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MODELING AND SIMULATION OF HEAT FLUX AND VERIFICATION OF SUPERB POTENTIAL FOR GREEN ROOF APPLICATION IN TAMILNADU USING MICROSOFT OFFICE EXCEL SOFTWARE

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Abstract : India is the largest and densely populated country in the world and with an increase in the population, the energy demand of the country also increases steadily. It is observed that houses located in Tamil Nadu region of India are not capable to provide thermal comfort throughout a year except for two months. In the present work behaviour of green roof (GR) as compared to the conventional bare roof (BR) is analysed for the building located at Central Tamil Nadu (at Trichy city area). The experiment was conducted for a green roof and a conventional bare roof. The temperature was recorded with the temperature sensors installed at different locations. There was 36% of the reduction in the total heat flux in the green roof while comparing it with the bare one.

Index Terms - Green Roof, Heat Transfer, Heat Flux, Thermocouple, Heat Island, Heat Shield, Green Building.

I. INTRODUCTION

India is the largest and densely populated country in the world and with an increase in the population, the energy demand of the country also increases steadily. Also for a developing country to be self-sustained it needs to fulfil its energy requirement. Its demand for energy is expected to grow by 95% by 2030 [Hughes, 2013]. Coal is the primary source of energy production in India and it contributes more than 75% of the total power generated in by the year 2020 [Tiewsoh, Jirasek and Sivek, 2019]. Houses located in many parts of India are not capable to provide thermal comfort throughout a year except for two months [Cheung, Schiavon, Parkinson, Li and Brager, 2019]. The maximum temperature reaches to 48ºC during extreme summer in Trichy city area. Therefore the consumption of electricity increases to achieve the comfort temperature. Government is trying to reduce the energy dependency on conventional resources. Green roof (GR) can prove to a very good alternative to decrease the cooling load demand of the building. As the forest area and greenery is decreasing; using green roof in the ceiling area of the building can lead to many advantages. Green roof effectively helps to decrease the Urban Heat Island (UHI) and effective rainwater management. It even increases the life expectancy of the ceiling by limiting the contraction and expansion due to temperature fluctuations of roof membranes [Lindholm, Bass and Rowe, 2007]. It also improves human health, decreases the noise and air pollution [Rowe, 2011].

II. MATERIALS AND METHODS

A green roof is the roofing system supports the vegetation growth on building rooftop. Green roof affects the thermal properties of the roof in the following ways (i) substrate (soil) acts as an additional insulating material layer (ii) the plant canopy provides shading to the roof area (iii) evapo-transpiration. The soil depth, composition of the growing media and the kind of vegetation chosen according to the Leaf Area Index (LAI) are the controllable sensitive factors, which also forms the basic component of a green roof. The soil thickness usually ranges from 15-20cm to about 1m height. Experiment results showed significant temperature difference in rooftop temperature between 12-20cm soil thicknesses [Raimondo, Trifilo, Lo Gullo, Andri, Savi and Nardini, 2015]. The substrate is a lightweight porous layer that supports the growth of the vegetation by retaining moisture and providing necessary nutrients required for the growth of the plant. The filter or cloth membrane prevents drainage clogging by containing the substrate and roots. Extra water on the roof is extracted by the drainage layer to the roof drain and ventilates/aerates the substrate. Finally, the water proofing membrane prevents the moisture leakage to the roof. Section view and a component of a green roof are shown in "**Fig.1**".

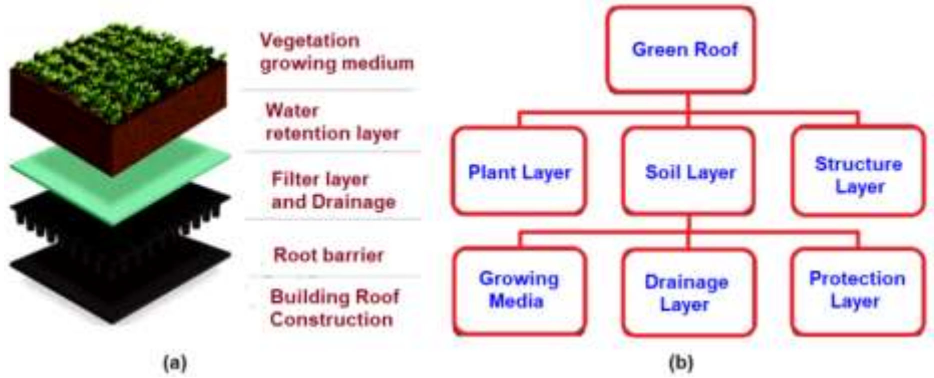

Figure 1. (a) Sectional view of green roof (b) Various components of the green roof

Green roofs are distinguished mainly of two types based on the soil depth and the height of vegetation grown as shown in "**Fig.2**". Generally, soil depth up to 20cm is categorized as extensive type green roof. Growth of large shrubs and even medium-height trees are considered to be intensive; since theplant species are greatly dependent on soil depth. Different types of plant species can be grown on the green roof such as native plants grasses, and drought-tolerant plants. The researchers have studied the performance of Sedum and Delosperma plant species on the green roof [Becker and Wang, 2011].

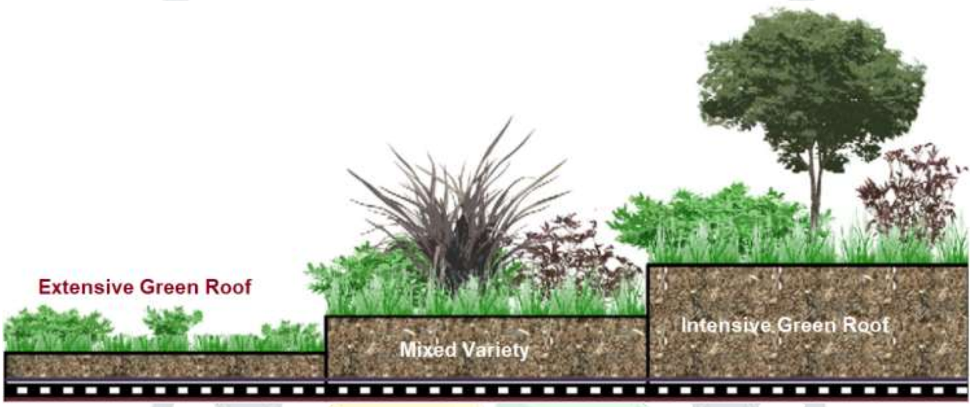

Figure 2. Types of green roof

In the present work, the thermal performance of the green roof as compared to conventional bare is analyzed for the building located at India. The vegetation on the green roof is taken as grass. The principal objective of the green roof is to provide shading to the roof to decrease its temperature as compared to the conventional bare roof (BR). The incoming short wave radiation from the sun interacts with the plant canopy and the substrate. The following assumptions were made while developing the mathematical model for calculation of the cooling demand of the building: (i) The green roof system is categorized into three layers: the plant layer, a soil layer, and the structural layer, (ii) Plant layer and soil layer are assumed to be homogeneous, and the thermal transfer takes place only along the length of the plant, (iii) The plant canopy is assumed as a layer of semi-transparent medium, (iv) The structure layer is assumed to be waterproof, and moisture transfer through the layer is negligible and (v) The biochemical process and heat transfer along the plant stems are neglected. Many heat transfer models have been developed by various researchers [Nayak, Srivastava, Singh and & Sodha, 1982; Palomo and Barrio, 1998; Sailor, 2008; Tabares and Srebric, 2012; Belinda, Hrvoje and Ksenija, 2021]. All these models consider three cases since the green roof cannot be covered 100% throughout their lifespan. The three cases are (i) Green roof without vegetation, (ii) Green roof with vegetation and (iii) Green roof partially covered with vegetation which is perhaps the best realistic scenario to be considered.

Case 1 - Green roof without vegetation : It is considered when there is no vegetation grown over the soil. It may happen because the plant is dead either due to dryness or wilt which is the worst-case scenario for the green roof (see "**Eq.1**").

$$R_{sh,abs} = (1 - \rho_{soil})R_{sh} \tag{1}$$

Soil reflectivity ρ Soil reflectivity (typically ranges from 0.10-0.35 for soil. In contrast, soil emissivity is ranged from 0.90-0.98 [9]. Out of the total solar radiation absorbed, the heat transfer will take place from the substrate to the environment. So calculating the individual film heat transfer can be done by the following procedure mentioned in "**Fig. 3**".

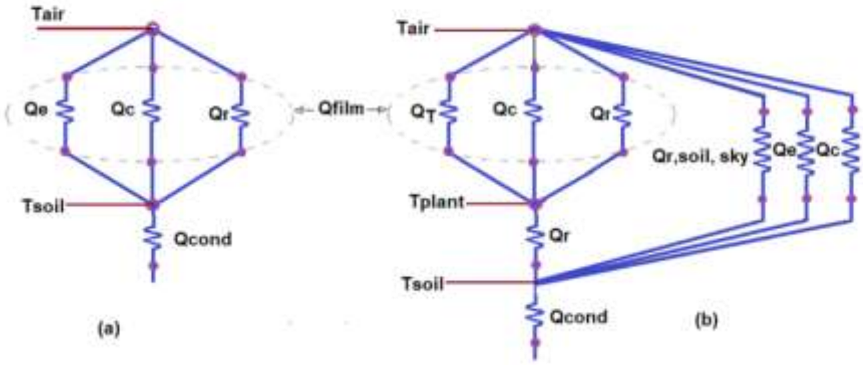

Figure 3. Resistance Network Analysis of green roof (a) without vegetation, (b) with vegetation

For substrate evaporation, evaporative heat flux (QE) through the substrate is shown in "**Fig. 3**", it can be calculated by the following equation ("**Eq.2**").

$$Q_z = \frac{\delta C_p}{\gamma(r_{subs}+r_a)}(e_{soil} - e_{air}) \quad (2)$$

Where, r_a is the aerodynamic resistance and r_{subs} is the substrate surface resistance to mass transfer, finally γ is the psychometric constant. For long wave radiative heat flux, the radiative heat transfer takes between the sky and the substrate ("**Eq.3**").

$$Q_{IR} = \epsilon_{subs}.\sigma[T^4_{top\ subs} - T^4_{sky}] \quad (3)$$

Where, $T_{top\ subs}$ is the upper substrate layer which remains in contact with the air. There are many models to calculate the sky temperature. For conductive heat flux, the heat transfer takes place between the top and bottom substrate layer through conduction. It is calculated by the following equation ("**Eq.4**").

$$Q_{cond} = k_{subs}\frac{T_{top\ subs} - T_{bottom\ subs}}{L} \quad (4)$$

Case 2 - Green roof with vegetation : It contains following 4 different conditions.For absorbed short-wave radiation, the amount of solar radiation absorbed by the plants and the substrate underneath it depends on the properties of both surfaces, as well as the vegetation density in terms of LAI. Absorbed solar radiation by the plants is given by the following equations ("**Eqs.5&6**").

$$R_{sh,abs,plant} = (1 - \rho_{plant} - \tau_{plant,solar})(1 + \tau_{plant}.\rho_{subs})R_{sh} \quad (5)$$

$$R_{sh,abs,subs} = \tau_{plant,solar}(1 - \rho_{subs}).R_{sh} \quad (6)$$

Furthermore, when the sky is clear, thermal radiation between plants, substrate, and sky needs to be considered. This can be calculated by the following two equations ("**Eqs.7&8**").

$$Q_{IR,plant,sky} = (1 - \tau_{plant,IR}).\varepsilon_{plant}.\sigma(T^4_{plant} - T^4_{sky}) \quad (7)$$

$$Q_{IR,subs,covered,sky} = \tau_{plant,IR}.\varepsilon_{subs}.\sigma(T^4_{plant} - T^4_{sky}) \quad (8)$$

For long-wave radiation between plants and substrate, radiation heat transfer between the plant canopy and the top layer of the substrate can be calculated by the following equation ("**Eq.9**").

$$Q_{IR,S,P} = (1 - \tau_{IR})\frac{\sigma(T^4_{plant} - T^4_{top,subs})}{\frac{1}{\varepsilon_{subs}} + \frac{1}{\varepsilon_{plant}} - 1} \quad (9)$$

For convective heat transfer, hat transfer in the plants through convection takes from the leaves. Also, the convection at the substrate is calculated by taking into the air velocity ("**Eqs.10&11**").

$$Q_{conv,plant} = 1.5\ LAI.\,h_{conv}.(T_{plant} - T_{air}) \quad (10)$$

$$Q_{conv,subs} = h_{subs}(T_{top\ subs} - T_{air}) \quad (11)$$

For evapotranspiration, substrate evaporation is calculated using the approach shown in the following equations ("**Eq.12**").

$$Q_\tau = LAI\frac{\delta\ C_p}{\gamma(r_s + r_a)}(e_{s,plant} - e_{air}) \quad (12)$$

Case 3 - Green roof partially covered with vegetation : This is the best case to be considered and can be calculated by taking the plant coverage into account. However, the conclusion drawn is that for this case, the green roof without vegetation and with vegetation should be calculated simultaneously to determine the total heat flux through the roof. Plant coverage needs to be considered in the model for more accurate results (“**Eqs.13&14**”)

$$Q_{subs} = \sigma_f Q_{subs\ covered} + (1 - \sigma_f) Q_{subs\ bare} \tag{13}$$

$$Q_{\varepsilon T,total} = \sigma_f \left(Q_{\varepsilon,subs,covered} + Q_{T,plant} \right) + (1 - \sigma_f) Q_{\epsilon,subs\ bare} \tag{14}$$

III. Results and Discussion

The experiment was conducted for a green roof and a conventional bare roof. The temperature was recorded with the temperature sensors installed at different locations, as shown in **“Figs. 4 & 5”**. The different heat flux associated with the green roof was calculated for a particular day on which the experiment was done with the help of mathematical model adopted above and the thermocouple-sensor accuracy is determined to be ±0.1ºC. Table 1 gives the numerical values of key input parameters used in heat flux calculation.

Figure 4. Temperature sensor placed at various locations (a) Green Roof (b) Bare Roof

The summer season in Trichy location prevails more than half time of the year as the winter season comes just for the two months. The inside room temperature is also affected by the retrofitting of a green roof in the building. The inside room temperature of the green roof remained constant around 27 ºC, we can see from **“Fig.6”**, while, that the bare room temperature reaches higher than that of the atmospheric temperature after 02.00 PM. Thus the heat coming inside also significantly reduces by incorporating a green roof. The overall heat transfer coefficient calculated for the GR was found to be 0.6641 W/m^2 K. Surface temperature measure for GR and BR are shown in **“Fig.7”**.

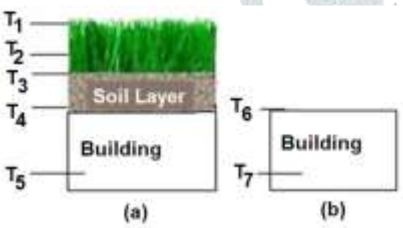

Figure 5. Schematic diagram of temperature sensor placed at various locations (a) Green Roof, (b) Bare Roof. Where, T_1=plant temperature, T_2=plant canopy temperature, T_3=top soil layer temperature, T_4=bottom soil layer temperature, T_5=inside green room temperature, T_6=bare roof temperature, T_7=inside bare room temperature.

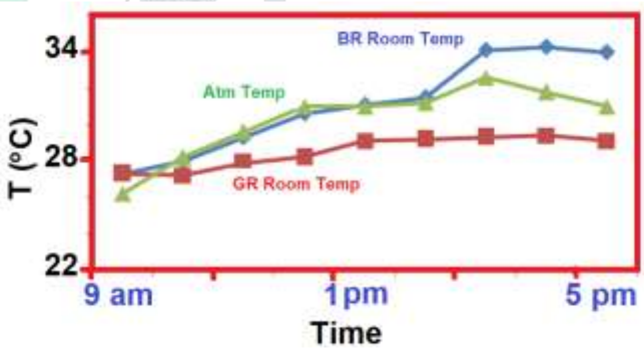

Figure 6. Inside room temperature measured on May 25, 2021

Table 1. Values of key input parameters

Parameters	Values
Leaf Area Index (LAI)	2.5
Plant height	0.07m
Thermal Conductivity of soil	0.41W/mK
Media thickness	0.18m
Foliage density	0.85

The roof membrane expands and contracts due to temperature difference and between 25-35°C it does not have much effect. In **“Fig.8”**, the bottom soil temperature does not change much throughout the day. Thus it also increases the life expectancy of the roof due to minimal contraction and expansion.

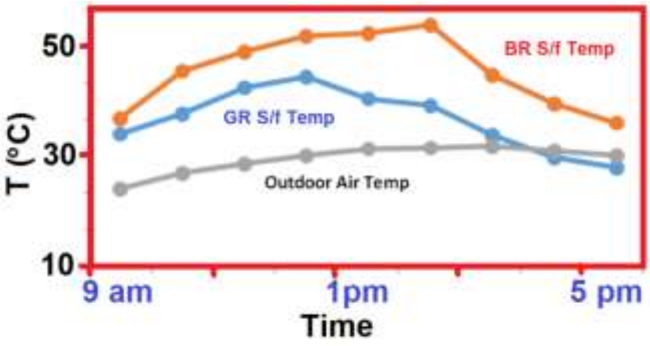

Figure 7. Surface Temperature (S/F) measured on May 25, 2021

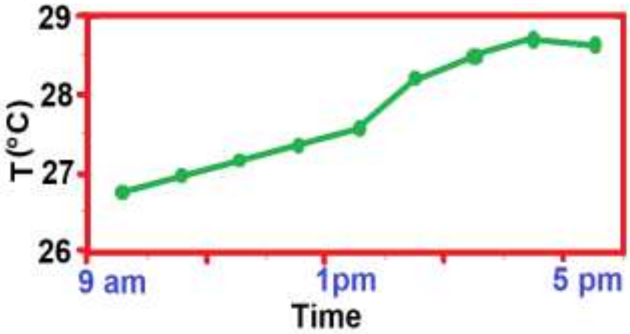

Figure 8. Bottom soil temperature as measured on May 25, 2021

The temperature measured at the various location of the GR, the top and bottom substrate. Based on this temperature the total heat flux of substrate was calculated. The foliage density and leaf area index takes place an important role in the heat flux, as it increases with an increase in these two parameters. Since the foliage density directly stops the incoming short wave radiation coming from the extraterrestrial atmosphere. Evapo-transpiration takes place in the leaf surface, therefore increase in LAI value decreases the heat going inside the room through conduction. It helps to keep the temperature nominal throughout the daytime hours. Comparison of heat flux between GR and BR is carried out in **"Figs.9 & 10"**, for throughout a day and throughout a year respectively. There was a total of 36% of the reduction in the heat flux in the green roof while comparing it with the bare roof.

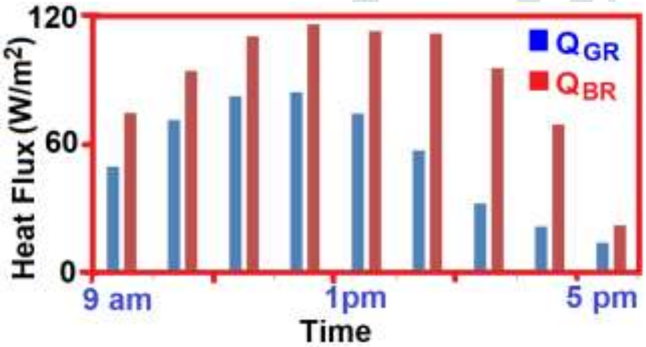

Figure 9. Heat flux through the roofs as calculated on May 25, 2021

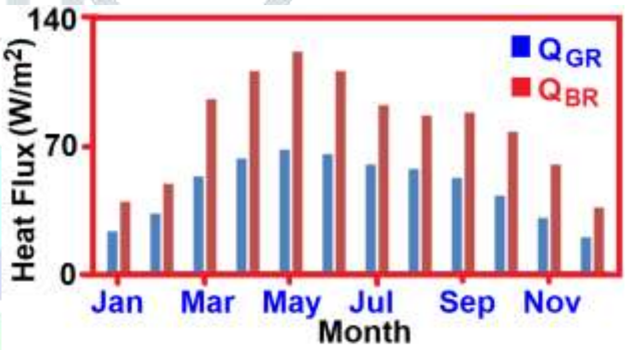

Figure 10. Heat flux through the roof as calculated for Year 2021

IV. CONCLUSIONS

The model chosen for calculation was a combination of two popular models [Palomo and Barrio, 1998 Sailor,2008]; Sailor (year 2008) model has not performed the experiment analysis and Cesar model explained in other paper [Palomo and Barrio, 1998] tends to underestimate peak evapotranspiration rates. The type of plant species chosen affects the heat transfer as the LAI is an important sensitive parameter. The overall heat transfer coefficient calculated for the GR was found to be 0.6641W/m^2 K. There was a total 36% of the reduction in the heat flux in the green roof while comparing it with the bare roof. The reduction in the total heat flux of the GR also shows the reduction in the power consumption which is also associated with the total saving in the coal used and CO_2 credit released in the atmosphere.

NOMENCLATURE

C_p	Specific heat of air, J/kg K
e_{air}	Vapor pressure of the air, kPa
e_{soil}	Vapor pressure at the soil surface, kPa
h_{conv}	Convective heat transfer for plant layer, W/m^{2}K
h_{subs}	Convective heat transfer for soil, W/m^{2}K
k_{subs}	Soil thermal conductivity, W/mK
L	Characteristics length of green roof, m
$Q_{(s,s)}$	Sensible heat flux between green roof substrate and surround air by convection, W/m^2
Q_{film}	Heat transfer between plant & surrounding by convection, transpiration & radiation, W/m^2
$Q_{(IR,subs,conv,sky)}$	Thermal radiation between substrate and sky, W/m^2
R_{sh}	Solar radiation on the surface, W/m^2
$R_{(sh,abs)}$	Absorbed solar radiation, W/m^2
$r_{(s,min)}$	Minimum stomatal resistance to mass transfer, s/m
r_s	Stomatal resistance, s/m

r_{subs}	Evaporation substrate resistance, s/m
r_a	Aerodynamic resistance, s/m
T_{sky}	Sky temperature, K
T_{plant}	Plant temperature, K
$T_{(top\ subs)}$	Soil outer layer temperature, K
$T_{(bottom\ subs)}$	Soil inner layer temperature, K
VWC	Substrate volumetric water content
VWC_{sat}	Substrate volumetric water content at saturated condition
W_{af}	Wind velocity, m/s
$\tau_{(plant,solar)}$	Shortwave transmittance of a canopy
σ_f	Foliage density
ε	Emissivity
τ_{IR}	Transmittance of thermal radiation
γ	Psychrometric constant, $KPa/^0C$
σ	Stefan-Boltzmann constant, W/m^2K^4

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