ASSESSMENT OF GREEN ROOF ENERGY SAVINGS COMPARED TO CONVENTIONAL ROOF

Ghassem Heidarinejad[1], Arash Esmaili[2]

[1]Tarbiat Modares University, Tehran, Iran

[2]Tarbiat Modares University, Tehran, Iran

ABSTRACT

Modeling of mass transfer and heat transfer in Green Roofs as an excellent new way to reduce building cooling load is obtained through solution of governing equations in four components of the roof structure, growth environment, vegetation and air. The governing equations for each component includes non-linear equations and the coupled mass transfer and heat transfer. Based on results contribution of plant metabolisms heat flux is 11.1% which shows that cannot be neglected. Over 40 models among 100 are adopted for the evaluation of thermal, physical and biological parameters in order to achieve best accuracy in numerical results (with average difference of 8% with experimental data). Finally from assessment of cooling potential it can be concluded that the green roof, compared with conventional roof, causing a significant reduction in the surface temperature of the roof (as much as 44 degrees Celsius) and consequently reduce 77 percent of the flux through the roof inside the building.

INTRODUCTION

World energy consumption is on the rise where buildings are in the upper portion of the account (40 percent in the U.S.) [1]. The amount of energy consumed is increasing due to the factors such as population growth, economic growth and energy demand for the modified and new services, like electronics. An increase in energy consumption is not without an increase in air pollution, since, a big share of energy is produced by burning fossil fuels and releasing detrimental gases in the air.

A large portion of the total energy consumed in the buildings, is for air conditioning; therefore, finding a manner to reduce energy consumption with respect to cooling, can significantly reduce the burden directly, as well as the greenhouse gas emissions indirectly. One of the technologies to reduce cooling loads is *Green Roof* which is a special type of roof

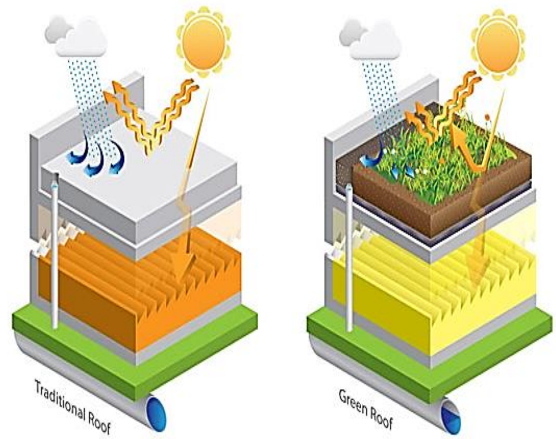

Figure 1- heat dissipation in green roof in contrast with conventional roof

implementation system, where plants are grown on the conventional roof tops. Plants on the roof, prevent direct sunlight incident on the roof surface. The plants have different radiative and thermal properties compared to the building materials and through their two main mechanism of photosynthesis and transpiration, they contribute to disposal of the heat absorbed by the roof (Fig.1)

For modeling the heat and mass transfer in green roof, Barrio introduced a model based on the three elements of plant, soil and structure [2]. In her model, which is one of the first basic models in green roof, simplified representation of the dynamic thermal behavior of actual green roofs has been done and sensitivity analyses have been carried out to assess the cooling potential of green roofs in summer. In the model volumetric water content of soil is considered as a constant, while the air between the canopies is not accounted for separate analysis. In another model the governing equations related to plant and soil are solved, but the thermal inertia of soil is neglected in spite of improvement in soil modeling [3]. Alexandri and Jones have presented a model that includes heat and mass transfer equation and variable air humidity but the role of plant metabolism has been neglected

[4].Studies have been also carried out in recent years; in a study multilayer heat transfer scheme has been used [5] and in another heat transfer through a green roof has been partitioned into two stages of the heat budget of the plant layer and the substrate surface, and the conduction of heat through the substrate to the underlying structure and for each part different strategies has been utilized [6]. Both of the studies neglect the significant role of plant metabolism in their modeling. Feng et al have shown that this phenomenon can't be ignored in green roof energy balance but their calculations in other mechanisms of heat transfer is very rough [7] so there is need for a study to calculate all of the heat and mass exchange phenomena by exact numerical solution of the governing partial differential equations with considering contribution of plant metabolisms.

In this study the mass and heat exchanges between the air and vegetation are considered. Unlike the previous models the role of the plant metabolism is accounted for and by modeling the air above the canopy, the mitigation of urban heat island (UHI) effect by green roof can be quantified.

METHODOLOGY

The one-dimensional model of green roof in current research consists of 4 elements; air, plant, soil and roof structure. In each one of the elements of the system, equations of heat and mass transfer are solved according to relevance among them. Boundary conditions are determined to match the physics of the problem and to guarantee the conservation of heat and mass fluxes.

Moist urban air is considered as the binary mixture of air and vapor which govern the following equations;

$$\frac{\partial T}{\partial t}=\alpha_a\frac{\partial^2 T}{\partial z^2}+\frac{DQ*}{c_{pa}}-(\frac{c_1-c_2}{c_{pa}})(D\frac{\partial q}{\partial z}\frac{\partial T}{\partial z}) \tag{1}$$

$$\frac{\partial \varphi}{\partial t}=D\frac{\partial^2 \varphi}{\partial z^2}+\frac{Dc_{m1}Q*}{T}\frac{\partial^2 T}{\partial z^2} \tag{2}$$

where, T is temperature (K), t is the time (sec), z is the vertical dimension (m), α_a is the coefficient of thermal diffusivity of air (m^2/s), D is the binary diffusion coefficient (m^2/s), $Q*$ is the isothermal mass transfer heat (J/kg), c_{pa} is the isobaric specific heat capacity of air (J/kgK), c_1 and c_2 are the isobaric specific heat of moisture and air, respectively, and φ is the moisture content of air (kg of the substance /kg of the dry body). In Eq (2), the c_{m1} is the specific mass capacity of moisture.

Soil is considered as the porous medium. One of common soil types in green roof is silt loam and based on this type thermophysical and hydraulic properties has been extracted from soil science handbooks [8]. Heat and mass transfer equations in soil are presented as follows [9]:

$$\frac{\partial T_s}{\partial t}=\frac{1}{\rho_g c_g}\frac{\partial}{\partial z}(K_s\frac{\partial T_s}{\partial z}) \tag{3}$$

$$\frac{\partial \omega_g}{\partial t}=\frac{\partial}{\partial z}(K_g(\frac{\partial \psi_p}{\partial z}+1)) \tag{4}$$

$$\psi_p=\psi_{p,s}(\frac{\omega_{g,s}}{\omega_g})^b \tag{5}$$

where, $\rho_g c_g$ is the heat capacity of mixture (soil, water and air) (J/ m3K), K_s is the thermal conductivity of mixture (W/mK), ω_g is the volumetric water content of the soil (m^3 of liquid water / m^3 of the soil-water-air mixture), K_g is the hydraulic conductivity of soil (m/s) and ψ_p is the moisture potential of soil tension (m). in Eq. (5) $\psi_{p,s}$ and $\omega_{g,s}$ are moisture potential and volumetric water content of soil in saturated state. Both of these parameters along with b are dependent to type of soil.

Soil moisture is obtained by solving the Richard equations [10]. Moisture content at every level of soil (as a porous medium) is subject to gravity and capillary forces. The moisture exchange among soil, air close to soil and plant tissues greatly influence the soil moisture balance.

Roof material is considered to be concrete and conductive heat transfer is predominant in this area.

Heat and mass transfer in plants

Unlike construction materials, plants are living beings which respond to the environment. Plants affect the energy balance through two important natural processes: evapotranspiration and photosynthesis.

Evapotranspiration is a combined process of evaporation from soil and transpiration in plants' living tissues. Since the evaporation and transpiration occur simultaneously and are very difficult to be studied on separately, their combined effect can be considered as a phenomenon named evapotranspiration.

Photosynthesis is the synthesis of organic compounds, usually the carbohydrates, by using carbon dioxide and water, which can convert solar energy into chemical energy.
Here, a model is introduced for photosynthesis based on radiation intensity. In this model, first, the integrative effect of photosynthesis and evapotranspiration is captured in 24h interval, next, for instantaneous calculation; this captured effect is divided and weighed by radiation intensity in a certain moment of *(t)* as follows:

$$q_{ph}(t) = \frac{\int_t^{t+dt} I(t)dt}{\lambda \int_0^{24h} I(t)dt} \frac{\Delta H_{reac}}{ETP} \frac{R_{ph,net}}{M_{C_6H_{12}O_6}} \times \int_0^{24h} q_{ETP}(t)dt \qquad (6)$$

where, q_{ph} is the photosynthesis heat flux in time t, I is the radiation intensity, ΔH_{reac} is the enthalpy of photosynthesis reaction, *ETP* is the evapotranspiration rate, $R_{ph,net}$ is the net photosynthesis rate, $M_{C6H12O6}$ is the glucose molar mass, and q_{ETP} is the evapotranspiration heat flux. It should be noted that the procedure mentioned above is only valid for plants that use CAM pathway.

RESULTS

The results obtained from computer program (FORTRAN code which has been produced completely by author) are compared with that of the published experimental results [4].

As observed in Fig.2, the numerical and experimental data are in good agreement. The maximum difference of about 15% in temperature occurs during the day due to an increase in the performance rate of mechanisms such as photosynthesis and transpiration of the plants. It should be known that the mathematical model of this phenomenon (due to their complexity) cannot simulate the complete occurrence.

After validation of the computer codes and checking the grid independency, the program is designed for a hot summer day (with maximum irradiation of 1280 W/m^2 and maximum temperature of 306 K) simulation and some other results has been obtained.

In Fig.3 vertical temperature profiles of the plant in different hours has been shown. As observed, in the early hours of the day the temperature is at its minimum state. By starting irradiation the plant temperature increases. The temperature of the lower layers of the plant is less than the upper layers due to the shading effect. This effect applied to the model by considering extinction coefficient for solar radiation through vegetation layer.

Also contribution of heat fluxes in green roof system as a whole has been obtained and the results which is shown in Table 1 indicates that plant metabolisms and specifically photosynthesis can't be neglected form green roof energy balance.

The program is run again, this time for a conventional roof and results are compared with the green roof results (Fig.4). This comparison is made for air 1 meter above the roof, boundary air node (BAN), roof surface (BSN, soil for green roof and concrete for conventional roof), 10 centimeter inside roof structure, and the internal roof surface.

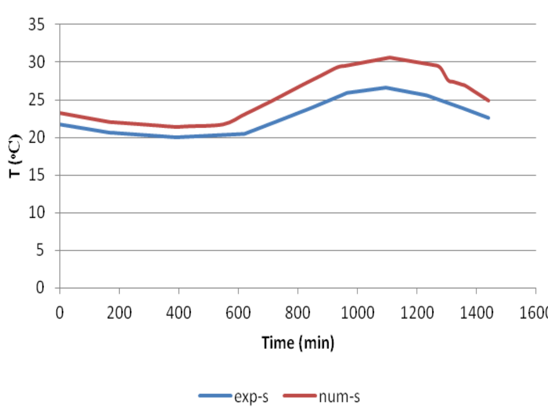

Figure 2- Numerical results Vs. experimental data on middle soil node

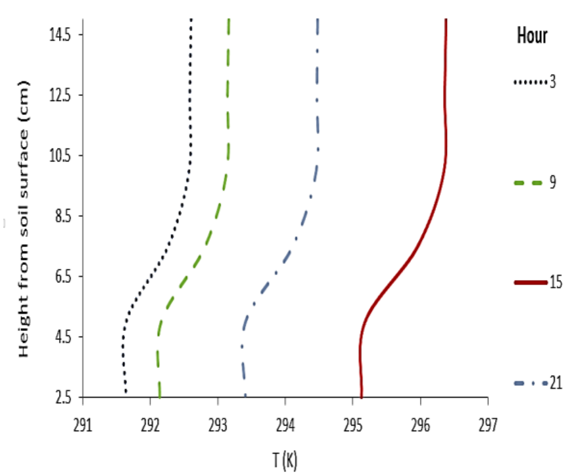

Figure 3- Plant temperature profile in 6-hour period in 24 hours

Table 1- contribution of heat fluxes in green roof energy balance

FLUX TYPE	FLUX NAME	CONTRIBUTION %
In	Solar Radiation	100.0
Out	Evapotranspiration	53.2
	Convection	6.5
	Photosynthesis	11.1
	Net Longwave Radiation	26.4
	Transmitted to the Building	1.3
Storage	By Soil	1.1
	By Plant	0.4

Solid lines and dashed lines relate to concrete and green roof, respectively. As observed here, the green roof by its thermal mass, the specific radiation properties and plant metabolisms mitigates the mean value and the minimal and maximal of temperature domain, which shows indicating its influence on both the indoor and outdoor air qualities.

Cooling effect of green roof can be sensed by temperature difference of corresponding points in conventional and green roof which is 13, 44, 28 and 6 degrees of Celsius for air 1 meter above the roof, roof surface, 10 centimeter inside the roof structure, and indoor air node, respectively.

This dual effect is also reported for green facades which can be a proof for existence of this phenomenon [11].

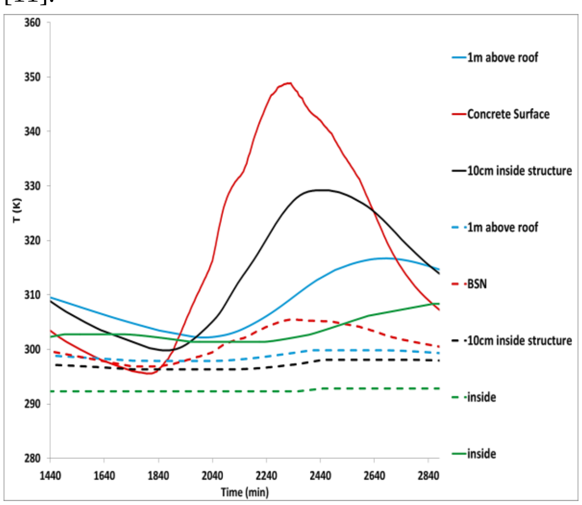

Figure 4- Comparison of temperatures of green roof and conventional roof

As for a quantitative survey, the heat flux passage is computed by considering 1 m^2 of both concrete and green roof. Calculations indicate that in hottest period of the day 132.5 W/m^2 of heat flux is transmitted through the concrete roof, while only 30 W/m^2 is transmitted through the green roof, indicating about 77% reduction in heat flux transmission (Fig.5).

CONCLUSION

Green roof modeling involves vast number of theoretical, empirical and semi-empirical theories, models and equations, while selecting the most consistent and intelligent of them would yield accurate results. There exist some simplifications in modeling which endanger the validity of the model. For example considering air and plants as a single solid layer or assuming constant hydraulic and thermal properties for all layers of soil without considering moisture transfer convert the novel bioenergy problem to a simple U-value heat transfer problem.

In validation step the average difference between numerical results and experimental data is about 8%, indicating a good agreement. Nonetheless, one should note that no experiment is free of instrument or human error.

These results indicate that the green roof has a significant effect on reducing the energy consumption required for cooling a building and urban heat island effect, simultaneously.

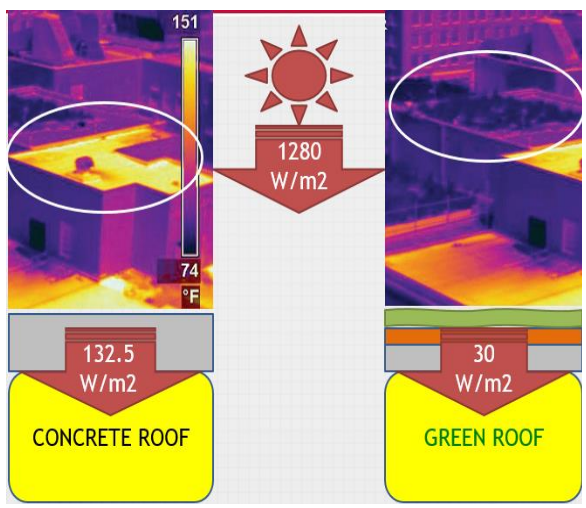

Figure 5- Comparison of heat flux transmission in green roof and concrete roof

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