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EXPERIMENTAL TESTS OF THERMAL PROPERTIES PERTAINING TO VERTICAL PLANT SYSTEMS IN THE CLIMATE OF LOWER SILESIA

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ABSTRACT

Current fast development of cities causes obsolescence of green areas, which is partly the reason for the rise in temperature within cities, and for the creation of the "urban heat island" effect. In order to limit the heating of the agglomeration, alternative ways of introducing greenery to urban areas should be explored. One of these is the use of green walls on the façades of buildings. The vertical garden affects the air temperature, reducing the temperature on the surface of the heated building; furthermore, green walls improve the aesthetic values of the city, introducing peace into the harsh landscape of modern architecture, and they clean the air of toxins. In the present work, we discuss the problems pertaining to green wall thermals. Tests were run on experimental models during 2016 in Lower Silesia Province at the Agro-Hydrometeorology Observatory Wrocław-Swojec of Wrocław University of Environmental and Life Sciences. The main objective of those tests was to check impact of green walls on the environment and on the temperatures inside green wall. Observations were run on the south elevation on building. Performed tests indicated that plant cover works as isolation on wall. Due to these properties, it is possible to stabilize conditions on the wall behind the green panel. All the measurements were run simultaneously on the green wall, and on the reference model – a wall without plant cover. Comparing both models indicated that the green wall limits heating of the outer part of building, which can hold down variation of temperature inside the building.

Keywords: green wall, vertical garden, analysis, temperature, thermal insulation

INTRODUCTION

Rapid growth of urbanization is the domain of today's world. Cities are growing, and the areas within city centres are becoming increasingly developed (Charlesworth et al., 2011). Garden plots or previously green areas give way to further construction projects. The effect of this phenomenon, combined with global warming, is the emergence of urban heat islands. This results in deterioration in the health condition of city dwellers, coupled with an increase in energy consumption (Mądry and Słysz, 2011).

Our proper functioning as human beings is affected by biological, chemical, physical, psychological, and social factors. The developing cities expose their inhabitants to general weakness of the organism, which leads to more and more people every year suffering from diabetes, asthma, depression, or cancer (Wong et al., 2010) (Małuszyńska et al., 2014). Currently, the policy of urban planning should be aimed at mitigating the phenomenon of the urban heat island, and at limiting the energy consumption by the city's buildings (Arnfield, 2003). Due to the fact that the outer surfaces of the buildings offer a huge amount of potential space for vegetation, locating the latter on the roofs and façades has become one of the most innovative ways to reduce pollution in cities. Smooth surfaces of buildings heat up much faster, whereas the use of horizontal and vertical greenery has a significant impact on the thermal performance of buildings and the urban

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environment, both in summer and in winter. Plants act as a solar filter, and they play a significant role in preventing the adsorption of thermal radiation of building materials. In cooler climates, evergreen plant species form an external insulating layer, and they contribute to energy savings and the reduction of heat losses (Perini et al., 2011). Vegetation can also significantly reduce the maximum air temperature inside the building, by shading the walls from the sun, so that daily fluctuations of temperature can be reduced by up to 50%. By evapotranspiration, large amounts of solar radiation are transformed into latent heat, which does not increase the temperature. In addition, in summer, the façade that is covered entirely with greenery is protected from strong radiation, and it is able to reflect or absorb up to 80% of incident rays (Perini et al., 2011).

The study that we have conducted aimed at determining the impact of plant cover on the spatial distribution of air temperature in experimental models of green walls. We aimed to determine, how thermal relations are shaped at specific levels, and in different parts of the model, as well as in its immediate environment.

RESERACH MATERIAL AND METHODS

The study was carried out during the growing season in the months from May to September 2016 at the experimental facility located in Lower Silesia, in the Agro-Hydrometeorology Observatory of Wrocław-Swojec, belonging to the University of Environmental and Life Sciences in Wrocław. Data for the analysis were obtained from recorders, which were installed on the examined object, on its south side. 12 multi-probes have been installed on the green wall. For the needs of the present study, data from centrally located measuring equipment were analysed. Additionally, in order to be able to compare thermal insulation capacities of the vegetation-covered surface, the measuring apparatus was also mounted on the reference model. Data on the climatic conditions of the Lower Silesia were obtained from a meteorological station located within the area of the Wrocław-Swojec Observatory.

In order to determine the temperatures in the experimental models at individual heights of the green wall, Dallas DS18B20 sensors have been installed, which registered the air temperature at the time interval of every 1 minute, with an accuracy of 0.1°C, whereas the measurement was carried out using the 1 Wire serial bus. Each probe possessed 9 sensors for measuring the air temperature. In order to determine what impact the green walls have on the environment and on the building's elevations, the measurement system was deployed at various heights and depths throughout the structure. The first sensor was located in the immediate vicinity of the wall, just behind the panel. The second sensor measured the temperature centrally on the depth of the substrate, the thickness of which was 15 centimetres. Another probe was responsible for the measurement at a distance of 5 centimetres from the substrate panel, at the place where the plants were located. The last sensor recorded data at a distance of 10 cm from the panel, in close proximity to the plants. Multi-probes were located at different heights of the green wall. The first was located at 188 cm above the ground, another at 140 cm, yet another at 92 cm, and the lowest multi-probe was placed at the height of 44 cm from the ground level (see: Fig. 1).

The study was carried out using two experimental models, built in the form of wooden houses with dimensions of 1.5 m × 1.5 m × 2.5 m, of which one was a retention model (that is, a wall covered with vegetation), and the other a reference model (a wall with a smooth surface). The walls of the houses were made of OSB boards and covered with PVC elevation panels on the outside, and insulated inside with a layer of Styrofoam, 15 centimetres thick. The roofing of the structure had a biologically active surface being an extensive green roof, made in such a way as to enable access to the interior of the station from above. The models were placed according to the cardinal directions (Kania et al., 2013).

The green wall, which is a retention model, was equipped with 40 aluminium panels, the dimensions of which were 26 × 26 × 15 centimetres. Each of these panels was filled with a specially prepared soil substrate, placed in geotextile bags with a weight of 50 g × m^{-2}.

In order to provide plants with perfect conditions for their development, a special ground substrate was developed, consisting of: horticultural soil, peat of pH 6.5, fine sand, fine and coarse expanded clay aggregate, mixed at a ratio of 50:15:10:25. Panels with vegetation were provided with automatic drip irrigation systems,

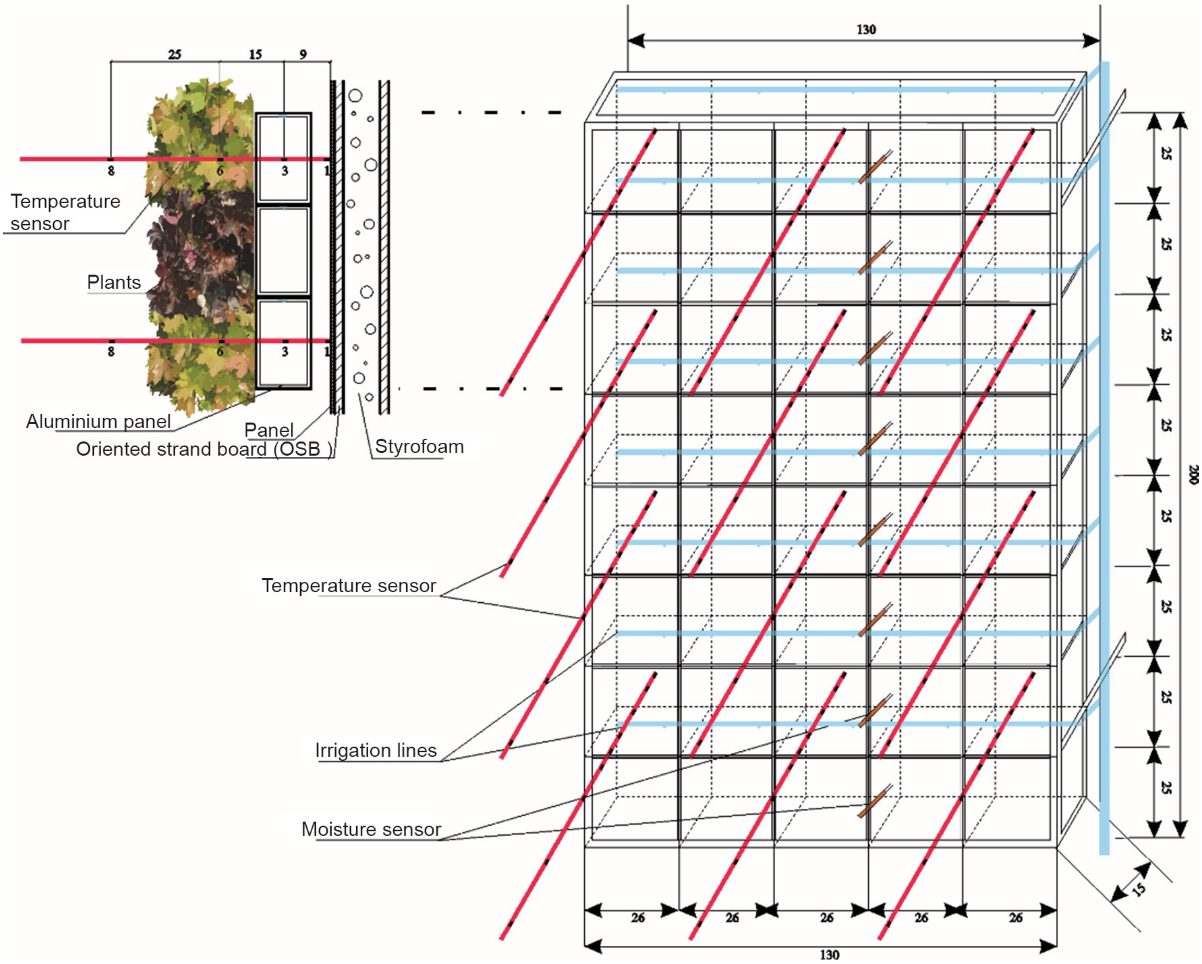

Fig. 1. Cross-section diagram of the green wall, along with the location of the sensors

and the irrigation took place twice a day. The wall contained the following plants: geranium of the *Geranium macrorrhizum* variety, varieties of alumroot including "Melting Fire" (*Heuchera americana*), "Palace Purple" (*Heucher micrantha*), and "Coral Forest" (*Heuchera sanguinea*), stonecrop of the *Sedum spectabile* variety, and grasses: sedge of *Carex flacca* variety and true sedge of the *Carex Montana* variety.

RESULTS

Two warmest days were selected for the analysis of the daily (24-hour) temperature distribution, as recorded between May 23 and September 13 in 2016; and these were plotted on the ambient temperature graphs. Extreme temperatures best reflect the impact of ambient temperature on the entire structure of the green wall. It shows the dependence on the surrounding environment, and determines how its individual parts heat up compared to each other, and whether they protect each other from excessive cooling or heating.

The first day to be analysed was May 28, and the second was July 25, 2016. In May, on the southern side, in a research model covered with vegetation, the temperature ranged from 12.1°C to as much as 38.4°C. In the case of July 25, the temperature span ranged from 17.8°C to 34.6°C. On these two days, the temperature was analysed in two ways. The first one was to show the temperature distribution vertically, at the height of 44 cm, 92 cm, 140 cm, and 188 cm, and the second way showed how the distribution of air temperature in the individual layers of the green wall is shaped: in plants and in substrate, in front of the wall (in its immediate vicinity) and directly behind the wall to which it was attached.

In the analysed experimental model, on the south wall, the smallest temperature fluctuations at all examined heights on both analysed days were recorded in the substrate (see: Fig. 1 and 2). The substrate forms the basis for the plants to grow. In the substrate, ideally there should be constant thermal conditions throughout the life of the plant, and that will have a positive impact on that plant's development. The roots are to develop in the substrate, and take their nutrients and water from it. During the day, warm atmospheric air heats the substrate, however, the intensity of heating depends mainly on the moisture content of the soil substrate. In the evening hours, the phenomenon is reversed: the previously heated soil material gradually releases some heat to the atmosphere, and is thus cooling down. That is why it was here that the lowest differences between extreme temperatures were recorded. On May 28, the amplitude was 5.6°C over the 24 hours, while on July 25, the amplitude reached only 4.3°C.

When analysing measurement data from May (see: Fig. 1), we have noticed that the amplitudes of temperatures below half the height of the green wall were the smallest throughout the entire structure, and they amounted to 5.7°C at the height of 44 cm, and to 5.6°C at the height of 92 cm above the surface. The smallest difference was recorded in the multi-probe at a distance of 140 cm from the ground level, amounting to only 5.4°C, which is a small value compared to the amplitude of temperatures in the outdoor conditions that prevailed on that day. At the time when the highest temperature occurred (see: Table 1) within the 24 hour period, in the observatory, the substrate demonstrated soothing properties, preventing sudden spikes in temperature, according to the measurements carried out on July 25 (see: Fig. 2). The process of warming up this part of the green wall was slow, and it took almost 10 hours. On the analysed day, the temperatures in the substrate decreased, to reach an extreme of 18.5°C at 8:00 in the morning. The temperature distribution, only for this height has reached much higher temperatures between 11:00 and 19:40, which was caused by inflows of heated atmospheric air. That phenomenon was affected by the green roof, located at 2.05 m above the ground. However, the said temperature variation disappeared, and from 20:00 onwards, the multi-probes in the substrate recorded very similar temperatures over the entire span of the green wall.

The multi-probes registered the largest temperature amplitudes at every height in the tested model near the plants, outside the green wall. On the warmest day of May, from 9:00 a.m. onwards, the temperature began to grow rapidly at a height of 188cm above the ground level, to reach 38.4°C at 14:26 (see: Table 3), being the maximum for the entire structure. On this day, the temperature amplitude at this point read 25.5°C, and

Table 1. Characteristic temperatures in the substrate on 28 May 2016, shown for respective heights above the ground

	44 cm	92 cm	140 cm	188 cm	environment	reference model
t_{mean}	17.6°C	17.8°C	17.6°C	19.6°C	20.0°C	20.5°C
t_{max}	20.4°C	20.4°C	20.2°C	24.8°C	26.9°C	34.4°C
t_{min}	14.7°C	14.9°C	14.8°C	15.0°C	13.3°C	11.3°C

Table 2. Characteristic temperatures in the substrate on 25 July 2016, shown for respective heights above the ground

	44 cm	92 cm	140 cm	188 cm	environment	reference model
t_{mean}	20.5°C	20.6°C	20.6°C	21.0°C	22.2°C	23.0°C
t_{max}	22.7°C	23.0°C	22.8°C	24.1°C	28.8°C	35.3°C
t_{min}	18.8°C	18.8°C	18.8°C	18.5°C	17.0°C	15.8°C

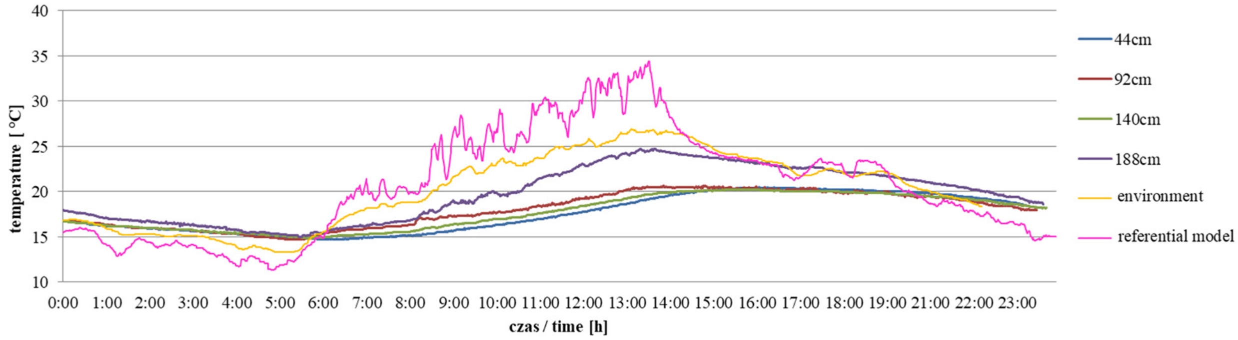

Fig. 2. Distribution of temperatures within the substrate on 28 May 2016

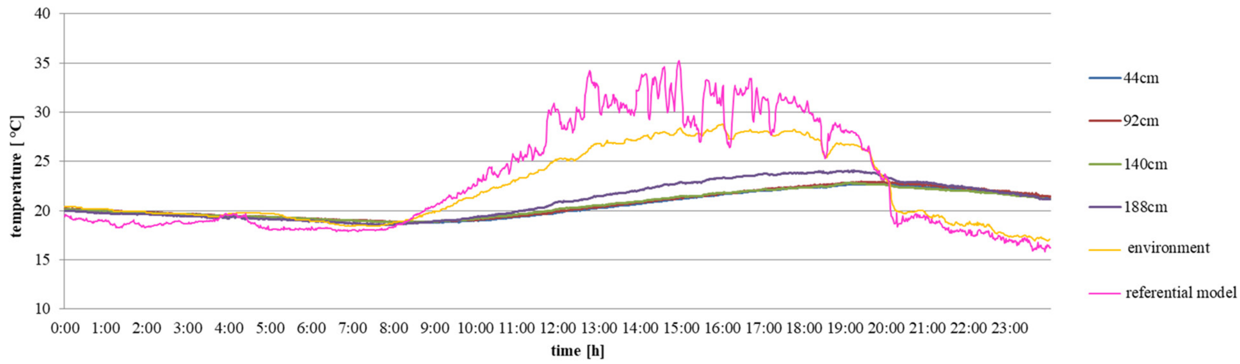

Fig. 3. Distribution of temperatures within the substrate on 25 July 2016

it was higher than the temperature, which was recorded on the reference model. Most likely, on that day there was high solar radiation, coupled with low wind speeds, which limited the exchange of warm and humid air from the close vicinity of the plants. In the case of the analysed day in July (see: Fig. 4), the thermal relations developed in the same way as in the case of May 28. The highest temperature was recorded just outside the green wall, at 188 cm above ground level. From 12:00 noon onwards, the temperature outside the green wall in close proximity to the plant surface has reached values above 30°C, to reach its maximum of 34.6°C after 14:00, and then, decrease its value by several degrees, in step changes. When comparing the temperature values read from the sensors located in close proximity to the plants against the temperatures on the reference model, it was observed that on the smooth surface there were more rapid temperature fluctuations, and higher extremes were recorded in both the highest and lowest temperatures.

Table 3. Characteristic temperatures at a distance of 10 cm from the plant surface on 28 May 2016, shown for respective heights above the ground

	44 cm	92 cm	140 cm	188 cm	environment	reference model
t_{mean}	20.4°C	19.9°C	19.9°C	21.0°C	20.0°C	20.5°C
t_{max}	34.1°C	32.0°C	31.6°C	38.4°C	26.9°C	34.4°C
t_{min}	12.1°C	12.2°C	12.6°C	12.5°C	13.3°C	11.3°C

Table 4. Characteristic temperatures at a distance of 10 cm from the plant surface on 25 July 2016, shown for respective heights above the ground

	44 cm	92 cm	140 cm	188 cm	environment	reference model
t_{mean}	22.5°C	22.2°C	22.2°C	22.5°C	22.2°C	23.0°C
t_{max}	32.2°C	30.8°C	30.3°C	34.6°C	28.8°C	35.3°C
t_{min}	18.2°C	18.2°C	18.1°C	17.8°C	17.0°C	15.8°C

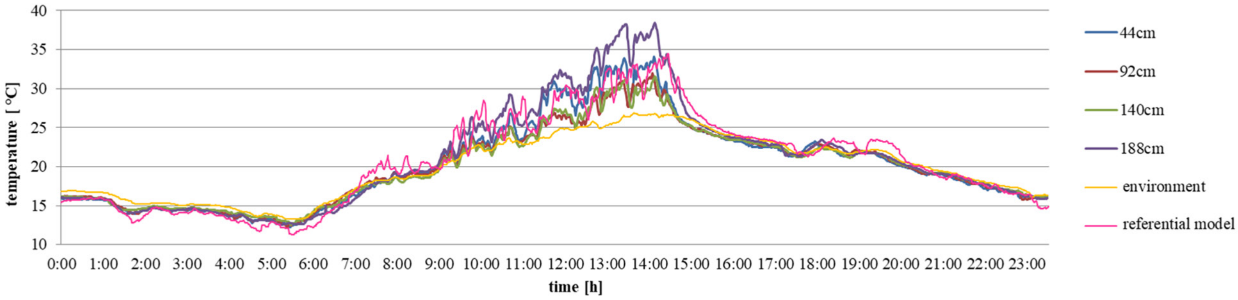

Fig. 4. Distribution of temperatures at a distance of 10 cm from the plant surface on 28 May 2016

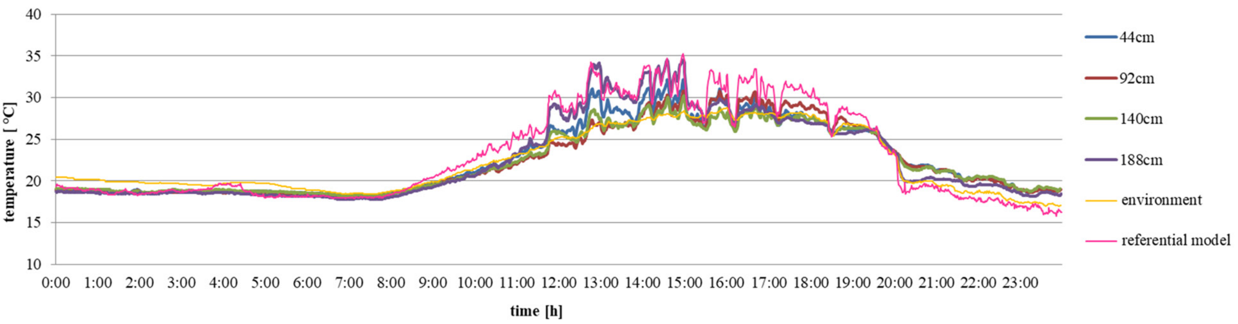

Fig. 5. Distribution of temperatures at a distance of 10 cm from the plant surface on 25 July 2016

The sensors located on the wall behind the panel reflect how the green wall is able to reduce the temperature on the façade of the building. When comparing the extreme values as well as the temperature course during the day, at the highest point of 188 cm above the ground, the highest temperatures during the day were recorded, and the maximum value for 28 May was recorded as 28.4°C at 14.28. At the same time, the lowest temperature occurred at 92 cm, reaching 20.3°C. When comparing the temperatures at both measuring points with the values on the reference model, a reduction in temperature was noted by about 6°C. When observing the temperature distribution on July 25, it was found that the ambient temperature was higher than that temperature recorded on the vegetation-covered wall. The extreme value was registered at a height of 188 cm above ground level, and it was 1.4°C lower than the air temperature (see: Fig. 6). However, the temperature distributions (see: Fig. 5 and 6) show that the thermal relations in the lower parts of the green wall change much more mildly than in the case of higher locations. The temperature amplitude in the lower part of the tested model in May varied from 6°C at the height of 92 cm, to 7.3°C at the height of 44 cm, to 9.9°C at the height of 140 cm. In July, the lowest temperature difference occurred at a height of 92 cm, and it amounted to 4.8°C. In May, temperatures up to 6:00 a.m. remained at a similar level across the entire structure. After 9:00 a.m., the temperature began to increase dramatically from the middle of the height of the green wall upwards. In the case of July, until 9:30 a.m., the temperature in the entire structure differed between the measurement points by a maximum of 1°C. It is worth noting that the green wall heats up evenly.

Table 5. Characteristic temperatures on the wall behind the panel on 28 May 2016, shown for respective heights above the ground

	44 cm	92 cm	140 cm	188 cm	environment	reference model
t_{mean}	18.5°C	18.0°C	18.9°C	20.3°C	20.0°C	20.5°C
t_{max}	21.8°C	20.7°C	23.9°C	28.4°C	26.9°C	34.4°C
t_{min}	14.5°C	14.7°C	14.0°C	13.7°C	13.3°C	11.3°C

Table 6. Characteristic temperatures on the wall behind the panel on 25 July 2016, shown for respective heights above the ground

	44 cm	92 cm	140 cm	188 cm	environment	reference model
t_{mean}	20.8°C	20.6°C	21.6°C	22.2°C	22.2°C	23.0°C
t_{max}	24.4°C	23.4°C	27.3°C	27.4°C	28.8°C	35.3°C
t_{min}	18.5°C	18.6°C	18.6°C	18.4°C	17.0°C	15.8°C

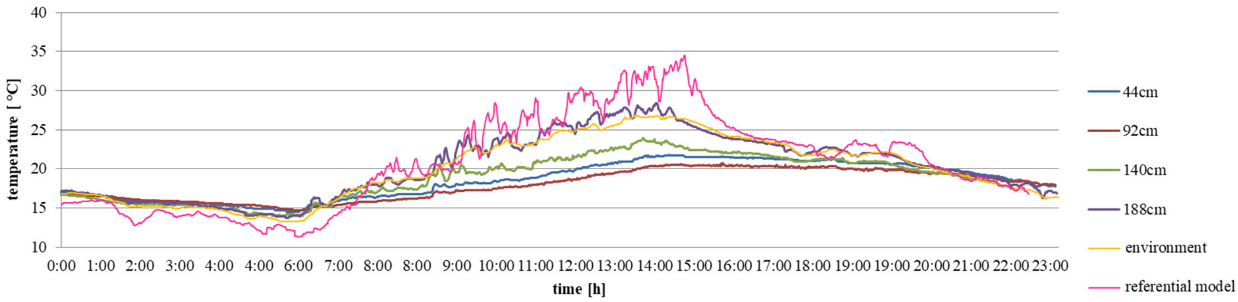

Fig. 6. Distribution of temperatures on the wall behind the panel on 28 May 2016

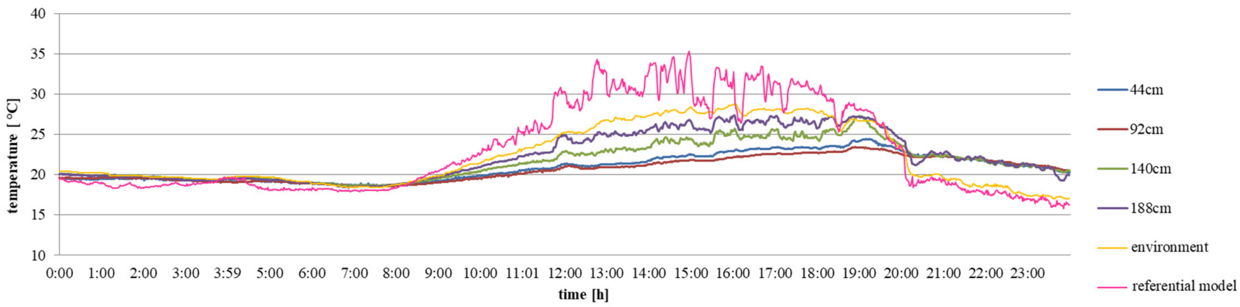

Fig. 7. Characteristic temperatures on the wall behind the panel on 25 July 2016

DISCUSSION

Similar studies were carried out in Singapore on 8 different walls of building elevations, covered with vegetation. The test results from the green wall were compared with measurements recorded on a smooth wall, and with a green wall located inside the building. The measurements were carried out using 16 Hobo H8 sets, recording the temperature and humidity. The devices were placed in front of the control wall, and also on vertical greenery systems, namely at 0.15 m, 0.30 m, and 0.60 m from the ground. The study has shown that the surface covered with greenery can reduce the air temperature by up to 11ºC. Analyses carried out in Lower Silesia, in the Agro-Hydrometeorology Observatory in Wrocław-Swojec, belonging to the University of Environmental and Life Sciences in Wrocław, showed the highest reduction of air temperature in the case of substrate and smooth surfaces, which was 14ºC. In the case of prevailing conditions in the substrate in Singapore, a reduction in the temperature of about 9°C was observed, as compared to the control surface (Wong et al., 2009).

In Turin, a green wall was built, made of modules similar to those in the Wrocław-Swojec Observatory. Temperature analyses in Italy in the winter months showed a reduction of up to 40% in comparison with a plastered wall, which had a noticeable effect on the energy passing through the façade during the heating season. The benefits of using green walls have been noticed during the summer season, when in the presence of vegetation, the surface temperature of the outer wall was reduced down to 23°C, in the case of walls located in Lower Silesia, where the average air temperature behind the panel with vegetation was 21°C (Bianco et al., 2017). Also on the roof of the Hepia School in Geneva, the LEEA Laboratory carried out an experiment using green walls. It consisted in analysing the results of green wall samples (sized 1 m^2), and the walls without a plant cover. During the study, the influence of the green wall on three factors was observed, affecting the thermal balance, evapotranspiration, solar radiation, and convection. The results of the experiment showed that plants covering the walls act as an insulating layer against convective and infrared rays. The average wall surface temperature was about 10°C lower compared to the control wall. The highest temperature reduction was observed when the leaf density was the highest (Malys et al., 2014).

In turn, the experiment carried out at the University of Bari (Italy) lasted two years. During this time, three vertical walls made of perforated bricks were tested: two were covered with evergreen plants, and the third wall was exposed and used as a control unit. Temperatures recorded during the day on the walls that were covered with vegetation were lower by as much as 9.0°C than on the smooth wall. Similar reductions were noted during research at the Wrocław-Swojec observatory, where temperature difference between the reference model and the air temperature on the wall behind the panel was about 10°C. Night-time temperatures during cold days for vegetated walls were higher by 3.5°C as compared to the temperature recorded on the control wall. The thermal effects of the façades during the day were caused by solar radiation, wind speed and relative humidity. The greatest impact of such parameters on the cooling occurred at wind speed of 3–4 m × s^{-1}, relative humidity in the range 30–60%, and solar radiation higher than 800 Wm^2 (Vox et al., 2018).

At the University of La Rochelle in France, mock-ups of buildings and streets were created, whereas the buildings were covered with greenery. The main objective of the study was to assess the impact of green buildings through relative comparisons with the reference street without vegetation under real climatic conditions. Measurements show that the green wall relieves the summer temperature increase by about 1°C to 5°C. These measurements are used to calibrate the street canyon model, in order to assess the energy performance of vegetation-covered buildings subjected to microclimatic conditions (Djedjig et al., 2016). It was noticed that the green wall reduced the temperature on the façade behind the green wall by about 15°C. When the temperature of the smooth façade surface reached 45°C, at the surface covered by the green wall, it did not exceed 28°C. This decrease in surface temperature is the result of the combined effects of evapotranspiration, solar shading and thermal resistance of the substrate and the air layer (Djedjig and al., 2017). Similar research was carried out in Lublin in Poland. The green wall structure was attached to the south and north walls on the university building in Lublin. In the month with the highest average air temperature (June, 2016), the difference between the temperature behind and in front of the wall was on average 4.68ºC during the day, and it was lower behind the green wall. During the night, the difference was on average 1.82ºC, and it was lower in front of the vertical garden. The amplitude of temperatures between day and night in the month of June 2016 was on average 8.33ºC on the wall, and 1.83ºC behind the wall (Mojski et al., 2018).

CONCLUSIONS

Urban development causes the disappearance of green areas in the cities, and in connection with this phenomenon, alternative ways of introducing greenery to urbanized areas are sought. One of them is the use of green walls on the façades of buildings. The vertical garden affects the air temperature, by reducing the temperature on the surface of the heated building, while also further improving the aesthetic value of the city, introducing peace into the harsh landscape of modern architecture, and purifying the air from toxins (Sheweka and Mohamed, 2012)

The research aimed at determining the impact of plant cover on the spatial distribution of temperatures in experimental models of green walls, through the analysis of thermal relations at certain levels, in different parts of the model, but also in its close vicinity. Temperature differences were determined between the green wall, and a smooth wall without plant cover. The results obtained allowed us to draw the following conclusions:

1) The plant cover acted like a heat-insulating layer. The surface of the leaves of the plants partially absorbs, and also reflects the radiation, creating a shaded area in the soil substrate. The proof of this is the temperature lower by 6°C as recorded in the substrate, compared to the air temperature prevailing in the observatory where the test was carried out.
2) The analysis of the temperature distribution for the reference model demonstrated that the temperature amplitude was much higher than in the green wall model. On July 25, the amplitude was 19.5°C, and at the same time, the temperature amplitude of 9.8°C was recorded on the wall covered with plants.
3) During the research, it was observed that the surface of the wall without the plant cover heated up much faster than the biologically active surface, reaching values higher than the air temperature by an average of 2.6°C. A similar situation occurred when the heat was passed off by the reference model, which was cooler by as much as 1.2°C than the atmospheric air.
   High temperature fluctuations in the reference model may be caused by sudden changes in the direction and force of the wind, which causes the movement of the heated air.
4) When comparing the models, it can be concluded that the use of a green wall on the façade of the building has positive impact on mitigating fluctuations in air temperature, and thus on the microclimate within the structure.

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BADANIA EKSPERYMENTALNE WŁAŚCIWOŚCI CIEPLNYCH W PIONOWYCH SYSTEMACH ROŚLINNYCH

ABSTRAKT

Rozwój miast powoduje zanikanie powierzchni zazielenionych w mieście, co częściowo jest przyczyną wzrostu temperatury w miastach i powstawania efektu „wyspy ciepła". Aby ograniczyć nagrzewanie aglomeracji powinno się zacząć stosować alternatywne sposoby wprowadzania zieleni na tereny zurbanizowane. Jednym z nich jest zastosowanie zielonych ścian na elewacjach budynków. Wertykalny ogród wpływa na temperaturę powietrza, redukując temperaturę na powierzchni nagrzanego budynku. Dodatkowo zielone ściany poprawiają walory estetyczne miasta, wprowadzając równowagę w surowy krajobraz nowoczesnej architektury oczyszczają powietrze z toksyn. W pracy omówiono problematykę związaną z termiką zielonych ścian. Badania były prowadzone w 2016 roku na modelach doświadczalnych zlokalizowanych na terenie Dolnego Śląska na terenie obserwatorium Agro-Hydrometeorologii Wrocław-Swojec, Uniwersytetu Przyrodniczego we Wrocławiu. Celem badań było określenie wpływu otoczenia na kształtowanie się stosunków termicznych wewnątrz zielonej ściany. Obserwacje były prowadzone na południowej stronie budynku. Przeprowadzone analizy pokazały, że pokrywa roślinna działa jak warstwa izolacyjna. Dzięki niej można ustabilizować warunki termiczne panujące na ścianie za panelem. Dla porównania właściwości pionowego ogrodu obserwacje były równocześnie prowadzone na modelu referencyjnym będącym gładką ścianą bez pokrywy roślinnej. Porównując wyniki badań z obu modeli stwierdzono, że zielona ściana w jest w stanie ograniczać nagrzewanie się zewnętrznej części budynku, a co za tym idzie ograniczyć wahania temperaturowe powietrza w pomieszczeniach.

Słowa kluczowe: zielona ściana, pionowy ogród, temperatura powietrza, termoizolacja