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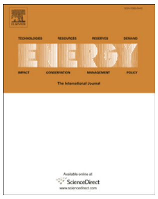

On detailed thermal response modeling of vertical greenery systems as cooling measure for buildings and cities in summer conditions

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A B S T R A C T

Vertical greenery systems (VGSs) are becoming a common architectural element in urban environments. In addition to the aesthetics of VGSs, impacts on building's energy demand and heat island mitigation in cities has been identified. In the present study, experimental results of thermal response and properties of VGSs with vertical leaf area index (LAIV) equal to 6.1 and 7.2 are presented. Experimental results show that VGSs can impact up to 34 K lower surface temperatures of a façade, while maintaining air temperatures in the VGSs' canopies close to ambient temperatures. Properties of the VGSs were used as a basis as well as an input for a detailed mathematical model of the thermal response of a building envelope with a VGS. The validated mathematical model was used for parametrical analysis of the impact of thermal resistance of a building envelope on the cooling potential of the VGSs. The results show that the cooling effect is more significant for less insulated façades, and that a VGS can be modeled as an independent urban cooling element. Finally, a parametrical model of the latent heat flux of a VGS was developed and can be used as a boundary condition in urban heat island studies.

1. Introduction

In the past, the primary role of greenery in the urban environments was its aesthetics [1]. Recently, the importance of greenery in urban environments has been increased due to the identified impact on the mitigation of the heat island effect [2,3] and buildings' energy demand, when applied on roofs [4,5] or façades [6]. The latter enable a greater potential for energy savings as façades represent the marginal share of a building envelope surface in urban environments. Due to the various architectural approaches, VGSs can be divided into direct and indirect VGSs, living wall, and double-skin façades with plants [7,8].

It has been proven that VGSs impact temperature and flow conditions at a building envelope boundary due to evaporative cooling, the shading of a façade, the selective absorption of solar radiation and structural properties of VGSs [9,10]. In addition, due to the adaptive properties of VGSs, greenery represents a convenient way to upgrade a static building envelope into an adaptive one [11], which is a rapidly developing research area [12,13].

The thermal response of VGSs is most frequently evaluated with *in situ* measurements of temperatures in consecutive layers from a façade's surface towards the environment [14]. Results from the whole-year survey carried out by Pérez et al. [15] showed that VGSs are most effective in summer conditions. Furthermore, due to the evaporative cooling and shading of the façade, surface temperatures of the façade with a VGS are up to 15 K lower in comparison to the reference façade [6,7,16,17]. Moreover, in the thermal response study of double-skin façade with plants, Stec et al. [6] reported that greenery is more efficient in the reduction of air temperature than conventional shades; however, according to findings from Fang et al. [17], it does not reduce the overheating of a double-skin façade. Conclusively, the lower surface temperature of a façade with a VGS can cause a 20% reduction of cooling demand [6]. In addition, lower surface temperatures prolong the life expectancy of a façade and reduce maintenance costs [16].

Wong et al. [14] showed that a VGS as an independent heat island mitigation measure does not reduce the urban heat island (UHI) effect significantly. A similar conclusion can be drawn from *in situ* experimental studies on air temperatures in the vicinity of a VGS [7,16]. In contrast, results from a comprehensive CFD study under the assumption of the application of the greenery on all urban surfaces from Vidrih [18] show significant reductions of air temperatures in the urban area.

In order to model the thermal response of a building envelope

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with a VGS, information on a VGS must be provided, such as density (characterized with the leaf area index (LAI) [19]), transmitivity [6], coverage factor or view factors and evapotranspiration (ET), defined as the amount of water evaporated from the surface of leaves [19].

Stec et al. [6] developed a lumped-capacitance model of the double skin façade with plants and validated it with laboratory experiments. For quantification of evapotranspiration, the Pennman-Monteith method [19] was used and compared with a proposed simplified method for ET. The transmitivity of the VGS was determined experimentally, though LAI was not evaluated. Most recently Flores Larsen et al. [20] adopted Stec's [6] model and upgraded the simplified model of the ET.

Kontoleon and Eumorfopoulou [21] also developed a lumped-capacitance model of VGS, validated it with results from previous research [22], and carried out a parametrical analysis of an impact of a façade orientation and proportion of a leaf coverage on the VGS's cooling performance. The evapotranspiration, i.e. latent heat flux, was not explained. Susorova et al. [23] developed a similar mathematical model, where the latent heat flux has been accounted for with an empirical relation for leaf temperature, based on the greenery properties available in the literature.

VGSs in urban environments can be modeled in CFD tools either as a temperature boundary condition or a heat flux boundary condition based on the latent heat flux of a VGS [18]. The latter can be formed as the VGS's volumetric cooling power boundary condition, which is rarely mentioned in literature, according to Gromke et al. [24].

The majority of available studies focused on experiments, less so on numerical modeling, and few use experiments to validate mathematical models, thus providing general applicability. To the authors' knowledge, no research provides both a detailed validated mathematical model and experimentally quantified properties of VGS. The latter is essential for evaluation of radiation and latent heat transfer as two of the most influential physical processes in a VGS.

In the present study, we have developed such a mathematical model and validated it with *in situ* experimental results of the thermal response of the VGS with two densities (*LAIV* equal to 6.1 and 7.2). Measured properties of VGSs, such as transmitivity, leaf area index and view factors, were used as model inputs. Furthermore, the model's applicability was demonstrated with a parametrical analysis of the VGSs' impact on a building envelope and vice-versa. In addition, the validated mathematical model was used for the development of the parametrical model of the latent heat flux of the VGSs that can be used as a boundary condition in the UHI mitigation research.

2. Experiment

The experiment, as depicted in Fig. 1a, has been designed based on the experience from the previous study [11] and upgraded with latest findings from the literature review. The experiment was located in the vicinity of the city center of Ljubljana, Slovenia (46.12059, 14.49543).

2.1. Plant selection and VGS design

For the VGS, the plant *Phaseolus Vulgaris* L was chosen because it is adapted to the local climate, is fast growing, and has a thick canopy. The VGS was applied to the façade indirectly, forming an 8 cm air gap (microclimatic layer) with the façade (Fig. 1b). A supporting construction for the greenery was designed to allow an assembly of the one- and two-layered VGS (Fig. 1c and d), the canopy density thus varies, and enable a preparation of the back-up VGSs. Maximal availability of irrigation water was enabled with an automated irrigation system placed in the containers.

2.2. Experimental setup

The central component of the experimental setup was a thermostated test cell. The interior air temperature of the test cell was maintained at 23.5 ± 0.5 °C. A south-orientated façade of the test cell was divided by a non-transparent high-reflective wind barrier into two parts: the left side served as a reference façade and on the right side the VGS was installed (Fig. 2c). The wind barrier was also placed on the opposite side of the VGS, preventing wind-driven ambient air from entering the air gap between the VGS and the façade (Fig. 2c) [11].

The sensor distribution on the test facility is outlined in Fig. 2. Global solar radiation on the vertical surface was measured with the Kipp&Zonen CM11-P pyranometer (non-linearity ± 0.6%, temperature dependence ± 1%, tilt error ± 0.25%). The Kipp&Zonen CG1 pyrgeometer (non-linearity ±1%, temperature dependence ±2%) was used for measurements of downward long-wave radiation. Ambient air temperature (RTD ±0.5%) and relative humidity (AHLBORN FHA 646 E1 ±2% RH), and wind velocity (Fischer 451214 ± 0.3 m/s) were measured at a height 1.3 m in the front of

Fig. 1. A front view of the experiment with the thermo-stated test cell with and without the VGS (a), a side-view of the VGS positioned at the thermo-stated test cell (b), a schematic of the one-layered (c) and the two-layered VGS (d).