

QUANTIFYING THE EVAPOTRANSPIRATION PROCESS OF GREEN ROOF SYSTEM IN HOT AND DRY CLIMATIC CONDITION OF INDIA

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Abstract

It is predictable that approximately 40 % of universal energy is associated with the buildings maintenance and building construction so building segment is associated very huge amount of energy utilization worldwide .So there is very high energy economy prospective in building segment .Building segment are also associated 33 % of green house gas production internationally. Due to the very high amount of energy consumption in building construction and maintenance and greenhouse gas ambition .There are so many sustainable approaches and environment friendly technologies have been introduced in this category, green roofs are identified as an important energy efficient technology that could potentially offer, the several benefits to society and environment. Plants on the green roofs can purify the air, plants and substrate can purify the rain water runoff as well as delay the storm peak.

The evapotranspiration had most significant role of reducing the intensity of all the solar heat fluxes by modeling, diverting and outgoing heat flexes, depending on state of plants like desert native plants and crassulacean acid metabolism plants. Due to numerous biological reactions in experimental set up 69% of heat flexes was reduced by evapotranspiration process. We measured that temperature outside and inside temperature reduction was 46% green roof with moisture. Interestingly, the lowest conductive heat fluxes through the green roof were found when the green roof was wet.

The experimental and calculated data shows that model tends to predict 69% of evapotranspiration, 23% sensible heat, 5 % soil convection heat and 3% heat for conduction, transpiration, photosynthesis respiration reaction process for energy balance for green roof system with moisture. In the summer conditions when temperature is high thus increase the evapotranspiration process it reduces air cooling load (HVAC) inside of building.

Keywords :- Transpiration , Evaporation, Urban Heat Island , Geophytes , Photosynthesis, Stomata apertures

1. Introduction

An extensive green roof system is categorized of its plants (height < 20 cm) (U Berardi et al .,2014) ,ranging from sedums to small grasses, herbs and flowering herbaceous plants, which need small maintenance and no permanent irrigation system (W C Li et al .,2014) . The substrate depth for an extensive green roof arrangement is typically 2 cm to 20 cm. These systems are perfect for efficient storm water management with low maintenance requirement. Extensive green roofs are extremely cost efficient (Banting et al., 2005). An intensive green roof system is categorized by its selection of plants ranging from herbaceous plants to small trees with professional maintenance and advanced green roof irrigation systems. A typical growing medium depth of an intensive green roof is 15 cm to 200 cm. Semi-intensive green roofs require a deeper soil layer 12 cm to 100 cm. (Banting et al., 2005).

2. Components of green roof

According to report of UNI 11235: 2007 there are various types of layers composing in the green roofs system.

- i. Plant layer- vegetation like - Plants, shrubs, trees
- ii. Growing medium (Substrate) - Most commonly soil with fertiliser
- iii. Filter fabric layer – To protect the layer of substrate.
- iv. Moisture retention layer- Watering for dry periods.
- v. Drainage layer - Draining the extra water of the roof.
- vi. Protection mat- To protect the root barrier from destroy.
- vii. Root barrier layer- To protect building roof from the roots of the plants and trees made of hard plastic .
- viii. Water proofing layer – To protect the roof from filtration of water normally made of PVC or bitumen.
- ix. Structural layer –Main function is bearing the load.

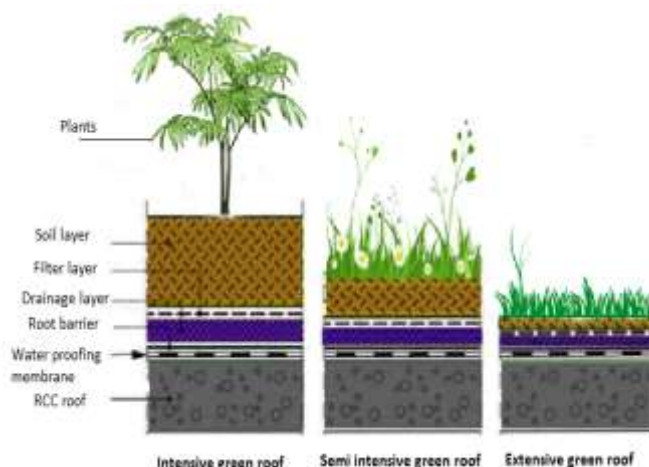


Figure No 1 : Typical section of intensive , Extensive green roof system

2.1 Plants layer

The plants are upper most layer of the green roof system .The success of green roofs depends on the physical condition of the plants. The Plants improve, air quality and thermal performance, storm water runoff quality (k Vijayaraghavan et al.,2016) .The foliage protects the building from solar radiation and reduce the temperature inside of building. Due to the biological reactions of plants such as photosynthesis, respiration ,evaporation and transpiration absorb the a important segment of solar radiation (A. Niachou, et al ., 2001).The top surface area of foliage and its roughness make vegetation more effective to sink of all pollutions. Vegetation also has direct impact on pollution sinking and modifying macroclimatic conditions (Beckett et al., 1998).

2.12 Succulent plants

Succulent plants are plants that have several parts are more than usually thickened and fleshy, usually to retain water in hot and dry climates. Succulent plants may store water in various structures, such as leaves and stems. Some definitions also include roots, thus geophytes that stay alive critical periods by dying back to underground storage organs may be regarded as succulents. Succulents are often developed as decorative plants because of their outstanding and unusual appearance. Succulent plants are generally appropriate for extensive green roofs in hot and dry climatic conditions, because of their survive in draught conditions (Dvorak B. et al., 2010).

Name of species	Survival time without water	References
Sedum spp.	Four months	Durhman A. et al ,2006
S . Rubrotinctum	Two years	Terri J. et al ,1986



Table No 1 : - Characteristics of Sedum Plants

Figure No 2 : Succulent plants

2.13 Crassulacean acids metabolism

Crassulacean acid metabolism, also recognized as CAM photosynthesis, is a carbon fixation pathway that evolved in several vegetation as an adaptation to arid conditions. In a plant using full CAM, the stomata in the leaves stay shut during the day to reduce evapotranspiration, but open at night to collect carbon dioxide (CO₂).CAM which can increase water use efficiency allowing stomata opening and CO₂ store during the night when evapotranspiration rate is lower than during the day (Ting et al ,1985).Thus CAM plants which can stay alive for a long periods of time without watering (Liu et al ,2012)

2.2 Growth substrates

Growth substrate easily manipulate the plant growth and performance of green growth .Consequently choosing the suitable substrate is a important for successful performance of green roofs .It is always recommended to design green roof substrate using local waste materials which can make green roof more economical. It is recommended that substrate should have low dry and wet bulk density because the majority of the buildings have load limitations particularly the older buildings (Viayaraghavan , Raja et al .,2014). Water holding capacity of substrate of substrate is another significant property for survival plants under drought environment. Water holding capacity also facilitate to use non succulent species (Viayaraghavan , Raja et al .,2014) .

3.0 Irrigation to green roofs

Green roof could utilize grey water as an irrigation sources (Van Mechelen et al ., 2015) .Grey water accounts 65 % to 90 % of domestic waste water production which originates from kitchen , bathroom ,laundry (Katukiza A. et al ., 2014). The application of grey water solves water requirements and also enables to selects more vegetables species .Grey water from kitchen usually rich in nutrients hence minimise fertilizer requirements of green roofs (Ouldboukhithine S et al ., 2014) . Biological oxygen demand (BOD) of grey was significantly reduced after passing through green roof. So green roofs may serve as a filter for grey water (Cameron R. et al., 2009) .

4.0 Heat and mass transfer of green roof

4.1 Transpiration process

Transpiration is the procedure of water movement throughout a plant and its evaporation from above ground parts, such as leaves, stems and flowers. Water is necessary for plants but only a small amount of water taken up by the roots is used for expansion and metabolism. The remaining 97–99.5% is lost by transpiration and water drops on surface. Leaf surfaces are dotted with pores called stomata, and in most plants they are more frequent on the undersides of the foliage. The stomata are bordered by guard cells and their stomata accessory cells that open and close the pore. Transpiration occurs through the stomata apertures, and can be thought of as a necessary "cost" associated with the opening of the stomata to allow the diffusion of carbon dioxide gas from the air for photosynthesis (Principle of Physics).



Figure no 3 : Transpiration,

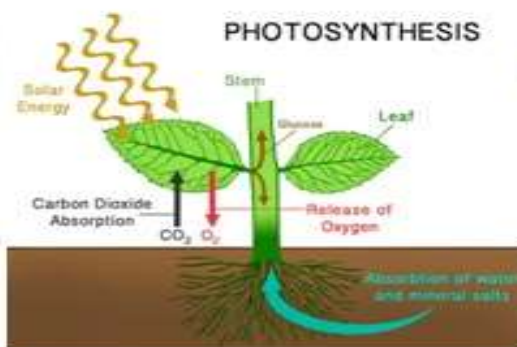


Figure no 4: Evaporation

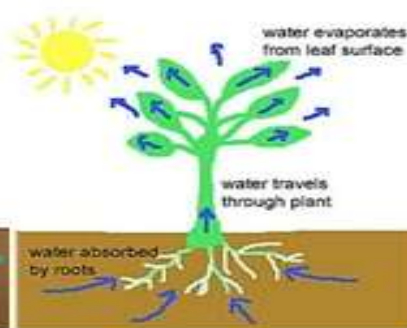


Figure no 5 : Photosynthesis of plants of plants

4.2 Evaporation of moisture of soil

Evaporating surface when the molecules of the liquid collide, they transfer energy to each other based on how they collide. When a molecule close to the outside absorbs sufficient energy to overcome the vapour pressure, it will escape and go into the surrounding air as a gas. When evaporation occurs, the energy removed from the vaporized liquid will thus decrease the ambient temperature of the liquid, ensuing in evaporative cooling (Principle of Physics) .

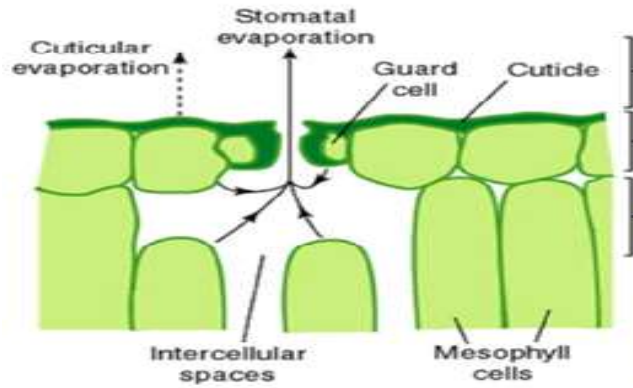


Figure No 6 :- Stomata of leaves

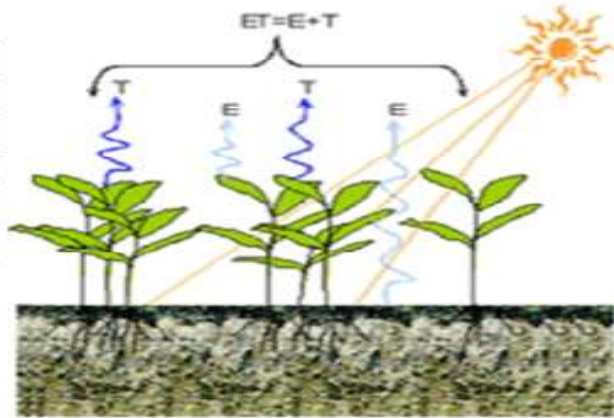


Figure No 7 :- Evapotranspiration process

4.3 Energy balance for a green roof

The thermal presentation of green roof is the difficult due to heat and mass transfer process through the roof by mean of Evapotranspiration is combine process of transpiration in plants and evaporation process on the surface of soil .Transpiration occurs when water from the leave surface goes into the air by convection .Most of the water is lost by transpiration process through plant stomata which is adjustable by small porous of in the leaf that allow the entry of gas needed for photosynthesis such as carbon dioxide and release oxygen and water vapour thus plant can control their transpiration rate by opening and closing their stomata (Paulo Cesar Tabrares Velasco and Srebric, et al ,.2009) . The energy balance for a green roof can generalized as following equation (Hillel et al ,.1998),(Jones et al ,.1992).

$$R_n = ET + Q_{sensible} + Q_{conduction} + S_{thermal} + M$$

Whereas - R_n = Net radiation solar radiation flex, ET = Evapotranspiration or latent heat flux by convection, $Q_{sensible}$ = Sensible heat flux by convection, $S_{thermal}$ = Thermal heat storage for soil, M = Metabolic heat storage for photosynthesis and respiration.

In this equation thermal heat storage of vegetation is normally ignored by the most of green roofs models. The metabolic solar heat storage is normally neglected because its contribution to the total energy sum is around 1% to 2% of net solar radiation in extensive green roofs (C Feng et al., 2010). (Jones 1992, Gates ,.1990) (C Feng et al., 2010).

The radiation balance for a leaf of a plant can be expressed as following (Jones et al ,.1992) ,(Nobel et al ,.1993) .

$$R_n = R_{sh} (1 + \alpha_{soil}) (1 - \alpha_{leaf}) + (\sigma \cdot T_{sky}^4 + \sigma \cdot \epsilon_{soil} \cdot T_{substrate}^4 - 2 \cdot \sigma \cdot \alpha_{leaf} \cdot T_{leaf}^4)$$

Where, R_n =Total solar radiation, R_{sh} = Solar or short wave radiation on the surface, α_{soil} =Albedo or reflectivity of the soil, α_{leaf} = Albedo or reflectivity of the leaf, σ = Stefan-Boltzmann constant , ϵ_{soil} = Emissivity of soil, ϵ_{leaf} = Emissivity of plant leaf, $T_{substrate}$ = Top substrate temperature, T_{leaf} = Temperature of leaf

4.4 Evapotranspiration process

Evapotranspiration is a combined name of evaporation and transpiration process. Water lost from soil surface called evaporation and transpiration process occurs in plants. Transpiration is the procedure of water transported through a plant and its dissipation from parts, for example, leaves. Water is essential for plants yet just a little measure of water taken up by the roots is utilized for development and digestion. The amount of 97% to 99.5% water is lost by transpiration. Most of the water losses in plants are through plant stomata. Stomata are flexible little pores in the leaf that permit the passage of gases necessary for photosynthesis therefore the discharge of O₂ and water vapor. Evaporation of fluid water into water vapor requires energy, which for this situation comes essentially from the capacity of the surrounding air thus decrease the temperature of ambient air. The creating force for evapotranspiration is the Vapor Pressure Deficit (VPT).The method to calculate evapotranspiration was developed by (Dalton in 1802). (Dalton's law of partial pressures)

$$E = (e_s - e_{air}) \cdot f(u) \quad (\text{Dalton in 1802})$$

$$f(u) = 74.4 (1 + 0.53 u) , w / m^2 / k Pa \quad (\text{Jensen et al ,.1990})$$

e_s = Vapor pressure at evaporative surface , e_{air} = Vapor pressure of air , $f(u)$ = function of wind speed.

According to August-Roche-Magnus formula temperature dependant on latent heat according to that saturated water pressure changes approximately exponentially with temperature under typically atmospheric conditions.

$$e_s(T) = 6.1 \exp (17.625 T / (T + 243.04))$$

whereas $e_s(T)$ = Saturated vapor pressure at particular temperature, T = Temperature of surface .

Bowen ratio is a method to calculate heat loss or gain .It depending on the water quantity in the soil (Jacobs et al., 1997)

$$\beta = Q_h / Q_e = Q_{sensible} / ET$$

$$ET = h_{convection} \cdot \Delta T / \beta = \text{Evapotranspiration (Latent heat)}$$

Where β = Bowen ratio

5.0 The model of experimental system

The building models were established in Jodhpur. The climate of Jodhpur is of an extreme type, with the variations in temperature range being very high. The Weather of Jodhpur is hot and dry, a typical desert weather. The average annual rainfall is approximately 32 cm. In summer, the maximum temperature is around 42 deg and the minimum temperature is around 37 deg C. In winters, the maximum temperature is around 27.5 deg C and the minimum temperature is around 15.5 deg C. Jodhpur is bright and sunny throughout the year. The experimental



Figure No 8 Block E, D, C building models (1m x 1m x 1m) green roofs without insulation outside



Figure No 9 Block E, D, C test cell (1m x 1m x 1m) green roofs covered with thermocol sheet

models of green roof with plants, green roof without plants and bare RCC were constructed on the terrace of Department of Architecture and Town Planning in M.B.M. Engineering College Jodhpur, Rajasthan .The experimental sessions described in this thesis from June 2017 to December 2017.The green roofs have an extensive type. We constructed five building models, the size of each model was 1 M x 1M x 1M and their walls was constructed.

5.1 Section of green roof system (Experimental)

The typical cross section of green roof system is shown Figure No-4.5 top first layer is plants 6” , second 100 mm thick soil layer ,third fabric filter 1.5 mm thick ,forth super aggregate size 6 mm 12 mm thick layer (Drainage layer) ,fifth layer 10 mm thick ceramic tile root barrier of plant ,six PVC plastic sheet 1 mm thick for the water proofing ,seventh RCC roof 100 mm thick the roof structure of building. The following instruments used for the field measurement: Dry bulb thermometer for Air temperature, Wed bulb thermometer for Air temperature at 100% humidity, Infra red thermometer for Temperatures of foliage of plants, soil and RCC surface , Pyranometer for Solar heat fluxes, Velocity meter for Air velocity .

5.2 Experimental data analyses

This chapter we compare the different methods used to measure the same physical phenomenon. The dynamic performance of different heat fluxes will be analyzed. The most significant role of evapotranspiration, convection, conduction Figure No 10 calculation of R- value of plant heat transfer processed and analyzed.

$$Q_2 = (T_1 - T_2) / (R_p + R_o) = (T_2 - T_3) / R_o$$

whereas –

T_1 = Surface temperature of leaf

T_2 = Surface temperature of soil

T_3 = Temperature inside of C- block

R_p = R-Value of plants

R_o = R-Value of remaining green roof

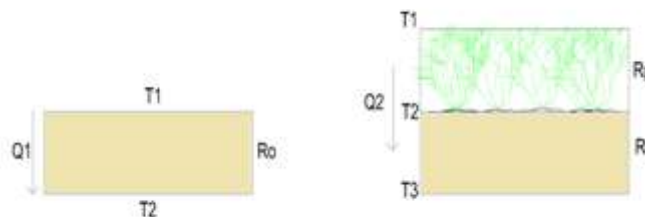


Table No :-2 Heat balance at foliage of plants

Date	Net short wave radiation (SW) for leaf at 2.00 pm (w/m ²)				Net long wave radiation (IR) at the surface of leaves (w/m ²)
R_n	$R_{sh} \cdot (1 + \alpha_{soil}) \cdot (1 - \alpha_{leaf})$				$(\sigma \cdot T_{sky}^4 + \sigma \cdot \epsilon_{soil} \cdot T_{substrate}^4 - 2 \cdot \sigma \cdot \alpha_{leaf} \cdot T_{leaf}^4)$
	R_{sh}	$(1 + \alpha_{soil})$	$(1 - \alpha_{leaf})$	Total	0.178
23.06.17	1012	1.1	0.7	779.24	0.167
09.07.17	988	1.1	0.7	760.76	0.082
12.09.17	780	1.1	0.7	600.6	0.057
11.10.17	652	1.1	0.7	502.04	0.178

Sky is clear, Wind speed moderate. Heat flux can be calculated by following equation:-

- $S_h = S_o \cdot \tau^m \cos z$
- S_h = Net solar radiation
- S_o = Solar constant = 1360 w/m²
- Z = Solar zenith angle
- τ^m = Heat Transmittance

τ^m varies .5 to .8 (C y Lim et al. , 2011) june-0.8, july-0.7, September 0.6, October -0.5

Table No 3: -Solar radiation calculation at foliage of plant and validation with experimental value

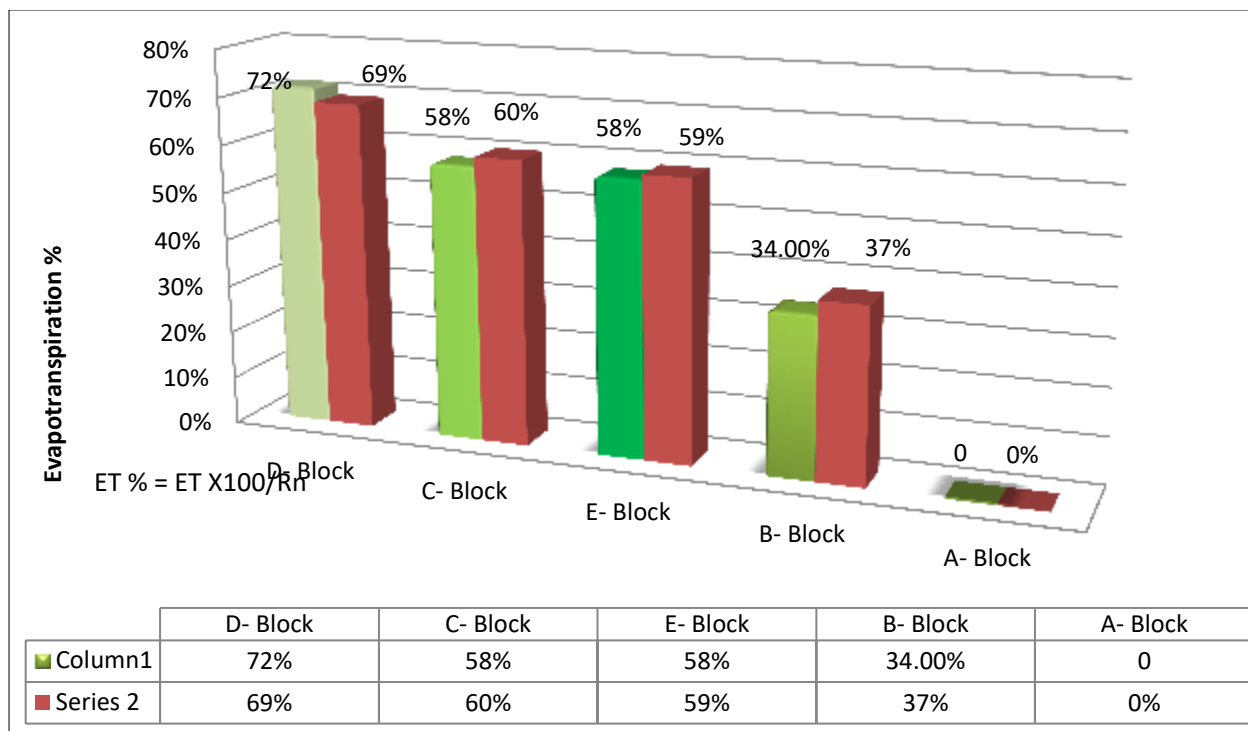
S_o w/m ²	τ^m (C Y Jim et al . 2011)	$\cos z$	$g_h = S_o \cdot \tau^m \cos z + S_o$ $(0.271 - 0.294 \tau^m) \cdot \cos z$	$g_{h\ net} = g_h$ $(1 - \alpha)$	Experimenta l value	Error %
1360	0.8 (June)	1	1136.69	795.7	779.24	4.4 %
1360	0.8 (July)	1	1136.69	795.7	760.76	2.1 %
1360	0.6 (Sept)	1	944.66	661.3	600.6	9.2 %
1360	0.5 (Oct)	1	848.64	594.0	502.04	15.5 %

Table No 4 :-- Heat flux mathematical values and experimental value comparisons

Heat flux with experiment		$S_h = S_o \cdot \tau^m \cos z$ (Theoretical value)	Percentage error
23.06.17	1012	1088	7.51
10.07.17	988	952	3.64
12.09.17	840	816	2.86
11.10.17	786	680	13.49

Table No 5 - Evapotranspiration calculation (Percentage) and ($Q_E \times 100 / R_n$) value (Green roof)

Evapotranspiration value	D-Model green roof	C- Model green roof	E- Model green roof	B- Model Soil top	A-Model Bare RCC
Dalton's law in 1802, August Ronche Mangnus formula	72 %	58 %	58 %	34 %	00 %
Newton's law of cooling Bowen ratio (β)	69.2 %	60.72. %	59.88 %	37.9 %	00 %
Tabares Valsco and Srebric et al., 2009	68 %	-	-	-	-
Gates et al ,1980	85 %	-	-	-	-
C Feng et al ,.2010	58.4 %	-	-	-	-
Lazzarin et al ,.2005	63 %	-	-	-	-



Graph No 1 : Calculation of evapotranspiration (Evapotranspiration percentage of various green roof)

If we compare the evapotranspiration of green roof with plants experimental and theoretical value these values have small differences. These differences may have due to sizes and angle of leaves, leave area index, climatic conditions, air velocity, air temperature health of plants, density of plants, seasons (summer, winter) ,characteristics of substrate .

According to data of green roof with moisture building model with moisture –D and the values of evapotranspiration predicted by Tabrares Velasco and Srebric, 2009 , Gates et al ,1980 ,Feng et al, 2010, Lazzarin et al ,2005 ,all the values have small differences thus we can say that our experimental , calculated data and recommended value evapotranspiration of Tabrares Velasco and Srebric, 2009 , Gates et al ,1980 , Lazzarin et al ,2005 numerical data shows similar trends .Evapotranspiration rate both of the cases green roof with plants and green roof without plants were estimated and the result shows that green roof without plant is very effective comparative to bare RCC roof

Conclusion

The theoretical data , to estimate thermal performance of extensive green roof is compared with experimental data .It shows that shortwave radiation has a positive relationship with sunshine duration and in clear sky condition (no clouds) the amount of infra red radiation estimated less than 1% comparative to shortwave radiation. Thermal performance of long wave radiation is negligible for calculations when sky is clear.

The sensible heat depends on air convection rate which is largely regulated by the temperature gradient between surface temperatures results shows convection heat of bare RCC roof is always very high to green roof .In addition, more heat storage is observed in green roofs due to lose of evapotranspiration (Latent heat) consumption The evapotranspiration heat consumption is notably more efficient in hot and dry climatic areas .Its efficiency on a summer sunny days becomes very high. The height of plants alone is not crucial factor affecting the thermal performance of extensive green roof.

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