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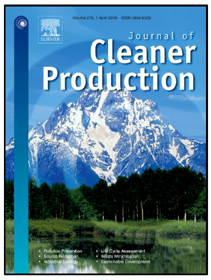

Heat flux transmission assessment of a vegetation wall influence on the building envelope thermal conductivity

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Heat flux transmission assessment of a vegetation wall influence on the building envelope thermal conductivity

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Abstract - Integration of vegetation into architectural objects can be a sustainable approach for the realization of objects' facades. Vegetation walls are innovative concepts of green construction. Vertically greened walls contribute to the improvement of energy properties of buildings and improve the design characteristics of buildings. Vegetation walls initiate the user's interactive attitude towards the object's envelope.
This study shows the potential of the green wall in the process of thermodynamic transmissions within the structure of facade wrappers during the summer. During the research, the energy specificities of the vegetation walls and their contribution to the improvement of the thermal properties of the facade wall were analyzed. For the needs of the research, an experimental model was developed on which the intensity of solar radiation, temperature values and heat fluxes were measured. Measurements have shown that vegetation affects the reduction of the surface temperature of the envelope and, consequently, it affects the value of the coefficient of thermal conductivity of the facade coating. The research shows that a wall that contains plants has a major influence on the temperature balance in the building envelope.
The methodology presented in this paper is based on the analysis of climatic characteristics, experimental measurement of the test model and comparative analysis with the reference element. During the experiment, the data on the external climate parameters, the temperature values and the coefficient of heat passing through the wall were continuously measured. The effects of thermal protection, using vegetation on the south-oriented wall, were analyzed. From the previous research it was concluded that the south oriented wall has a lower thermal absorption and a lower value of the heat flux than the other walls.
Data analysis enabled the assessment of the efficiency of thermal insulation of the wall using vegetation during the summer period. The distribution of temperature values, measured on the experimental model, showed a fall in temperature relative to the reference wall, which leads to a reduction in the total energy required to the object in the summer period. The proposed methodology enables a quantitative analysis of the effects of vertical greenery. The values obtained by measuring in the experimental model correspond to the empirical results. The use of vegetation walls in architecture has opened up new possibilities for reducing energy in the summer period when the experiment was carried out.

Keywords - green wall; building envelope; reduction of overheating; surface temperature; energy performance

1. Introduction

There are a large number of studies and surveys that cover the vegetation walls. The technology of vegetation walls and their application from the functional, design, aesthetic, energy and economic aspect are treated in them. This research was done as part of a complex process of analyzing green cell technology development, treating them as passive energy saving systems. The main goal of the architecture of the vegetation walls is to provide architecture with a new type of aesthetic recognition. Depending on the urban context in which the vegetation wall is located, it provides a whole range of sensitive phenomena (Fig.1).

Fig. 1 Dynamics of the form of vegetation walls

This research is based on an experimental approach that uses the estimation of the effect of vegetation on the thermal performance of the object. Evaluation of potential benefits of vegetative walls can stimulate its use in urban environments. The green walls in this experiment are treated as elements of shading [1]. The analyzes presented in this paper are based on an experimental model. It can be confirmed that vegetation walls influence the energy balance of the shell in the summer period. This effect is directly related to the plant species used, the density of the leaf cover (LAI), the evapotranspiration factor and the modular substrate of the vegetation wall [2].

The energy potential of the envelope of the architectural object is determined by the structure of the cover itself, the location climatic conditions and the mode of use of the object.

The fluctuation of the wall surface temperature during the exploitation time leads to undesirable effects on building materials applied in architectural objects. Vegetative walls provide additional external insulation and in this way balance the total heat flux. The plant structure of the wall protects the bearing wall surface from excessive UV radiation and atmospheric precipitation. Since the goal of the architecture of the future is to increase energy efficiency in buildings using different materials, vegetation plays an important role in this process. It increases sound insulation and

creates more comfortable interior spaces and improves air quality. Reduced temperature on green facades is achieved by: a) reduced heat absorption in the vegetation wall b) evaporative cooling caused by water for irrigation of plants; c) heat resistance due to low thermal conductivity of plants acting as thermal insulators (M. A. Haggag, S. K. Elmasry & A. Hassan, 2012.) [3].
Green walls are living organisms which growth and development depends on a number of influencing factors. The vegetation covering the facade coating causes cooling of the interior space reflecting and absorbing the sun's radiation, allowing cooling by evapotranspiration, improving the isolation and acting as a thermal barrier. The vegetative shield provides an additional obstacle between the interior space of the building and the outer environment (Marjorie Musy, Laurent Malys, Christian Inard, 2017.) [4].
The amount of cooling provided by the vegetation wall depends to a large extent on the climatic conditions and the way of forming the vegetation wall. (H. Feng, K. Hewage 2013). It was observed that during the summer period, vegetation walls contribute to the reduction of the surface temperature of the reference wall surfaces. The use of green walls can play an important role during the summer season and greatly affect the energy balance of the building in this period. Certain studies show that vegetation in facade coatings, besides a significant reduction in energy consumption, simultaneously improves the effects of urban heat islands (Badrulzaman Jaafar, Ismail Said, Mohd Hisyam Rasidi 2011) [5].

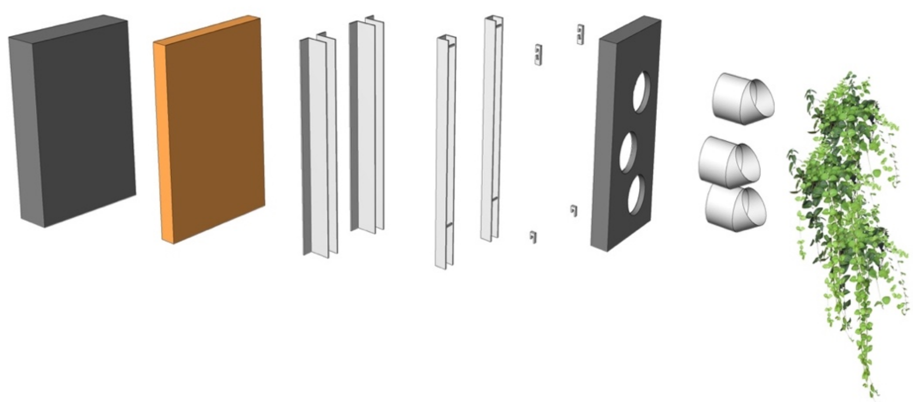

Fig. 2 Modular substrate of the vegetation wall

Various methods have been developed to study the thermodynamics of vertical vegetation ecosystems. Some papers deal with fundamental research, and some experimental approach attempts to find the interdependence of the elements of the vegetation wall and their impact on the energy balance of the building (Carl-Magnus Capener, Eva Sikander 2015) [6].
Experimental results may vary depending on the climatic zone where these walls are used. For this analysis, knowledge of the characteristics of different plant species in local weather conditions was essential for more efficient use of green walls. Due to their specificity, these walls alter certain microclimate effects in their surroundings. The total solar radiation that falls on the leaf surface of the vegetation wall is distributed as follows: the part is reflected, the part is used for photosynthesis of plants, the part is used in the evapotranspiration process, while the smaller part comes to the facade wall.

The amount of energy absorbed by vegetation can be related to the biophysical properties of vegetation, the gradients of humidity between the surface and the atmosphere and the temperature values within the structure of the vegetation wall (L. Hadba, P. Mendonça, L. T. Silva 2017) [7].
In continental climatic conditions, the plant maintenance problem are late spring frosts as well as frosts occurring in the early autumn, when vegetation is still in progress. The resistance of plant seedlings to low temperatures depends on hereditary properties of plants, balanced nutrition, cultivation of resistant hybrids and varieties, soil quality and soil drainage.

Fig. 3 Part of experimental green wall

The quantitative analysis of the ratio of the amount of solar radiation and the energy savings that the vegetation provides is based on the determination of the conditions and the value of the radiation regime. The radiation regime is in the function of the physical features of the leaf surface and the surface of the vegetation wall (Rodolfo Thomazelli, Fernando Caetano, Stelamaris Bertoli 2016) [8].
The study of the senile effect of the vegetative structure is key to understanding the thermal performance of vegetation walls. These characteristics are largely influenced by the biological-horticultural characteristics of plant species and conditions for growth (C.Y. Jim, Hongming He 2011.) [9].
Climatic characteristics of the forest, geographical influences and microclimate characteristics are the main factors for the successful cultivation of certain plant species.
The primary goal of this research is the attempt to establish the correlation between the temperature elements of the vegetation wall, the surface of the vegetation wall and its design. To understand thermodynamic processes taking place in the vegetation wall, an experimental model has been developed to monitor the amount of solar radiation and external climatic conditions. Based on the measurement and observation of the experimental model, a simulation of the heat flux and temperature relationship was performed.

2. Materials and methods

2.1. Experimental design and data acquisition

For the purpose of this experiment, a vegetation wall was formed with certain characteristics. The basic structure of the vegetation wall consists of (Figure 2): the supporting part, the substrate and the plant seedlings. When defining the vegetation wall, factors that influence the energy performance of the element are treated [10]. Measurement of heat flux and temperature were performed in Belgrade, Serbia. The experiment consisted of contingent observation and measurement of the south-oriented vegetation wall. The wall dimension was 300 cm wide and 240 cm high. Vegetation wall is made of modular elements with closed containers. The modular system of vegetation walls implies the application of controlled systems of planting and maintenance of plant species containing soil and autonomous irrigation systems. Vegetation wall is made of 40 elements with 120 plants planted, in 12 rows with 10 plants in each row. There was a 5 cm gap between the supporting, reference wall and vegetation wall. The greens are planted in a substrate which is a mixture of 92% light peat (granulation 01-25 mm) and 8% black peat (granulation 01-30 mm).

Fig. 4 Vegetation wall

The application of modular systems for the formation of vegetation walls belongs to a group of more complex systems. This way of forming the assembly allows us to easily design, usability on objects without restrictions, greater durability, undisturbed use of technology in the maintenance process. Panels measuring 30x60 cm were selected. and they are placed on metal brackets.

The use of such systems enables the diversification of the use of plant species, resulting in an increase in the design potential of vegetation walls. These walls in the aesthetic aspect of the realization of vegetation walls can be treated throughout the year, providing a more complex design. Plants are planted in specially made modules directly on the facade or indirectly on the ground. Hedera helix and plant from Araliaceae family were used [11]. For experimental research, a plant with different leaf surface density (LAI) was used. The plants used have a good cover effect. The structure of leaves is different. The data obtained by measuring the intensity of solar radiation, the temperature of certain elements, the measured values of the heat flux, the microclimate conditions of the soil, the external climatic conditions, were recorded at intervals of 15 min. (Fig.5). In addition to the temperature, the coefficient of heat transfer is also measured. The coefficient of heat transfer by calculation is determined and compared with the measured values based on the known thermal characteristics of the elements of the wall construction[12]. Measurements were made during the daytime, from 7:00 to 19:00. Land moisture and soil temperature were measured in different layers of the plant background. Meteorological factors were measured using a weather station located near the vegetation wall, including relative humidity, air temperature and wind speed. The obtained results were compared with the measured temperatures of the reference wall. During this period, the surface temperatures of the façade wall, with and without vegetation structure, were measured from the outside of the wall, the temperature of the plant plant leaf, the temperature of the outer surface of the modular element and the temperature on the inside of the element.

Fig. 5 Experimental measurements

2.2. Belgrade climate conditions

The climate of Belgrade can also be treated as a city climate that differs from the climate in the environment due to increased construction and urbanization of the area, a large amount of different aerosols, radiation smashing and reducing the duration of sunshine, reducing wind speed, reducing air humidity in relation to the environment, and the amount of precipitation is larger due to higher production of condensing cores. Belgrade is at 44 ° 48 'north latitude and 20 ° 28' east longitude, with an average altitude of 132 m. The climate characteristics of Belgrade are treated as a set of different microclimate conditions and are presented as part of a moderate continental climate with an average annual mean temperature of 11.9 ° C for the period from 1961 to 1990, but it changes over the years. Thus, for example, the average annual temperature for the period 1981 - 2010 is 12.5 ° C.

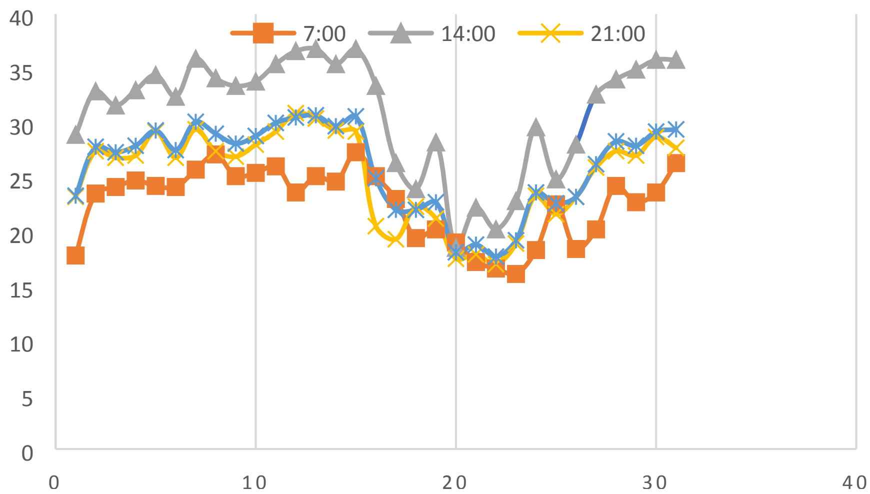

Fig. 6 Graphical representation of the comparative values of the measured air temperature

The Belgrade Climate Area is characterized by the largest insolation period of around 10 hours per day in July and August, while the highest cloudiness in December and January, when the insolation length is on average 2 up to 2.3 hours. (Fig. 6). The average value of direct solar radiation is 80 w / m2. It can be concluded that the intensity of direct solar radiation in the central parts of the city is smaller compared to the suburban zones due to the cloudiness of the air and the level of urbanization.

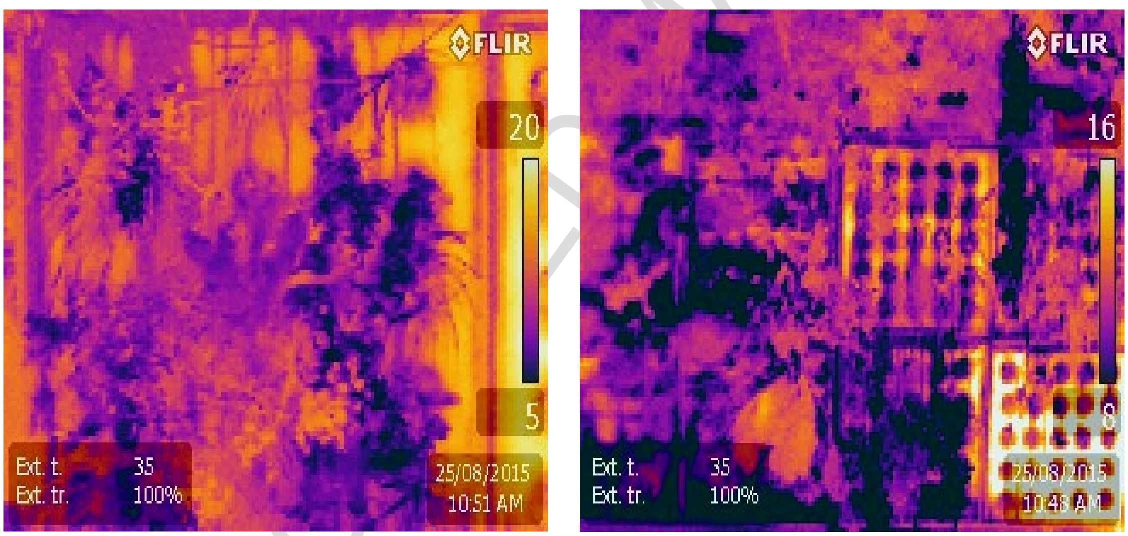

Fig. 7 Thermo-visual image of the vegetation wall

2.3. Evaluation of model performance

On the tested sample there are sensors for measuring the heat flux and temperature of the sample surfaces and thermocouples for measuring the surface temperature of the sample. The heat flow velocity was measured by means of a heat flow meter - a heat flux meter, whose sensors were glued to the surface of the test sample. Since in this case the fluxmeter sensors were measured and the surface temperature of the sample, the sensors were placed on both sides of the test sample. Fluxmeter, for two sensors, is placed on the opposite sides of the same part of the sample [13].

The coefficient of heat transfer is determined by calculation and compared with the measured values based on the known thermal characteristics of the elements of the wall construction.

$$U = \frac{1}{\frac{1}{\alpha_u} + \sum_{i=1}^{n} \frac{l_i}{\lambda_i} + \frac{1}{\alpha_s}} \quad (1)$$

Where $\frac{1}{\alpha_u}$ and $\frac{1}{\alpha_s}$ [m^2·K/W] represent the heat transfer resistance from the air to the inner surface of the wall, and from the outer surface of the wall in the air and they are taken from the appropriate standards. $\frac{l_i}{\lambda_i}$ [m^2·K/W] represent resistance to heat conduction through the i-th element of the building construction, thickness l_i [m] and heat conductivity coefficient λ_i [W/mK] [11].

The temperature of the surface (Fig. 7) of the sample was measured using the heat fluxometer sensor placed on it, but also using a thermocouple. The heat flux sensors recorded the temperature on the sample surfaces and the heat flux through the sample. The temperature of the warmer and cooler surface of the sample was measured.

In the processing of data obtained by means of measurement, the calculation of the difference in the temperature of the warmer and cooler surface and the thermal resistance of the tested model was calculated. In this section, the difference in temperature is calculated for each measured period.

$$\Delta\theta = \theta_t - \theta_h$$

Where:

θt- temperature of the warmer surface of the sample, in oC,

θh- temperature of the cooler surface of the sample, in oC,

Δθ- difference in the temperature of the warmer and cooler surface of the sample, in oC,

The results obtained enabled us to counteract the heat flow resistance

$$R = \frac{\Delta\theta}{q_k}.$$

R resistance to the heat flow of the sample, in m^2K / W,

Δθ- difference in the temperature of the warmer and cooler surface of the sample, in ^{o}C,

qk- density of heat flow, heat flux, i.e. the amount of heat flow per unit area through which this flow passes, in W / m^2 and

The mean value of the temperature difference is obtained on the basis of the equation

$$\Delta\theta_{sr} = \frac{1}{n} \cdot \sum_{i=1}^{n} (\Delta\theta)_i$$

A mean value of heat flux:

$$q_{sr} = \frac{1}{m} \cdot \sum_{j=1}^{m} (q_k)_j ,$$

where n is the number of values of the temperature difference, and m is the number of measuring points of the heat flux. Resistance to the heat flow of the tested sample is derived from the relationship:

$$R = \frac{\Delta\theta_{sr}}{q_{sr}}$$

The obtained values of the heat flow resistance for every 2 seconds will now be time-centered. In this way, the desired value of resistance to the heat flow through the sample material is obtained. It can be concluded that the transmission of radiation is in correlation with the structure of vegetation and the translucency and reflection of the leaf surface.
The mathematical model for calculating the value of the heat transfer coefficient is:

$$k = \frac{1}{R_i + R + R_e}$$

R_i je otpor toplotnom protoku usled prelaza toplote sa unutrašnje strane uzorka (recipročna vrednost koeficijenta prelaza toplote između uzorka i vazduha u prostoriji u kojoj uzorak treba da stoji) a R_e je otpor toplotnom protoku usled prelaza toplote sa spoljne strane uzorka (recipročna vrednost koeficijenta prelaza toplote između uzorka i spoljašnjeg vazduha)
Ri is resistance to heat flow due to the heat transfer from the inside of the sample (the reciprocal value of the coefficient of heat transfer between the sample and the air in the room in which the sample should stand) and Re is resistance to heat flow due to the heat transfer from the outside of the sample (reciprocal value of the heat transfer coefficient between the sample and the outside air)

$$k_S = \frac{1}{R_i + R_S + R_e}$$

$$k_O = \frac{1}{R_i + R_O + R_e}$$

In the end, according to the given relation, the coefficient of heat sample passage is determined:

$$k = \frac{k_S \cdot F_S + k_O \cdot F_O}{F_P}$$ [14].

The basis for analyzing and determining the parameters of the façade (Fig.8) assembly is reflected in the collection of adequate climate parameters and technical characteristics of the set model of the vegetation wall with precise registration of influencing factors. Experimental measurements were made on a reference wall 35 cm thick from brick. The reference wall has a calculated heat transfer coefficient U = 0.482 W/m^2K. During the experiment, an automatic irrigation system was activated. Wall modules are irrigated at a time interval of 3 hours per 1 minute. The distribution of water was horizontal and moderate.

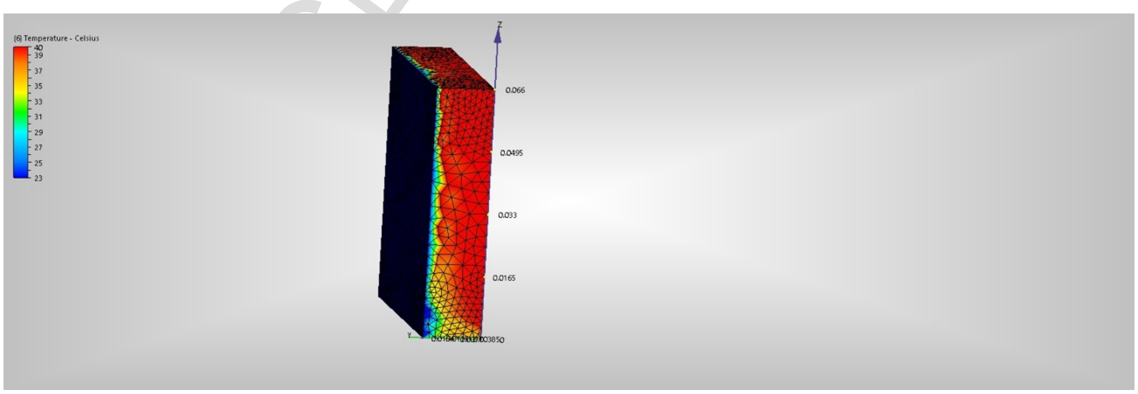

Fig. 8 Thermal simulation of the model

The main objective of the study was testing and analyzing the effect of vegetation on the reduction of temperature and heat transfer coefficients for the reference wall on a typical summer day [5]. An analysis of the typical summer day results shows that the maximum daily outdoor air temperature is 24.1 ° C, measured at 17:40, a minimum temperature of 11.5 ° C, measured at 5:34 hours and an average temperature during the measurement of 20.25 ° C. Solar radiation shows a maximum value of 995.6 W / m2, measured at 13:06 . Air humidity varies in the range of 97% to 46%. It is perceived that the maximum humidity value is measured in the early morning hours, min. Humidity was measured at 17:38. (Fig. 9).
The predicted effects of the vegetation module on the object were compared with experimental data to confirm its accuracy. The temperature measurement in several measuring points within the green wall was monitored using a sensor connected to the data logger. The data logger has recorded temperature changes of air at all specific points of the experimental installation. The main temperature properties of the experimental model were measured with the aim of producing a numerical analysis. Measured values show the influence of plant species, with different characteristics of the plant surface on the thermal behavior of experimental modules [15-19].

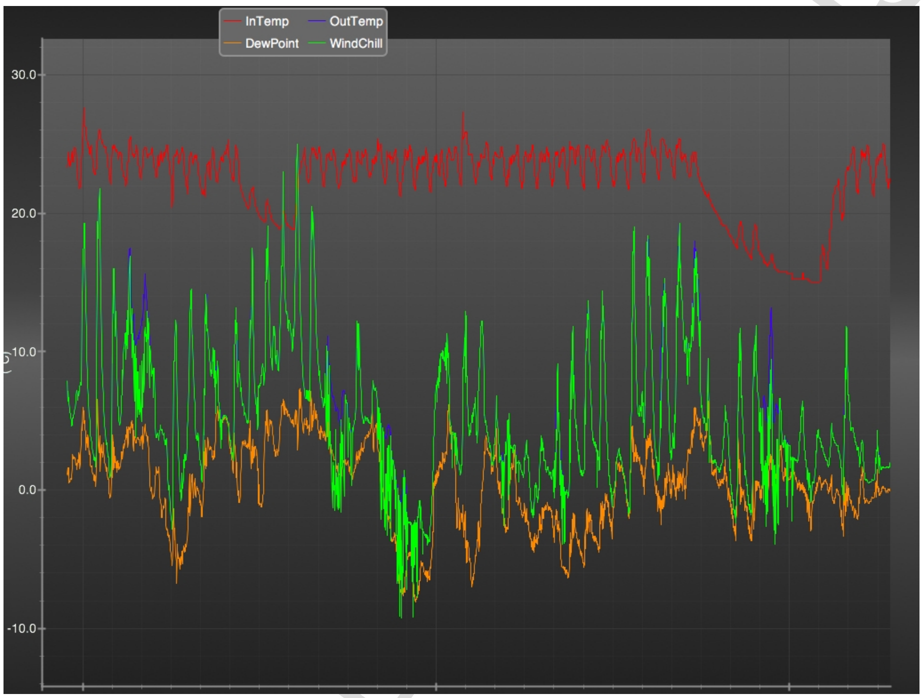

Fig. 9 Graph of the measured external temperature

The measurements and results of the modules and budget analysis within the assumed model show the uniformity of the obtained results. Measurements and analyzes have shown that the temperature on the surface of the wall with vegetation is considerably lower compared to the dismantled wall without vegetation. These data indicate that vegetation modules influence the reduction of the wall surface temperature. Experimentally we measured Tev - external air temperature, Tez - outside temperature of the wall without greenery, Tiz - external temperature of the wall with green, Te - temperature of the surface of the module behind the vegetation.
During the southern orientation, the mean outside air temperature was 20.5 °C. The measured mean outside temperature in the part without vegetation was 22.38 °C, and in the part where the wall was covered with vegetation, the wall temperature was 20.91 °C for the PB1 model, PB2

19.45 °C, PB3 19.12 °C. It can be noticed that the temperature of the reference façade wall is higher compared to the part of the façade wall where the vegetation wall for 1.47 °C or 6.57% was set for the experiment purposes in the PB1 model, 2.93 ° C PB2 or 13.10% and 3.26 °C in the model PB3 or 14.58%.

It can be concluded that the highest measured outdoor air temperature during this period was 23.5 ° C measured at 17:00 hours, and that the lowest measured temperature of 13.1 °C was measured at 7:00 am. The mean average temperature measured in July was 26.76 °C and in August 26.10 °C. The highest measured air humidity in the same periods as measured by the Hydrometeorological Institute in Belgrade was 93% and the lowest 21%. The highest mean moisture content in July was 62%. In August, the highest mean air humidity was measured with a value of 86% and the lowest 32%.

When it comes to the mean value of the length of insolation in the measurement periods in Belgrade, its balance is observed for the months of July and August. Given the daily surface temperature of the reference wall, the difference between the green modules and the gauge is about 3 °C. This information points to the effect of cooling green modules. During the day, green modules reach the highest temperature in the afternoon at 16:00.

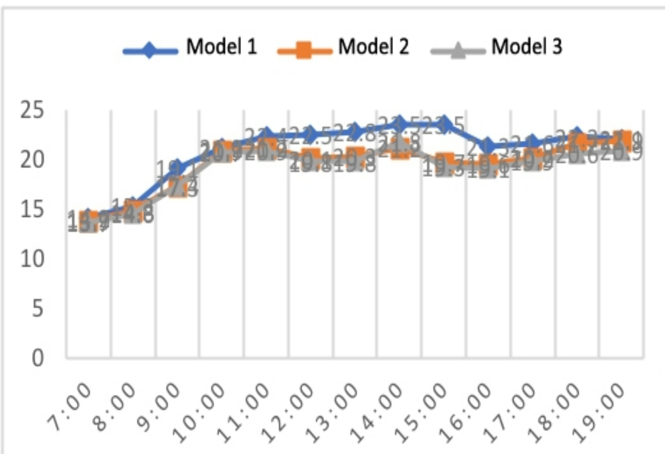

Fig. 10 Graphical representation of measured temperature values by models

The green module temperature starts to decrease later in the afternoon. It is interesting to analyze the temperature behavior of plants, related to temperature and weather. The graph shows the surface temperature of the three modules. Temperature decreases in different temperature ranges. It can be noticed that irrigation has an influence on the temperature of the vegetation module [20-24].

The vertical temperature of the vegetation module is reached in the period from 14-16 h. The green wall in this experiment slowly releases accumulated heat from the reference wall. Obviously, the surface temperature of the vegetation module exposed to sunlight during the evening is reduced under the influence of vegetation. These experimental measurements and numerical analysis have shown that green walls reduce the heat flow on the vegetative parts of the building envelope. It is noticeable that the surface temperature of the elements is reduced and the thermal transition through the wall is reduced.The effect of shading and the evapotranspiration process is greatly influenced. Analyzing the obtained results, it is noticeable that there is a temperature difference between the parts of the facade coating that is treated with vegetation in relation to the parts where it does not exist. The mean values of the measured temperatures were taken in the analysis.

4. Conclusion and discussion

The analyzes made in this experimental study show the thermal behavior of the vegetation modular system in comparison to the conventional wall. Their comparison was done by measuring the temperature and coefficient of heat transfer by a measuring device. Reference comparisons were made using three distinct plant breeds with the same coefficient of leaf surface. A comparison was made by evaluating the experimental data collected during the measurement in the summer period [25-29].

Unlike conventional material for facade materialization, vegetation walls do not absorb the received solar radiation. The solar radiation that falls on the leafy surface of the vegetation walls partly reflects, the part is used for photosynthesis, the part is used in the evapotranspiration process, and the smaller part comes to the supporting part of the facade coating. Apart from this, the plant structure influences the reduction of the amount of ultraviolet radiation to other parts of the facade coat, acting as an element of the shade (Fig. 10). As the value of the coefficient of heat transfer of the façade wall with the added vegetation wall U = 0.3738 W / m2K is obtained, it can be concluded that the requirements according to the valid energy efficiency policy have been met. During the research, the influence of the insolation length, the amount of solar radiation, the size of the leaf surface on the vegetative performance of the wall has been proven. The selection of the system of greening plays a key role in the optimization process, because it allows for its performance a greater or lesser percentage contribution of the selected module in the process of improving the facade coating. Measurements have shown that the application of vegetation walls in architectural buildings provides a reduction in the required cooling energy during the summer period in the range of 6-12% [30-32].

Based on these results, it can be concluded that the analyzed model fully meets the assumed energy potentials of the vegetation walls. This experimental study examines the thermal behavior of vertical greenery in a modular system, made of thermo concrete, applied to a conventional insulated wall.

His behavior was compared to the measured values on the reference omalterisation of the wall. Measurements during the summer showed a considerable reduction in temperature on the facade facade surfaces. Vegetation walls throughout the study were treated as passive systems in the energy efficiency of architectural objects.

It was concluded that the selection of the system of greening plays a key role in the optimization process, because it allows its performance to increase or decrease the percentage contribution of the selected model in the process of improving the facade coating. Unlike conventional materials for facade materialization, vegetation walls absorb much more absorbed solar radiation [33-35].

It can be concluded that vegetation of the green wall absorbs a certain amount of solar radiation and thus does not allow its penetration to the surface of the envelope.

Locality and climatic conditions are important factors to be included in the process of designing a vegetation wall. Belgrade has a continental climate, with a warm summer and a cold winter.

The experimental model model was able to generate precise simulation results. The heat flux coefficient model is proportional to the bandwidth bursts of the green wall and fits well with empirical values.

The analysis has proven that vegetation improves the energy performance of objects in our climatic conditions [36-40]. In further research and work on vegetation walls, it is recommended that, from the point of view of energy optimization of objects, the relations of energy optimization of the building and the required surface of the vegetation wall are analyzed so that the entire process would have economic justification. This question has not been addressed in this research

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