIX B

RESEARCH OUTPUT

This section presents the outputs associated with this research and other academic activities performed during the research period. These include paper presentations at local and international conferences as well as publication in DHET accredited journals.

B1 Paper presentation (local)

1. Overen K. Ochuko, Edson L. Meyer and Golden Makaka (2017), *Air Exchange Rate Analysis of a Building Integrated Photovoltaic Passive Solar House*; 62nd South Africa Institute of Physics Conference, Stellenbosch University, Stellenbosch, South Africa.
2. Overen K. Ochuko, Edson L. Meyer and Golden Makaka (2017), *A Passive Solar Building Response to Selective Components of Solar Irradiance*; 62nd South Africa Institute of Physics Conference, Stellenbosch University, Stellenbosch, South Africa.
3. Overen K. Ochuko, Edson L. Meyer and Golden Makaka (2017), *Opaque Components Solar heat Gain Analysis of a Passive Solar House*; Renewable and Sustainable Energy Postgraduate Symposium, Stellenbosch University, Stellenbosch, South Africa.

B2 Conference proceedings

B2.1 Local

1. Overen K. Ochuko, Edson L. Meyer and Golden Makaka, (2017), *Perimeter walls Solar Heat Gain, a Mechanism for Building Design*; 11th Building Environment Conference, Association of School of Southern Africa, Durban, South Africa.

B2.2 International

1. Overen K. Ochuko, Edson L. Meyer and Golden Makaka, (2017), *Thermal Behavior of a Low-Cost House Coated with Transparent Infrared Reflective Paint*; World Sustainable Built Environment Conference, Construction Industry Council, Hong Kong.
2. Overen K. Ochuko, Edson L. Meyer and Golden Makaka, (2019), *A Commercial Building Lighting Demand-Side Management through Passive Solar Design*; Central Europe towards Sustainable Building, Construction Industry Council, Prague, Czech Republic, Abstract under review.
3. Overen K. Ochuko, Edson L. Meyer and Golden Makaka, (2019), *Holistic Thermal Characterization of a Passive Solar House in South Africa*; Young Researchers in Sustainable Building, Prague, Czech Republic, Abstract under review.

B3 Publications

1. Overen K. Ochuko, Edson L. Meyer and Golden Makaka, (2017), *Thermal, Economic and Environmental Analysis of a Low-Cost House in Alice, South Africa*. Sustainability, MDPI Publishing, Basel, Switzerland, Publication 2017, 9, 425; doi: 10.3390/su9030425 (online).
2. Overen K. Ochuko, Edson L. Meyer, Golden Makaka, Sosten Zuiku and Sampson Mamphweli, (2018), *Zonal Air Exchange Rate of a Passive Solar House and Resultant Sensible Air Heat transfer*, Indoor and Built Environment, SAGE Publishing, IBE-18-0102; Under Review.
3. Overen K. Ochuko, Edson L. Meyer and Golden Makaka, (2018), *Daylighting and Thermal Analysis of Windows in A Passive Solar House, South Africa*. Science and Technology for the Built Environment, Taylor and Francis Publishing, STBE-0112-2018; Under Review.