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Thermal Impacts of Vertical Greenery Systems in the Conditions of Lower Silesia

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1. Introduction

Dense urban development, widening of the roadway and designing underground installations make it impossible to plant trees and other street greenery. The decreasing amount of greenery affects, inter alia, the quality of the environment. In urban areas, green walls are one of the alternatives to conventional forms of greenery and are consistent with the generally understood principles of sustainability (Pawłowski 2011, Wong et al. 2009). In the world literature, we find information about architectural assumptions with the use of organic architecture. The concept of vertical gardens is relatively new on the world stage urban ecology. In Europe, it only appeared in the early years the eighties of the twentieth century. Currently, it is gaining more and more popularity. Until now, the substitute for such assumptions was creepers – ivy Common (Hedera helix) and ivy Boston (Parthenocissus tricuspidata).

They pay attention mainly to the aesthetic values and ecological properties, especially to the possibility of regulation of the temperature inside and around the building (Pérez et al. 2011). It was found that during the summer the temperature decrease around the green walls can reach even from 2 to 11°C, while in the winter the structure of the vertical garden protects the buildings elevation against the impact of wind power, reducing energy consumption for heating. Numerous studies have shown a positive effect of greenery on the microclimate and temperature cooling processes (Alexandri & Jones 2008, Bas & Baskaran 2003, Cuce 2017, Holm 1989, Hopkins & Goodwin 2011, McPherson 1994, Mazzali et al. 2013, Papadakis et al. 2001, Peck et al. 1999, Price et al. 2015, Santamouris 2001, Safikhani 2014, Serra et al. 2017). Currently, there are few studies on the functioning of plant wall systems in local climatic conditions of Poland taking into account the construction of plant panels, the type of substrate and its humidity, and the degree of coverage of the wall surface by vegetation (Pęczkowski 2017). In order to determine the thermal properties of green walls in the local climatic conditions of Wrocław, in 2009-2014 at the Institute of Environmental Protection and Development of the University of Environmental and Life Sciences in Wroclaw, research on experimental models of selected modular plant walls were carried out.

2. Characteristics of the facility, scope and methodology

The research facility located in the eastern part of Wroclaw consists of free-standing experimental models made in the form of wooden structures with dimensions: length 1.5 m, width 1.5 m and height 2.0 m. On the walls of models with an area of 1 m^2 the plant panels were placed. Each façade has been equipped with 9 panels with dimensions of 33x33 cm. The panels were installed on a wooden frame 2 cm from the construction of the experimental model (Fig. 1, Fig. 2). The examined models differed in construction (Tab. 1), and their elevations were located in relation to the directions of the world. A total of 60 species of plants representing shrubs, perennials and grasses have been planted in the plant panels. The set of plant panels on experimental models was equipped with an automatic drip irrigation system. In the system, water was pumped to the top of the plant wall, and then after hydrating, excess water was collected for reuse in the lower reservoirs. The total water dose for each façade was 3.6 l day^{-1}.

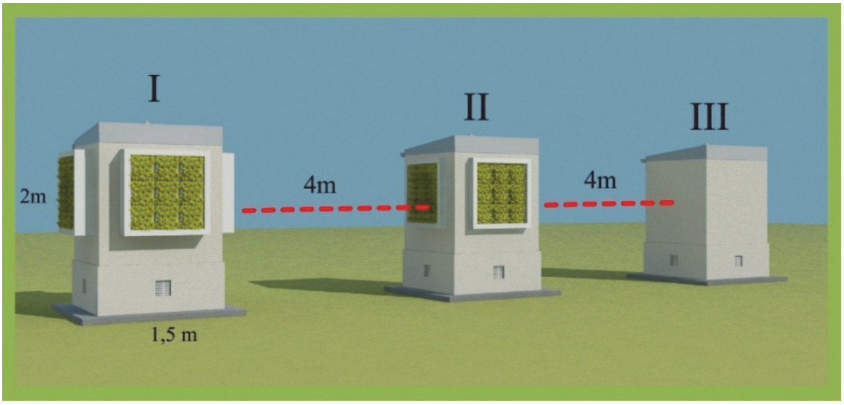

Fig. 1. Experimental models of modular plant walls
(retention model I, economic II and reference III)
Rys. 1. Modele doświadczalne modułowych roślinnych ścian
(model retencyjny I, ekonomiczny II i referencyjny III)

Fig. 2. Real experimental models, retention and economic
Rys. 2. Rzeczywiste modele eksperymentalne, retencyjny i ekonomiczny

Table 1. The thickness of vegetative medium with plants on experimental models
Tabela 1. Miąższość podłoża wegetacyjnego z roślinami na modelach doświadczalnych

Green wall system		Thickness (cm)		
Experimental model	Type of vegetative medium	Substrate	Plants	Total
Retention model (I)	Soil substrate	15	15	30
Economic model (II)	Geotextile	5	15	20
Reference model (III)	Wall without plants	–	–	–

Measurements of the spatial temperature distribution were made using the innovative probe system developed in 2007 for the needs of temperature distribution tests (Wiśniewski et al. 2008). The probes were equipped with Maxim Integrated – Dallas DS18B20 sensor set with programmable resolution enabling measurement with an accuracy of 0.1°C. Communication of sensors with datalogger was carried out using a 1-wire bus. The individual sensors were installed in aluminum tubes with a special construction ensuring precise temperature measurement. In contrast to the standard measurement methods, the probes enable to measure the temperature distribution in the profile of plant walls in 5-9 points placed in a line near the wall (Fig. 3). The measurement was carried out in several layers: inside the object, on the surface of the wall, inside the substrate and the infiltration mat, inside the leaves and in front of the plant surface. On the reference wall only the surface and the façade temperature was measured. The recording was performed in a time interval of 1 minute. The daily temperature distribution was analyzed with regard to the southern, northern, eastern and western exposition of experimental models. In the tests, the analysis of the temperature distribution in the winter season was omitted due to the spot icing of the used temperature probes. The warmest days from the research period 2009-2012 were selected for the analysis of the daily temperature distribution.

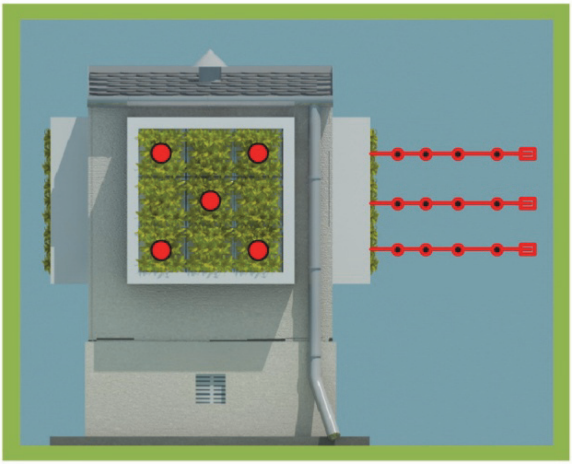

Fig. 3. Layout of temperature probes on individual facades of experimental models
Rys. 3. Rozmieszczenie sond temperaturowych na poszczególnych elewacjach modeli doświadczalnych

3. Results and discussion

Analysis of the temperature distribution within 24 hours on the tested experimental models showed that in the night hours the temperature of the walls and the ambient temperature were similar. During the day, the highest temperature occurred at the southern exposure of the reference model (III) without plants from 12.00-18.00. It exceeded the average air temperature (Fig. 4). On both models with plant panels, significantly lower temperatures were recorded on all façades during the day compared to the air temperature. Experiment has shown that the interaction of plant surfaces, the substrate and the operation of the sun's rays is complex, resulting in different results in terms of reducing the surface temperature of the walls during the day and night. Assessing the formation of thermal relations in the analyzed period of research, it was found that the exposure has a significant impact on the temperature distribution throughout the day. The best cooling properties of plant walls were obtained at the southern exposure, and the lowest at the northern exposure. On the planted experimental models less temperature fluctuations are observed compared to the reference model without plants. At night time, the surface temperature of exposed façades is smaller than behind the plant panels, indicating faster cooling of the façade without plants (Fig. 4). The highest thermal stability was recorded on the retention model (I) with soil substrate at the northern exposure, with the difference in extreme temperatures of 3.2°C. However, the largest difference in extreme temperatures of 5.3°C was recorded at the southern exposure with the value for the reference model (III) equal to 20.8°C (Tab. 2). The resulting maximum difference in the surface temperatures during the day between the experimental models is significant, reaching the highest value of 16.0°C at the eastern exposure between the retention model (I) and the reference model (III) (Tab. 3).

Table 2. Extreme temperatures (T_{max} and T_{min} [°C]) on the test surfaces of the retention (I), economic (II) and reference (III) models in the summer half

Tabela 2. Temperatury ekstremalne (T_{max} i T_{min} [°C]) na badanych powierzchniach modelu retencyjnego (I), ekonomicznego (II) i referencyjnego (III) w półroczu letnim

Surface	Exposition					
	S			N		
	T_{max} [°C]	T_{min} [°C]	T_{max}-T_{min} [°C]	T_{max} [°C]	T_{min} [°C]	T_{max}-T_{min} [°C]
$T_{ex}(I)$	22.2	16.9	5.3	21.4	18.3	3.2
$T_{ex}(II)$	24.2	16.1	8.1	26.5	15.2	11.2
$T_{ex}(III)$	34.9	14.1	20.8	28.2	14.3	14.0
	E			W		
$T_{ex}(I)$	21.4	17.6	3.8	21.2	17.1	4.1
$T_{ex}(II)$	25.0	15.8	9.2	24.8	15.5	9.3
$T_{ex}(III)$	33.7	14.3	19.4	33.3	14.0	19.3

$T_{ex}(I)$, $T_{ex}(II)$, $T_{ex}(III)$ – extreme surface temperature (maximum and minimum) on retention (I), economic (II), and reference model (III)

$T_{ex}(I)$, $T_{ex}(II)$, $T_{ex}(III)$ – ekstremalne temperatury powierzchni ścian (maksymalne i minimalne) na modelu retencyjnym (I), ekonomicznym (II) i referencyjnym (III)

Table 3. Maximum temperature differences between studied retention (I) and economic (II) models compared with the reference (III) model during the 24th day of the summer half
Tabela 3. Maksymalne różnice temperatur pomiędzy badanymi powierzchniami modelu retencyjnego (I) i ekonomicznego (II) względem modelu referencyjnego (III) w ciągu doby w półroczu letnim

Maximum temperature differences per day [°C]	Exposition			
	S	N	E	W
$T_{mx}(III\text{-}I)$	13.8	8.7	16.0	12.4
$T_{mx}(III\text{-}II)$	11.7	5.9	10.9	8.6

$T_{mx}(III\text{-}I)$ – maximum temperature difference between the exposed elevation of the reference model (III) and the elevation temperature behind the plant panels with the soil substrate retention model (I) per day,
$T_{mx}(III\text{-}II)$ – maximum temperature difference between the exposed elevation of the reference model (III) and the elevation temperature behind the plant panels with the hydroponic felt of the economic model (II).
$T_{mx}(III\text{-}I)$ – maksymalna różnica temperatur pomiędzy odsłoniętą elewacją modelu referencyjnego (III), a temperaturą na elewacji za panelami roślinnymi z substratem glebowym modelu retencyjnego (I) w ciągu doby
$T_{mx}(III\text{-}II)$ – maksymalna różnica temperatur pomiędzy odsłoniętą elewacją modelu referencyjnego (III), a temperaturą na elewacji za panelami roślinnymi z filcem hydroponicznym modelu ekonomicznego (II) w ciągu doby

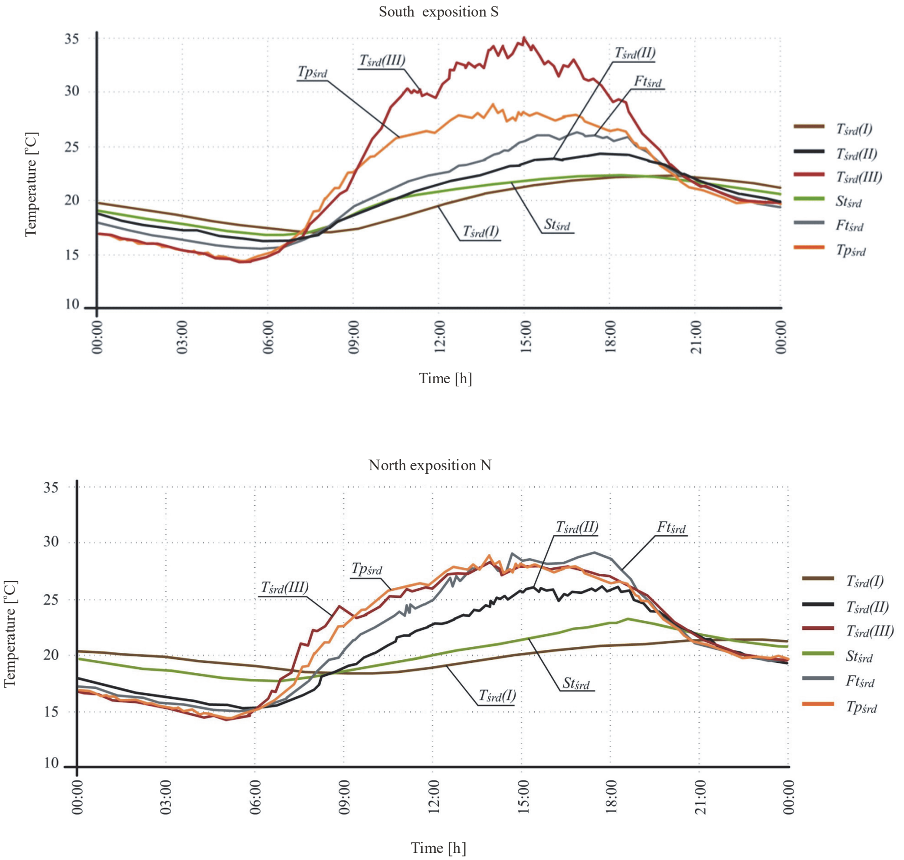

Fig. 4. Daytime distribution of average temperatures on the elevation surface of the $T_{\text{śrd}}$(I) retention model, $T_{\text{śrd}}$(II), reference model $T_{\text{śrd}}$(III), and $St_{\text{śrd}}$ substrate and $Ft_{\text{śrd}}$ bottom mats on S, N, E, W show against the mean air temperature $Tp_{\text{śrd}}$ Based on warm days during the 2009-2012 study period

Rys. 4. Rozkład dobowy średnich temperatur na powierzchni elewacji modelu retencyjnego $T_{śrd}(I)$, modelu ekonomicznego $T_{śrd}(II)$, modelu referencyjnego $T_{śrd}(III)$ oraz substratu $St_{śrd}$ i maty podsiąkowej $Ft_{śrd}$ na wystawach S, N, E, W na tle średniej temperatury powietrza $Tp_{śrd}$ otrzymanych na podstawie wybranych ciepłych dni w okresie badań 2009-2012

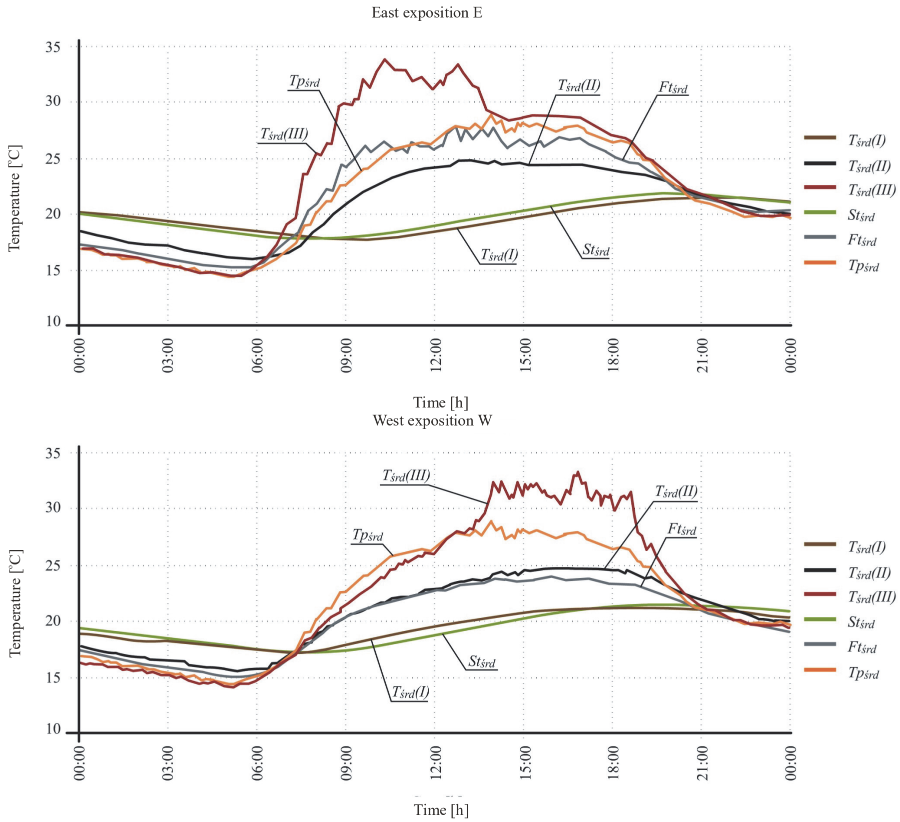

Fig. 4. cont.
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Comparison of the surface temperature differences between the retention model (I) and the economic model (II), as well as the reference model (III) allows to determine the insulation efficiency of the plant wall system. For this purpose, the insulation efficiency index used to determine heat losses was modified. It is a modification of determining the efficiency of a thermal machine based on the Carnot Cycle, defined as the ratio of mechanical work done by the system to the collected net heat. The insulation efficiency index is expressed in the ratio of reducing the heat loss due to insolation of the facility to heat losses of the uninsulated object (Berge & Johansson 2012, Szczeniowski 1964, Strzeszewski 2005):

$$\eta = \frac{Q_1 - Q_2}{Q_1} \cdot 100\ [\%] \tag{1}$$

where:
η – insolation efficiency [%]
Q1 – unit heat loss of the insulated facility
Q2 – unit heat loss of the uninsulated facility

The evaluation of the insulation efficiency of plant wall systems was determined on the basis of the ratio of average and maximum temperature differences obtained on individual façades of experimental models. According to the Carnot Cycle principle, in the experiment the difference between the elevation temperature of the reference model (III), and the elevation temperature of the model with the installation of the vegetal wall is equal to the value of work done by the system (plant panel), a modified index of insulating efficiency of vegetal walls was calculated using the following formulas:

$$R_{av}(I) = \frac{T_{av}(III) - T_{av}(II)}{T_{av}(III)} \cdot 100\ [\%] \tag{2}$$

$$R_{av}(II) = \frac{T_{av}(III) - T_{av}(II)}{T_{av}(III)} \cdot 100\ [\%] \tag{3}$$

where:
$R_{av}(I)$, $R_{av}(II)$ – average insulation efficiency index on the retention (I) and economic model (II) relative to the reference model (III)
$T_{av}(I)$, $T_{av}(II)$, $T_{av}(II)$ – average elevation temperature on the retention (I), economic (II) and reference model (III)

$$R_{ex}(I) = \frac{T_{ex}(III - I)}{T_{ex}(III)} \cdot 100\ [\%] \tag{4}$$

$$R_{ex}(II) = \frac{T_{ex}(III - II)}{T_{ex}(III)} \cdot 100\ [\%] \tag{5}$$

where:

$R_{ex}(I)$, $R_{ex}(II)$ – maximum insulation efficiency index on the façade on the retention (I) and economic (II) model relative to the reference model (III)

$T_{ex}(III\text{-}I)$, $T_{ex}(III\text{-}II)$ – maximum temperature difference on the façade on the retention (I) and economic (II) model relative to the reference model (III)

$T_{ex}(III)$ – maximum façade temperature on the reference model (III)

Analysis of the insulating efficiency of plant walls showed that in the local climatic conditions of Lower Silesia the best insulating properties were obtained by plant panels with soil substrate on the retention model (I). The greatest reduction of the average surface temperature was obtained at the most effective efficiency at the eastern exposure and it reached 17% (Tab. 4). Panels with the subsurface irrigation mat showed lower insulation efficiency with the largest average reduction of 13% at the southern exposure. In addition, the analysis of the maximum reduction of temperature against the values on the walls of the reference model (III) showed the possibility of the temperature increase limitation within the range of 21-47% depending on the exposure and the applied plant wall system (Tab. 4). The obtained results indicate the possibility of the plant wall systems use in modeling the thermal efficiency of building façades. However, the differences in the temperature reduction on individual façades indicate potential thermal insulation possibilities with the use of plant panels, especially at the southern and eastern exposure.

The difference in the efficiency of plant wall systems in cooling the façade surface results from several factors such as the type and thickness of the substrate, the design of plant panels, substrate moisture as well as the degree of shading and surface coverage by vegetation. In the plant wall system, the interactions between leaf surface, coverage, plastic variability and microclimatic parameters are complex, which significantly affects cooling efficiency during the day. During the research, changes in distribution patterns and temperature reduction were also observed in relation to the quality of greening, especially in places where the leaves died or withered. This dependence indicates the need to ensure proper coverage of the plant wall system with healthy plants in order to obtain effective thermal efficiency. In order to obtain the best effects and benefits resulting from installation of the plant wall, it is therefore necessary to properly select plant species for the system and local climatic conditions.

Table 4. Rate of average insulation efficiency [%] and maximum insulation efficiency Rex [%] on the surface of the individual facades of the retention model (I) and economic (II) relative to the reference model (III)
Tabela 4. Wskaźnik średniej sprawności izolacyjnej $R_{śr}$ [%] i maksymalnej sprawności izolacyjnej R_{ex} [%] na powierzchni poszczególnych elewacji modelu retencyjnym (I) i ekonomicznym (II) względem modelu referencyjnego (III)

Exposition	Average temperature on the surface of the wall [°C]			Indicator of average insulation efficiency [%]	
	$T_{śr}(I)$	$T_{śr}(II)$	$T_{śr}(III)$	$R_{śr}(I)$	$R_{śr}(II)$
S	19.7	20.2	23.3	15	13
N	19.8	20.5	21.9	10	6
E	19.5	20.8	23.5	17	11
W	19.4	20.6	22.4	13	8
Exposition	Extreme temperatures on the surface of the wall [°C]			Indicator of maximum insulation efficiency [%]	
	$T_{ex}(III\text{-}I)$	$T_{ex}(III\text{-}II)$	$T_{ex}(III)$	$R_{ex}(I)$	$R_{ex}(II)$
S	13.8	11.7	34.9	40	34
N	8.7	5.9	28.2	31	21
E	16.0	10.8	33.7	47	32
W	12.4	8.6	33.3	37	26

Vertical gardens are primarily aesthetic values and ecological properties that have a significant impact in compact urban development. Such solutions affect the enhancement of biodiversity in agglomerations (Francis & Lorimer 2011) and biofiltration effects of atmospheric air (Franco-Salas et al. 2012). The results obtained so far in relation to façade cooling have shown that plants can affect the temperature inside and around the building due to natural shading, and in the case of external walls they reduce thermal conductivity improving energy efficiency of buildings, as well as protection against UV radiation which usually causes gradual deterioration of construction materials properties (Maslauskas 2015). In addition, reducing the fluctuation of daytime temperatures can significantly affect the processes of premature aging of building materials exposed to thermal stresses. An equally important phenomenon which should not be underestimated is the effect of the urban heat island which significantly affects the environment, well-being of people and housing conditions. Research carried out on the green wall of Seville University for four types of substrates (among others on the basis of coconut fiber and geotextile), monitoring of the temperature, humidity, plant growth and water consumption showed a reduction of temperature by 4°C, and at selected very warm periods up to 6°C (Fernandez et al. 2012). Plant moisture has a particular impact on the cooling processes in their environment. The change in temperature may occur through the mechanism of absorbing some of the energy by plants and the isolation provided by among others the substrate and thereby increasing humidity (Perez et al. 2011, Hunter et al. 2014). Green walls are a passive energy saving system (Susorova et al. 2013) because the plant layer can improve thermal resistance (Mazzali et al. 2013). Mazzali and other studies have shown that the incoming heat flux through the reference wall was higher than in the case of surface with plants. It may also be important to properly select the distribution of plants and species, which will have a major impact on reducing the energy demand for cooling (Meier 2010). In the literature on the subject, there are also opinions that the general benefits of green wall thermics compared to a properly designed traditional construction may be small, and therefore, before implementing such systems, a full assessment of the potential benefits should be carried out. It should also be emphasized that the selection and quality of plant species (Marternsson et al. 2014) and additional lighting of green areas depending on the exposure (Egea et al. 2014) as well as the insulation, properties and durability of construction materials (Perini et al. 2013) are still an important insufficiently recognized problems.

The results obtained in the experiment on the retention (I) and economic (II) model indicate the potential benefits of insulation of building façades using plant wall systems. The maximum reduction of 16.0°C on the façade surface is significant and can lead to savings in energy consumption for lowering the indoor temperature. In order to verify and confirm the obtained results, further experiments should be carried out on actual building elevations. This will allow for a more precise specification of the thermal efficiency range of the tested systems. In addition, many factors such as the dimensions of plant panels, the use of different construction materials, the type of soil substrate, system thickness, substrate moisture and the choice of plant species can have a significant impact on the thermal performance.

4. Conclusions

1. The obtained results indicate that the wall exposure has a significant impact on the value of the elevation temperature reduction. Temperature reduction is most visible at the southern exposures, indicating the benefits of reducing the temperature on these façades by installing a plant wall.
2. Installation of the plant wall allows to reduce temperature fluctuations within 24 hours on the elevation surface, thus contributing to the durability of the materials used for the construction and coverage of the façade of the building.
3. It was found that the vegetal wall with the substrate has better insulating properties and allows to reduce the maximum surface temperature depending on the exposure from 8.7°C to 16.0°C. On the model with the subsurface irrigation mat, lower values were obtained with a reduction of 5.9°C to 11.7°C depending on the façade.
4. The best insulating properties were obtained for panels with substrate with medium and maximum insulation efficiency of 17 and 47% respectively at the eastern exposure and 15 and 40% at the southern exposure. This indicates the possibility of using plant wall systems in modeling the thermal efficiency of building façades.

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Termika pionowych systemów roślinnych w warunkach Dolnego Śląska

Streszczenie

Kształtowanie się stosunków termicznych w systemach roślinnych ścian oceniono na podstawie badań terenowych prowadzonych w latach 2009-2012, na obiekcie doświadczalnym zlokalizowanym we Wrocławiu. Autorskie modele doświadczalne wykonano w formie wolnostojących konstrukcji – domków drewnianych o wymiarach 1,5 x 1,5 x 2,0 m oraz paneli roślinnych o powierzchni 1 m^2. W pracy porównano model retencyjny z substratem i ekonomiczny z matą podsiąkową względem modelu referencyjnego bez roślinności. Analiza rozkładu temperatur w ciągu doby w okresie półrocza letniego na wystawach modelu retencyjnego, ekonomicznego i referencyjnego wykazała, że w godzinach nocnych temperatura ścian i otoczenia była zbliżona. W ciągu dnia najwyższa temperatura występowała na wystawie południowej na modelu referencyjnym bez roślin, przewyższając średnią temperaturę powietrza. Na obydwu modelach z panelami roślinnymi odnotowano znacznie niższe temperatury na wszystkich elewacjach w ciągu dnia w porównaniu z temperaturą powietrza oraz temperaturami na modelu referencyjnym. W zależności od wystawy modelu średnia redukcja temperatury na powierzchni ściany modelu z substratem w ciągu dnia wyniosła 2,1-4,0°C, a maksymalna 8,7-16,0°C. Na konstrukcji z matą podsiąkową uzyskano wynik redukcji średniej temperatury na powierzchni ściany w przedziale 1,4-3,1°C i maksymalnej w ciągu dnia wynoszącej 5,9-11,7°C. Porównanie sprawności izolacyjnej roślinnych ścian wykazało, że w lokalnych warunkach klimatycznych Wrocławia najlepsze właściwości izolacyjne uzyskały panele roślinne z substratem. Analiza maksymalnej redukcji temperatur w modelach z roślinnością oraz powierzchnią kontrolną wykazała możliwość ograniczenia temperatur w granicach 21-47% w zależności od wystawy i zastosowanego systemu.

Abstract

The formation of thermal relations in the systems of the plant walls was assessed on the basis of field studies conducted in 2009-2012 at an experimental facility located in Wrocław. The original experimental models were made in the form of free-standing structures - wooden houses with dimensions of 1.5 x 1.5 x 2.0 m and plant panels with an area of 1 m^2. The work compared the retention model with the substrate and the economic one with the subsurface irrigation mat to the reference model without vegetation. Analysis of the temperature distribution during 24 hours in the summer half-year at exposures of the retention model, economic model and reference model showed that during the night hours the temperature of the walls and surroundings was similar. During the day, the highest temperature occurred at the southern exposure on the reference model without plants, surpassing the average air temperature. On both models with plant panels, significantly lower temperatures were recorded on all facades during the day compared to the air temperature and temperatures on the reference model. Depending on the model's exposure, the average temperature reduction on the wall surface of the model with substrate during the day was 2.1-4.0°C, and the maximum 8.7-17.0°C. On the construction with the subsurface irrigation mat, obtained the result of reduction of the average temperature on the wall surface in the range of 1.4-3.1°C and the maximum during the day of 5.9-11.7°C. Comparison of the insulating efficiency of plant walls showed that in the local climatic conditions in Wrocław the best insulating properties were obtained by plant panels with a substrate. The analysis of maximum temperature reduction in models with vegetation and the control surface showed the possibility of the temperature limitation within 21-47% depending on the exposure and the type of applied system.

Słowa kluczowe:
roślinne ściany, sprawność izolacyjna, redukcja temperatury,
wydajność systemów roślinnych

Keywords:
green walls, insulation efficiency, temperature reduction,
efficiency of plant systems