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Summertime thermal and energy performance of a double-skin green facade: A case study in Shanghai

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A R T I C L E I N F O

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A B S T R A C T

Vertical greening system(VGS) for buildings is drawing more and more research, because that it provides passive cooling for both indoors and outdoors without occupying valuable urban land, and thus can be a remedy for the deteriorating thermal environment of today's high density urban areas. This paper reports an investigation on the summertime cooling performance of double-skin green facade (DSGF) of a recently-renovated 5-storey administrative building in a university campus in Shanghai. The results show that, the VGS created a distinctive microclimate in the cavity: air temperature T_a averagely dropped by about 0.4 °C in a daily circle, and maximally 5.5 °C for the Southern facade; and by 0.2 °C in average and 3.3 °C maximally for the Northern facade. The mean exterior surface temperature T_s reduction of the Southern facade by the VGS is 1.5 °C and maximally ∼9 °C, whereas the mean interior T_s reduction is 1.2 °C and maximally 2 °C. The corresponding figures of the Northern facade is 0.5 °C, 4.2 °C, 0.5 °C and 1.3 °C, respectively. The indoor thermal improvement by the VGS, evaluated by operative temperature (T_{op}), is 1.1 °C averagely and 2.7 °C maximally on the South-facing office, and 0.6 °C averagely and 1.9 °C maximally on the North-facing office. The initial findings suggest clear potential of VGS in thermal comfort improvement and cooling energy saving, further study is needed to evaluate the yearly energy and comfort effects of VGS on radiation, convective and conduction heat transfer and on daylighting through building envelop, for comprehensive energy assessment considering cooling, heating and artificial lighting.

1. Introduction

Urban green space plays an important role in maintaining a good urban thermal and ecological environment. In high-density Asian megacities such as Shanghai, it is a challenge to maintain a reasonable development density while enhance the ecological service of urban green space. Integration of greenery with urban buildings can contribute to partially restoration of lost green land (Xue, Gou, & Lau, 2017). Vertical greening system (VGS) emerges as a promising strategy in high-density urban development, because it provides valuable "green space" for dense urbanized area and associated environmental, social and economical benefits without occupying much land area (Dunnett, 2004). There are studies demonstrating the benefits of VGS with respect to urban heat island mitigation (Afshari, 2017), microclimate modification (Ip, Lam, & Miller, 2010) and improving pedestrian thermal comfort (Morakinyo, Lai, Lau, & Ng, 2018).

VGS is also considered a potential strategy to improving building thermal and energy performance. Building consumes about one third of the overall energy use by human society (International Energy Agency, 2013), thus building energy efficiency is important in coping with global climate change, regional and urban warming (urban heat island) and deteriorating urban environment (Baker and Steemer, 2000; Lechner, 2015). As urbanization in China is entering a new phase of the so-called "New Normal", in many cities, new construction is on the decrease whereas more and more existing buildings require renovation to meet up-to-date energy codes and indoor environmental quality standards. In fact, compared with developed countries, the overall environmental and energy performance of building stock in Chinese cities is far from satisfactory (Tu, 2011). Under the hot-humid subtropical climate of Shanghai, VGS is not only an attractive face-lift surgery for aged buildings but could also remediate heat flux through building envelope, improving thermal comfort and decreasing cooling load and energy consumption (Wong et al., 2010).

Although there are controversial opinions on various forms of VGS regarding costs, complexity and aesthetic value, deeper understanding on its sustainable application requires more systematic research on the tangible and intangible benefits that VGS brings to the urban society (Riley, 2017), and continuous evaluation of VGS environmental

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performance in comparison to other construction solutions could lead to increased application of VGS and reduced costs (Manso and Castro-Gomes, 2015).

Based on growing substrate and support system, VGS can be classified into green facades and living walls (Pérez, Coma, Martorell, & Cabeza, 2014). Living walls are vegetation grown out of usually-modularized panels attached to building facades either directly or by supportive structures. Green facades can be further classified into traditional green facade, in which climber plants are attached to existing building walls, and double-skin green facade (DSGF), in which climber plants are supported by an added frame to the original building wall and act as a new skin of the old building.

From the perspective of building physics, VGS moderates the indoor thermal environment by manipulating the radiative, convective and conductive heat transfer processes (Eumorfopoulou and Kontoleon, 2009). Kerez et al. summarize the four fundamental mechanisms of VGS as a passive building design system: shading, insulation, evapotranspiration and variation of wind effect (Pérez, Rincón, Vila, González, & Cabeza, 2011). Shading is the most significant approach to reduce indoor heat gain by intercepting direct and diffuse (which can be significant in humid climates) solar radiation. Factors influencing the shading effect of VGS include leaf density (e.g., leaf area index), leaf solar transmittance, leaf area coverage etc. (Raji, Tenpierik, & van den Dobbelsteen, 2015). But VGS differs with other man-made shading materials, in that vegetation is a living component, and its evapotranspiration diverts a portion of sensible heat into latent heat flux, therefore leaf surface temperature is reduced compared to metal shading devices, and so is the radiative heat transfer between leaves and walls and leaves and interior (through windows and openings) (Hoelscher, Nehls, Jänicke, & Wessolek, 2016). Factors influencing evapotranspiration performance of VGS include climatic condition, type and exposure of plant, substrate moisture content, leaf stomata characteristics, etc. (Pérez et al., 2011; Davis and Hirmer, 2015). To model the cooling mechanism of evapotranspiration by vegetation is not straightforward (Flores Larsen, Filippín, & Lesino, 2015), A study in Berlin indicates that the cooling effect of direct green facades (climbers on brick wall) in summer was contributed mainly by shading in clear days but transpiration became more prominent in cloudy days (Hoelscher et al., 2016). A energy balance analysis on a living wall system under Shanghai climate indicates that evapotranspiration can account for more than 50% of heat release in summer (He, Yu, Ozaki, Dong, & Zheng, 2017).

Insulation effect of green facade is associated with foliage density and air change rate of the buffer space in between wall and greenery (Pérez et al., 2011). An experimental study in the UK using brick cuboids array suggests 21–37% heating energy savings achievable by applying direct green facade (*Hedera helix*) (Cameron, Taylor, & Emmett, 2015). For living walls, heat capacity and thermal resistance of the substrate should also be taken into account, and dependent on configuration, location and season, the thermal insulation is variable (Tudiwer and Korjenic, 2017; He et al., 2017).

When designing a VGS, modification on the nearby air movement also needs careful consideration to optimize the energy implication. Air speed within the cavity between wall and plant has strong influences on the convective heat transfer coefficient of the wall (Ottelé, Perini, Fraaij, Haas, & Raiteri, 2011). In general, plant species (deciduous or evergreen) with regard to facade orientation and spacing between foliage and wall should be taken into account, to encourage summertime air circulation while reduce wintertime wind speed. A comparative study indicates that, in cold climates, direct green facade and living wall system are more effective wind barriers compared to indirect (double skin) green facade system. And for the DSGF to effectively stagnant near-wall air movement, the cavity depth should be minimized, e.g., 40–60 mm (Perini, Ottelé, Fraaij, Haas, & Raiteri, 2011). A series of summertime field measurements on four pairs of walls of different plant coverage and orientations has found that, the ivy-covered walls had reduced wind speed immediately adjacent to the facade, ranging 0–43% depending on facade orientation and presence of nearby obstructions, and the ivy layers were estimated to averagely reduce 10% in heat flux through opaque walls, and reduce 4–12% in air infiltration rates per unit wall area (Susorova, Azimi, & Stephens, 2014).

An experimental study investigated the key traits contributing to cooling effects of vine plant traditional green facades, and identifies leaf percentage coverage and leaf solar transmittance as the two key traits (Koyama, Yoshinaga, Hayashi, Maeda, & Yamauchi, 2013). A study monitored a direct green facade in Nanjing China and found out that the cooling effect is linearly related to percentage of green coverage while plant thickness and volume of green facade were power function distributions (Yin et al., 2017). A two-year experiment with South-facing green facades under the Mediterranean climate indicates a year-round thermal- mediating effect from the greenery, and that the highest cooling occurs with ambient wind speed of 3–4 m/s, relative humidity of 30–60% and solar radiation higher than 800 W/m^2 (Vox, Blanco, & Schettini, 2018). A numerical simulation study also supports that leaf density and thickness, indicated by leaf area index and shading coefficient, improve building thermal insulation and reduce air-conditioning electricity consumption (Wong, Tan, Tan, & Wong, 2009). Larsen et al. analyzed the DSGF's thermal regulating mechanisms involving evapotranspiration process, and proposes a simplified method to simulation DSGF with standard transient simulation software (Flores Larsen et al., 2015). Susorova et al. developed a mathematical model for a climber-covered exterior wall. The model takes into account plant stomata resistance in transpiration process (Susorova, Angulo, Bahrami, & Brent, 2013). A comparative study on energy performances between LWS and DSGF in Spain shows a 58% cooling electricity reduction by LWS and 34% by DSGF (Coma et al., 2017). In China, an experiment examined the impacts of a number of design parameters on a West-facing living wall system in Wuhan, and tested sensitivities of cavity depth and cavity ventilation rates with the cooling effect during hot-humid summer months (Chen, Li, & Liu, 2013). He et al. developed a coupled heat and moisture transfer model of a living wall system and validated it by field experiments in Shanghai (He et al., 2017). The above two experiments employed rooftop test chambers made of light structure (e.g. thin foam sandwich panel in the case of Shanghai), therefore the measured envelope and indoor thermal condition can be affected by the low heat capacity, and differ with that of normal buildings. A theoretical analysis on DSGF on high-rise residential buildings in Hong Kong indicates a total cooling energy savings of up to 76% (Wong and Baldwin, 2016). The simplified calculation aims at understanding the potential energy savings and feasibility of applying DSGF to residential buildings at the urban scale. At the building scale, more detailed examination on transient heat transfer process would be necessary in energy savings analysis.

Previous research has indicated that for the cities in the Northern hemisphere, the cooling efficiency of VGS on indoor environment can be profound for West-oriented facades in summer (Kontoleon and Eumorfopoulou, 2010), and North-oriented facades in winter (He et al., 2017). However, the dominant orientation of residential and small ($< 20{,}000\ M^2$ in TFA) non-residential buildings in Southern Chinese cities is South-North. This is due to the wide application of passive design to utilize solar heating and wind-driven indoor ventilation (Yang, Lau, & Qian, 2011). Therefore, when considering the total thermal and energy benefits of building stock in Southern Chinese cities, performance of VGS on South and North facades deserve equal, if not prioritized, research effort.

Previous research investigated various types of VGS in cities mostly located in Europe and North America. There are very few studies that reported site-monitored summertime cooling performance of DSGF on real-world buildings in Asian megacities with a hot-humid Sub-tropical climate. The present paper reports an empirical study on a recently-renovated office building in a university campus in Shanghai, the largest city in China. During summer months, the thermal and