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Original Article

Methodology of thermal resistance and cooling effect testing of green roofs

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Abstract

For the first time, methodological approaches have been developed and given to determine heat exchange processes in the living vegetation layers of green roofs using total thermal resistance, which takes into account the heat exchange processes directly in it and the heat transfer on its free surface. The approaches take into account wind speed. In addition, for the first time, clarification has been made in the understanding of the term “cooling effect”, as the difference of the temperatures between the living plant layer and the air. The method of its determination is proposed. Engineering approach to thermotechnical calculation of the green roofs is given taking into account the “cooling effect”. Influence of the wind speed on the “cooling effect” has been determined. Based on the influence, the recommendations for parapet construction are provided for “cooling effect control” maximizing energy efficiency of buildings.

Keywords: green roof, green construction, green structures, vegetation layer, cooling effect

1. Introduction

Today, there is growing interest in green building around the world. This is due, on the one hand, to the energy crisis, on the other – environmental and social problems. One of the most important areas of green building is green roofs (Gaffin *et al.*, 2008; Heng, Ning, Jianpin, Xiaoyan, & Yun-Fei, 2015; Institute for Research and Construction [IRC], 2003; Liu & Baskaran, 2003; Lui & Minor, 2005; Minke, 2014; Niachou, Papakonstantinou, Santamouris, Tsangrassou lis, & Mihalakakou, 2001; Ouldboukhitine & Belarbi, 2015; Rakotondramiarana, Ranaivoarisoa & Morau, 2015; RICS Research [RICS], 2007; Wong, Chena, Ong, & Sia, 2003). They have a number of advantages, the main of which are: reducing the load on storm sewage, saving drinking water, additional heat insulation, evaporative cooling through evapotranspiration (evaporation of moisture by plants and soil or substratum), sound-proofing, reduction of the effect of “thermal islands”, the conservation of flora and fauna. Thermotechnical characteristics of them require additional researches.

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2. Overview of Existing Researches

In studying the thermal physics processes occurring in the green layer of the green roof, it was established that the thermal resistance is determined by radiation heat exchange between the plants, the soil and the environment, heat conductivity of the plants themselves and air between them, convection from the plants to the air between them and vice-versa, and also heat transfer to the environment (also convection). The last two processes cannot be separated because of complexity.

Research on these issues can be divided into three groups: the first, full-scale practical studies; second is laboratory tests on physical models, and third is mathematical simulations. It is believed that in summer the green roof works as a passive cooler. Investigation of the "cooling effect" of a green roof is based on comparison of air temperature above non-green roofs with air temperature above green roofs with vegetation layers. The temperature over non-green roofs is much higher than over the green ones. According to Cambridge University, in summer surface temperature of a black roof can reach 80 °C, but temperature above the green roof is only 27 °C (RICS, 2007). Test results (Heng *et al.*, 2015) in China showed that in summer temperature of bare ground (approximately the same as grey non-greened roof) could reach 47 °C, but it is only 41 °C above the green roof. The temperature above a reflective roof (new galvanized steel) should be even lower. Thus, this definition of "cooling effect" characterizes rather a non-greened surface.

In 2005, Gaffin *et al.* (2008) assumed that the green roofs are cooled as effectively as non-greened white roofs. Cooling of the green roofs is transformation of sensible heat into the latent one and improving reflectance of direct solar radiation. Albedo (Oke, 1987) of white or whitewash painting is 0.5-0.9; typical tar or gravel roof – 0.08-0.18; tile – 0.10-0.35; slate – 0.1; thatch – 0.15-0.2. Thus, heating of the non-greened roof by solar radiation is very dependent on material and finishing. Therefore, the definition above of “cooling effect” indicates properties of the non-greened roof rather than the green one. Thus, the term “cooling effect” requires clarification.

Wong *et al.* (2003), based on temperature field measurements, concluded that the albedo of green roofs is smaller causing lower heat storage effect of them. In daytime at high solar radiation, the non-greened roofs store heat, which afterward continue to be transferred to the building at night. Green roofs store less heat in daytime, so the heat flow to the building at night is significantly reduced. After sunset, ambient air temperature on the green roofs continues decreasing. Thus, the city “thermal island” effect can be reduced. Studies (IRC, 2003) in Canada (Ottawa) have also demonstrated lowering the temperature on the green roofs.

Lui and Minor (2005) studied the heat resistance of green roofs. Natural research was carried out on a green roof and roof without plants (steel sheets with thermal insulation). Thermocouples were located at a different depth throughout the structure together with the rooms below. As a result of the research, it was found that peak temperatures in the summertime over green roofs decreased by 70-90%, and the temperature drops in the winter decreased by 10-30%.

Heat losses through green roofs are determined by heat transfer coefficient U [W/(m^2·K)] (so-called U-value) or thermal resistance $R_q = 1/U$ [m^2·K/W].

In many countries, old buildings have been inherited. The thermal resistance was accepted very low comparably to the current building norms. Therefore, part of the construction fund has a higher U-value. It could be improved by using green roofs.

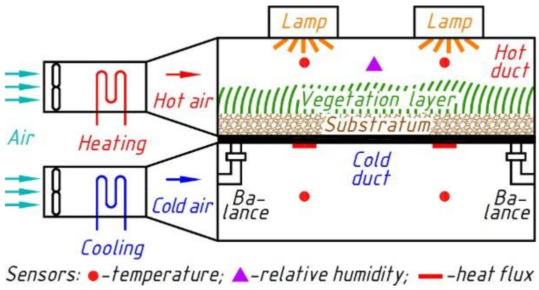
It is assumed that green roofs work, mainly, as a passive cooler in summer and not as a heat insulator in winter. Nevertheless, Nichou *et al.* (2001) investigated thermal saving. The authors concluded that for well-insulated buildings annual energy saving is relatively small (2 %), and for poorly insulated buildings significant saving (31-44%) is possible. The greatest savings occur during winter heating (45-46%), but not for summer cooling (22-45%). That is, green roofs can be considered as a technique of passive cooling and heat saving. It is actually for European and Asian countries because of full climate range, from very cold to very warm.

Salah-Eddin Ouldbukhhitin and Rafik Belarbi at French University of Lassi have developed (Ouldboukhitine & Belarbi, 2015) the most advanced research methodology for today. Their installation has a two-duct ventilation system with hot and cold ducts (Figure 1). The hot duct with substratum and vegetation layer has adjustable illumination.

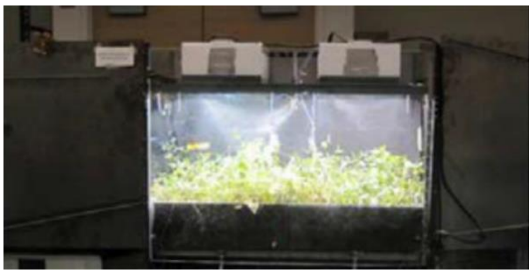
In the given work, balance equations are well developed. Many factors are investigated: radiation, convective heat transfer, absorption of light energy etc. The experimental determination of the thermal resistance of the layer is carried out at a high scientific level. Interesting data on thermal resistance for the layer without plants (R_q = 0,8 m^2·K/W), the layer with a barberry (R_q = 1,27 m^2·K/W), the layer with a lawn (R_q = 0,92 m^2·K/W) was obtained. However, height of the grass is not given.

The disadvantages of the model are that the aerodynamic resistance of air passing through the plant layer is not taken into account and the wind speed is constant (2 m/s). Although, for example, in warm period of year, quite a lot of hottest days are corresponds to calm. I.e. in Ukraine, the calmness in July is 48.7 %, but the maximum wind speed reaches 5.7 m/s. Wind speeds of 4-5 m/s and 1-2 m/s are typical for many Ukrainian cities. Thus, it is necessary to take into account the changeable wind speed. There is a possibility of artificially increasing the wind speed by a parapet design. This way can control the “cooling effect”.

The studies give averaged value of the thermal resistance of the vegetation layer. However, in the experimental setup (Figure 1), there is significant uneven growth of plants. The distribution of local thermal resistance by area of the vegetation layer is also important. The design of the ducts in the experimental setup, which is called “wind tunnel”, cannot achieve the uniformity of the airflow.



a



b

Figure 1. Schematic (a) and general view of working part (b) of wind tunnel for measuring heat transfer in green roofs (Ouldboukhitine & Belarbi, 2015).

As can be seen from Figure 1, the plant layer occupies up to 50 % of the duct section. This causes significant airflow disturbances and up to twice velocity increase. As it follows from the Figure 1, the upper level of the substratum (the boundary "substratum-plant") is located above the bottom of the duct. This creates significant separation flows on the edge at the windward side. The uniform distribution of air temperature in the cold channel is not provided. Therefore, this technique is not perfect enough. It is necessary to develop experimental methods without the limitations above. Green roofs have multi-layered design. Most layers are solid. Thermal resistance (Sukhatme, 2005) of these layers $R_{q,i}$ [m²·K/W] may be added. Thermal resistance of heat transfer from/to the inside $1/\alpha_{int}$ [m²·K /W] and the total thermal resistance of the vegetation layer $R_{q,veg,\Sigma}$ [m²·K/W] may be added too:

$$R_{q,\sum} = (1/\alpha_{int}) + \sum R_{q,\mathrm{i}} + R_{q,veg,\sum}. \quad (1)$$

All thermal resistances in equation (1), except the last one, can be experimentally determined according to standard methods. Heat-mass transfer in the vegetation layer is insufficiently explored. Separate determination of the heat transfer coefficient α_{ext} [W/(m²·K)] between the top boundary of the vegetation layer and the ambient air is practically impossible, since the shape of the upper boundary of the vegetation layer is quite complicated and variable (depending on random factors: the height of each individual plant and density of their growth). Therefore, we propose describe this process with total thermal resistance of the layer that takes into account heat exchange processes directly in it and heat transfer on its free surface ($R_{q,veg,\Sigma}$ [m²·K/W]). We identify the main thermal processes occurring in the vegetation layer of the roof (Figure 2).

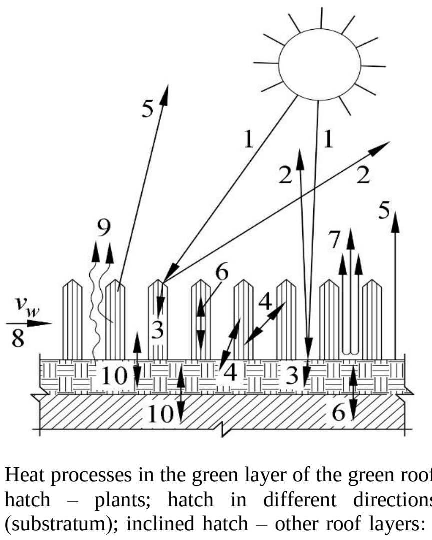


Figure 2. Heat processes in the green layer of the green roof: vertical hatch – plants; hatch in different directions – soil (substratum); inclined hatch – other roof layers: 1 – solar radiation; 2 – reflection and dispersion of the solar radiation; 3 – absorption of solar radiation; 4 – radiation heat exchange between plants and between plants and soil (substratum); 5 – radiation heat exchange with the environment; 6 – thermal conductivity (described by the Fourier-Kirchhoff equation); 7 – heat transfer by natural convection; 8 – heat transfer by forced convection under the influence of wind; 9 – evapotranspiration; 10 – heat storage.

3. Materials and Methods

3.1. Experimental stand

The main problem of research (Ouldboukhitine & Belarbi, 2015) is the lack of possibility to control distribution of air parameters in the cold duct under the soil. Therefore, we recommend discarding this duct and replacing it with:

1. A film heater with not less than IP67 (IP68 recommended) protection under the soil (substratum) to simulate heat transfer from a room to the environment (Figure 3a);

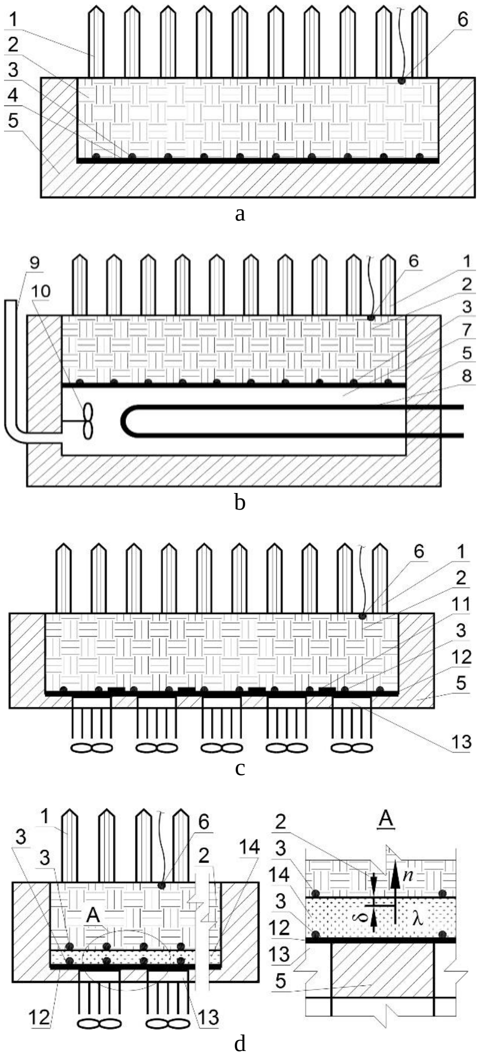


Figure 3. Section of the stand with film heater (a), temperature calibrator (b), Peltier refrigerators with heat flux sensor (c), Peltier refrigerators with calibrated layer (d):1 – vegetation layer; 2 – soil (substratum); 3 – temperature sensors; 4 – film heater; 5 – heat insulation; 6 – free movable thermal sensor; 7 – tank with air, water or other liquid (gas), 8 – heat exchanger or electric heater; 9 – expansion tube or connection of an expansion tank; 10 – mixer; 11 – heat flux sensor; 12 – heat distribution plate; 13 – Peltier refrigerator (element with radiator); 14 – calibrated layer.

2. A sealed chamber filled with air or water with constant temperature and intensive mixing (a temperature calibrator), to study the heat flow in any direction (Figure 3b);

3. Peltier refrigerators (Figure 3c) to study the heat flow from the environment to a room. Above them, there is a distribution plate of high thermal conductivity metal. Above it, in turn, there is the soil (substratum). The same principle can be used with a wire heater or electric heating modules to study the reverse heat flow direction.

The stand may be placed in a wind tunnel of any type with working part of near to rectangular cross-section and enough level of flow uniformity. The top level of the soil (substratum) should be located on the lower level of the working part without formation of separation flows directly on any edge of the stand. The vegetation layer itself must occupy no more than 10% of the cross-section of the working part, depending on the requirements for the accuracy of the study. When electrical heating was used there was no need to install heat flow sensors. The flow can be calculated by the power of the heater. It is recommended to measure the power according to 4-wire circuit, and electric current may be distributed according to the principle of accompanying flows (Figure 4). Power and measuring wires must have minimum possible cross-section to minimize heat leakage.

When using the Peltier refrigerators, the best option will be the placement of specially designed sensors for heat flow under the soil (substratum). To reduce the research cost, it is possible to place a uniform calibrated layer with known thermal resistance (Figure 3d), which is equipped with evenly distributed temperature sensors at upper and lower bounds. The larger numbers of them cause higher accuracy of the study.

The thickness of the distribution plate, the number of Peltier refrigerators, and the distance between them in order to limit the unevenness of the heat flux can be determined by simulating the installation in specialized software for simulation of the heat conductivity. The value of the coefficient of thermal conductivity [W/(m·K)] of the soil (substratum) can be taken approximately.

It is impossible to separate the layer of soil (substratum) and the vegetation layer without breaking the plants. Therefore, it is impossible to place heat sensors on the soil (substratum) surface without disturbing the vegetation layer. Therefore, measurements of heat flux in the soil are possible indirectly only. An additional temperature sensor is required, which can be installed in the top level of soil (substratum) alternately at any measuring point.

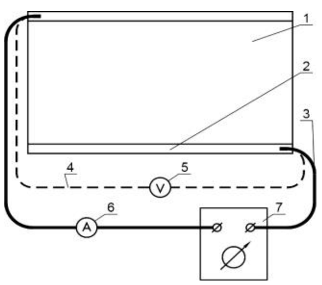


Figure 4. Connection scheme of the film (wire, modular) heater in the installation: 1 – film heater (or wire or modules); 2 – busbar; 3 – power wire; 4 – measuring wire; 5 – voltmeter; 6 – ampermeter; 7 – adjustable voltage source.

Simultaneous use of a large number of sensors on the surface of the soil is not recommended, since measuring wires to them can disrupt the aerodynamics of the flow and cause an additional heat leakage. The same sensor can measure temperature of air above the vegetation layer. The result will be a) temperature in the air flow; b) temperature field on the soil surface under the plant layer; c) temperature field on the bottom surface of the soil; and d) distribution of heat flow under the soil (uniform when using a film heater and practically uniform when using Peltier refrigerators without an additional calibrated layer) or temperature field under the calibrated layer.

3.2. Processing the results

Measurement is carried out after stabilization of reading of all sensors – in the steady state. The main task of result processing is to determine the distribution of the heat flow by the surface of the soil under the plant layer.

Let us consider the calibrated layer. Since this layer is homogeneous, we can write the Fourier-Kirchhoff equation [K/s]:

$$(\partial \Theta / \partial t) - a \nabla^2 \theta^2 = \Phi(\mathbf{r}, t), \tag{2}$$

where θ – is temperature [K]; t – time [c]; a – thermal diffusivity [m^2/s]; ∇^2 – Laplacian; Φ –function of heat sources [K/s], $\mathbf{r}$ – is the point vector [m].

For the stationary process, the first “non-stationary” member is zero. Since there are no internal heat sources, the right-hand side of the equation is also zero. The equation (2) transforms to the Laplace equation

$$\nabla^2 \theta = 0. \tag{3}$$

By Equation (3), the temperature distribution is self-similar by the thermal diffusivity a [m^2/s]. Therefore, according to the known temperature field [K] under and above the calibration layer it is possible to determine the temperature distribution throughout the volume of the layer. Equation (3) can be solved by finite element method (Mirkov, Rasuo, & Kenjeres, 2015). According to the known temperature distribution and coefficient of thermal conductivity λ [W/(m·K)], it is possible to find local heat flux at any point of the upper surface of the calibrated layer [W/m^2]:

$$\varphi = \lim_{\delta \to 0} \left(\Delta\theta_n \frac{\lambda}{\delta} \right) = \lambda \lim_{\delta \to 0} \left(\frac{\Delta\theta_n}{\delta} \right) = \lambda \frac{\partial \theta}{\partial \mathbf{n}}, \tag{4}$$

where $\Delta\theta_n$ – growth of temperature along the normal $\mathbf{n}$ [m] to the upper surface of the layer in direction of the heat flux [K], δ – thickness [m] along the normal $\mathbf{n}$ [m].

It is recommended to estimate the distribution of temperature and heat flux on the surfaces of the layer using interpolation of the obtained values. If a film heater is used, then its output heat flow [W/m^2] is evenly distributed and its density

$$\overline{\varphi} = \Phi / S = U \cdot I / S, \tag{5}$$

where U – voltage [V]; I – current [A]; S – area of the working part of the stand [m^2].

To avoid complex calculations it is possible to simulate the layer in special software for heat conductivity simulation.

The next step is the distribution of temperature and heat flow in the soil (substratum). In this case, the size of the soil (substratum) particles and cavities should be incomparably small in comparison with the size of the soil (substratum) layer. The particles and the cavities should be placed evenly. In this case, the soil (substratum) can be considered as having a uniformly distributed average thermal conductivity. Otherwise, simulation is not possible. The temperature distribution is determined by the equation (3) in a similar way to the calibrated layer. In contrast to the calibrated layer, the coefficient of thermal conductivity λ [W/(m·K)] is unknown but distributed uniformly. It is possible to use the equation (4), dividing it's both parts by the average heat flux [W/m^2]:

$$\begin{cases} \dfrac{\varphi}{\overline{\varphi}} = \dfrac{\lambda\partial\theta/\partial n}{\overline{\lambda\partial\theta/\partial n}} = \dfrac{\lambda\partial\theta/\partial n}{\lambda\overline{\partial\theta/\partial n}} = \dfrac{\partial\theta/\partial n}{\overline{\partial\theta/\partial n}}; \\ \int\limits_S \dfrac{\varphi}{\overline{\varphi}}\dfrac{dS}{S} = \dfrac{1}{\overline{\varphi}}\int\limits_S \varphi dS/S = \overline{\varphi}/\overline{\varphi} = 1, \end{cases} \tag{6}$$

where over-line above an expression means averaging over the whole area S, m^2.

It is easy to find distribution of the heat flux by the soil surface from the system of equations (6) if the average heat flux [W/m^2] is known by the Equation (4):

$$\varphi = \overline{\varphi}\left(d\theta/dn\right)/\left(\overline{d\theta/dn}\right). \tag{7}$$

For avoiding complex calculations, it is possible to use standard software for simulation of heat conductivity. A model of a rectangular parallelepiped according to the size of the layer using any homogeneous material may be prepared. The temperature field on the surfaces has been measured and may be input to the simulation model. Distribution of the heat flux on the upper surface φ' [W/m^2] and the average value of the heat flux [W/m^2] may be simulated. The actual heat flux φ [W/m^2] can be determined eliminating the wrong coefficient of thermal conductivity in the simulation using the equation (7):

$$\varphi = \overline{\varphi}\varphi'/\overline{\varphi}' . \tag{8}$$

For measured temperature field under the plant layer [K] and obtained distribution of heat flux φ [W/m^2], the distribution of thermal resistance of the plant layer ($R_{q,veg,\Sigma}$ [m^2·K/W]) may be determined:

$$R_{q,veg,\Sigma} = \Delta\theta_{veg} / \varphi, \tag{9}$$

where $\Delta\theta_{veg}$ – is local temperature difference between the airflow and the upper soil (substratum) bound.

If processing of the experimental data does not take into account the cooling effect, then the local thermal resistance of the layer is proposed to be called generalized. It may vary from minus infinity to plus infinity.

3.3. Determination of the “cooling effect” of the vegetation layer

For today, there is no consensus how to take into account the cooling effect Δθ [K] properly. The processes of converting heat from sensible to latent by the evapotranspiration occur in the entire vegetation layer and, in general, cannot be separated from the processes of heat transfer in the layer. For engineering calculations, these processes need to be separated conventionally. We propose to take into account the cooling effect as a correction Δθ [K] for the normative or experimental outside air temperature $\theta_{ext,act}$ [K or °C]. Corrected temperature [K or °C] of the outside air or airflow in the wind tunnel:

$$\theta_{ext} = \theta_{ext,act} - \Delta\theta. \tag{10}$$

In this case, the thermal resistance in the formula (9) will be called equivalent. This technique allows the most simply perform thermotechnical engineering calculations of building envelope. In our studies, we understand the “cooling effect” as temperature difference between the soil (substratum) surface and the ambient air.

Studies are carried out on the same stand with switched off heating and cooling. Temperature at the top boundary of the soil (substratum) at different points and the airflow temperature are measured. The temperature difference is a cooling effect Δθ [K]. Studies are carried out at different air velocity, resulting in the regression equations used in engineering calculations.

4. Approbation of Research Methodology

On the basis of the ventilation laboratory of Kiev National University of Construction and Architecture, a study has been made of the thermal resistance of the lawn vegetation layer on a stand by the first variant in a wind tunnel (Figure 5).

Figure 5. Experimental stand.

The studies without airflow showed an uneven distribution of the thermal resistance (Figure 6a), which is explained by different grass height and unevenness of its growth (density). The “cooling effect” research without wind speed and heating has shown that the difference in temperature of the upper layer of soil and ambient air is within 0.5-1 °C.

In the wind tunnel at a wind speed of 6.02 m/s (Figure 6b), there is also an uneven distribution of the heat flux and greater “cooling effect”. As the wind speed reaches 9.76 m/s, the “cooling effect” of the grass increases and the thermal resistance stay very uneven (Figure 6c).

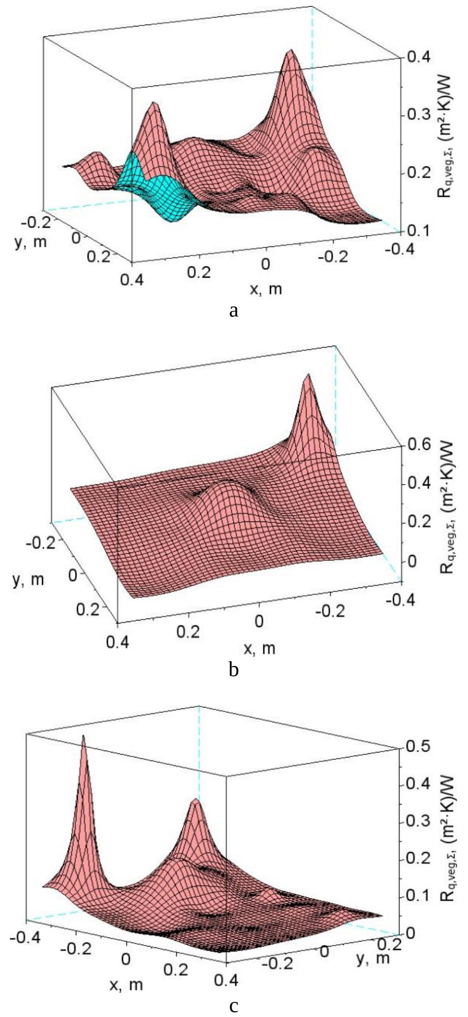


Figure 6. Equivalent thermal resistance of the green roof without wind speed (a), at wind speed of 6.03 m/s (b) and 9.76 m/s (c).

At some points on the boundary of the model, there is intense heat removal with a strong wind flow and the value of the heat transfer coefficient increases.

For essential evaporative cooling in warm period, the effect of wind is required. It is recommended to blow up the roof as much as possible (install perforated parapets). In cold and transition period, to reduce the evapotranspiration and the heat transfer coefficient, on the contrary, it is recommended to install a blank parapet or close all parapet perforations. This requires additional researches and simulations of the flows on the roofs. Simulation can be performed more easily by the author’s approach (Gumen, Dovhaliuk, Mileikovskyi, Lebedieva, & Dziubenko, 2017). It is based on geometric and kinematic analysis of large-scale turbulent macrostructure in jets.

4. Conclusions

Proposed method of experimental diagnostic of thermotechnical characteristics of vegetation layers on green roofs allows determining the thermal resistance and “cooling effect” of it. This is necessary for thermotechnical calculations of envelope of buildings with green roofs. A new definition of the “cooling effect” is proposed and used in the method. The “cooling effect” of the green roof and the coefficient of heat transfer increases with the increase in wind speed, as this increases evapotranspiration and intensifies heat transfer to the air. The requirements for parapet on green roofs are proposed to maximize energy efficiency: maximum perforation at warm conditions and maximum blank at cold conditions. The method may be applied in thermal certification of vegetation layers of “green structures” with different plants. The future researches of authors will be performed on different types of plants used on “green structures”.

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