THERMAL MODELLING OF GREEN ROOFED URBAN BUILDINGS

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ABSTRACT
The study of the effects of green roof has intensified over recent years, mostly because of the need to make our dwellings energy efficient. This study aims to develop a new thermal model, called GRUBCLIM, that predicts the indoor air temperature of urban buildings with living green roofs and to examine the thermal effects of green roofs on indoor air temperature. A field experiment study was conducted in Kenya, where microclimate parameters used in validation and simulation of the model were measured. The experiment was carried out in a way that the effect of both natural and mechanical ventilation was shut out. Modelling and simulation was done in MATLAB/SIMULINK. The model was validated with data measured at the field site for 12 days. Simulations were carried out for another 19 days. The results show a good agreement of the predicted indoor air temperature of GRUBCLIM with the measured values. The thermal reductions inside the building offered by the living green roofs were averagely 2.16 °C during daytime, signifying their importance in heat gain reduction.

KEYWORDS: *Thermal modelling, urban buildings, microclimate, green roofs, energy*

I. INTRODUCTION

Buildings situated in urban areas consume more energy as compared to other areas. The Urban Heat Island (UHI) of the Urban Canopy Layer (UCL), can increase energy consumption, increase ambient air temperature, and reduce human thermal comfort [1]. This is as a result of higher temperatures, caused by the large presence of materials that act as heat sinks such as concrete and asphalt, in urban areas. The heat island in the city of Athens, Greece, doubles the cooling load of buildings and almost triples their peak electricity demand [2].
The need for air conditioning arises due to heat gains from sunlight and electric lighting-which causes high temperature in rooms-unless windows are opened to let in the natural air ventilate the place. When the windows are open, other unwanted comfort levels might be reached such as draughts caused by wind, noise, dirt and odorous smell can flow in, hence, making the place uncomfortable. Human beings are comfortable around the range of 20 to 60 per cent of humidity [3].
Current design of buildings considers the climate of the region the building is located and the construction material without the need for anthropogenic heating or cooling [4] in the analysis. This kind of design is called energy efficient design of buildings. Its primary purpose is to reduce the amount of energy to be consumed by these buildings i.e. energy efficient buildings. However, this efficiency is also limited even though the climate is taken into effect. Building owners and designers possess little or no control in the values of urban temperatures and the intensity of sunshine, however, they do possess a maximum control of how these increased temperature and solar radiation gets into the house.
Optimized selection of building materials for making the external envelop plays an important role in achieving thermal comfort in buildings, where thermal comfort is achieved through passive – cooling, strategies such as green roofs. A green roof constitutes a layered structure of waterproofing membrane, growing medium and the vegetation layer itself [5][6][7]. More generally, it refers to any

type of roof that a green technology has been incorperated [8]. Because of their ability to reduce the proportion of solar radiation that reaches the roof beneath [5] and subsequent penetration into the building [9], it possess the potential in reducing the energy [6], [10], [11], [12], that would have been used in cooling the higher heated spaces. The trees and open spaces have multiple uses and their presence in outdoors make a major contribution to the saving of energy inside the buildings [13].
Most of the studies on green roofs in the world (Singapore, Athens, Taiwan, South Korea, Japan, China, Hong Kong, [14]), have been carried out in none African countries. Therefore, necessitating this research appropriate for the local climate. Most of the models developed for predicting indoor thermal temperatures of building were carried out outside of Africa [15], [16], [17]. These researches carried out an energy and mass balance for predicting indoor air temperature of zones of their experiment [15]. In India, some researchers carried out black-box modelling of indoor air temperature together with the outdoor temperature [16]. A model for predicting inner temperature of single storied buildings was also done in Australia [17]. Furthermore, other researches were only carried out for buildings without a living green roof [18]. The study was only looking at different thermal masses of the building [18]. In addition, many concentrated on the vegetation found outside (in the neighbourhood) of the building or the different thermal masses of the building envelope. This study is necessitated by the fact that an individual house owner may have little or no control of the design of his neighbourhood and the developments (urban planning) in it, or the control of the intensity of sunshine, or the cost of electricity in the city. However, the individual has control over how energy is consumed or what fraction of sunshine goes into his/her house; therefore, he/she can design or employ certain features on the building envelope to make it energy efficient (bioclimatic design).
The objectives of this study are thus:

1. To develop a thermal model that will predict the indoor thermal microclimate of green roofed urban buildings.
2. To investigate the thermal effects of living green roofs in a sub-Saharan climate.

Generally, this paper is arranged in a unified manner. After the introduction of the paper, while highlighting studies from previous researches, the objectives were listed. Thereafter, the details of the field experiment was expatiated, with photos of it shown. Subsequently, the process of deriving the physical model, called GRUBCLIM was shown. Results of the validation and simulation were discussed in writing, including two graphs showing predicted values of GRUBCLIM compared with measured values, and also measured indoor temperature compared with outdoor temperature.

II. FIELD EXPERIMENT

An urban like house was erected in order to measure microclimatic data used for the study.

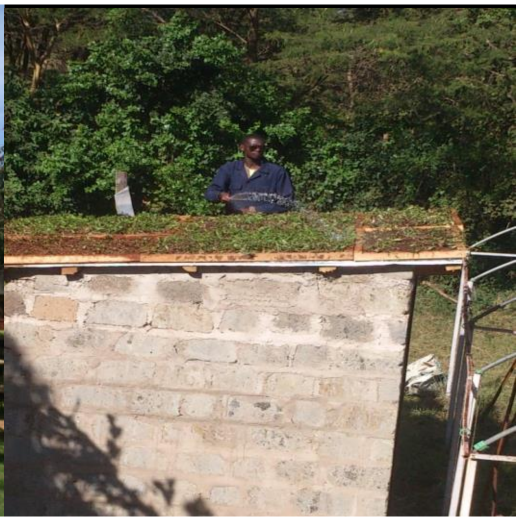
1.1 location of the study

The field experiments were located at Jomo Kenyatta University of Agriculture and Technology, Juja campus, Kenya, which represented an urban like area, complete with paved areas, concrete buildings and asphalted roads. The place is located in Central Kenya, an equatorial high altitude region on latitude 1° 11' 00" S and longitude 37° N 07' 00" with an altitude of 1416m (4648ft) above sea level [19].

1.2 model description

The model houses are as shown in figure 1. An urban like room was built with natural stones, commonly found and used for construction. The foundation was 100mm deep without any column footings. The floors of the rooms were decked with murram, stone ballast and thereafter a fine finish of cement mortar was made on the surface. Polyethylene was used below the floors and around the perimeter of the floor to prevent moisture rise in the rooms. The inside wall surfaces, with the exclusion of the outside surfaces, were finished with cement mortar. A conventional roof was made, slanting in one direction, covered with gauge 30 aluminium roofing sheet. There is a single door and window located in opposite direction, across the axis of the sun. The door was made with timber while a single glazing window was used. No ceiling was installed. In essence, the procedure represents the exact construction procedure in the locality.


a.


b.


c.


d.

Figure 1. The different views of the field scale model (a) The full model. (b) The vegetation boxes on the roof. (c) The door. (d) The window (on opposite of the door).

1.3 construction of green roof

Boxes about 100mm deep were made with the same corrugated iron sheet used on the roofing of the structure together with timber nailed by the 4 sides, such that, the top was open. The corrugated sheet forming the base was perforated in order to aid drainage of water for the green roof. A soil layer was later added about 90mm in depth to serve as the growing media of the vegetation used. Six boxes were made that covered the entire roof area when placed on top of the model.

1.4 data acquisition

The Temperature/RH smart sensor (S-THB-M008) is designed to work with smart sensor-compatible HOBO data loggers. HOBO instruments have been used in the research in predicitng the envelope performance of commercial office buildings in Singapore [20]. All sensor parameters are stored inside the smart sensor which automatically communicates information to the logger. For temperature readings, it has a measurement range between -40 to 75° C with an accuracy of +/-0.21°C from 0 to

50°C. Its resolution is 0.02° C at 25° C and a response time of 5 minutes in air moving 1m/sec. It has a drift of < 0.1°C per year. All measurements were taken at 10 minutes interval.

III. PHYSICAL MODELLING

3.1 heat flow through walls

The principles of heat transmission are on the basis of heat conduction through materials and heat transfer from surfaces by radiation and convection [21]. The rate of heat transmission through building materials depends on the characteristics of the material- its density, the size and arrangement of its particles or fibres, moisture content, temperature, and surface characteristics [21]. Heat transfer obeys several laws. Amongst which are the basic laws of thermodynamics.

For this analysis, a steady state heat transfer is assumed to occur. The condition for steady state heat transfer is temperatures in the system shall be independent of time and as a consequence, the rate of heat transfer out of the system must equal the rate of heat transfer in to the system. The formal categorization of heat transfer into radiation, convection and conduction (distinct and separate) as discussed below is somewhat arbitrary, because it is possible to encounter more than one of these mechanisms occurring at the same time and therefore need to be considered in combination during analysis [22]. However, the distinction is useful in analysing complex technical problems.

3.2 radiation

Buildings' external surfaces such as walls and roofs are always exposed to the atmosphere and therefore subject to a different heat exchange [23]. So the radiation exchange (Q_r) between the exposed parts of the building and the atmosphere is an important factor. The heat exchange between the building surface and the sky is given by

$$Qr = A\varepsilon\sigma(T_s^4 - T_{sky}^4) \qquad (1)$$

Where

A = area of the building exposed surface (m^2), ε = emissivity of the building exposed surface, σ = Stefan-Boltzmann constant ($5.67 * 10^{-8}$ W/m^2K^4) T_s = temperature of the building exposed surface (K), T_{sky} = sky temperature (K).

T_{sky} represents the temperature of an equivalent atmosphere. It considers the fact that the atmosphere is not at a uniform temperature, and that the atmosphere radiates only in certain wavelengths.

3.3 heat transmission coefficient for walls

The determination of the overall heat transmission coefficient is necessary if the wall is made up of different materials including air spaces and surfaces. R can be represented as the overall thermal resistance of the wall (R = 1/U) is the overall thermal resistance per unit area of the wall. However, this applies only for steady state conditions of heat flow rate. The temperature drops at the two outer surfaces and through the wall components are

$$ti - t1 = QR1 \qquad (2)$$

$$t1 - t2 = QR2 \qquad (3)$$

$$t2 - to = QR3 \qquad (4)$$

This can be rewritten in terms of the resistances, since the total temperature drop *ti – to* equals the sum of the temperature drops corresponding to the thermal resistances R1, R2 and R3, and the heat Q is the same through each resistance, thus:

$$R = R1 + R2 + R3 = \frac{1}{fi} + \frac{Lj}{kj} + \frac{1}{fo} \qquad (5)$$

$$U = \frac{1}{R} = 1(\frac{1}{fi} + \frac{Lj}{kj} + \frac{1}{fo}) \qquad (6)$$

fi and *fo* respectively, are the inside and outside heat transfer coefficients. See table 1.0 below. *Lj* is the thickness of the *jth* layer and *kj* is the thermal conductivity of its material.

Table 1.0. Values of surface heat transfer heat coefficient [18]

Serial No.	Wind Speed	Position of Surface	Direction of Heat Flow	Surface Heat Transfer Coefficient (W/m^2-k)
1	Still air	Horizontal	Up	9.3
		Sloping 45°	Up	9.1
		Vertical	Horizontal	8.3
		Sloping 45°	Down	7.5
		Horizontal	Down	6.1
2	Moving air 12 (km/h)	Any position	Any direction	22.7
	Moving air 24 (km/h)	Any position	Any direction	34.1

3.4 solar radiation gain

The solar radiation that goes into a building is given by:

$$Qr_{(in)} = Qr_{(out)} \times Tr \qquad (7)$$

$Qr_{(in)}$: solar radiant energy into the building [w/m^2]
$Qr_{(out)}$: solar radiant energy outside the building [w/m^2]
Tr: Transmissivity of the wall material [-]

3.5 conduction

Energy transfer via conduction can take place in solids, liquids and gases. This process happens when there is a transfer of energy from the more energetic particles of a substance to adjacent particles that are less energetic due to interactions between particles [24]. Or simply, it is the process of heat transfer from one part of a body at a higher temperature to another (or between bodies in direct contact) at a lower temperature [25]. Conduction is quantified by Fourier's law that says heat flux is proportional to the temperature gradient in the direction of the outward normal.
Considering the transfer through, the basic equation of heat conduction is given by:

$$Q_{cd} = kA\frac{\Delta T}{D} \qquad (8)$$

Q_{cd} : Quantity of heat flow/ Heat flux due to conduction [w], k: thermal conductivity of the material [w/m/K], A: Surface area [m^2], ΔT: Temperature difference of the two media [K], D: Thickness of the material [m].

3.6 simplified model of heat loss through urban buildings

Based on the above equations, the rate of heat loss through any building envelope element such as roof, wall or floor under steady state can be calculated, however, it is a cumbersome task due to the difficulty and inaccuracy in estimating the many parameters involved [15]. Furthermore, it is not always obvious which mechanism will be predominant, and indeed, more than one mechanism may be pertinent [26]. The simplified model representing the heat loss through the building is given by:

$$Q = UA\,\Delta T \quad \text{[w]} \qquad (9)$$

A = surface area (m^2), U = overall heat thermal transmittance (W/ m^2- K), ΔT = temperature difference between inside and outside air (K).

3.7 energy balance

The term energy balance is used to refer to the mathematical analysis of the gains, losses and storage of energy by an object. With the exception of solar radiation, the energy fluxes created by the individual heat transfer processes can be formulated in terms of differences in temperature. Thermodynamically, temperatures of objects or zones can be determined through an energy balance equation [27]. This can be achieved by taking into consideration the known temperatures of all the objects or processes which interact with the object or zone. A new Green Roofed Urban Building Microclimate model called GRUBCLIM is developed in this study through energy balance. It is arrived at by considering the building as a system exposed to local weather conditions such as wind,

solar radiation and rainfall on its outside and internal heat gain via the envelope and fenestration systems. Figure 2 below shows the flowchart of GRUBCLIM.
A basic assumption is made that the indoor air is uniformly mixed; hence, the energy balance for the urban building with a green roof can be generalized as:

$$Q_T = Q_W + Q_F + Q_G + Q_R + Q_D \quad (10)$$

Where,
Q_T: Total energy that comes into the house [w], Q_W: Energy loss through the walls [w], Q_F: Energy loss into the floor [w], Q_G: Energy loss through the glazing (window) [w], Q_R: Energy loss through the green roof [w], Q_D: Energy loss through the door [w].
$Q_{T\ is}$ calculated by multiplying the total solar radiation that comes into the building by the floor area of the house. All other parameters in the above equation (10) can be substituted with equation (9), which uses the overall heat transfer coefficient (U) of heat transfer. Thus:

$$Q_T = U_W A_W \Delta T + U_F A_F \Delta T + U_G A_G \Delta T + U_R A_R \Delta T + U_D A_D \Delta T \quad (11)$$

For each building element that comprises of different materials, such as the wall and the roof, the overall U-value is arrived at using equation (6) above. All single U-values of materials were taken from literature quoted above and mentioned in table 2.0. To predict the indoor air temperature (*Ti*), equation (11) is solved provided the external climatic parameters measured (solar radiation and outside temperature).

Table 2.0. Thickness, thermal conductivity and U-value of different materials used for the analysis

		U-values			
S/N	Element	Composition	Thickness (m)	Thermal conductivity (w/m-K)	U-value (w/m^2-K)
1	Wall	Plaster	0.05	0.721	
		Stone	0.15	2.3	3.516514197
2	Door	Timber	0.05	0.21	2.577969142
3	Window	Single glazing	0.01	5	6.587311521
4	Floor	Plaster	0.05	0.721	
		DPC	0.1	1.74	
		DPM	0.00025	0.33	3.605111024
5	Roof	Plants		0.5	
		Soil layer	0.1	1.59	
		Veg box	0.00025	105.9	
		Roofing sheet (Al + Zn + Fe)	0.00025	105.9*	1.429082217

*Calculated based on manufacturer details.

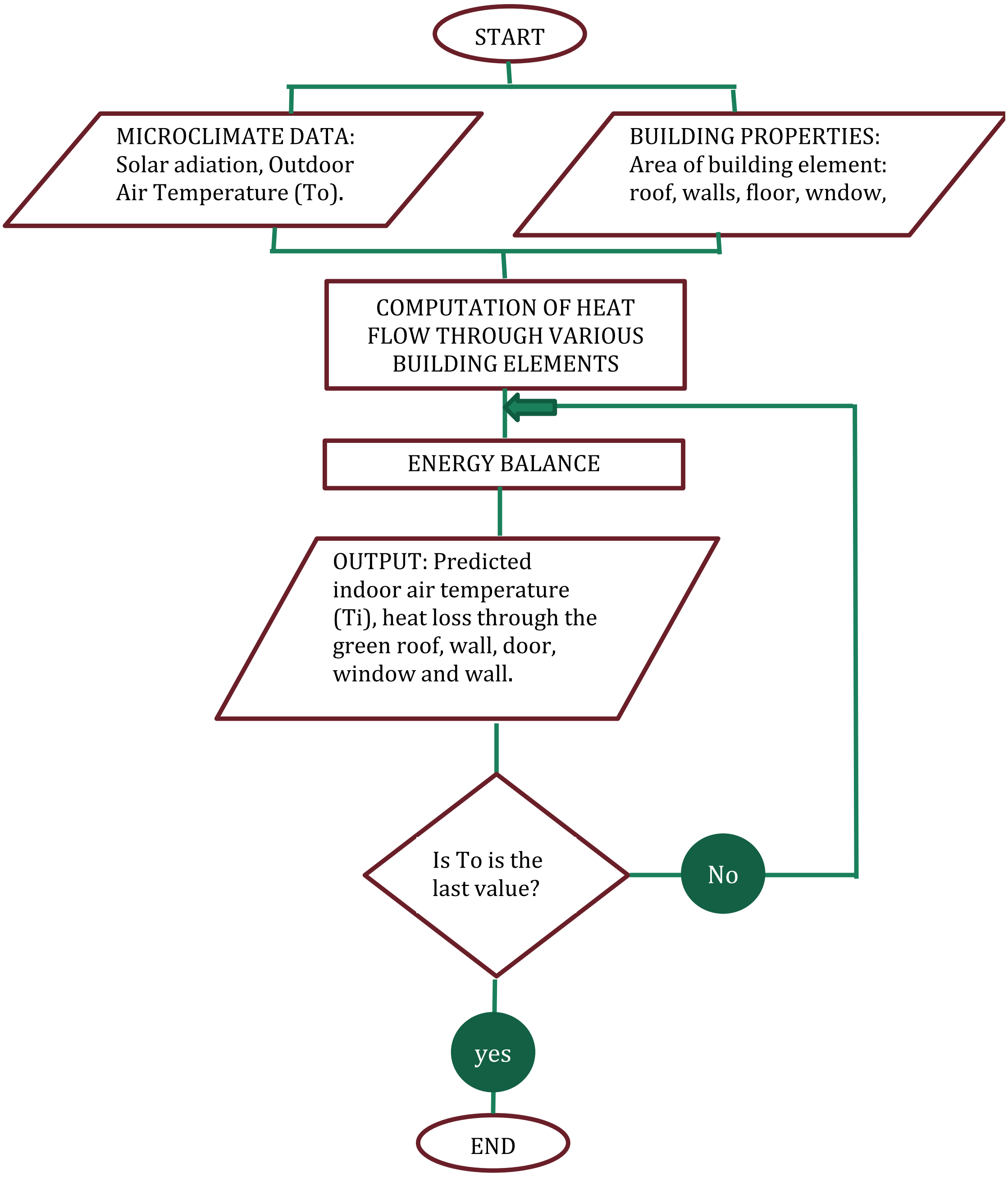


Figure 2.0. Flowchart of GRUBCLIM

3.8 simulation of grubclim

GRUBCLIM is modelled in SIMULINK, a module in MATLAB. The inputs of GRUBCLIM are outdoor air temperature and solar radiation, all measured just outside the field model. The GRUBCLIM simulation model masks various subsystems. Each subsystem does a different function and returns the output. See figure 3 below for the block diagram in SIMULINK environment.

The tasks performed in the SIMULINK model are:

Reading Input File: The input is the weather data collected at the field model site, i.e. Outdoor air temperature, indoor air temperature and global solar radiation. The measured indoor air temperature is comparison purposes with the predicted values from the GRUBCLIM only.

Computations: The following computations are done: calculation of heat loss through the roof, calculation of heat loss through the walls, calculation of heat loss through the window, calculation of heat loss through the door, calculation of heat loss through the floor, calculation of energy balance and prediction of indoor air temperature. See figure 2 below.

Other constant parameters used in the model are:
Specific heat capacity of air: 1004 J/kg/K,
Density of air: 1.225 kg/m^3,
The model outputs include the following parameters: predicted indoor air temperature [°C], heat loss through the roof, window, door, floor and walls [W].

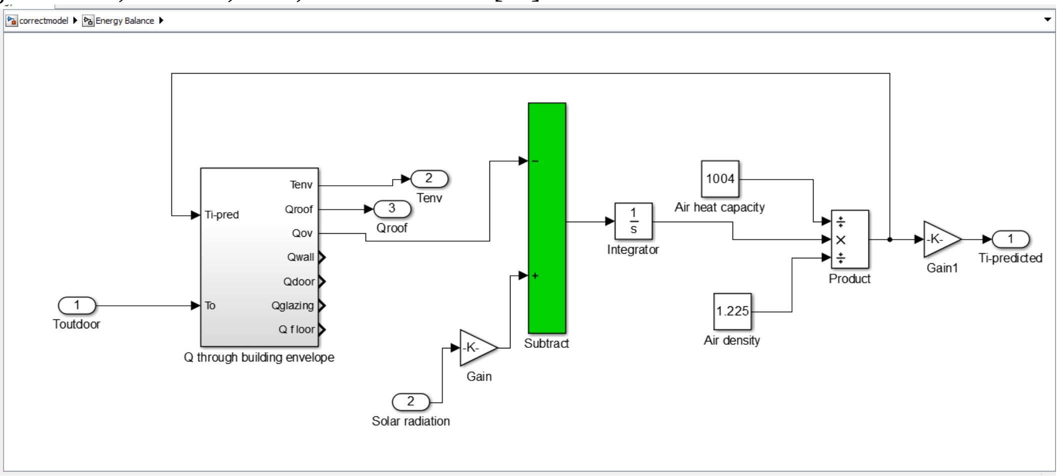


Figure 3. Block diagram of the energy balance in SIMULINK

IV. Simulation Results And Conclusions

4.1 results

The model was validated using data (temperature and solar radiation) measured at the field scale model site. The validation data was measured from 28th April to 8th May, 2014. Thereafter, the model was simulated and compared against another set of data measured between 18th May and 5th June, 2014.
Figure 4 shows the comparison graph of predicted indoor air temperatures from GRUBCLIM and the measured values. From the graph, it can be seen that the predicted values are in good agreement with the measured values. The model has a correlation coefficient of 0.885. The highest temperature value observed was 22.64°C against the highest predicted by the model at 22.08°C. Similarly, the lowest temperature predicted is 15.78°C against the measured value of 17.65°C. The highest difference recorded between the two values is 3.58°C. These differences can be attributed to the standard error of 0.0529 of the predicted values. Generally, GRUBCLIM over predicts and under predicts values at different times of the day.

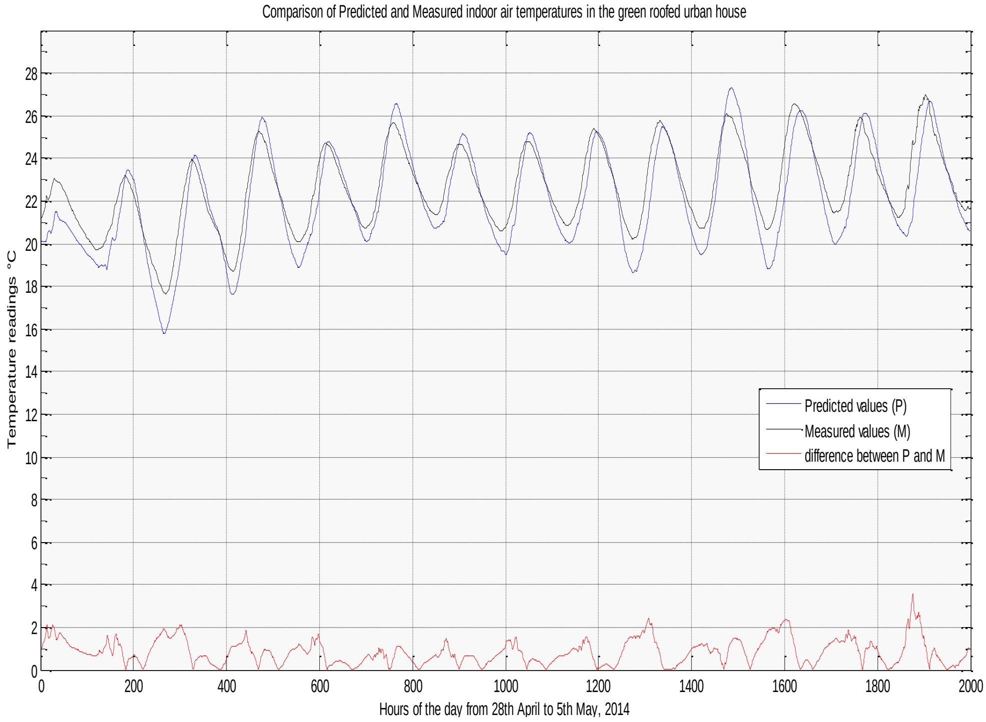


Figure 4. Graph showing the predicted air temperature from GRUBCLIM, the measured value and the difference at each point of the two values.

Figure 5 sheds more understanding to the possible reason of under and over prediction of GRUBCLIM. It can be seen that during the daytime, when the outdoor temperature is higher than the indoor temperature, GRUBCLIM under predicts. Conversely, during the night time, when the outdoor temperature is below the indoor temperature, GRUBCLIM over predicts. A z-test was carried out to compare the differences between the measured and the predicted temperature values. Results showed that there is a significant difference (means difference 0.562762) between the measured and predicted values. The analysis returned a p-value of 1.11022E-16 against the significance level of 5%.

The investigation of the degree of temperature reduction offered by the green roof showed that an average of 2.16°C difference was maintained during the daytime. The peak difference recorded during the daytime was 6.494°C at 2.00pm on 1st June, 2014. During the nights of the observation period, there was an average difference of 3.92°C between the indoor temperature of the green roofed urban building and the outdoor temperature. The lowest difference between the two measurements is 7.387°C, recorded at around 1.20am on 2nd June, 2014. This phenomenon show green roofs effectively provides thermal insulation during cold weather. Furthermore, this thermal insulation would mean the energy used in heating the indoor environment will be reduced due to the heat entrapped. Considering there is no ventilation system, the indoor thermal environment was less fluctuant thus, more heat is conserved.

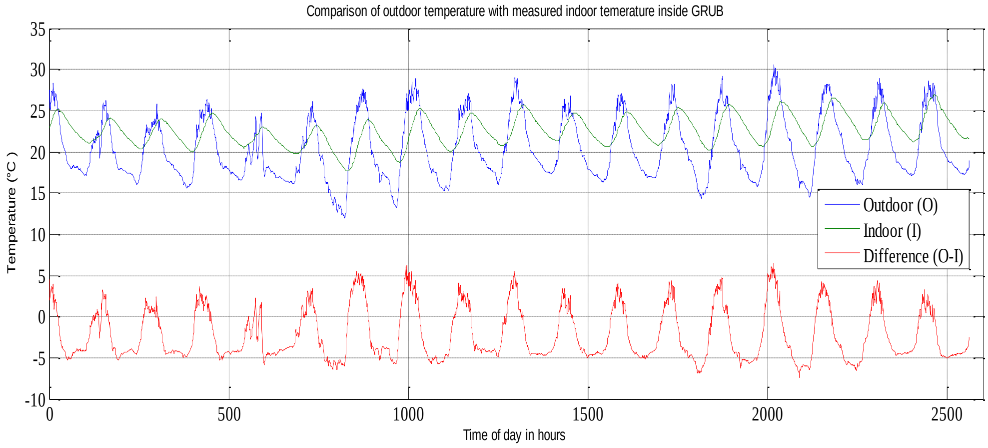


Figure 5. Graph showing the measured outdoor temperature and the measured indoor temperature inside the GRUB.

V. CONCLUSION

In this paper, a new physical model GRUBCLIM that predicts the indoor temperature of urban building with living green roofs and without any form of ventilation was modelled. A field scale model was erected at Jomo Kenyatta University of Agriculture and Technology, Juja, Nairobi to observe real time changes of a house with a living green roof. Microclimatic parameters used in validating the model were measured at the field site. Another set of data used for simulation was also measured at the field scale model site. Results of the predicted indoor air temperature were compared with the observed values at the scale model site. The results show a correlation of 0.885 between the predicted values and the observed values. This study opens our understanding of heat loss and gain of urban buildings located in Nairobi (sub-Saharan Africa) with living green roofs, without any form of ventilation, either natural or mechanical.

VI. PROPOSED FUTURE WORK

Future researches can improve the physical model also by accounting for the heat storage capacity of the building envelope. As evident from the foregoing statement, only the overall heat transmission coefficient (U-value) for the different building envelope elements was considered. This study was also carried out where airflow within buildings was favourable. Future researches can conduct the research in a denser urban environment where mechanical or natural ventilation will have to be sought after.

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