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EXPERIMENTAL EVALUATION OF THERMAL PERFORMANCE AND PASSIVE COOLING EFFECT OF GREEN ROOF ON SUNNY SUMMERTIME

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ABSTRACT

This study investigated the thermal performance and passive cooling effect of an extensive green roof based on an experiment conducted on sunny days in the summer of 2007, for a room with a green roof and a room with a bare roof under air-conditioned and non-air-conditioned states. Three different heat transfer scenarios in terms of average heat flux inside the green roof are defined: (1) heat transfer from indoor space to the green roof when the indoor-outdoor air temperature difference is relatively small, (2) heat transfer from the green roof to the indoor space when the indoor-outdoor air temperature difference is large, (3) ideal thermal equilibrium scenario that heat flux between green roof and indoor space equal to zero. "Cooling flux" is proposed to explain and qualify the passive cooling effect from evapotranspiration on sunny days. A simple method to approximate the "cooling flux" is purposed. The result shows at least 27.4% of the heat flux was absorbed by the passive "cooling flux" under air conditioned status.

Keywords: Extensive green roof; critical air temperature; heat flux; cooling flux

NONMENCLATURE

Abbreviations	
$t_{a.ex}$ (°C)	Outdoor air temperature
$t_{a.in}$ (°C)	Indoor air temperature
$t_{a.in.cri}$ (°C)	Indoor critical air temperature
t_s (°C)	Surface temperature
$t_{s.ex}$ (°C)	External surface temperature
$t_{s.in}$ (°C)	Inner surface temperature
q_{cool} (W/m2)	Cooling flux by vegetation
q_i (W/m2)	Heat flux through the inner surface of the roof

Subscripts:	
g	Green roof
b	Bare roof
soil	Soil layer

1. INTRODUCTION

Green roof is an essential energy-saving technology that significantly reduces the energy consumption of buildings through evapotranspiration, photosynthesis, shading effect, and thermal insulation of substrates [1,2]. Knowledge of the heat flux inside the green roof under different indoor conditions is essential for the evaluation of the thermal benefits. Previous research has revealed the divergence of the heat flux direction through green roofs under varying indoor conditions in the summertime. Past studies found that the roof with green cover had heat flux transfer from the interior to the outside (i.e., negative heat flux) [4]. In contrast, when the indoor air temperature was relatively low under the air-conditioned state, the heat flux through the green roof was constantly positive. These studies demonstrate the effect of the indoor air temperature on the direction of heat flux through the green roof, which is because of the passive cooling effect by the evapotranspiration of plants and soil. A recent study shows that 26% to 35% of incident solar radiation lost by evapotranspiration in summer [3]. However, the reduction of heat flux by passive cooling effect on has not been experimentally investigated.

2. METHODOLOGY

2.1 Experimental site

The experiment was conducted in Xinzhuang, Shanghai in 2007. A four-room single-story building is utilized for the experiment. The building roofs were constructed by 120 mm hollow-core slabs and a 20 mm cement mortar bed with waterproofing protection. Half of the roof was covered with sedum lineare planting modules. The two adjacent rooms in the middle were selected for experimental use, one was under the bare roof and the other was under the green roof. The rooms

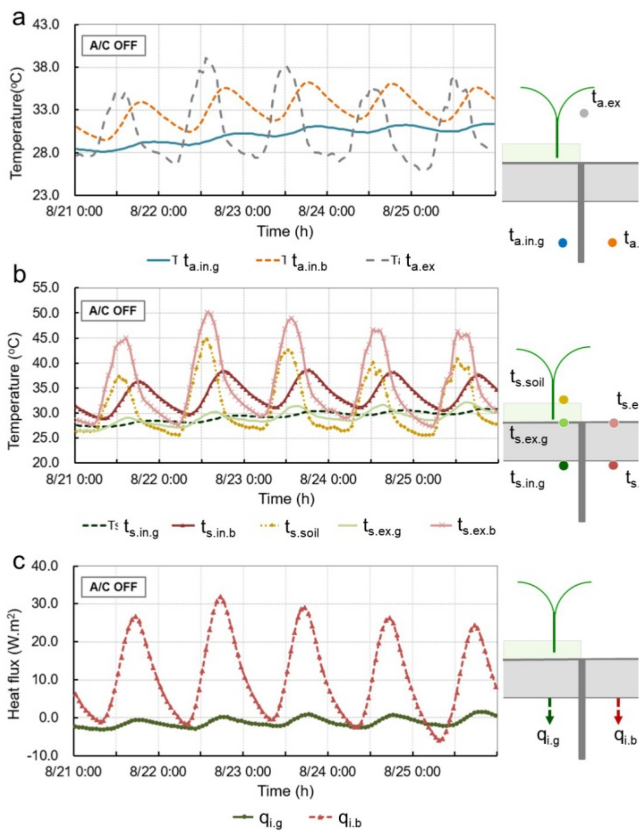

Fig. 1 Measured data of five sunny days (8/21-8/25) during the second typical period: (a) air temperatures; (b) surfacae temperature; (c) same for heat fluxes. (Tang and Zheng, 2019)

were installed with the same wall-mounted air conditioners with the cooling capacity of 3250 W.

2.2 *Measurement step*

The green roof and reference bare roof were monitored in August. The whole period was divided into two observation periods. August 7–18 was the first observation period. The air conditioners were switched on with the temperature setting of 25 °C. The second observation period was August 19–30, with the air conditioners switched off.

The outdoor air temperature ($t_{a.ex}$) and indoor air temperature ($t_{a.in}$) of both rooms were measured by thermocouples. Thermocouples were also applied to measure the surface temperature, including the external surface temperatures ($t_{s.ex}$) and the inner surface temperature ($t_{s.in}$) of the two roofs, and the soil surface temperature of the green roof ($t_{s.soil}$). Note that the external surface temperature of the green roof ($t_{s.ex.g}$) was measured at the interface between planting modules and the roof structure. Heat flux through the inner surface of the roofs (q_i) was measured by heat flux sensors. The locations of measurement apparatus and parameters are shown on the right side of Fig. 1. More details information about the experimental site and measurement step can be found in Ref. [5].

3. RESULTS

3.1 *Characteristic of heat transfer*

Four successive sunny days (August 7 to 10) with air conditioner switched on were selected as the first typical period. The measured air temperature, surface temperatures, and heat flux can be found in Ref. [5]. Similarly, five successive sunny days (August 21–25) with air conditioner switched off were selected as the second typical period, and the measured data are illustrated in Fig. 1a, b, and c. For the green roof, unusually characteristic was observed. Fig. 1c indicates that the heat flux through the inner surface of the roof was mostly negative before August 25, which means that heat was transferred from the indoor space to the roof structure. The positive heat flux was observed in a

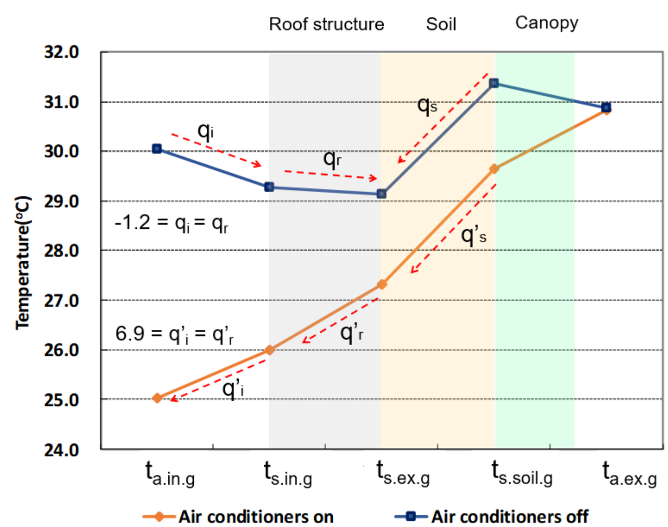

Fig. 2 Profile of average temperature of the green roof on the first typical period and the second typical period (marked as ')

few hours in the afternoon of August 25.

The temperatures inside the green are averaged from August 7-10 and August 21–25, and the temperature profiles are shown in Fig. 2. For the second typical period with air conditioner switched off (blue line), the lowest temperature was found at the interface between the soil layer and the roof structure ($t_{s.ex.g}$) among the five measuring positions. The temperature profiles indicate two different heat transfer scenarios inside the green roof in terms of average heat flux. The first is represented by the status of the green roof from August 21–25, when the air conditioners were switched off and the indoor-outdoor air temperature difference was relatively small ($t_{a.in.g} > t_{s.in.g} > t_{s.ex.g}$, see Fig. 2 and Fig. 3a). It seems that there is a "cooling source" near

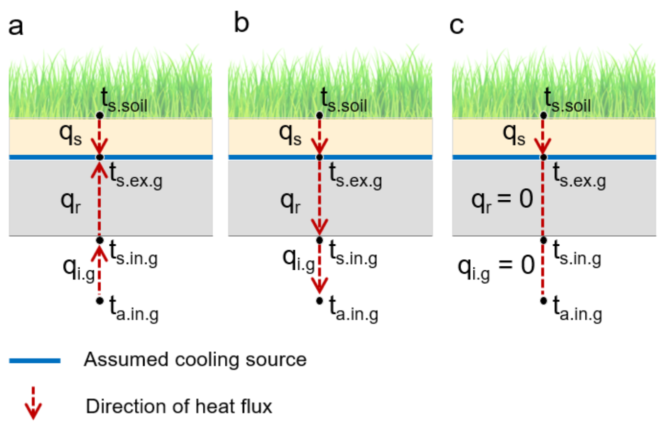

Fig. 3 Three typical heat transfer scenarios

the bottom layer of the soil that absorbed heat from the upside and downside, and this "cooling flux" came from the passive cooling effect by the evapotranspiration of plants and soil [6]. The second scenario is represented by the status of the green roof from August 7–10, when air conditioners were switched on and the indoor-outdoor air temperature difference was big ($t_{a.in.g} < t_{s.in.g} < t_{s.ex.g}$). The heat from the outdoor space was partly absorbed by the green roof (Fig. 3b). The cooling flux (q_{cool}) in the two scenarios can be simplified and expressed as follows:

$$q_{cool} = q_s - q_r \quad (1)$$

where q_s was the heat flux transferred from the outside to the "cooling source". q_r was the heat flux transferred from the "cooling source" to the roof structure, which was equal to the heat flux through the inner surface of the green roof ($q_{i.g}$). In the first scenario, q_r is negative and in the second scenario, q_r is positive.

$$q_{cool} = q_s \quad (2)$$

Based on the two scenarios above, we can deduce that there is a potential ideal thermal equilibrium scenario exists. As shown in Fig. 3c, the heat flow on the inner surface of the roof is equal to zero ($q_{i.g} = q_r = 0$, $t_{a.in.g} = t_{s.in.g} = t_{s.ex.g}$), which means all the heat flux transferred from the outside was absorbed by the "cooling flux" (Eq. 2). The indoor average air temperature ($t_{a.in.g}$) at this state is the indoor critical air temperature ($t_{a.in.cri}$) [5,7], which will be estimated in 3.3.

3.2 Estimation of "cooling flux"

Table. 1 Average measured data from the two typical periods

Air conditioners	Outdoor air temperature $t_{a.ex}$ (°C)	Solar radiation (W/m^2)	Indoor air temperature $t_{a.in.g}$ (°C)	Heat flux $q_{i.g}$ (W/m^2)
On	30.8	258.1	25.0	6.9
Off	30.9	252.8	30.0	–1.2

As we know, q_{cool} comes from the evaporation cooling effect of the vegetation and substrate layer. It mainly depends on the solar radiation and the state of plants. Table 1 summarized the averaged measured data from August 7-10 (air conditioners on) and August 21–25 (air conditioners off). The outdoor air temperature and solar radiation show that the climatic conditions of the two typical periods are quite similar. Therefore, we assume that the two typical periods have the same average q_{cool} and sol-air temperature ($t_{sol\text{-}ai}$). Based on the heat balance law, the total heat transferred across the whole roof construction is the thermal transmittance coefficient multiply by the temperature difference between outdoor sol-air temperature and indoor air temperature. As q_r is equal to $q_{i.g}$, we can rewrite Eq. 1 as follows:

$$q_{cool} = U\,(t_{sol\text{-}ai} - t_{a.in.g}) - q_{i.g} \quad (3)$$

where U is the assumed average thermal transmittance coefficient of the whole roof construction, which is a constant during the two typical periods. Table.1 indicates $q_{i.g} = 6.9$ W/m^2 and $t_{a.in.g} = 25$ °C for the first typical period, and $q_{i.g} = -1.2$ W/m^2 and $t_{a.in.g} = 30$ °C for the second typical period. Eq. 3 can be solved by substituting the two pair of values, resulted in U = 1.62 and q_{cool} as follows:

$$q_{cool} = 1.62t_{sol\text{-}ai} - 47.4 \quad (4)$$

Therefore, the cooling flux is correlated with $t_{sol\text{-}ai}$. As $t_{sol\text{-}ai}$ is always higher than the outdoor air temperature, the most conservative estimation of q_{cool} is taking the average outdoor air temperature of the two typical periods (=30.85°C) as $t_{sol\text{-}ai}$, then the q_{cool} is calculated to be 2.6 W/m^2. If there was no passive cooling effect, the average heat flux entering into the roof would be 6.9 + 2.6 = 9.5 W/m^2 during the first typical period. This means at least 27.4% of the heat flux into the roof was absorbed by the passive cooling effect of the vegetation.

3.3 Estimation of indoor critical air temperature

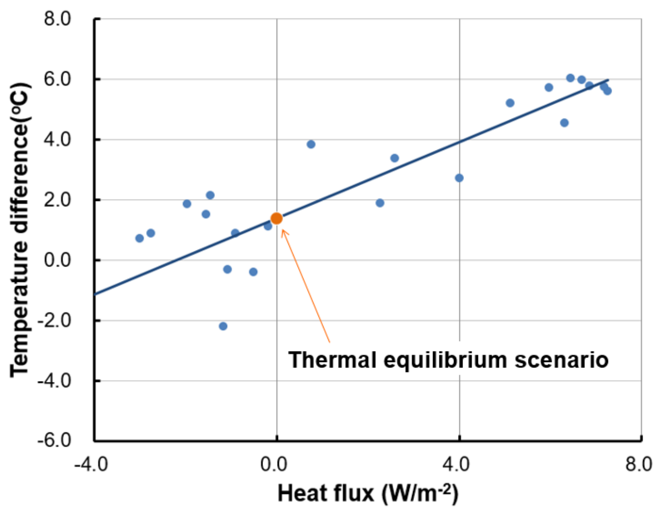

Fig. 4 Results of heat flux and indoor-outdoor air temperature difference in 24 days and the correlation between them

Theoretically, the indoor-outdoor air temperature difference caused heat transfer through the building envelope. Since the building construction has its own thermal mass, the heat flux through the inner surface of the roof does not change synchronously with the indoor-outdoor temperature difference. To take the daily periodicity into consideration, the measured indoor-outdoor air temperature difference and the heat flux were averaged on a daily basis. The data from 24 days (7th to 30th August) are scattered in Fig. 4. The correlation between the heat flux and the indoor-outdoor air temperature difference was generated by linear regression with correlation coefficients of 0.9 [5], and expressed in Eq. (5):

$$t_{a.ex} - t_{a.in.g} = 0.632q_{i.g} + 1.377 \qquad (5)$$

In particular, the thermal equilibrium scenario is achieved when the heat flux in the equation is zero ($q_{i.g} = 0$), and the outdoor air temperature is 1.377 °C higher than the indoor critical air temperature. In the present study, the outdoor average temperature in Shanghai was around 30 °C. Given that the indoor critical air temperature is 1.377 °C lower than the outdoor air temperature, the indoor air temperature can be reduced to 28.6 °C on average with lower fluctuations. This almost reaches the thermal comfort zone for a passive house.

4. CONCLUSION

Based on the measured data from two typical periods, two different heat transfer scenarios inside the green roof are found, respectively. "Cooling flux" is proposed to explain the absorbing of heat flux by the green roof. A third scenario that all the heat flux transferred from the outside was absorbed by the "cooling flux" is assumed. This ideal thermal equilibrium scenario is achieved when the indoor air temperature is equal to the indoor critical air temperature, which is estimated to be 1.4 °C lower than the outdoor air temperature in the present study. In the early design stage, indoor critical air temperature can be a useful parameter to estimate the thermal comfort of a passive building. A simple method to approximate the "cooling flux" is purposed. The "cooling flux" is linearly correlated to the sol-air temperature (t_{sol-ai}) and estimated in a conservative way. The results show that at least 27.4% of the heat flux entering the room under air conditioned status was absorbed by the "cooling flux".

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