Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 78 (2015) 1195 – 1200
Energy Procedia

6th International Building Physics Conference, IBPC 2015

A Hydro-Thermal Study of the Bionic Leaf - A Basic Structural Element of the Bionic Façade Inspired by Vertical Greenery

Tomaž Šuklje*, Ciril Arkar, Sašo Medved

Laboratory for Sustainable Technologies in Buildings, Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, 1000 Ljubljana, Slovenia

Abstract

Vertical greenery systems (VGS) are proven to decrease energy consumption for cooling of the building due to the evapotranspiration and shading of the building envelope. Despite innovative architectural solutions, there are some drawbacks of VGS that are most commonly related to the maintenance. Alternatively, bionic façade inspired by VGS can be developed with the use of innovative materials to mimic positives and eliminate disadvantages. In the present experimental research a water mass-flow-rate into the bionic façade is evaluated in respect to the simulated meteorological parameters. Based on the results from the parametrical analysis, an empirical model of water mass-flow-rate of the bionic façade is developed and compared with evapotranspiration of the VGS in real conditions.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: evaporative cooloing; green façade; adaptive façade; CO_2 sink; heat and mass transfer

1. Introduction

The basic role of the building envelope is the separation of the exterior from the interior environment. The role has not been upgraded since recently, when adaptive façade concepts are being presented in the form of integrated façades, alternating façades etc. [1]. Great potential for energy savings is expected as majority of façades adapt neither to the needs of users nor to the changing conditions in the exterior environment. In the future, they are expected to adjust to periodic changes (i.e. seasons, schedules, etc.), as well as to sudden changes (i.e. change of schedules of building users, change of building’s facility type, etc.), while simultaneously enabling the utilization of renewable energy [2].

* Corresponding author. Tel.: +386-1-4771-236.
E-mail address: tomaz.suklje@fs.uni-lj.si

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.108

A step towards adaptive building envelopes are vertical greenery systems (VGS), commonly addressed as green façades. Based on latest research it has been ascertained that façades with vertical greenery incorporate adaptive properties; such as evaporative cooling, shading of building envelope, selective absorption of solar radiation, sink of CO_2 emissions and other air pollutants, passive acoustic insulation [3-7]. Among listed properties, evapotranspiration and shading of the building envelope develop a microclimatic layer at building boundary, which decreases the energy consumption for cooling [8-10]. Despite innovative architectural solutions, there are some drawbacks of VGS that are most commonly related to the maintenance [11]. Therefore a façade system, which mimics positives and eliminates disadvantages should be considered.

Such a system can be developed with the use of bionic principle, which is about the nature observation at its properties and principles, and the transformation and the development of these principles into sophisticated technological solutions [12]. Various bionic solutions have been implemented in building envelopes recently, as concepts as well as working prototypes [13]. In the precedent research, an idea of a bionic leaf as basic structural element of the bionic façade was presented [14]. The bionic leaf consisted of a polycrystalline photovoltaic cell and an evaporative matrix. Enabling evaporative cooling, shading of the building envelope and reduction of CO_2 footprint of the building. To evaluate the thermal response of the microclimatic boundary layer caused by the bionic façade, an array of bionic leaves was installed and analyzed. The study showed promising results, however the performance of the bionic leaf should be further researched.

In the present research a hydro-thermal experimental study of the bionic leaf is performed. For the purpose, laboratory test apparatus has been developed and an array of bionic leaves installed. The aim of the research is to develop a parametrical model of the water mass-flow-rate of the bionic façade analogous to the evapotranspiration of the VGS. Which will be used in the future research for the numerical study of the thermal response of the full-scale bionic façade. Finally, a water mass-flow-rate of the bionic façade and the evapotranspiration of the VGS are compared and steps for further research and development are outlined.

2. Methodology

2.1. Evapotranspiration

The latent heat flow of VGS (Eq. 1) is most commonly assessed using the Penmann-Monteith evapotranspiration model [15]. Evapotranspiration ET [kg/s] is calculated using Eq. 2, where $\dot{q}_{net}$ is net radiation heat flux, $\dot{q}_{soil}$ soil heat flux, ρ_{air} [kg/m^3] is air density, $c_{p,air}$ [J/(kg.K)] is the specific heat of the air, $(p_{v,s} - p_{v,a})$ [kPa] represents vapor pressure deficit of air, Δ [kPa/°C] represents the slope of the saturation vapor pressure temperature relationship, γ [kPa/°C] is the psychrometric constant, r_s [s/m] and r_a [s/m] are the (bulk) surface and aerodynamic resistances, and r_{lat} [J/kg] is specific heat of water evaporation.

$$\dot{q}_{lat} = ET \cdot r_{lat} \tag{1}$$

$$ET = \frac{\Delta\left(\dot{q}_{net} - \dot{q}_{soil}\right) + \rho_{air} c_{p,\mathrm{air}} \dfrac{\left(p_{v,s} - p_{v,a}\right)}{r_a}}{r_{lat}\left(\Delta + \gamma\left(1 + \dfrac{r_S}{r_a}\right)\right)} \tag{2}$$

The heat flow from ground is neglected as the heat transfer in the horizontal direction is analyzed. Remaining independent variables are as follows; an ambient temperature T_{amb}, a net radiation heat flux $\dot{q}_{net}$, a relative humidity RH and a wind velocity v. Listed variables are expected to impact water mass-flow-rate of the bionic façade and are therefore considered in the experiment.

2.2. The experiment

The hydro-thermal experimental study of the bionic leaf was performed in a climatic chamber (Fig. 1a) at Faculty of Mechanical Engineering, University of Ljubljana. The ambient temperature was maintained with a heater and a cooler via a PID controller. Similarly, the relative humidity was controlled with a humidifier and a dehumidifier. The wind velocity with constant upward direction was simulated with tangential fans. The absorbed solar radiation was simulated with plate resistive electric heaters to obtain a general empirical model. All influential variables were maintained at levels significant for the local climate (Ljubljana, Slovenia).

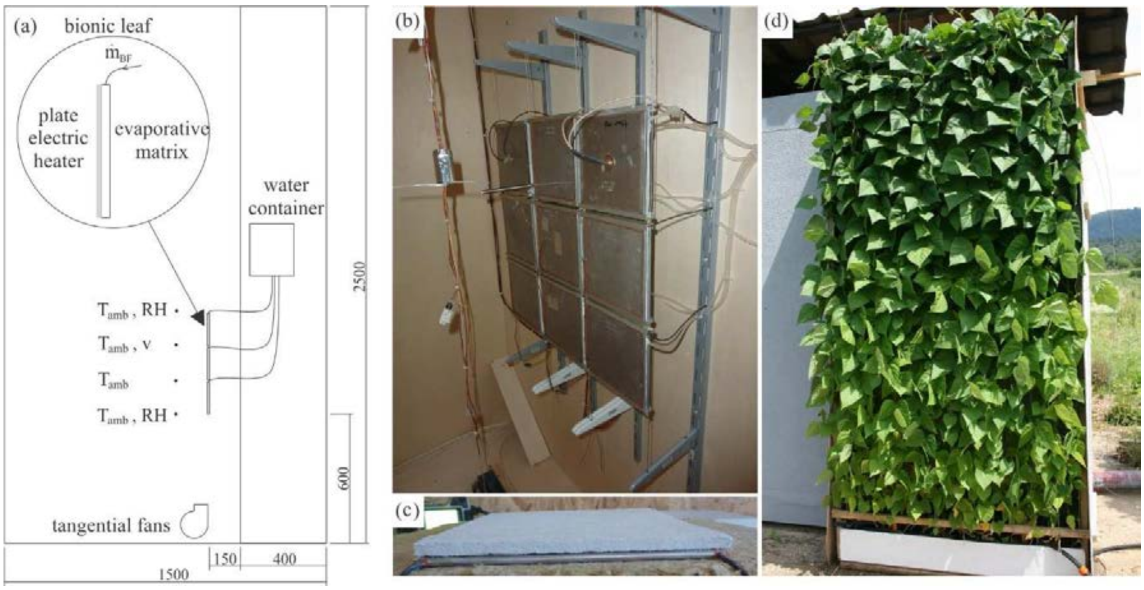

Fig. 1. (a) Schematics of the experimental setup; (b) an array of bionic leaves in the climatic chamber; (c) the bionic leaf; (d) the VGS at the outdoor test facility.

In order to ensure relevant microclimatic conditions at the wall boundary in the climatic chamber, an array of nine bionic leaves parallel to the wall (150 mm offset) was installed (Fig. 1b). All containing a plate resistive heater (150mm x 150mm), replacing a photovoltaic cell, and a 7 mm evaporative matrix made of calcium silicate (Fig. 1c). The material was chosen based on its morphing ability and a high capillary pull. Both properties are desired for an optimal design of the bionic leaf. Containers for water supply of bionic leaves were kept at the back-side of the climate chamber, maintained at the ambient temperature (Fig. 1a). Water supply system is designed based on the hydrostatic pressure, balanced with pressure drop in the evaporative matrix. Consequently, maximal quantity of water is available at all times and, considering saturated evaporative matrix, the water mass-flow-rate into the bionic leaf is dependent solely on the evaporation from the bionic leaf.

Meteorological parameters in the climatic chamber were maintained at levels listed in Table 1. Together, 40 combinations were measured. Each combination was maintained stationary for an experimentally determined time interval.

Table 1. Maintained meteorological parameters

Meteorological parameters	Range
ambient temperature T_{amb} [°C]	20 - 35
relative humidity RH [%]	30 - 60
wind velocity v [m/s]	0.3 – 1.5
net radiation heat flux $\dot{q}_{net}$ [W/m^2]	100 - 850

3. Results and discussion

Findings from the precedent study showed lower surface temperatures of the bionic leaf, compared to the photovoltaic cell [14]. However, the water mass-flow-rate into the bionic leaf has not been analyzed and is the objective of the present study.

3.1. Development of a parametrical model

Firstly, the measured heat flux of the electric heater has been corrected with the long wave net radiation flux in the climatic chamber and water mass-flow-rate into bionic leaf normalized to the m^2 of the bionic façade. Later on, the relation between the water mass-flow-rate m_{BF} and each influential parameter has been analyzed separately (Fig. 2). It has been ascertained that relation between the water mass-flow-rate and all meteorological parameters is linear. Consequently a multiple linear regression model (Eq. 3) has been proposed to fit the data.

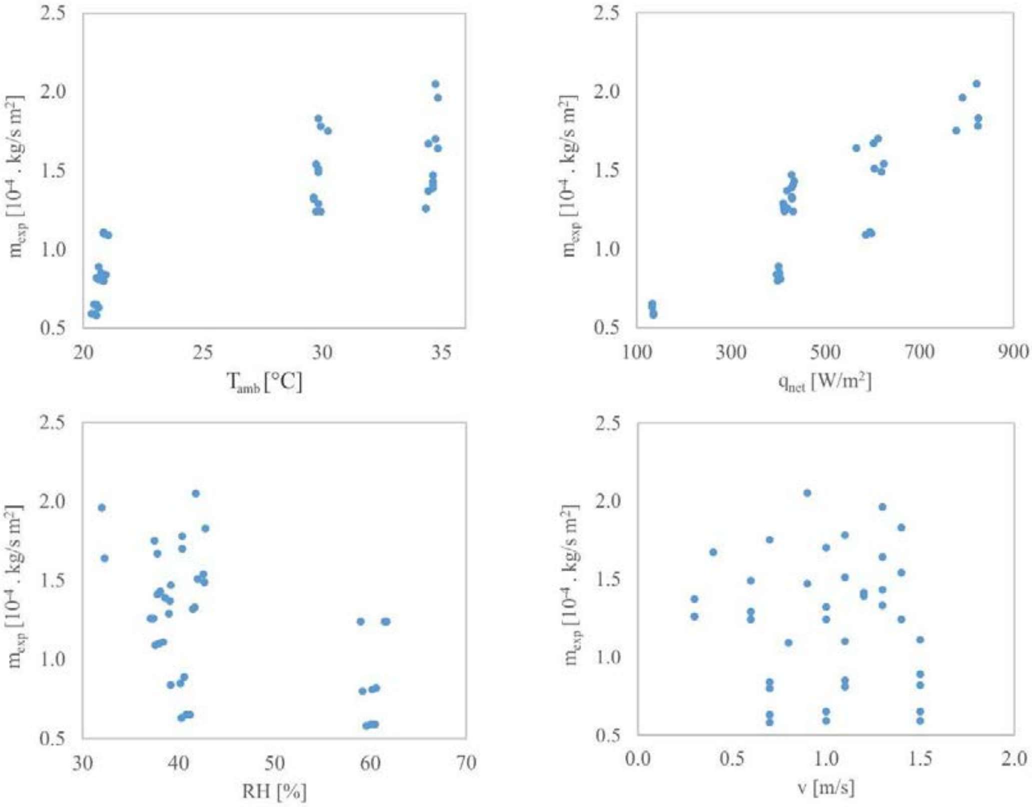

Fig. 2 Scatter plots of individual correlations between water mass-flow-rate of the bionic façade and meteorological parameters.

F-test and level of characteristics showed that there is dependence of the water mass-flow-rate m_{BF} on the ambient temperature T_{amb}, the net radiation heat flux $\dot{q}_{net}$, the relative humidity RH and the wind velocity v. Student's t-tests and the level of significance for the regression coefficients showed that all regression coefficients are significantly different ($p<0.05$). The results of the residual analysis indicated that residuals are independent, distributed in a normal distribution with an average of 0. All these statistical indicators, along with the comparison of measured and calculated values (Fig. 3) show the suitability of the derived multiple linear regression model.

$$\dot{m}_{BF} = -3.89 \cdot 10^{-5} + 3.75 \cdot 10^{-6} \cdot T_{amb} + 1.22 \cdot 10^{-7} \cdot \dot{q}_{net} - 1.17 \cdot 10^{-7} \cdot RH + 6.48 \cdot 10^{-6} \cdot v \quad (3)$$

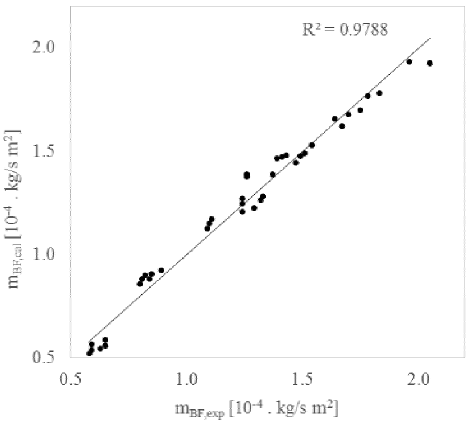

Fig. 3 Comparison of measured $m_{BF,exp}$ and calculated $m_{BF,cal}$ water mass-flow-rates of the bionic façade.

3.2. Comparison with the evapotranspiration

The developed parametrical hydro-thermal model of the water mass-flow-rate of the bionic façade (Eq. 3) has been used with the real meteorological data. The results have been compared with the evapotranspiration of the VGS (Fig.1d) using Eq. 2. Surface resistance r_s and aerodynamic resistance r_a, were calculated according to the measured vertical leaf area index *LAIV* and geometrical properties of the experimental setup [5], respectively [15]. Properties of the VGS and bionic façade used in the simulation are summoned in the Table 3. The surface temperature of the basic building envelope is considered to be equal to the back-side of the VGS and the bionic façade. For simulation purposes meteorological data on a summer week (from 14th till 21st July 2014) in Ljubljana, Slovenia has been chosen.

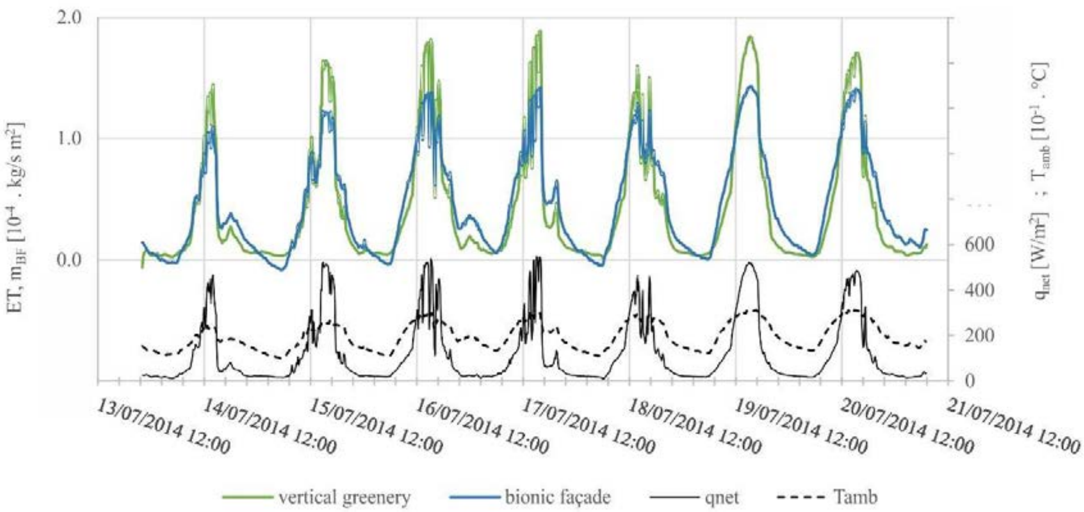

Fig. 4 Simulation results of the evapotranspiration of VGS (green line) and the water mass-flow-rate of the bionic façade (blue line); ambient temperature (dotted line) and net radiation heat flux (black line).

Based on the results it has been ascertained that on the summer week net radiation heat flux $\dot{q}_{net}$ and ambient temperature T_{amb} ranging from 102 W/m² to 548W/m² and 20.3°C to 31.4°C, daily evaporated water mass from VGS and the bionic façade ranged from 1.7kg/m² to 4.1kg/m² and from 1.5kg/m² to 3.8kg/m², respectively. Therefore it can be concluded that that the water mass-flow-rate of the bionic façade is comparable to the evapotranspiration of the VGS. However, the evapotranspiration process tends to be more effective in terms of evaporative cooling of the building envelope compared to the bionic façade at the highest values of ambient temperatures and net radiation heat fluxes. The developed model is valid in the range of daytime meteorological parameters, consequently the results for nighttime are not a subject of the comparison.

Table 3. Properties used in the simulation

Properties	VGS	bionic façade
solar absorptivity [-]	0.768	0.9
long-wave spectral emissivity [-]	0.983	0.9
vertical leaf area index *LAIV* [-]	6.06	-

Future research will be focused on an enhancement of the water evaporation of the bionic façade. Measures, such as an alteration of the bionic leaf's tilt angle in respect to the solar radiation and an alteration of the evaporative matrix's shape, will be taken. Both measures are expected to allow for better convective mass transfer. First, due to the opened cavity and changed air flow conditions, second due the surface extension of the evaporative matrix.

4. Conclusions

In the present study the hydro-thermal model of the bionic façade was presented. Based on the laboratory experiment the parametrical model of the water mass-flow-rate into the bionic façade has been developed. The results from the statistical analysis show, that the developed model is significant and suitable. Further on, the water mass-flow-rate of the bionic façade was compared with the evapotranspiration of the VGS. The comparison showed that evaporation rate from bionic leaves is comparable to the evapotranspiration. However, the evapotranspiration tends to be more intensive at the highest of the thermal load, thus more effective in terms of evaporative cooling of the building envelope.

In the future research, measures for an enhanced evaporation rate from bionic leaves should be taken. Mimicking natural leaves, a tilt angle of bionic leaves in respect to the solar radiation should be altered. In addition, the design of the evaporative matrix should be optimized.

References

[1] Knaack, U., Facades – Principles of Construction, 2007, Berlin: Birkhauser Verlag AG.
[2] Loonen, R., Climate adaptive building shells: What can we simulate?, 2010, Technische Universiteit Eindhoven: Eindhoven.
[3] Pérez, G., et al., Vertical Greenery Systems (VGS) for energy saving in buildings: A review. Renewable and Sustainable Energy Reviews, 2014. 39(0): p. 139-165.
[4] Ottelé, M., H.D. van Bohemen, and A.L.A. Fraaij, Quantifying the deposition of particulate matter on climber vegetation on living walls. Ecological Engineering, 2010. 36(2): p. 154-162.
[5] Šuklje, T., C. Arkar, and S. Medved, The Local Ventilation System Coupled With The Indirect Green Façade: A Priliminary Study. International Journal of Design & Nature and Ecodynamics, 2014. 9(4): p. 314 - 320.
[6] Marchi, M., et al., Carbon dioxide sequestration model of a vertical greenery system. Ecological Modelling, (2014). doi:10.1016/j.ecolmodel.2014.08.013
[7] Azkorra, Z., et al., Evaluation of green walls as a passive acoustic insulation system for buildings. Applied Acoustics, 2015. 89(0): p. 46-56.
[8] Wong, N.H., et al., Energy simulation of vertical greenery systems. Energy and Buildings 2009. 41: p. 1401-1408.
[9] Kontoleon, K.J. and E.A. Eumorfopoulou, The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. Building and Environment, 2010. 45(5): p. 1287-1303.
[10] Safikhani, T., et al., A review of energy characteristic of vertical greenery systems. Renewable and Sustainable Energy Reviews, 2014. 40(0): p. 450-462.
[11] Ottelé, M., et al., Comparative life cycle analysis for green façades and living wall systems. Energy and Buildings, 2011. 43(12): p. 3419-3429.
[12] Badarnah, L. and U. Kadri, A methodology for the generation of biomimetic design concepts. Architectural Science Review, 2014: p. 1-14.
[13] Loonen, R.C.G.M., Bio-inspired Adaptive Building Skins, in Biotechnologies and Biomimetics for Civil Engineering, F. Pacheco Torgal, et al., Editors. 2015, Springer International Publishing. p. 115-134.
[14] Šuklje, T., S. Medved, and C. Arkar, An Experimental Study on a Microclimatic Layer of a Bionic Façade Inspired by Vertical Greenery. Journal of Bionic Engineering, 2013. 10(2): p. 177-185.
[15] Allen, R.G., Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study. Journal of Hydrology, 2000. 229(1–2): p. 27-41.