

# Long-term Thermal Performance Evaluation of Green Roof System in Shanghai District Based on a New Model



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## Abstract

In recent years, most studies of green roof system are focused on short period measurement or modelling without considering long-term performance, however, the latter is concerned by many architects and engineers. And this paper is aimed to evaluate green roof's long-term thermal performance in Shanghai district based on a new model and analyze various factors' effect on thermal index. Green roof is usually divided into three big layers, namely plant layer, substrate layer and structure layer. The model developed in this paper not only considers the effect of wind velocity's vertical distribution on coupled hygrothermal transfer, but also involves multiple reflection of solar radiation between different layers. Based on the field measurement from July, 2014 to June, 2015, the model has a good agreement in most cases. And simulation results indicate that green roof has a better insulation effect than corresponding common roof both in summer and winter, and its equivalent thermal resistance is not a fixed value. Many factors shows significant effect on green roof's long term thermal performance, such as LAI, soil's thermal conductivity, indoor temperature etc. According to the method in this paper, it is possible to have a quick comparison of thermal performance between green roof and common roof, and judge whether green roof system meets the insulation rule of local energy conservation.

**Keywords:** Long-term thermal performance, Green roof system, Coupled hygrothermal modelling, Equivalent thermal resistance.



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## 1. Introduction

As a kind of building component with long history, green roof has received much attention for its multiple benefits in recent years. According to the thickness of substrate, green roofs are typically divided into two categories: including intensive green roof and extensive green roof. Although better in some benefits, intensive green roof is less commonly used than extensive green roof for extra structural reinforcement and expensive maintenance. Thermal and energy performance is one of the most concerned topics of green roof system nowadays, some researchers conducted field or laboratory measurement in various areas (Saadatian, et al., 2013), and some others analyze thermal performance of green roof system by developing various models based on heat and mass balance (Djedjig, et al., 2012). However, most studies are focused on instantaneous or just short period's performance without considering its long-term seasonal effect. In addition, research based on field measurement, although of great interest for understanding the behavior of the type of roof analyzed, are difficult to extrapolate for other conditions. What's more, there is lack of thermal performance evaluation index of green roof system, and it is difficult to carry out a quick and accurate comparison between green roof and other type of roof. In the past decade, Shanghai's government has released various rules to promote city vertical greening, one of which is related to green roof whose area must reach more than 30% of total roof area. And this paper is focused on long term thermal performance of extensive green roof system by simulation based on a new model which is validated by data of field measurement in typical seasons, and sensitive analysis is carried out to obtain the parameters that has significant effect.

## 2. Methodology

### 2.1 Field experiment of green roof and common roof

As is illustrated in Fig.1, there were two test rooms using the same building materials located at Jiading Campus of Tongji University, the dimensions were both 3m\*3m\*2.7m. The left roof was extensive green roof, and the right one was just common roof that was made of foam sandwich panel (75mm thick). Extensive green roof was made up of foam sandwich panel and 36 prefabricated greenery modules which was connected by buckles, and the size of every module was 50cm\*50cm\*7cm (not including the canopy layer). The greenery module was well designed, which combined plant layer, substrate layer, filtering membrane and drainage layer together (Fig.2). The plant was sedum linear, a type of succulent vegetation, which is very common in Shanghai district. The substrate was about 4cm thick and was comprised of peat soil, powdered perlite, vermiculite aggregate and organic fertilizer. During the experiment, the windows and door were locked, and indoor temperature was controlled by air conditioner at 26°C in summer and 24°C in winter. A weather station was installed near the roof to record the local meteorological data, including air temperature, relative humidity, solar radiation, wind speed and precipitation. Type-T thermocouples were set at different heights along the vertical direction of green roof and common roof, measuring temperatures of different layers. For green roof, 28 thermocouples measured temperature of seven positions, including indoor air, inner and outer surface of sandwich panel layer, drainage layer, substrate layer, canopy layer and local air temperature 15cm above vegetation. And for common roof, 16 thermocouples measured temperatures of four positions, including indoor air, inner and outer surface of sandwich panel, air temperature 15cm above the panel. All the thermocouples were connected to a data acquisitions system which scanned all sensors every one minute and stored the data in a local computer. Four TDR (Time Domain Reflectometry) sensors were used to measure volumetric water content of substrate layer, and four humidity sensors were set above the roofs to record local relative humidity. Furthermore, six heat flux sensors were installed at the inner surface of sandwich panel to measure heat flux through both roofs. And these sensors were put near the center of the roof to avoid edge effect.

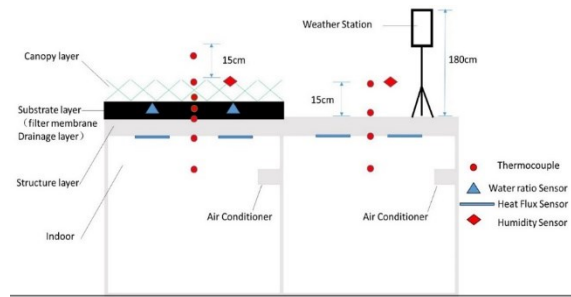


Figure 1 Schematic of experimental setup

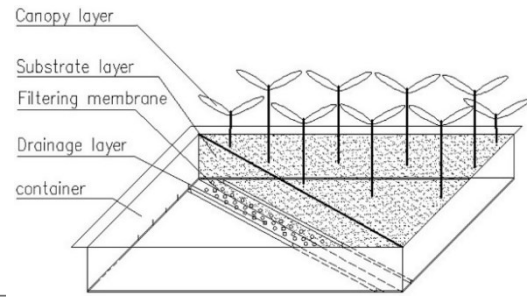


Figure 2 Structure view of greenery module

## 2.2 Numerical model of green roof

Adopting various simplifications, researchers proposed different models of green roof system. From the simplest thermal resistance model to heat and moisture balance model, more and more physical phenomena were considered. And this paper takes another three factors into green roof model based on SVAT1 theory proposed by Shuttleworth (Shuttleworth, et al., 1990): (1) Multiple solar reflection was considered between different layers of plant; (2) the effect of wind profile on turbulent transfer coefficients below and above canopy surface was considered; (3) Coupled heat and moisture transfer was applied in substrate layer based on the theory of Philip & de Vries (Philip and De Vries, 1957). As is illustrated in Fig.3, the following assumptions are used based on previous study (D.J. Sailor, 2008; E.P.D. Barrio, 1998): (1) Green roof is divided into three big layers, including plant layer, substrate layer and structure layer, and its area is large enough to be assumed horizontally homogeneous. (2) The biochemical reactions and heat conduction through plants are ignored. (3) The change of substrate water content equals to the water loss through evapotranspiration, and plant's water loss is not considered. (4) The canopy is considered as a semi-transparent medium, in which radiation obeys Beer's law. (5) The structure layer is waterproof, where moisture transfer is not involved.

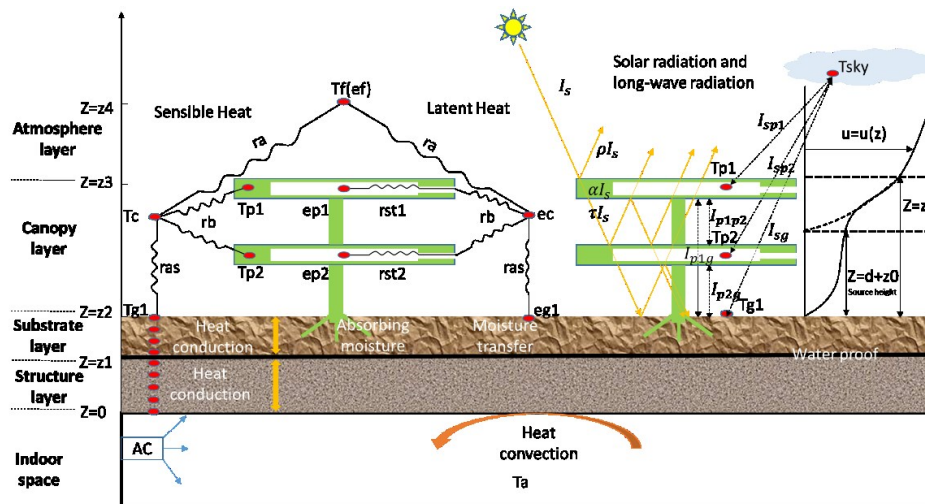


Figure 3 Schematic of heat and moisture transfer of green roof system

### 2.2.1 Longwave radiation distribution

In longwave range, transmittance and reflectance of the leaf tissue are negligible. The canopy will transmit only the radiation which is not even once intercepted by a leaf. In this paper, plant layer of green roof system is divided into  $n$  parts, and the longwave transmittance of plant layer can be calculated by the following equation:

<sup>1</sup> SVAT: Soil-Vegetation-Atmosphere Transfer

$$\tau_{LR,c} = \exp(-k_{LR} \cdot LAI) \quad (1)$$

Where,  $k_{LR}$  is the extinction coefficient for longwave radiation, some values of it are supplied in literatures. LAI is leaf area index of plant layer.

And longwave radiation that each part receives can be derived as follows:

$$R_{l,fi} = F_{ij} \cdot \varepsilon_i \varepsilon_j \sigma (T_{p,j}^4 - T_{p,i}^4) + F_{ig} \cdot \varepsilon_i \varepsilon_g \sigma (T_g^4 - T_{p,i}^4) + F_{isky} \cdot \varepsilon_i (I_{sky} - \sigma T_{p,i}^4) \quad (2)$$

where,  $R_{l,fi}$  is longwave radiation of each part of plant layer,  $F_{ij}$  is radiation view factor,  $\varepsilon$  is longwaver radiation absorption coefficient,  $T_g$  and  $T_p$  are ground surface temperature and leaf temperature of each layer.

When  $j < i$ ,

$$F_{ij} = (1 - \tau_{LR,c,i}) \cdot \tau_{LR,c,i-1} \cdot \tau_{LR,c,i-2} \cdots \tau_{LR,c,j+1} \cdot (1 - \tau_{LR,c,j}) \quad (3)$$

When  $j > i$ ,

$$F_{ij} = (1 - \tau_{LR,c,i}) \cdot \tau_{LR,c,i+1} \cdot \tau_{LR,c,i+2} \cdots \tau_{LR,c,j-1} \cdot (1 - \tau_{LR,c,j}) \quad (4)$$

$$F_{ig} = (1 - \tau_{LR,c,i}) \cdot \tau_{LR,c,i+1} \cdot \tau_{LR,c,i+2} \cdots \tau_{LR,c,n-1} \cdot (1 - \tau_{LR,c,n}) \quad (5)$$

$$F_{isky} = (1 - \tau_{LR,c,i}) \cdot \tau_{LR,c,i-1} \cdot \tau_{LR,c,i-2} \cdots \tau_{LR,c,2} \cdot (1 - \tau_{LR,c,1}) \quad (6)$$

### 2.2.2 Solar radiation distribution

Absorptivity, reflectivity and transmissivity of each part of plant layer is defined as following equations:

$$\alpha_{SR,c} = 1 - \rho_{SR,c} - \tau_{SR,c} \quad (7)$$

$$\rho_{SR,c} = (1 - \tau_{SR,c}) \cdot \rho_{SR,p} \quad (8)$$

$$\tau_{SR,c} = \exp(-k_{SR} \cdot L_c \eta LAI) \quad (9)$$

$$k_{SR} = [(1 - \tau_{SR,p})^2 - \rho_{SR,p}^2]^{1/2} \cdot k_{LR} \quad (10)$$

Where,  $k_{SR}$  is the extinction coefficient for solar radiation,  $\tau_{SR,p}$  and  $\rho_{SR,p}$  are transmittance and reflectance of the leaf tissue respectively.

After multiple reflection, absorption and transmittance, the total absorptivity can be derived as follows:

$$\alpha_{12 \dots n} = \alpha_1 \left( 1 + \frac{\tau_1 \rho_{23 \dots n}}{1 - \rho_1 \rho_{23 \dots n}} \right) \quad (11)$$

$$\alpha_{12 \dots i \dots j} = \alpha_{12 \dots i \dots n} - \alpha_{12 \dots i+1 \dots n} \quad (12)$$

$$\alpha_{12 \dots j} = \frac{\tau_{12 \dots j-1} \alpha_j}{1 - \rho_{j-1 \dots 21} \rho_j} \quad (13)$$

Where,

$$\tau_{12 \dots j} = \frac{\tau_{12 \dots j-1} \tau_j}{1 - \rho_{j-1 \dots 21} \rho_j} \quad (14)$$

$$\rho_{j \dots 21} = \rho_j + \frac{\tau_j^2 \rho_{j-1 \dots 21}}{1 - \rho_j \rho_{j-1 \dots 21}} \quad (15)$$

$$\alpha_{12 \dots i \dots j} = \frac{\tau_{12 \dots i-1} \alpha_{i \dots j}}{1 - \rho_{i-1 \dots 21} \rho_{i \dots j}} \quad (16)$$

$$\alpha_{i \dots j} = 1 - \tau_{i \dots j} - \rho_{i \dots j} \quad (17)$$

Then solar radiation of each part of plant layer can be calculated by multiplying incident solar radiation above green roof by total absorptivity  $\alpha_{12 \dots i \dots j}$ :

$$R_{S,fi} = \alpha_{12 \dots i \dots j} \times R_{in} \quad (18)$$

### 2.2.3 Energy balance of plant layer

$$(\rho C_p)_f d_f LAI_i \frac{dT_{fi}}{d\tau} = R_{s,fi} + R_{l,fi} + H_{fi} + E_{fi} \quad (19)$$

$$H_{fi} = 2LAI_i (\rho C_p)_a \frac{(T_{fi} - T_c)}{(r_b)} \quad (20)$$

$$E_{fi} = 2LAI_i \frac{(\rho C_p)_a (e_{fi} - e_c)}{\gamma (r_{st} + r_b)} \quad (21)$$

where  $(\rho C_p)_f$  is volumetric heat capacity of plant layer,  $d_f$  is leaf thickness,  $T_{fi}$  is average temperature of each part of plant layer,  $\tau$  is time,  $H_{fi}$  and  $E_{fi}$  are sensible heat and latent heat transfer of each part of plant layer respectively,  $r_b$  is leaf boundary layer resistance,  $r_{st}$  is leaf stomatal resistance,  $T_c$  is average temperature of canopy space.  $e_{fi}$  is saturated vapor pressure of plant temperature,  $e_c$  is vapor pressure of canopy space.  $\gamma$  is psychrometric constant.  $(\rho C_p)_a$  is volumetric heat capacity of air.

### 2.2.4 Energy and moisture balance of substrate surface

$$-\lambda_g \frac{\partial T_g}{\partial z} \Big|_{z=0} - r_v (D_{v\theta} \frac{\partial \theta}{\partial z} + D_{vT} \frac{\partial T_g}{\partial z}) = R_{n,g} + H_g + E_g \quad (22)$$

$$\rho_w \Delta z \frac{d\theta}{d\tau} = -\frac{\partial(q_l + q_v)}{\partial z} - \frac{E_g}{r_v} - S + P \quad (23)$$

$$H_g = (\rho C_p)_a \frac{(T_g - T_c)}{(r_{as})} \quad (24)$$

$$E_g = \frac{(\rho C_p)_a (e_g - e_c)}{\gamma (r_{gs} + r_{as})} \quad (25)$$

where  $\lambda_g$  is thermal conductivity of substrate layer,  $T_g$  is temperature of substrate layer,  $r_v$  is latent heat of moisture,  $D_{v\theta}$  and  $D_{vT}$  are transfer coefficients of water vapor under gradient of moisture and temperature,  $\theta$  is volumetric water ratio of substrate layer,  $R_{n,g}$  is net radiation of substrate surface,  $H_g$  and  $E_g$  is sensible heat and latent heat transfer of substrate surface,  $\rho_w$  is density of liquid water,  $\Delta z$  is grid step of substrate layer,  $q_l$  and  $q_v$  are liquid water and gas water transfer,  $S$  and  $P$  are evaporation water loss and precipitation.  $r_{gs}$  and  $r_{as}$  are water vapor resistance of substrate surface and canopy space.  $e_g$  is saturated water vapor of substrate surface.

### 2.2.5 Energy balance of canopy air

$$(\rho C_p)_a (L - d_f LAI) \frac{dT_c}{d\tau} = -H_f - H_g - H_a \quad (26)$$

$$H_a = (\rho C_p)_a \frac{(T_r - T_c)}{(r_a)} \quad (27)$$

$$(L - d_f LAI) \frac{dq_{ci}}{d\tau} = \frac{E_f}{r_v} + \frac{E_g}{r_v} + \frac{(\rho C_p)_a (e_c - e_r)}{\gamma r_a} \quad (28)$$

Where  $H_f$  and  $H_g$  are sensible heat transfer from plant and substrate surface to canopy space, and  $H_a$  is sensible heat transfer from reference height to canopy space.  $T_r$  is temperature of reference height,  $T_c$  is temperature of canopy space,  $e_r$  is water vapor pressure of reference height,  $L$  is height of canopy space, and  $q_{ci}$  is absolute humidity of canopy space.

### 2.2.6 Coupled hygrothermal transfer of substrate layer

$$\rho_w \Delta z \frac{\partial \theta}{\partial \tau} = -\frac{\partial(q_l + q_v)}{\partial z} - S \quad (29)$$

$$(\rho C_p)_g \frac{\partial T_g}{\partial \tau} + (\rho C_p)_w q_l \frac{\partial T_g}{\partial z} = -\frac{\partial q_h}{\partial z} \quad (30)$$

$$q_l = \left( -\left( D_{l\theta} \frac{\partial \theta}{\partial z} + D_{lT} \frac{\partial T_g}{\partial z} \right) - K \right) \quad (31)$$

$$q_v = -\left( D_{v\theta} \frac{\partial \theta}{\partial z} + D_{vT} \frac{\partial T_g}{\partial z} \right) \quad (32)$$

$$q_h = -\lambda_g \frac{\partial T_g}{\partial z} - r_v \rho_w (D_{vT} \frac{\partial T_g}{\partial z} + D_{v\theta} \frac{\partial \theta}{\partial z}) \quad (33)$$

Where  $(\rho C_p)_g$  is volumetric heat capacity of substrate layer, and  $q_h$  is the total of sensible and latent heat transfer in substrate layer,  $D_{l\theta}$  and  $D_{lT}$  are liquid water transfer under the gradient of water ratio and temperature,  $K$  is water conductivity of substrate layer.

### 2.2.7 Heat transfer process of structure layer

$$(\rho C_p)_s \frac{\partial T_s}{\partial \tau} = \lambda_s \frac{\partial^2 T_s}{\partial z^2} \quad (34)$$

Where  $(\rho C_p)_s$  is volumetric heat capacity of structure layer,  $T_s$  is temperature of structure layer,  $\lambda_s$  is thermal conductivity of structure layer.

### 2.2.8 Boundary conditions of structure layer

$$-\lambda_s \frac{\partial T_s}{\partial z} \Big|_{z=0} = h_{in} (T_s \Big|_{z=0} - t_{in}) \quad (35)$$

Where  $h_{in}$  is indoor heat convection coefficient,  $R_{n,s}$  is net radiation of structure surface,  $t_{in}$  is indoor air temperature.

### 2.2.9 Resistance of heat and moisture transfer

According to the SVAT theory of Shuttleworth (Shuttleworth, et al., 1990), the turbulent resistance below and above canopy surface as well as canopy boundary layer resistance can be calculated as follows,

$$r_a^s = \frac{h \exp(n)}{n K_h} \left( \exp\left(\frac{-n z_0^s}{h}\right) - \exp\left(\frac{-n(Z_0 + d_p)}{h}\right) \right) \quad (36)$$

$$r_a^a = \frac{1}{k u_*} \ln \left[ \frac{z_r - d}{h - d} \right] + \frac{h}{n K_h} \left[ \exp\{n[1 - (Z_0 + d_p)/h]\} - 1 \right] \quad (37)$$

$$r_a^c = \frac{r_b}{2LAI} = \left(\frac{100}{n}\right) \left(\frac{w}{u_h}\right)^{\frac{1}{2}} \left[1 - \exp\left(-\frac{n}{2}\right)\right]^{-1} / 2LAI \quad (38)$$

Stomatal vapor resistance of plant layer and substrate surface vapor resistance is from the study of Tabares-Velasco (Tabares-Velasco and Srebric, 2012).

$$r_{st} = \frac{r_{s,min}}{2LAI} f_1(R_s) f_2(T_f) f_3(\theta) f_4(e_f - e_r) \quad (39)$$

$$f_1(R_s) = 1 + e^{-0.034(R_s - 3.5)} \quad (40)$$

$$f_2(T_f) = \frac{e^{0.3(T_f - 273.15)} + 258}{e^{0.3(T_f - 273.15)} + 27} \quad (41)$$

$$f_3(\theta) = \frac{\theta^{max} - \theta^{min}}{\theta - \theta^{min}} \quad (42)$$

$$f_4(e_f - e_r) = 4 \times 10^{-3} + e^{-0.73 \frac{0.622 \times 10^3}{P_{atm}} (e_f - e_r)} \quad (43)$$

$$r_{gs} = 34.5 \times \left(\frac{\theta}{\theta^{max}}\right)^{-3.3} \quad (44)$$

## 2.3 Numerical model of common roof

### 2.3.1 Heat balance of outer surface of structure layer

$$-\lambda_s \frac{\partial T_s}{\partial z} \Big|_{z=h} = R_{n,s} + h_{out} (T_s \Big|_{z=h} - T_{out}) \quad (45)$$

where  $h_{out}$  is outdoor heat convection coefficient.

### 2.3.2 Heat transfer of structure layer

$$(\rho C_p)_s \frac{\partial T_s}{\partial \tau} = \lambda_s \frac{\partial^2 T_s}{\partial z^2} \quad (46)$$

### 2.3.3 Boundary condition of structure layer

$$-\lambda_s \frac{\partial T_s}{\partial z} \Big|_{z=0} = h_{in}(T_s|_{z=0} - t_{in}) \quad (47)$$

## 2.4 Methods of calculating equivalent thermal resistance

In order to quantify the relative benefit of green roof compared with common roof from the viewpoint of long-term thermal performance, equivalent thermal resistance based on hotbox method is adopted. Under the same climate, common roof with thermal resistance has the same heat insulation effect as green roof, this thermal resistance is called equivalent thermal resistance. It reflects the average thermal insulation effect. In Chinese rule of energy conservation in mixed climate, the added resistance value of green roof is fixed to be  $0.9 \text{ m}^2 \cdot \text{K}/\text{W}$ . As is illustrated in Fig 4. The basic interior temperature of hotbox is set to be  $25^\circ\text{C}$  in summer and  $20^\circ\text{C}$  in winter, and typical meteorological year weather data of Shanghai are used in the simulation. Summer simulation begins from 6/01 to 9/30, and winter simulation is from 12/01 to 3/30, and typical weather year data are used.

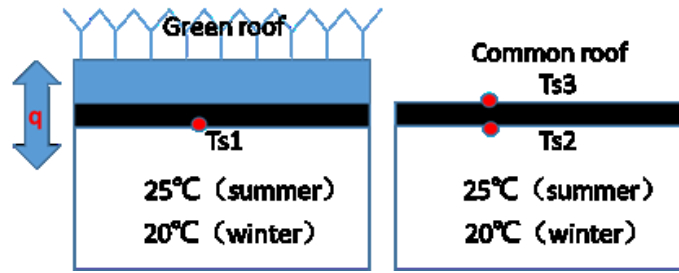


Figure 4 Schematic map of hot box method

$$\bar{R} = (\bar{T}_{s3} - \bar{T}_{s1}) / (\bar{q}) \quad (48)$$

$\bar{T}_{s3}$ : Average outer surface temperature of corresponding common roof.  $\bar{T}_{s1}$ : Average inner surface temperature of corresponding green roof.  $\bar{q}$ : Heat flux through corresponding green roof.  $\bar{R}$ : Equivalent thermal resistance.

## 3. Results and discussion

### 3.1 Green roof and common roof's model validation

The observation data on typical summer and winter days are used to validate the two roof models, and input parameters of green roof and common roof models are shown in table 1. During the measurement, the average outdoor temperature and relative humidity for summer are  $24.6^\circ\text{C}$  and 81% respectively, and  $5.5^\circ\text{C}$  and 55% respectively for winter. In order to evaluate two roof models, the following parameters are adopted: green roof's foliage temperature, soil surface temperature, soil water ratio and heat flux through green roof, common roof's inner surface and outer surface temperature as well as heat flux through common roof. Fig. 5~Fig. 6 shows that good agreement was obtained between the results of numerical model and measured data.

Table 1: Input parameters of green roof and common roof models

Parameter	value	Parameter	Value
Average LAI	5(summer),1(winter)	Thermal capacity of structure layer(J/m3K)	2358333
Height of plant(cm)	15(summer),5(winter)	Thermal conductivity of structure layer (W/m·K)	0.234
Minimum stomata resistance(s/m)	750	Depth of structure layer(cm)	24
Emissivity of plants	0.95	Reflectivity of structure layer surface	0.2
Reflectivity of leaves	0.3	Emissivity of structure surface	0.9
Soil depth (cm)	4	Emissivity of soil surface	0.9
Soil conductivity (W/m·K)	$0.374 * (\theta)^{0.403}$	Field water capacity of substrate layer	0.63
soil thermal capacity(J/m3K)	600*1000		
Soil water conductivity (m/s)	$2.37 * 10^{-5} * (\theta)^{24.42}$		
Soil water capacity(pa-1)	$1.575 * (\theta^{-4.35})$		
Soil reflectivity	0.2		

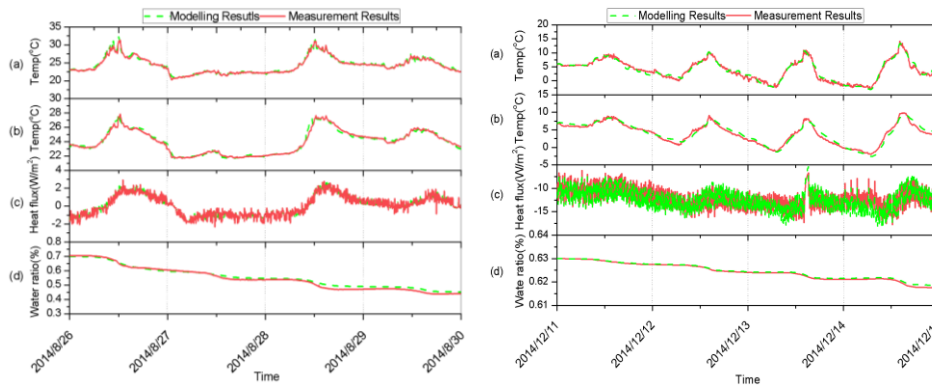


Figure 5 Model validation of green roof in summer (left) and winter (right). a) Foliage temperature of canopy layer, b) Outer surface temperature of substrate layer, c) Heat flux through green roof, d) Average water ratio of substrate layer.

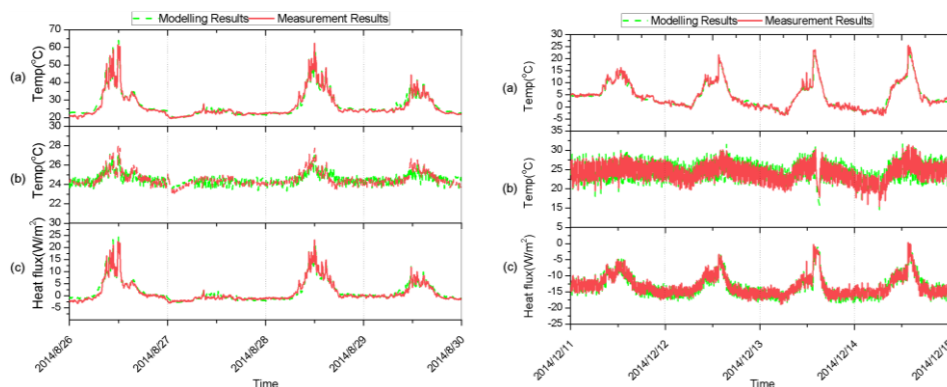


Figure 6 Model validation of common roof in summer (left) and winter (right). a) Outer surface temperature of structure layer, b) Inner surface temperature of structure layer, c) Heat flux through roof.

### 3.2 Green roof long-term thermal performance evaluation

Based on hot box method, the average thermal performance of green roof and common roof is shown in table 2. Green roof's added thermal resistance is about 8.12 in summer and 0.29 in winter under this setting condition. It can be deduced that green roof's equivalent thermal resistance is not a fixed value in different season, and different factors should be considered during evaluation.

Table 2: Equivalent thermal resistance of green roof and common roof

Items	Summer		Winter		
	Common roof	Green roof	Common roof	Green roof	
$\overline{T_{s3}}$ (oC)	29.71		6.86		
$\overline{T_{s2}}(CR)$ (oC)	$\overline{T_{s1}}(GR)$ (oC)	25.49	25.06	18.63	18.91
$\overline{q_c}(CR)$ (W/m <sup>2</sup> )	$\overline{q_c}(GR)$ (W/m <sup>2</sup> )	4.19	0.51	-11.89	-9.38
Equivalent thermal resistance (m <sup>2</sup> K/W)	1	9.12	0.99	1.28	

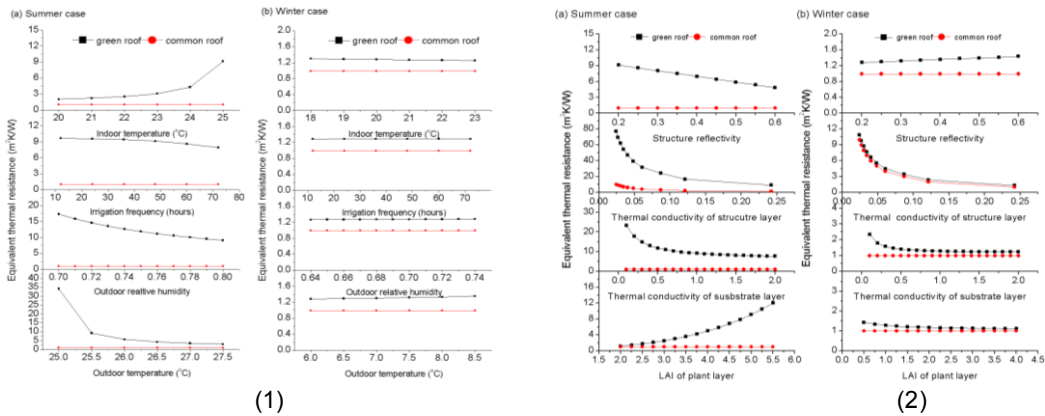


Figure 7 Significant factors' effect on equivalent thermal resistance of green roof system: (1) External factors. (2) Internal factors.

Based the model above, there are mainly two types of factors that may affect green roof's thermal performance, i.e., external factors and internal factors. According to sensitive analysis, the following factors have significant effect on green roof's equivalent thermal resistance. As is illustrated in Fig. 7 (1), in summer, indoor temperature's effect is opposite to outdoor temperature. And when indoor temperature is larger, green roof's equivalent thermal resistance will be larger. Relative humidity's effect is also opposite to indoor temperature, higher relative humidity weakens evapotranspiration of plants, so heat flux into the room becomes larger. Improving the frequency of irrigation also helps to enhance evapotranspiration, so it increases the equivalent thermal resistance. But this benefit shrinks when irrigation frequency becomes shorter and shorter. Although these factors have a significant effect in summer, their effect in winter is limited. The main reason lies in that plant is almost dead (average LAI becomes small) in winter, its shading and transpiration effect decrease a lot. And green roof's effect in winter mainly depends on substrate layer's property. Significant internal factors are shown in Fig. 7(2). LAI has a great effect on shading and plant's transpiration, a larger LAI in summer but a lower value in winter will have more thermal benefit. Thermal conductivity of substrate layer has a similar effect on equivalent thermal resistance as thermal conductivity of structure layer in both seasons, and decreasing thermal conductivity can improve green roof's thermal insulation. However, as the conductivity of structure layer decrease, the relative benefit of green roof becomes small compared with the corresponding common roof. Similar to plant's LAI, Reflectivity of structure layer has an opposite effect on green roof's thermal performance in summer and winter. In both seasons, as reflectivity rise, the surface temperature  $\overline{T_{s3}}$  of common roof gets smaller. But temperature difference ( $\overline{T_{s3}} - \overline{T_{s1}}$ ) is opposite, so equivalent thermal resistance get larger in winter but smaller in summer.

#### 4. Conclusion

This paper proposes a new model of green roof system, and based on this method, it is found that green roof has a better insulation effect than corresponding common roof no matter in summer or in winter of Shanghai. In addition, green roof's equivalent thermal resistance is not a fixed value and it is affected by internal and external factors significantly, such as Plant's LAI, outdoor temperature etc. By using the method mentioned above, it is able to have a quick and relative accurate evaluation of green roof's thermal performance, and judge whether green roof system reaches the insulation rule of local energy conservation.

#### 5. Reference

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