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Thermal regulation performance of green living walls in buildings

Dr. Sam C. M. HUI* and Miss ZHAO Zheng

Department of Mechanical Engineering, The University of Hong Kong
Pokfulam Road, Hong Kong
* E-mail: cmhui@hku.hk, Tel: (852) 2859-2123, Fax: (852) 2858-5415

Abstract

Green living wall is an emerging new technology and a sustainable design strategy for high performance green buildings. By using the natural processes of the vegetation, it can provide the potential benefits for mitigating urban heat island, enhancing building's thermal performance and improving air quality. For densely populated urban cities like Hong Kong, the space available for greening is very limited and green living walls can be applied to the exterior and interior surfaces of buildings to improve the city environment.

This research aims to investigate the thermal regulation performance of green living walls. The basic principles and mechanisms of thermal regulation of green living walls were studied. The major characteristics of the heat transfer processes were evaluated and the key factors affecting the thermal regulation were identified. Theoretical models were developed for assessing the thermal regulation performance of different types of green living wall systems. It is hoped that the information obtained can offer useful knowledge and hints for designing and applying green living walls in urban cities.

(169 words)

Keywords: Green living walls, thermal regulation performance, urban cities, Hong Kong.

綠色活牆在建築物的熱調節性能

許俊民，趙崢
(香港大學機械工程系)

關鍵詞: 綠色活牆，熱調節性能，都市，香港。

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1. INTRODUCTION

A healthy and comfortable environment is the basic desire for human beings. However, the rapid urbanization and industrialization have brought about many environmental problems, such as urban heat island and air pollution. These problems are often caused by replacing the natural vegetation with concrete buildings and the imbalance of ecosystems. In recent years, some measures and attempts are taken to strengthen the connection between nature and cities. Obviously, greening the city is the best choice to bring about a new sustainable urban lifestyle (Sheweka and Mohamed, 2012).

Green roofs are believed to provide a cooler interior environment (Takakura et al., 2000) and have the potential to save building energy consumption (Castleton et al., 2010). However, the limited space for greening on rooftop leads to the application of vertical greenery in densely populated urban areas. Actually, it is not a new concept when using green living walls for decorating and cooling a building during hot summer. In recent decades, vertical greenery has attracted an increasing attention as it can contribute to preventing the urban areas from changing into a deteriorated environment and adjusting urban microclimate (Cheng et al., 2010; Chiang and Tan, 2009; Jaafar et al., 2011).

The microclimate could be adjusted by plants absorbing a large amount of solar radiation for their growth and their biological functions, such as photosynthesis, respiration, transpiration and evaporation (Holm, 1989). In addition, the plant-covered layer acts like a solar barrier that would reduce the absorption of solar energy by reflecting the incident solar radiation. Furthermore, plant-covered walls not only could offer the thermal comfort within building (Sunakorn and Yimprayoon, 2011), but also could restrict the wind effect and manage the humidity of the building environment (Eumorfopoulou and Kontoleon, 2009). Thus, vertical greenery offers an alternative way to overcome the open land scarcity due to its flexible shape, aesthetic value and heat island mitigation impact (Cheng et al., 2010).

However, a good understanding of the thermal process and characteristics of green living walls is still lacking. In this research, the basic principles and mechanisms of thermal regulation of green living walls will be studied. The major characteristics of the heat transfer processes were evaluated. Then, thermal model of living wall systems will be developed for assessing their thermal performance. Some practical factors affecting the thermal performance would be examined as well.

2. GREEN LIVING WALLS

Green wall, green façade, living wall, vertical green and vertical garden are descriptive terms that are used to refer to all forms of vegetated wall surfaces (Ottelé, 2011). According to their growing method, there are two major categories namely: "support" and "carrier". The support systems use some structures to assist plants upwards while carrier systems are installed on the vertical surface with media. The support systems are commonly termed as "green facades" and the carrier are called "living walls" (Jaafar et al., 2011).

Living wall systems (LWS) include pre-cultivated panels, vertical modules or planter boxes filled with artificial substrate/potting soil that are vertically fixed to a support or on the wall (Pérez et al., 2011). The panels can provide support to great varieties and density of plant species like ferns, low shrubs, and perennial flower and edible plants. In addition, living wall systems usually needs more intensive maintenance because the plants rely on the irrigation systems and nutrients supplement to live and grow (GRHC, 2008).

2.1 Types of Living Walls

There are mainly three types of living wall systems namely: panel systems, felt systems and container and/or trellis systems (GRHC, 2008). Figure 1 shows the structure of the three generic living wall systems.

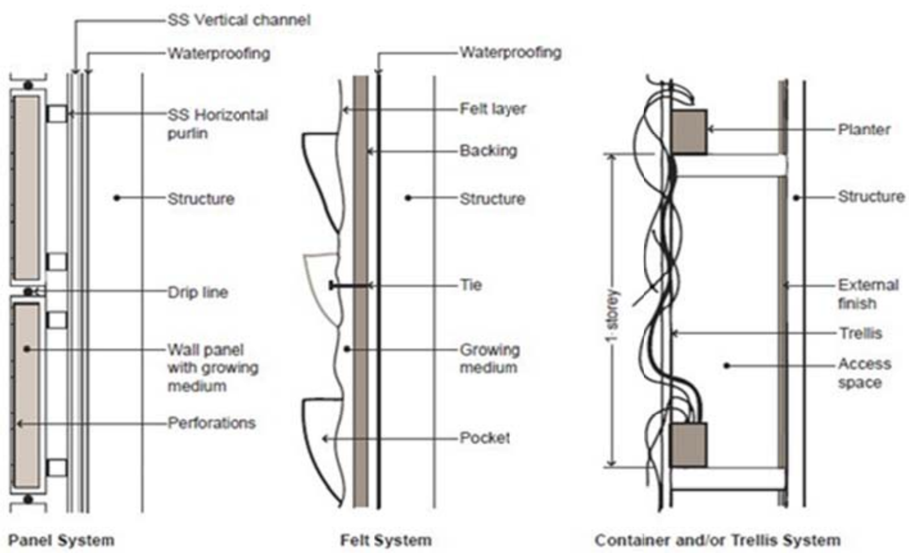

Figure 1. The structure of the three generic living wall systems (Source: Loh (2008), Drawing by M. Murray)

Panel systems include rectangular panels which contain growing media to support plants' life. The nutrients would be supplied in the growing media and the water would be provided by irrigation systems at different levels along the wall. Panel systems use pre-grown plants and can be installed on both indoor and outdoor walls.

Felt systems are quite thin even in multiple layers. The type of plants on the mat should be limited because the thin mat cannot support too high plants. There is a waterproof membrane between the mat and the building surface for the high moisture within the mat. The nutrients are provided through the irrigation system which water cycle circulation from top to bottom.

Container and/or trellis systems have plants growing in containers climbing onto trellises. Irrigation drip-lines are usually used in the plant containers to control watering and feeding (Loh, 2008).

2.2 Benefits of Living Wall Systems

Living wall systems, as one type of the vertical greenery, share the common benefits including social, environment and economic for a building and the whole city. The major benefits brought by LWS are summarized in Table 1. The benefits offered by LWS depend on some issues including the density and the thickness of leaf, type of the plants, site conditions and other factors.

Table 1. Benefits of living wall systems
(Source: Chiang and Tan (2009), Sheweka and Magdy (2011))

Category	Benefits
Environment	● Reduce urban heat island effect and regulate the microclimate ● Improve both outdoor and indoor air quality by absorbing pollutants and regulating the concentration of CO_2 ● Increase the biodiversity and beautify the environment
Social	● Offer aesthetic value in urban environment ● Improve human health and mental well-being ● Enhance public spaces ● Adding identity of a building
Economic	● Improve energy efficiency through better insulation and shading ● Protect building structures ● Reduce noise ● Increase property values

3 BASIC PRINCIPLES AND MECHANISMS

As mentioned before, there are three main types of LWS. However, the basic principles of LWS that regulate the temperature both indoor and outdoor are the same. LWS could affect the temperature both indoor and outdoor, contribute to saving energy consumption and mitigating the urban heat island based on the four mechanisms described below.

3.1 Shading Effect

The green wall could provide shading to the building. It is very straightforward that more thermal energy flows into the non-shade walls due to direct exposure to the sun (Papadakis et al., 2001). A facade fully covered by greenery is protected from intense solar radiation in the summer and can reflect or absorb in its leaf cover between 40% and 80% of the received radiation, depending on the amount and type of greenery. The shading effect could significantly reduce the heat flux flow through the wall and thus the temperature in the ambient.

3.2 Evaporative Cooling

In tropical or sub-tropical climate, the evaporative cooling effect of plants is significant which leads to reducing the temperature and enhancing the humidity around the building (Wong et al., 2003). The ivy covered model demonstrated evapotranspiration had a large cooling effect on the indoor temperature (Takakura et al., 2000). Through the evapotranspiration, large portion of the solar radiation can be converted into latent heat which would decrease the temperature around the building. This physical process generates the so-called “evaporative cooling”, which represents 2450 J for every gram of water evaporated. This evaporative cooling of the leaves depends on the type of plant and climatic conditions.

3.3 Inhibition of Wind

In winter, the wind would dramatically reduce the indoor temperature of buildings which have no insulation. Thus, the vegetation layers play a crucial role in reducing the wind speed and increasing the insulation effect. Perini et al. (2011) evaluated the effect of two green walls on wind velocity and found that plants create an external insulation layer and contribute to energy savings and loss of heat in colder time. In addition, the thermal resistance of the medium such as the substrate, supporting construction and the leaves would resist and delay the heat flux into the room.

4 HEAT TRANSFER PROCESSES

It is generally known that solar radiation is one of the principal inputs to the building envelope, and the heat transfer processes are complicated (Tang, 2002). When the system involves vertical plants, the biological characteristics of plant species increase the difficulty to establish the heat and mass transfer parameters when compared with metal or masonry (Ip et al., 2010).

4.1 Heat Flux

The heat flux transmission of LWS depends on the weather and its interaction with the vegetation (Jim and He, 2011). The main components of the heat flux include:

(a) *Solar Radiation*. It accounts for a significant part in the energy input of the system, which includes the incident solar radiation and the reflected short-wave radiation reaching the vegetation and the substrate surface. The intensity of direct solar radiation is influenced by many complex climatic factors, such as the cloudiness of the sky, the position of the sun in the sky and the atmosphere characteristics.

(b) *Long-wave Radiation*. Everything emits thermal radiation at its surface when its temperature is above absolute zero and long-wave radiation contains a smaller amount of energy compared with shortwave radiation. The rate of thermal radiant energy emitted by a surface depends on its absolute temperature and its surface characteristics. The main long-wave radiation processes involved are: the long-wave radiation between the leaves and the sky, the leaves and the substrate.

(c) *Sensible or Convective Heat Exchange*. The sensible heat exchange by convection occurs between the foliage and the air within it, and the soil surface and the air. Sensible heat is the energy required to change the temperature of a substance without phase change. In addition, the magnitude of sensible heat is the product of the body’s mass, its specific heat capacity and its temperature above a reference temperature.

(d) *Latent Heat Exchange*. Latent heat indicates the changes of state at a constant temperature. In foliage layer, the latent heat flux derived from evapotranspiration and this process includes water evaporation inside the leaves, and vapor diffusion to the leaves surface. Furthermore, the latent heat flux comes from the evaporation of water in the soil surface.

4.2 Factors Influencing the Thermal Transfer Process

Key factors influencing the heat transfer process in LWS are summarized as follows:

(a) *Weather Conditions*. The thermal performance of the green wall is directly influenced by the weather conditions. Alexandri and Jones (2008) evaluated the thermal behavior of vegetation covered building envelope in various climates in nine cities. The results show that the vegetation has an obvious effect in lowering the urban temperature, especially in the hot and dry climate. The research conducted by Getter et al. (2011) indicated the variation of thermal performance of the green wall in different seasons in Michigan.

(b) *Plant Species*. The nature of plants exerts an effect on the thermal performance of the green wall as well. The photosynthesis mode of various plants is different and some plants transpire during the day while others during the night time, which would influence the transpiration cooling effect (Wong et al., 2007).

(c) *Orientation and Proportion of Plant-covered Wall Layer*. Kontoleon and Eumorfopoulou (2010) analyzed the influence of the orientation and proportion of plant-covered wall section on the thermal behavior in summer when the construction parameters are taken into consideration. It is reported that the west-oriented wall showed the highest temperature difference in daily peak temperature between the bare and plant-covered wall parts, and the exterior and the interior surface temperature difference could reach 16.85 ℃ and 3.27℃, respectively. In addition, the minimum and the maximum temperature indoor are almost linearly decreasing with the plant foliage percentage increasing.

5 THEORETICAL MODELS

To accurately describe the heat transfer through LWS is almost impossible due to the inherent spatial complexity and inhomogeneity of the foliage and moment changing of the environment. Thus, some assumptions are necessary to simplify the model in order to figure out a reasonable model that could represent the core processes. The LWS is supposed to be large enough to assume vertical homogeneity. Heat transfer is assumed to take place along a horizontal plane through the foliage layer to the support structural layer, which ignores the heat flux in the vertical direction. Thus, one-dimensional models can be used to describe the thermal behavior of the LWS components.

5.1 Bare Wall Model

In order to analyze the cooling effect of living wall system, the bare wall model should be developed for comparison. Overall, bare wall model includes equations for radiation and conduction through the wall. Figure 2 shows the thermal circuit for heat flux considered in the bare wall model. Equation (1) shows the energy balance across the bare wall for quasi-steady state environmental conditions:

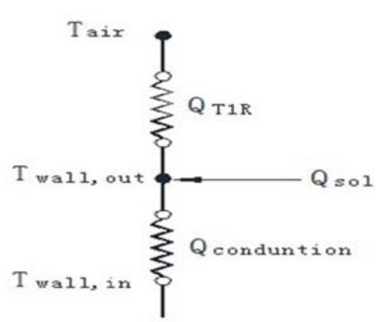

Figure 2. Thermal circuits for heat flux considered in bare wall model

$$Q = Q_{sol,abs,wall} + Q_{TIR,wall,sky} + Q_{conduction,wall} \quad (1)$$

5.2 Thermal Model of LWS

Because the structure of the three types of LWS is different, different models are used to describe the system. Panel and mat systems are composed by foliage layer, substrate and support structure, together with the coupling models which will be described here. For container and/or trellis systems, the components include foliage layer, air layer and support structure (wall). Table 2 summarizes the models used for different living wall systems. The models represent the real boundary conditions at the canopy-substrate and canopy-support interfaces, satisfying the physical constraint of continuity for the states variables and the flux densities.

Table 2. Summary of models used for living wall systems

Types	**Systems**	**Model used**
1	Panel system and Mat system	Canopy model+ Substrate model + Support structure model (with wall)
2	Container or trellis system	Canopy model + Air model + Wall

(a) *Canopy with Substrate Model*

The foliage layer consists of leaves and the air within the leaf cover. The main processes contributing to the heat flux are shortwave and longwave radiation, sensible heat exchange and latent heat flux. In addition, the substrate surface heat flux play an important role in energy balance with a small leaf area index (LAI) (van der Meulen and Klaassen, 1996). In the substrate energy budget, net radiation, sensible heat, latent heat and conduction through the substrate are taken into account. Figure 3 shows the heat flux on the LWS.

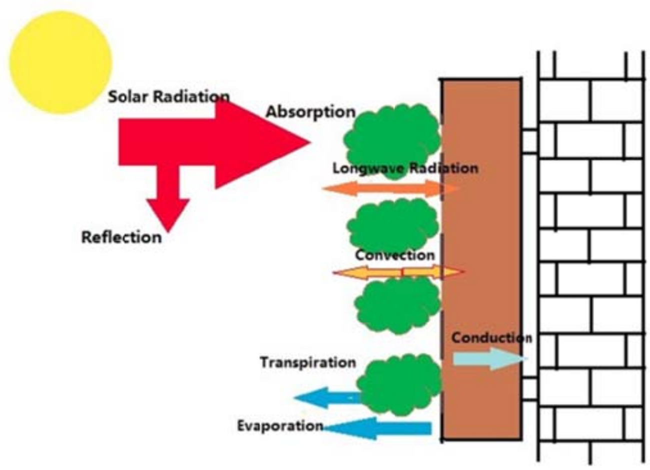

Figure 3. Heat flux through the canopy with substrate model

Figure 4 shows the thermal circuit for heat flux considered in canopy model with substrate.

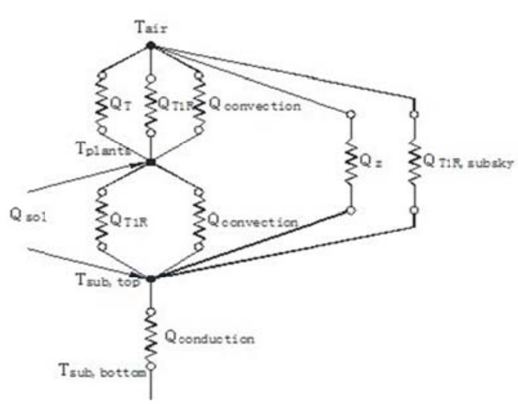

Figure 4. Thermal circuits for heat flux considered in canopy model with substrate

Assuming negligible thermal storage and metabolic rate, the energy balance for the foliage canopy and the substrate underneath the plants are given by the following equations:

$$(\rho c_p)_f \cdot LAI \cdot L_{plants} \frac{dT_{plants}}{dt} = Q_{sol,abs,plants} + Q_{TIR,plants,sky} + Q_{TIR,palnts,sub} + Q_{convection,plants} + Q_T \quad (2)$$

$$(\rho c_p)_{sub} \frac{\partial T_{sub}}{\partial t} = Q_{sol,abs,sub} + Q_{TIR,sub,sky} + Q_{TIR,sub,plants} + Q_{convection,sub} + Q_E + Q_{conduction,sub} \quad (3)$$

(b) *Canopy Model with Air*

Since the structure of the container and/or trellis system, of which the substrate is usually on the bottom and cannot provide the function of resisting the heat flux, thus, the canopy model established before should be made little adjustments and be defined by equation (4).

$$(\rho c_p)_f \cdot LAI \cdot L_{plants} \frac{dT_{plants}}{dt} = Q_{sol,abs,plants} + Q_{TIR,plants,sky} + Q_{TIR,palnts,air(s)} + Q_{convection,plants} + Q_T \quad (4)$$

Figure 5 shows the thermal circuit for heat flux considered in canopy model with air.

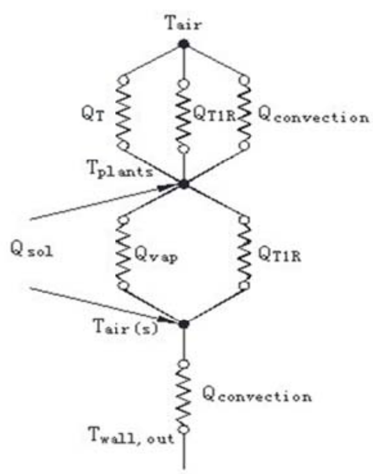

Figure 5. Thermal circuit for heat flux considered in canopy model with air

An air layer which is trapped between the vegetation and the wall also helps in heat transfer process. The heat flux components involved includes convection between the air outside and the space air, the air and the wall, and the air with the vegetation, and the vapor flux between the air and outside air, this could be calculated by equation (5):

$$Q_{conv,air(s),air(\infty)} = Q_{TIR,palnts,air(s)} + Q_{conv,air(s),wall} + Q_{vap,air\infty} \quad (5)$$

(c) *Support Structure Model*

The energy balance of support could be expressed by one dimension conduction equation:

$$(\rho c_p)_{sup} \frac{\partial T_{sup}(z,t)}{\partial t} = \lambda_{sup} \frac{\partial^2 T_{sup}(z,t)}{\partial t^2} \quad (6)$$

The following boundary conditions are assumed:

$$\begin{cases} T_{sup}(z=0,t) = T_{sup,se}(t) \\ -\lambda_{sup}\frac{\partial T_{sup}(z,t)}{\partial z}\Big|_{z=L} = h_{sup}\left(T_{sup,si} - T_{in}\right) \end{cases} \quad (7)$$

Where $z = 0$ indicates the support layer surface which is connected to the substrate, $z = L$ represents the interior surface of the wall. L is the thickness of the overall support layer. T_{in} is the indoor air temperature, $T_{sup,se}$ is the exterior surface temperature of the support structure, and $T_{sup,\mathrm{si}}$ is the interior surface temperature of the support structure.

Table 5.1 summarizes the recommended equations for LWS.

Table 5.1 Summary of the recommended equations for LWS

Heat Flux	Equation
Energy Balance	$\left(\rho c_p\right)_{sub}\frac{\partial T_{sub}}{\partial t} = Q_{sol,abs,sub} + Q_{TIR,sub,sky} + Q_{\mathrm{TIR,sub,plants}} + Q_{\mathrm{convection,sub}} + Q_E + Q_{conduction,sub}$ $(\rho c_p)_f \cdot LAI \cdot \mathrm{L}_{plants}\frac{dT_{plants}}{dt} = Q_{sol,abs,plants} + Q_{TIR,plants,sky} + Q_{\mathrm{TIR,palnts,sub}} + Q_{\mathrm{convection,plants}} + Q_T$
Radiation	$Q_{sol,abs,plants} = \left(1 - \tau_{plants,sol} - \mathrm{\rho}_{plants}\right)\left(1 + \tau_{plants,sol}\,\mathrm{\rho}_{plants}\right)E_{t,v}$ $Q_{sol,abs,sub} = (1 - \rho_{substrate})\tau_{plants,sol}E_{t,v}$ $Q_{TIR,plants,sky} = \left(1 - \tau_{plants,TIR}\right)\varepsilon_{plants}\sigma\left(T_{plants}^4 - T_{sky}^4\right)$ $Q_{TIR,sub,sky} = \tau_{plants,TIR}\varepsilon_{sub}\sigma\left(T_{sub,top}^4 - T_{sky}^4\right)$ $Q_{TIR,plants,sub} = \varepsilon_{ps}\sigma\left(T_{sub,top}^4 - T_{plants}^4\right)$
Convection	$Q_{convection,plants} = -2LAI\frac{(\rho c_p)_{air}}{r_a}\left(T_{plants} - T_{air}\right)$ $Q_{convection,sub} = -\frac{\left(\rho c_p\right)_{air}}{(r_a + r_c)}(T_{sub,top} - T_{air})$ $r_a = \frac{665}{1+0.54u}$ $r_c = \frac{1}{a'+b'u_c}$ $u_c = f \cdot ue^{-a\left(1-\frac{0.05}{h_c}\right)}$ $\mathrm{a} = \sqrt{0.28\,LAI \cdot h_c d}$
Evapotranspiration	$Q_T = 2LAI\frac{(\rho c_p)_a}{\gamma(r_s+r_a)}\left(p_{plants} - p_{air}\right)$ $Q_E = \frac{(\rho c_p)_a}{r(r_{sub}+r_a)}(p_{sub} - p_{air})$ $r_s = \frac{r_{min}}{LAI}f_1\left(E_{t,v}\right)f_2\left(T_{plants}\right)f_3(SMC)f_4(VPD)$ $f_1\left(E_{t,v}\right) = 1 + e^{-0.034\left(E_{t,v}-3.5\right)}$ $f_2\left(T_{plants}\right) = \frac{e^{0.3\left(T_{plants}-273\right)}+258}{e^{0.3\left(T_{plants}-273\right)}+27}$ $f_3(\,SMC\,) = \frac{\omega_{sub}^{sat}}{\omega_{sub}}$ $f_4(\,VPD) = \frac{1}{1 - 0.41\,In\,(p_{plants} - p_{air}\,)}$ $r_{sub} = c_0 + c_1 \times \left(\frac{\omega_{sub}}{\omega_{sub}^{sat}}\right)^{-c_2}$
Conduction	$Q_{conduction,sub} = k_{sub}\frac{T_{sub,top}-T_{su,bottom}}{L_{sub}}$ $k_{sub} = a_1 + a_2 \times \omega_{sub}$

5.3 The Steady-state Heat Transfer Process

According to the Fourier's first law, heat flux density for a steady state flow is defined as:

$$\partial q = -\lambda A \frac{\partial T}{\partial Z} \quad (8)$$

After integrating and assembling the heat flux Q_n across the LWS:

$$Q_n = A_n U_n (T_{in} - T_{out}) \quad (9)$$

U-value is defined as the rate of heat flow over unit area of any building component through unit overall temperature difference between both sides of the component.

$$U = \frac{1}{\Sigma R} \quad (10)$$

6 CONCLUSIONS

The heat fluxes on the vegetated and on the non-vegetated surfaces are quite different. From the analysis of heat transfer processes, the heat flux transmitted into the wall through LWS decreases significantly when compared with the heat flux transmitted through a bare wall, the reduction could reach up to nearly 50% at maximum in daytime, especially during the hot time in the summer.

6.1 Major Factors

Solar radiation is the significant heat gain in all directions, and the contributions of heat gain from longwave radiation between air, vegetation and substrate are much less than solar radiation. The convective heat exchanges between the vegetation and air are milder than those between the solid concrete wall and air. In contrast, evapotranspiration of the vegetation and substrate acts constantly as a heat sink and thus reduces the air temperature immediately adjacent to the building compared to the concrete surfaces. In general, the larger amounts of solar radiation a surface receives, the larger its temperature decreases are when it is covered with vegetation.

The moisture content in substrate shows a strong association with the cooling effect mediated by evapotranspiration. More moisture contained with the substrate, more significant the evaporation effect is. Thus, maintain proper substrate moisture content is conducive to both heat flux reduction and energy saving that irrigation needed. Preliminary analyses show that orientation has the largest impact on heat flux since the solar radiation varies in different directions. For vegetation itself, LAI has a direct effect on transpiration and convection of vegetation and then influence the heat flux into the room.

6.2 Other Considerations

As an abstraction of reality, modeling cannot be perfect all times. In this model, only some main heat transfer processes through the LWS are considered, thus the photosynthesis effect of the vegetation that also makes contributions to heat dissipation is ignored. Thus, further model could study more details about that.

Green facade enjoys the benefit of enhancing the city landscape, mitigating the urban heat island effect and adjusting the microclimate. If only applied to one unit block, green facade can create a small area of mitigated temperatures to the urban heat island effect. However, when the area is extended to the whole city scale, the mitigation of urban temperature is distinct, especially for hot climates, bring temperatures down to more ‘human-friendly’ levels.

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